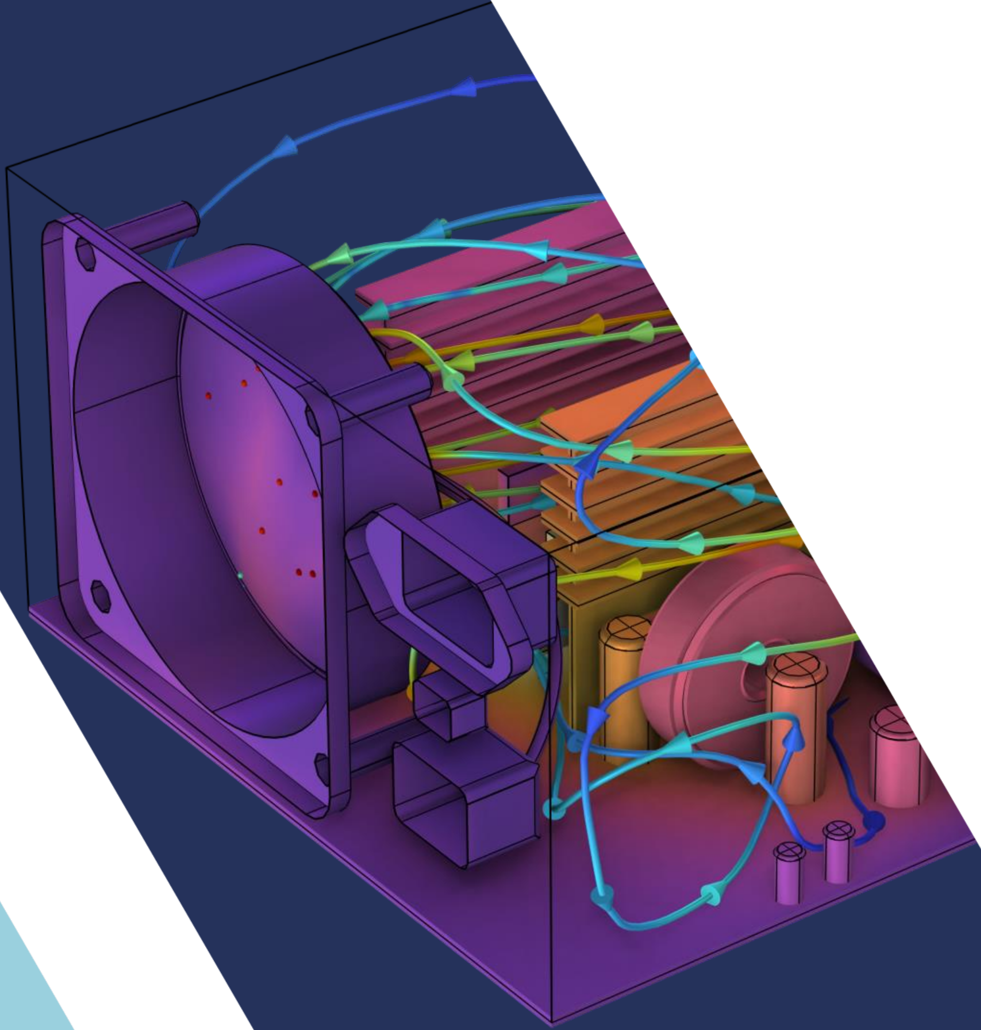

Electromagnetic Heating

Matouš Lorenc
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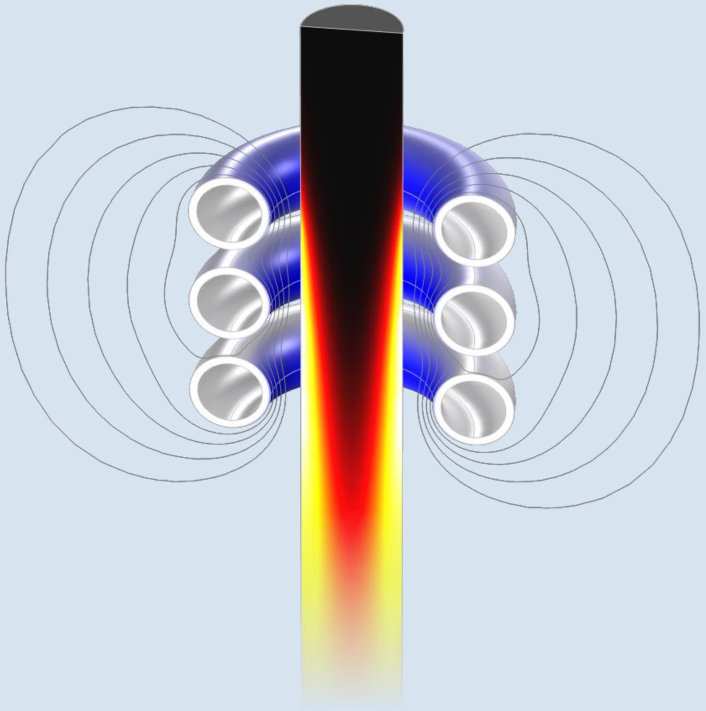
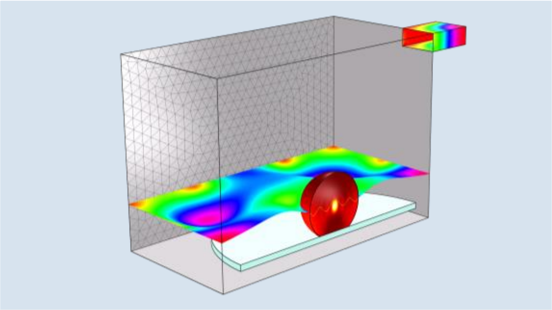
Agenda

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



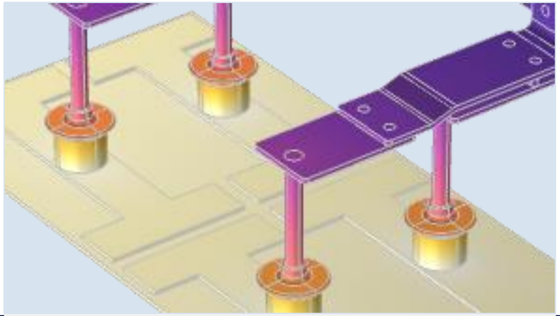
Induction heating of a ferritic steel rod with Curie point effect

Multiphysics Couplings



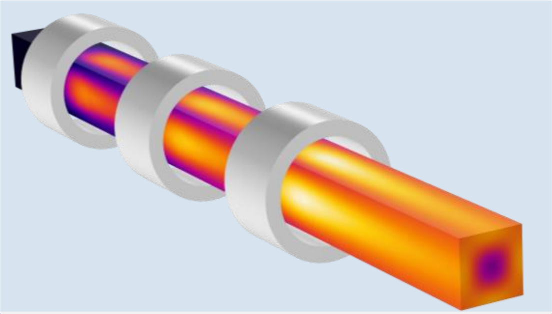
Microwave Heating

- Potato in microwave owen



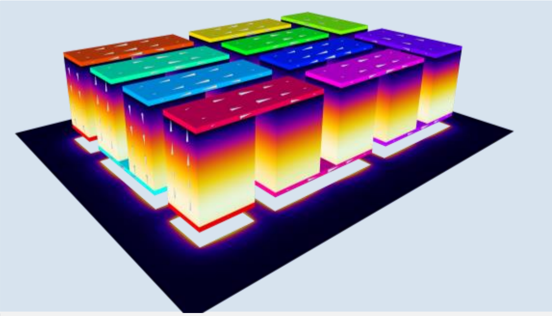
Joule Heating

- Busbar



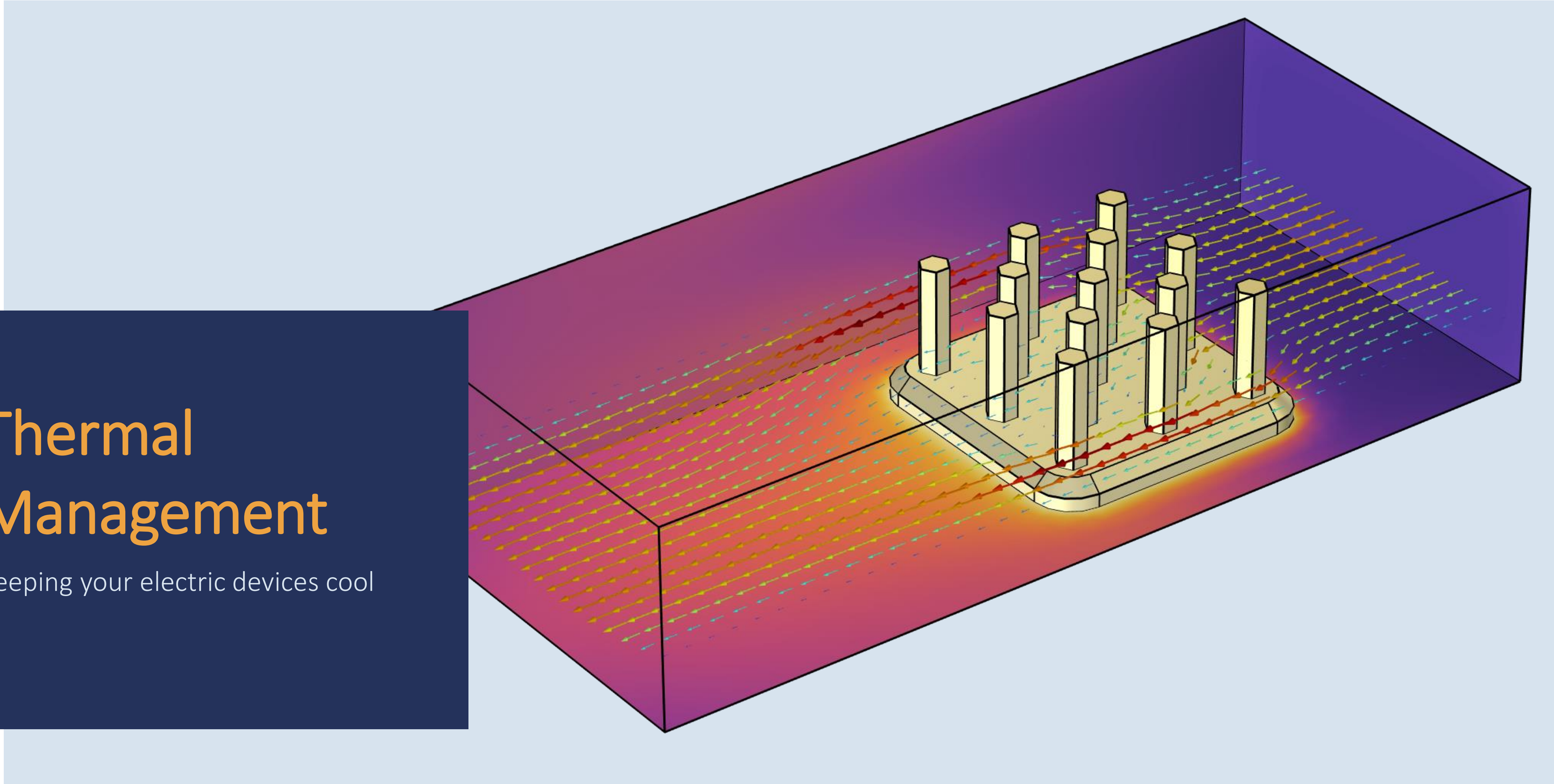
Inductive Heating

- Steel billet induction heating



Thermoelectric Effect

- Thermoelectric cooler



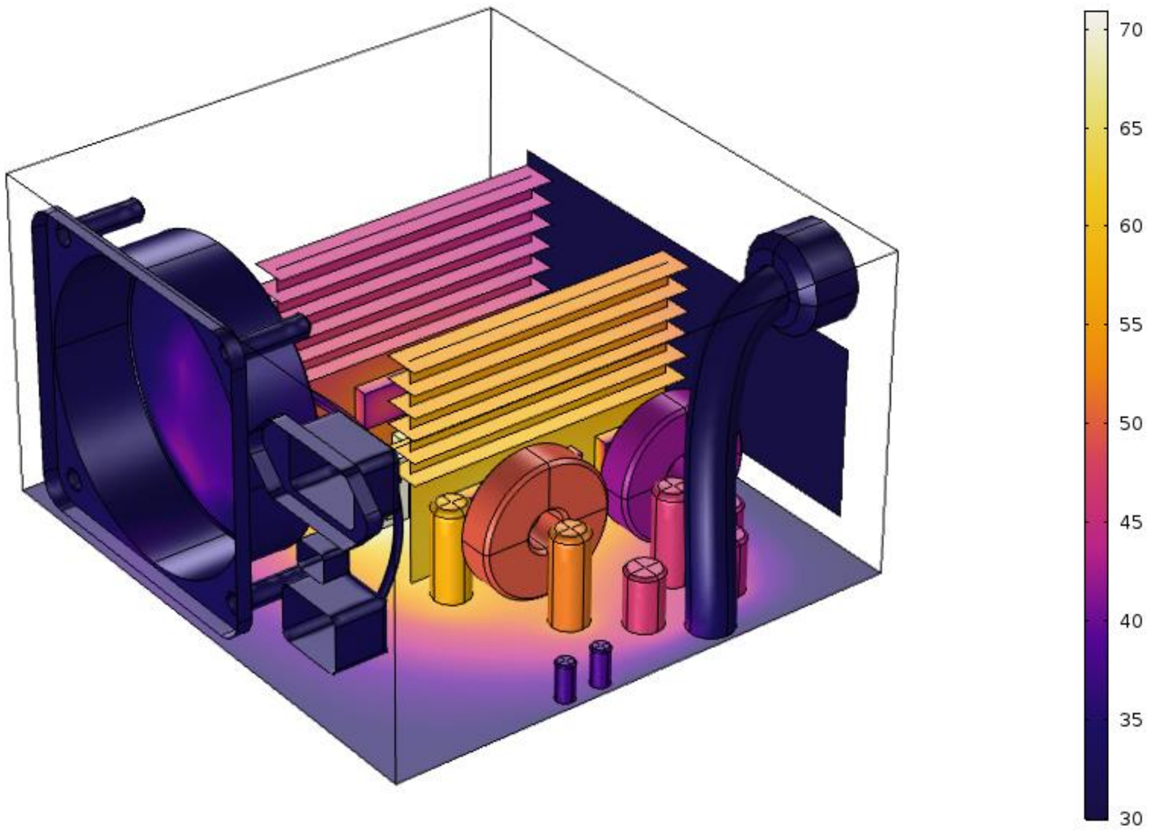
Thermal Management

Keeping your electric devices cool

COMSOL

Thermal Management: Motivation

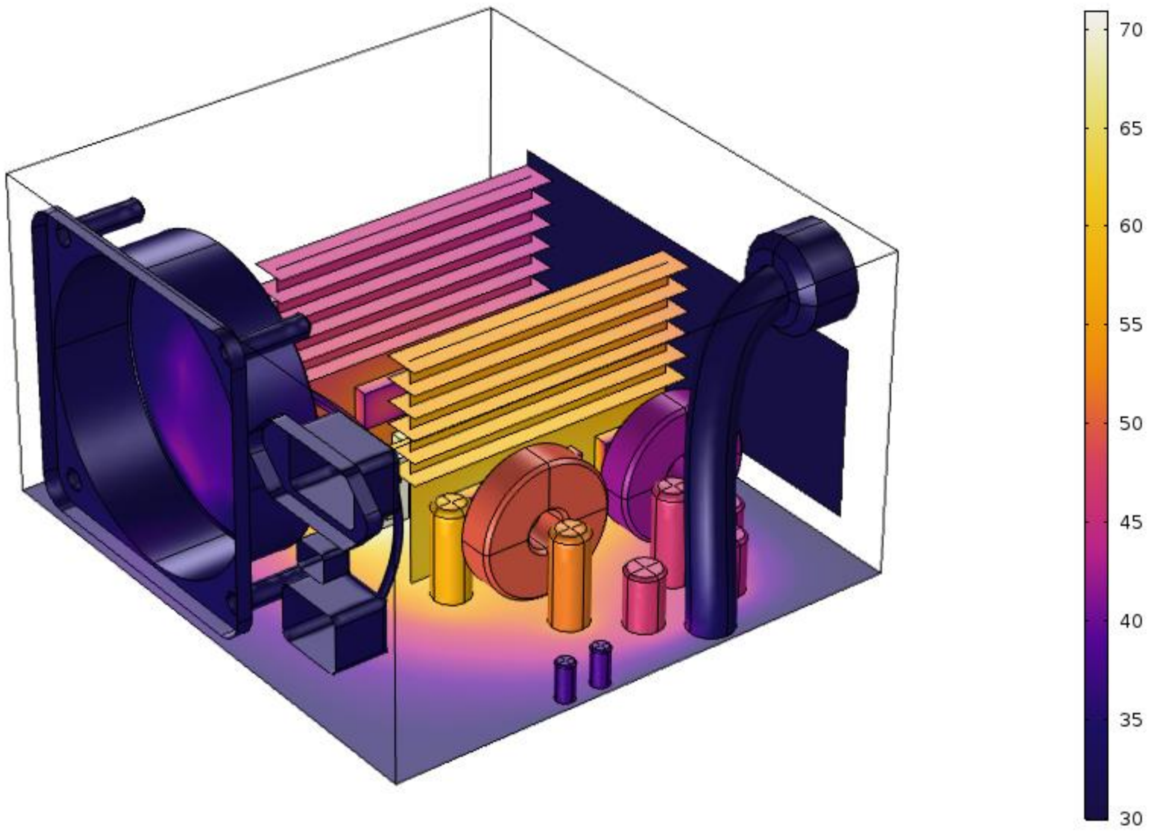
- Power electronics and electronic consumer devices generate heat
- Excessive heat can:
  - Cause malfunctions
  - Affect functionality
  - Decrease reliability
  - Shorten life span



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

Thermal Management: Motivation

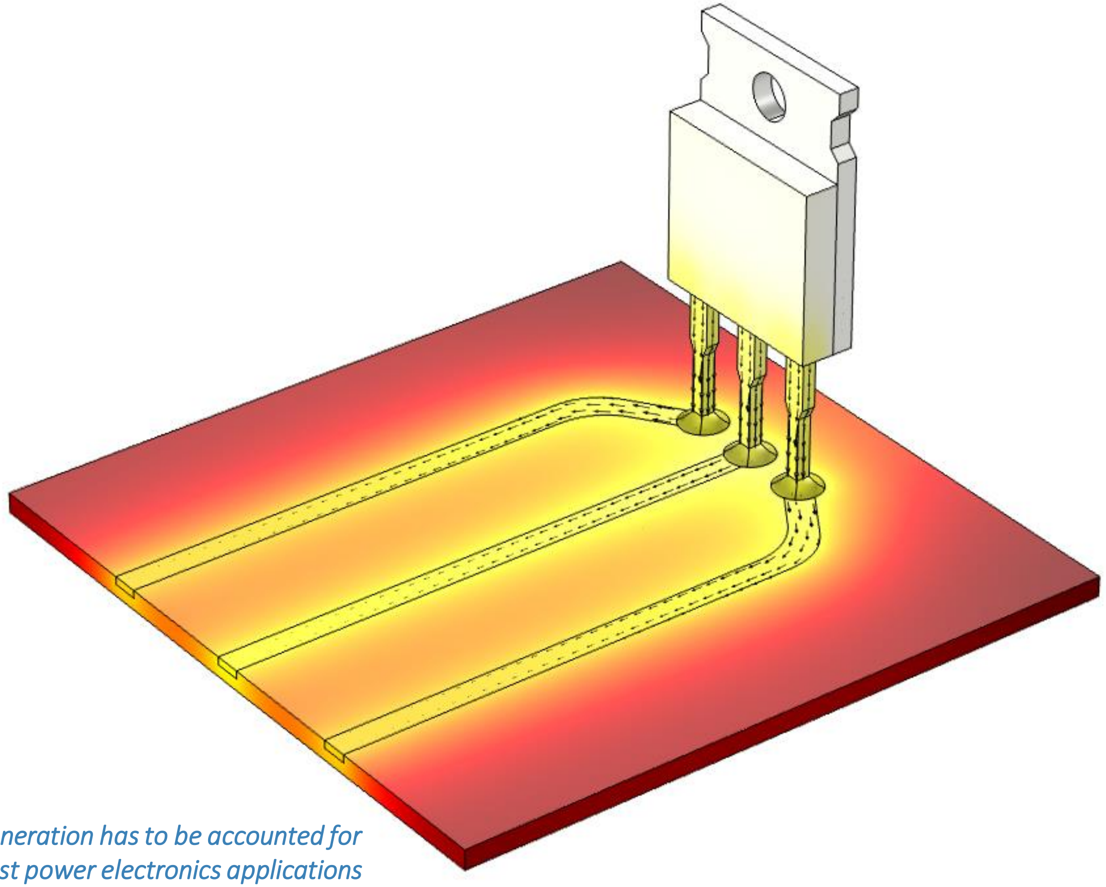
- Thermal management:
  - Ability to control temperature of system
  - Based on thermodynamics, fluid dynamics, electrochemistry, and electromagnetic effects
  - Active vs. passive management
  - Steady-state vs. time-dependent control



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

Thermal Management: Challenges

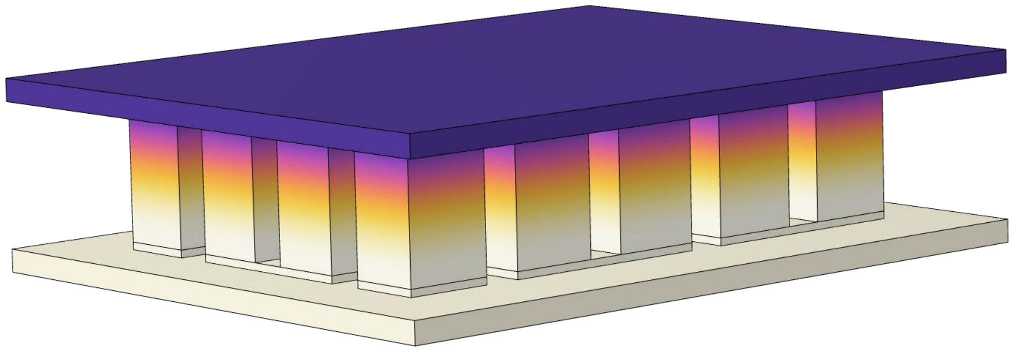
- Customer-focused design:
  - Greater miniaturization
  - Increased power demands
  - Longer expected life spans
  - Cost reduction/competition
- Various heat sources: chips, batteries, etc.
- New advanced, multicomponent systems
- Evermore challenging operating conditions
- Introduction of new materials



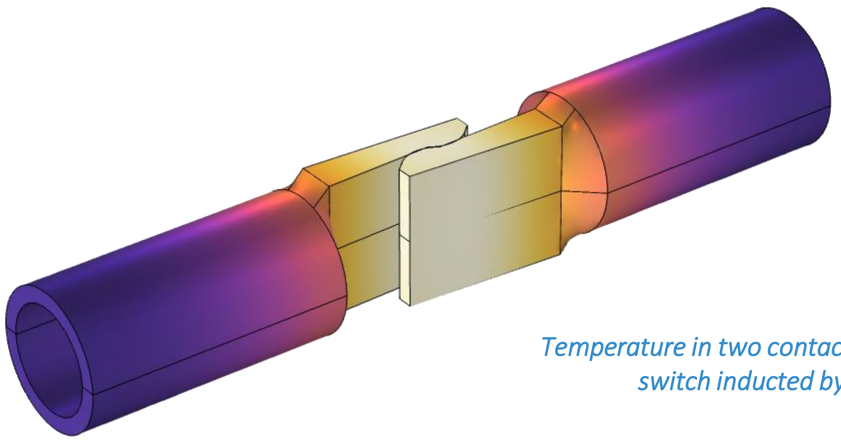
Power transistor: heat transfer and heat generation has to be accounted for in most power electronics applications

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



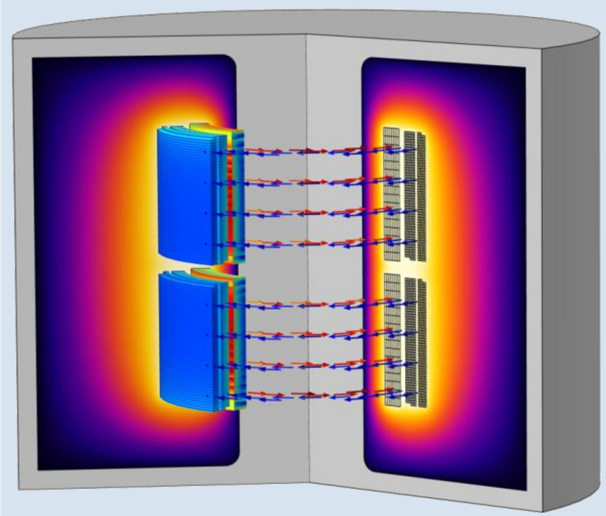
Temperature in two contacting parts of a switch inducted by Joule heating

COMSOL

Thermal Management in COMSOL Multiphysics®

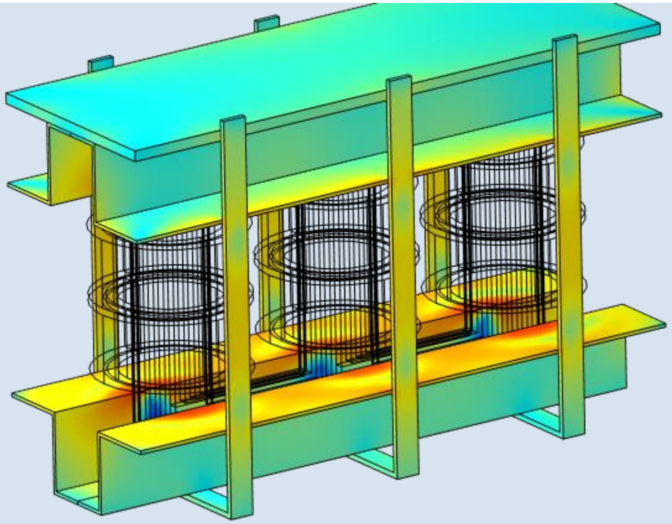
- Modules:
  - Heat Transfer Module: conduction, convection, and radiation modeling
  - AC/DC Module: electromagnetic heating
- One-way vs. two-way coupling
- Implicit vs. explicit modeling of heat sources
- Study types:
  - Stationary
  - Time dependent
  - Frequency-stationary and frequency-transient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

Electromagnetic Heating



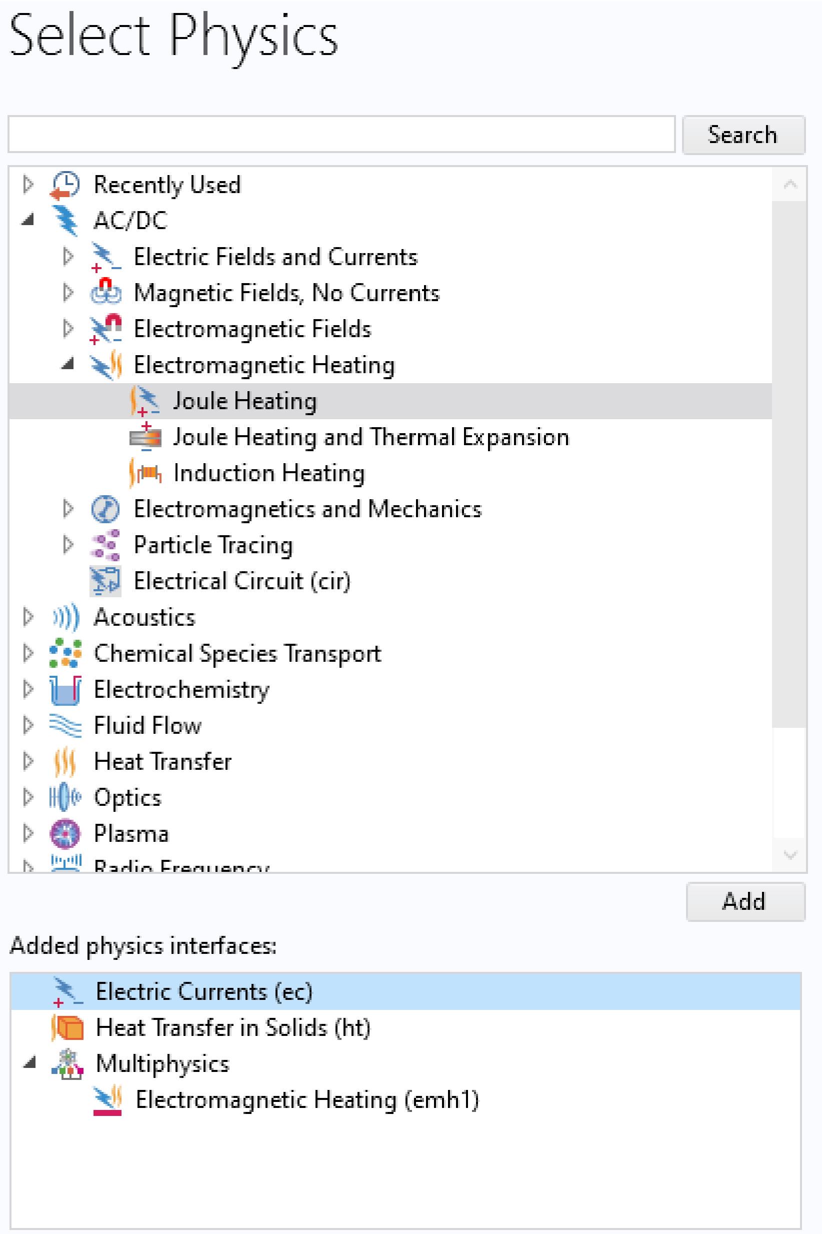
Joule Heating

- Electric Currents + Heat Transfer + Multiphysics Couplings



Induction Heating

- Magnetic Fields + Heat Transfer + Multiphysics Couplings



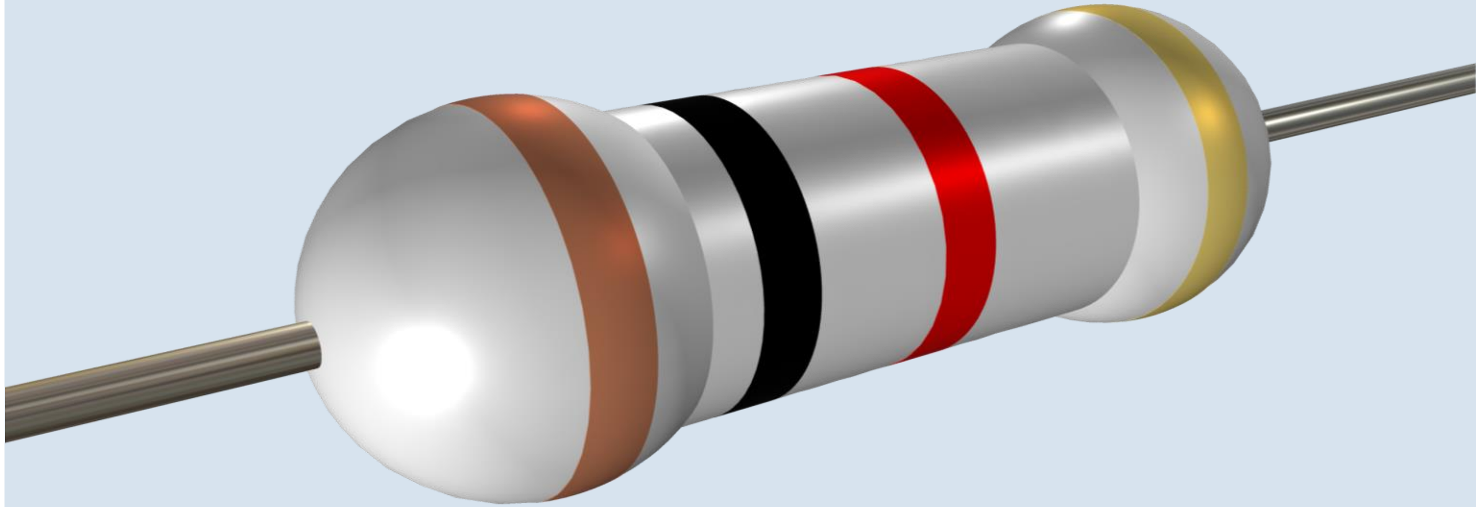
Joule Heating

- 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

COMSOL

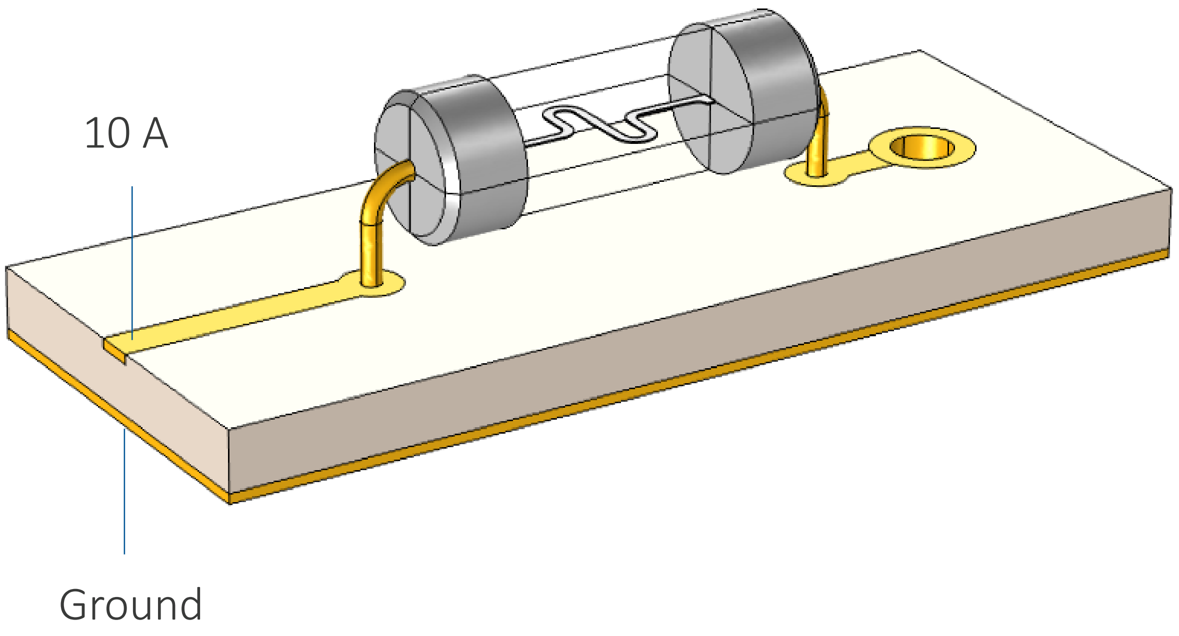
Electric Currents, Stationary

- 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.



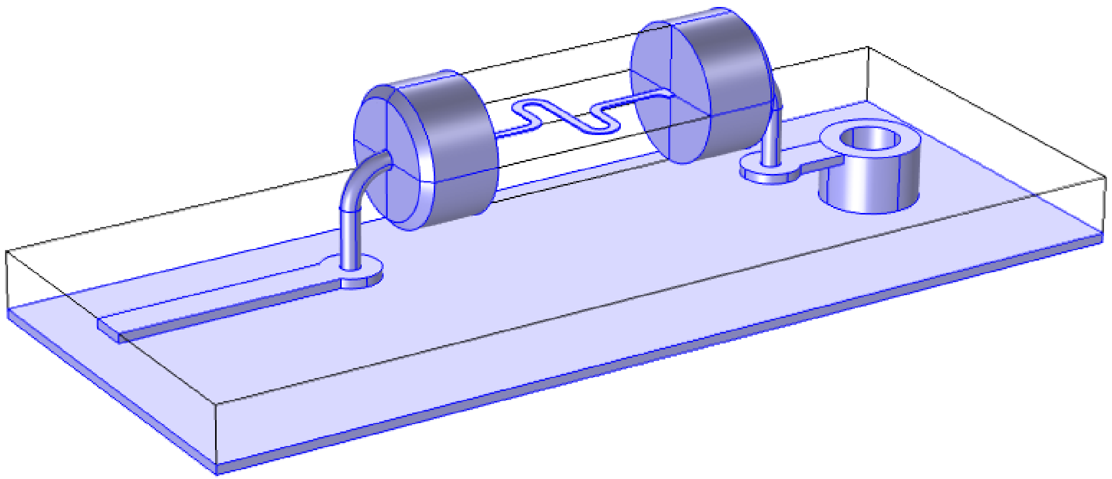
Joule Heating Demo: Fuse

- 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

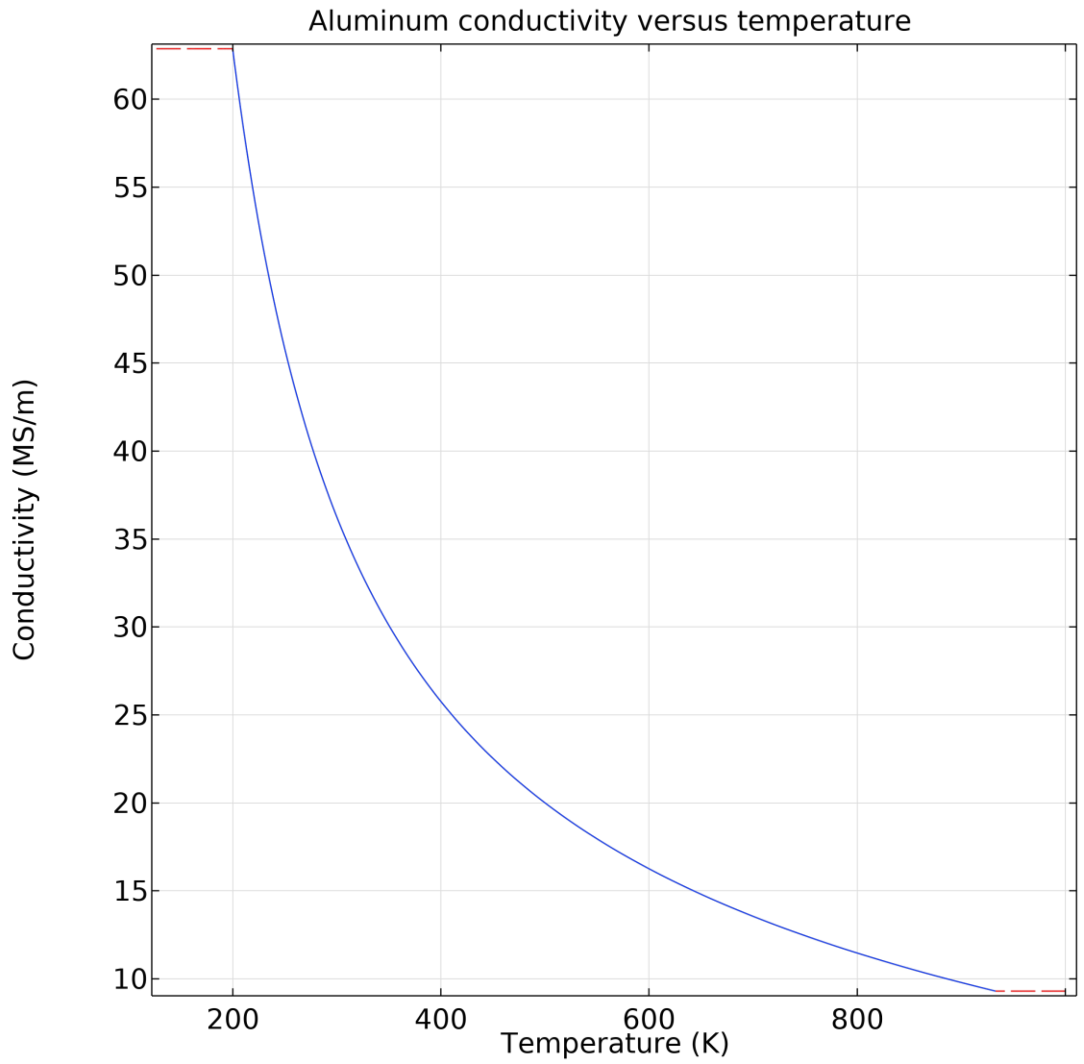
- Include only conductors in the simulation
- Skip also (relatively) very poor conductors, such as circuit board substrates
- Just like in electrostatics, include at least one ground (or potential) condition in order to get a unique solution



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

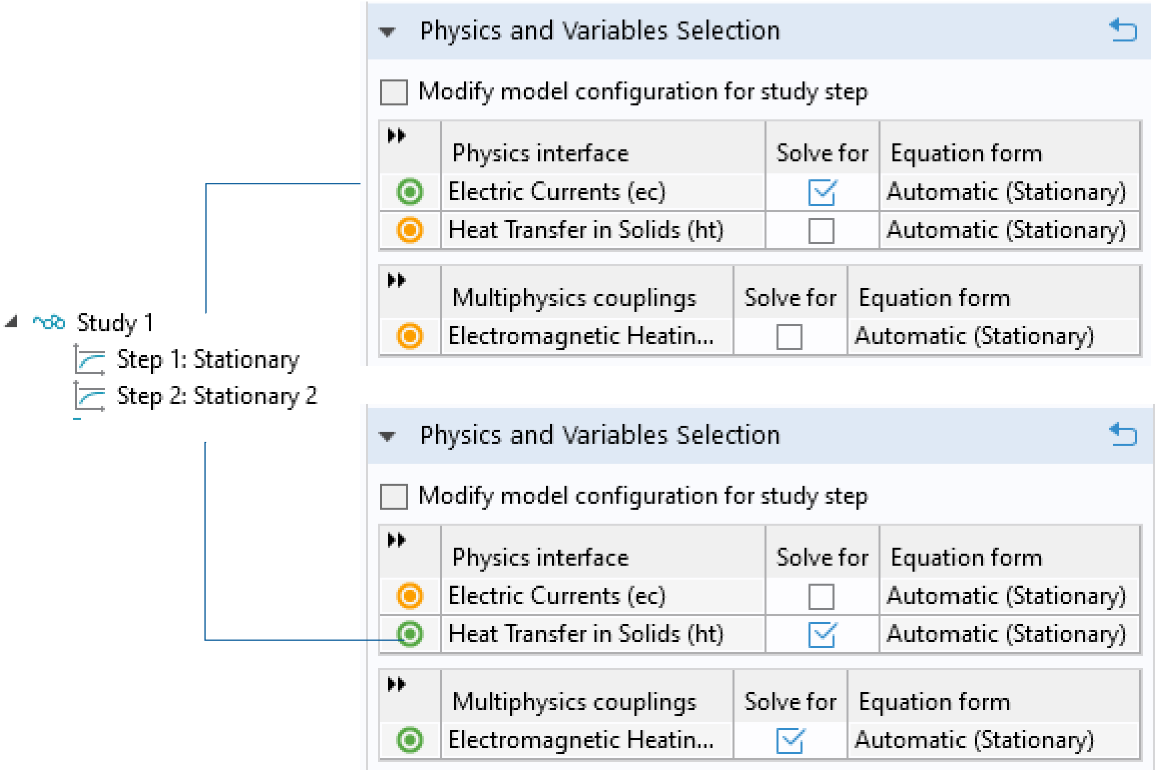
Joule (and Inductive) Heating Modeling Advice

- 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

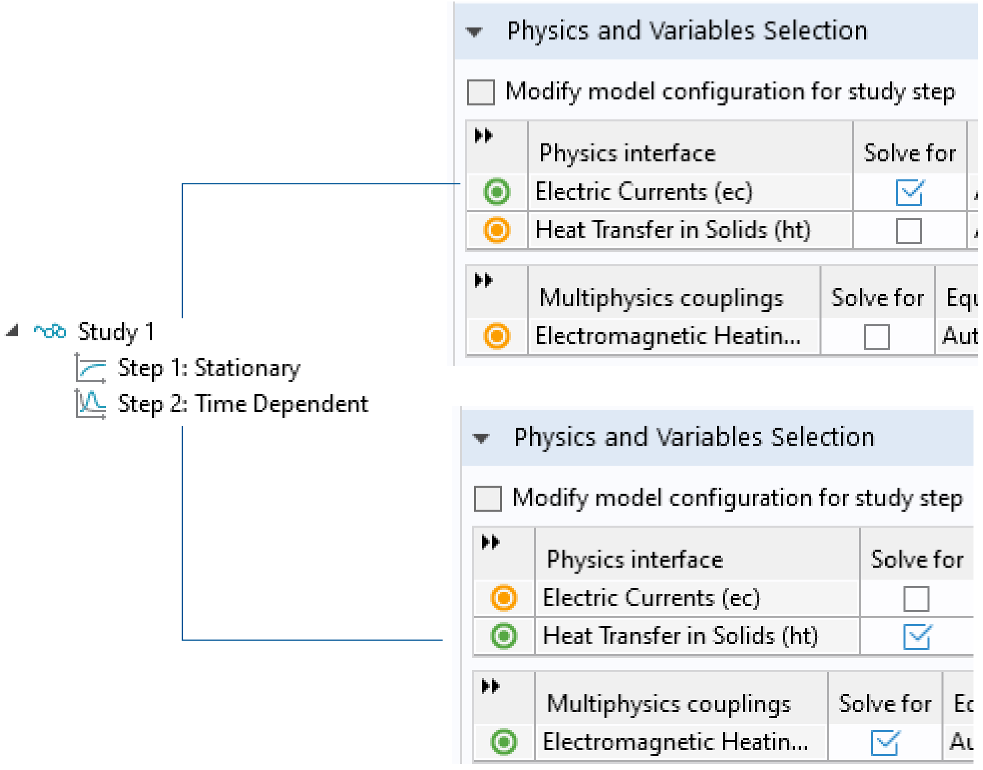


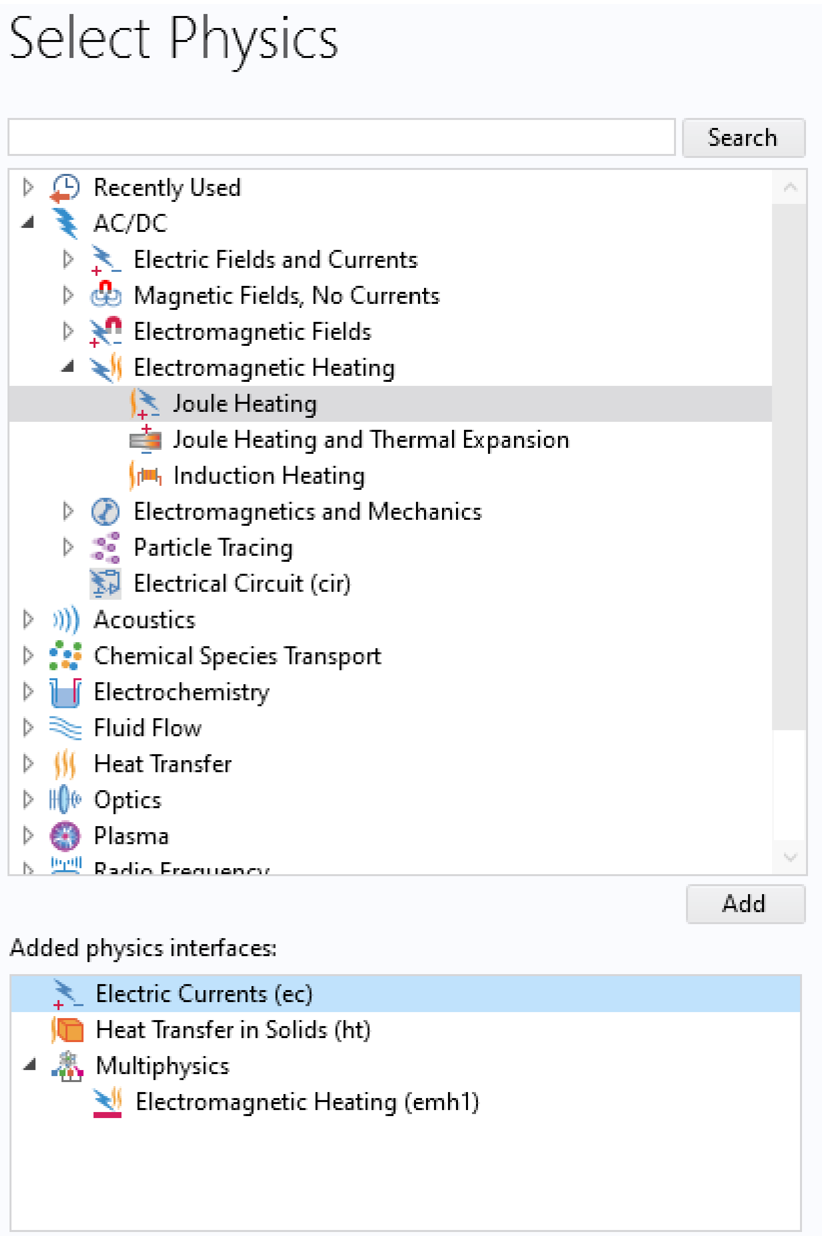
Joule (and Inductive) Heating Modeling Advice

Sequential solution with stationary heat transfer



Sequential solution with time dependent heat transfer





Induction Heating

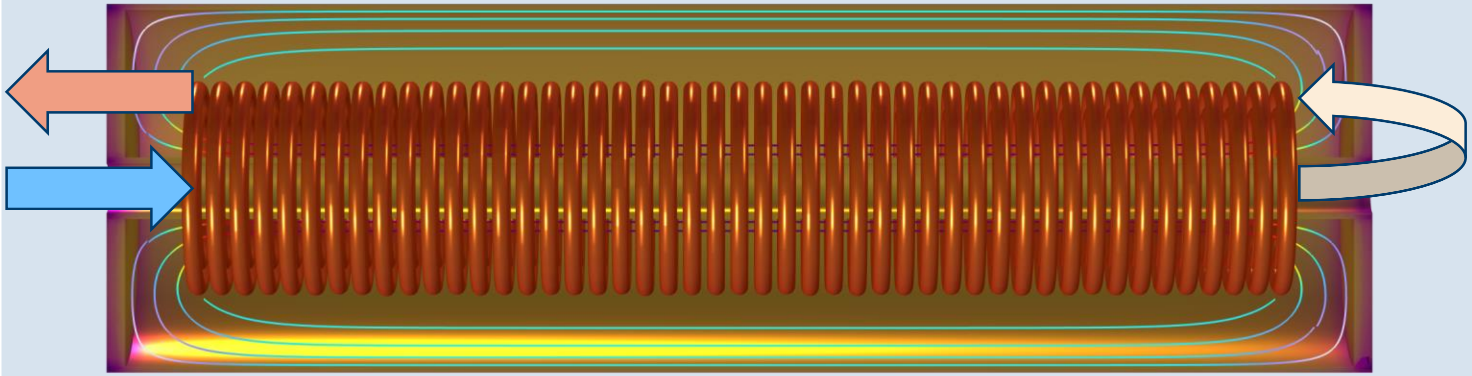
- Model inductive heating from AC currents, and resulting stationary or time-dependent temperature distribution
- Combines the *Magnetic Fields* and *Heat Transfer in Solids* interfaces, and adds an *Electromagnetic Heating* feature constituting the heat source
- Choose one of four preset studies:
 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

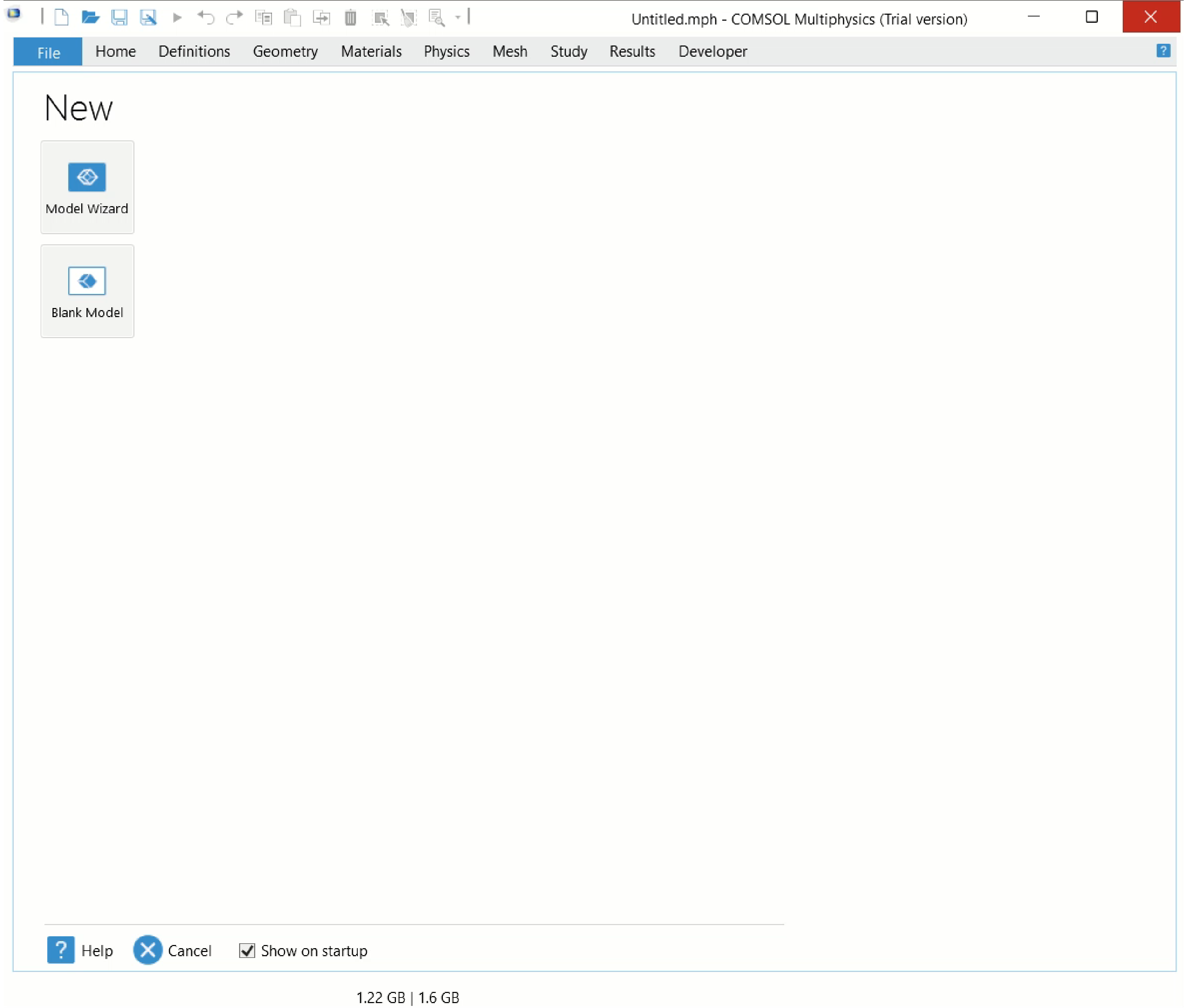
DEMO: Designing our "New Product"

- 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

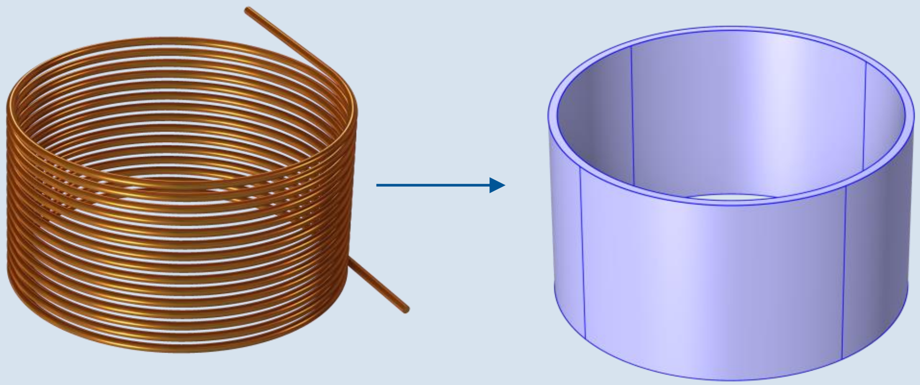
- Parameters can be:
  - Loaded from file
  - Manually filled
  - Organized into groups
  - Saved to file for further use
- Parameters define:
  - Geometry dimensions
  - Physics inputs
  - Meshing sequence constraints
  - And more…
- Parameters are great, use parameters!



Coils in 3D, Introduction

Solid Conductors

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

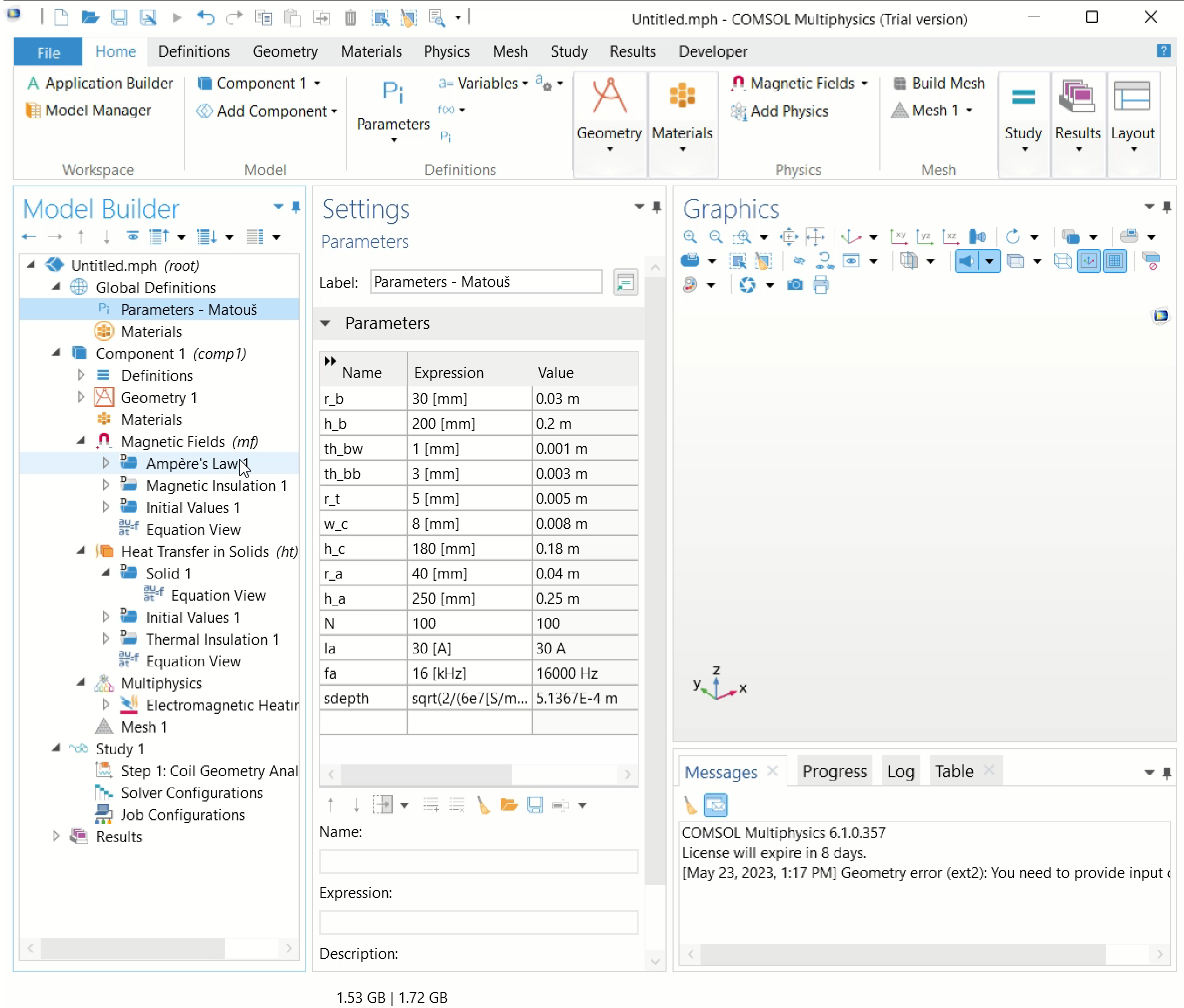


Homogenized Multiturn Coils

- 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

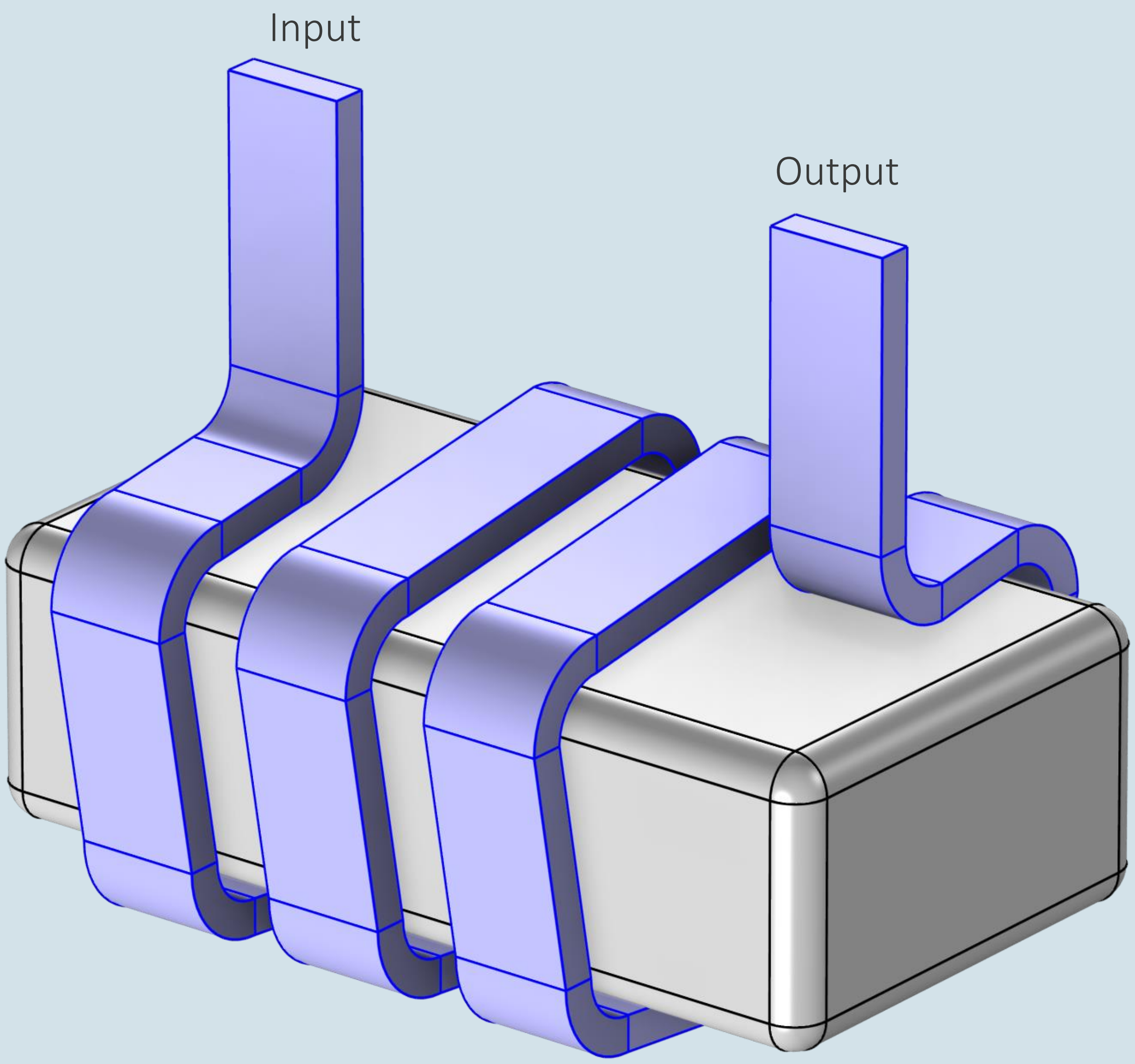
Induction Boiler: Geometry

- 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



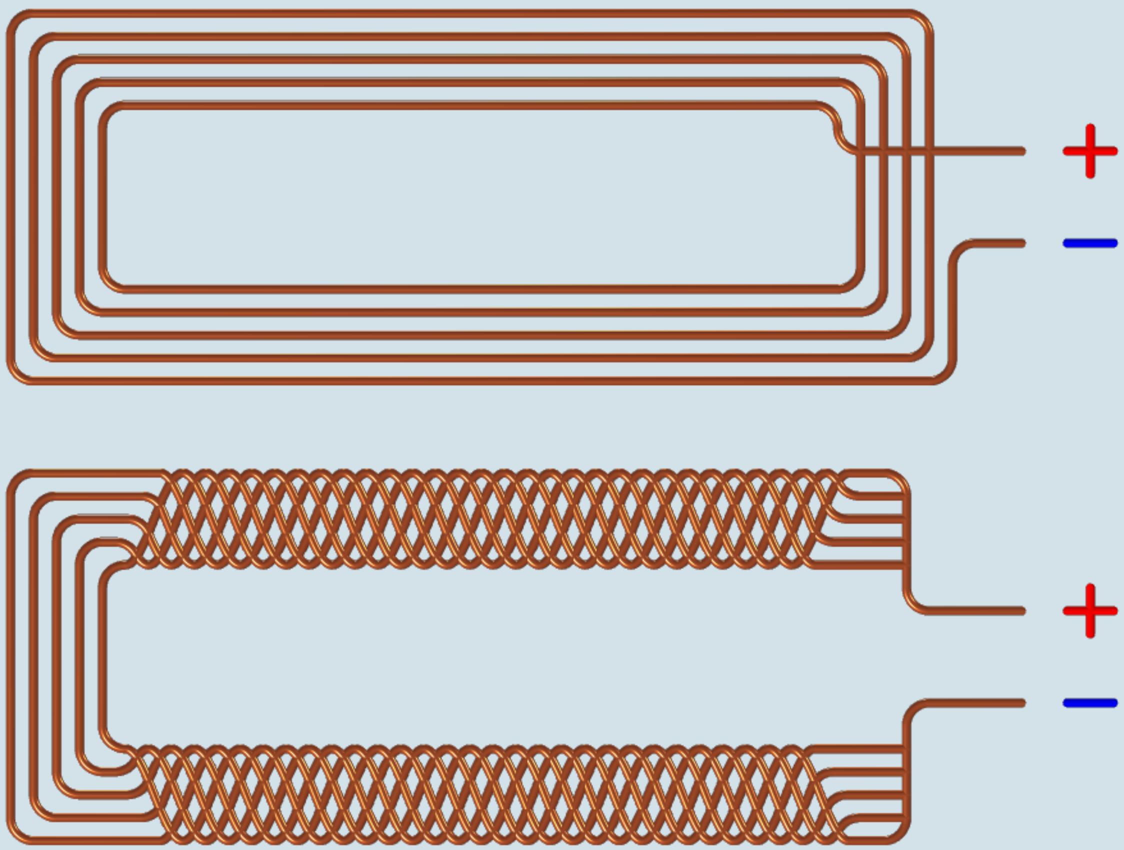
Homogenized Coils

- 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

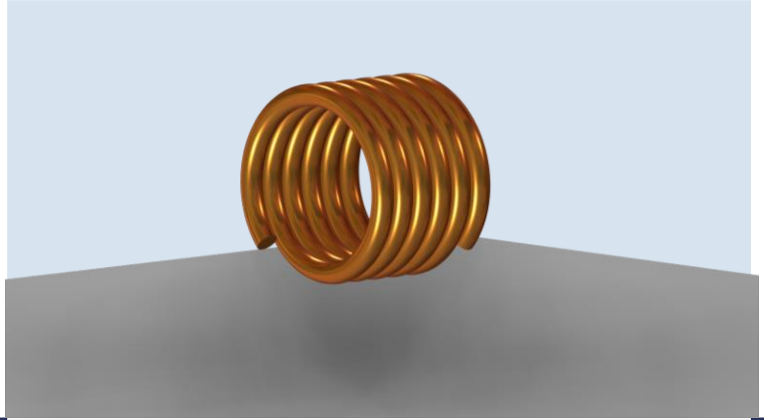


Coils and Litz Wires

- 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*

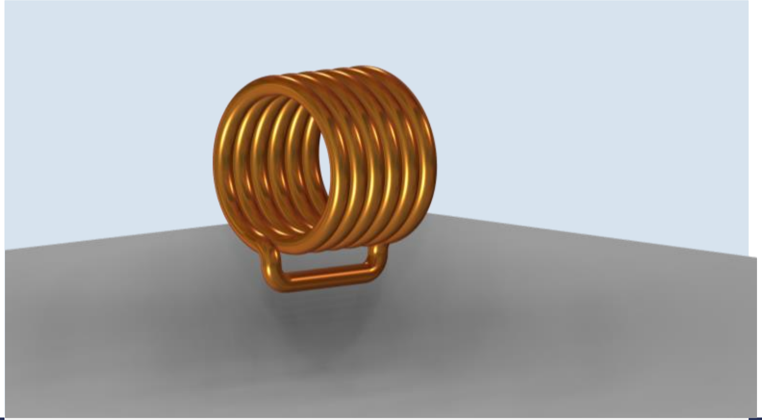


Numerical 3D Coil Geometries



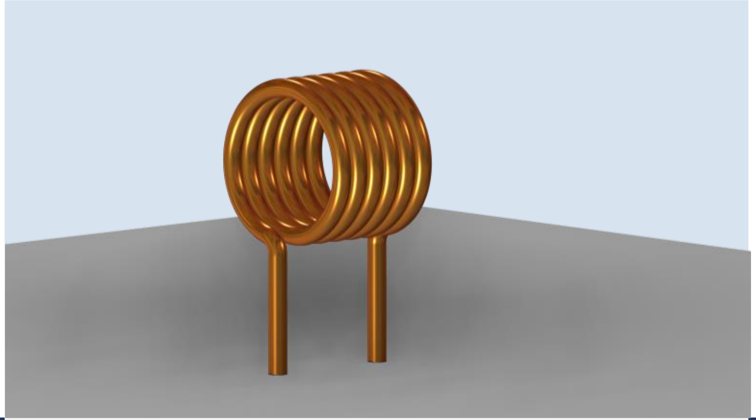
Incorrect

- 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

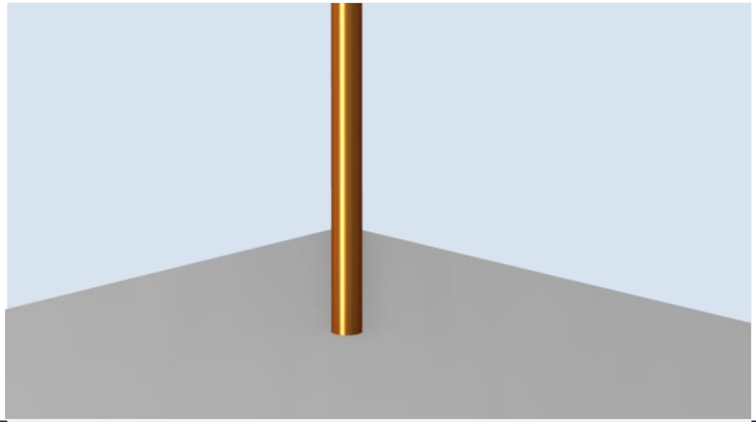
- The coil is closed inside the modeled geometry



Correct

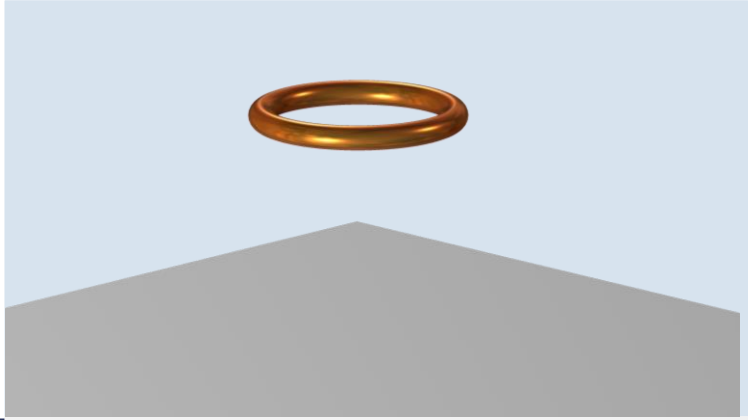
- Continuity is maintained by currents propagating on the exterior surface of the geometry

Analytical 3D Coil Geometries



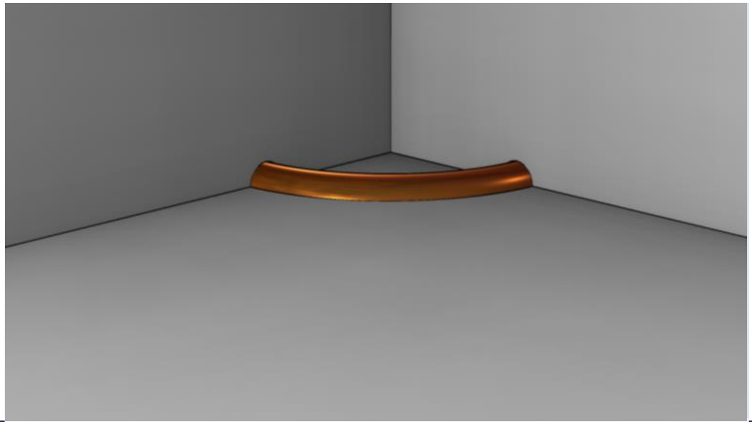
Linear Coil

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



Cylindrical Coil

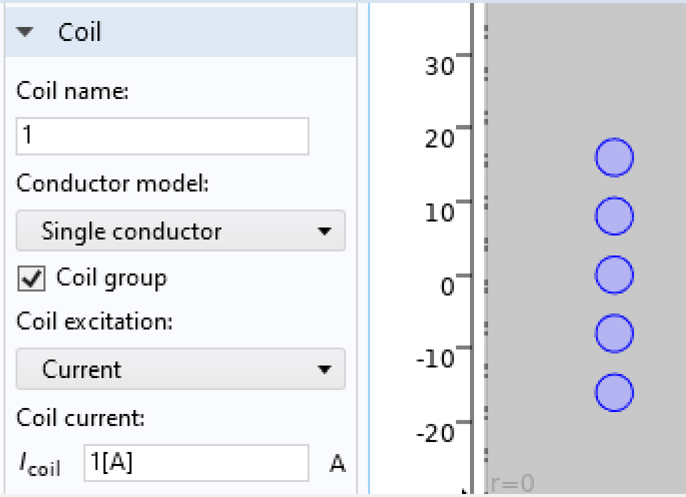
- Select a closed loop of edges



Cylindrical with Symmetries

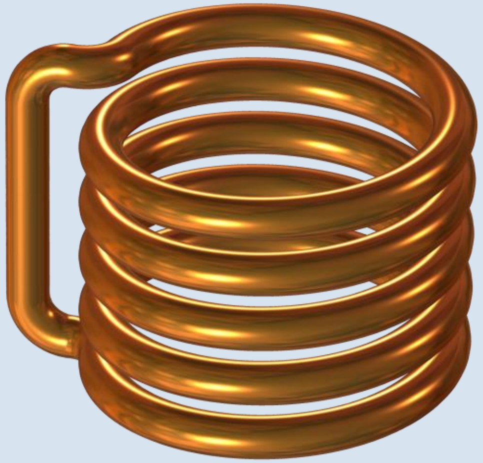
- Set length and area multiplication factors, here 4 and 2 respectively

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

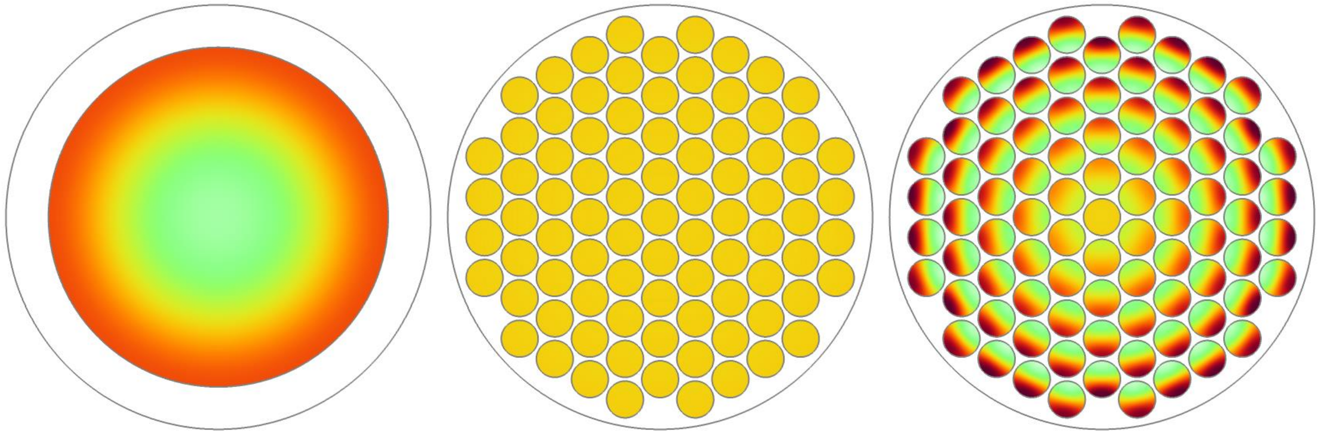
- The same amount of copper
- The same DC resistance
- The same current
- But not the same losses

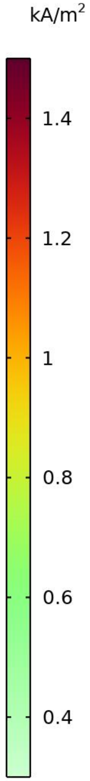
$$\delta \approx \sqrt{2/\omega\mu\sigma}$$

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

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

$1A\ 50Hz\ r/\delta = 2.0$	$1A\ 50Hz\ r/\delta = 0.22$	$1A\ 0.5kHz\ r/\delta = 0.7$
$Q_{AC}/Q_{DC} \approx 1.27$	$Q_{AC}/Q_{DC} \approx 1.02$	$Q_{AC}/Q_{DC} \approx 2.67$
Use a *Coil* feature, choose the *Single Conductor* conductor model setting, and keep the geometry.	Use a *Coil* feature, choose the *Homogenized Multiturn* conductor model setting, and simplify the geometry.	Use a *Coil* feature and choose the *Single Conductor* conductor model setting, or use an *RLC Coil Group* feature.





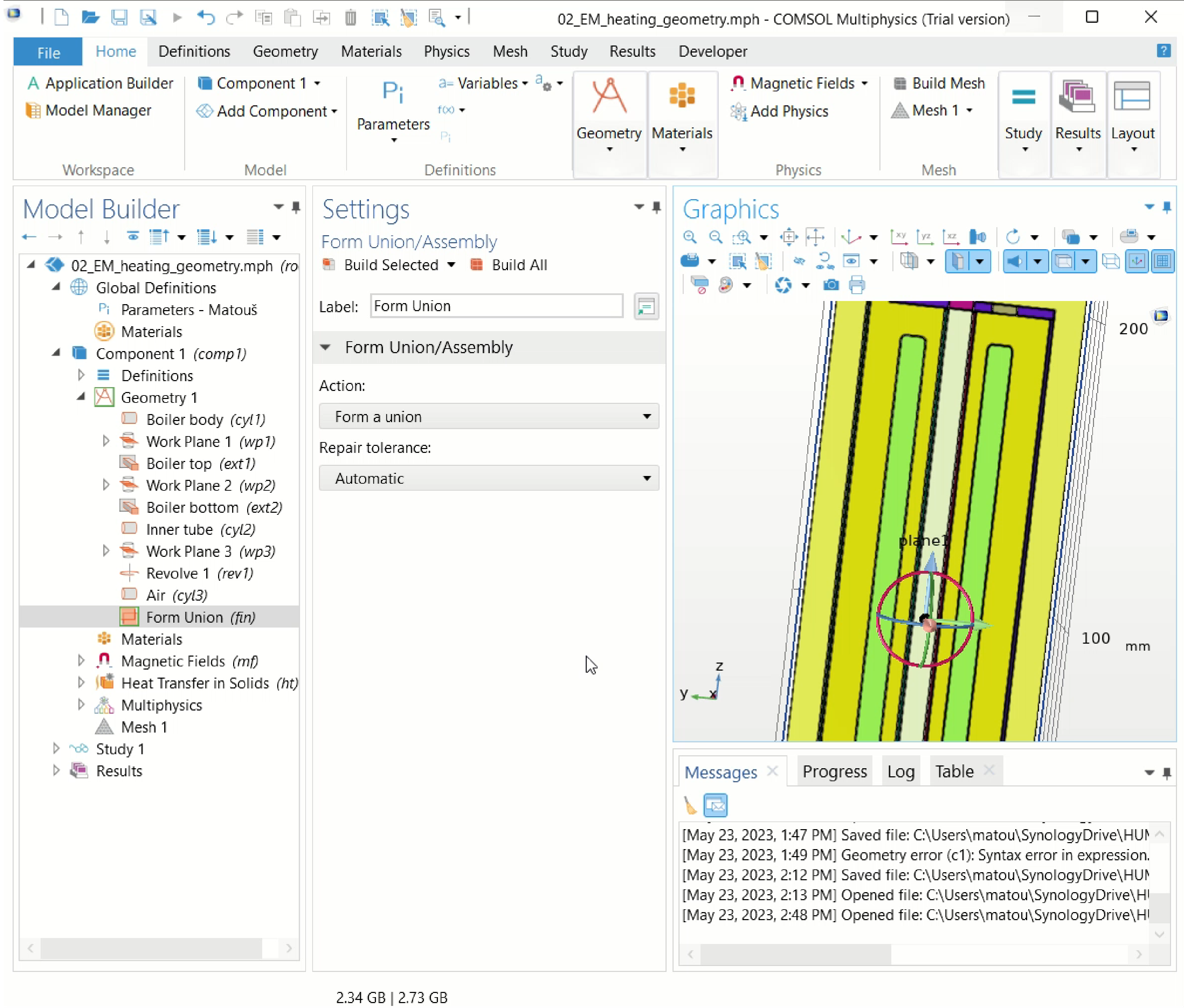
Magnetic Fields Modeling Advice

- 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

COMSOL

Induction Boiler: Materials

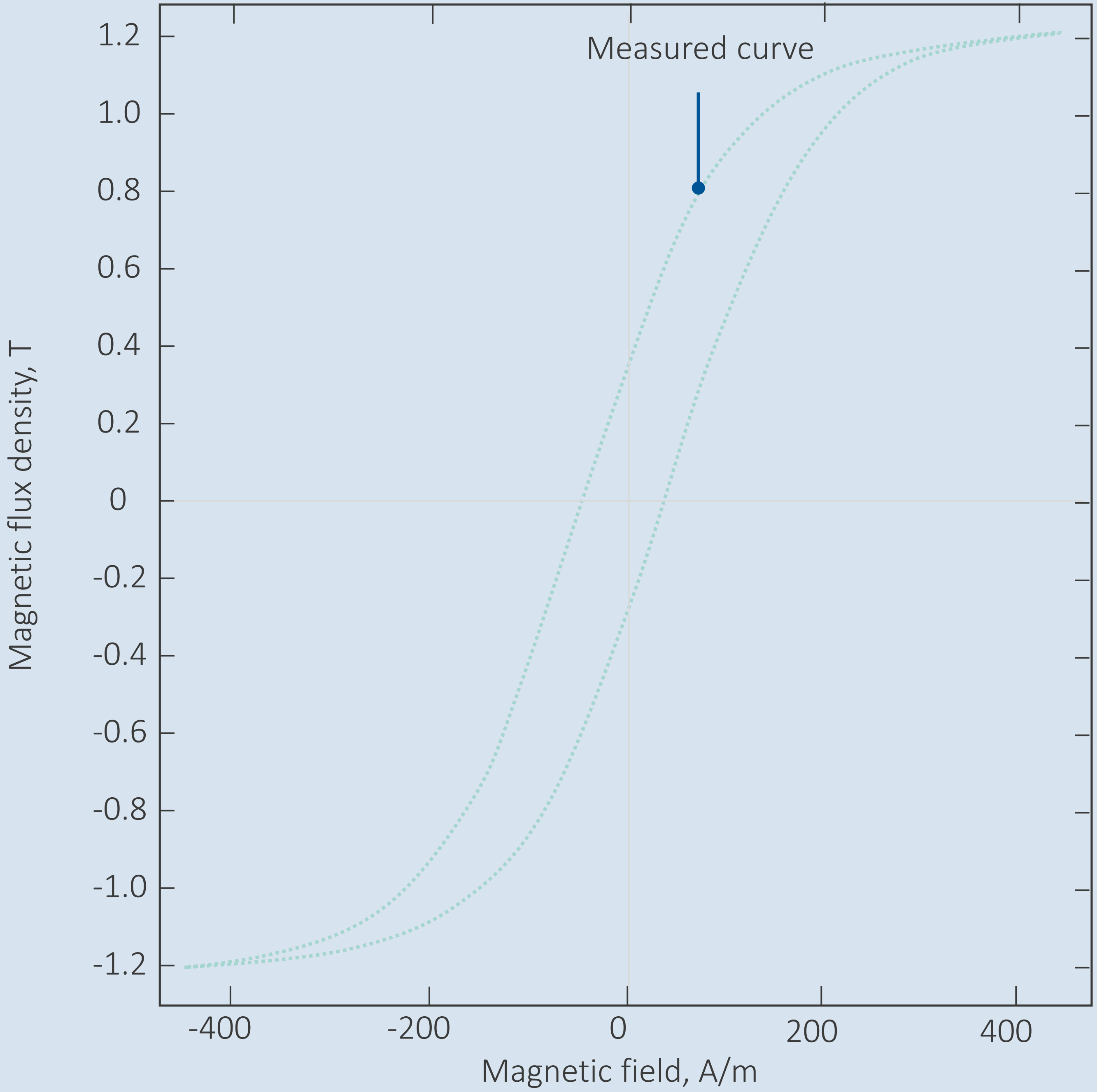
- Adding materials from Library
  - Copper
  - Water
  - Air
- Each material is defined by its:
  - Relative permeability
  - Electric conductivity
  - Relative permittivity
- Taking advantage of selected entities to create Explicit Selections for future use



COMSOL

Magnetic Material Models

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



Magnetic Material Models

- Constitutive relations $\mathbf{B} \leftrightarrow \mathbf{H}$
  - *Relative permeability*
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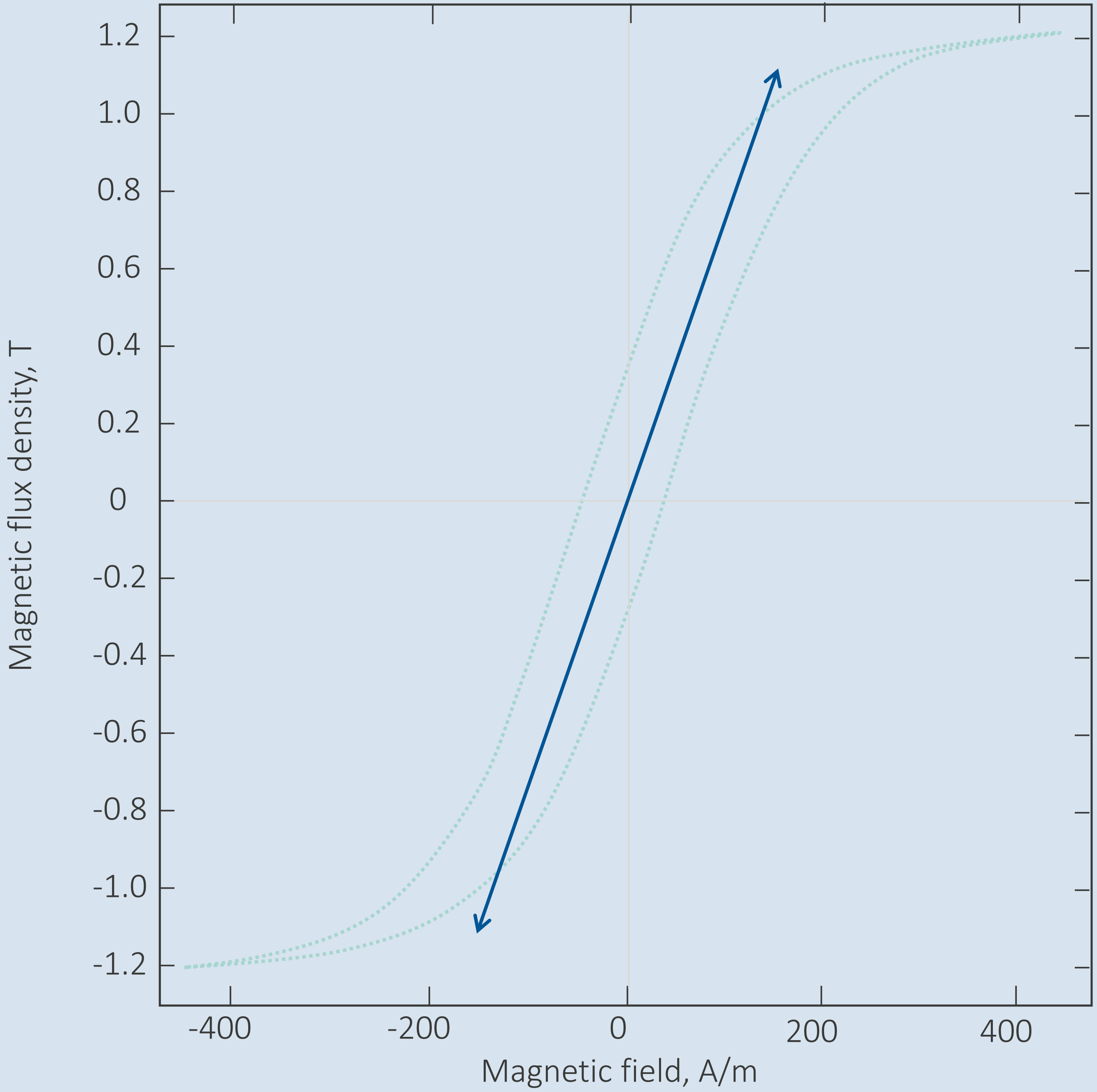

Magnetic Material Models

- 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
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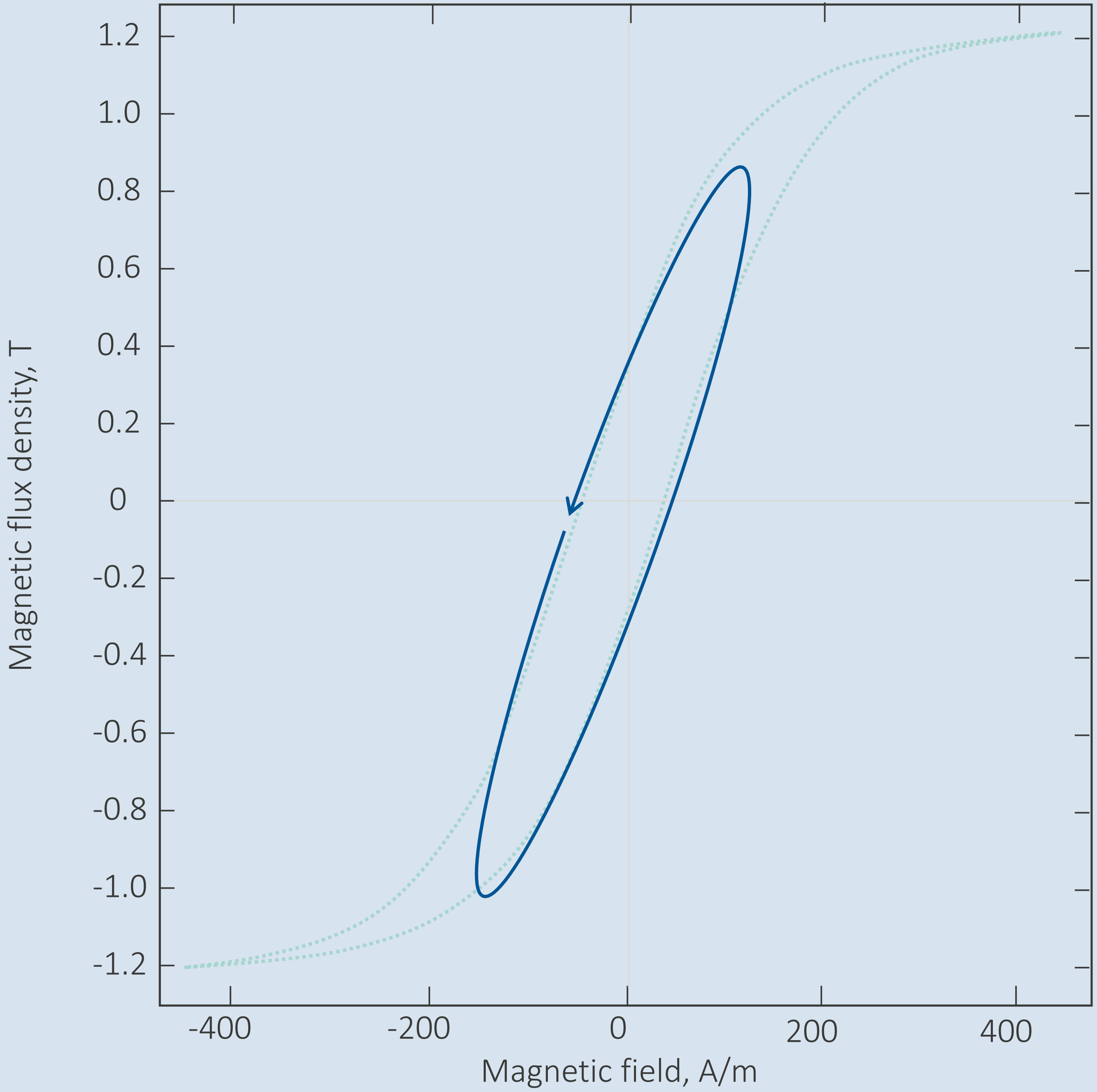
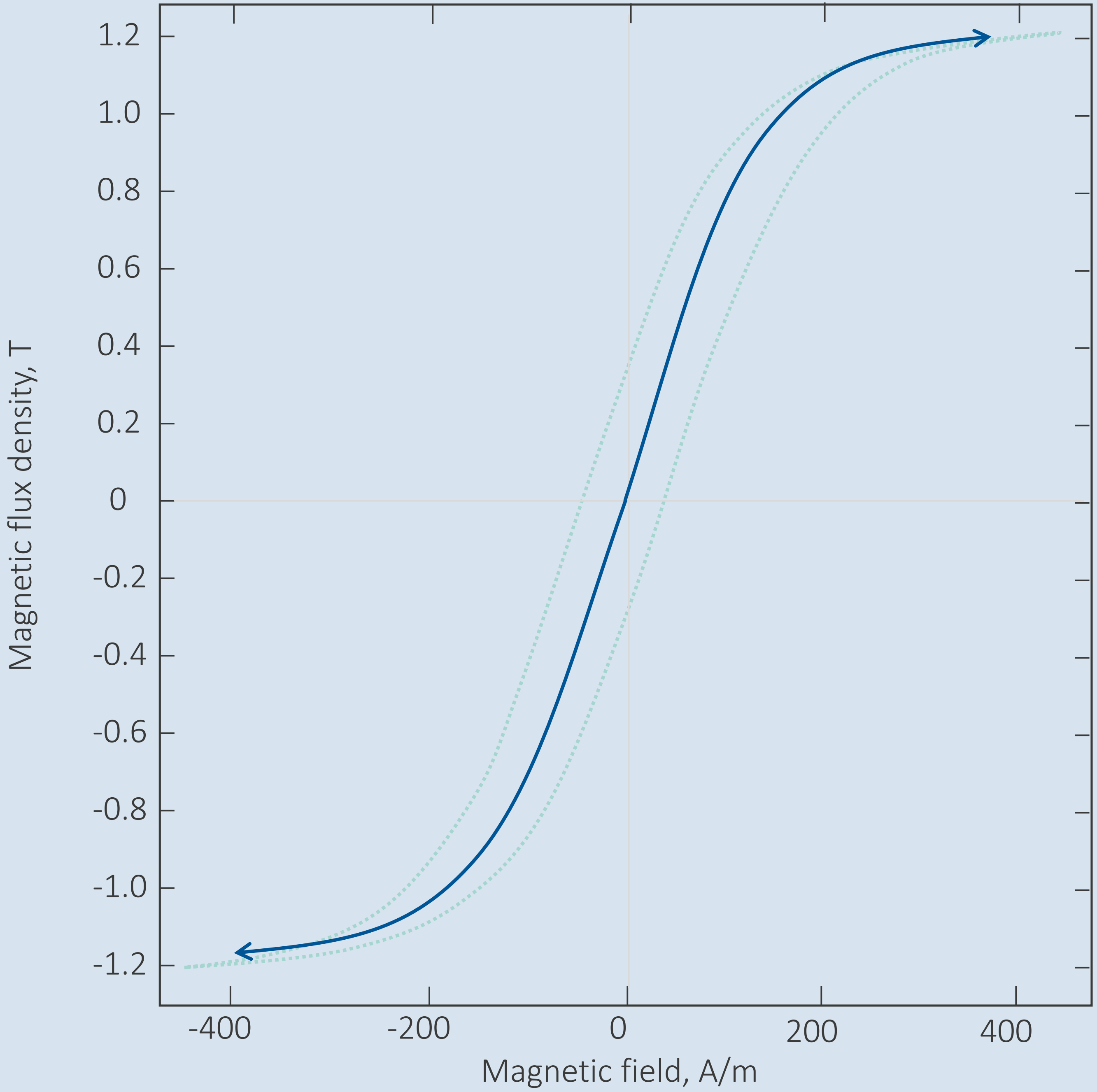


Magnetic Material Models

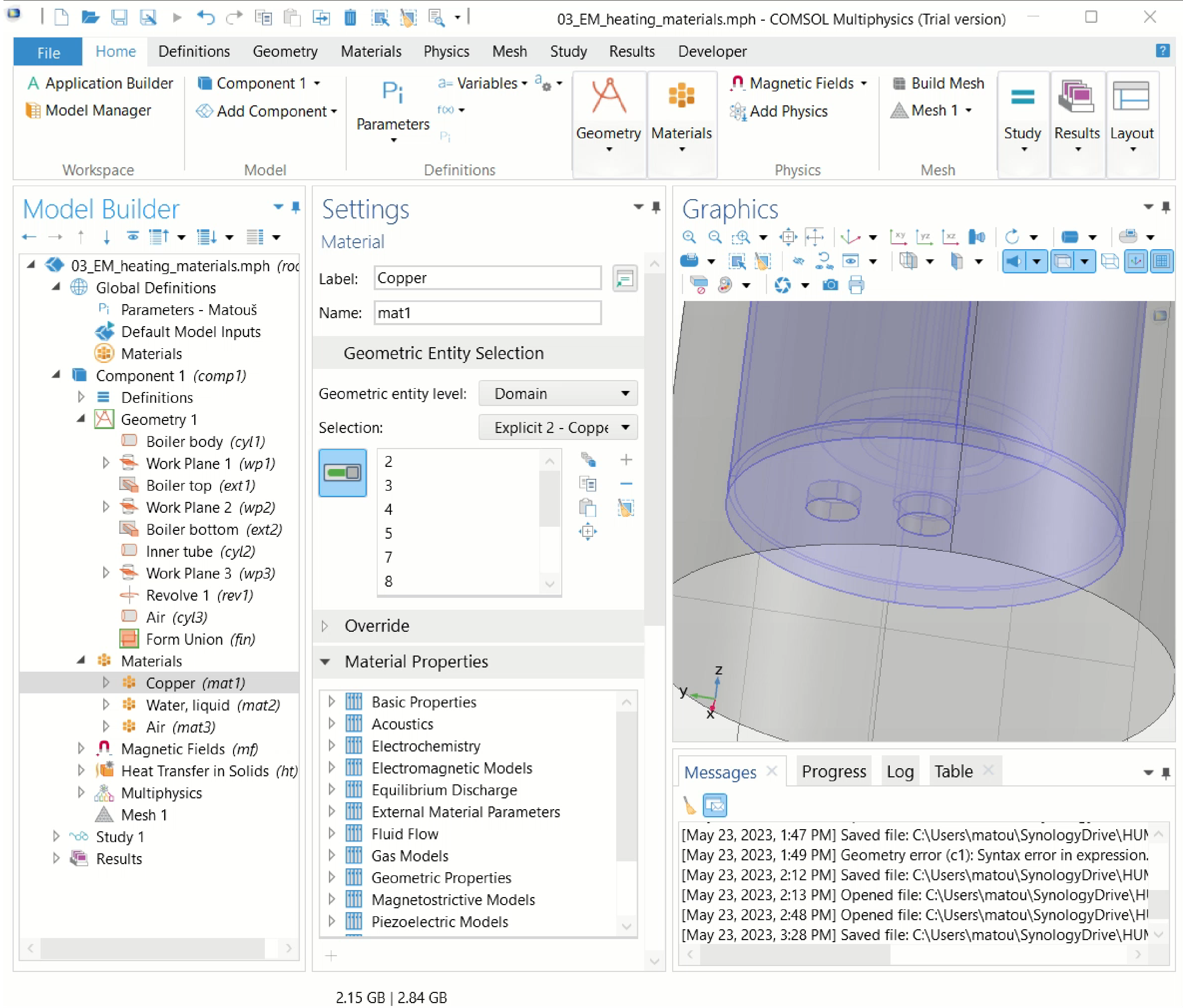
- Constitutive relations $\mathbf{B} \leftrightarrow \mathbf{H}$
  - Relative permeability
  - Magnetic losses
  - $\mathbf{B}(\mathbf{H})$ *curve*
  - Effective $\mathbf{B}(\mathbf{H})$ curve
  - Remanent flux density
  - Magnetization
  - $\mathbf{B}(\mathbf{H})$ nonlinear permanent magnet
  - Hysteresis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



COMSOL

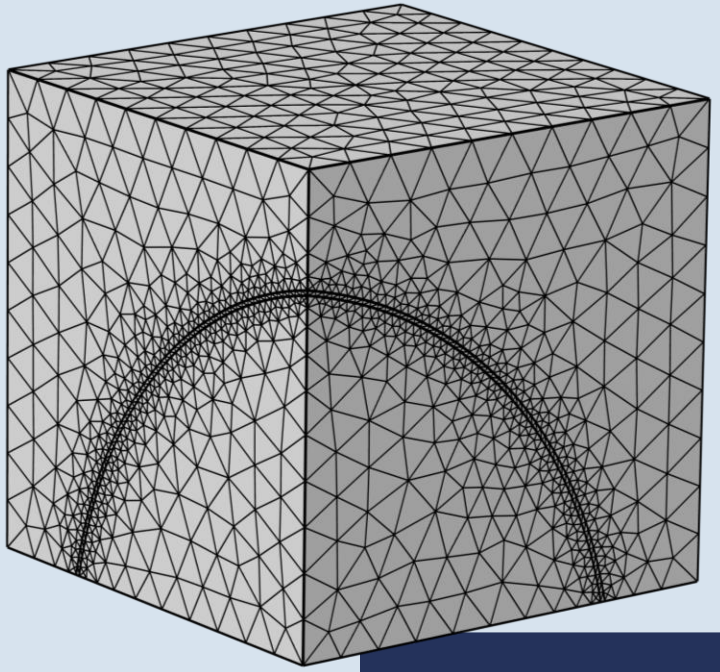
Induction Boiler: Magnetic Fields

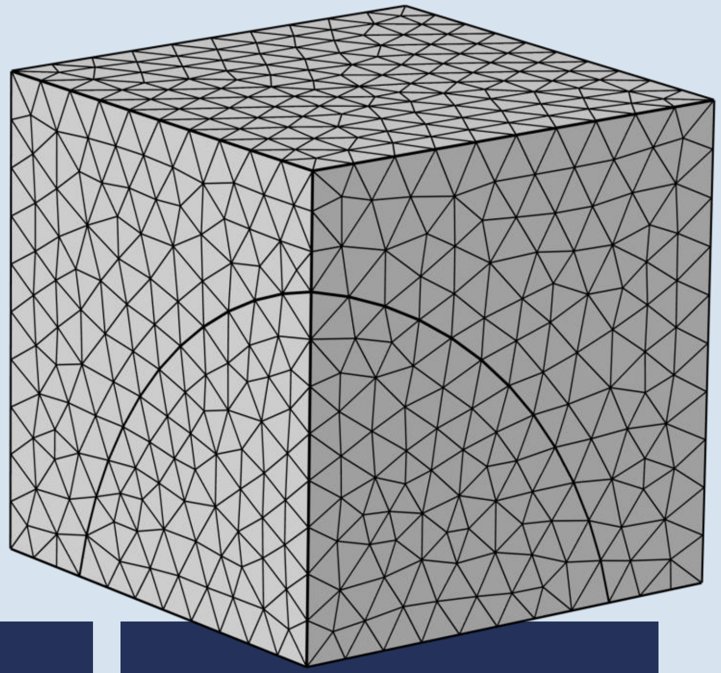
- Adding *Homogenized multiturn* coil to define primary winding with *N* turns, *Ia* input current and *Axs* inductor's cross sectional area
  - *Numeric* type coils need defined Input in the *Geometry Analysis* subnode and a *Coil geometry analysis* study step
- Defining boiler body and inner tube as 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 eletric conductors)





Volumetric Representation

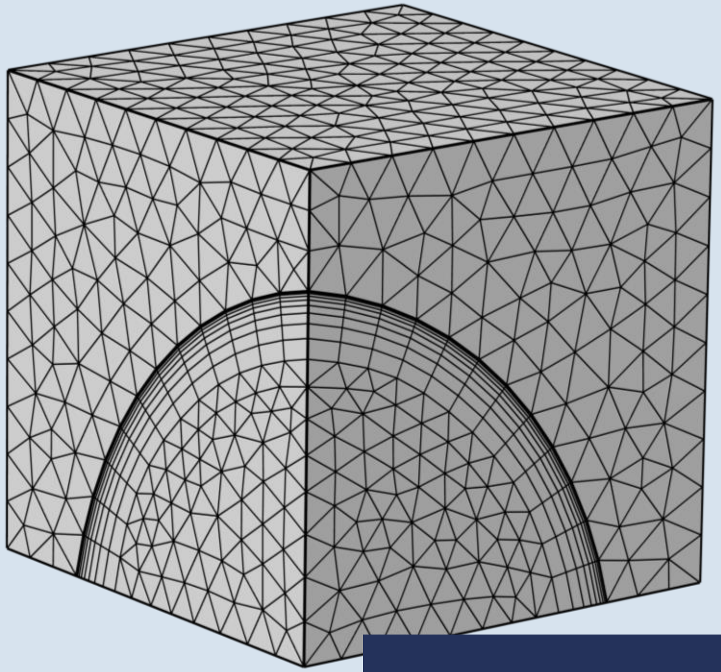
Avoids systematic errors but can be costly to mesh and solve

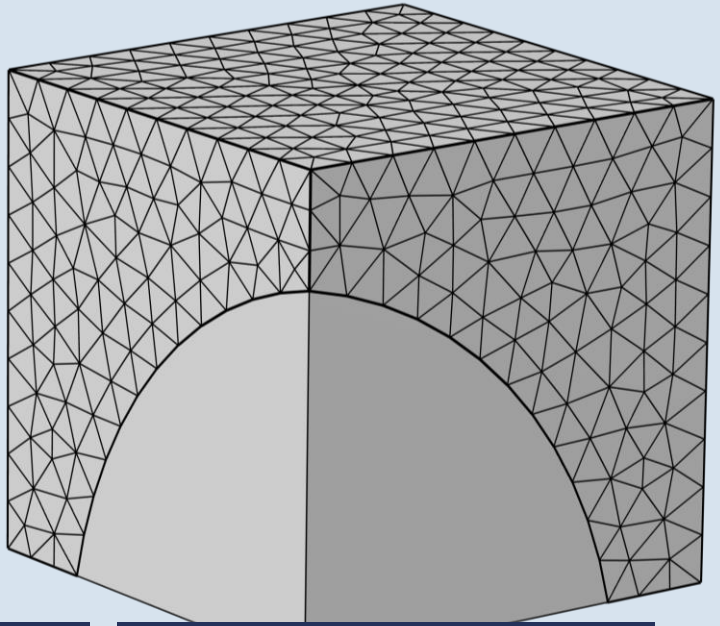
Thin Layer Condition

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

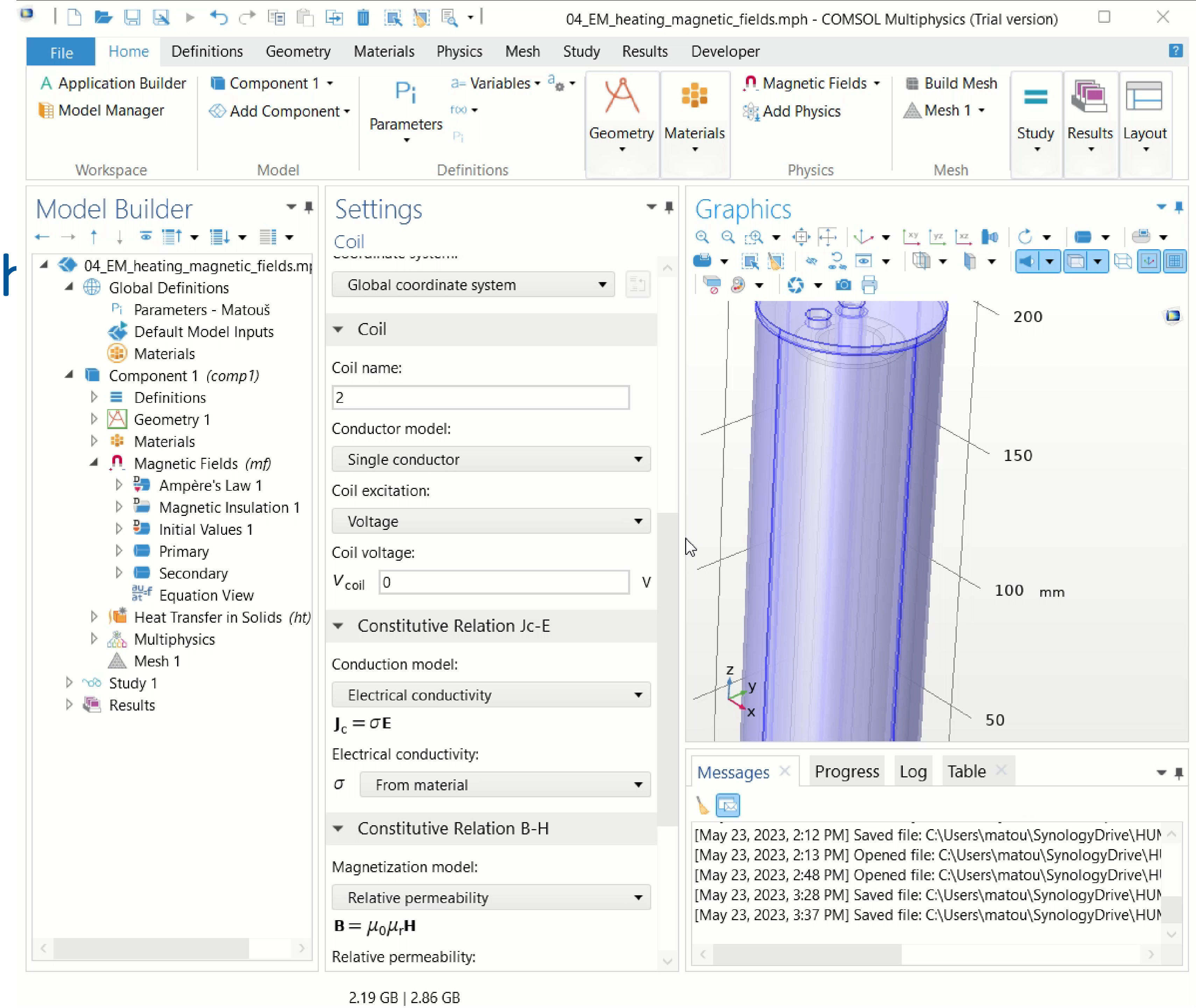
Avoids systematic errors but can be costly to mesh and solve

Impedance Condition

Saves time and memory when applicable

Induction Boiler: Mesh

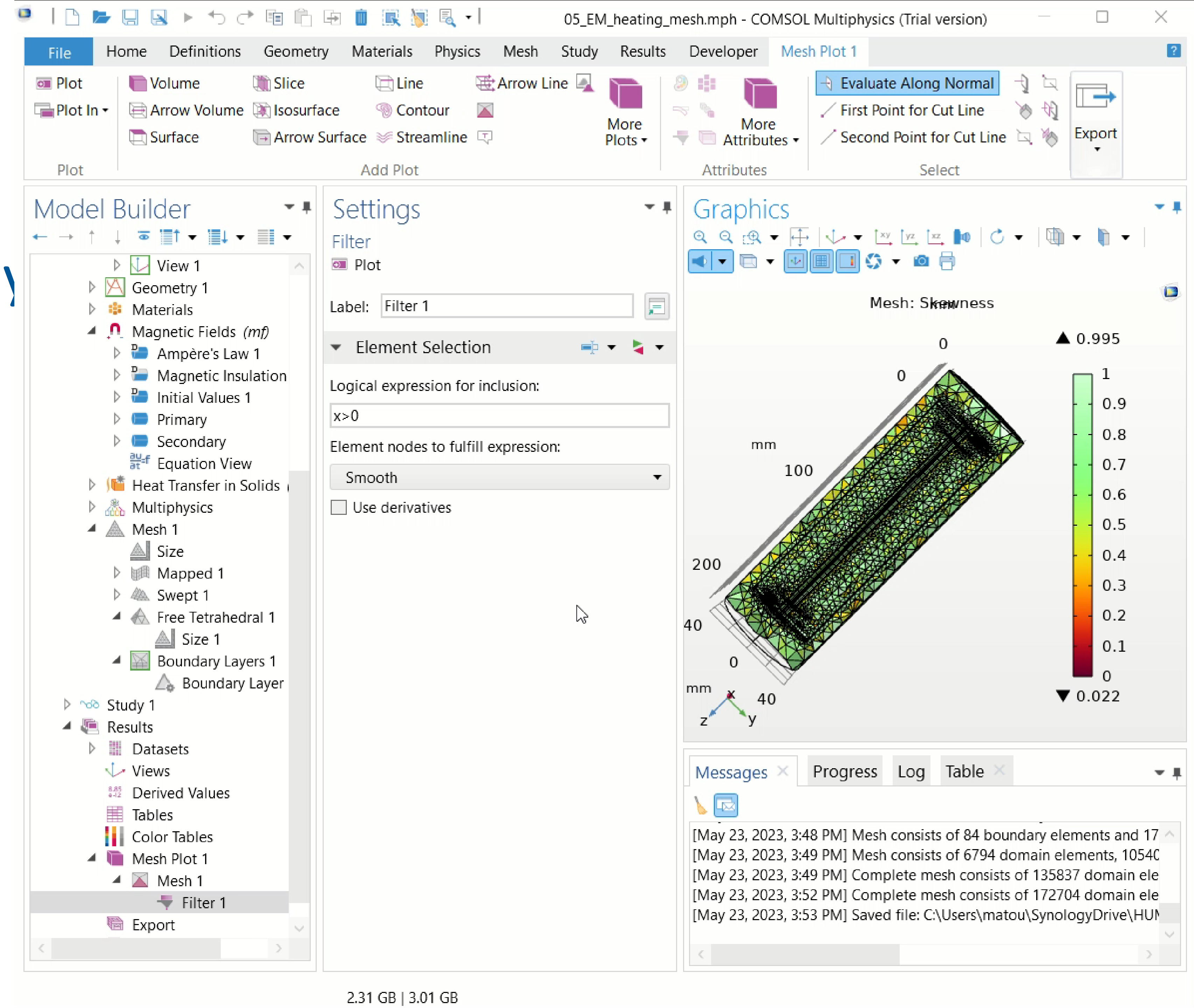
- 16 [kHz] is high enough energy for the skin effect to play important role but not high enough to use the *Impedance BC*
- *Swept* mesh in combination with *Boundary layers* are applied to resolve the skin effect
  - Thickness of boundary layer is given by skin depth defined in *Parameters* section



COMSOL

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