

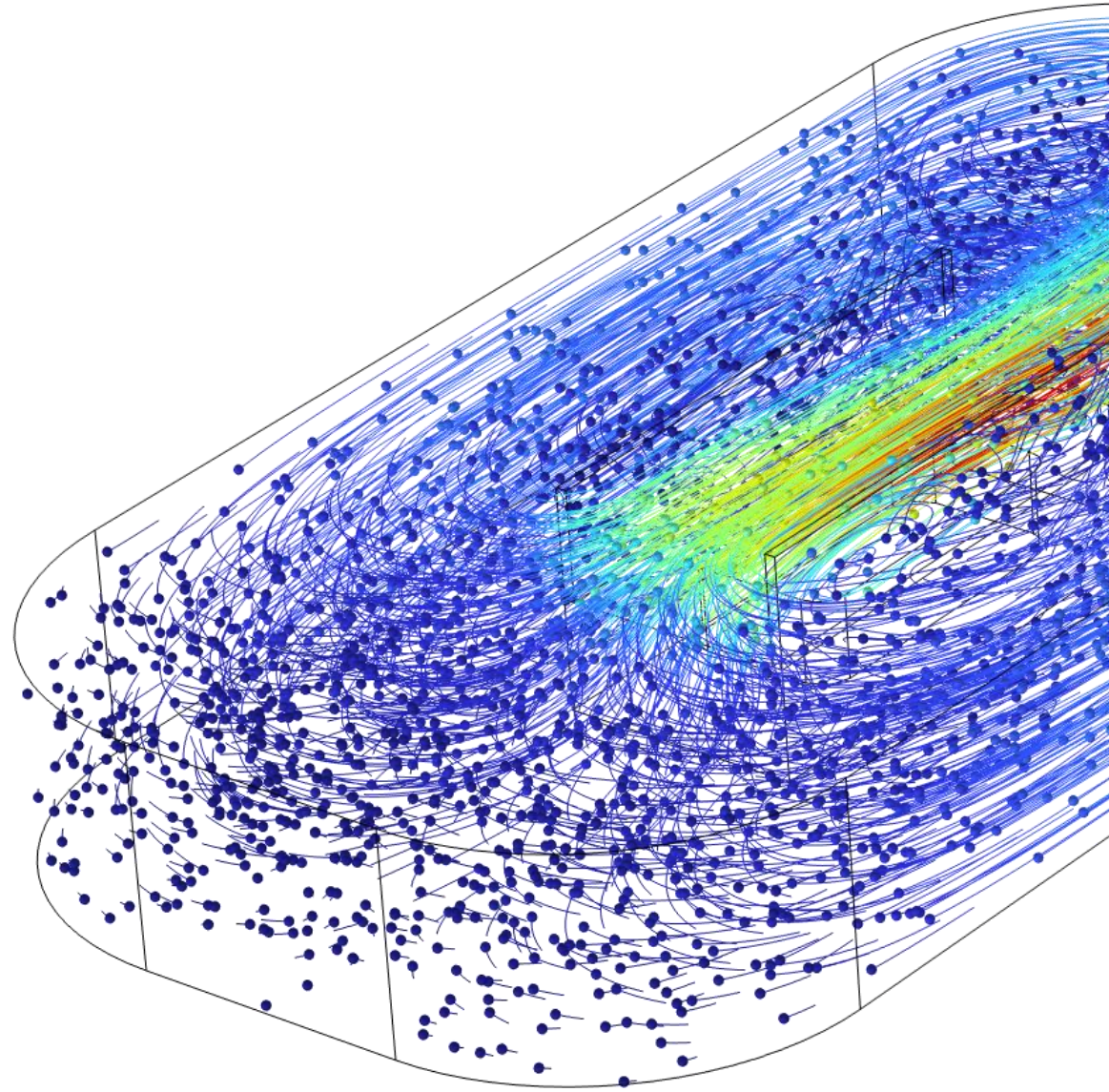
COMSOL Minicourse: Electromagnetism



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Agenda

1. Motivation
2. Scope of Electromagnetic Simulations
3. Static and Low-Frequency Fields
4. High-Frequency Fields



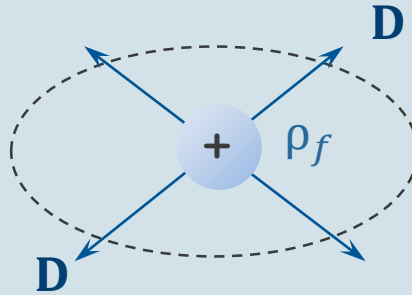
A stylized neuron with a central cell body and numerous branching processes. The neuron is rendered in glowing orange and yellow colors against a dark blue background. The branching processes extend across the frame, with some reaching towards the right edge. The central cell body is the brightest point, radiating outwards.

Why Simulate Electromagnetic Fields?

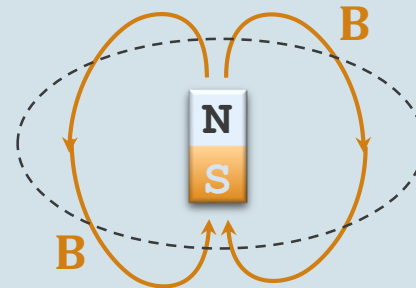
Motivation

- EM fields are omnipresent yet mainly invisible
- Wide spectrum of applications in different fields
- Often coupled with other phenomena
 - Heat
 - Force effects
 - Chemistry

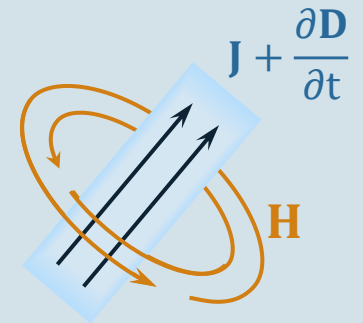
$$\nabla \cdot \mathbf{D} = \rho$$

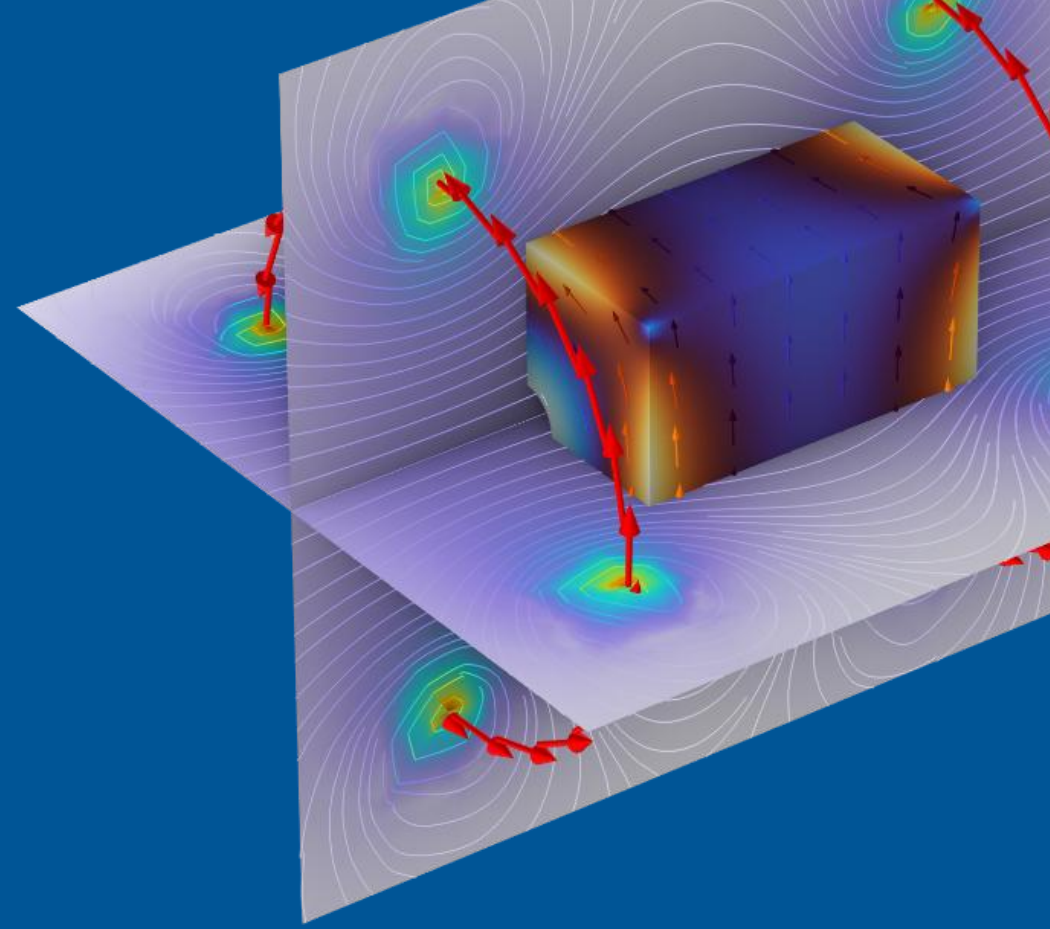


$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}$$

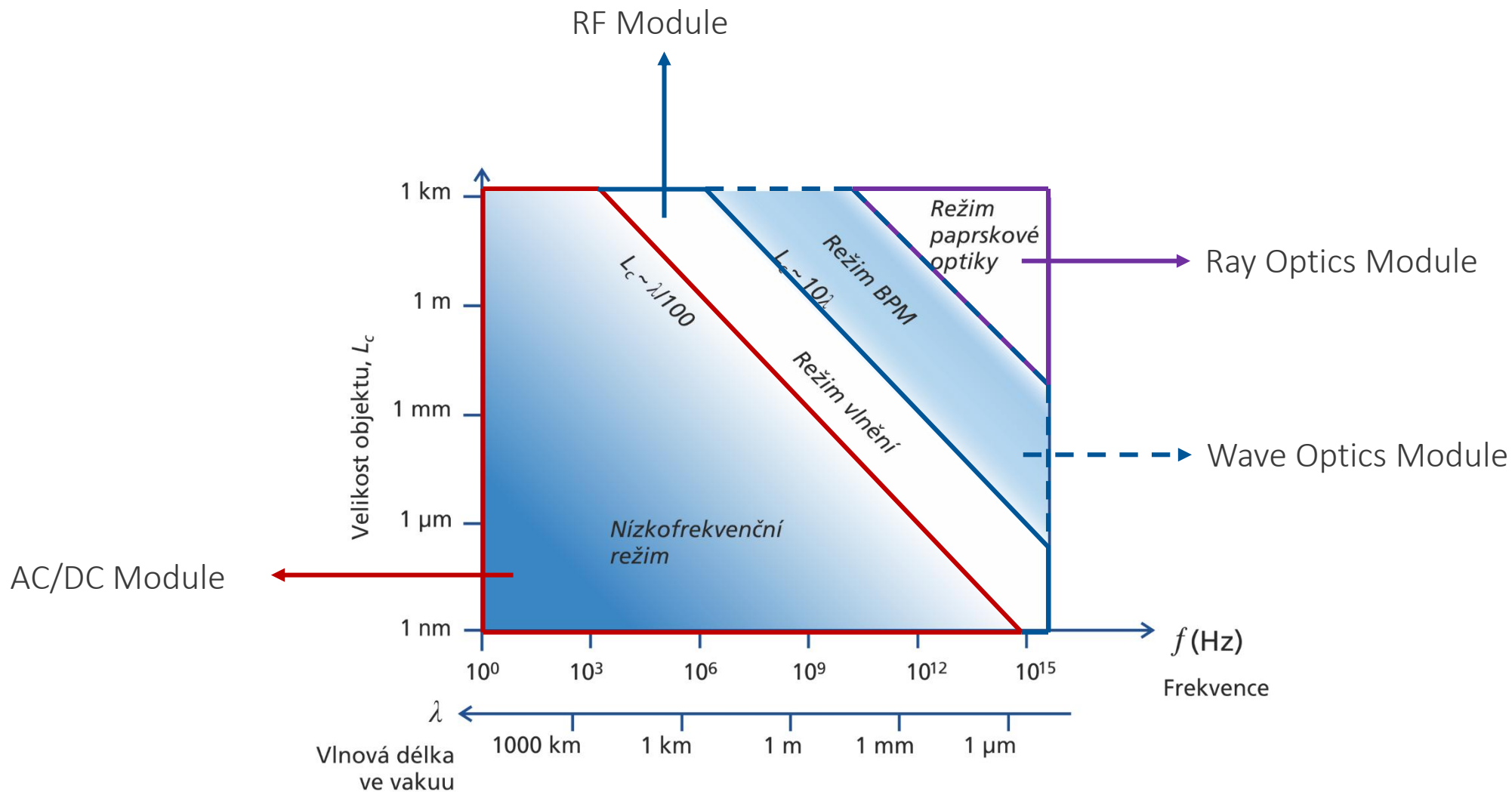


$$\nabla \cdot \mathbf{B} = 0$$





Scope of Electromagnetic Simulations



Model Key Characteristics

- Relaxation constant τ

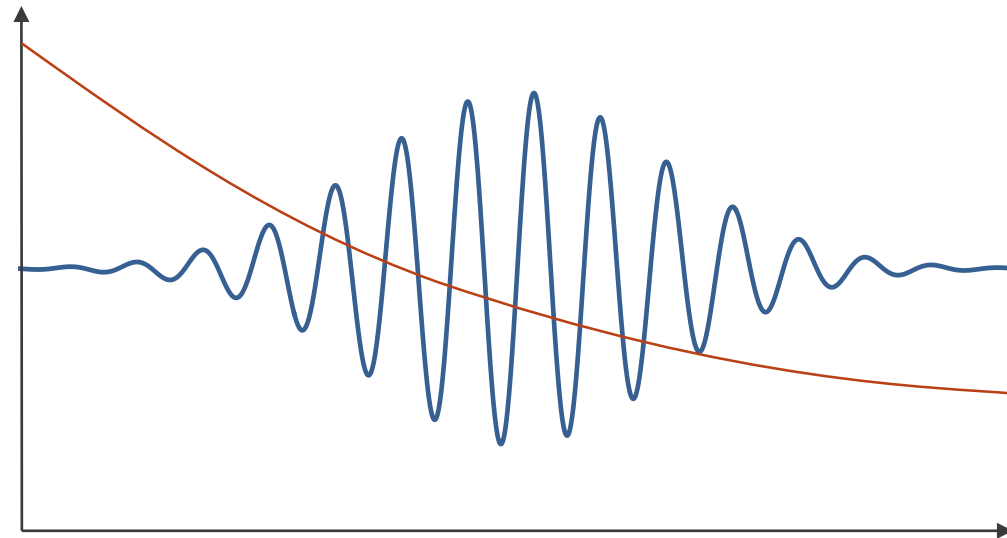
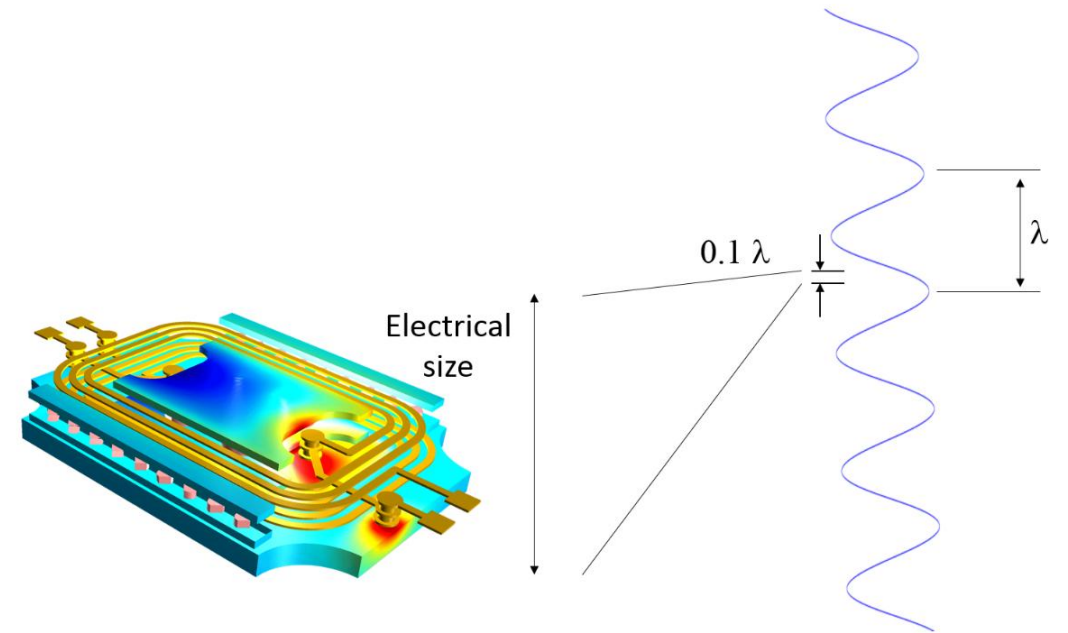
$$\tau = \frac{\varepsilon}{\sigma}, \quad \rho_f(t) = \rho_0 e^{-t/\tau}$$

- Penetration depth δ

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}, \quad \mathbf{J}(d) = \mathbf{J}_s e^{-d/\delta}$$

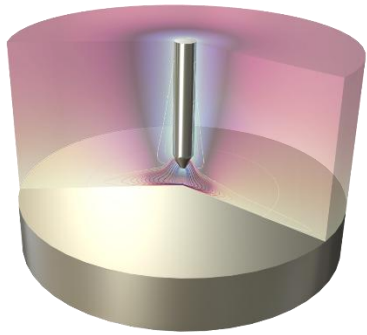
- Wavelength λ

$$\lambda_0 = \frac{c}{f}, \quad \lambda = \frac{\lambda_0}{n}$$



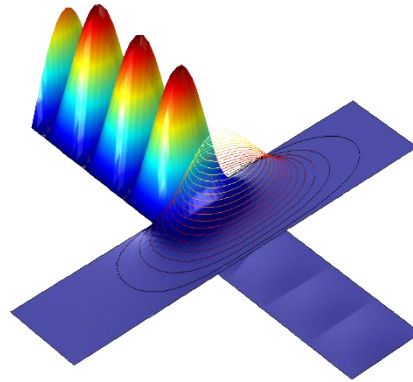
Relaxační konstanta materiálu musí být brána v potaz s ohledem na celkový pozorovací čas. Hloubka vniku zase s ohledem na celkovou velikost objektu.

When It's Not a Matter of Wavelength



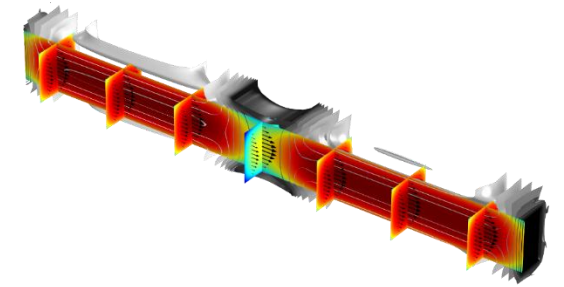
Electric Discharge

- Streamer and corona discharges
- Surface charge calculation
- Solid dielectrics
- Electric arcs



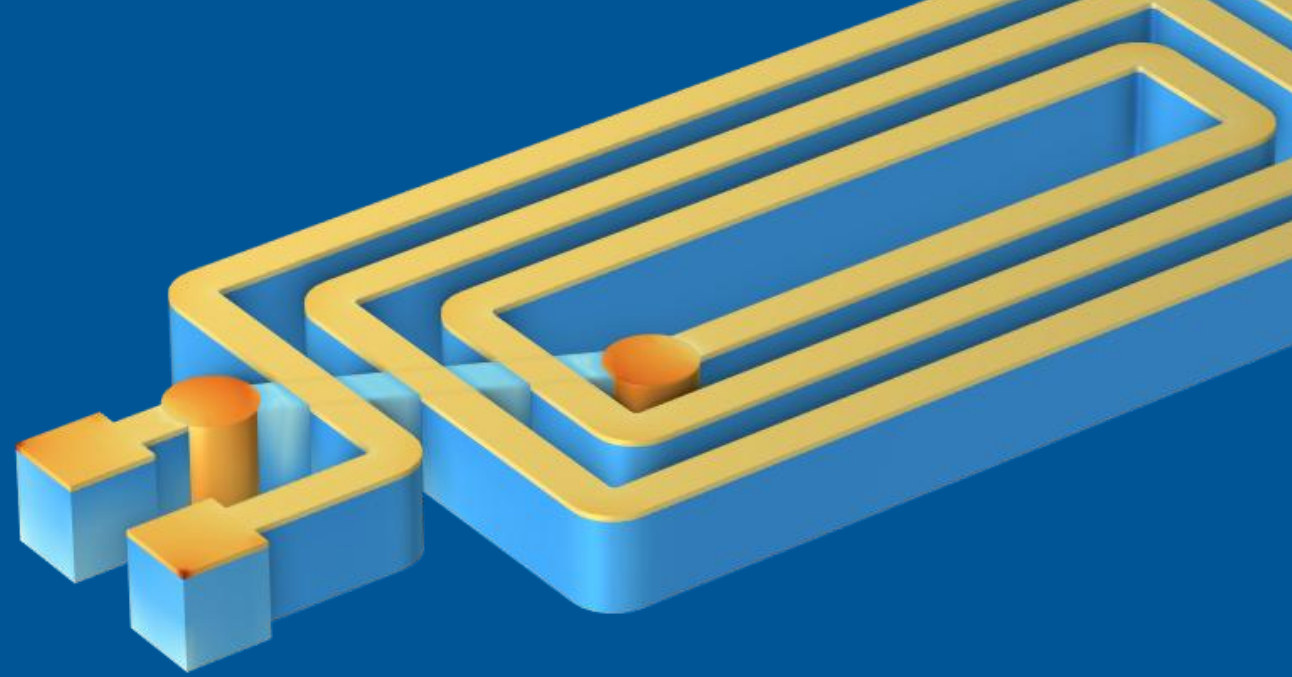
Plasma

- Electric discharges, induction and microwave coupled plasma
- Low pressure and low temperature plasma



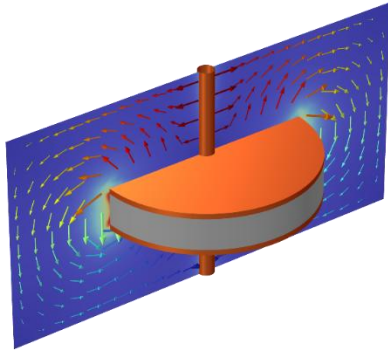
Semiconductors

- Transport equation for electron and hole concentration
- Conventional drift and diffusion model, density gradient model, Schrödinger(-Poisson) equation



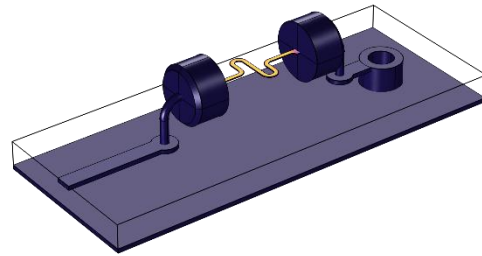
Static and Low-Frequency Fields

Electric Fields Interfaces



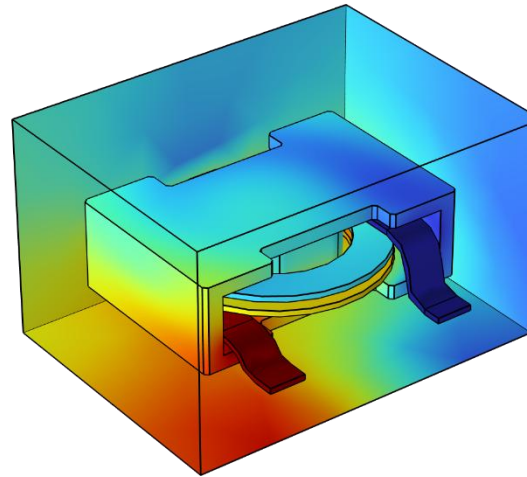
Electrostatics

- Dielectrics
- Electric potential distribution
- Electrostatic force calculation



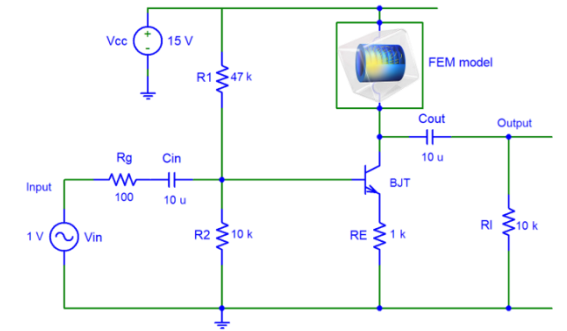
Electric Currents

- Conductive and displacement currents
- Capacitive and resistive effects
- Loss tangents



Magnetic and Electric Fields

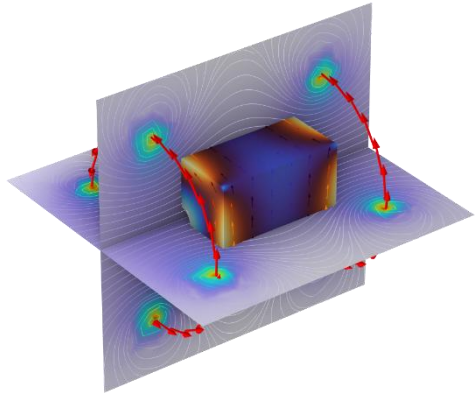
- Voltage-driven sources (terminals)
- RLC coils
- Capacitive coupling



Electric Circuits

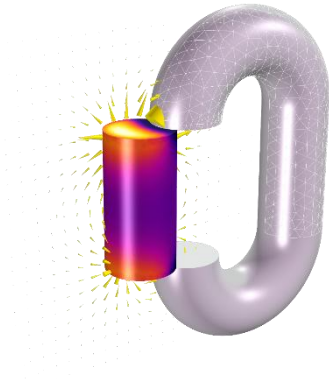
- Coupling of lumped systems and finite element models
- Import and export of SPICE netlists

Magnetic Fields Interfaces



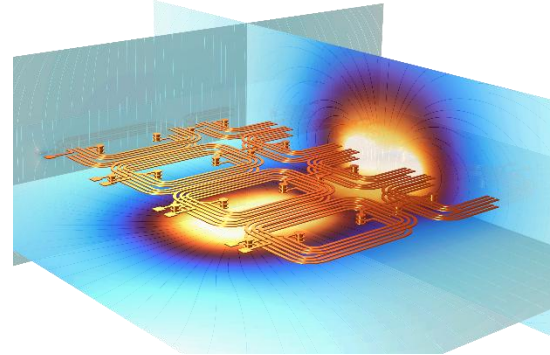
Magnetic Fields

- Current-driven sources (coils)
- Induced currents
- Nonlinear magnetic materials



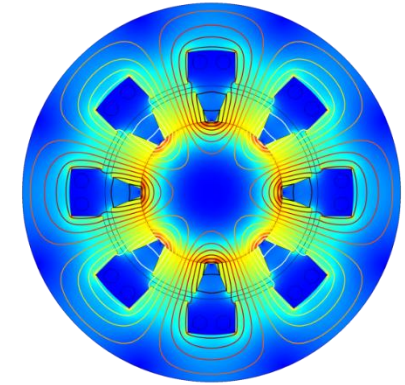
Magnetic Fields, No Currents

- Permanent magnets
- Magnetic force calculation
- Iron loss



Magnetic Fields, Currents Only

- Magnetic fields from currents in vacuum
- Source sweep with initialization study
- Inductance matrix

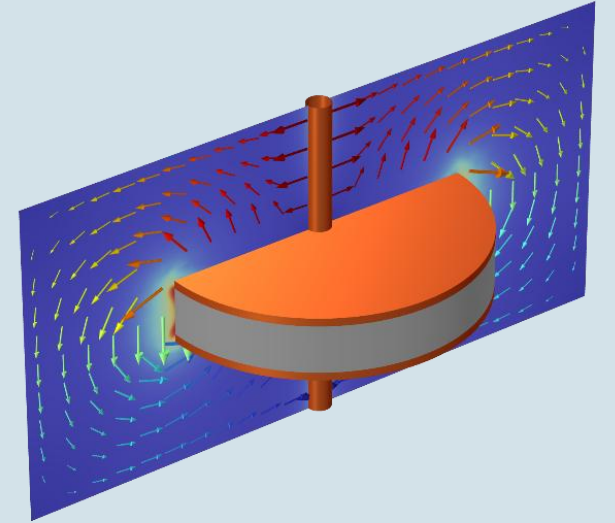


Rotating Machinery, Magnetics

- Electric motors and generators
- (Not only) Rotating domain
- Torque, forces and loss calculation

Capacitive Devices: *Electrostatics*

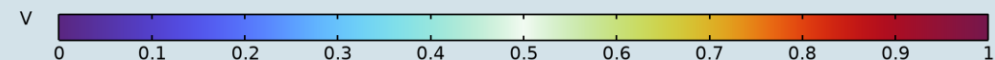
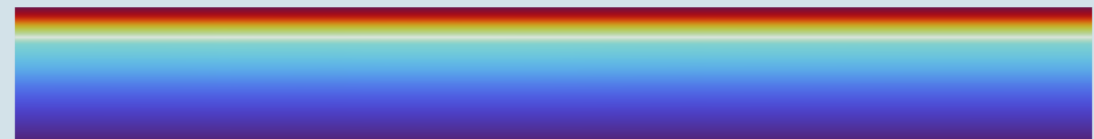
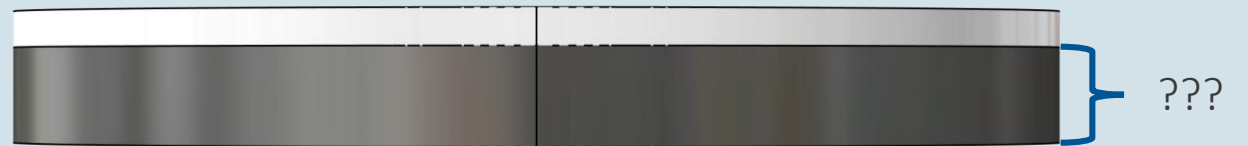
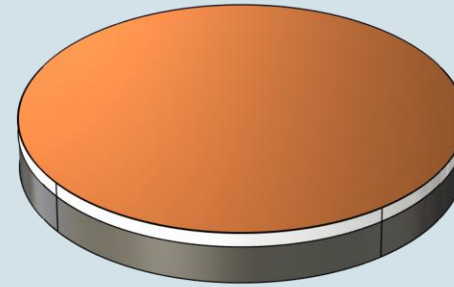
- Solves for electric fields in insulators
- Governing equation omits the term for conductivity – dielectrics are viewed as perfect insulators and conducting domains in the model are substituted by boundary conditions – *Terminal, Electric Potential or Ground*
- Serves to simulate capacitors, insulators, HVDC systems...
- Compute local electric fields, capacitance, electrostatic forces and resulting displacement/deformation

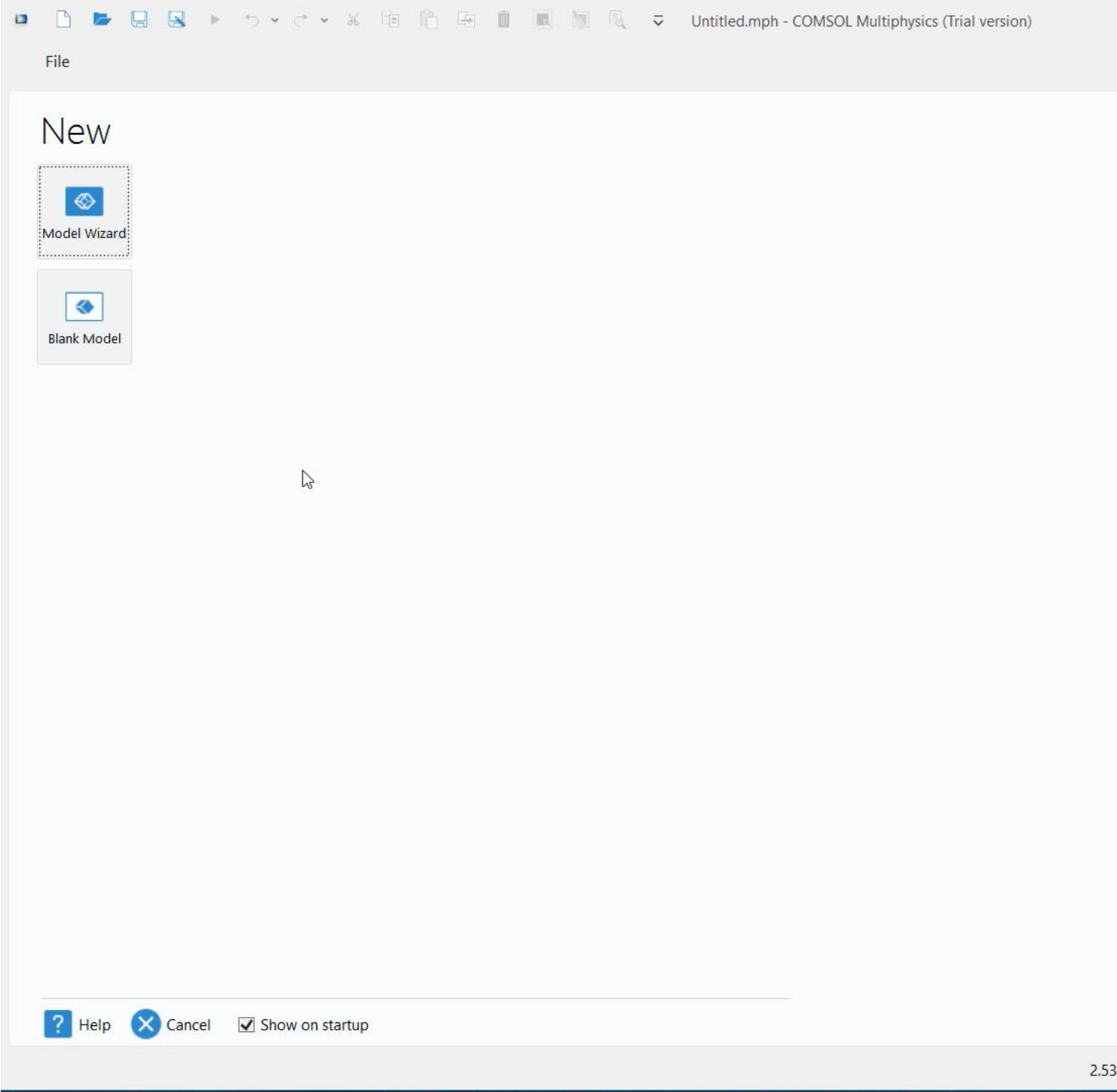


$$-\nabla(\epsilon_r \epsilon_0 \nabla V) = \rho_v$$

DEMO: Capacitor Optimization

- Finding optimal capacitor composition to reach target capacitance of 100 pF with two materials at hand
 - Zirconia ($\epsilon = 20$)
 - Titanium Dioxide ($\epsilon = 85$)
- *Electrostatics* interface combined with parameter optimization study



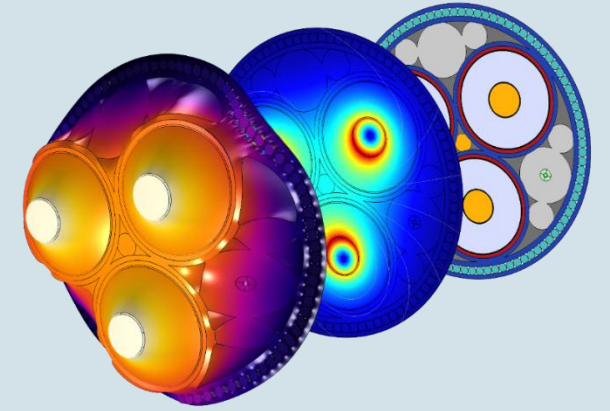


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Resistive Devices: *Electric Currents*

- The Electric Currents interface combines the electrostatic fields and stationary currents
 - This is valid only in case of time-varying input – for stationary problems insulators are ignored and conducting currents prevail
- Assumes negligible magnetic field effects
 - (For stationary problems) there is no need for ambient domain – only conductors suffice
 - Skin and proximity effects are ignored
- For transient simulations relaxation constant is a key material characteristic



$$-\nabla(\sigma \nabla V) = Q_v$$

$$-\nabla \left(\sigma \nabla V + \frac{\partial}{\partial t} (\epsilon_r \epsilon_0 \nabla V) \right) = Q_v$$

$$-\nabla((\sigma + j\omega \epsilon_r \epsilon_0) \nabla V) = Q_v$$

DEMO: Force Sensing Resistor

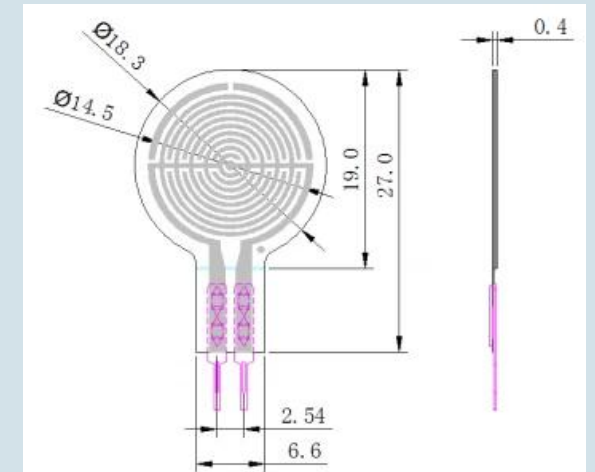
- Range 20 g – 6 kg
- Increasing pressure on the PET casing closes a cavity between silver traces and a conductive ink decreasing the sensor resistance
- Coupling *Solid Mechanics* and *Electric Current* interfaces to calculate the PET deformation and get the contact pressure between the ink and the traces

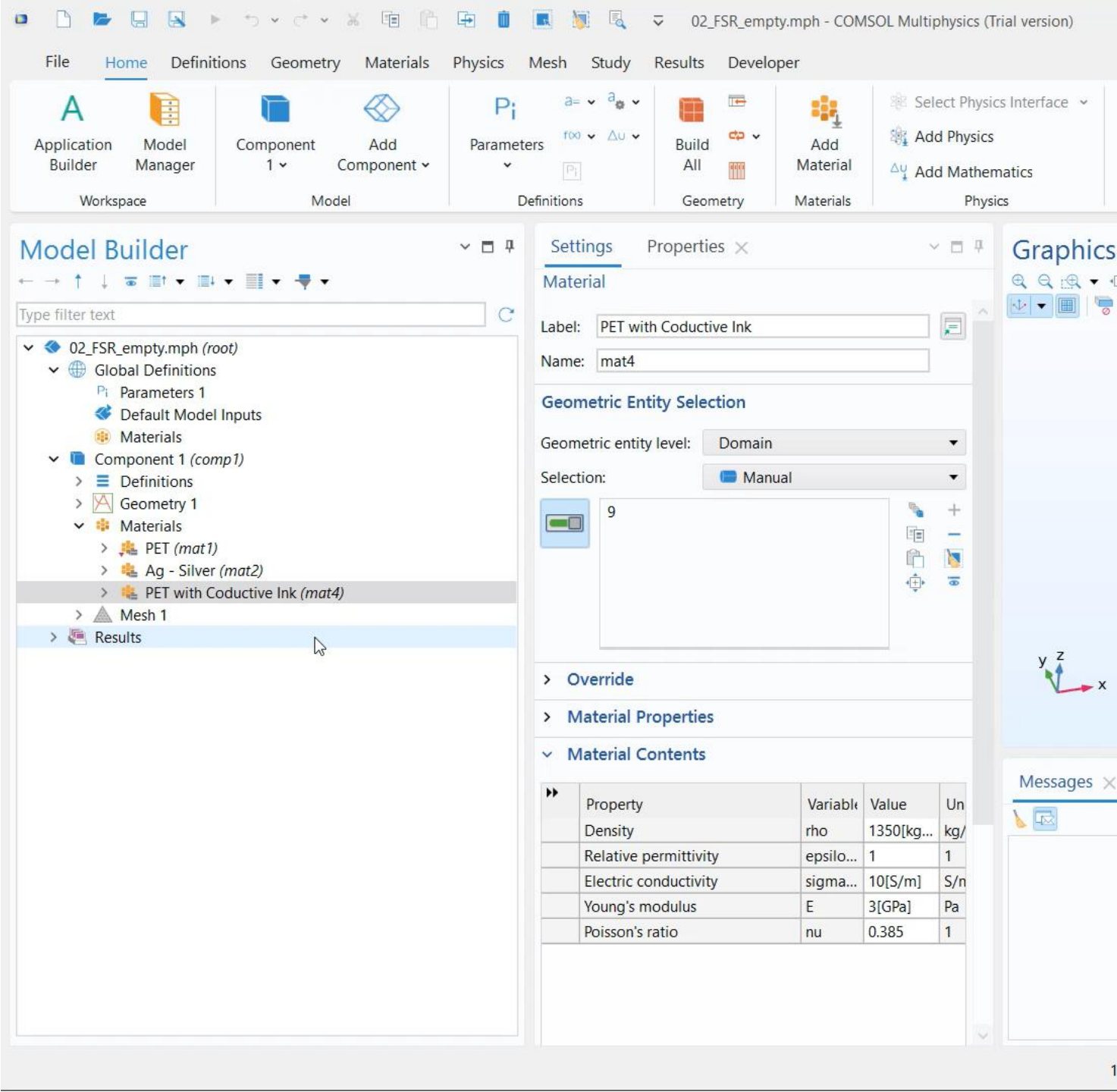


SEN0294 DFROBOT®



COMSOL FEM Model





DEMO: Force Sensing Resistor

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Inductive Devices: *Magnetic Fields*

- *Magnetic Fields*

Stationary

$$\nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) = \mathbf{J}$$

Transient

$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) = \mathbf{J}_e$$

Harmonic

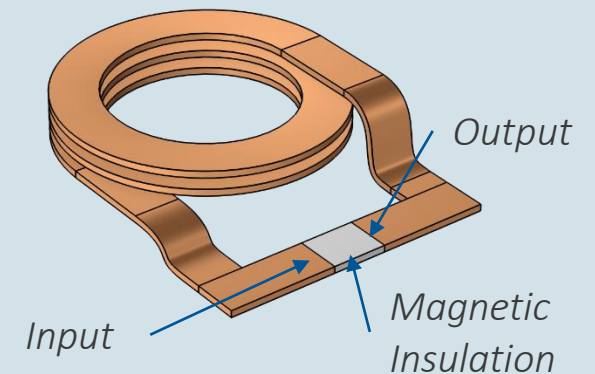
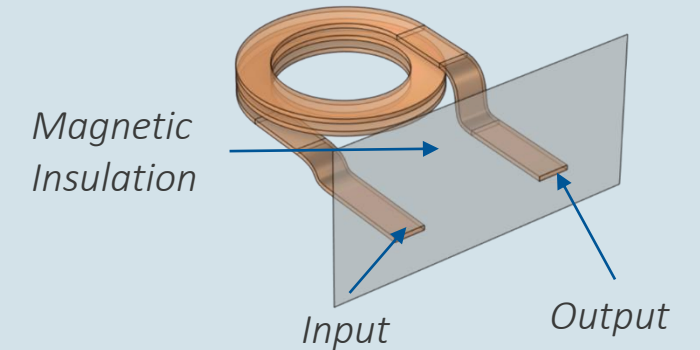
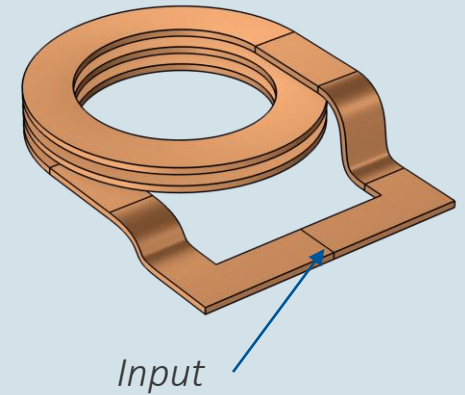
$$(j\omega\sigma - \omega^2\epsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A}) = \mathbf{J}_e$$

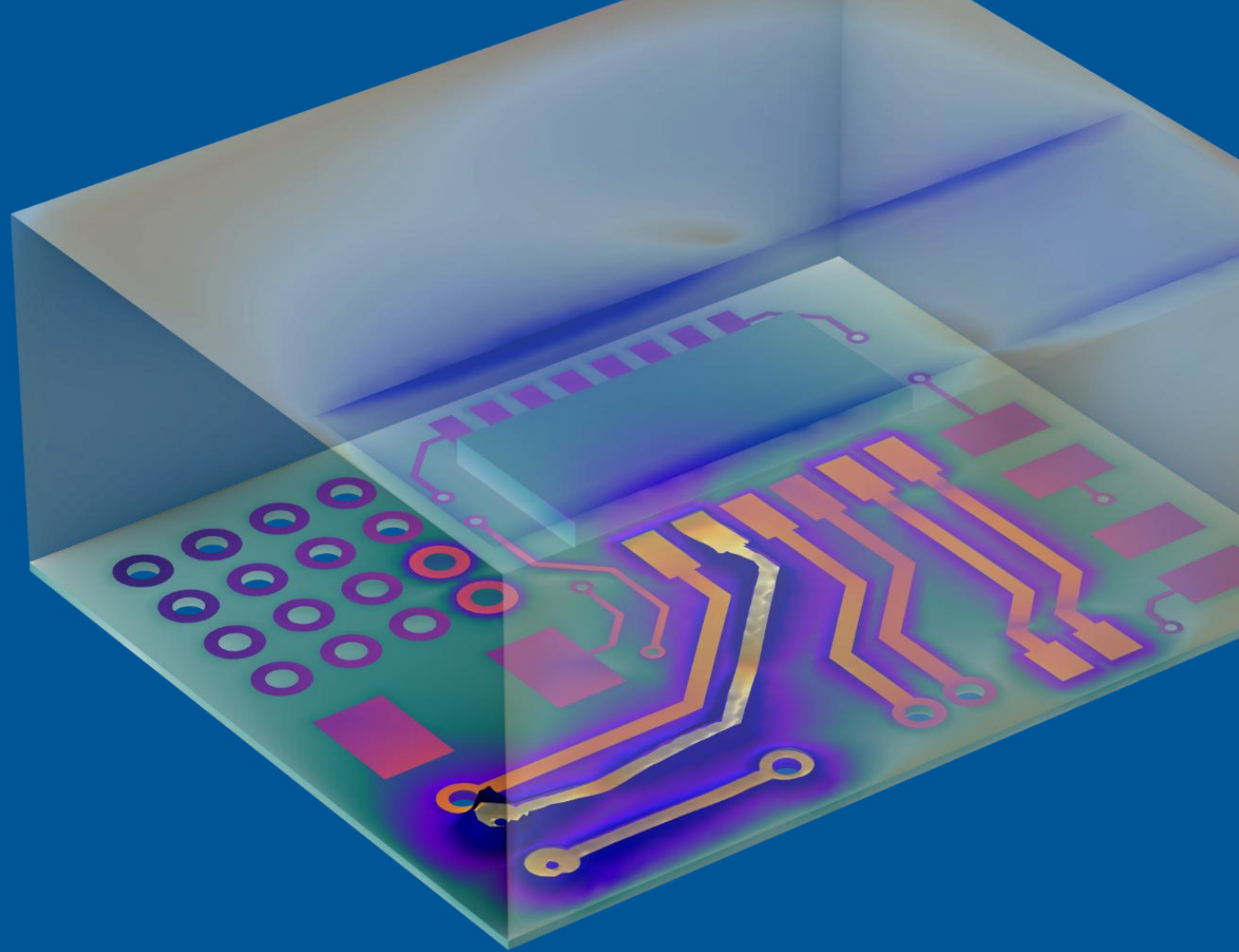
$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$$

$$\mathbf{E} = -j\omega\mathbf{A}$$

- Compute local electric and magnetic fields, taking resistive and inductive effects into account
- Other formulations
 - *No Currents* (Magnetostatics)
 - *Currents Only* (Inductance matrix calculation)
 - *And Electric Fields* (Capacitive effects, RLC coils)

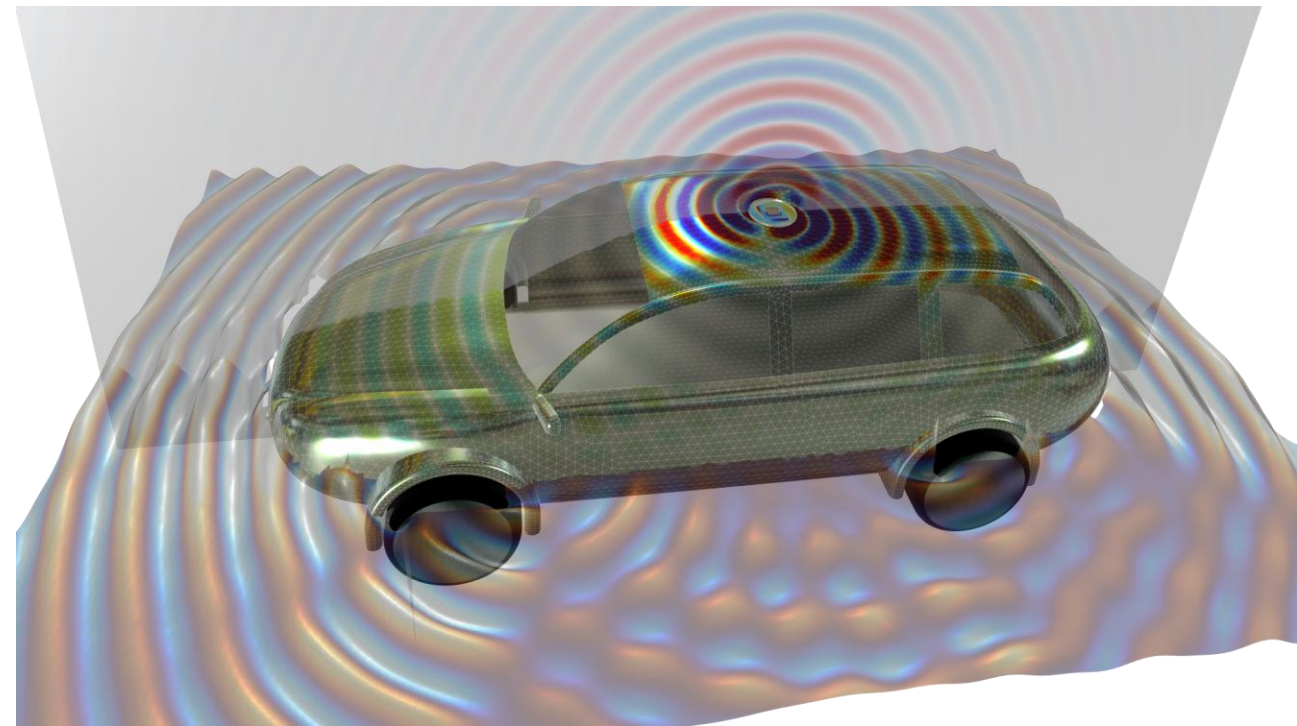
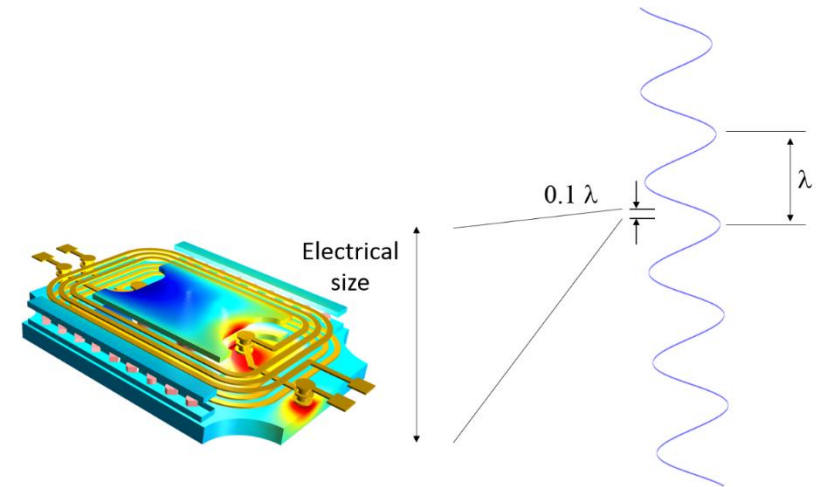




High-Frequency Fields

RF Simulations: Model Characteristics

- Object size \sim wavelength
- Ambient domain limitations (FEM)
 - Sampling theorem ($\lambda/5$)
 - $10\lambda \times 10\lambda \times 10\lambda$ (MAX)
- Alternatively:
 - Discontinuous Galerkin (dG-FEM)
 - Up to 10's of millions of degrees of freedom (DOF)
 - Boundary Element Method (BEM)
 - Open domains and scattering problems
 - Ray tracing (Ray Optics Module)
 - Wave propagation on distances several orders larger than wavelength (mm vs. km)



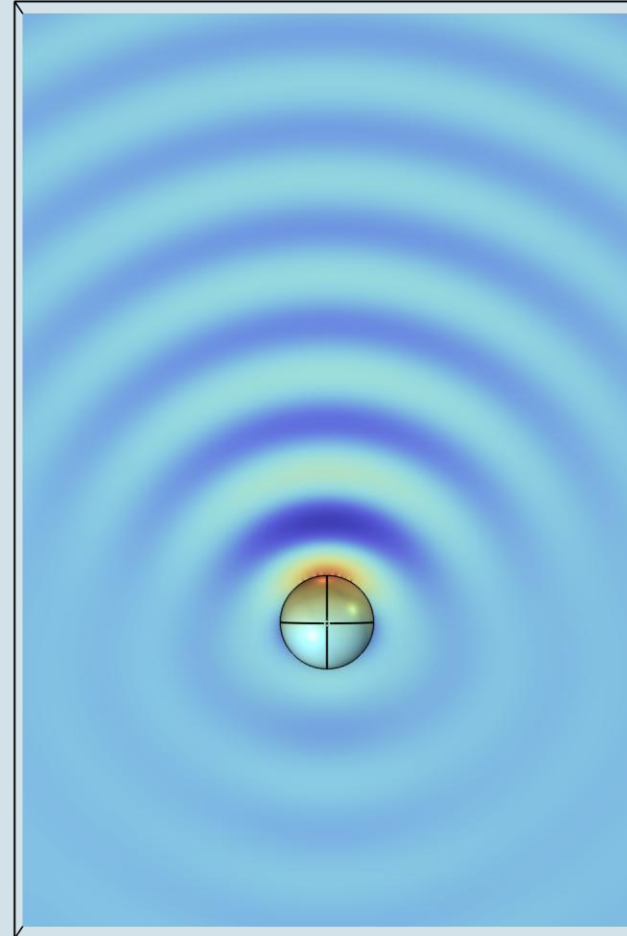
RF Module: Boundary Conditions

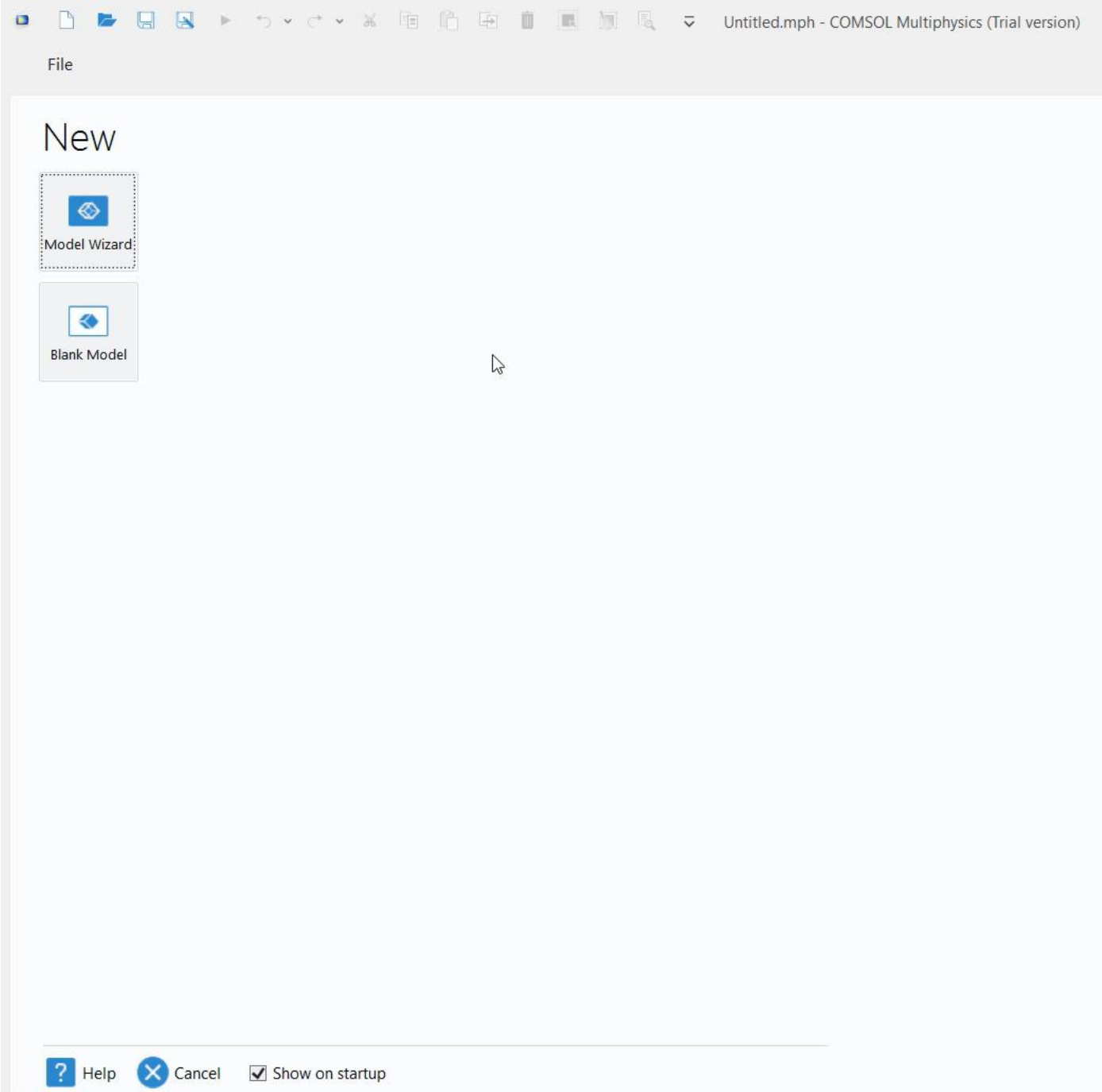
	Basic	Advanced
Excitation	Lumped port	Port (analytic, numeric, numeric TEM)
Absorption	Scattering BC (SBC 1 st)	SBC (2 nd), perfectly matched layer (PML)
Conducting layer	Perfect electric conductor (PEC)	Transition BC, impedance BC

- Port variability – coaxial feed, geometrically defined, numeric, lumped...
- Lumped capacitive, inductive and resistive elements
- Over 95 % of prototyped devices can be simulated using these boundary conditions

DEMO: FEM to BEM Coupling

- Patch antenna near field calculated using classic FEM interface
- Coupled with BEM to observe wave propagation outside the ambient domain into an infinite void
- Electric field vector coupled through Multiphysics interface
 - Electric Field Coupling





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