Motion in The Electromagnetic Field: Forces, Motors and Actuators

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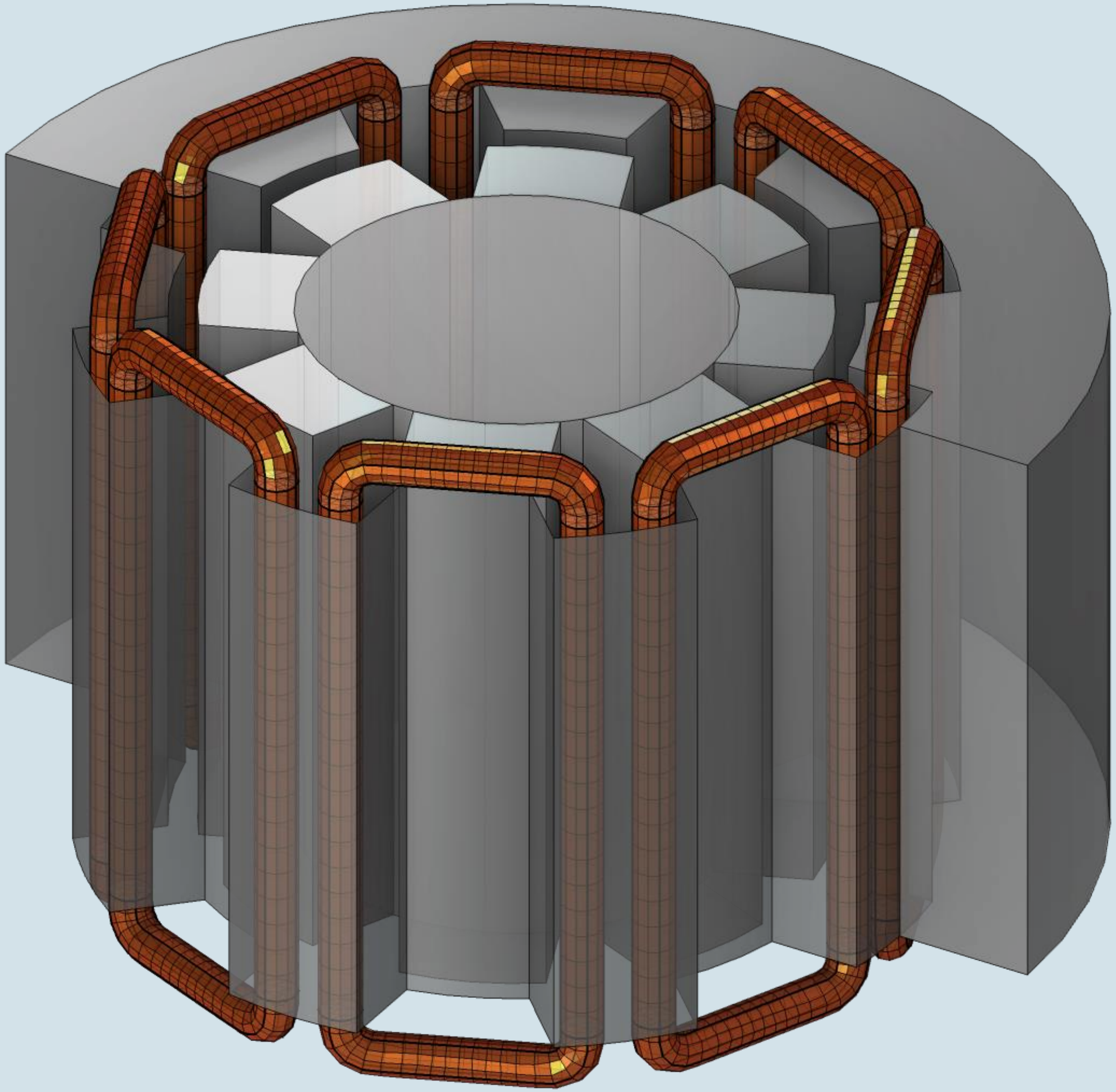
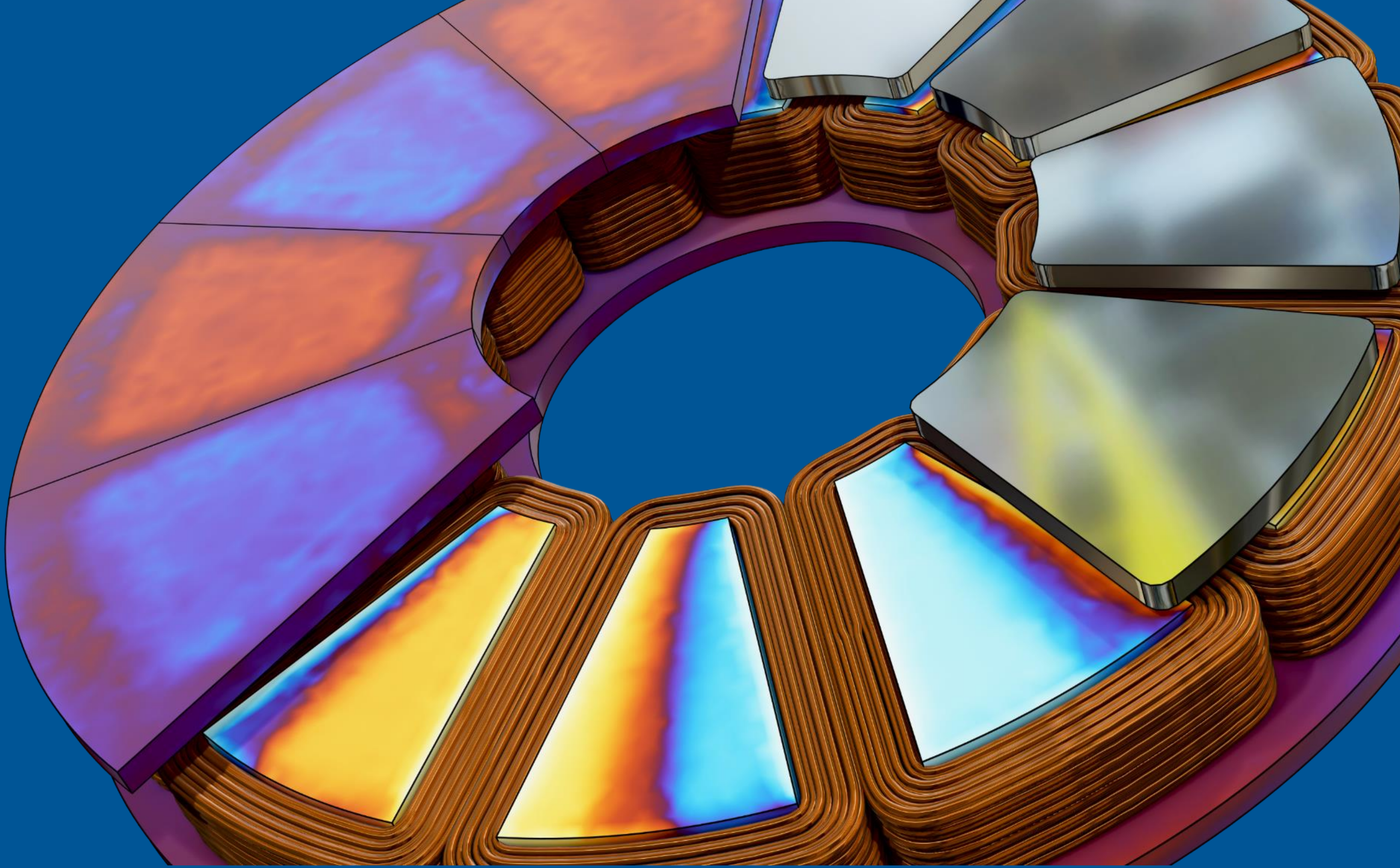
Schedule

1. Electromagnetic Force Calculation
2. Moving Mesh & Deformed Geometry
3. Actuators
4. Rotating Machinery

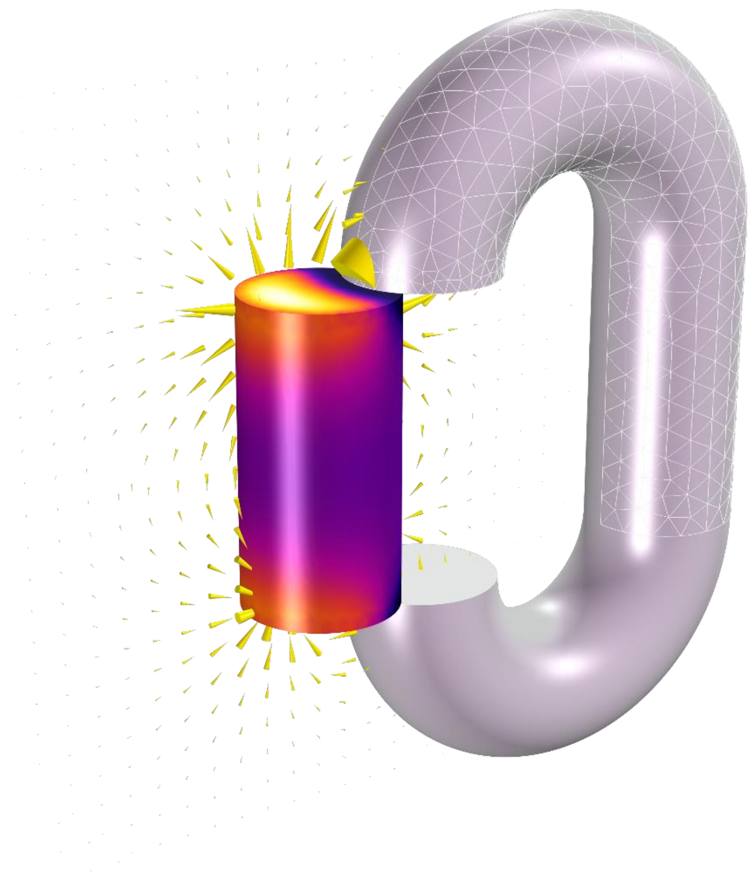




Electromagnetic Force Calculation

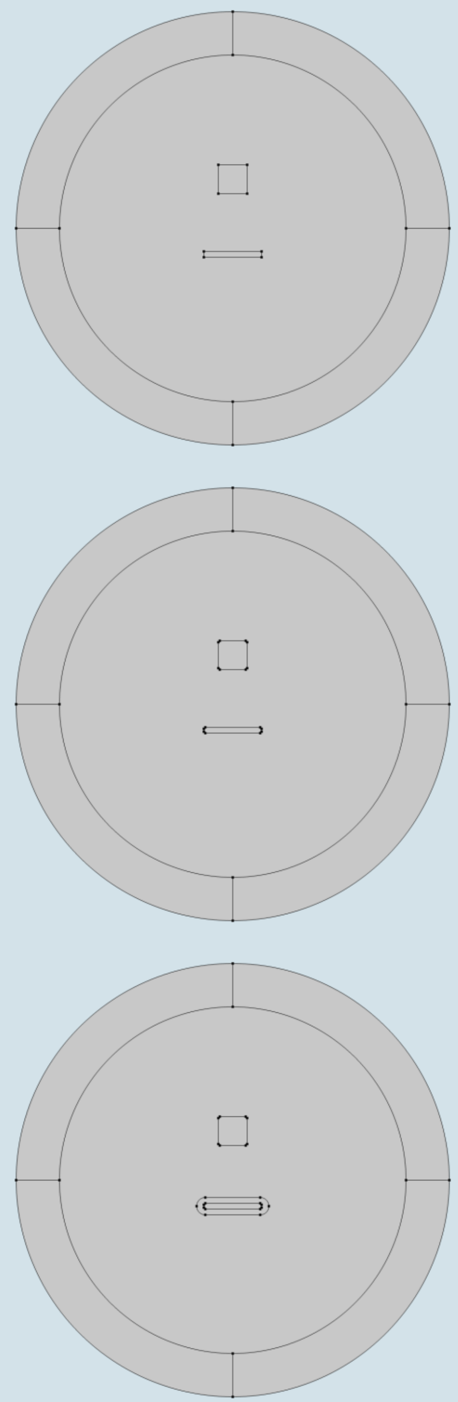
Means To Calculate The Electromagnetic Force

- Force Calculation
  - From surface integration of Maxwell tensor
    - Requires fine surface mesh and mesh verification study
  - Both magnetic and electric interfaces
- Lorentz Force
  - Requires electric current in conductive material
  - Automatically calculated where possible
- Virtual work
  - $W = \mathbf{F} \cdot \mathbf{s}$
- Electromechanics
- Magnetomechanics



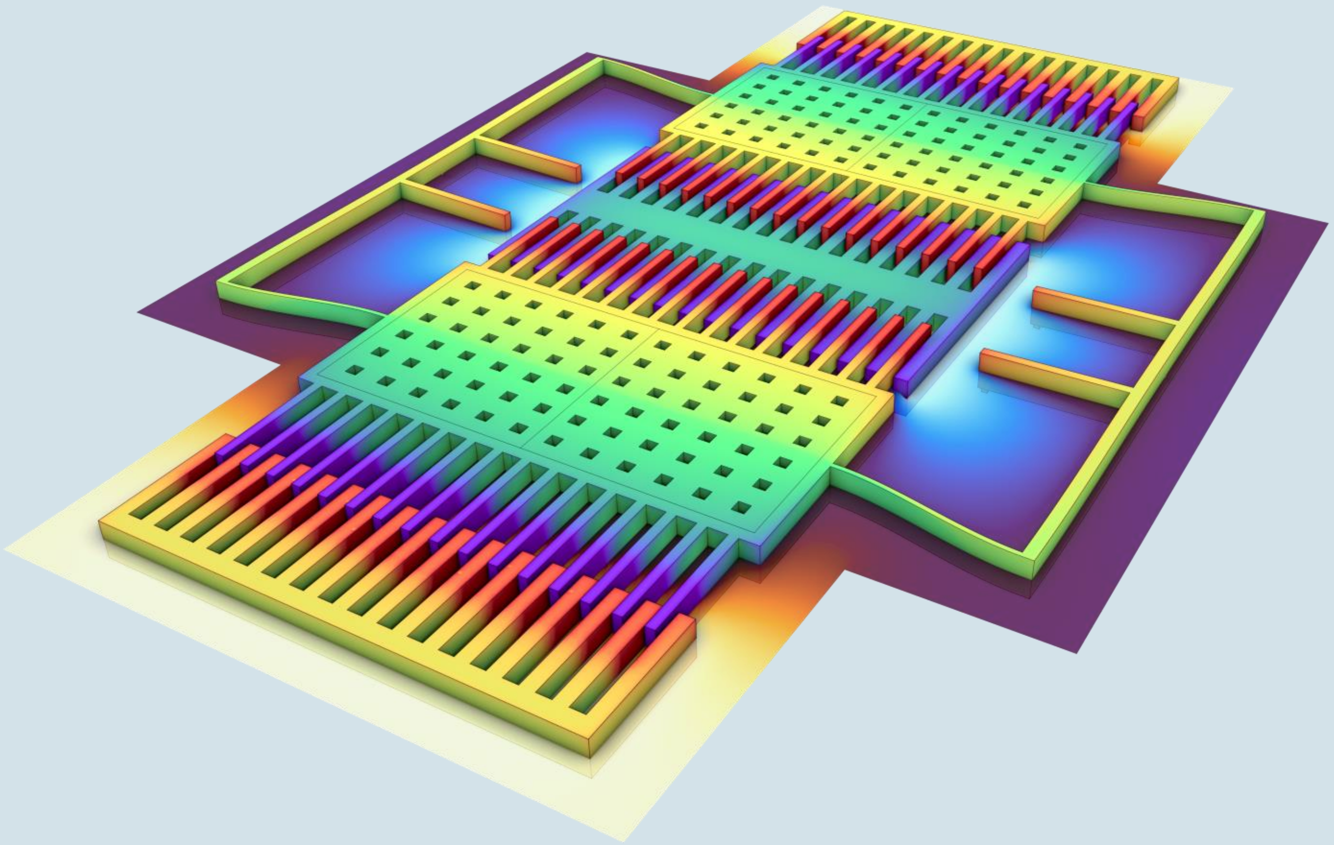
Tips for Accurate Force Calculation

- Do not apply the force calculation node to permanent magnet
- Avoid field singularities by filleting away sharp edges
- Focus on surface mesh quality of the target object
  - Improve the quality for surface integration of Maxwell tensor
- Create a circular domain around the target object
  - Avoid sharp edges
  - Can be applied to calculate forces acting on:
    - Permanent magnets
    - Magnetically soft materials
  - Reduce mesh dependency



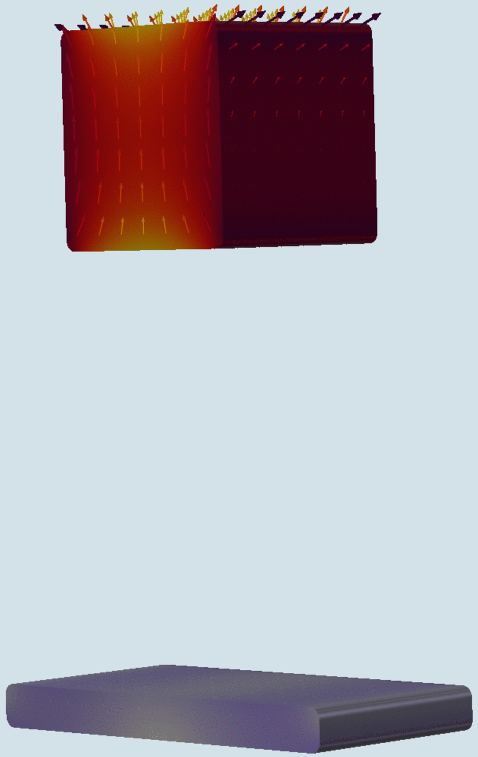
Electromechanics & Magnetomechanics

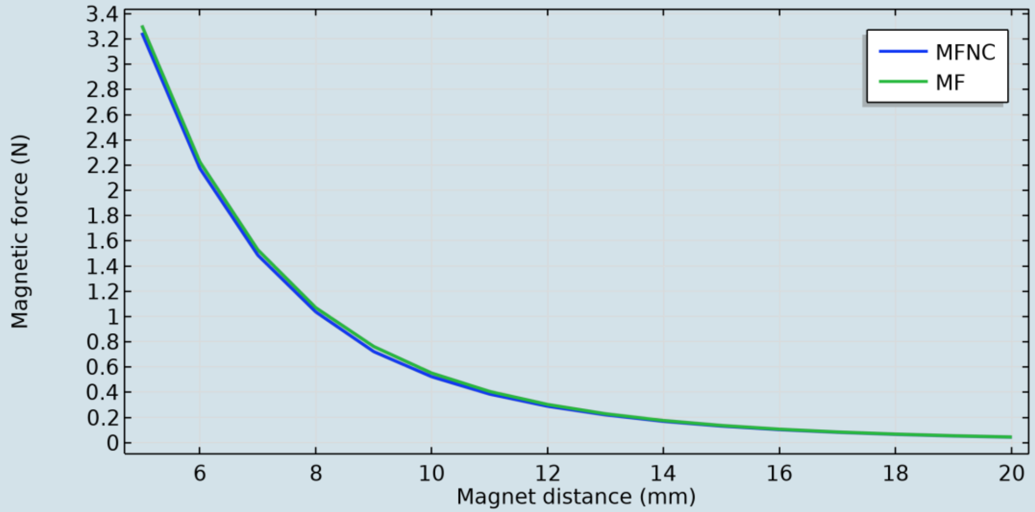
- Universal multiphysics interfaces coupling various force sources with arbitrary structural mechanics interface
  - Solid, Shell and Membrane
- Improved resolution of electrostatic singularities
- Unified into two multiphysics nodes in v6.2
- Accompanied by couplings for rotating machinery



DEMO:
Force Calculation

- Comparison of different approaches to calculate electromagnetic force
  - *Magnetic Fields (No Currents)*
- Improving accuracy by following the recommended steps
  - Filleting corners
  - Creating an extra force calculation domain





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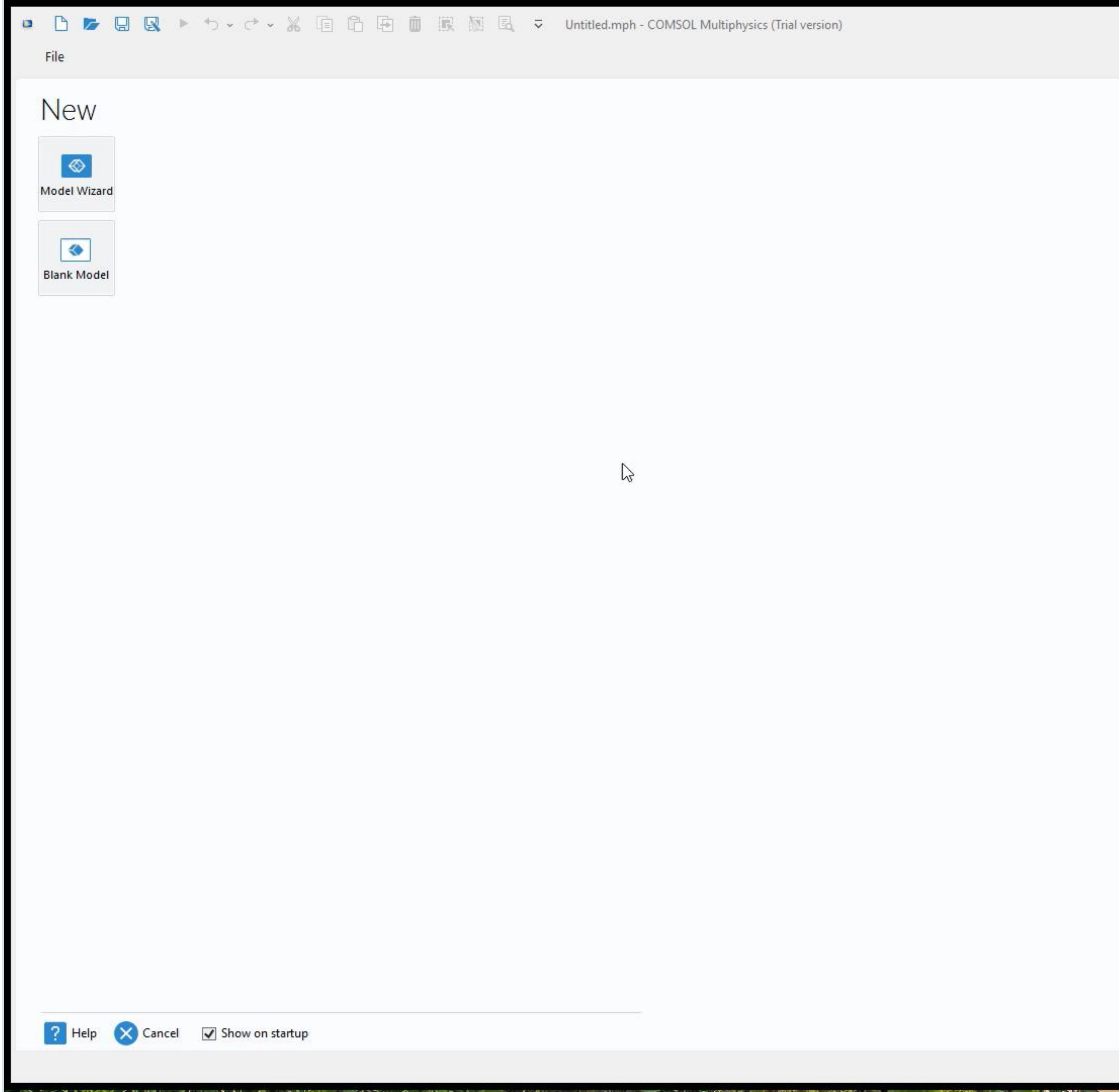
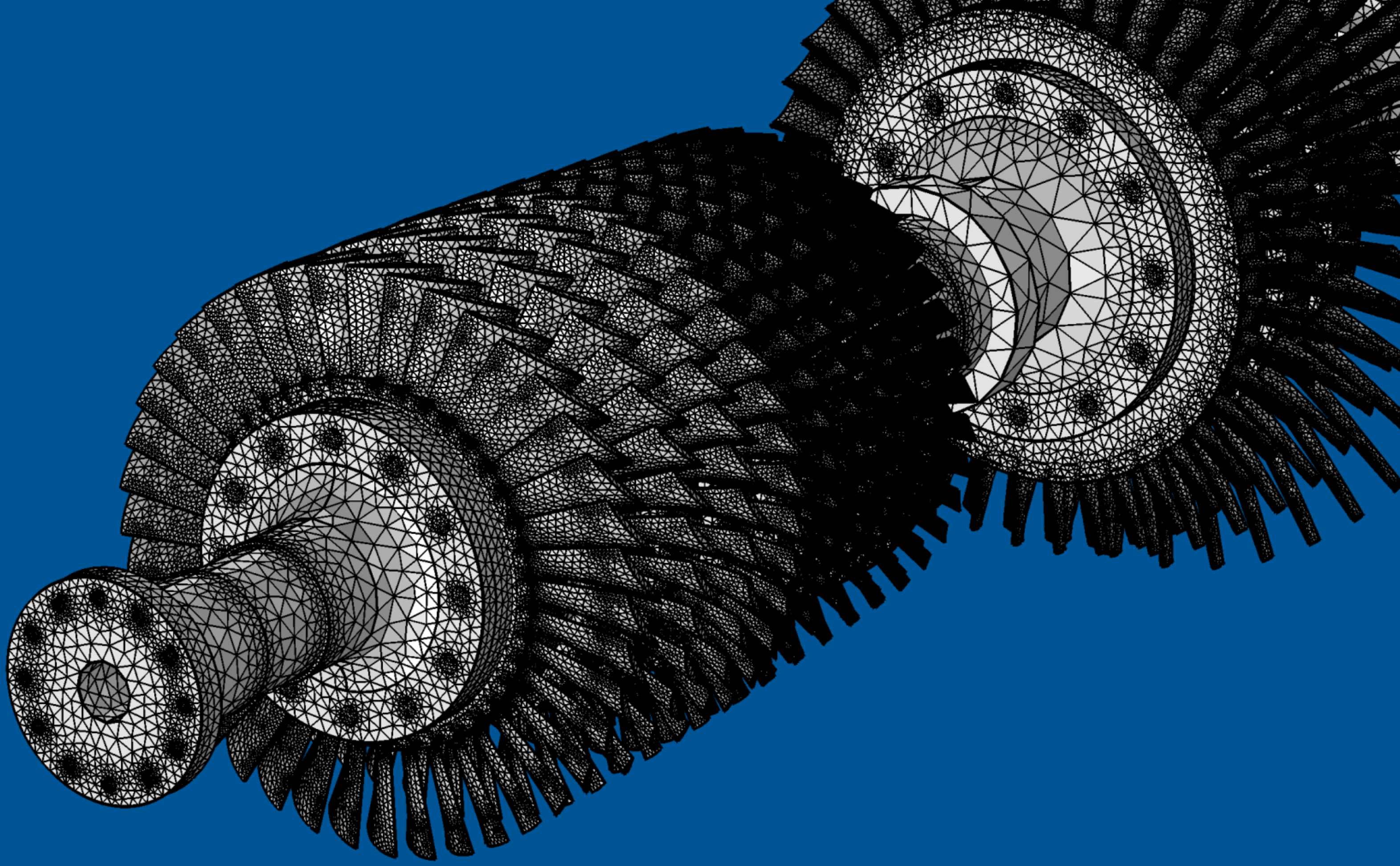
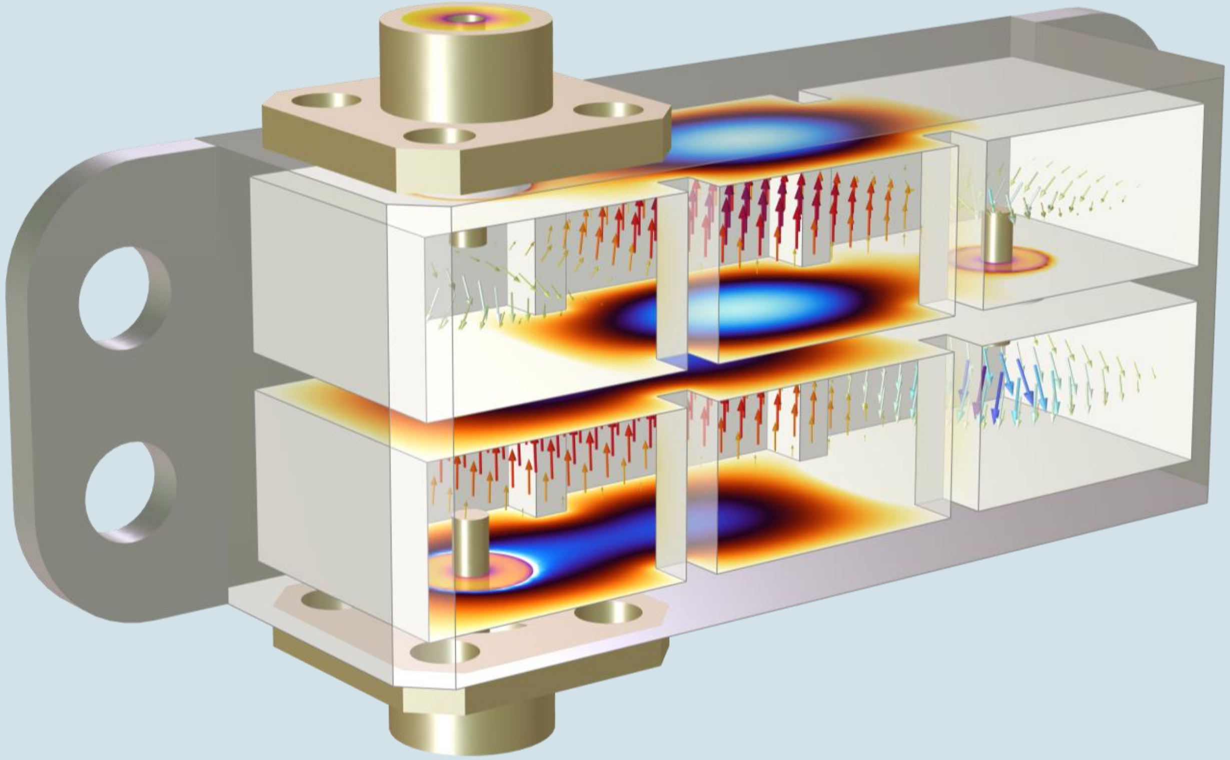




Moving Mesh & Deforming Domain

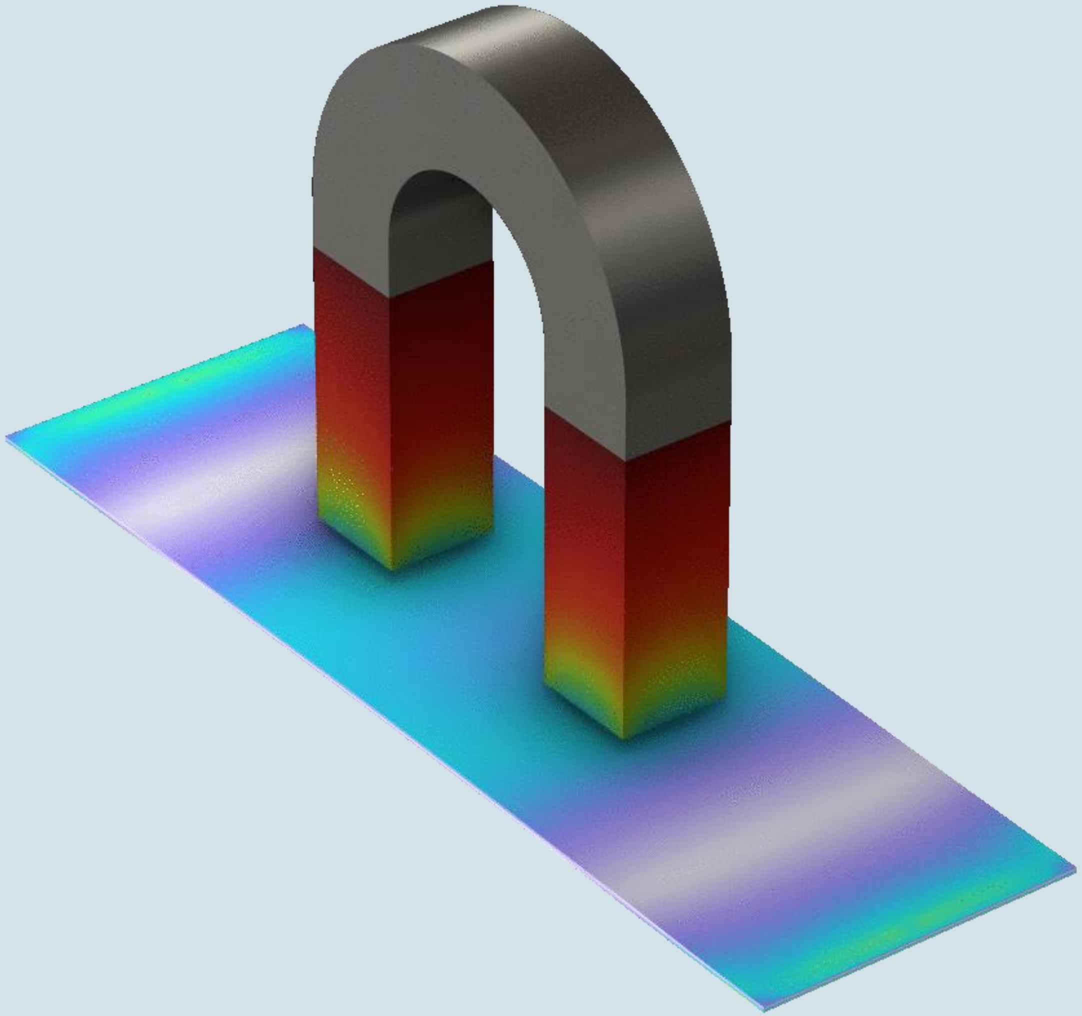
Moving Mesh

- Deforms *Spatial* frame relative to the *Material* frame
- *Deforming Domain* feature captures deformation of medium
  - E.g. air in a cavity filter
- Deformation comes from *Solid Mechanics* interface or is explicitly prescribed
  - FSI simulations
  - PZT cavity filter tuning
  - Rotating machinery



DEMO:
Moving Mesh

- Coupling *Magnetic Fields, No Currents* with *Solid Mechanics* using the *Magnetomechanics* multiphysics interface
- Setting up *Moving Mesh* interface
- Preparing geometry and mesh for domain deformation



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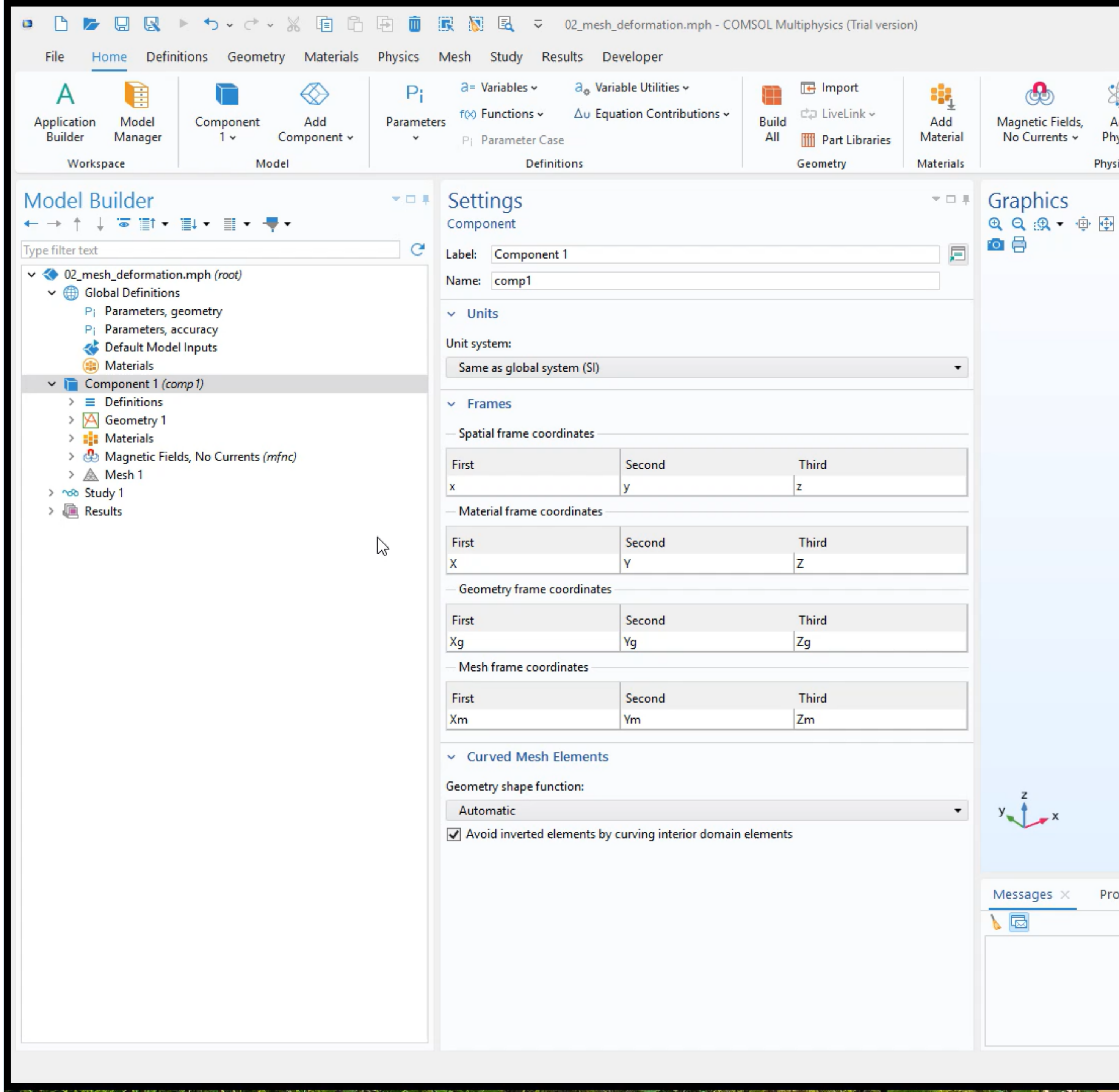
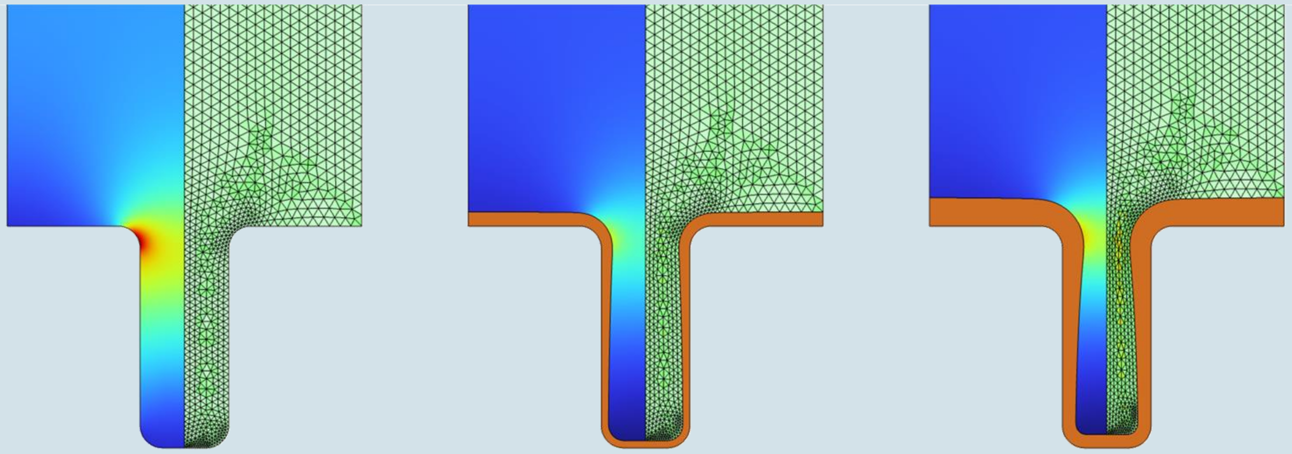


Deformed Geometry

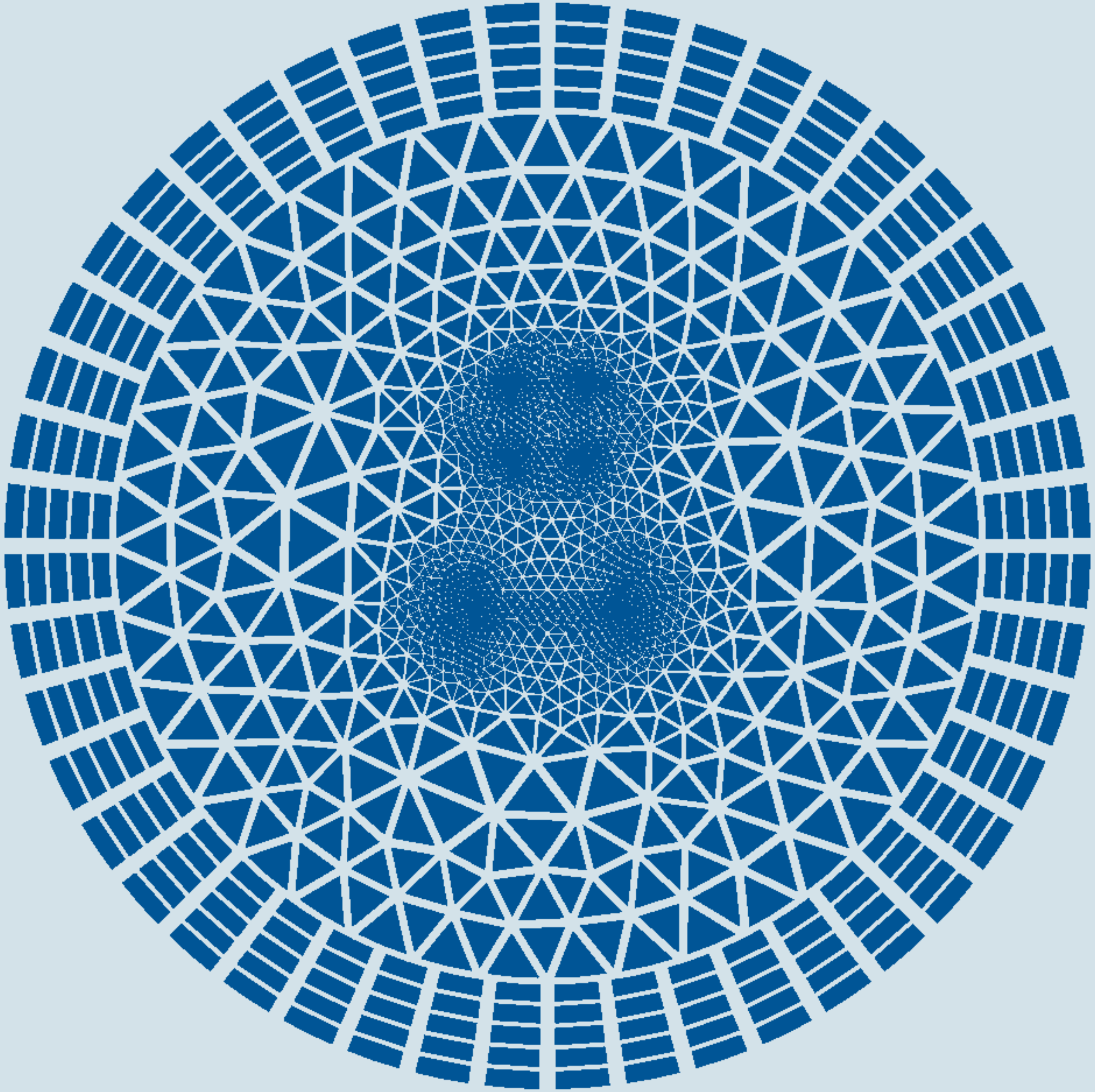
- Deforms *Material* frame relative to the *Geometry* frame
- *Deforming Domain* feature captures addition or removal of material
  - Copper electrodeposition
  - Laser welding (and evaporation)

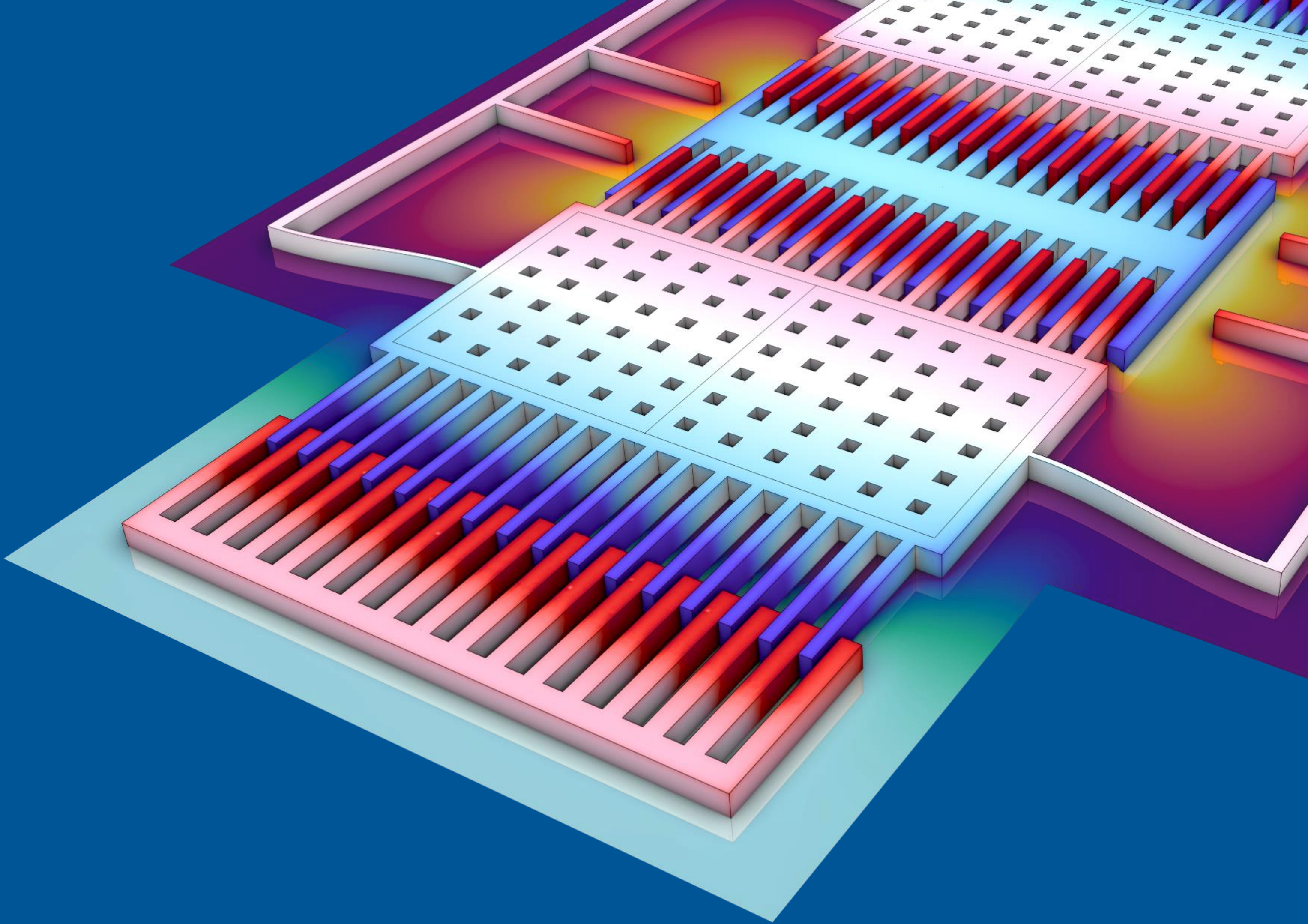


COMSOL

Rotating Domain

- Prescribing rotational movement
  - User defined relationship for rotation angle
  - Through rotational velocity
  - Treated as rigid body with applied moment and given moment of inertia
- Requires *Form Assembly* geometry closure
- Automatically added with certain physics

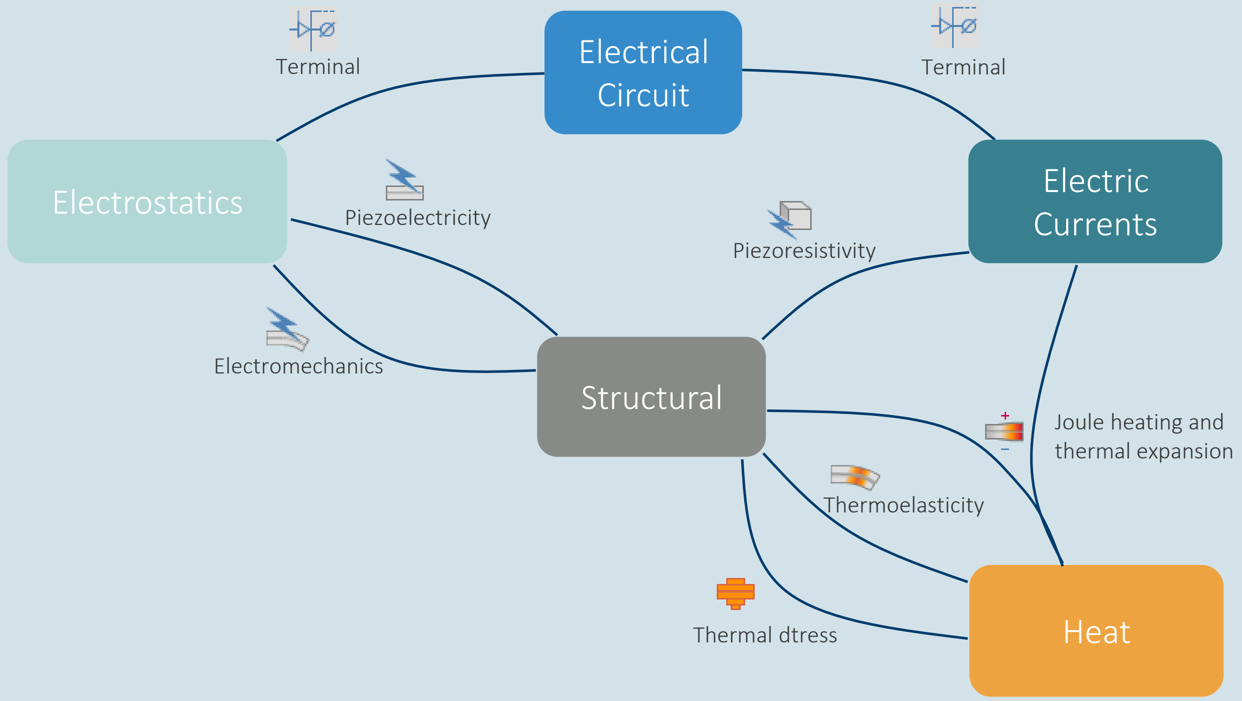




Actuators

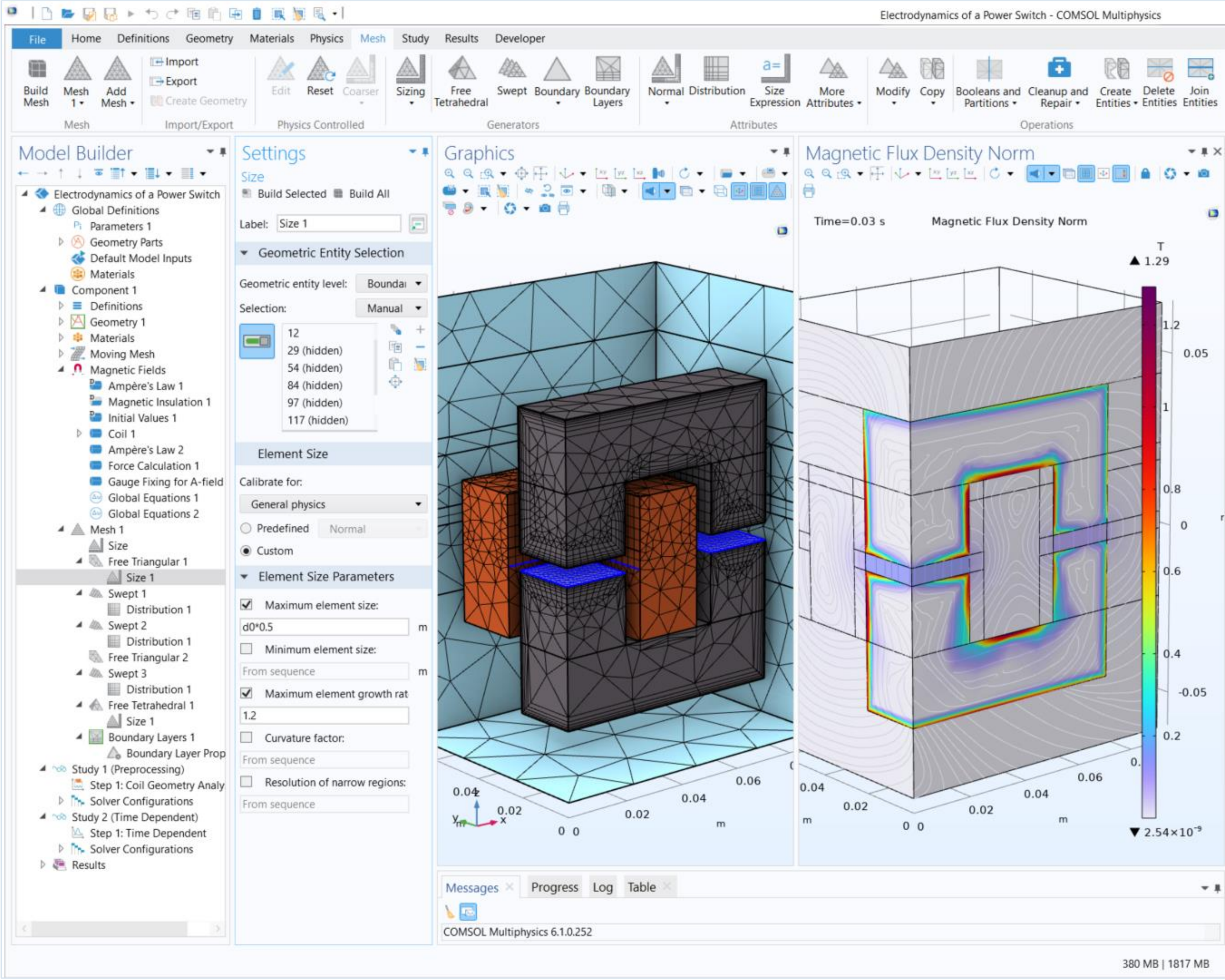
Electric Actuators

- Electrostatics combined with:
  - Structural mechanics
  - Piezoacoustics
  - Heat transfer
- Common use cases:
  - Small sensors or actuators, also referred to as microelectromechanical systems (MEMS) and consumer electronics, such as touchscreens

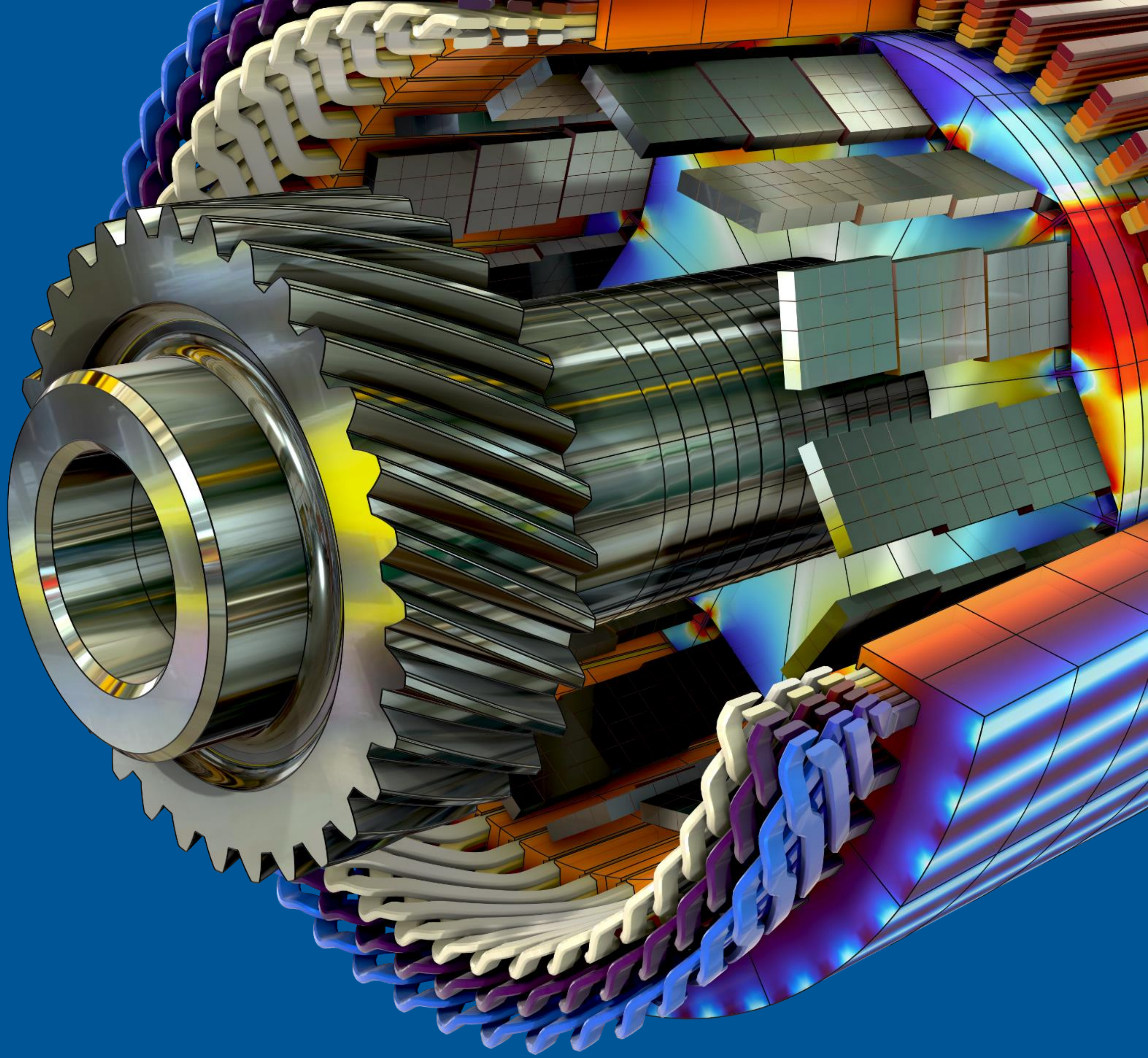


Electromagnetic Actuators

- Magnetic fields combined with
  - Structural mechanics
  - Piezomagnetics/Magnetostriction
- Quasistatic approach
  - Parametric sweep
- Dynamic approach
  - Time domain
  - Eddy currents handling
  - Linear discretization
  - Solver tuning

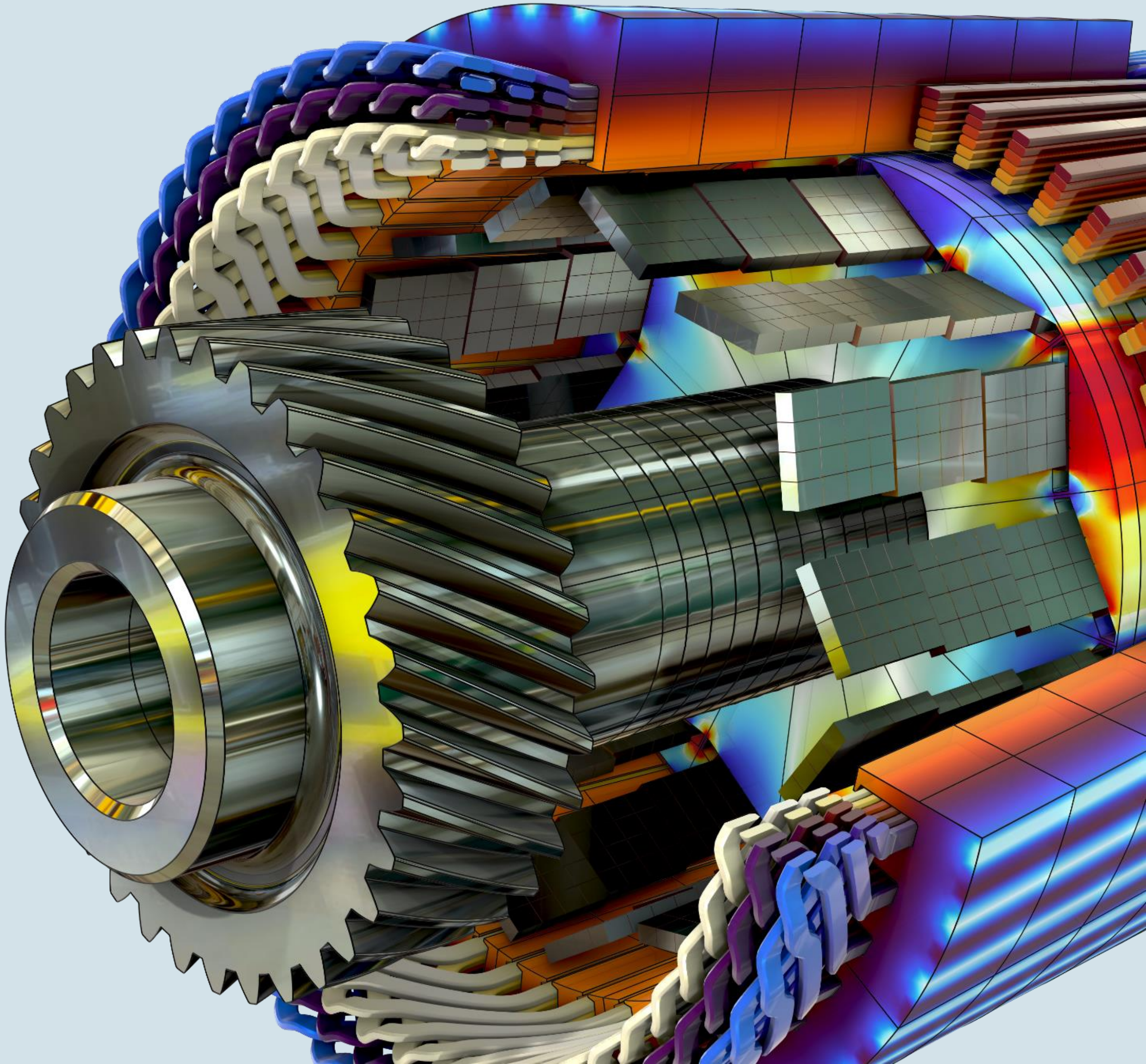


Rotating Machinery



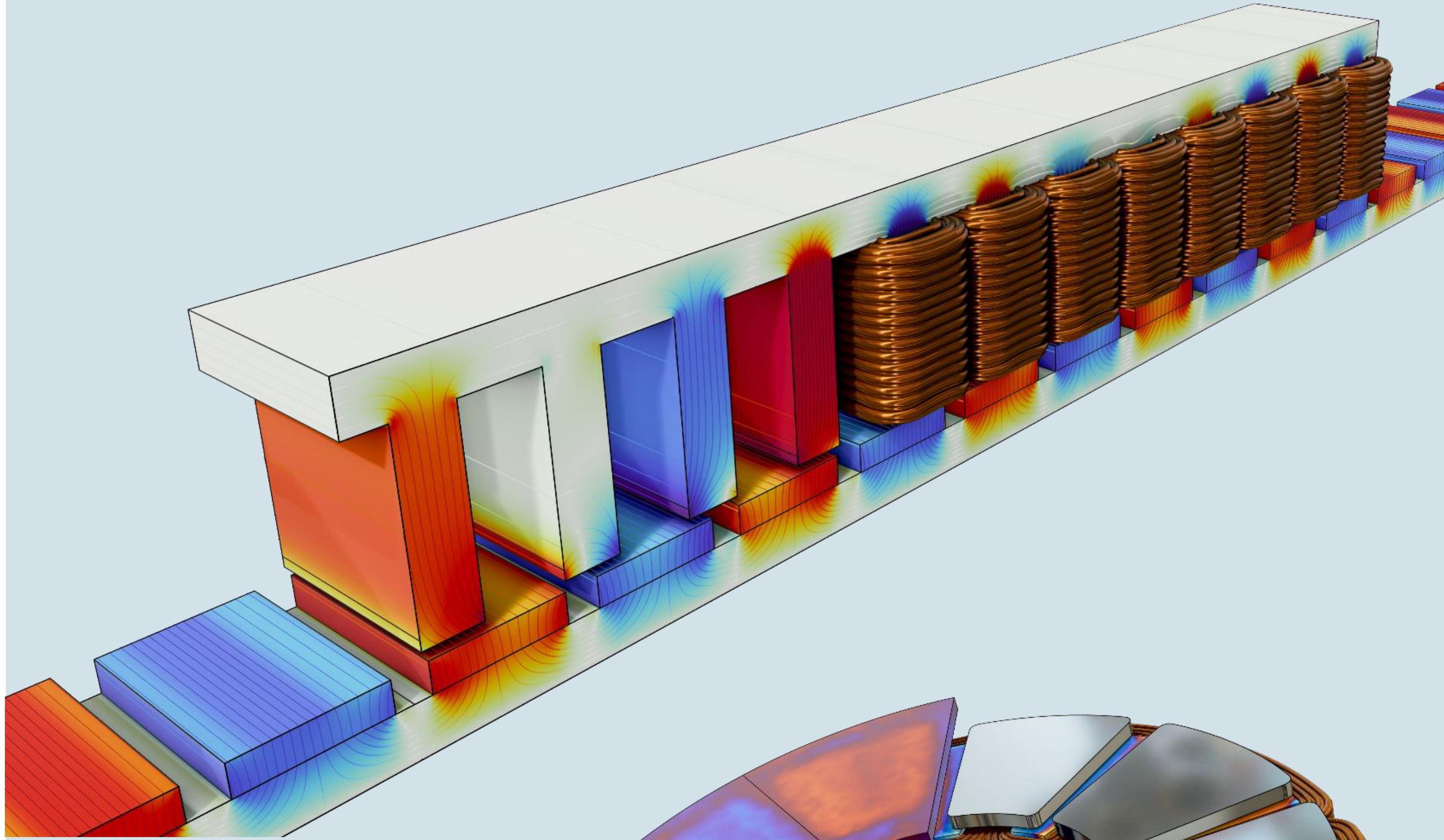
Radial Flux Machines

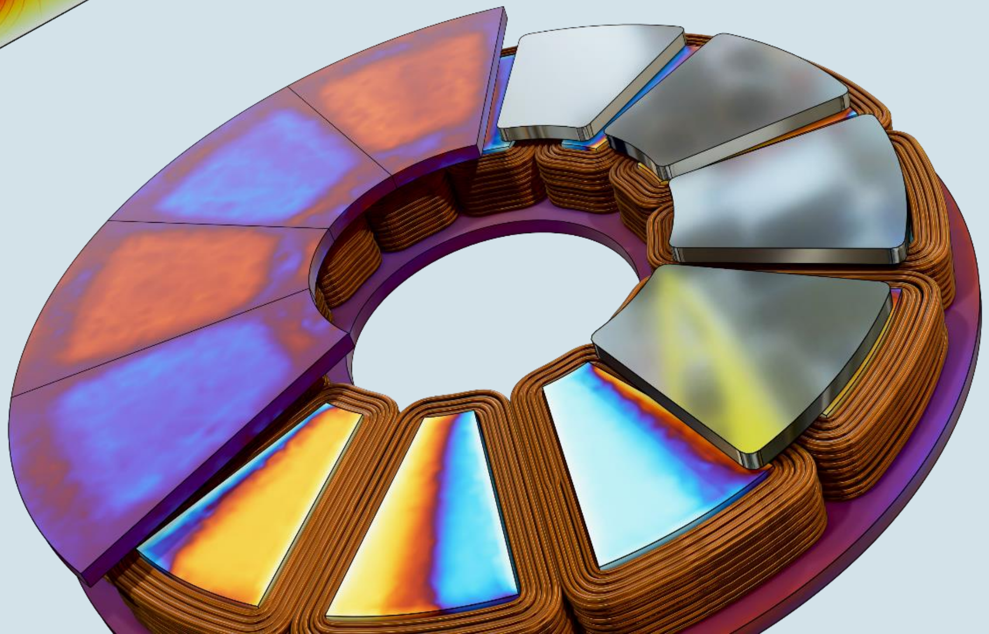
- 2D & 2.5D modeling
  - Suitable approximation for efficient prototyping, sweeping and optimization
- 3D modeling
  - Enables calibration of 2D models and investigation of the end effects, flux leakage in skewed rotors and stators, and circulating currents in the magnets



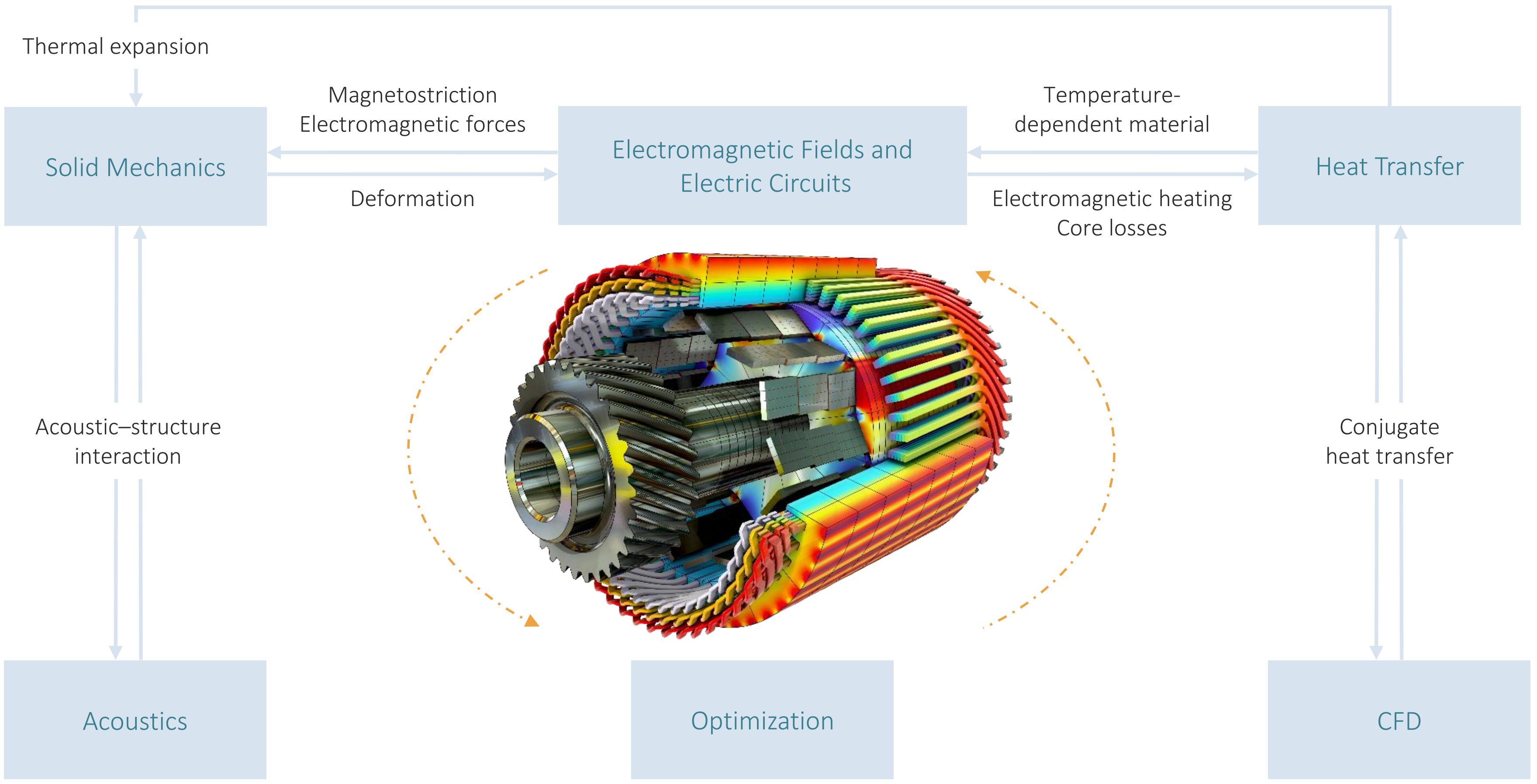
(Not Only) Rotating Machinery

- Axial flux motors
  - More inherently 3D (although 2D approximations are possible)
- Linear motors
  - Can be modeled in 2D, 2D axisymmetry (for tubular machines), or 3D
  - Sometimes approximated using periodic conditions, ignoring the end effects





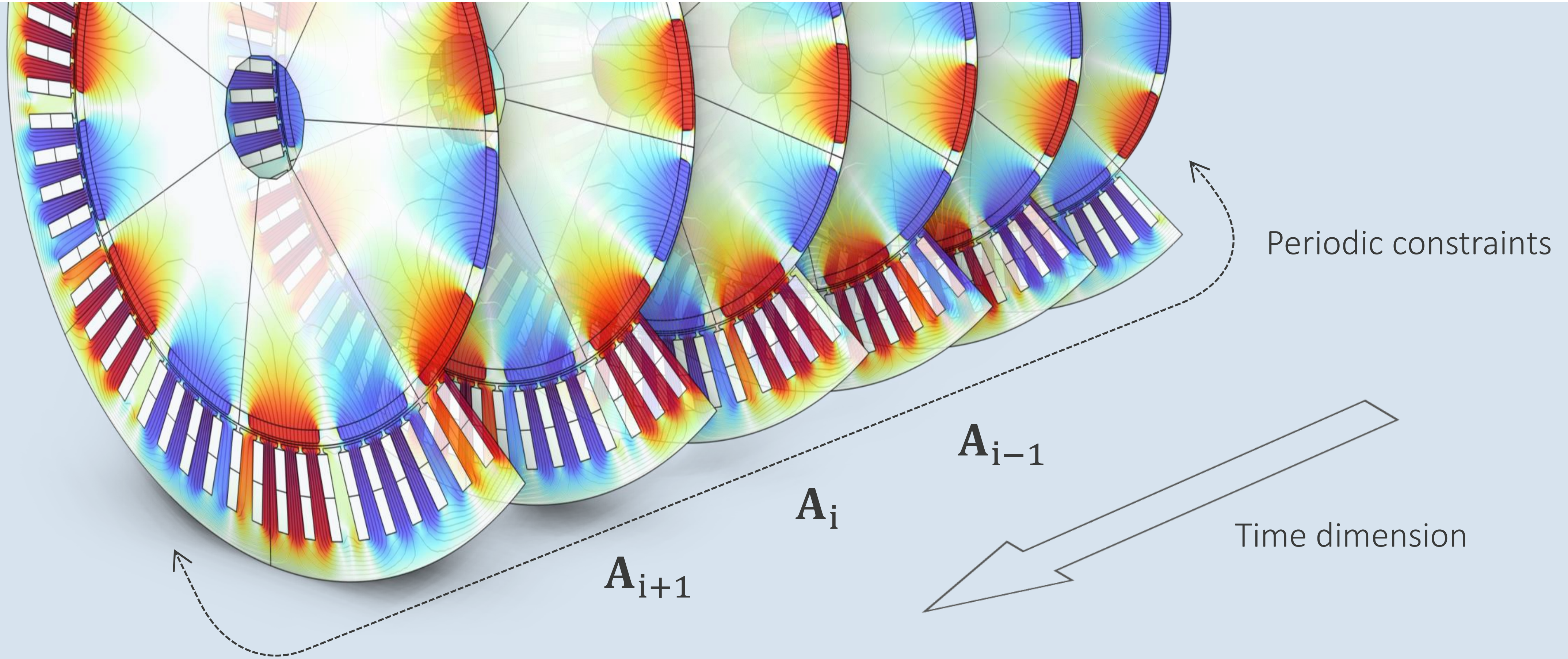
Multiphysics Behind Electric Motors



Time-Periodic Electromagnetics

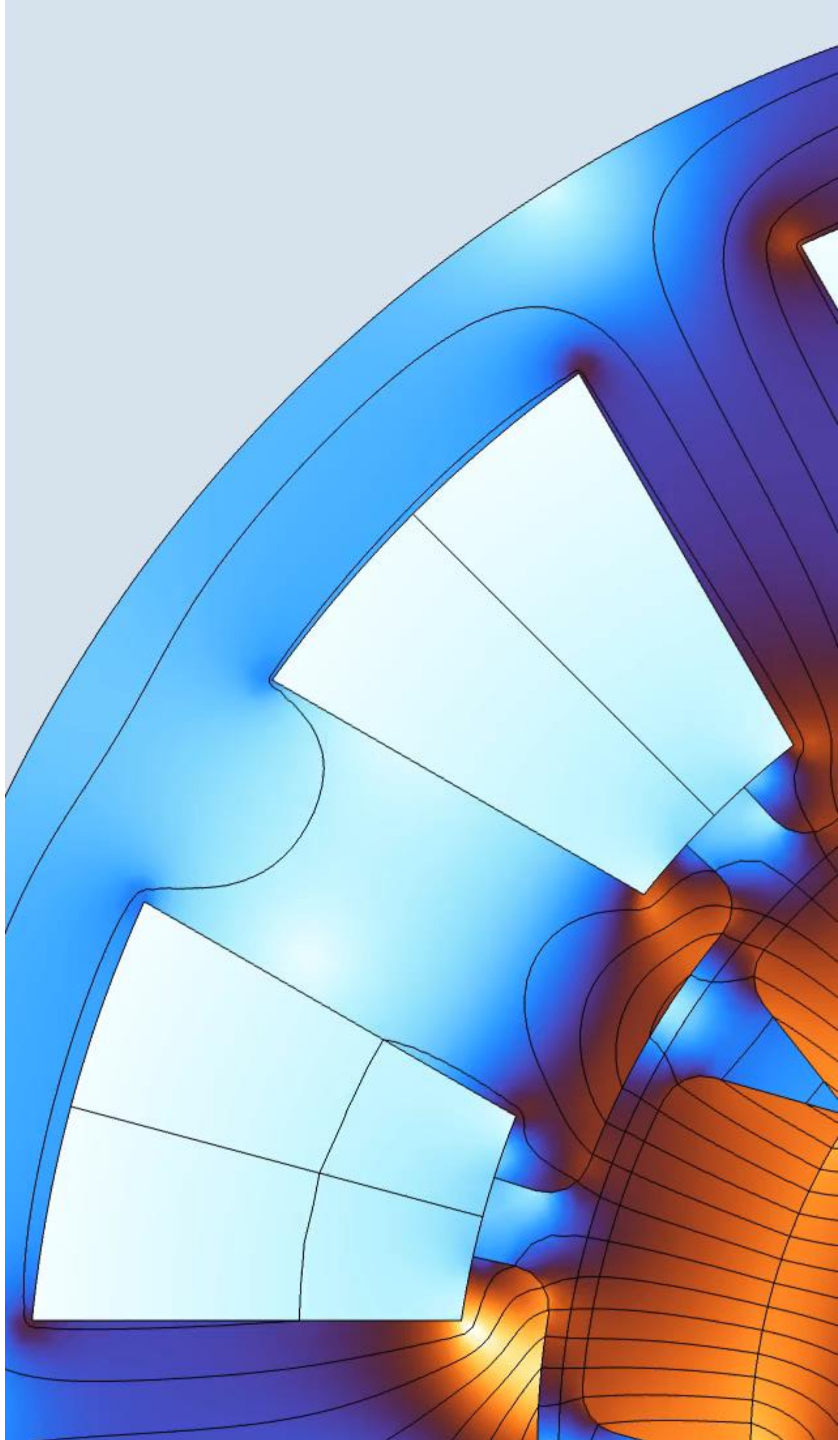
Traditional transient approach: $$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \mathbf{H} = 0$$

Time-periodic approach: $$\sigma \frac{\mathbf{A}_{i+1} - \mathbf{A}_{i-1}}{2dt} + \nabla \times \mathbf{H}_i = 0$$



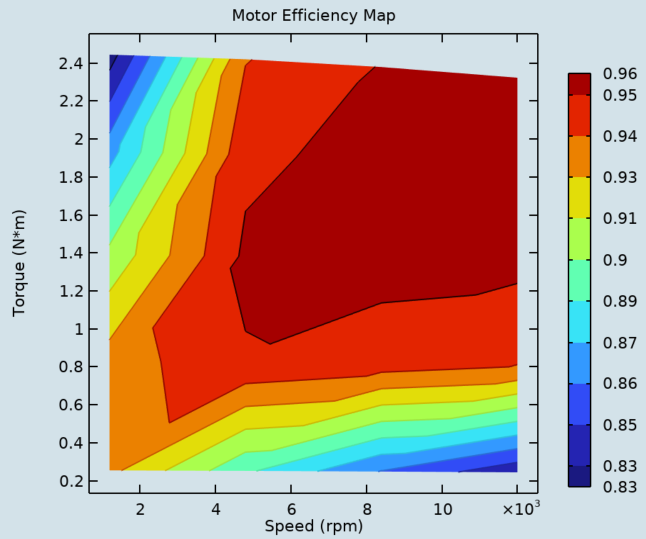
Time-Periodic Electromagnetics

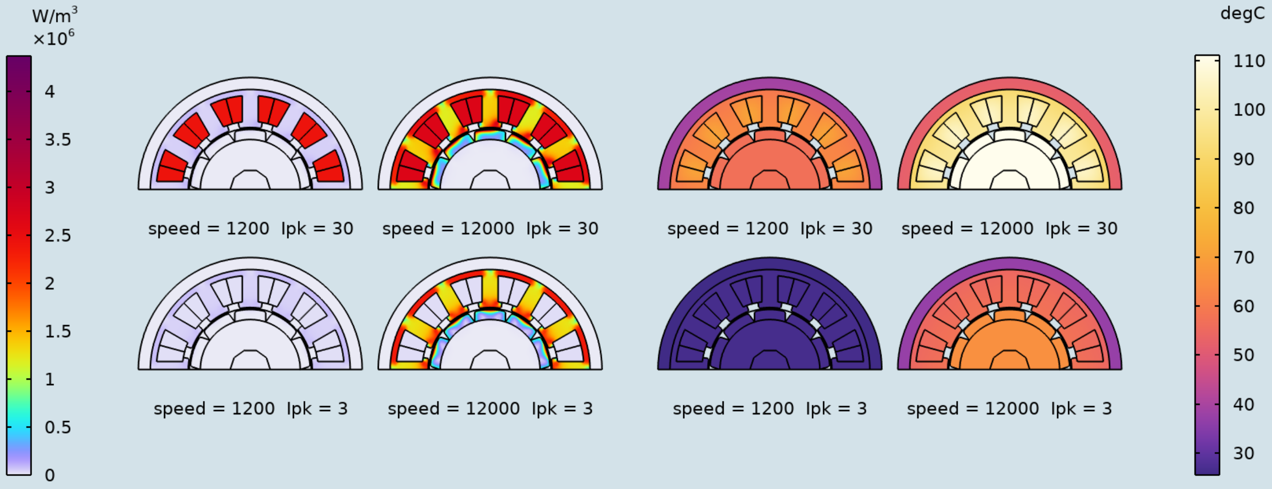
- For nonlinear time-periodic problems:
  - Solves for the steady-state conditions directly
  - Imposes periodicity in the time dimension
  - Solves for all time frames at once
- Supports the exact modeling of rotations, nonlinear magnetic materials, induced currents, and general periodic excitations
- Particularly well suited for:
  - Parametric studies — efficiency maps and temperature maps
  - Multiphysics — heat transfer, deformations, and vibrations
  - Optimization — topology optimization and objectives based on the fast Fourier transform (FFT)
  - Models that require many cycles to reach a steady state



Parametric Sweeps and Efficiency Maps

- Electromagnetics and heat transfer are solved together using a stationary solver
- Stationary, transient, and frequency-domain phenomena are all processed using the same solver
- No need to iterate between study types; this is true multiphysics
- When sweeping, previously obtained results can be reused to accelerate the solver
- Collecting 64 data points in one hour is achievable on an average laptop

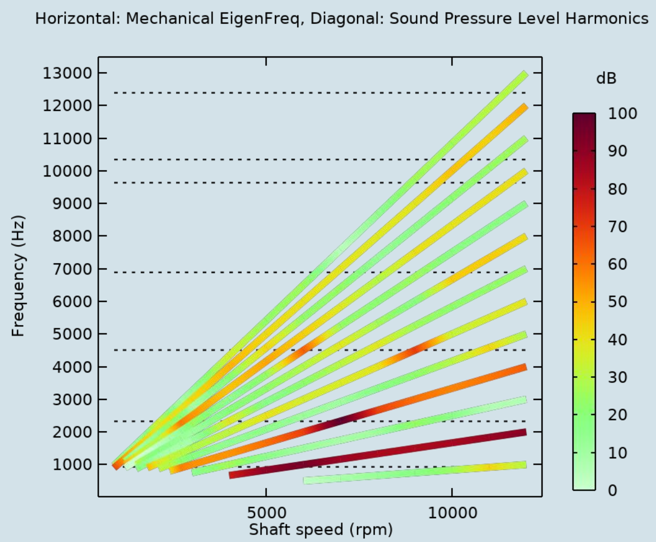


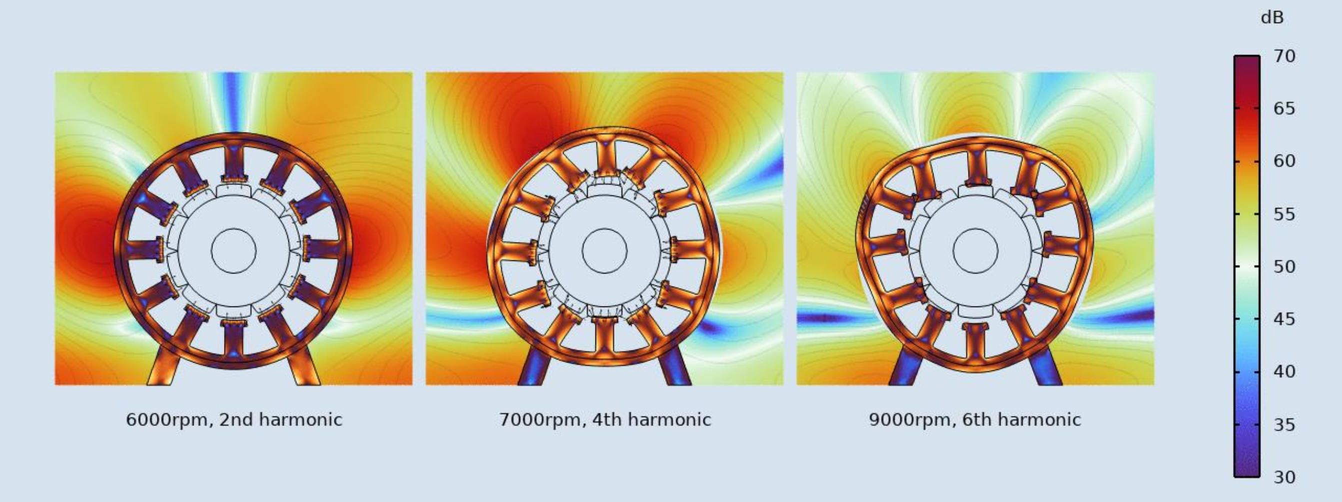


Going Beyond Thermal Efficiency

- Time-periodic electromagnetics can be one-way coupled to solid mechanics
  and acoustics — for a vibroacoustic analysis

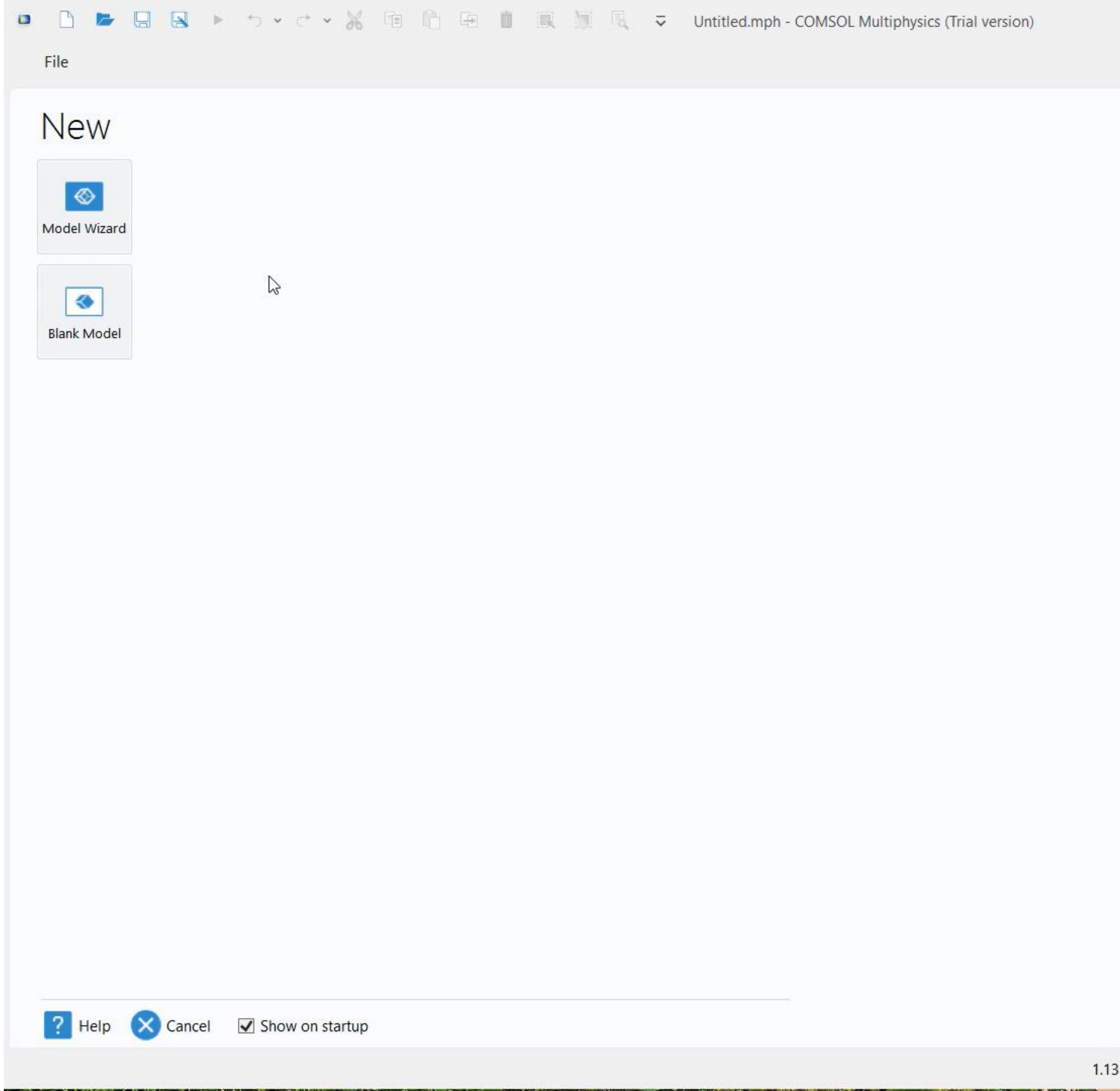
- The harmonics of the local electromagnetic force density can be extracted
  on the fly and directly coupled to a frequency-domain structural mechanics
  and acoustics analysis





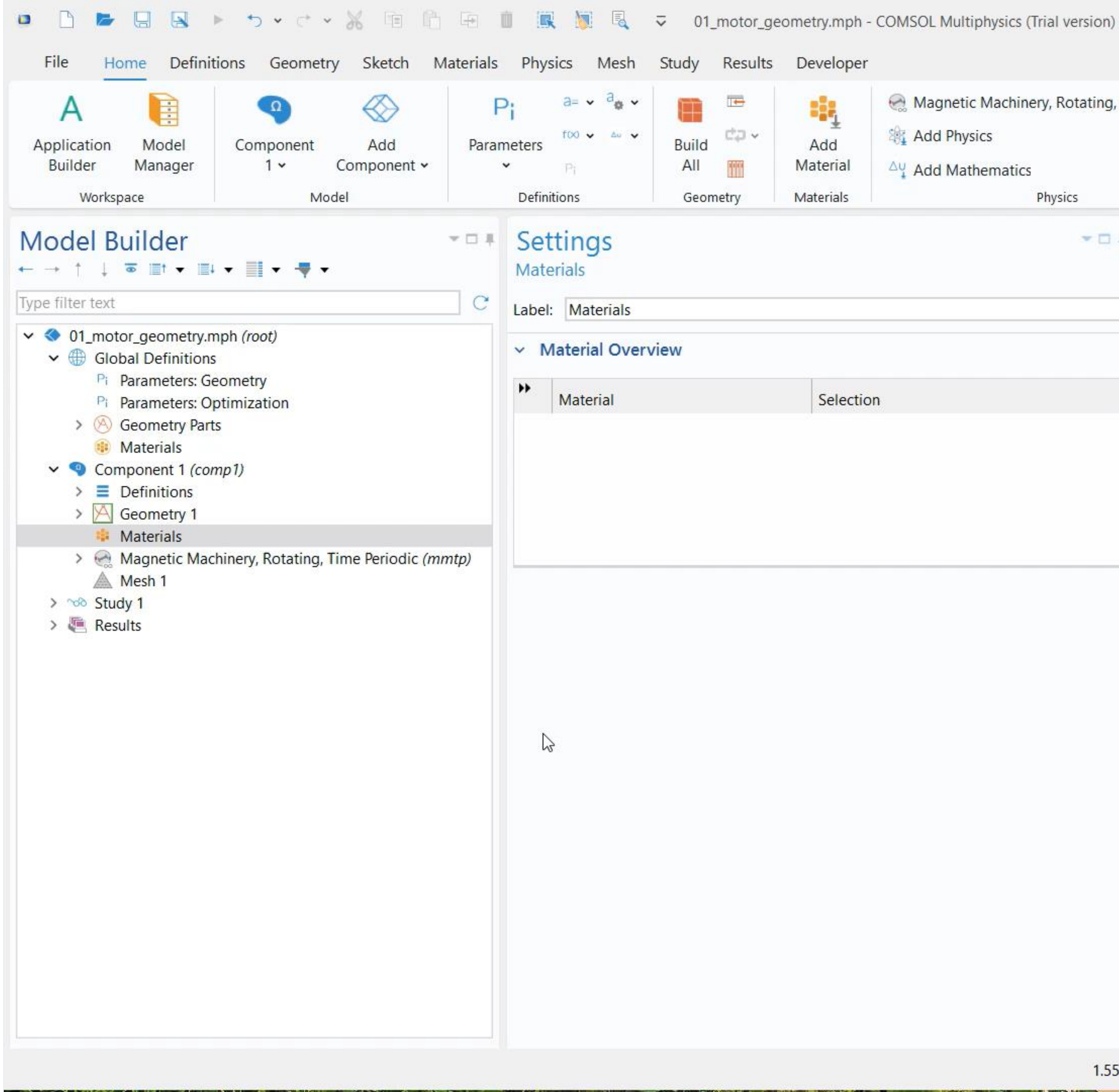
DEMO: Electric Motor Optimization

- Parametrized geometry



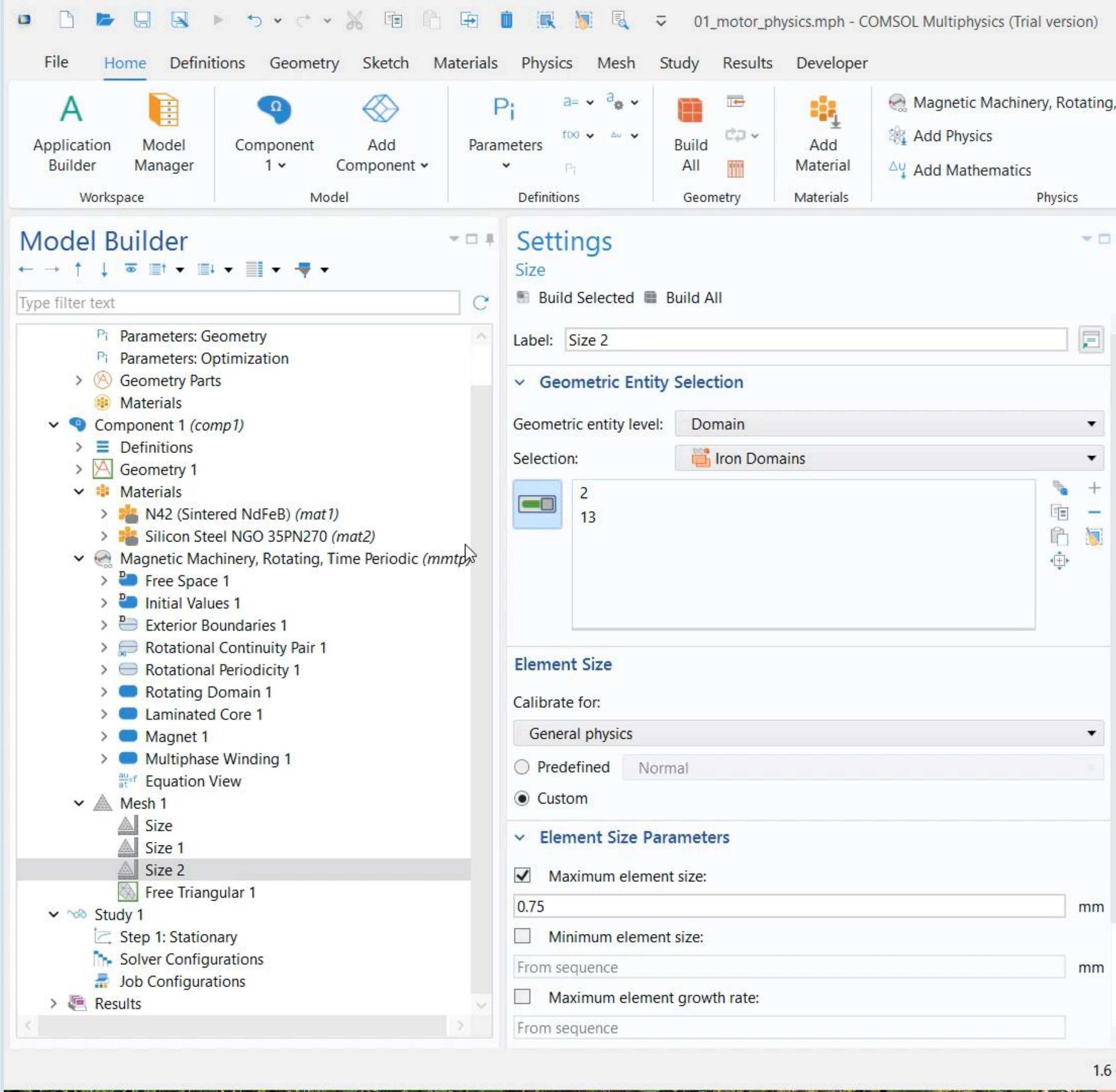
DEMO: Electric Motor Optimization

- Parametrized geometry
- Physics setup



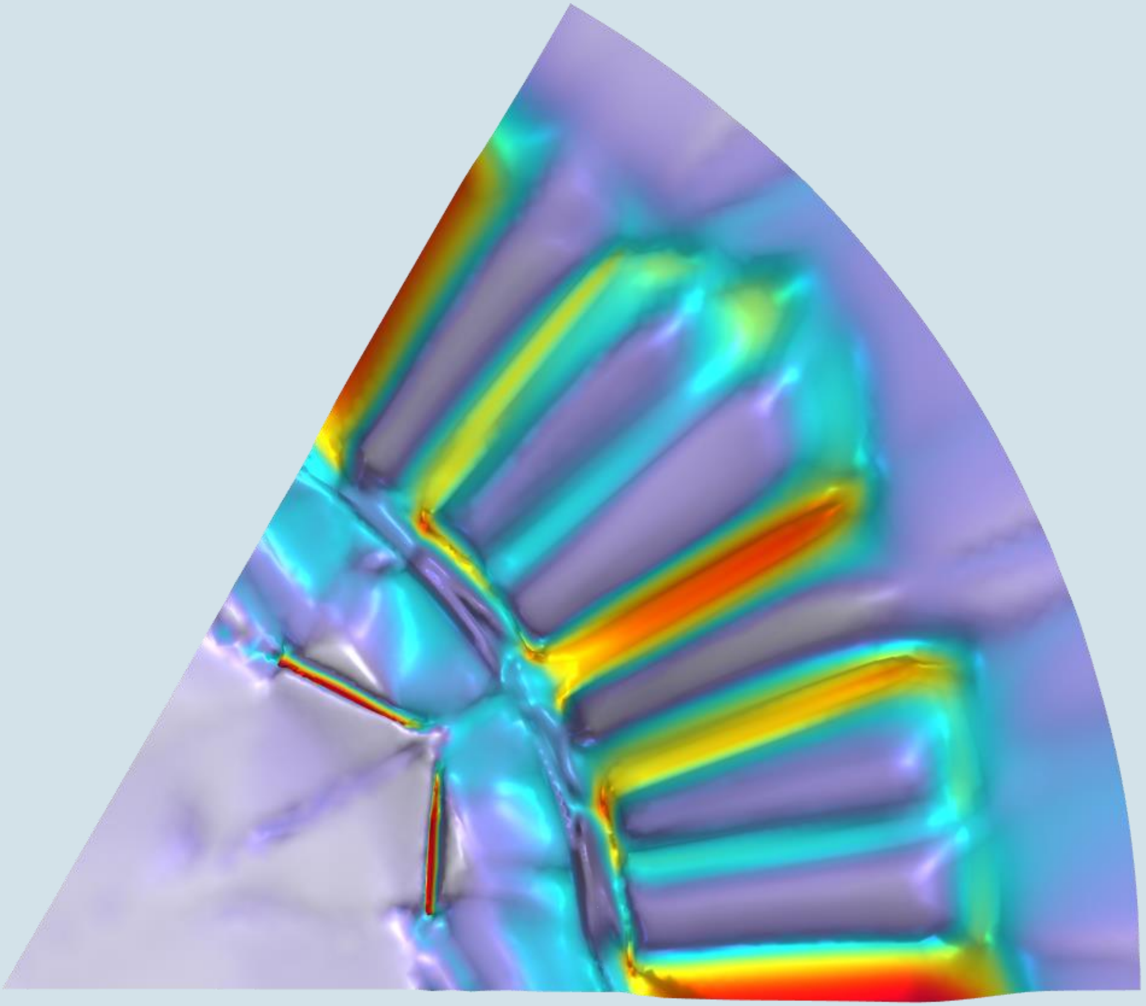
DEMO: Electric Motor Optimization

- Parametrized geometry
- Physics setup
- Optimization study



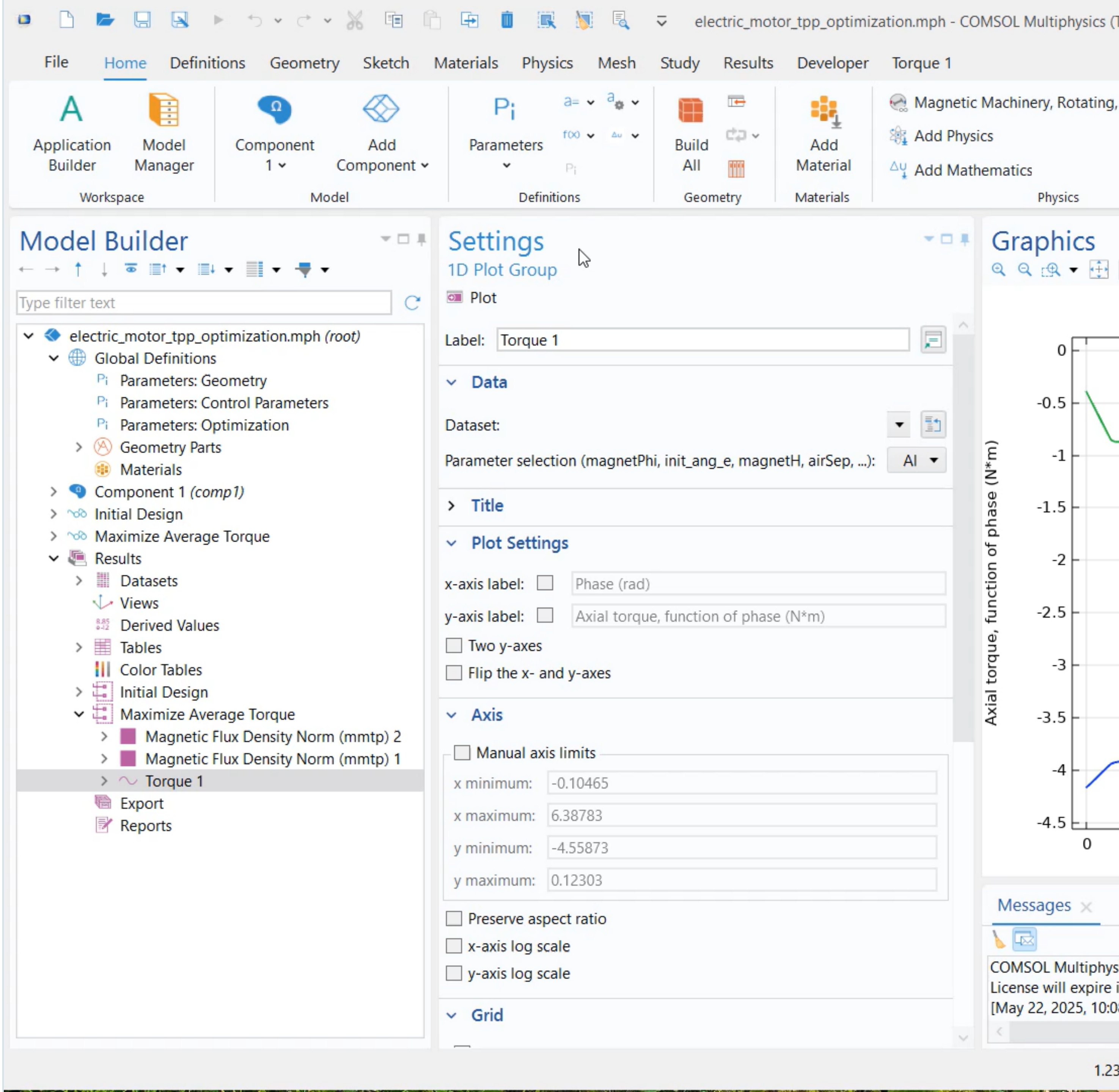
DEMO: Electric Motor Surrogate Model

- Parametrized geometry
- Physics setup
- Optimization study
- Surrogate model



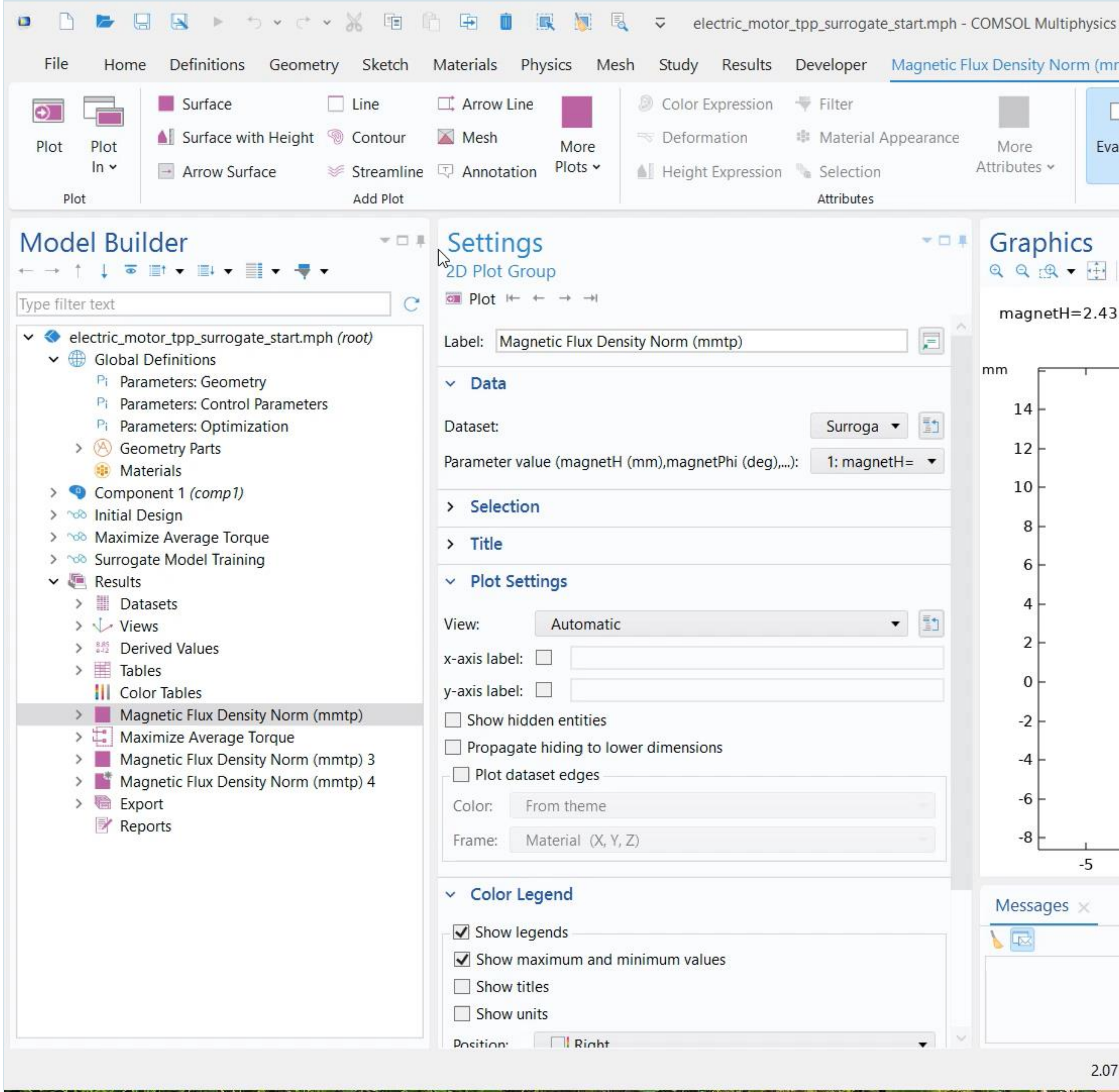
DEMO: Electric Motor Surrogate Model

- Parametrized geometry
- Physics setup
- Optimization study
- Surrogate model
  - Generating training data



DEMO: Electric Motor Surrogate Model

- Parametrized geometry
- Physics setup
- Optimization study
- Surrogate model
  - Generating training data
  - Training DNN's
    - Time period averaged torque
    - Spatial distribution of B-field



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- Parametrized geometry
- Physics setup
- Optimization study
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  - Generating training data
  - Training DNN’s
    - Time period averaged torque
    - Spatial distribution of B-field
  - Improve
    - Create more DNN’s representing different geometry domainds