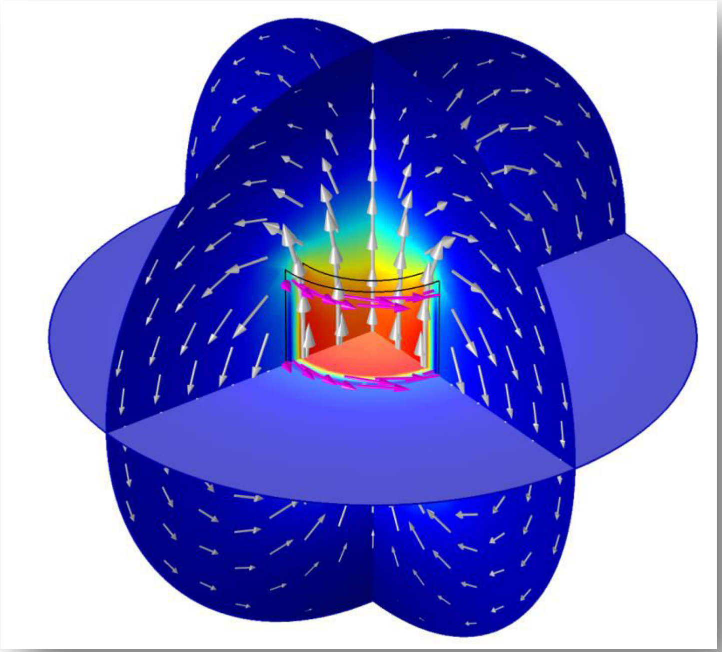
Single-turn and multi-turn coil domains in 3D

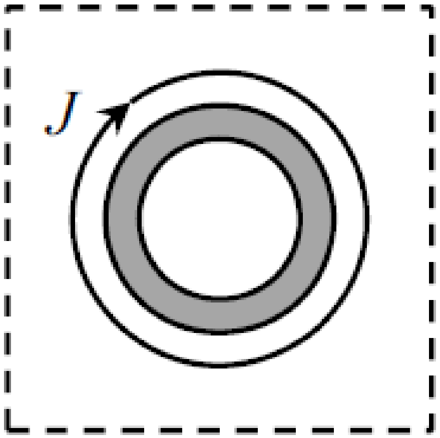


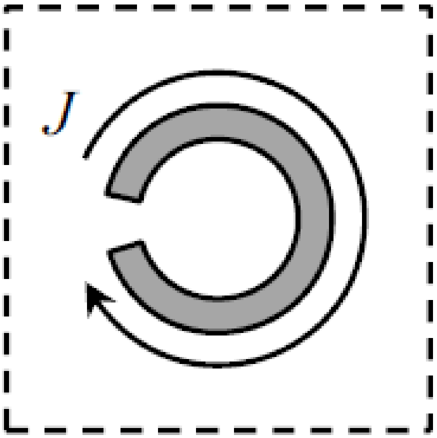
COMSOL

Introduction

- This tutorial shows how to use the Single-Turn Coil Domain and Multi-Turn Coil Domain features in COMSOL's Magnetic Fields interface for modeling coils in 3D
- These features are available only with the AC/DC Module
- They are suitable for computationally efficient modeling of current-carrying conductors creating magnetic field
- Additional information related to suitability of using these coil modeling features in DC and AC are provided

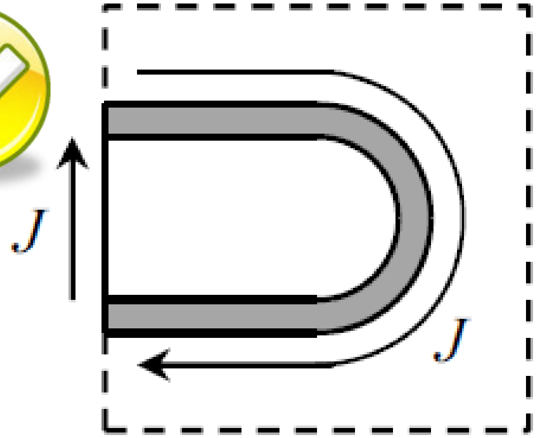
We should have a closed current loop

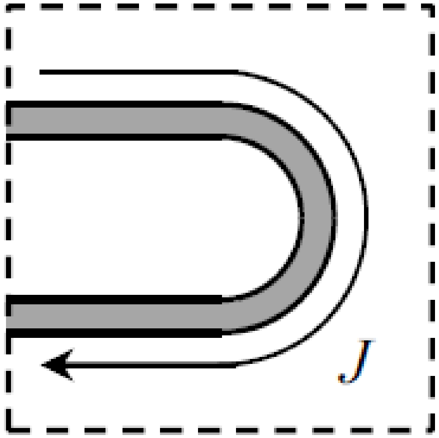




- Use a closed geometry
- Specify a closed current path using appropriate modeling techniques

When modeling magnetic field, we need to have a closed current loop





Use appropriate boundary conditions for open geometries

Overview

- This tutorial describes how to use the following features

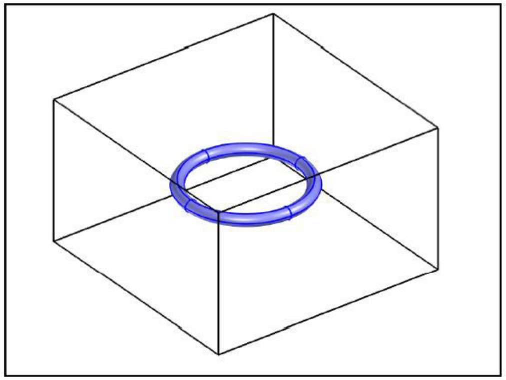
- Single-turn coil domain
  - Gap feed
  - Boundary feed

- Multi-turn coil domain
  - Linear coil
  - Circular coil
  - Numeric coil
  - Using symmetry
  - User-defined coil

Single-turn coil domain

- Model the actual conductor to compute magnitude and direction of current flow
- Use this information to find the magnetic field in and around the conductor
- Useful when you have a few turns
- Also when you want to resolve the current distribution in individual wires and turns

- **Note:** You need to model an air domain around the conductor



Single-turn toroidal coil

Modeling in frequency domain - AC

- Always use this when the signal is periodic (e.g. sinusoidal, square wave)

- Can be used for single-turn coil domain as long as the skin depth is not too small compared to the conductor thickness
  - When the skin depth is smaller than the conductor thickness, use a boundary layer mesh
  - When the skin depth is significantly smaller (< 1/20th) than the conductor thickness then we cannot use single-turn coil domain anymore

Modeling in time domain - Transient

- Cannot be used for single-turn coil domain
  - COMSOL uses an A-V formulation locally within the single-turn coil
  - Solves for both magnetic vector potential (A) and electric potential (V)
  - Transient simulation is not supported for such cases because V is not uniquely defined at each point in space
  - In time domain analysis, the voltage (V) is defined as a path integral between two points in space

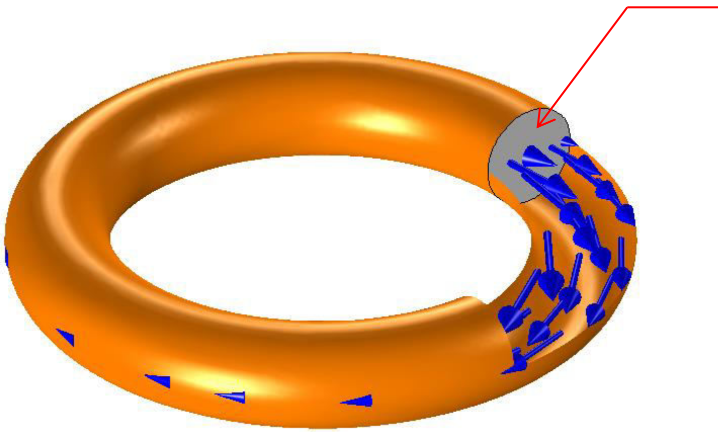
- For details on the A-V formulation, refer to the *AC/DC Module User's Guide*

Single-turn coil – Gap feed

- Single-turn coil
- Leads are not modeled
- Geometry must form a closed loop
- Cross section and shape can be arbitrary

Coil excitation method

- Excitation source is modeled as an internal cross section boundary called **gap feed**
- We need to be careful while drawing the geometry so that we create this internal boundary



Gap feed

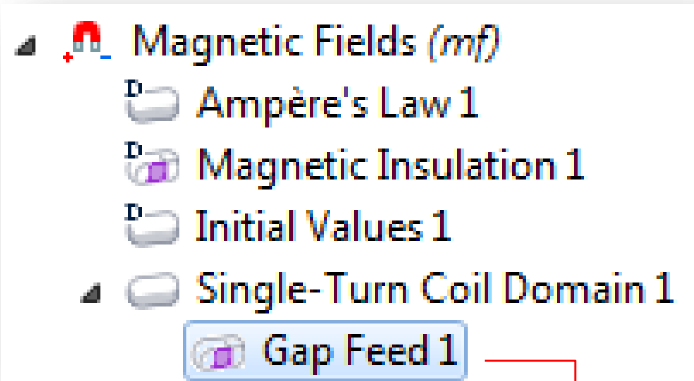
1. Specify the voltage across this boundary
2. Specify the current through this boundary
3. Options to connect to lumped electrical circuit

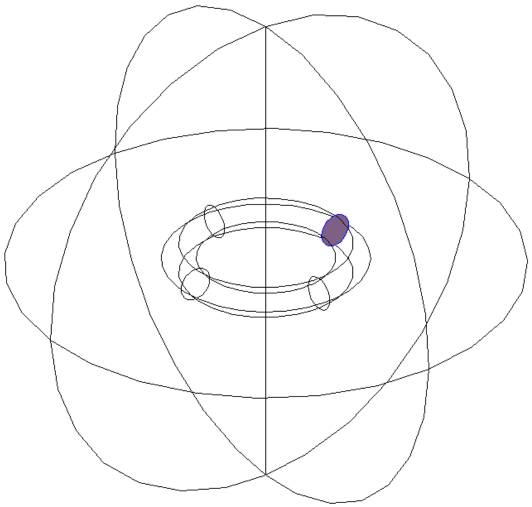
Modeling in COMSOL

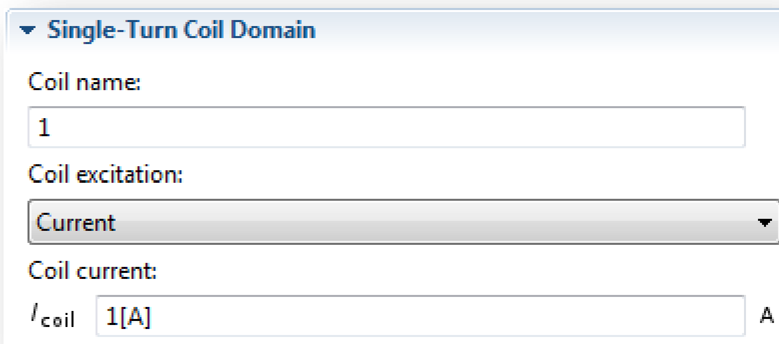
- For detailed modeling steps, see the following file:
  - *single_coil_gap_feed.mph*

- This model shows both DC and AC cases

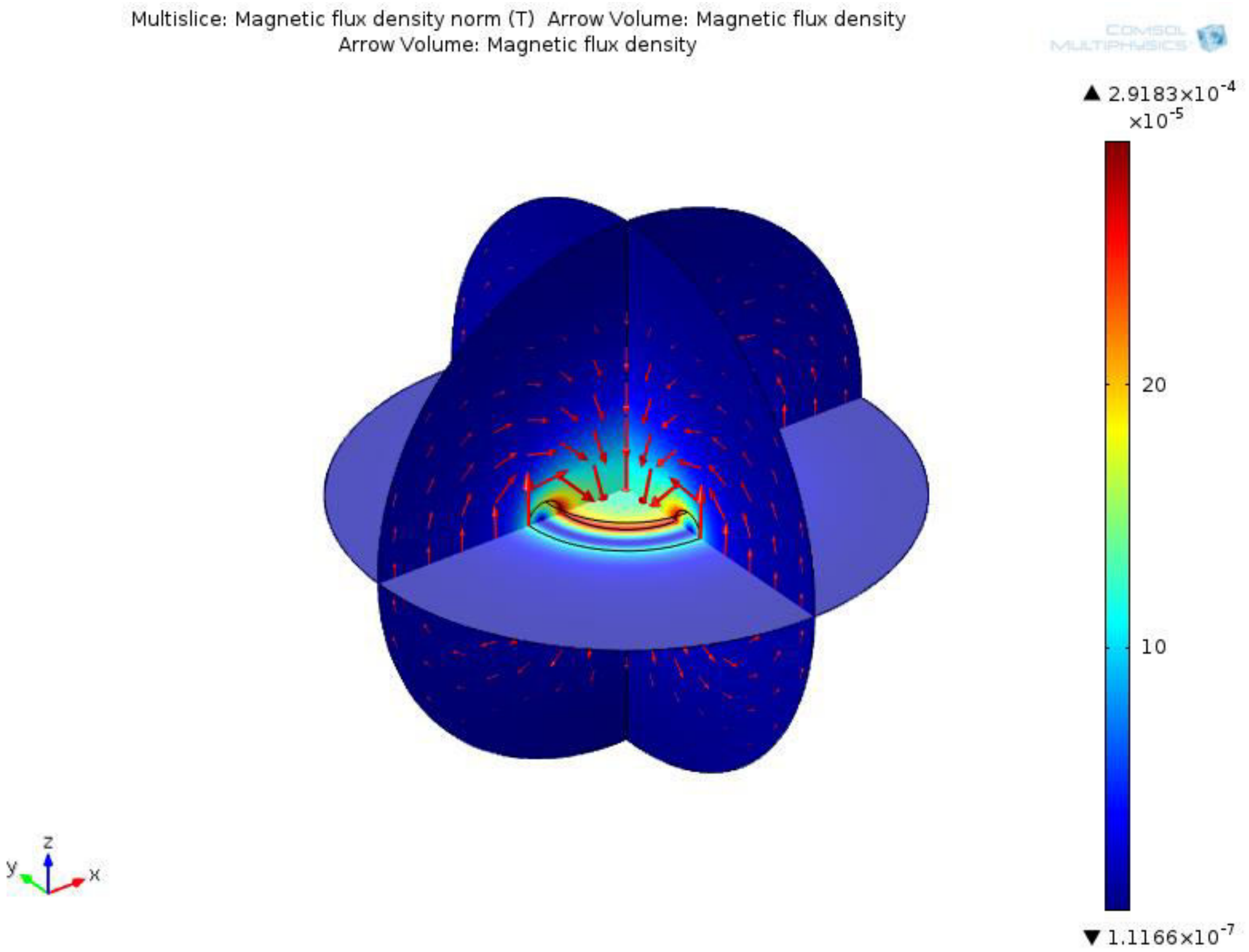
Using single-turn coil domain with gap feed





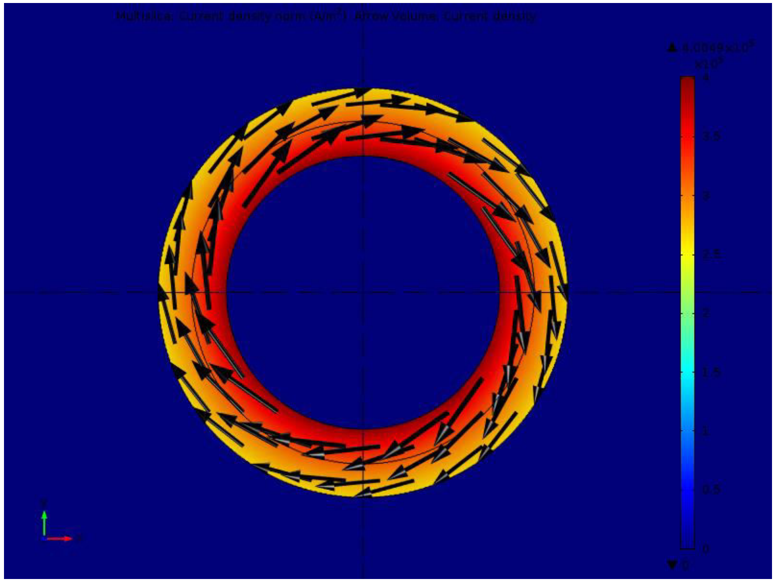


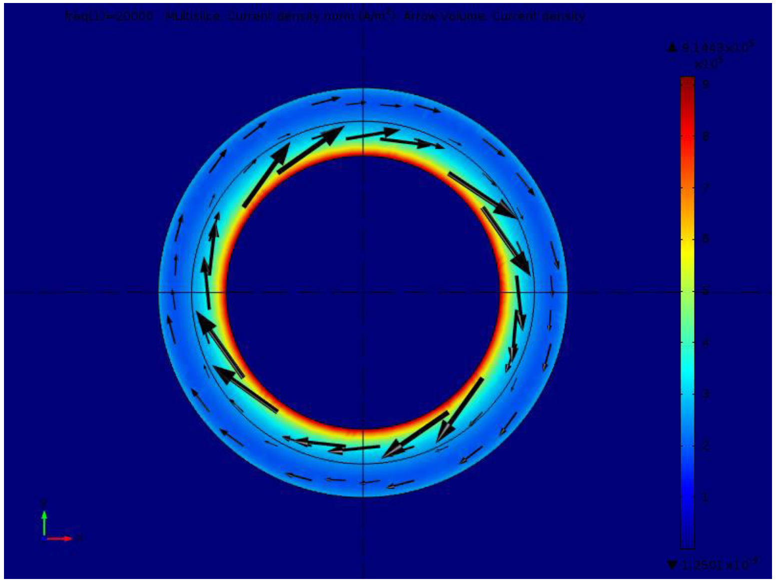
Results – Magnetic flux density (DC)



Inductance = 1.17e-8 H

Results – Current density





DC solution
Resistance = 1.65e-4 Ω

Higher current density along the inner radius indicates that more current is concentrated along a shorter conduction path

AC (20 kHz) solution
Impedance = 2.3e-4 + 0.001i Ω

Current distribution clearly shows the skin effect

COMSOL

Using gap feed in AC single-turn coil

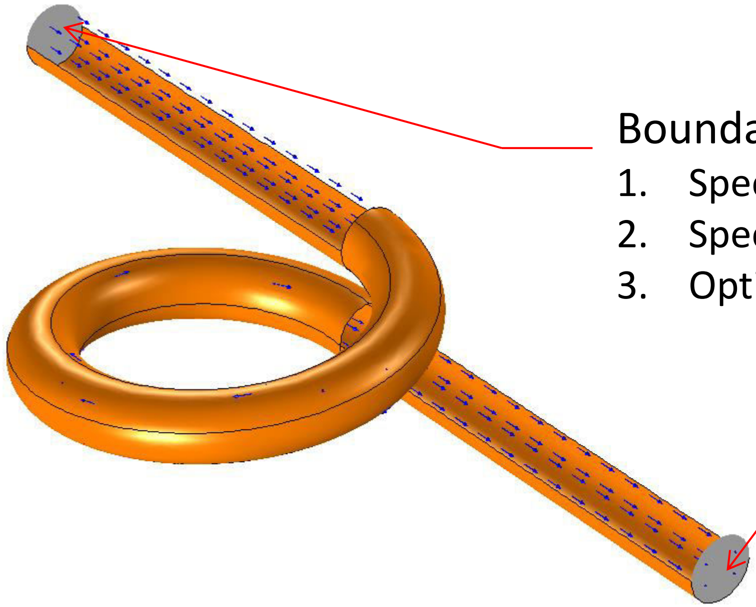
- Gap feed in AC indicates a connection to a transmission line
- In reality there is a capacitive coupling between the two ends of this "gap" feed
  - Capacitive coupling is more significant at higher frequencies
  - We cannot model it since we assume the gap feed to be a zero thickness surface
  - Gap impedance will depend on the actual gap thickness and material property of the "gap"
- Gap feed is perfectly accurate for DC models but a good approximation only for low frequency AC models

Single-turn coil – Boundary feed

- Single-turn coil
- Leads are modeled
- Geometry does not form a closed loop
- Cross section and shape can be arbitrary
- You can use this to model more than a single turn

Coil excitation method

- Direction of current flow is modeled by specifying a **ground** surface and a **boundary feed**
- These surfaces should touch the external walls of the air domain surrounding the conductor



Boundary feed

1. Specify the voltage at this boundary
2. Specify the current through this boundary
3. Options to connect to lumped electrical circuit

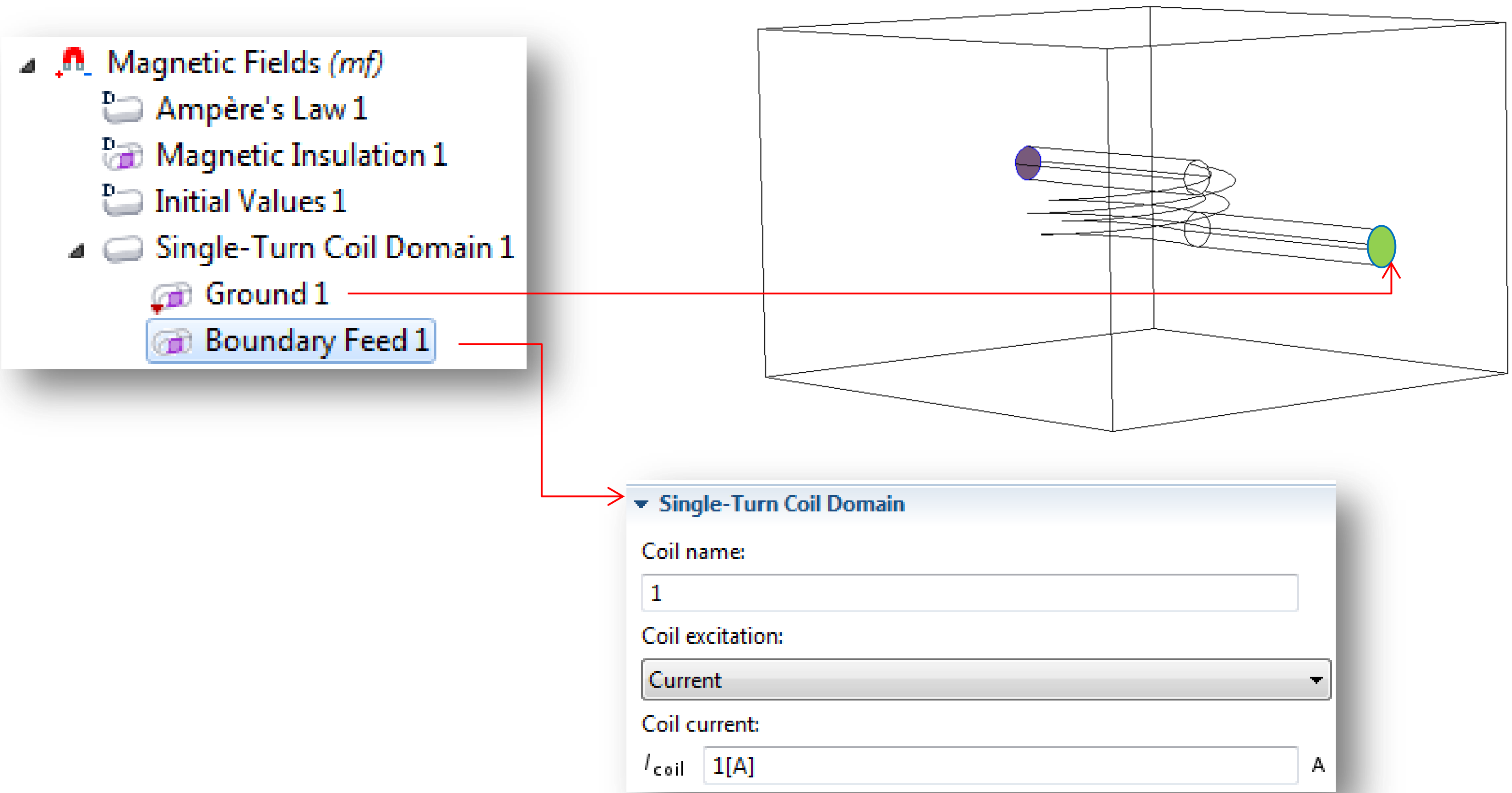
Ground

Modeling in COMSOL

- For detailed modeling steps, see the following file:
  - *single_coil_boundary_feed.mph*

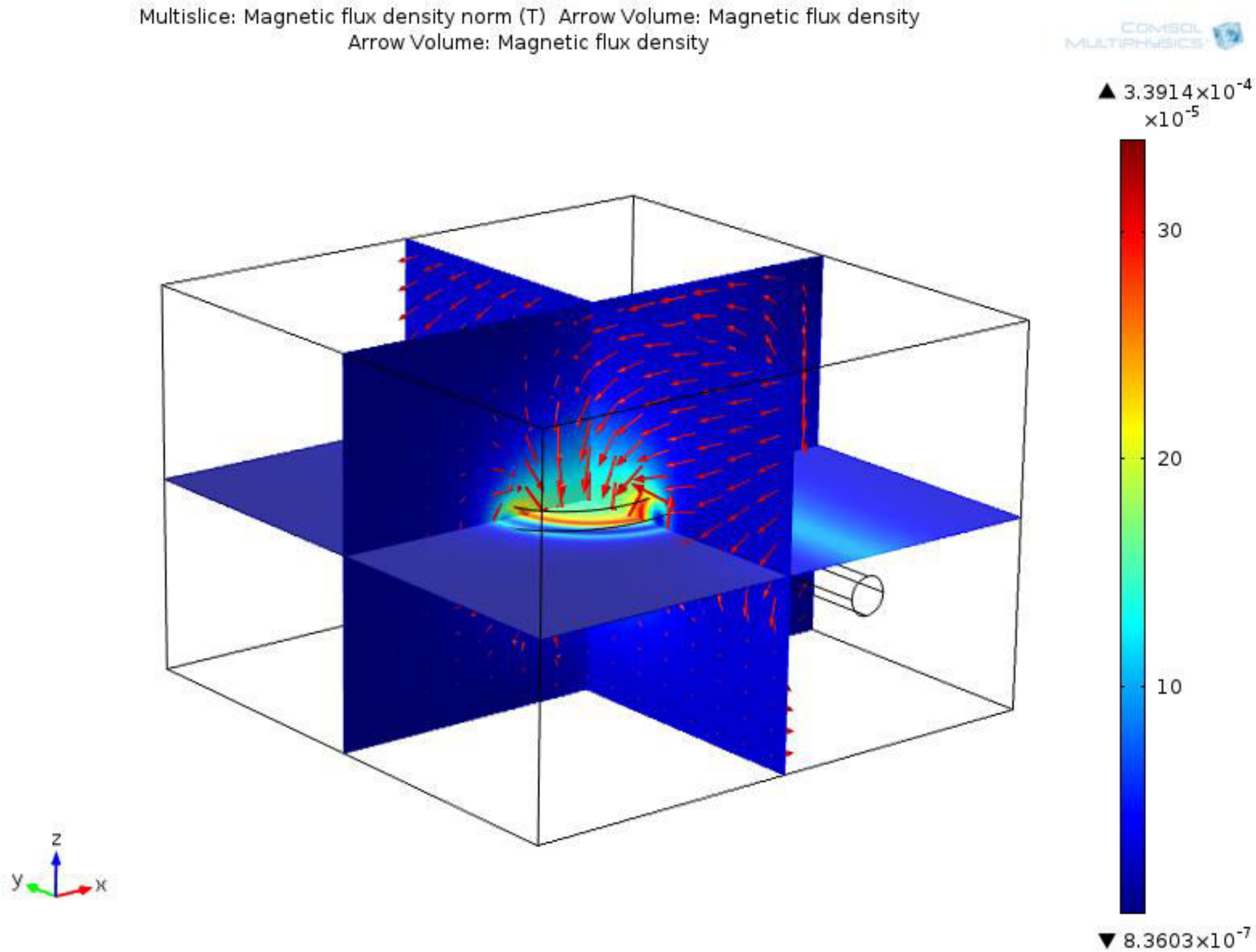
- This model shows both DC and AC cases

Using single-turn coil domain with ground and boundary feed



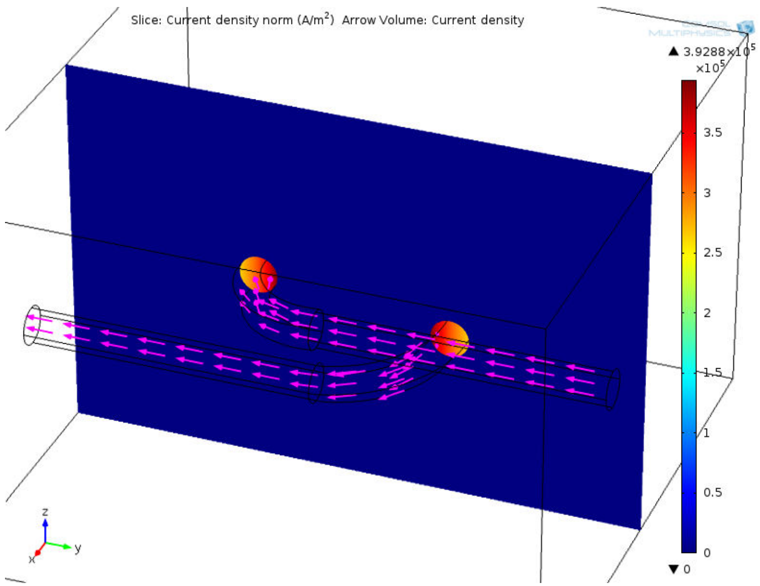
COMSOL

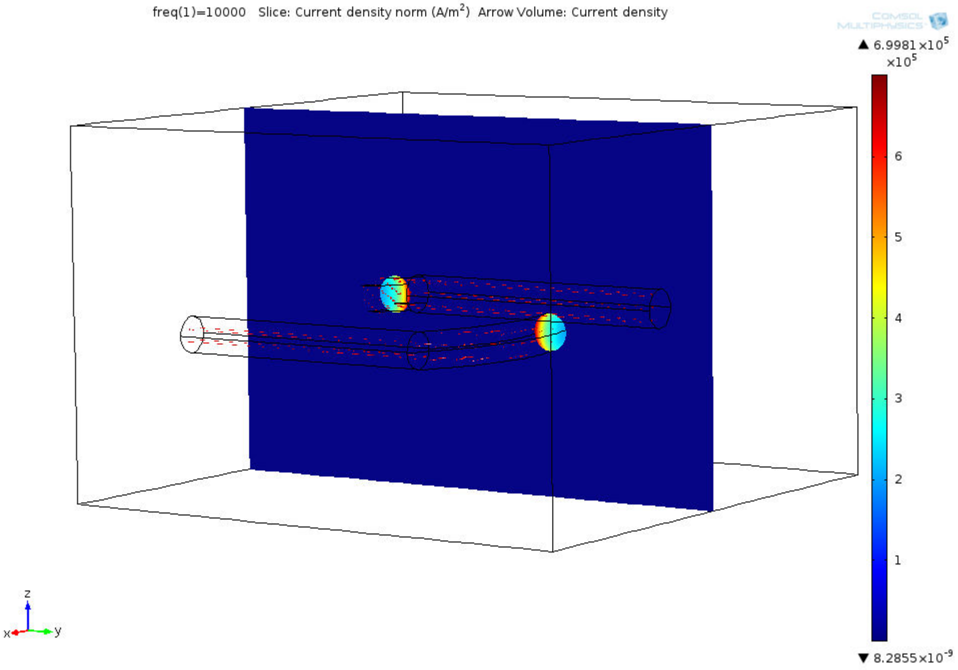
Results – Magnetic flux density (DC)



Inductance = 3.16e-8 H

Results – Current density





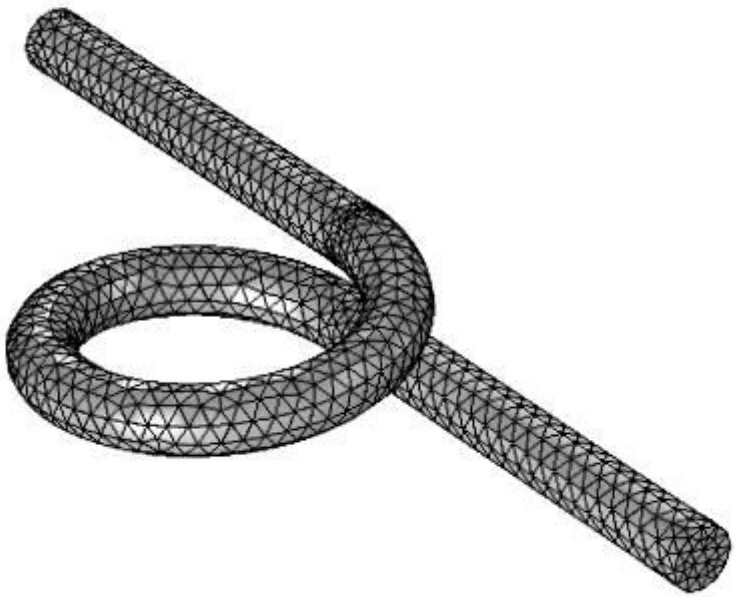
DC solution
Resistance = 3.25e-4 Ω

Higher current density along the inner edges indicates that more current is concentrated along a shorter conduction path

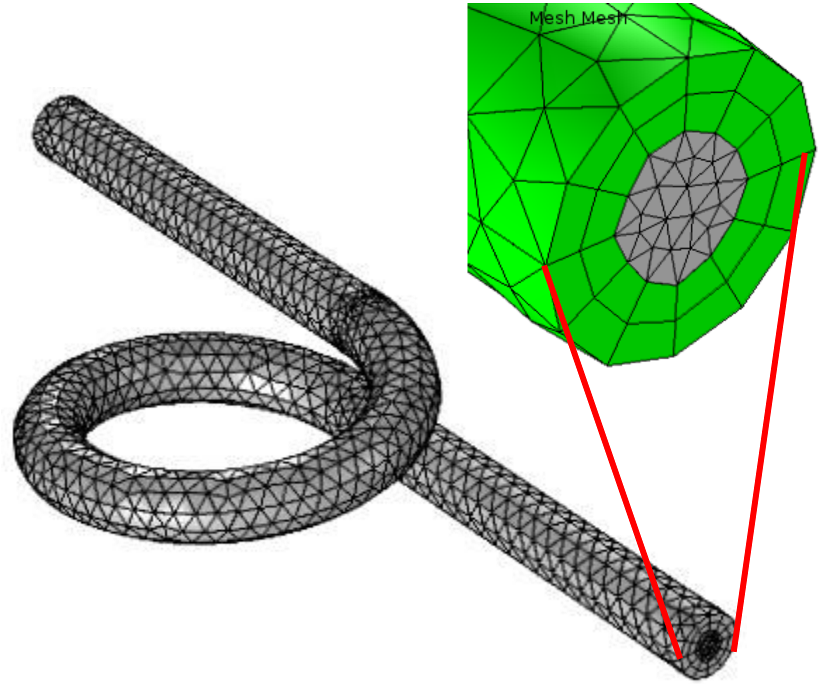
AC (10 kHz) solution
Impedance = 3.83e-4 + 0.002i Ω

Current distribution clearly shows the skin effect

Meshing considerations



Default free tetrahedral mesh is suitable for the DC problem

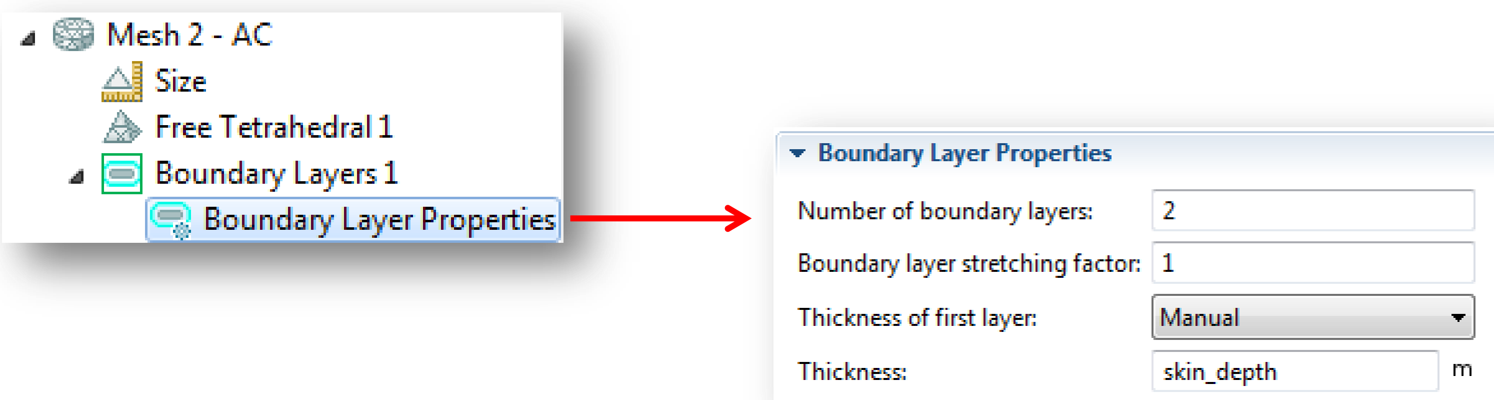


Boundary layer mesh is better to resolve the skin effect for AC problems where the skin depth is smaller than the conductor cross section

Resolving the skin effect in conductors using boundary layer mesh

- Compute skin depth: $\delta = \sqrt{\dfrac{2}{\omega \mu \sigma}}$

- If the skin depth is less than ½ the thickness of the conductor, consider using a boundary layer mesh
  - Two layers of mesh around the conductor wall is good enough
  - Each layer has the same thickness as the skin depth

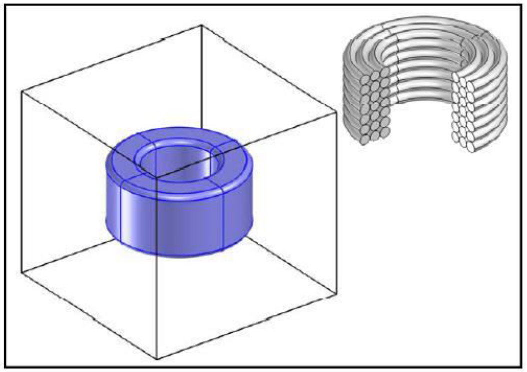


Multi-turn coil domain

- Model a homogenized current carrying region to compute magnitude and direction of current flow
- Use this information to find the magnetic field in and around the conductor
- Useful when you have a lot of turns

- Each individual wire is insulated – hence no shorting between conductors
- Individual wire and multiple layers are not resolved

- **<u>Note:</u>** You still need to model an air domain around the conductor



Homogenized multi-turn coil

COMSOL

Modeling in frequency and time domain

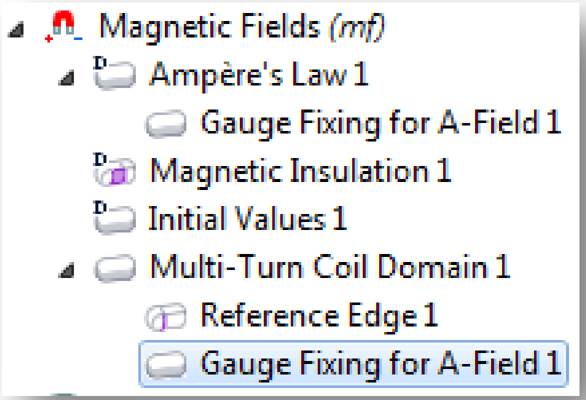
- Always use frequency domain when the signal is harmonic (i.e. sinusoidal)
  - Linear problem
  - Relatively easy to solve
- Can be used for multi-turn coil domain as long as the skin depth is much larger than the individual wire diameter

- Use time domain only if the signal is not harmonic (e.g. pulse)
  - Nonlinear problem
  - Requires more computational time and memory

Convergence tips when using 3D Multi-Turn Coil Domain in frequency domain models

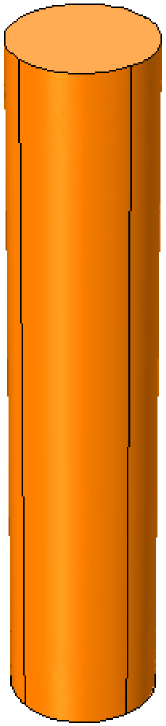
- Use a small non-zero electrical conductivity for Air
  - This is required to avoid creating a singular stiffness matrix
  - A value of 1[S/m] is a good guess
  - Using smaller values would increase computation time
  - Cannot use a very high value because that would affect the "physics" of the model

- May need Gauge fixing
  - Add Gauge Fixing to Ampere's Law
  - Add Gauge Fixing to Multi-Turn Coil Domain
  - Required to get a unique numerical solution



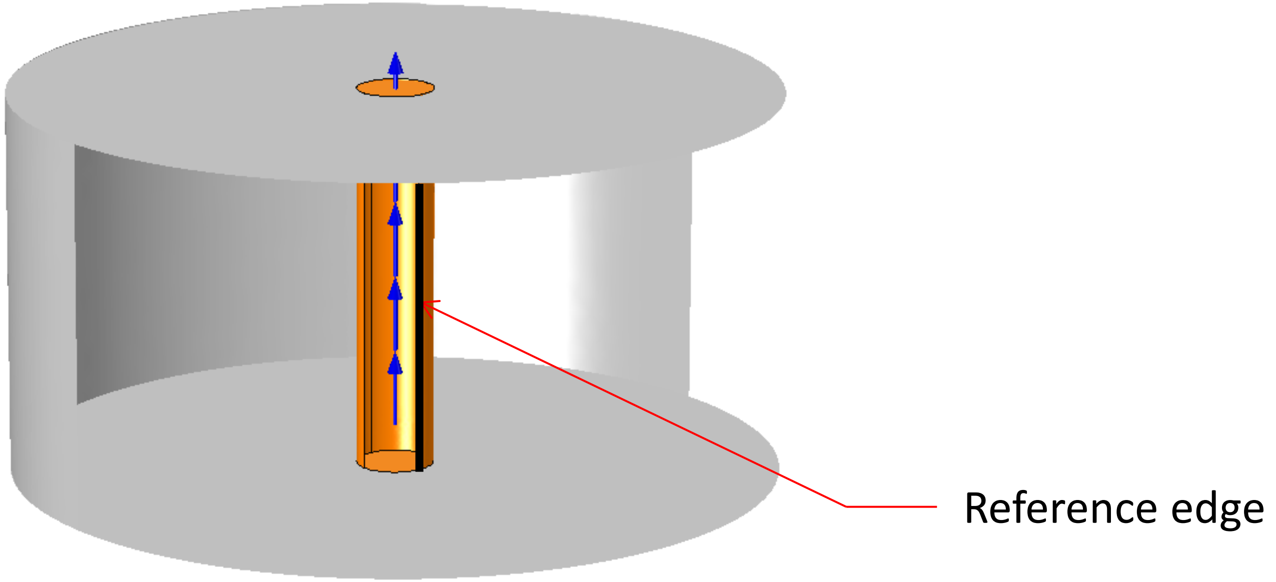
Multi-turn coil – Linear

- Multiple parallel straight wires bundled in a sleeve
- Leads are modeled
- Geometry should not form a closed loop and must have a straight longitudinal axis
- Cross section can be arbitrary



Coil excitation method

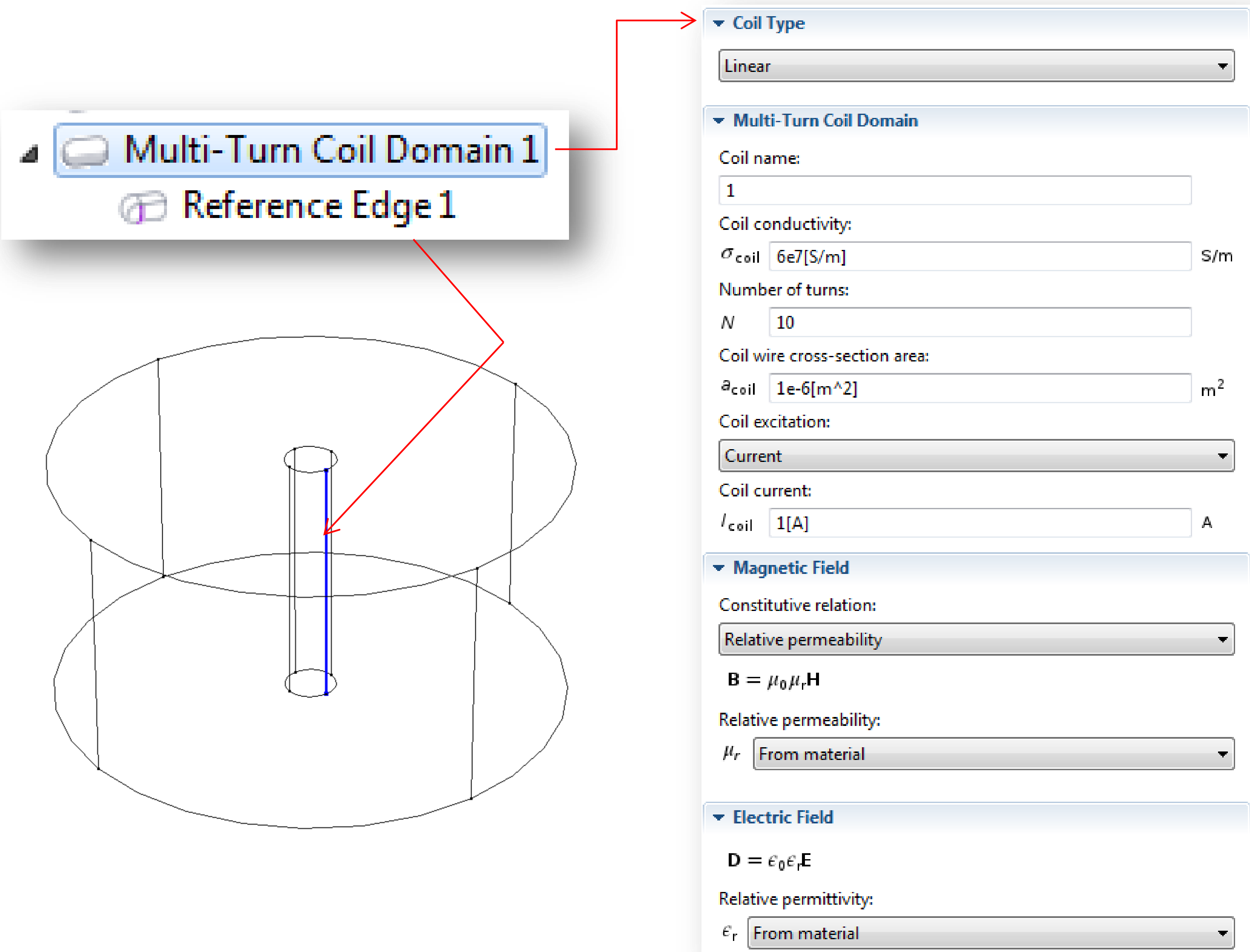
- Direction of current flow is modeled by specifying a **reference edge**
- Also the two end surfaces should touch the external walls of the air domain surrounding the conductor



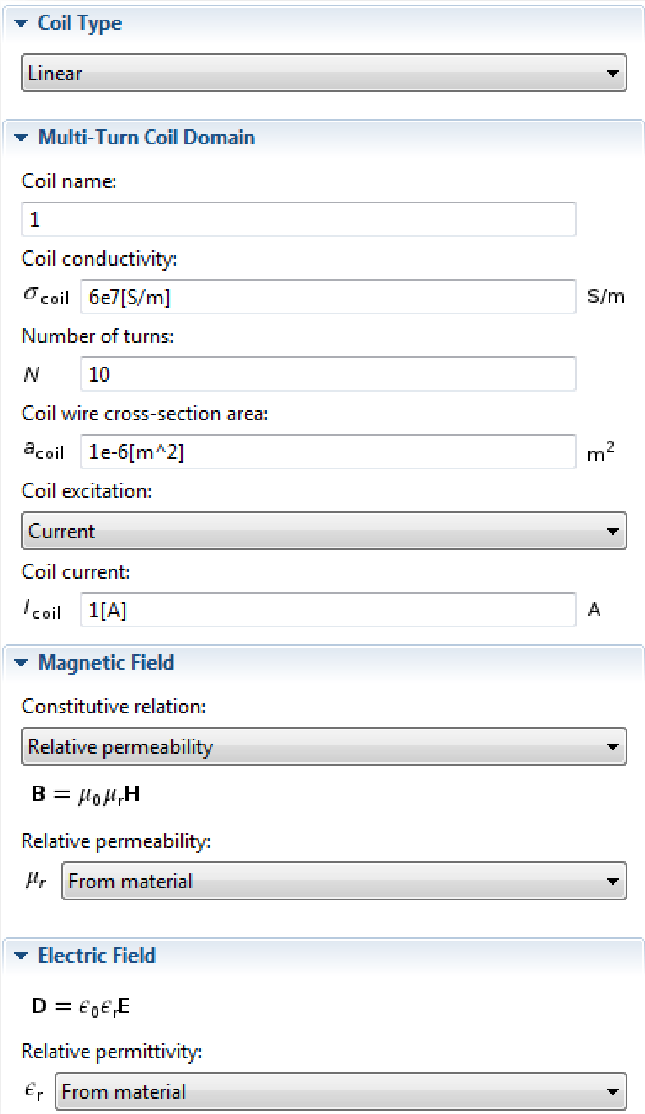
Modeling in COMSOL

- For detailed modeling steps, see the following file:
  - *multi_coil_linear.mph*
- This model shows only the DC case

Using multi-turn coil domain: Linear



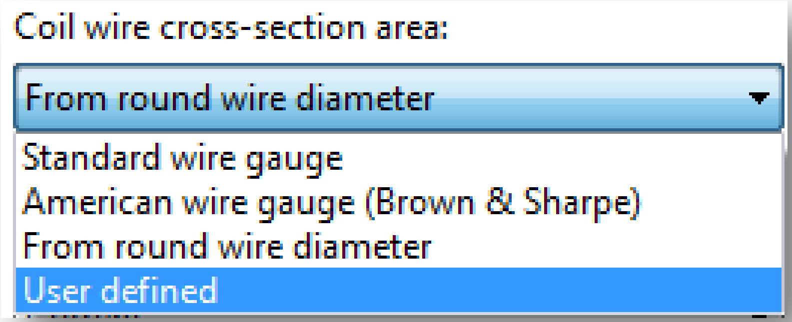
Note on coil properties



- This is the electrical conductivity of the wire material.
- This is the cross section area of each wire
- COMSOL uses these for computing coil resistance

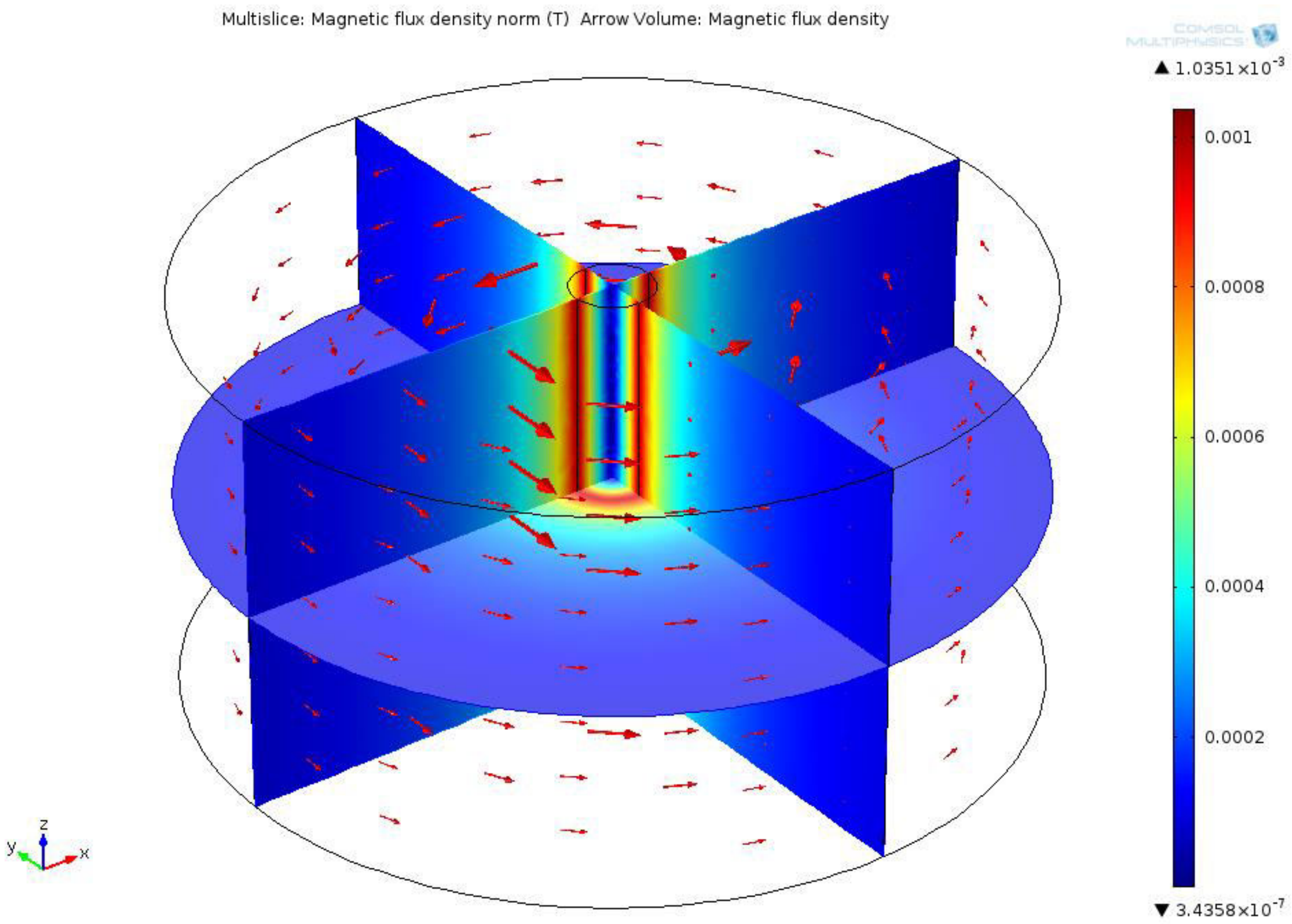
- The relative permeability and relative permittivity values are for the homogenized coil domain

Options for wire cross section



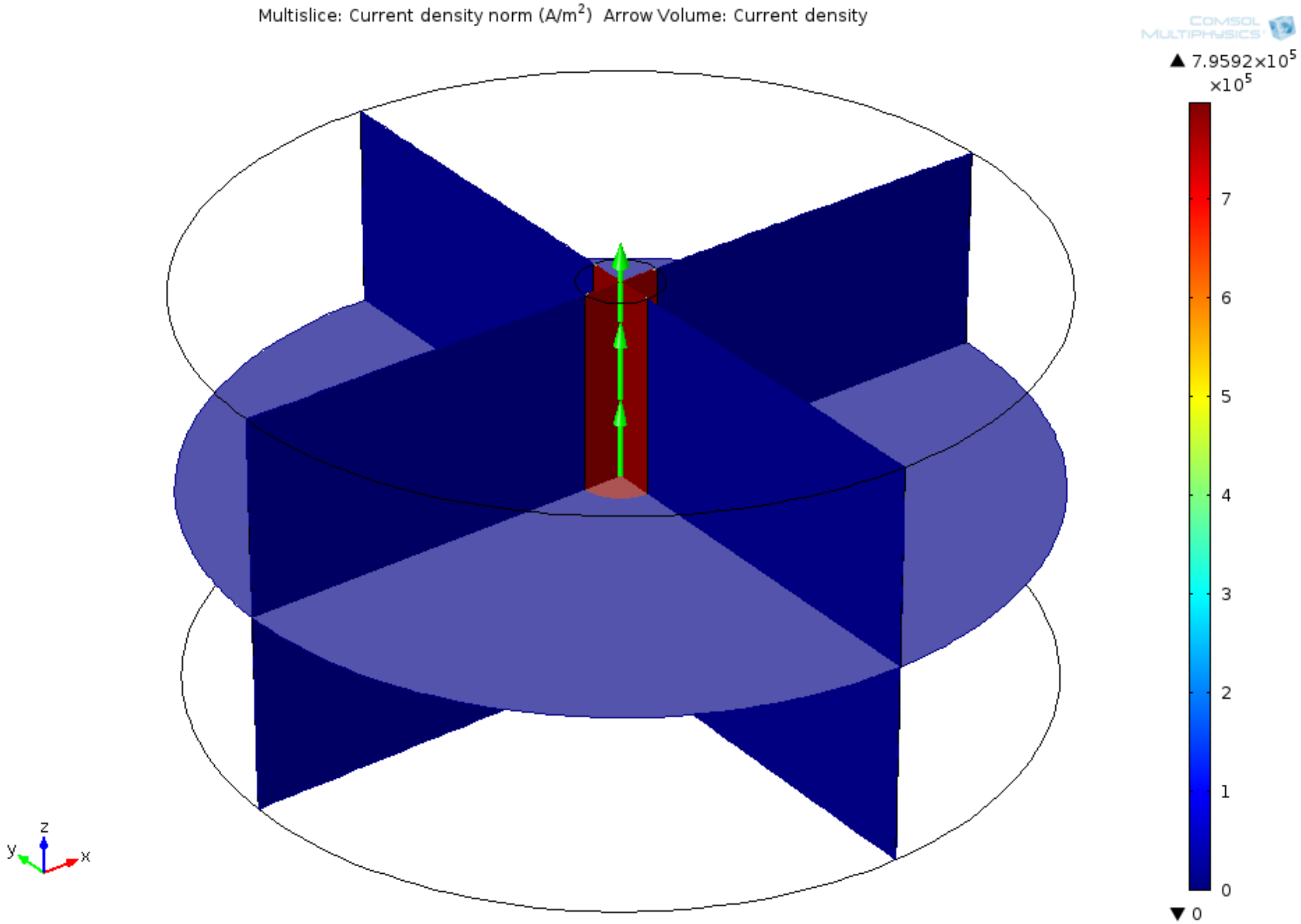
- Default is set to **User defined** cross section area
- Can specify the wire diameter of round wire
- Can also specify AWG or SWG number
- **Note:** We are still not geometrically resolving the wires

Results – Magnetic flux density



Inductance = 1.02e-6 H

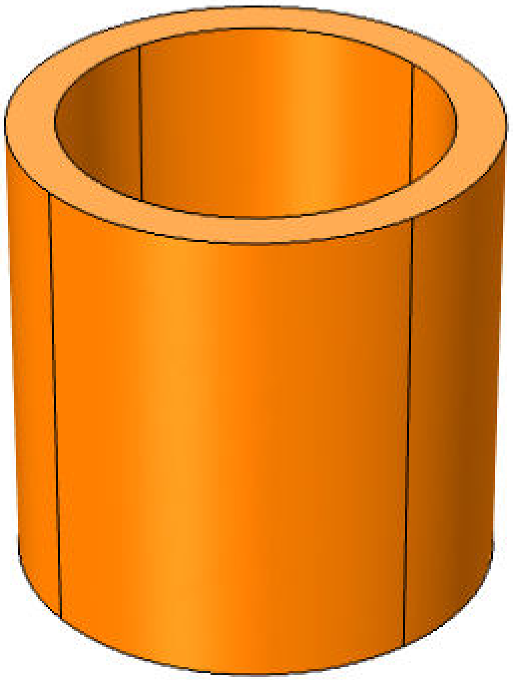
Results – Current density



Resistance = 0.003 Ω

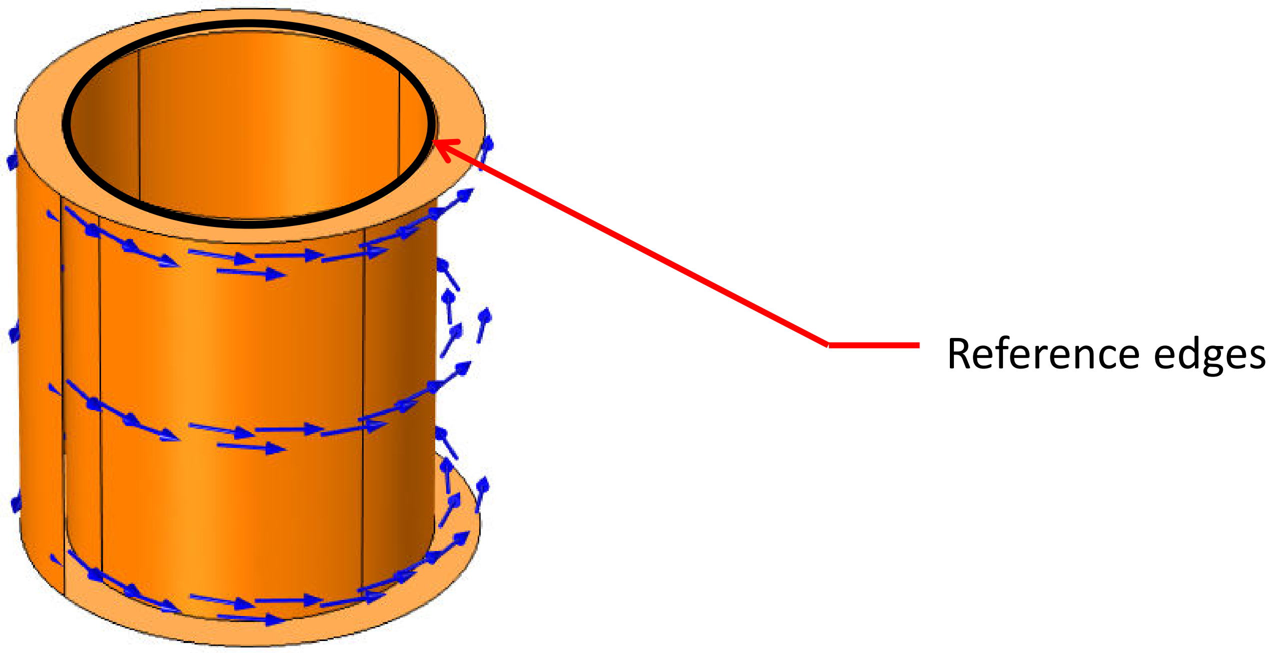
Multi-turn coil – Circular

- Multiple wires arranged as a circular coil and placed in a potting material
- Leads are not modeled
- Geometry must form a closed loop and must have a straight longitudinal axis
- Cross section must be circular



Coil excitation method

- Direction of current flow is modeled by specifying a **reference edge** (typically more than one edge) that should form a closed curve



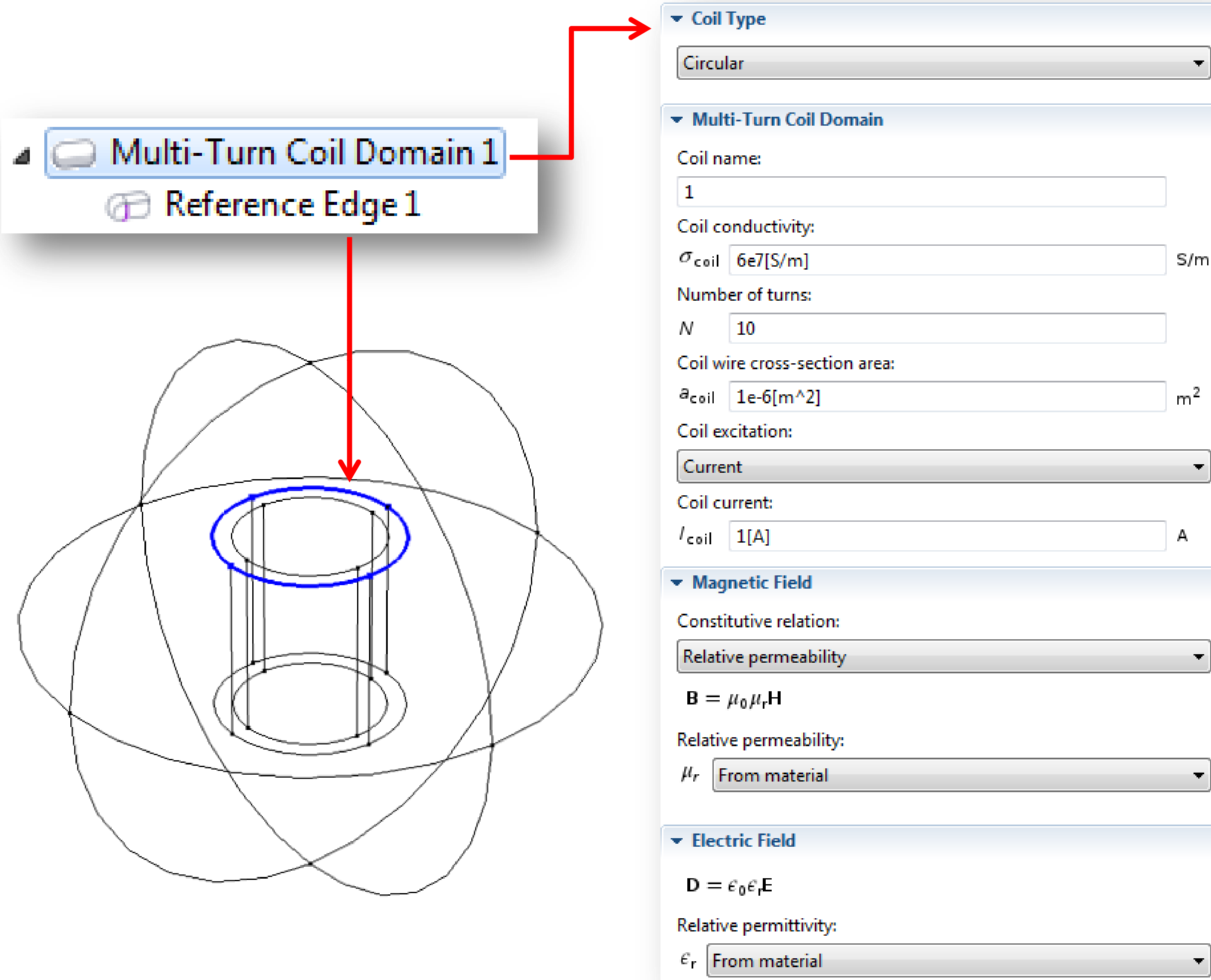
Modeling in COMSOL

- For detailed modeling steps, see the following file:
  - *multi_coil_circular.mph*

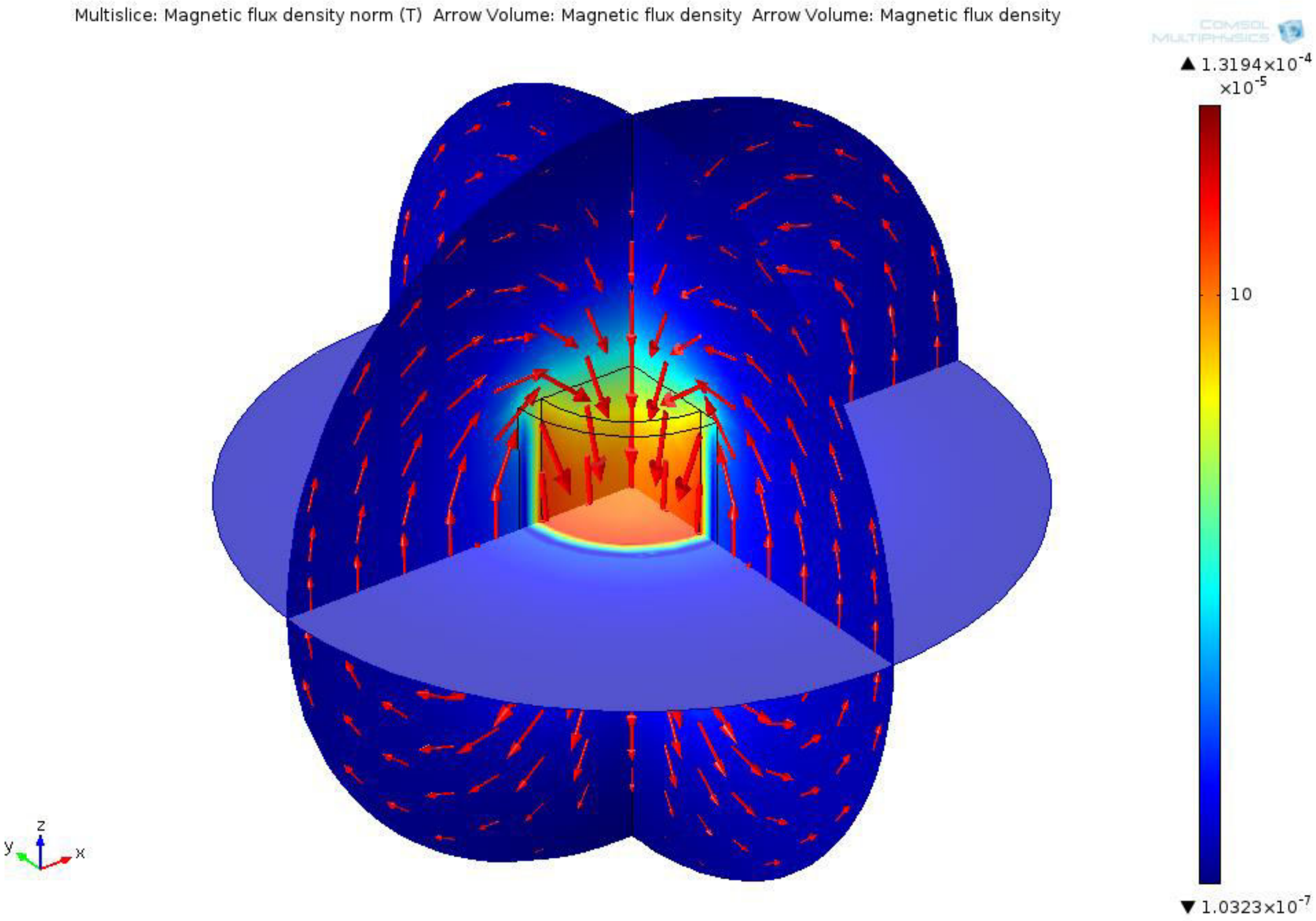
- This model shows both DC and AC cases

- The AC model shows the effect of induced current in a conductor placed in the AC magnetic field created by the multiturn coil

Using multi-turn coil domain: Circular

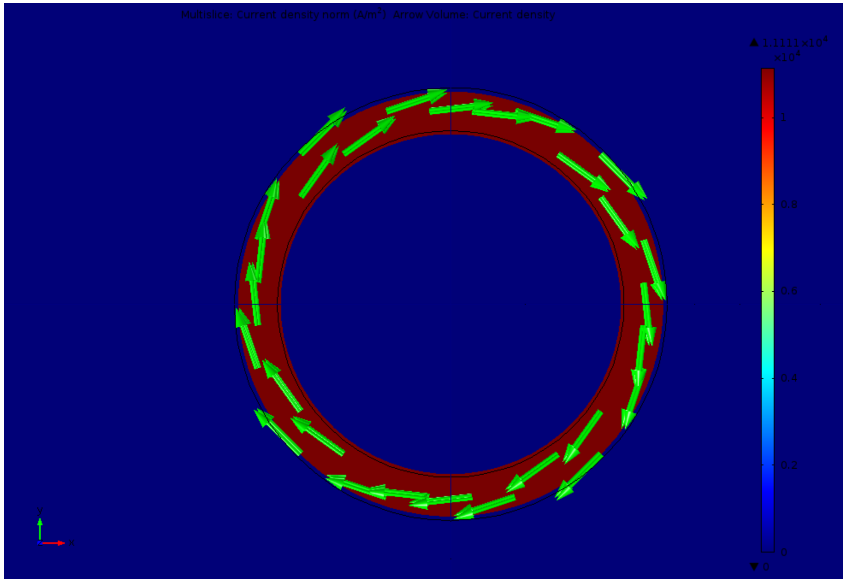


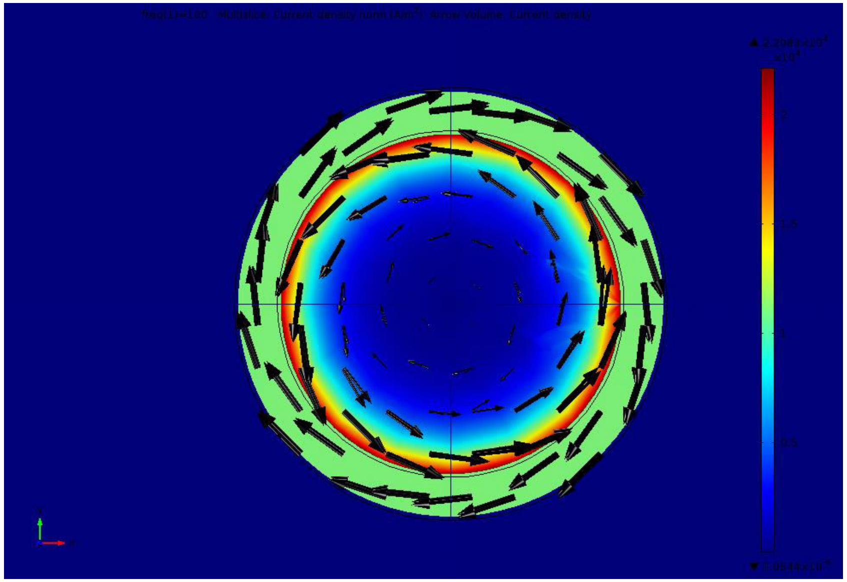
Results – Magnetic flux density (DC)



Inductance = 6.05e-6 H

Results – Current density





DC solution
Resistance = 0.052 Ω

Uniform current density in the homogenized coil domain

AC (100 Hz) solution
Impedance = 0.061 + 0.001i Ω

- Uniform current density in coil domain but skin effect is visible in the copper core
- The arrows show that the current direction is opposite in the coil and the core because of induction effect

Note on reference edge

- For circular coil, the "reference edge" is used for:
  - Defining the current direction
  - Defining the total length (L) of the wire where:

$$L = \oint_{reference\,edge} 1 \cdot dl$$

- The effective coil resistance (R) is computed as:

$$R = \frac{NL}{\sigma_{coil} A_{coil}}$$

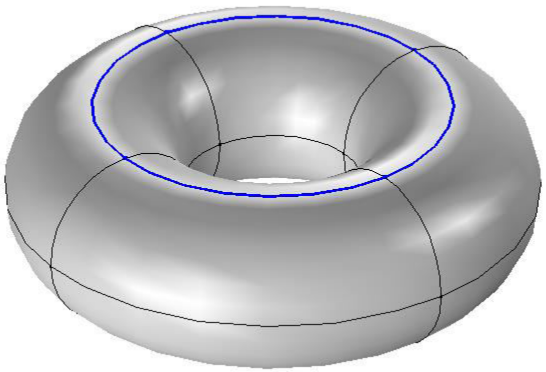
N = number of turns

σ_{coil} = electrical conductivity of wires

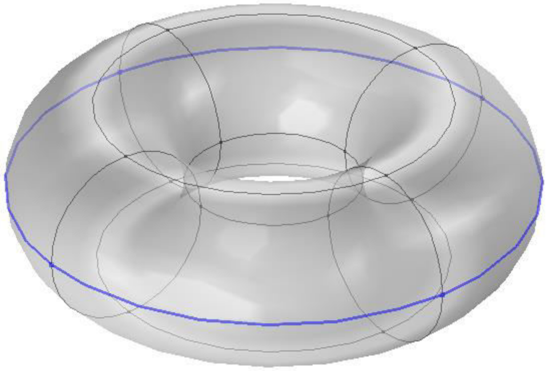
A_{coil} = cross-section area of individual wire

Choice of reference edge

- Choice of reference edge can affect the accuracy of computed coil resistance if the cross section is appreciably thick



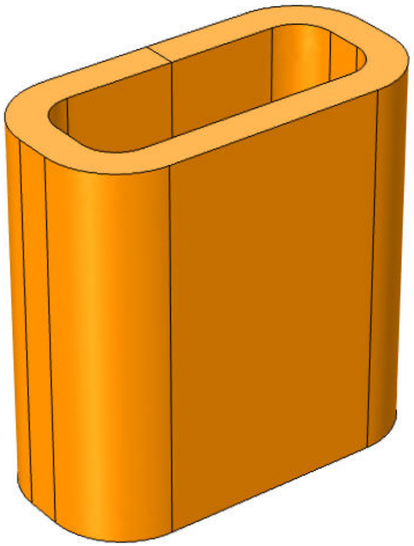
Choosing a set of edges which run through the middle of the thickness will give a better estimate of resistance



Choosing a set of edges which run around the outer or inner periphery will give an overestimate or underestimate respectively of resistance

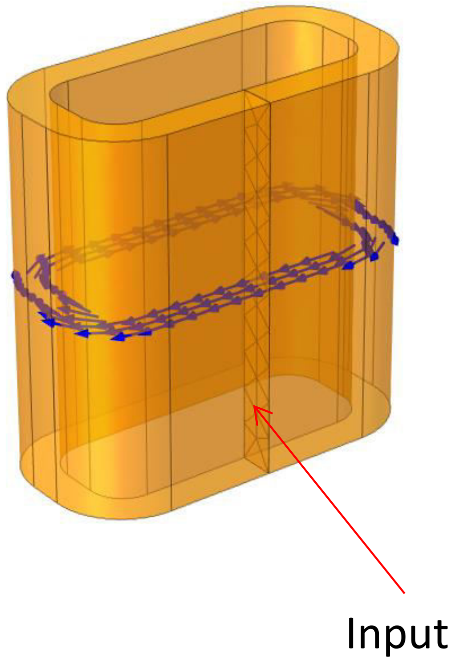
Multi-turn coil – Numeric

- Multiple wires arranged as a coil and placed in a potting material
- Leads are not modeled
- Geometry must form a closed loop
- Cross section can have arbitrary shape
  - Must have constant cross-section perpendicular to current direction
  - Preferable not to have sharp corners in the cross section
  - Use fillets



Coil excitation method

- Excitation source is modeled as an internal cross section boundary called an **Input**
- Need to take care while drawing the geometry so that we create this internal boundary
- Other boundaries of the multi-turn coil domain should be assigned to **Electric insulation**
  - Current flows parallel to these surfaces
- Need to add a **Coil Current Calculation** study step



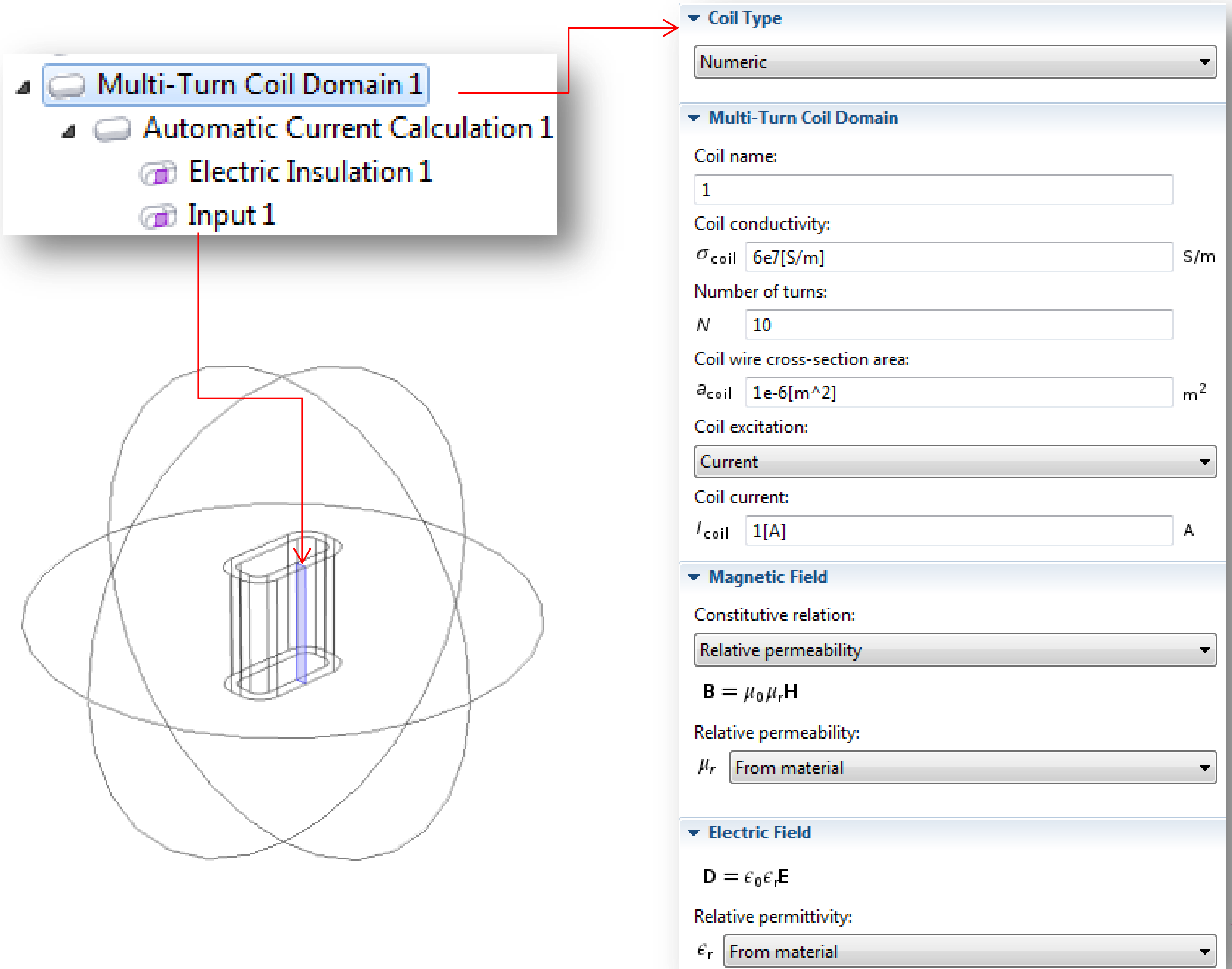
Modeling in COMSOL

- For detailed modeling steps, see the following file:
  - *multi_coil_numeric.mph*

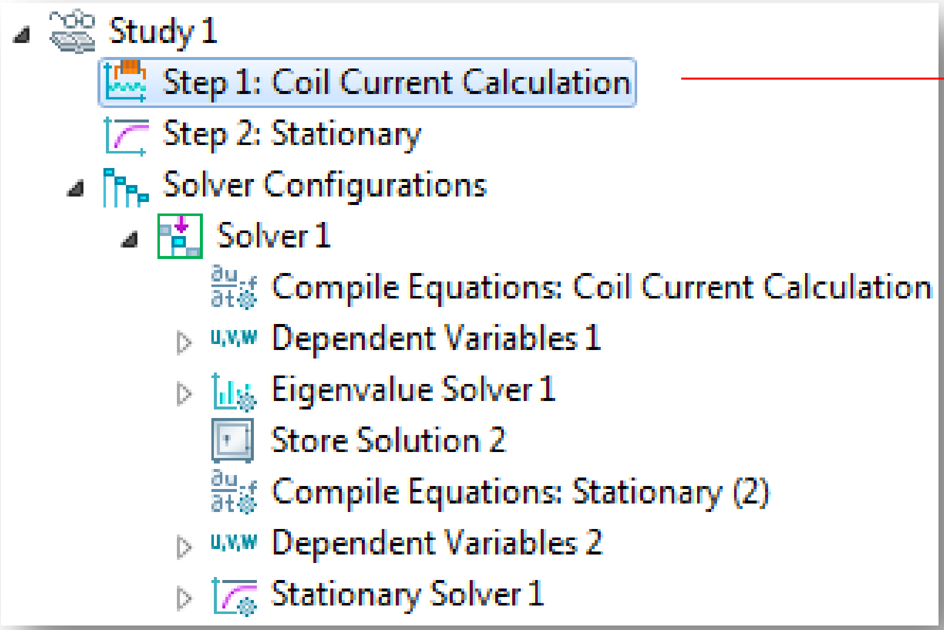
- This model shows the DC case

COMSOL

Using multi-turn coil domain: Numeric

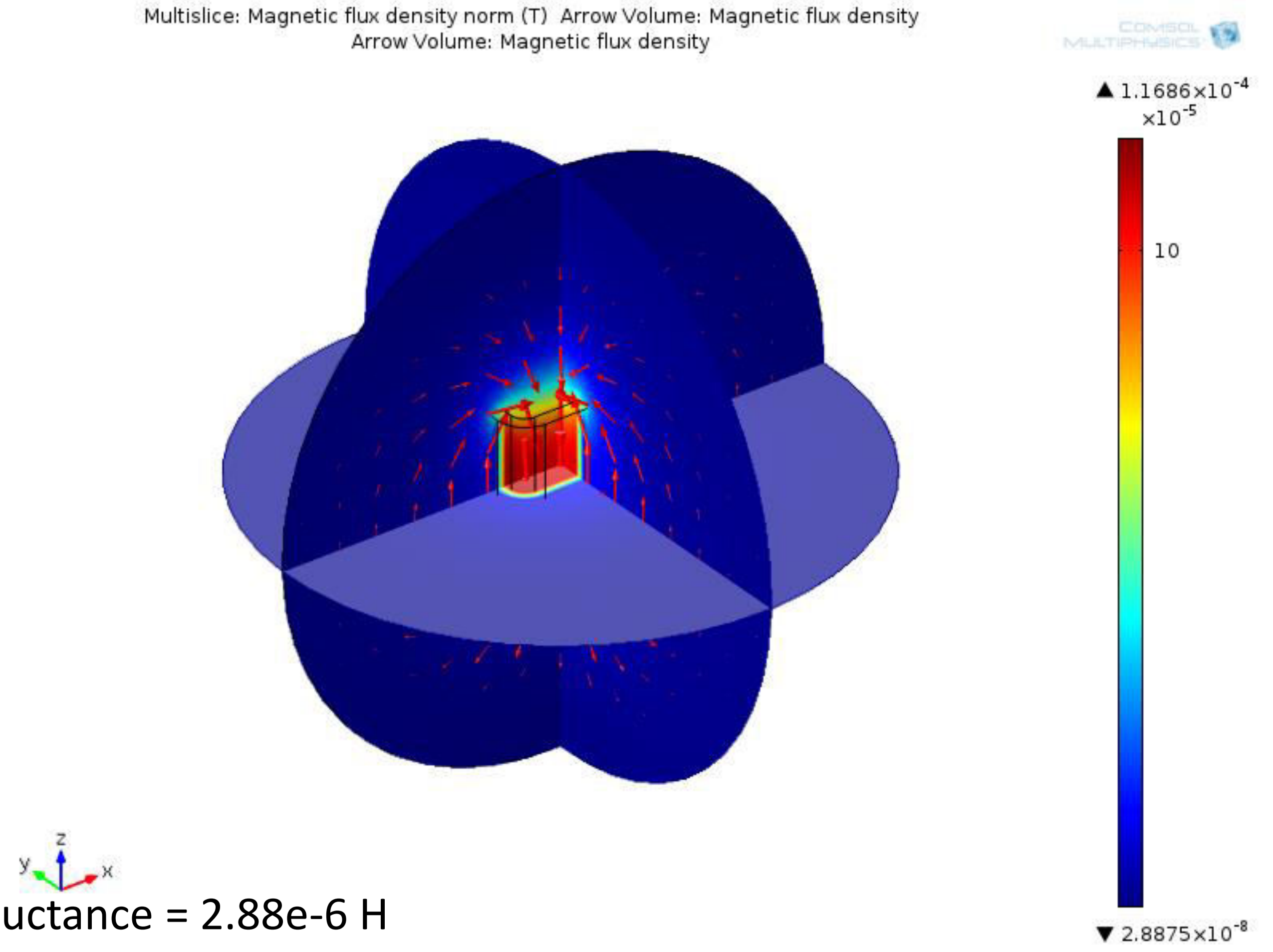


Study settings for numeric multi-turn coil



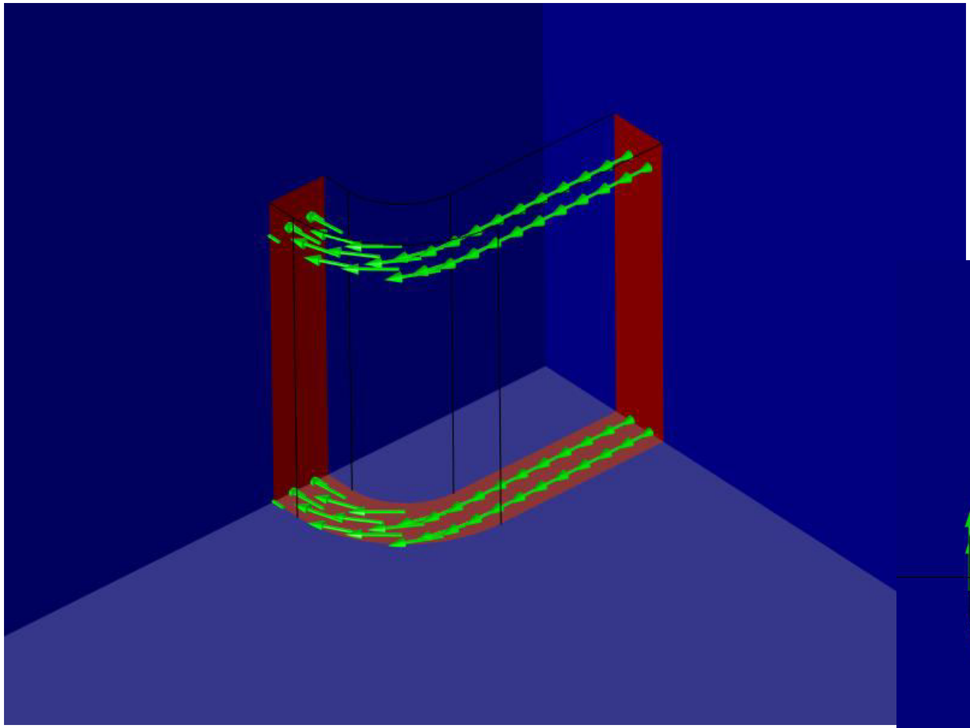
- Add this step manually from **Study 1 > Study Steps**
- Drag this step up and ensure that it is located above **Step 2: Stationary** under the Study branch
- COMSOL will automatically setup the appropriate solvers
- An eigenvalue solver will first compute the direction of current flow in the coil domain
- This information will be then used in the stationary solver

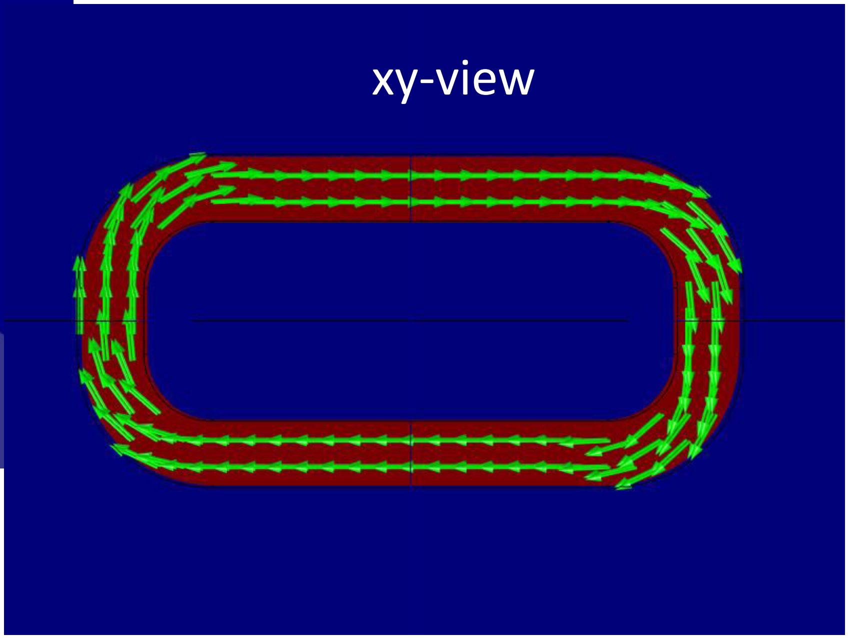
Results – Magnetic flux density



Inductance = 2.88e-6 H

Results – Current density

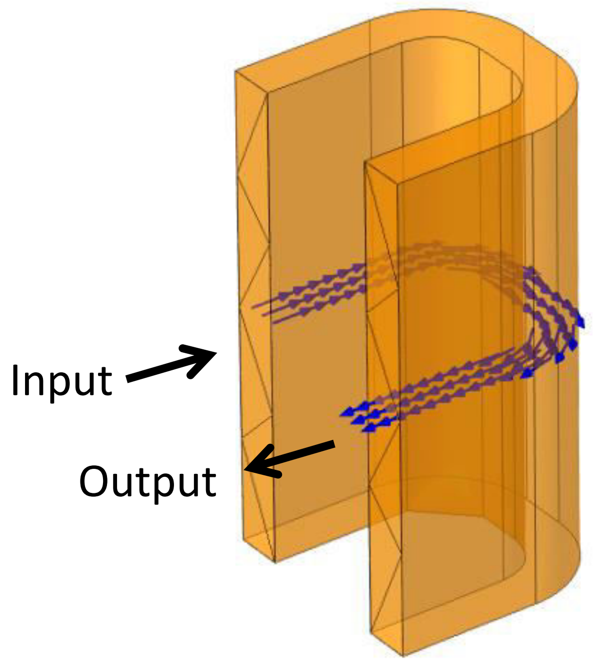




Resistance = 0.039 Ω

Using symmetry – 1/2

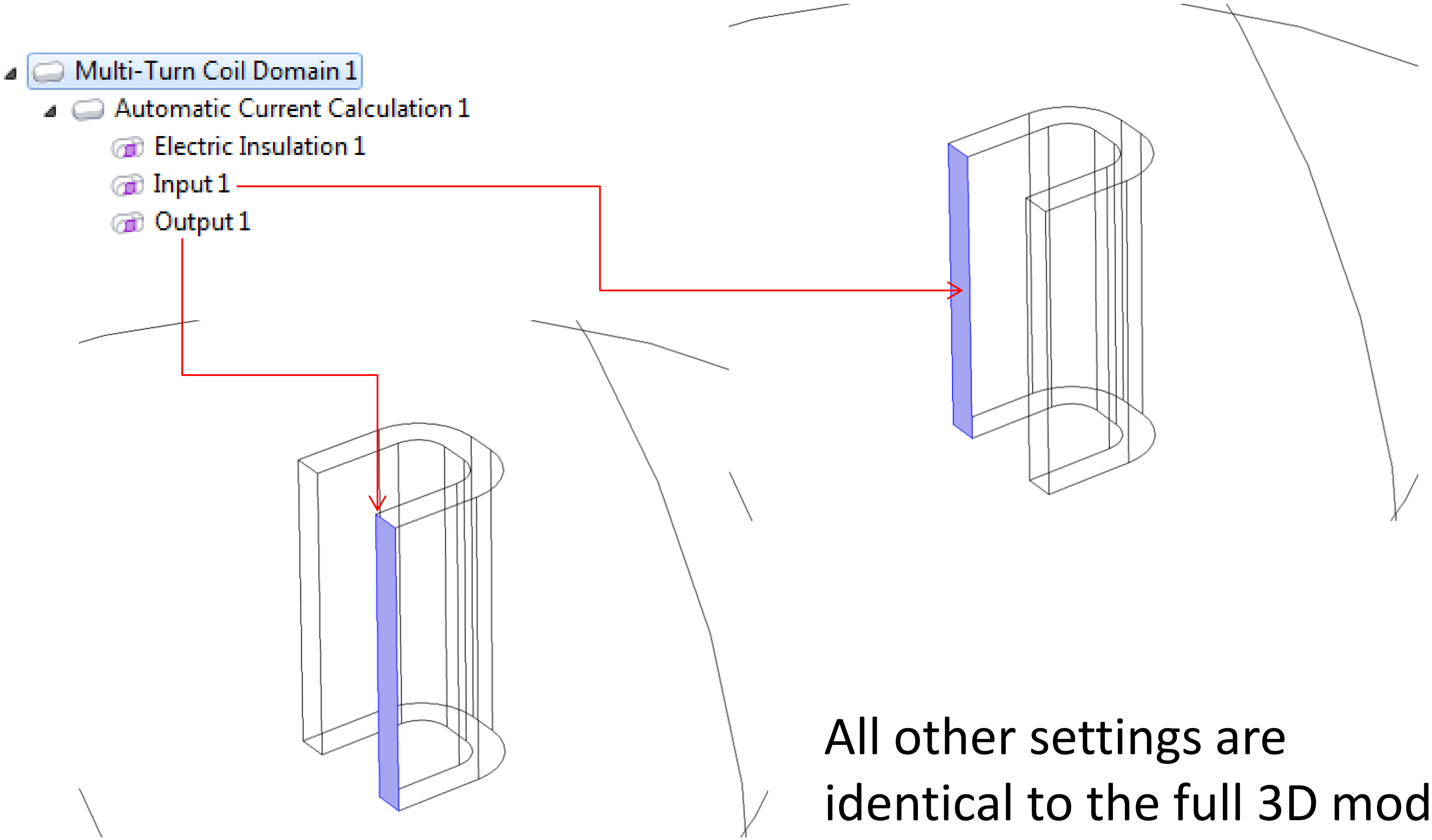
- Coil resistance and inductance is 2 times the computed value
- Need to use three boundary conditions for a numeric multi-turn coil domain
  - **Electric insulation**: current is parallel to these surfaces
  - **Input**: inlet surface for current flow
  - **Output**: outlet surface for current flow



Modeling in COMSOL

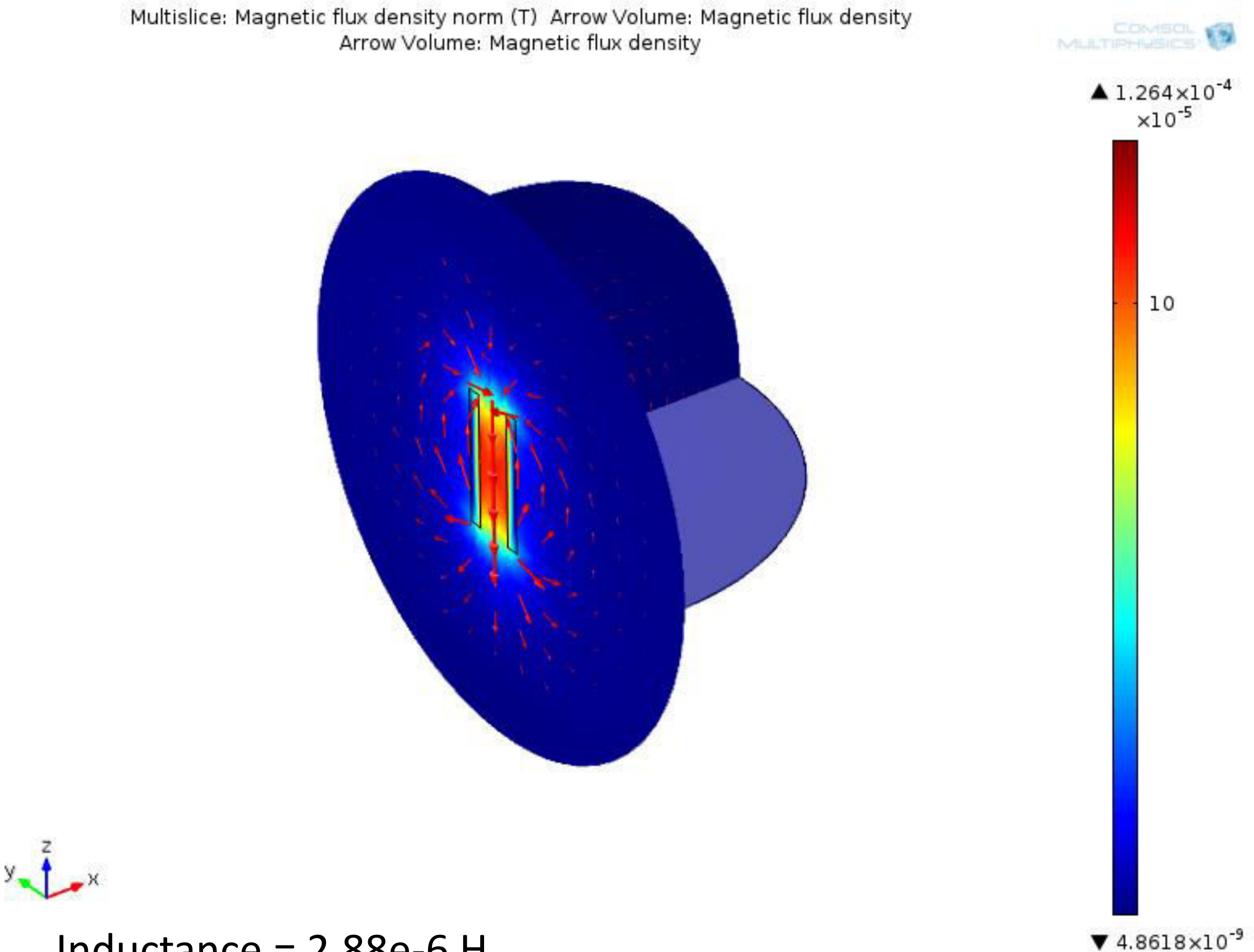
- For detailed modeling steps, see the following file:
  - *multi_coil_numeric_symmetry_half.mph*
- This model shows the DC case

Using multi-turn coil domain: Numeric



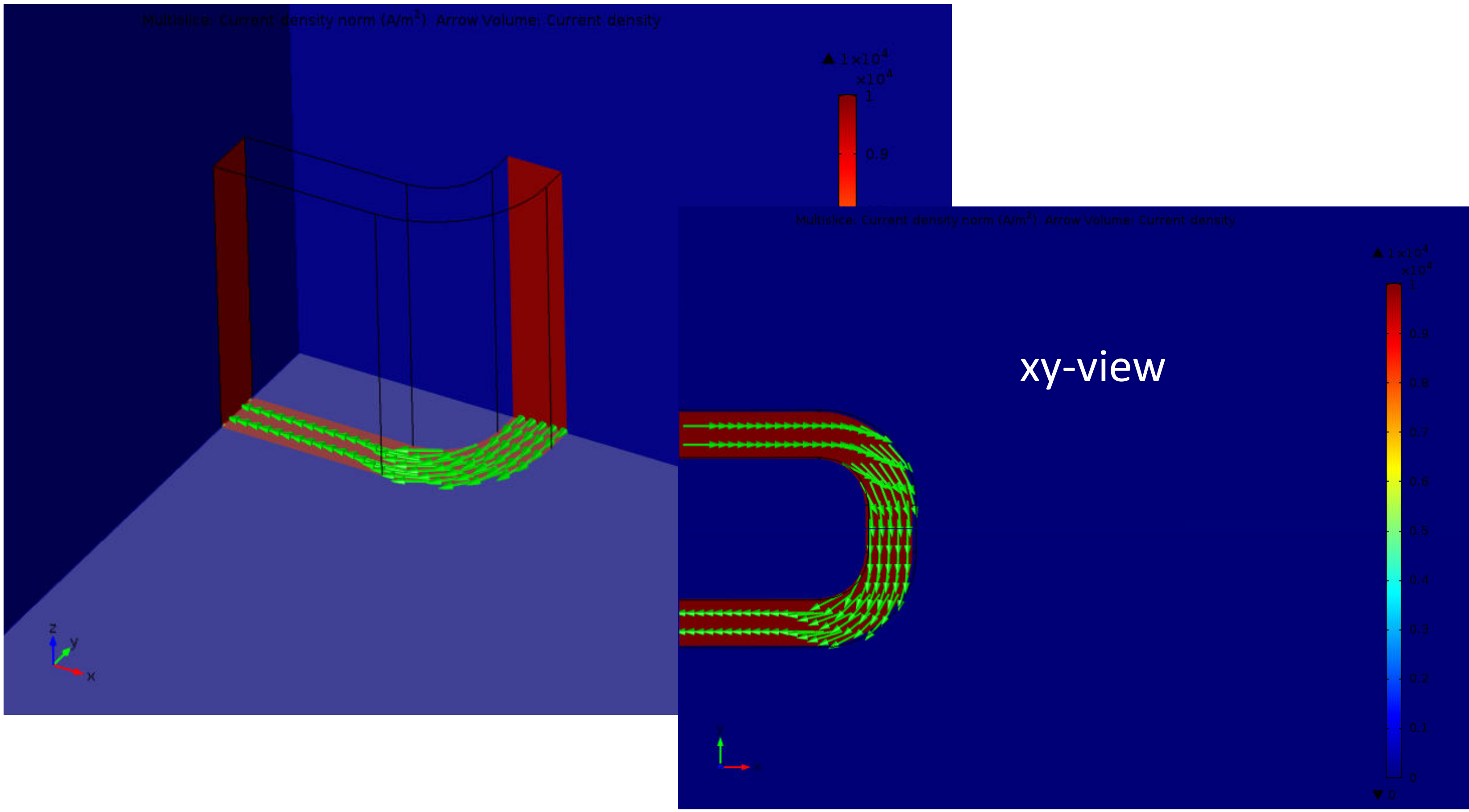
All other settings are identical to the full 3D model

Results – Magnetic flux density



Inductance = 2.88e-6 H

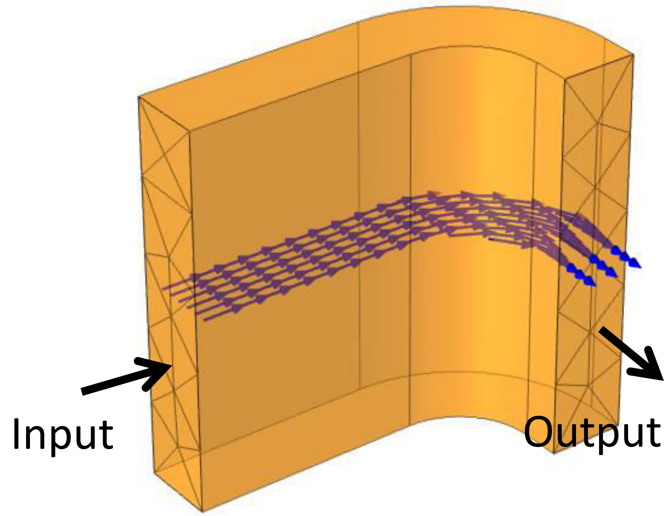
Results – Current density



Resistance = 0.039 Ω

Using symmetry – 1/8th model

- Coil resistance and inductance is 8 times the computed value
- Need to use three boundary conditions for a numeric multi-turn coil domain
  - **Electric insulation**: current is parallel to these surfaces
  - **Input**: inlet surface for current flow
  - **Output**: outlet surface for current flow

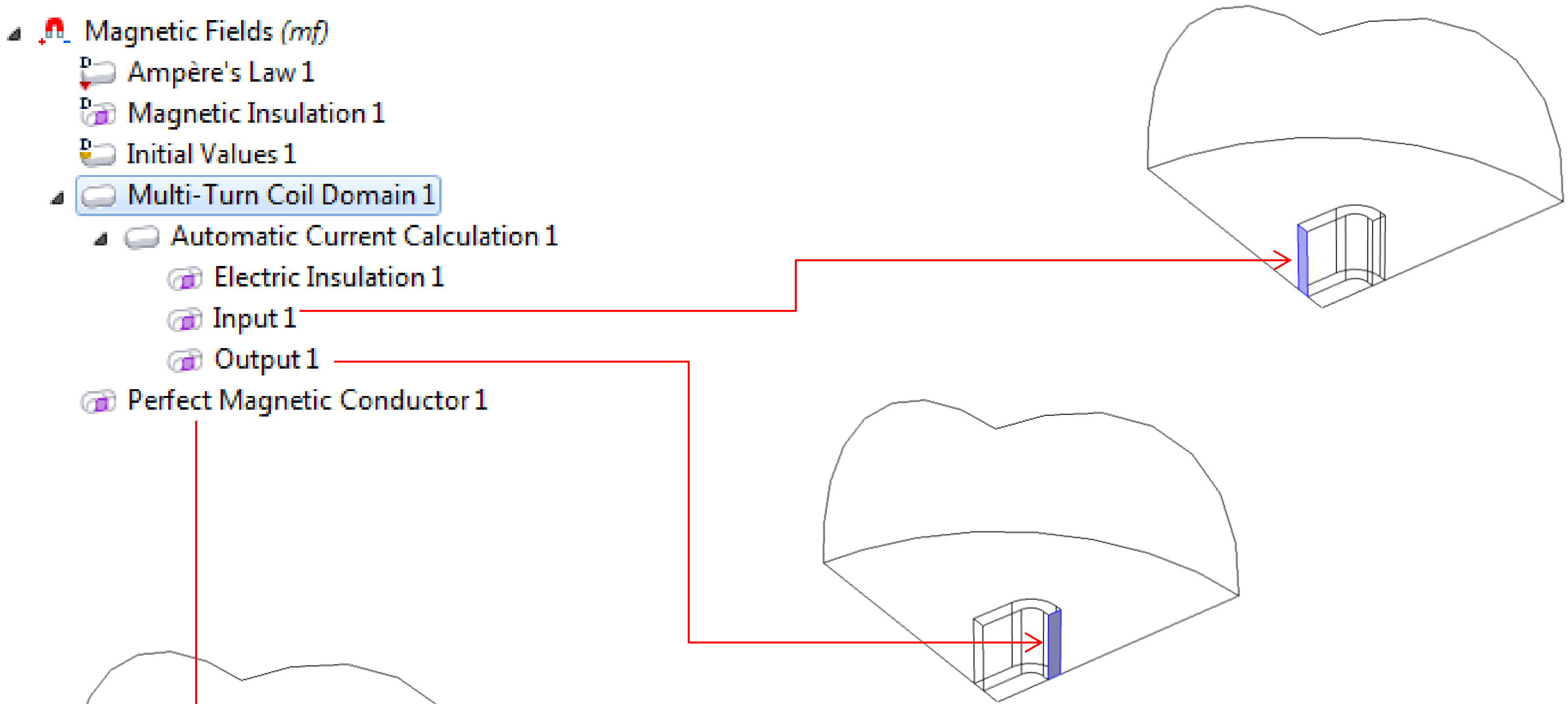


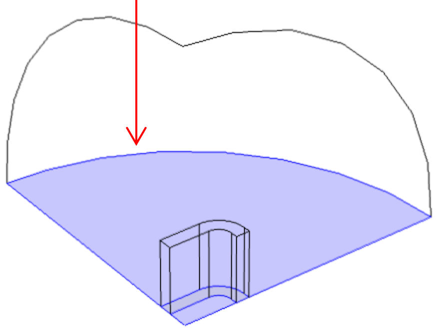
Modeling in COMSOL

- For detailed modeling steps, see the following file:
  - *multi_coil_numeric_symmetry_octant.mph*

- This model shows the DC case

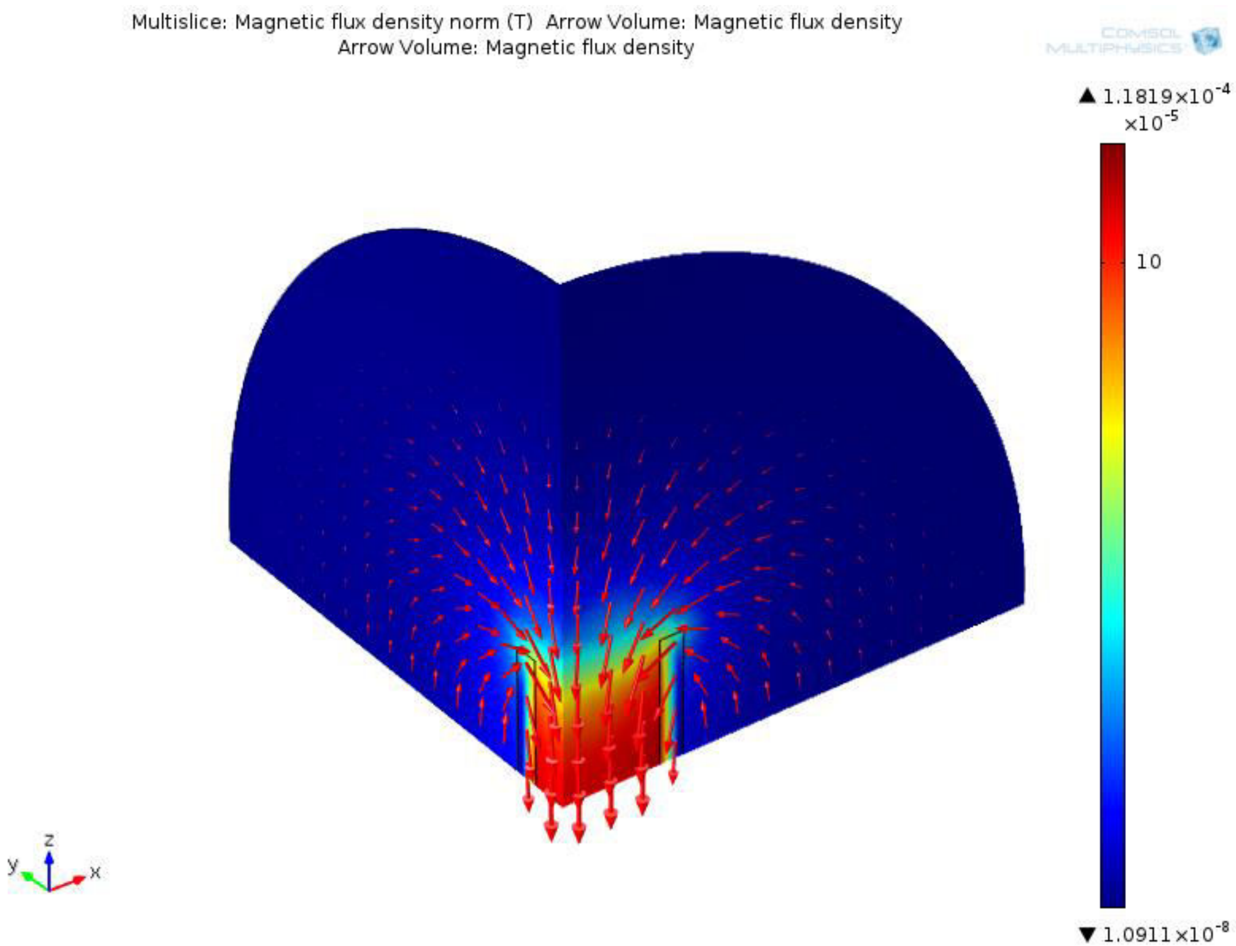
Using multi-turn coil domain: Numeric





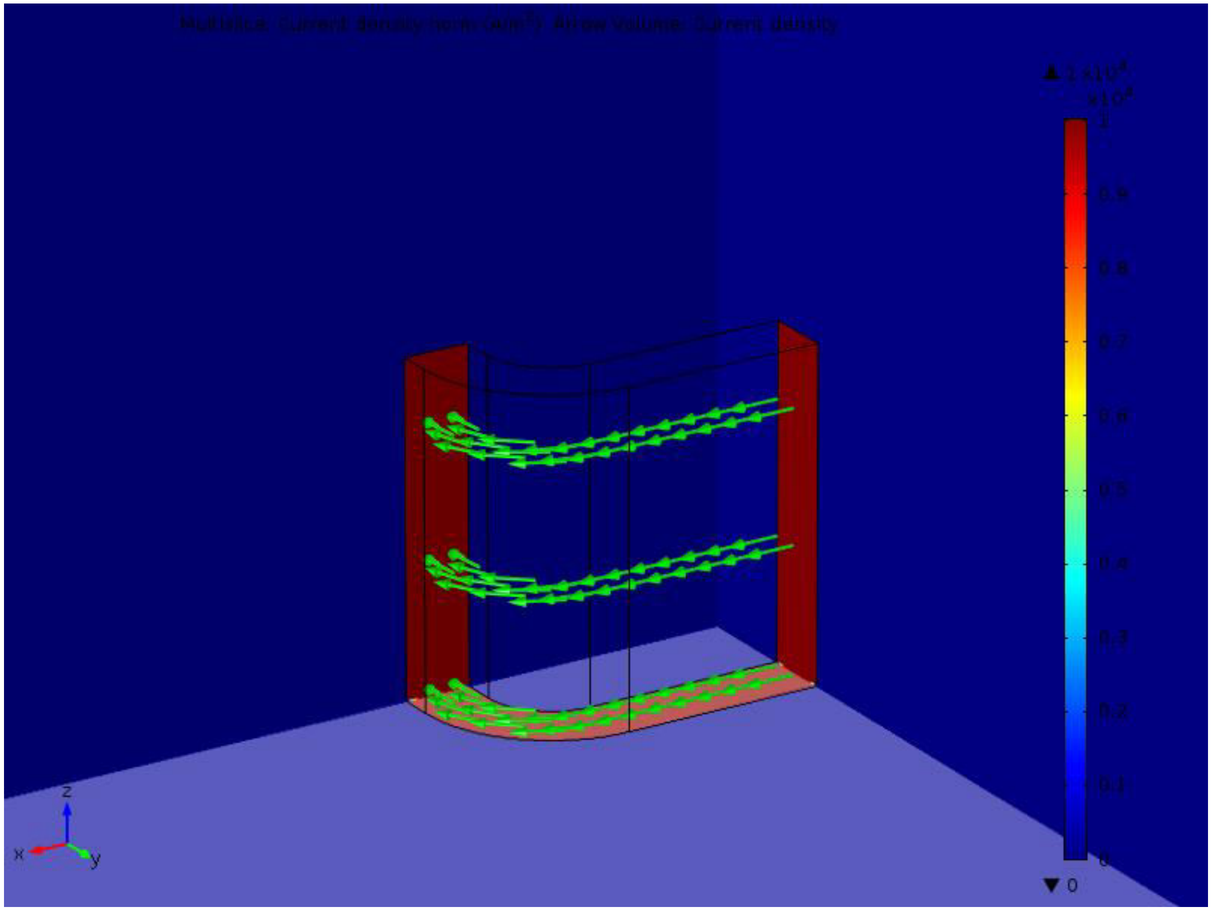
Use half the number of turns since we have cut the geometry by half along the length of the coil

Results – Magnetic flux density



Inductance = 2.88e-6 H

Results – Current density

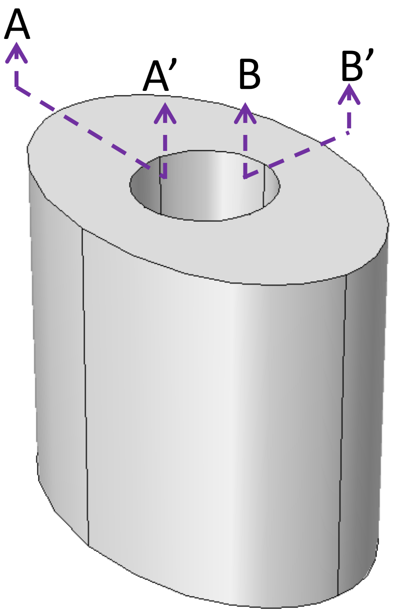


Resistance = 0.039 Ω

COMSOL

Note on cross section area

- **Longitudinal cross-section area must be constant**
- Coil Current Calculation study computes the local current direction
- It will not compute the local cross-section area
- This information is obtained from the area of the “input” boundary
- This means that current will not be conserved if the coil cross-sectional area changes along the current path



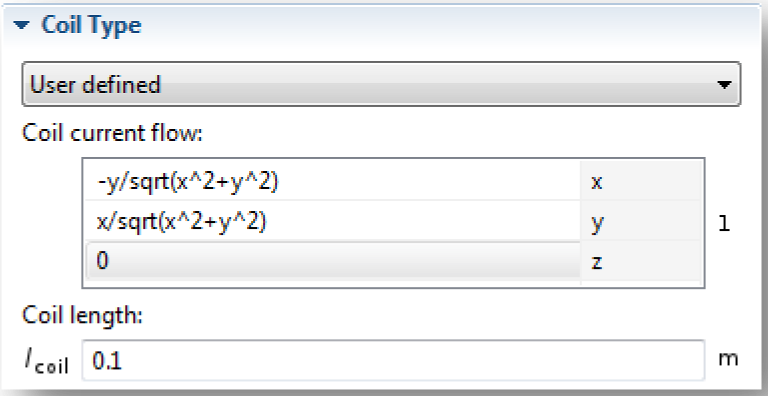
Sections AA’ and BB’ have significantly different cross section area

Which coil modeling option to choose?

- The **Linear** and **Circular** coil options are special cases
- You can use the **Numeric** coil option to model linear or circular coils
- Remember to add a Coil Current Calculation study whenever you use a Numeric coil

Multi-turn coil – User defined

- For general case
- Geometry need to form a closed loop
- Need to specify coil length
- Specify current direction using vectors
  - Could be a function of x, y and z coordinates
  - We need to ensure that the current direction creates a closed loop
- Do not need to add a **Coil Current Calculation** study step



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Summary

- This tutorial showed how to use the 3D single-turn and multi-turn coil domain features
- New modeling features
  - Gap feed, Boundary feed, Reference edge, Input, Output
- Considerations while drawing geometry
  - Need to create additional internal boundary for Single-turn coil domain with Gap feed and Numeric type Multi-turn coil domain
- Study set up
  - Coil Current Calculation study required only for Numeric type Multi-turn coil domain
- DC vs. AC
  - Meshing
  - Convergence tips