

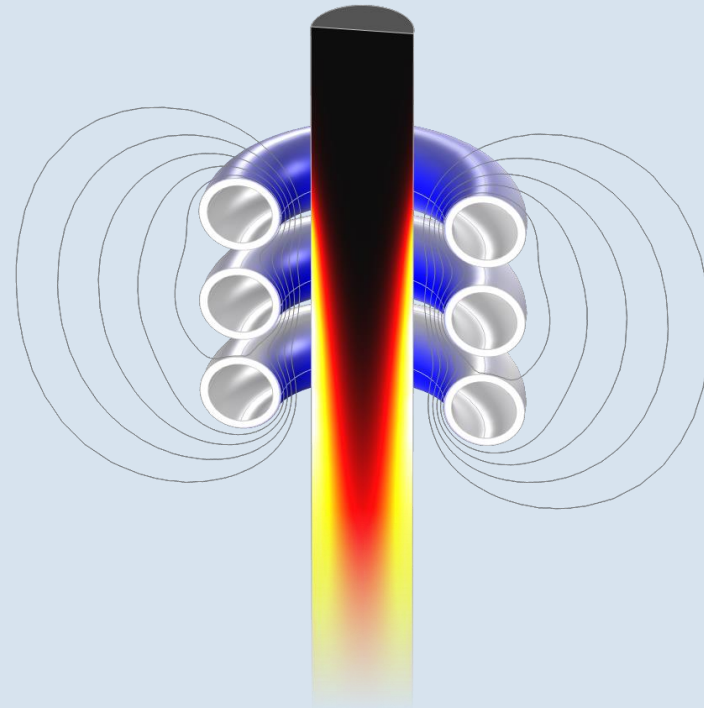
Electromagnetic Heating

Matouš Lorenc

lorenc@humusoft.cz

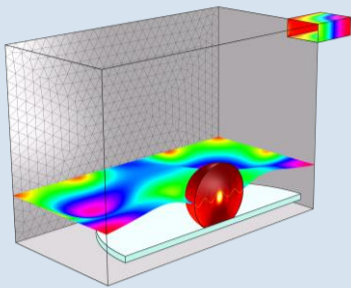
Agenda

- Thermal management of EM devices
- Joule heating
- Induction heating
- DEMO: Creating induction boiler from scratch



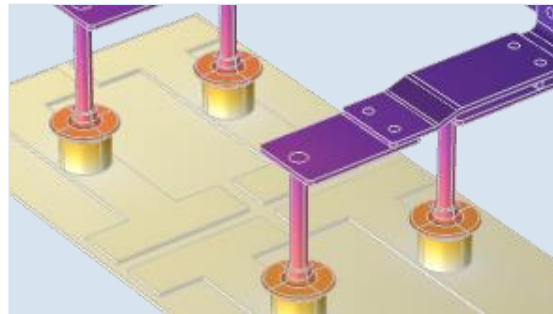
Induction heating of a ferritic steel rod with Curie point effect

Multiphysics Couplings



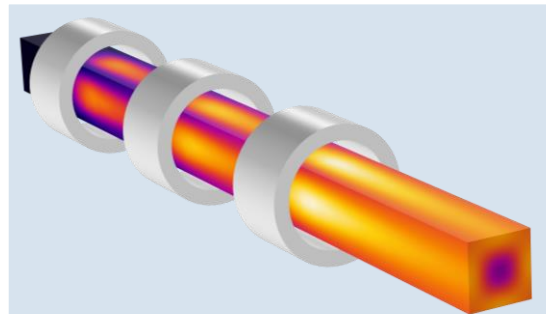
Microwave Heating

- Potato in microwave oven



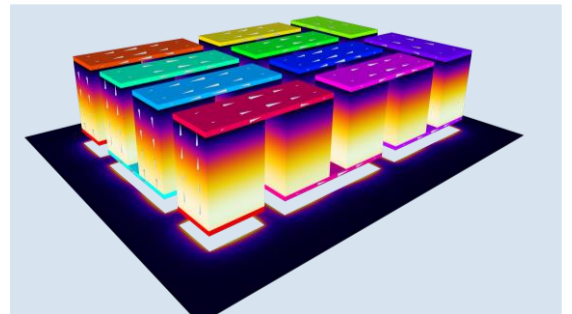
Joule Heating

- Busbar



Inductive Heating

- Steel billet induction heating

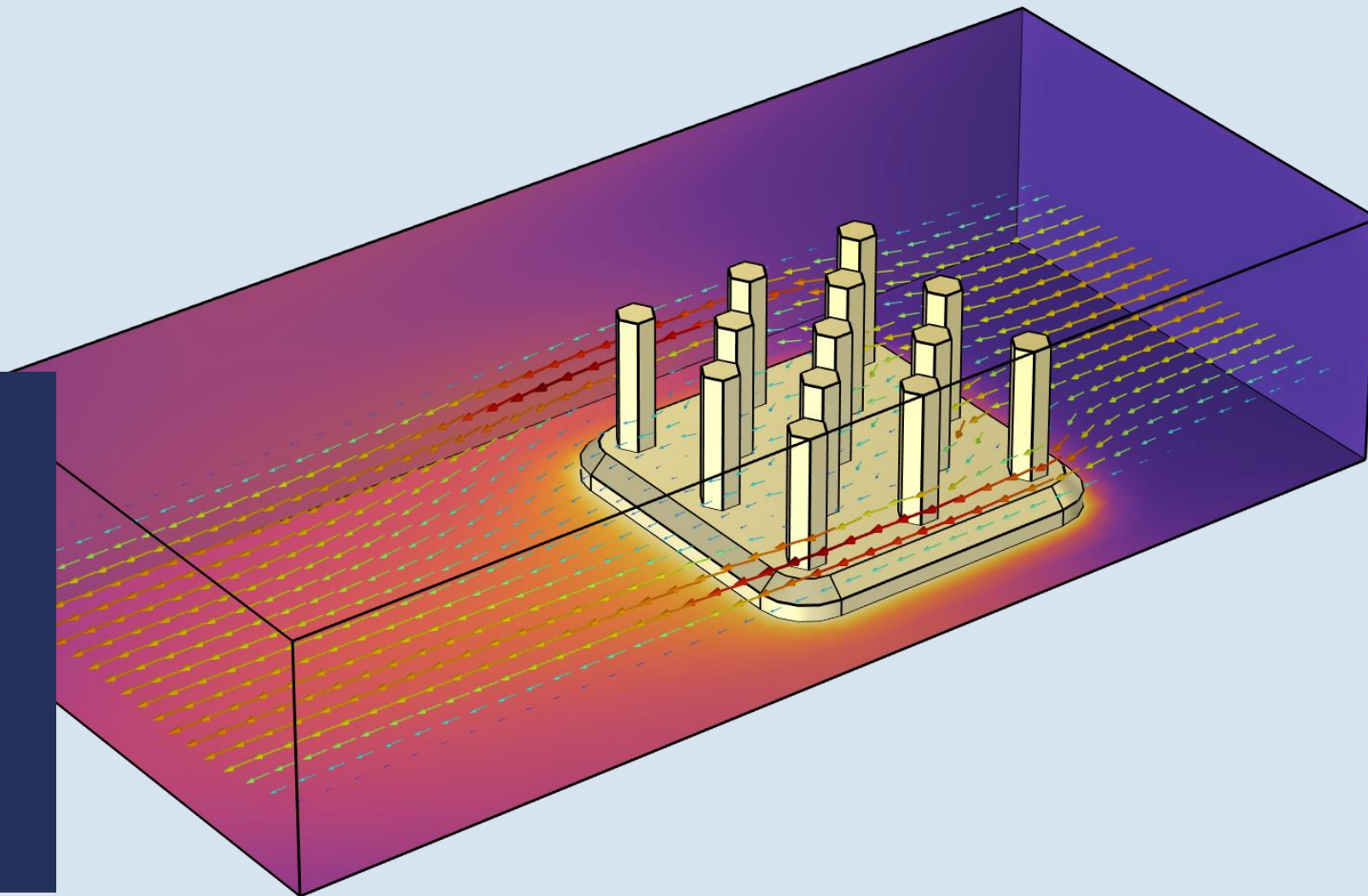


Thermoelectric Effect

- Thermoelectric cooler

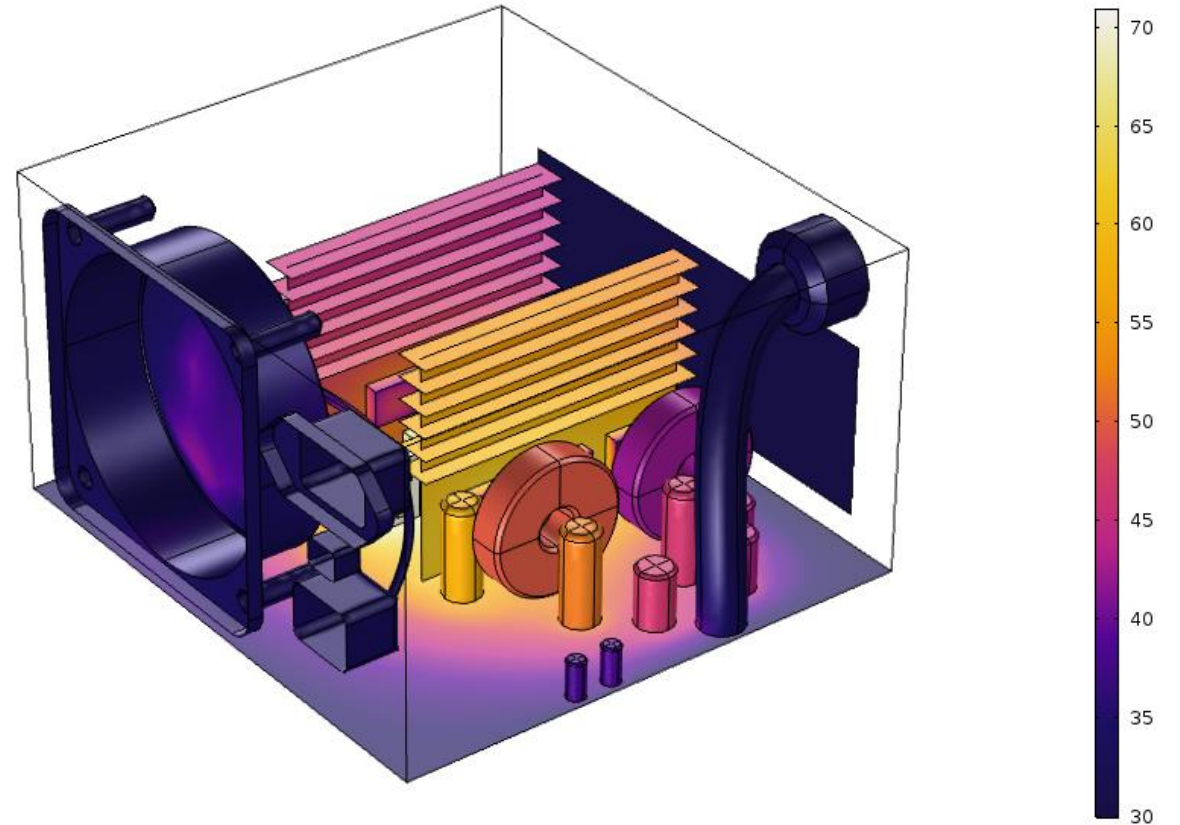
Thermal Management

Keeping your electric devices cool



Thermal Management: Motivation

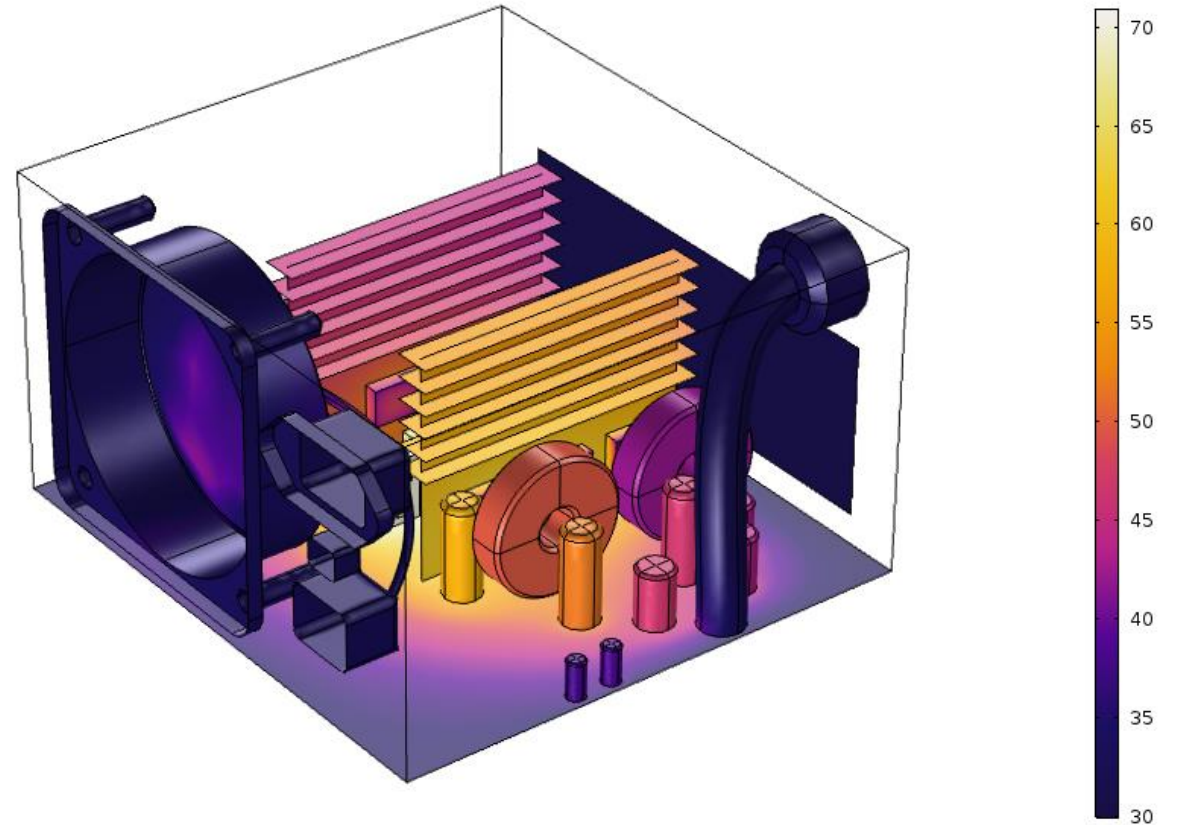
- Power electronics and electronic consumer devices generate heat
- Excessive heat can:
 - Cause malfunctions
 - Affect functionality
 - Decrease reliability
 - Shorten life span



A fan drives the forced convection (air cooling) across the power supply unit with multiple electronic components acting as heat sources

Thermal Management: Motivation

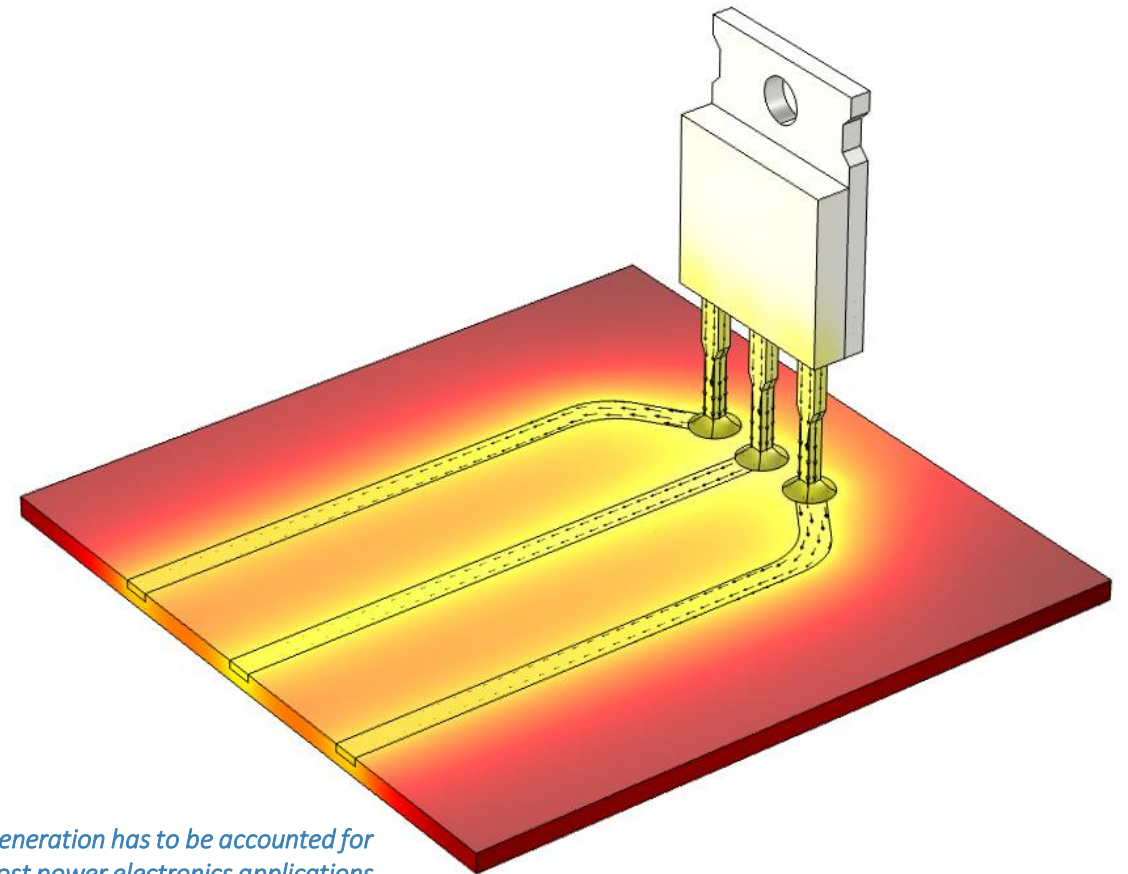
- Thermal management:
 - Ability to control temperature of system
 - Based on thermodynamics, fluid dynamics, electrochemistry, and electromagnetic effects
 - Active vs. passive management
 - Steady-state vs. time-dependent control



A fan drives the forced convection (air cooling) across the power supply unit with multiple electronic components acting as heat sources

Thermal Management: Challenges

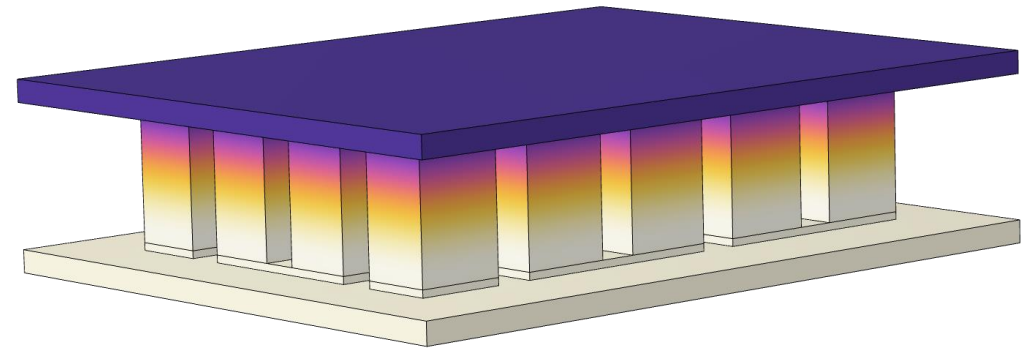
- Customer-focused design:
 - Greater miniaturization
 - Increased power demands
 - Longer expected life spans
 - Cost reduction/competition
- Various heat sources: chips, batteries, etc.
- New advanced, multicomponent systems
- Evermore challenging operating conditions
- Introduction of new materials



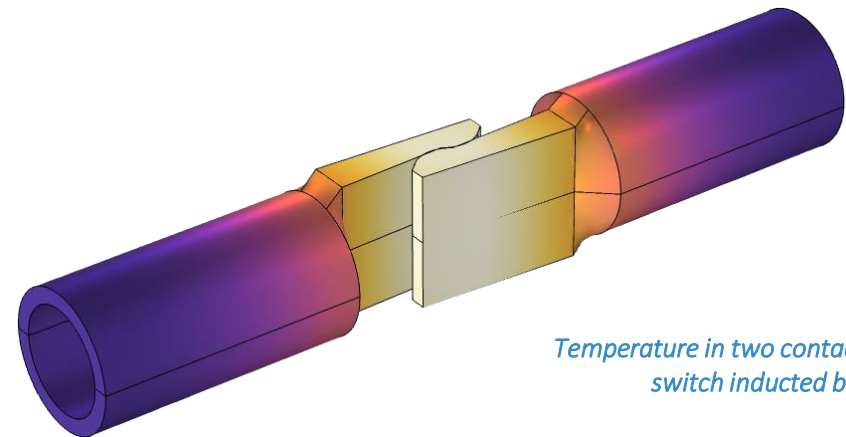
Power transistor: heat transfer and heat generation has to be accounted for in most power electronics applications

Thermal Management: Modeling

- Gain insight into design requirements and investigate potential improvements
- Advantages:
 - Advanced and flexible analysis tool
 - Reduce design time
 - Does not require physical prototype
 - Perform large parametric/design space studies
- Modeling options:
 - Full model including different physics
 - Simplified model with selected physics only
 - Lumped (sub-)models for system analysis



Temperature drop demonstrating Peltier effect in a single-stage thermoelectric cooler

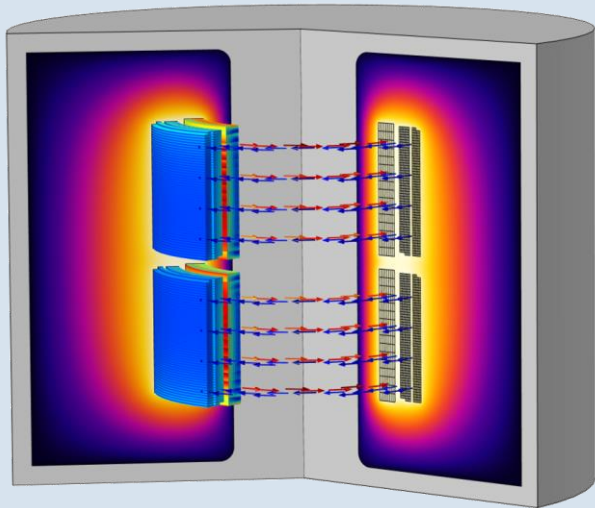


Temperature in two contacting parts of a switch induced by Joule heating

Thermal Management in COMSOL Multiphysics®

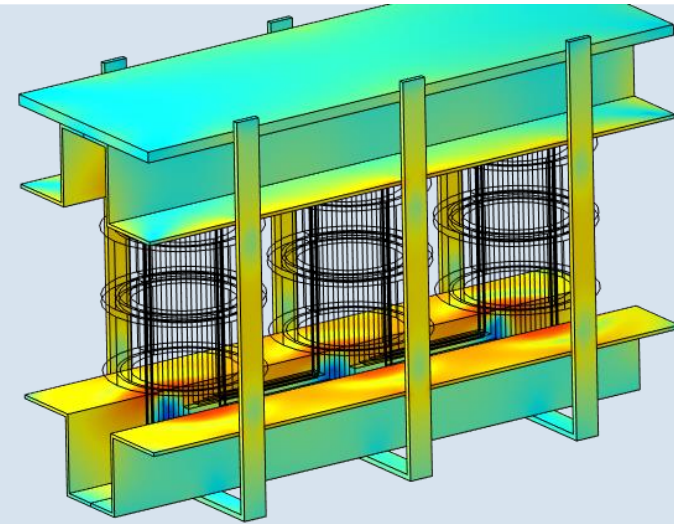
- Modules:
 - Heat Transfer Module: conduction, convection, and radiation modeling
 - AC/DC Module: electromagnetic heating
- One-way vs. two-way coupling
- Implicit vs. explicit modeling of heat sources
- Study types:
 - Stationary
 - Time dependent
 - Frequency-stationary and frequency-transient
- Postprocessing: visualizations, probes, energy balances, etc.

Electromagnetic Heating



Joule Heating

- Electric Currents + Heat Transfer + Multiphysics Couplings



Induction Heating

- Magnetic Fields + Heat Transfer + Multiphysics Couplings

Select Physics

Search

- Recently Used
- AC/DC
 - Electric Fields and Currents
 - Magnetic Fields, No Currents
 - Electromagnetic Fields
 - Electromagnetic Heating
 - Joule Heating
 - Joule Heating and Thermal Expansion
 - Induction Heating
 - Electromagnetics and Mechanics
 - Particle Tracing
 - Electrical Circuit (cir)
- Acoustics
- Chemical Species Transport
- Electrochemistry
- Fluid Flow
- Heat Transfer
- Optics
- Plasma
- Radio Frequency

Add

Added physics interfaces:

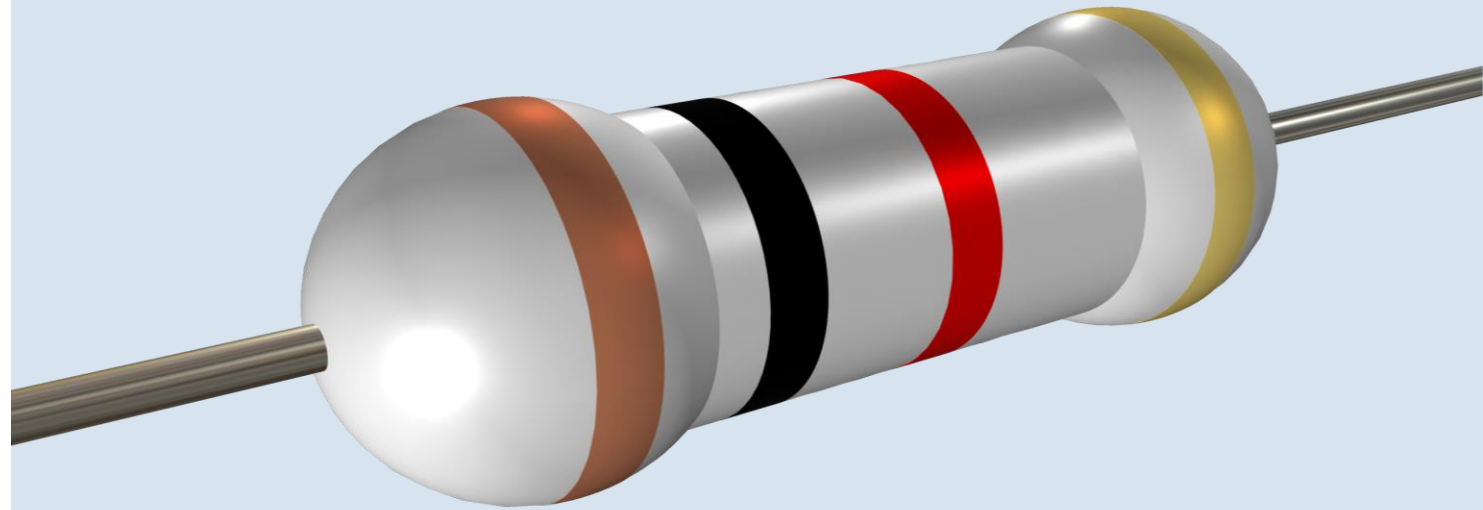
- Electric Currents (ec)
- Heat Transfer in Solids (ht)
- Multiphysics
 - Electromagnetic Heating (emh1)

Joule Heating

- Model resistive heating and resulting stationary or time-dependent temperature distribution
- Combines the *Electric Currents* and *Heat Transfer in Solids* interfaces, and adds an *Electromagnetic Heating* feature constituting the heat source

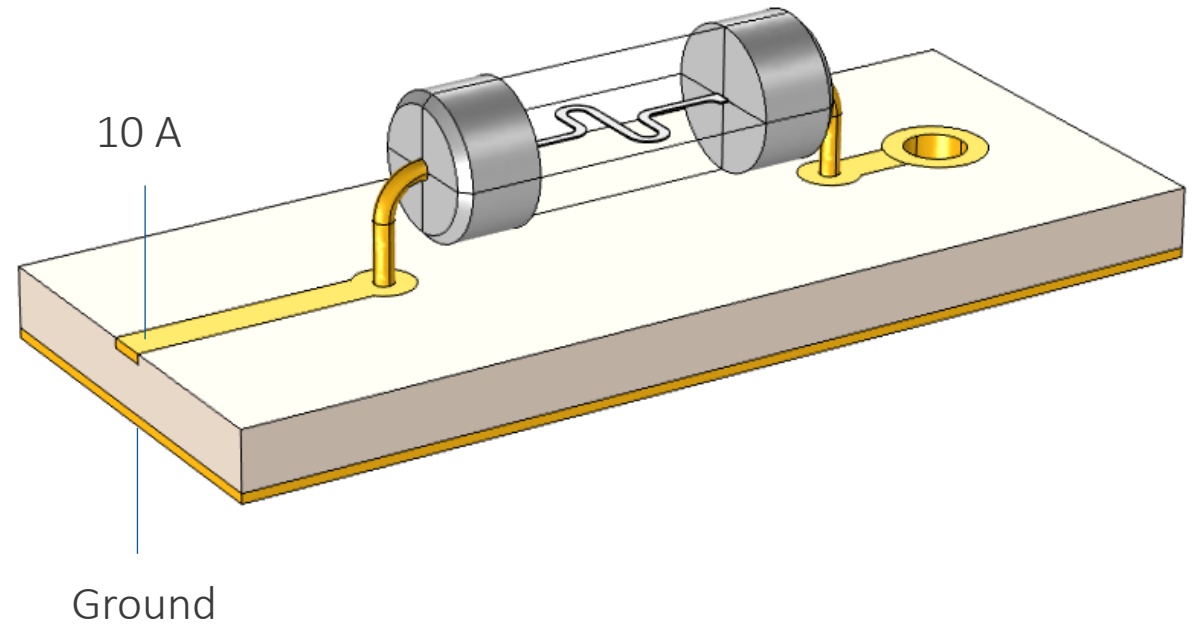
Electric Currents, Stationary

- Solve the equation
$$-\nabla \cdot (\sigma \nabla V) = Q_v$$
in conductors
- Model DC and slowly varying currents in wires, resistors, busbars, sea water, etc.
- Compute local electric fields and current densities, resistances, Joule heating, etc.



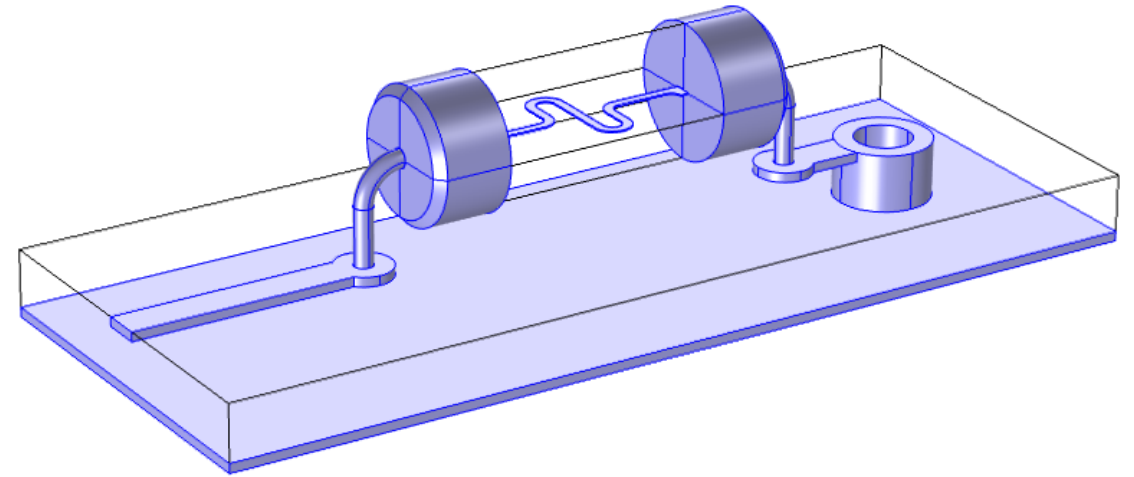
Joule Heating Demo: Fuse

- The traces are made of copper; the fuse heat sinks and wire of aluminum
- We will apply a current of 10 A through the fuse and calculate the resulting voltage and temperature distribution, assuming that the materials stay solid
- Aluminum melts at 660°C . If that temperature is exceeded, the fuse will break.



DC Electric Currents Modeling Advice

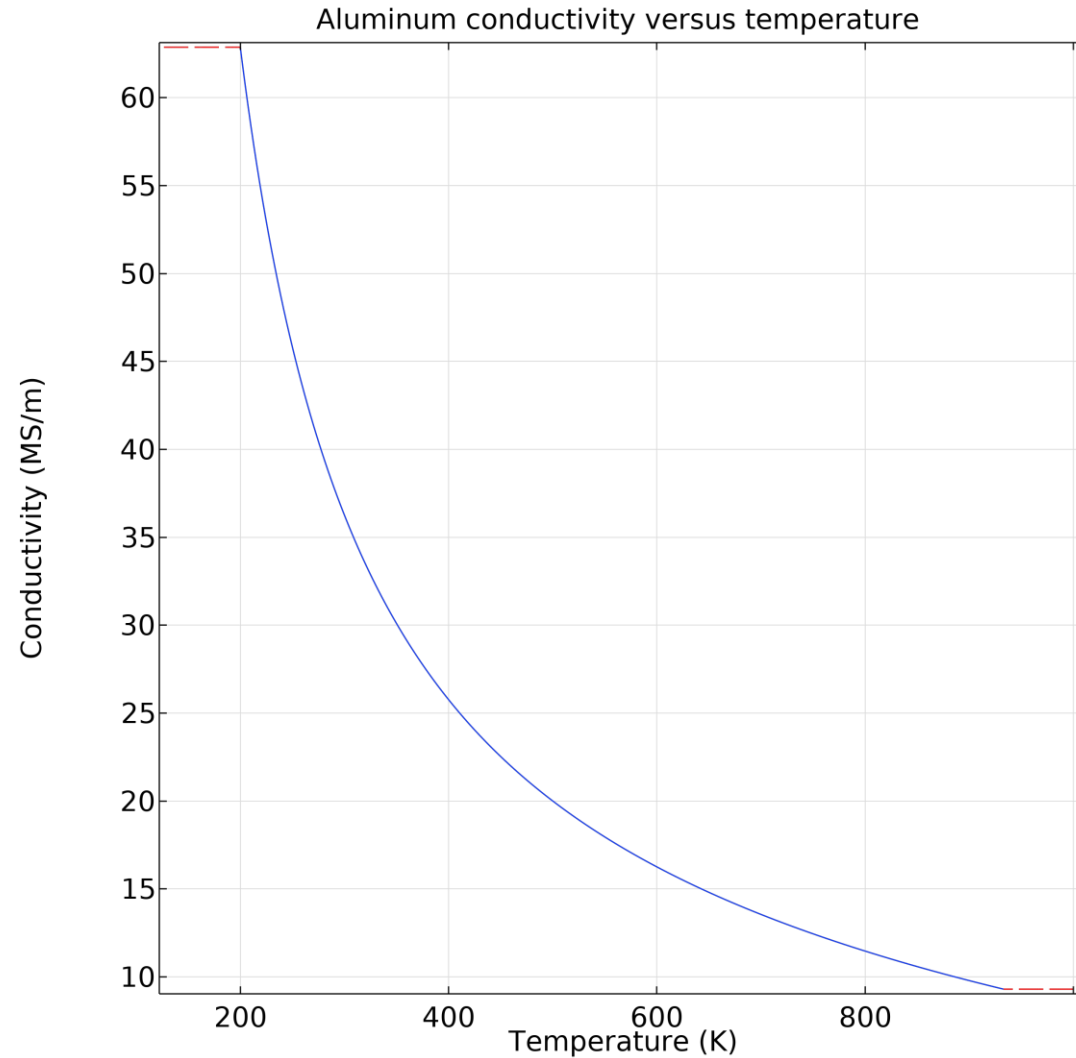
- Include only conductors in the simulation
- Skip also (relatively) very poor conductors, such as circuit board substrates
- Just like in electrostatics, include at least one ground (or potential) condition in order to get a unique solution



The conductors are marked in blue. The vacuum and circuit board domains are left out of the simulation.

Joule (and Inductive) Heating Modeling Advice

- Consider using temperature-dependent properties
- If you do, use a single study step (Stationary or Time Dependent) to solve both physics simultaneously, accounting for the two-way coupling
- If you choose to neglect the temperature dependence, a sequential solution approach is typically more efficient



Joule (and Inductive) Heating Modeling Advice

Sequential solution with stationary heat transfer

Study 1

- Step 1: Stationary
- Step 2: Stationary 2

Physics and Variables Selection			
<input type="checkbox"/> Modify model configuration for study step			
Physics interface	Solve for	Equation form	
<input checked="" type="radio"/> Electric Currents (ec)	<input checked="" type="checkbox"/>	Automatic (Stationary)	
<input checked="" type="radio"/> Heat Transfer in Solids (ht)	<input type="checkbox"/>	Automatic (Stationary)	
Multiphysics couplings			
Physics interface	Solve for	Equation form	
<input checked="" type="radio"/> Electromagnetic Heatin...	<input type="checkbox"/>	Automatic (Stationary)	

Physics and Variables Selection			
<input type="checkbox"/> Modify model configuration for study step			
Physics interface	Solve for	Equation form	
<input type="radio"/> Electric Currents (ec)	<input type="checkbox"/>	Automatic (Stationary)	
<input checked="" type="radio"/> Heat Transfer in Solids (ht)	<input checked="" type="checkbox"/>	Automatic (Stationary)	
Multiphysics couplings			
Physics interface	Solve for	Equation form	
<input checked="" type="radio"/> Electromagnetic Heatin...	<input checked="" type="checkbox"/>	Automatic (Stationary)	

Sequential solution with time dependent heat transfer

Study 1

- Step 1: Stationary
- Step 2: Time Dependent

Physics and Variables Selection			
<input type="checkbox"/> Modify model configuration for study step			
Physics interface	Solve for	Equation form	
<input checked="" type="radio"/> Electric Currents (ec)	<input checked="" type="checkbox"/>	Automatic (Stationary)	
<input checked="" type="radio"/> Heat Transfer in Solids (ht)	<input type="checkbox"/>	Automatic (Stationary)	
Multiphysics couplings			
Physics interface	Solve for	Equation form	
<input checked="" type="radio"/> Electromagnetic Heatin...	<input type="checkbox"/>	Automatic (Stationary)	

Physics and Variables Selection			
<input type="checkbox"/> Modify model configuration for study step			
Physics interface	Solve for	Equation form	
<input checked="" type="radio"/> Electric Currents (ec)	<input type="checkbox"/>	Automatic (Stationary)	
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Multiphysics couplings			
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<input checked="" type="radio"/> Electromagnetic Heatin...	<input checked="" type="checkbox"/>	Automatic (Stationary)	

Select Physics

Search

- ▶ Recently Used
- ▲ AC/DC
 - ▶ Electric Fields and Currents
 - ▶ Magnetic Fields, No Currents
 - ▶ Electromagnetic Fields
 - ▲ Electromagnetic Heating
 - ▶ Joule Heating
 - ▶ Joule Heating and Thermal Expansion
 - ▶ Induction Heating
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- ▶ Acoustics
- ▶ Chemical Species Transport
- ▶ Electrochemistry
- ▶ Fluid Flow
- ▶ Heat Transfer
- ▶ Optics
- ▶ Plasma
- ▶ Radio Frequency

Add

Added physics interfaces:

- ▶ Electric Currents (ec)
- ▶ Heat Transfer in Solids (ht)
- ▲ Multiphysics
 - ▶ Electromagnetic Heating (emh1)

Induction Heating

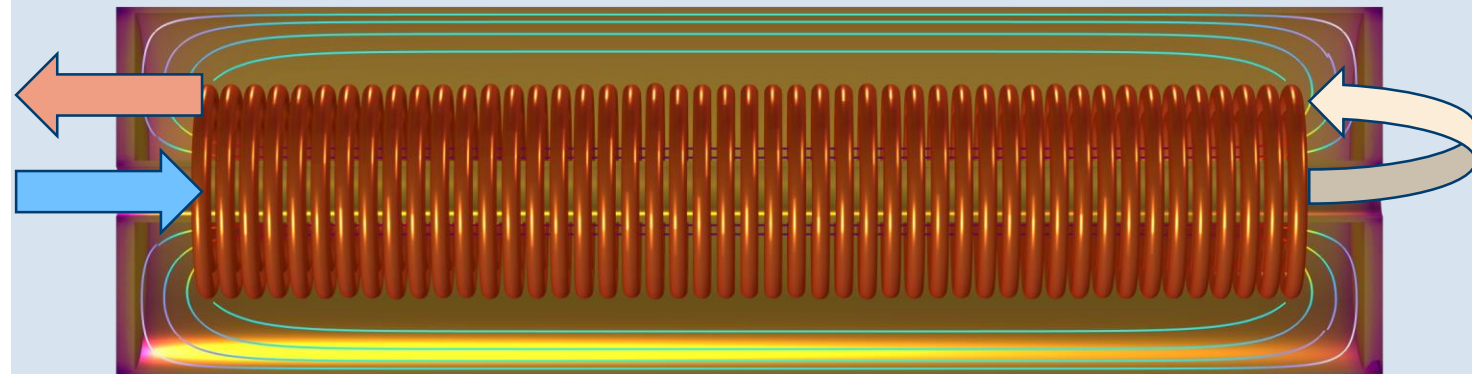
- Model inductive heating from AC currents, and resulting stationary or time-dependent temperature distribution
- Combines the *Magnetic Fields* and *Heat Transfer in Solids* interfaces, and adds an *Electromagnetic Heating* feature constituting the heat source
- Choose one of four preset studies:
 - *Frequency-Stationary*
 - *Frequency-Stationary, One-Way Electromagnetic Heating*
 - *Frequency-Transient*
 - *Frequency-Transient, One-Way Electromagnetic Heating*

Magnetic Fields

- Solve Maxwell–Ampère’s law for the magnetic vector potential
- Typical equation formulations, with $\mathbf{B} = \nabla \times \mathbf{A}$:
 - Stationary:
$$\nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) = \mathbf{J}$$
 - Time dependent:
$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) = \mathbf{J}_e, \mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$$
 - Frequency domain:
$$(j\omega\sigma - \omega^2 \varepsilon_0) \mathbf{A} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) = \mathbf{J}_e, \mathbf{E} = -j\omega \mathbf{A}$$
- Compute local electric and magnetic fields, taking resistive, capacitive, and inductive effects into account
- Common driving mechanisms: *Coil, Background Field, Lumped Port*

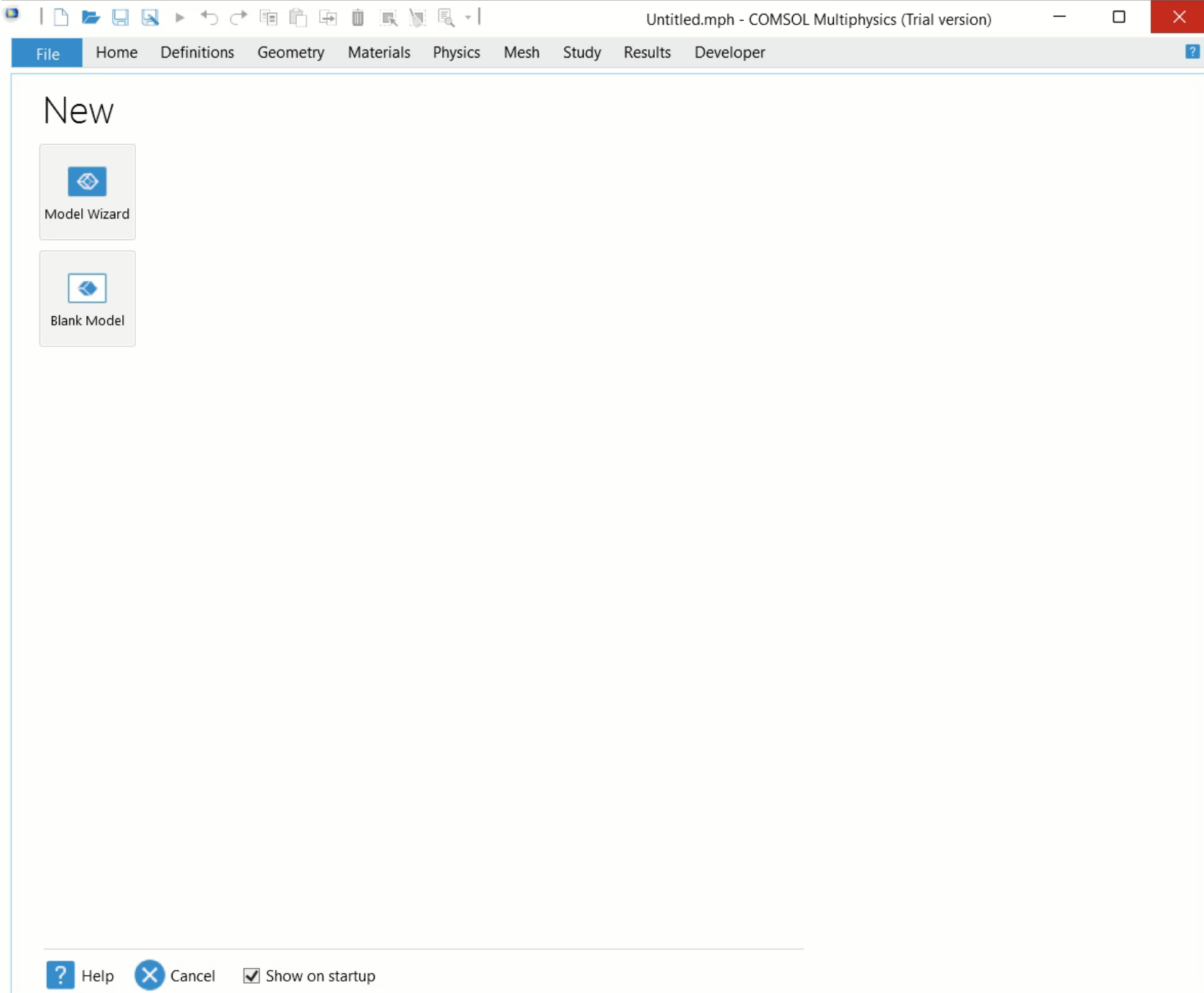
DEMO: Designing our “New Product”

- Compact boilers are a cheap and effective solution with easy power regulation based on water flow
- Our boiler’s design focuses on effectivity so that no Watt goes in vain
- Let’s start from the basic principles – with the induction heating

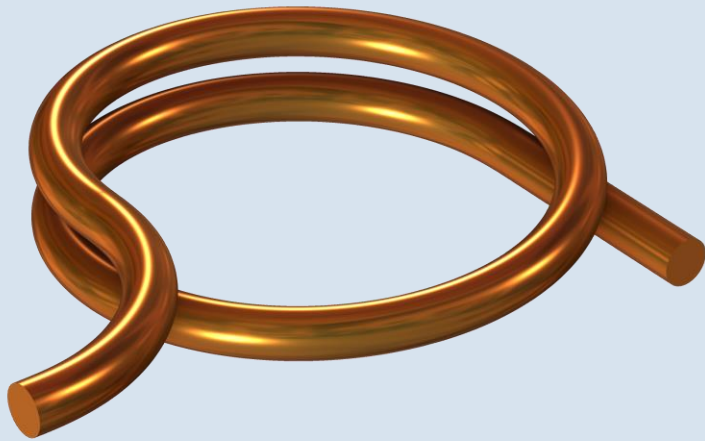


Induction Boiler: Parameters

- Parameters can be:
 - Loaded from file
 - Manually filled
 - Organized into groups
 - Saved to file for further use
- Parameters define:
 - Geometry dimensions
 - Physics inputs
 - Meshing sequence constraints
 - And more...
- Parameters are great, use parameters!

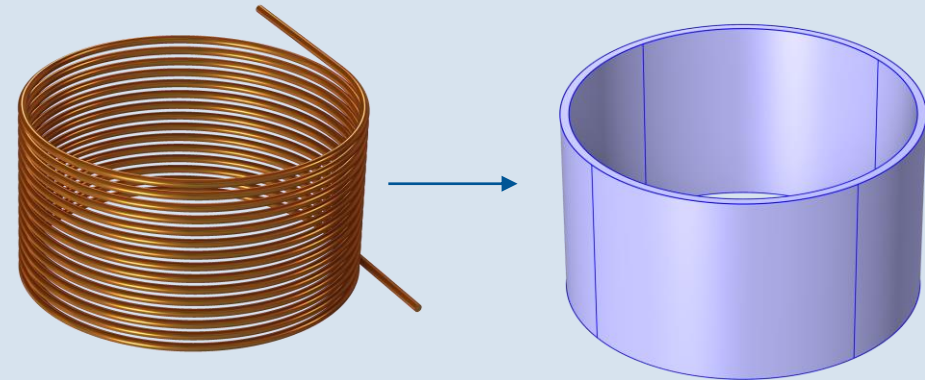


Coils in 3D, Introduction



Solid Conductors

- Draw the wire constituting the conductor as is
- Results include skin and proximity effects



Homogenized Multitrans Coils

- Draw a simplified geometry and specify the number of turns in the *Coil* feature
- Good approximation if the skin depth is much less than the wire radius

Induction Boiler: Geometry

- Geometry can be:
 - Imported from CAD or LiveLinked to one
 - Created from mesh file (.STL)
 - Created directly in COMSOL taking advantage of the Parasolid Kernel
- “Coil” domain is ready to be defined as a *Homogeneous multiturn coil*
- “Boiler body” together with the “Inner tube” compose the *Single conductor* type of coil
- “Air” domain is the necessary medium to calculate the magnetic field

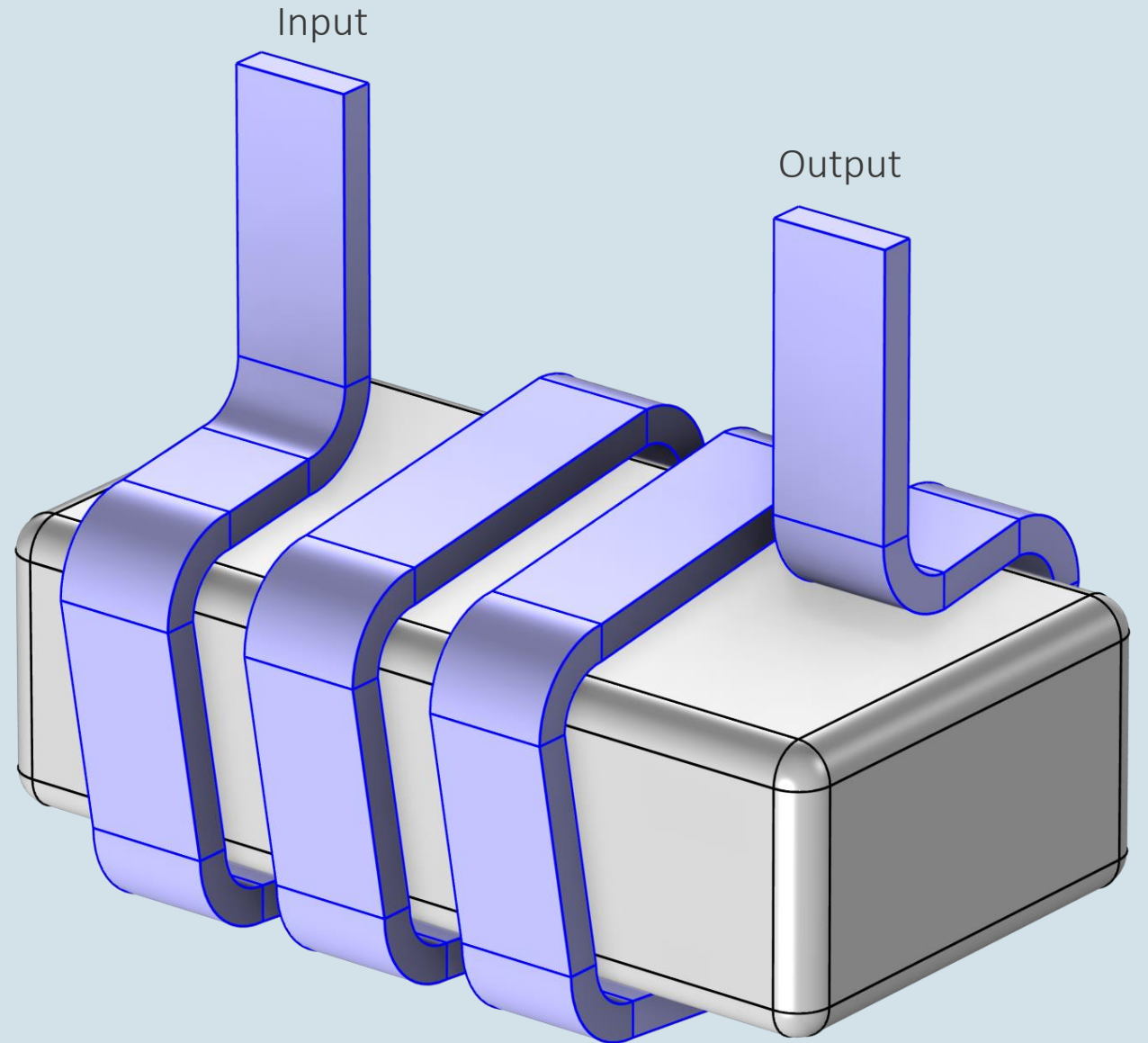
The screenshot displays the COMSOL Multiphysics interface for a model named "Untitled.mph". The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, Results, and Developer. The main workspace is divided into several panels:

- Model Builder:** Shows a hierarchical tree of the model structure. The "Parameters - Matouš" node is selected, and its sub-items include "Ampère's Law", "Magnetic Insulation 1", "Initial Values 1", "Equation View", "Heat Transfer in Solids (ht)", "Solid 1", "Equation View", "Initial Values 1", "Thermal Insulation 1", "Equation View", "Multiphysics", "Electromagnetic Heatir", "Mesh 1", "Study 1", "Step 1: Coil Geometry Anal", "Solver Configurations", "Job Configurations", and "Results".
- Settings:** Displays the configuration for the selected "Parameters - Matouš" node. It includes a "Label" field with the value "Parameters - Matouš" and a table of parameters.
- Graphics:** Shows a 3D coordinate system with x, y, and z axes.
- Messages:** A panel at the bottom right showing system messages, including a license expiration notice and a geometry error message: "COMSOL Multiphysics 6.1.0.357 License will expire in 8 days. [May 23, 2023, 1:17 PM] Geometry error (ext2): You need to provide input c".

Name	Expression	Value
r_b	30 [mm]	0.03 m
h_b	200 [mm]	0.2 m
th_bw	1 [mm]	0.001 m
th_bb	3 [mm]	0.003 m
r_t	5 [mm]	0.005 m
w_c	8 [mm]	0.008 m
h_c	180 [mm]	0.18 m
r_a	40 [mm]	0.04 m
h_a	250 [mm]	0.25 m
N	100	100
Ia	30 [A]	30 A
fa	16 [kHz]	16000 Hz
sdepth	sqrt(2)/(6e7[S/m...	5.1367E-4 m

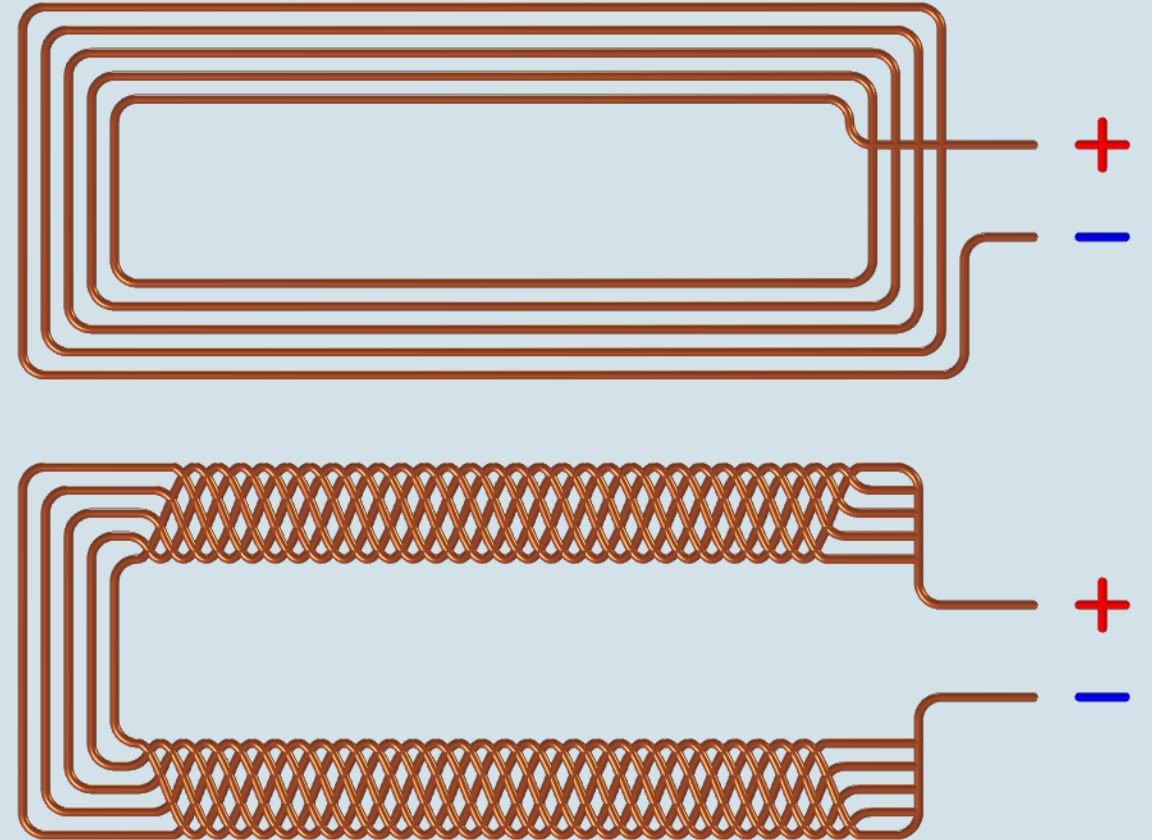
Homogenized Coils

- A winding making many turns or consisting of many litz wires can be too detailed to resolve explicitly in the geometry
- The *Coil* feature has an option for modeling homogenized multiturn coils
- *Input* and *Output* boundaries define the direction of the voltage or current excitation
- A dedicated *Coil Geometry Analysis* study step determines the local current direction

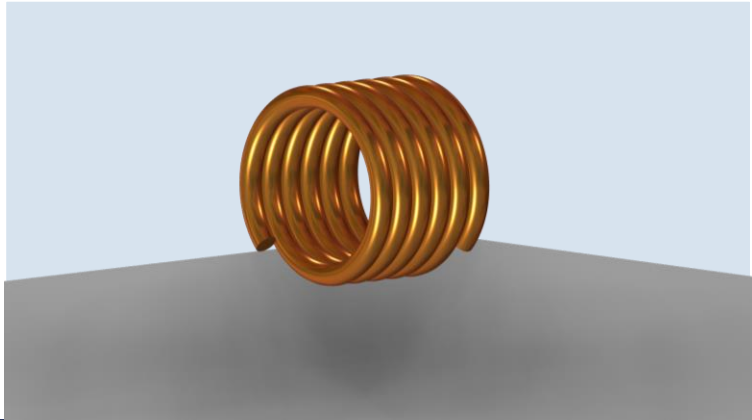


Coils and Litz Wires

- Coils: turns connected in series
- Litz wires: strands connected in parallel
- Model Litz wire with the *Coil* feature in 2D:
Use Coil Group setting
- Model Litz wire with the *Coil* feature in 3D:
Use Homogenized Multiturn setting; set the number of turns N to "1" and a_{coil} to the sum of all strands

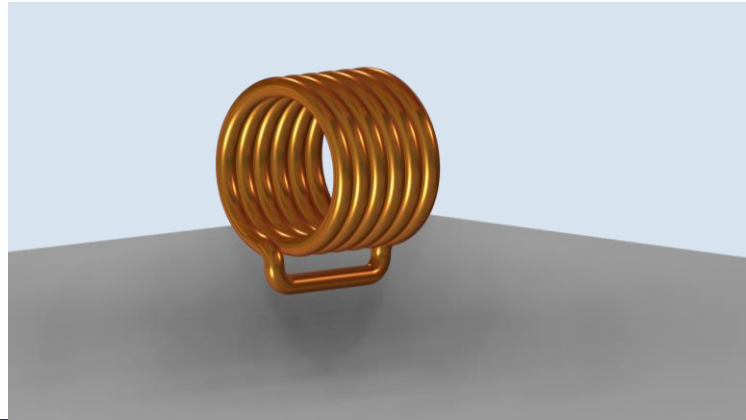


Numerical 3D Coil Geometries



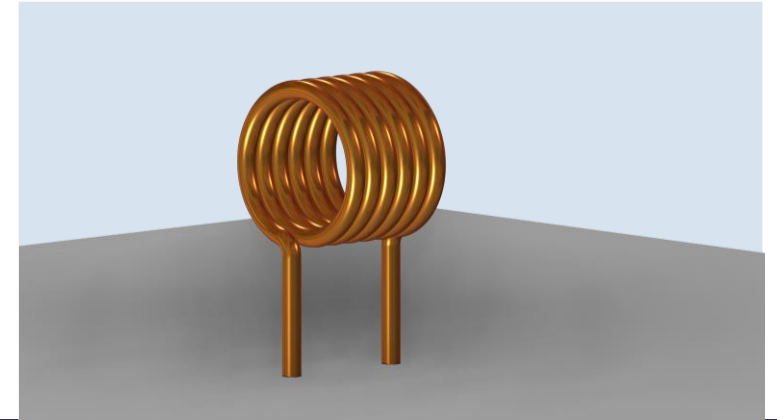
Incorrect

- This coil cannot be driven, as current continuity demands that the current that you feed into it would have to continue in the surrounding air



Correct

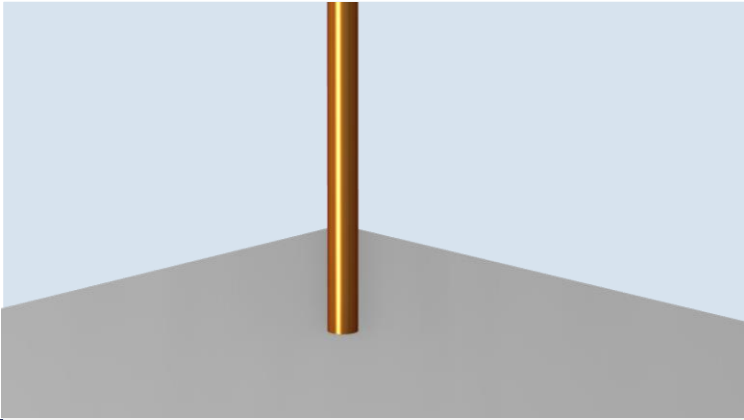
- The coil is closed inside the modeled geometry



Correct

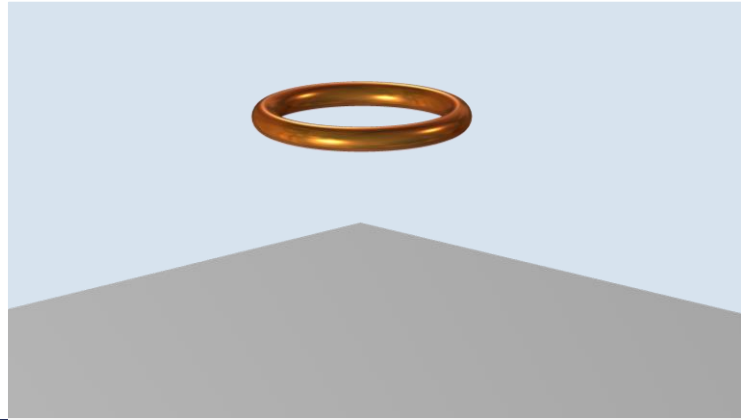
- Continuity is maintained by currents propagating on the exterior surface of the geometry

Analytical 3D Coil Geometries



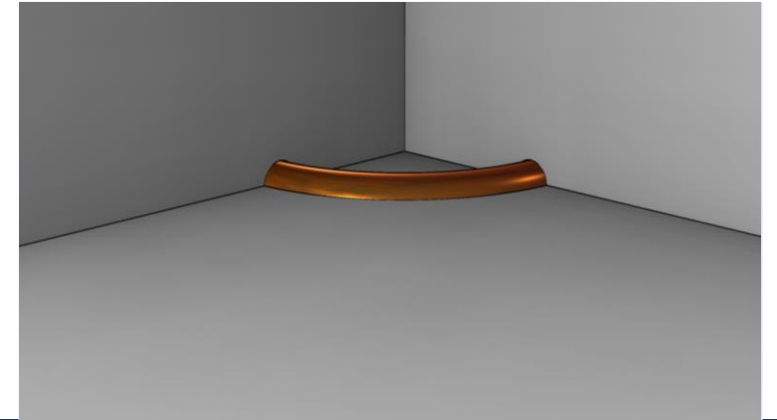
Linear Coil

- Select an edge to specify the direction
- Must begin and end at exterior boundaries



Cylindrical Coil

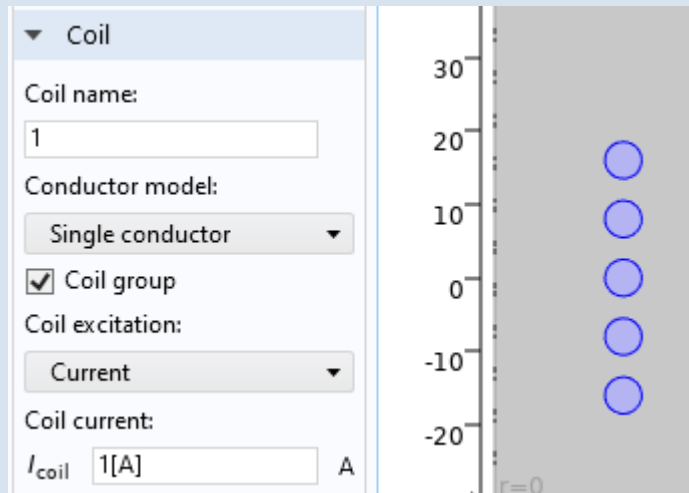
- Select a closed loop of edges



Cylindrical with Symmetries

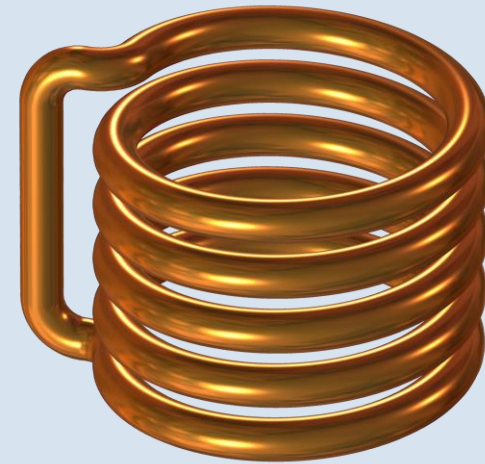
- Set length and area multiplication factors, here 4 and 2 respectively

Coils in Axisymmetric 2D



Setup in 2D Axisymmetry

- Use the *Coil group* option to connect turns in series
- The *RLC Coil group* (in the *Magnetic and Electric Fields* interface) includes capacitive effects



Approximate 3D Equivalent

- Coils must be circular and have a short turn-to-turn distance

Coils in 2D

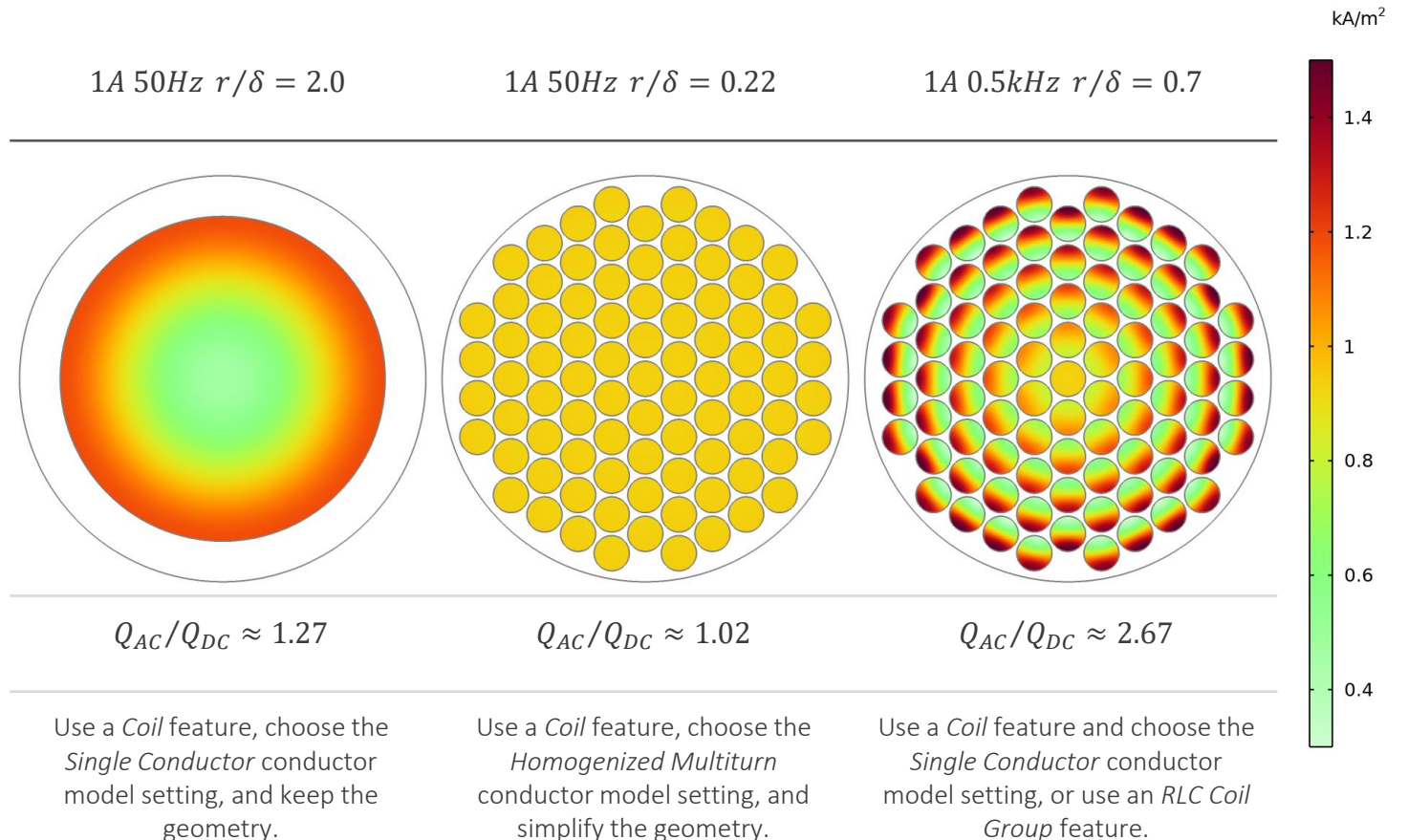
Three cables

- The same amount of copper
- The same DC resistance
- The same current
- But not the same losses

$$\delta \approx \sqrt{2/\omega\mu\sigma}$$

$$R_{DC} = 1/(\sigma\pi r^2)$$

$$Q_{DC} = I^2 R_{DC}$$



Magnetic Fields Modeling Advice

- In transient and low-frequency models, use a non-zero conductivity everywhere
- Resolve the skin depth or (in the frequency domain) use an *Impedance* condition
 - More on that later today
- In transient models, a direct solver is often faster and easier to work with
 - This requires that you add a *Gauge Fixing for A-Field* feature, active in all domains
- For speed in transient models, especially during the development phase, consider linear elements

Induction Boiler: Materials

- Adding materials from Library
 - Copper
 - Water
 - Air
- Each material is defined by its:
 - Relative permeability
 - Electric conductivity
 - Relative permittivity
- Taking advantage of selected entities to create Explicit Selections for future use

02_EM_heating_geometry.mph - COMSOL Multiphysics (Trial version)

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Component 1
Model Manager Add Component

Parameters a= Variables
foo
Pi

Geometry Materials

Magnetic Fields Build Mesh
Add Physics Mesh 1

Study Results Layout

Workspace Model Definitions Physics Mesh

Model Builder

02_EM_heating_geometry.mph (root)

- Global Definitions
 - Parameters - Matouš
 - Materials
- Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Boiler body (cyl1)
 - Work Plane 1 (wp1)
 - Boiler top (ext1)
 - Work Plane 2 (wp2)
 - Boiler bottom (ext2)
 - Inner tube (cyl2)
 - Work Plane 3 (wp3)
 - Revolve 1 (rev1)
 - Air (cyl3)
 - Form Union (fin)
- Materials
 - Magnetic Fields (mf)
 - Heat Transfer in Solids (ht)
 - Multiphysics
 - Mesh 1
- Study 1
- Results

Settings

Form Union/Assembly

Build Selected Build All

Label: Form Union

Form Union/Assembly

Action: Form a union

Repair tolerance: Automatic

Graphics

200

100 mm

plane1

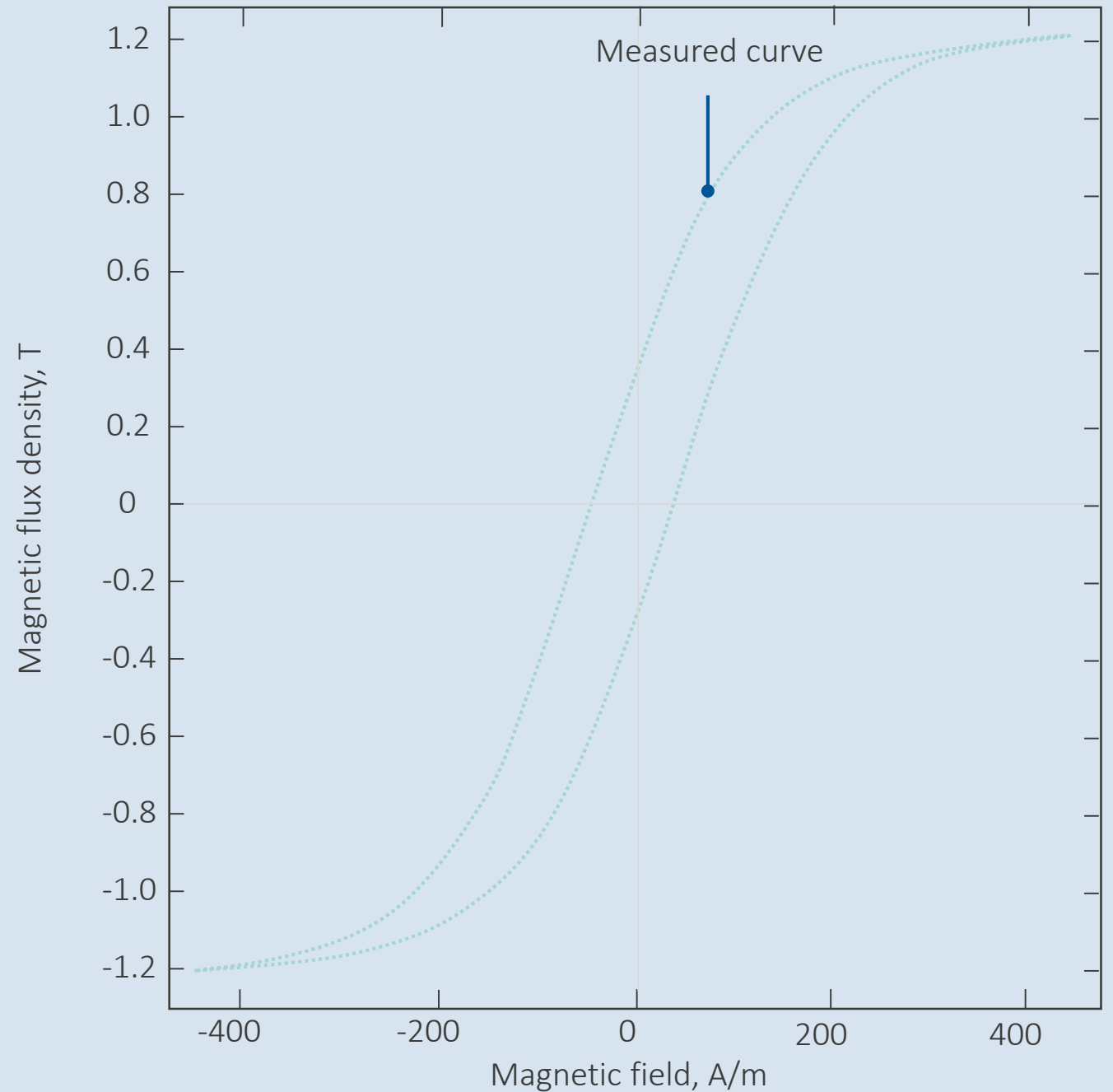
Messages Progress Log Table

[May 23, 2023, 1:47 PM] Saved file: C:\Users\matou\SynologyDrive\HUM ^
 [May 23, 2023, 1:49 PM] Geometry error (c1): Syntax error in expression.
 [May 23, 2023, 2:12 PM] Saved file: C:\Users\matou\SynologyDrive\HUM ^
 [May 23, 2023, 2:13 PM] Opened file: C:\Users\matou\SynologyDrive\HI ^
 [May 23, 2023, 2:48 PM] Opened file: C:\Users\matou\SynologyDrive\HI ^

2.34 GB | 2.73 GB

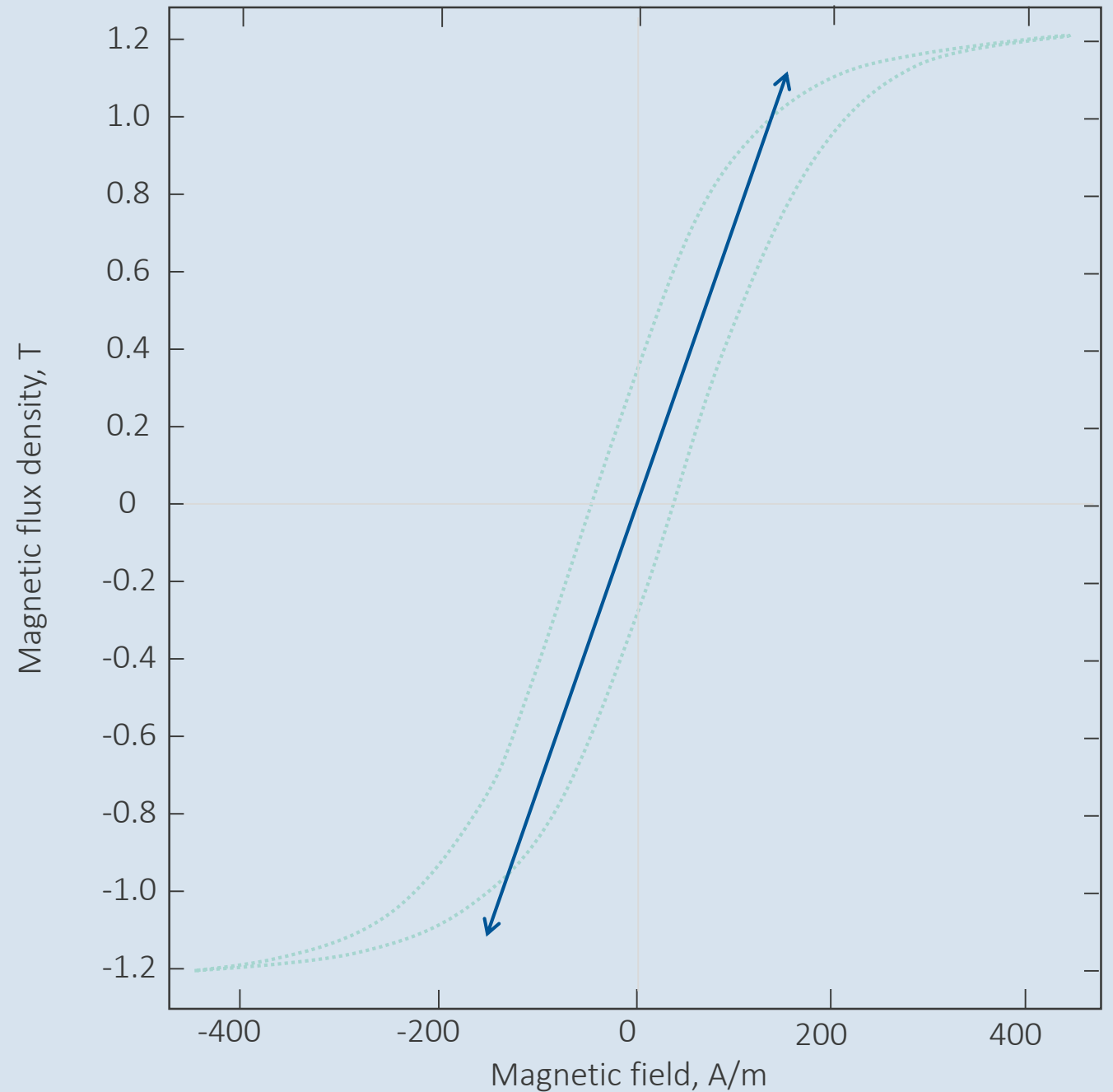
Magnetic Material Models

- *Constitutive relations* $\mathbf{B} \leftrightarrow \mathbf{H}$
 - Relative permeability
 - Magnetic losses
 - $B(H)$ curve
 - Effective $B(H)$ curve
 - Remanent flux density
 - Magnetization
 - $B(H)$ nonlinear permanent magnet
 - Hysteresis (Jiles–Atherton model)



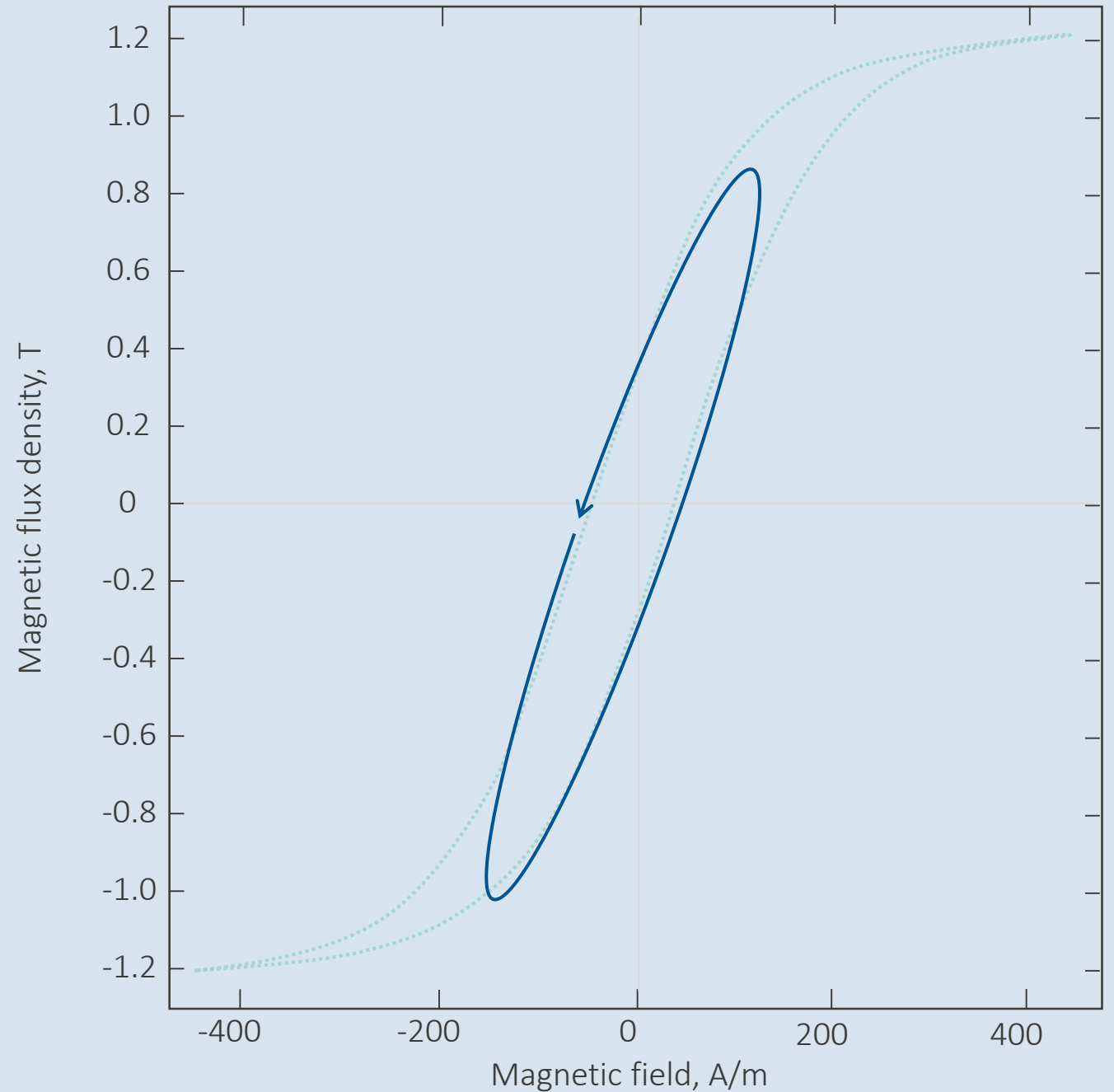
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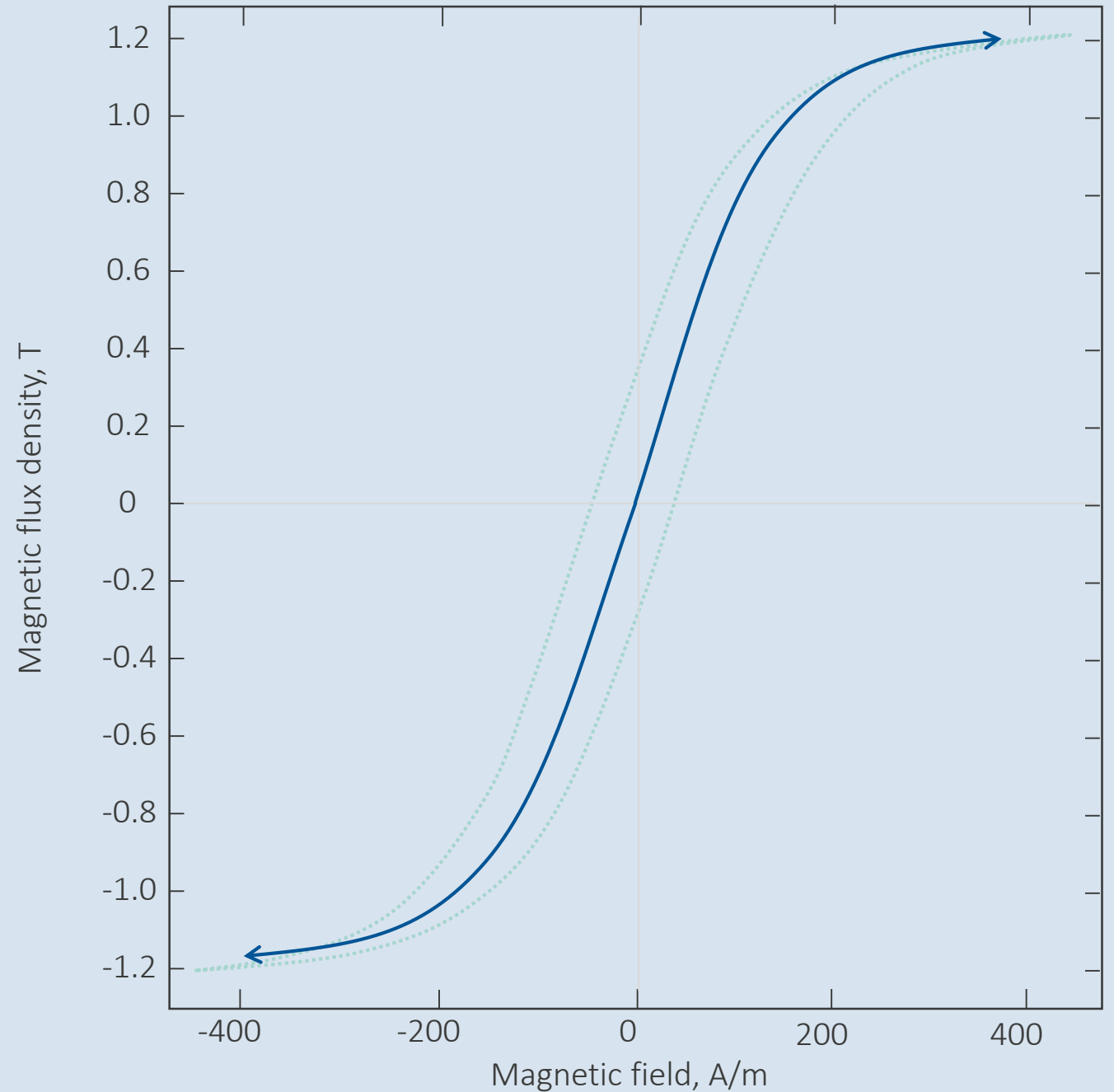
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 - $\mathbf{B}(\mathbf{H})$ nonlinear permanent magnet
 - Hysteresis (Jiles–Atherton model)



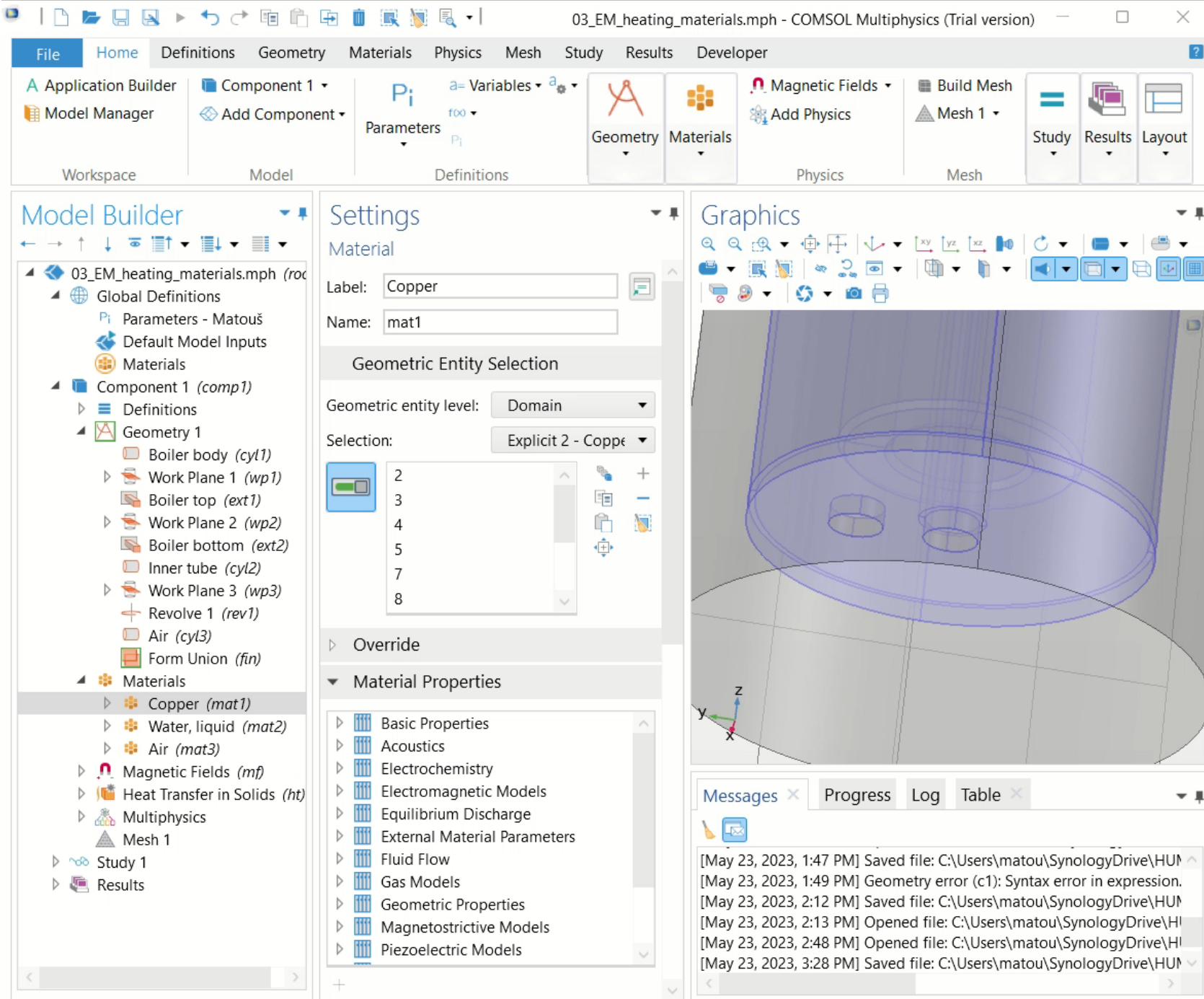
Magnetic Material Models

- Constitutive relations $\mathbf{B} \leftrightarrow \mathbf{H}$
 - Relative permeability
 - Magnetic losses
 - $\mathbf{B}(\mathbf{H})$ curve
 - Effective $\mathbf{B}(\mathbf{H})$ curve
 - Remanent flux density
 - Magnetization
 - $\mathbf{B}(\mathbf{H})$ nonlinear permanent magnet
 - Hysteresis (Jiles–Atherton model)



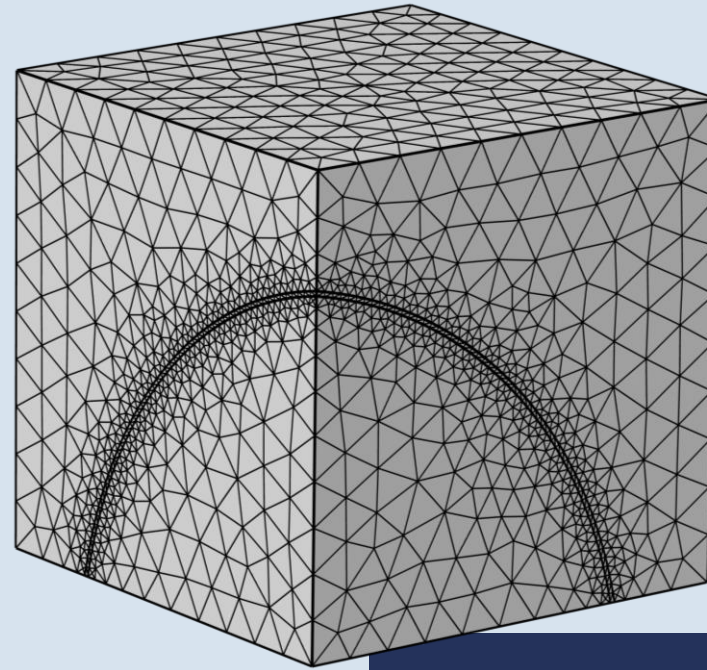
Induction Boiler: Magnetic Fields

- Adding *Homogenized multiturn* coil to define primary winding with N turns, I_a input current and A_x s inductor's cross sectional area
 - *Numeric* type coils need defined Input in the *Geometry Analysis* subnode and a *Coil geometry analysis* study step
- Defining boiler body and inner tube as secondary *Single conductor* coil
 - The same rules apply as for the *Numeric* multiturn coil



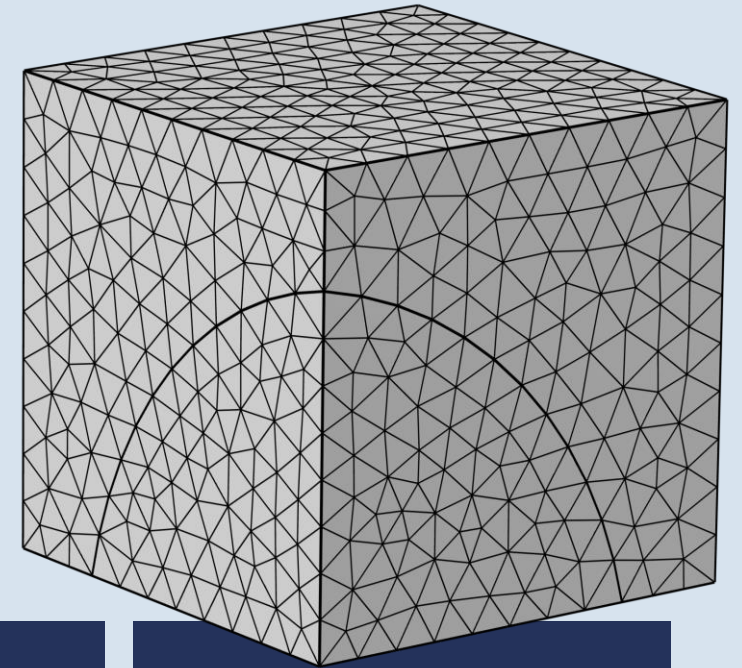
Thin Layer Conditions

- Electric shielding (high conductivity)
- Floating potential (infinite conductivity)
- Magnetic shielding (high permeability)
- Thin low permeability gap (air gap between magnetic conductors)
- Contact impedance (imperfect contact between electric conductors)



Volumetric Representation

Avoids systematic errors but can be costly to mesh and solve

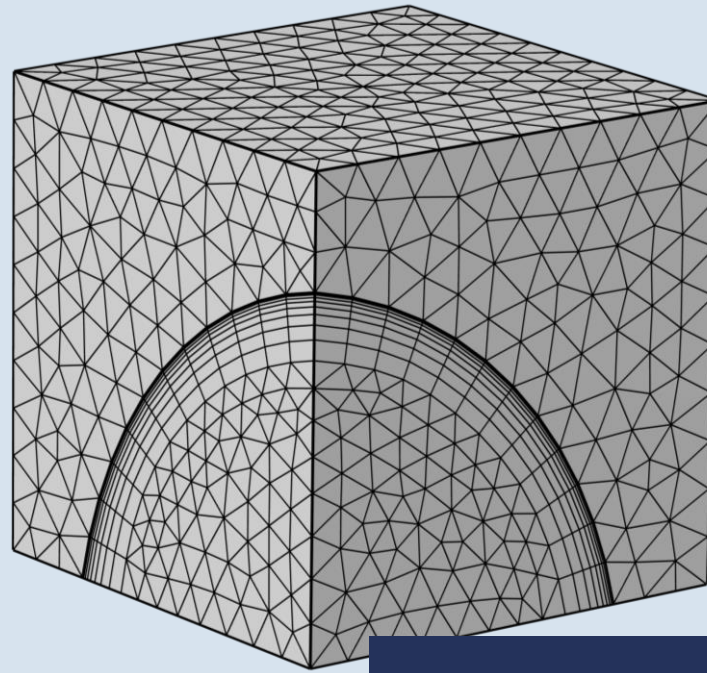


Thin Layer Condition

Saves time and memory when applicable

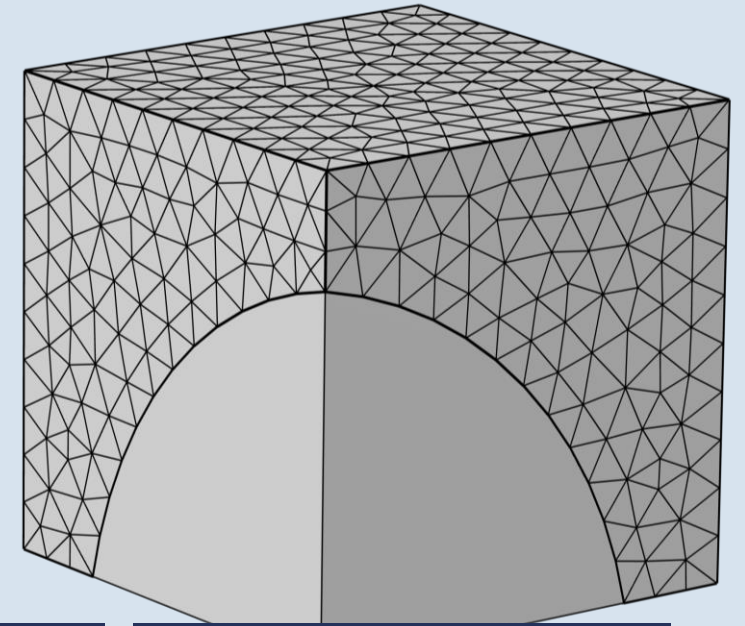
Impedance Condition

- Apply to surfaces of domains much thicker than the skin depth
- Exclude the domain from the physics interface
- Avoids the need to resolve the skin depth, and saves time and memory
- Thin layer counterparts: *Transition* and *Layered Transition* conditions



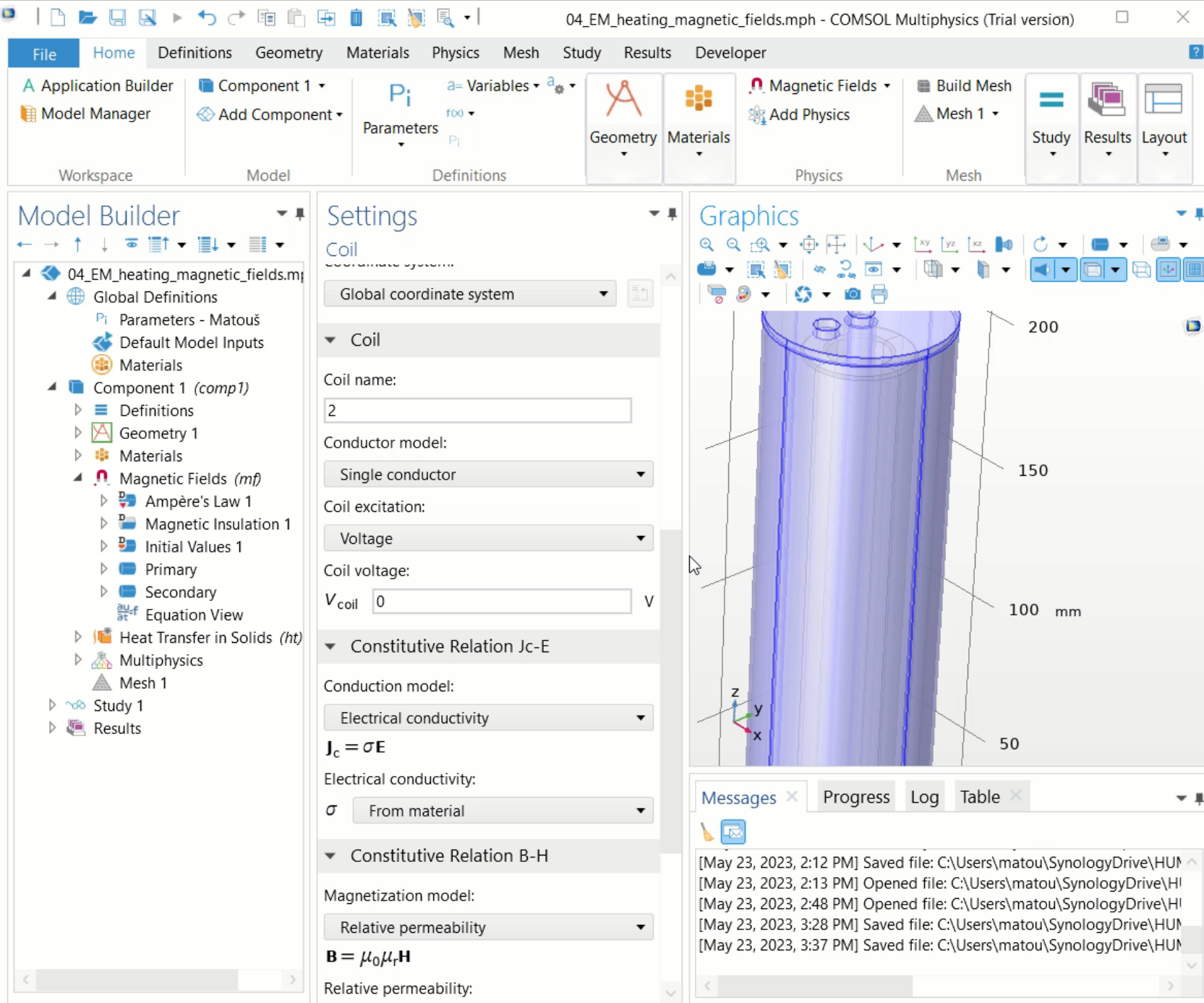
Volumetric Representation

Avoids systematic errors but can be costly to mesh and solve



Impedance Condition

Saves time and memory when applicable

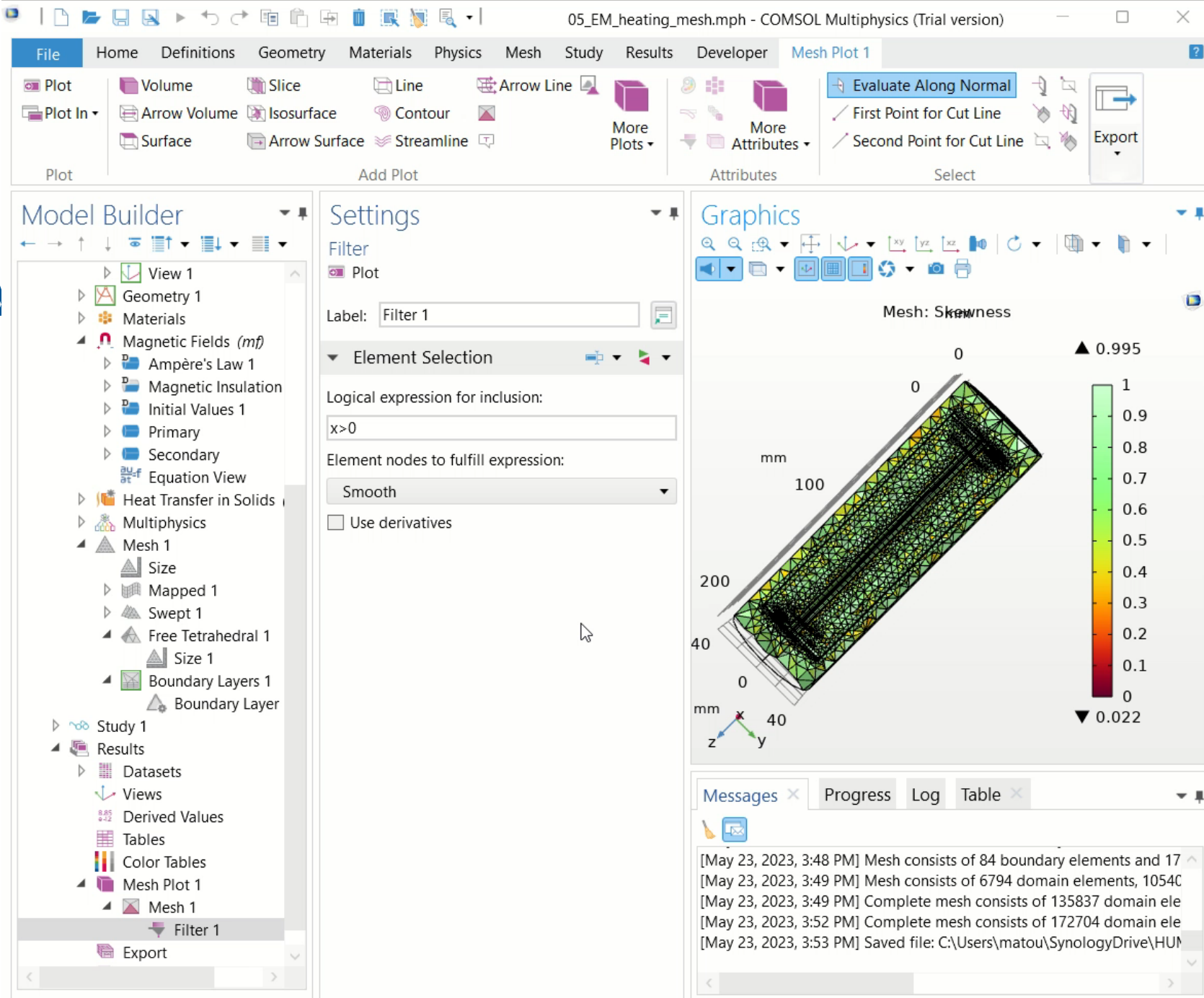


Induction Boiler: Mesh

- 16 [kHz] is high enough energy for the skin effect to play important role but not high enough to use the *Impedance BC*
- Swept mesh in combination with *Boundary layers* are applied to resolve the skin effect
 - Thickness of boundary layer is given by skin depth defined in *Parameters* section

Induction Boiler: Study

- *Coil Geometry Analysis* initialization step identifies current flux direction based on the defined *Input* (and *Output*) and coil's geometry
- *Frequency Domain* step solves for the *Magnetic Fields* physics interface with harmonic excitation
 - Solution of harmonic losses can be directly used as a time-averaged constant heat source in *Stationary* or *Time-dependent* studies



Induction Boiler: Postprocessing

- Automatically generated plot of Magnetic flux density norm
- Visualization of electromagnetic losses in 3D *Volume* plot
- Pimping up the plots by adding realistic *Material Appearance* feature and visualizing windings by *Streamlines* plot with *N* lines

05_EM_heating_study.mph - COMSOL Multiphysics (Trial version)

File Home Definitions Geometry Materials Physics Mesh Study Results Developer **Magnetic Flux Density Norm (mf)**

Plot Volume Slice Line Arrow Line More Plots
 Plot In Arrow Volume Isosurface Contour More Attributes
 Surface Arrow Surface Streamline

Evaluate Along Normal
 First Point for Cut Line
 Second Point for Cut Line Export

Model Builder
 05_EM_heating_study.mph (root)
 Global Definitions
 Parameters - Matous
 Default Model Inputs
 Materials
 Component 1 (comp1)
 Definitions
 Geometry 1
 Materials
 Magnetic Fields (mf)
 Heat Transfer in Solids (ht)
 Multiphysics
 Mesh 1
 Study 1
 Step 1: Coil Geometry Anal
 Step 2: Frequency Domain
 Solver Configurations
 Job Configurations
 Results
 Datasets
 Views
 Derived Values
 Tables
 Color Tables
 EM Heating
 Mesh Plot 1
Magnetic Flux Density Norm (mf)
 Export
 Reports

Settings
 3D Plot Group
 Plot
 Label: Magnetic Flux Density Norm (mf)
 Data
 Dataset: Study 1/S
 Parameter value (freq (Hz)): 16000
 Selection
 Title
 Plot Settings
 View: Automatic
 Show hidden entities
 Propagate hiding to lower dimensions
 Plot dataset edges
 Color: From theme
 Frame: Spatial (x, y, z)
 Color Legend
 Show legends
 Show maximum and minimum values
 Show units
 Position: Right
 Text color: From theme

Graphics
 Convergence Plot 1
 Convergence Plot 2
 freq(1)=16000 Hz Multislice: Magnetic flux density norm (T)
 0 0.0283
 20 ×10⁻³
 40
 25
 20
 15
 10
 5
 1.63×10⁻⁸
 100

Messages
 Progress Log Table
 [May 23, 2023, 3:53 PM] Saved file: C:\Users\matou\SynologyDrive\h
 [May 23, 2023, 3:57 PM] Number of degrees of freedom solved for: :
 [May 23, 2023, 3:59 PM] Number of degrees of freedom solved for: :
 [May 23, 2023, 4:07 PM] Solution time (Study 1): 616 s. (10 minutes, :
 [May 23, 2023, 4:28 PM] Saved file: C:\Users\matou\SynologyDrive\h

3.97 GB | 4.79 GB