Induction Heating
Multiphysics Simulation with JMAG

JMAG User's Conference
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Agenda

- Induction Heating
  - Fundamentals of Induction Heating
  - Application and Challenges
- FEA-Simulation
  - Advantages
  - JMAG Capabilities and Benefits
- Volvo Case Study
  - Study Setup: Custom Rotor Material
  - Study Setup: Coupled Analysis Multiphysics: Frequency and Thermal Analysis
  - Optimization Parameters and Objectives
- Key Takeaways

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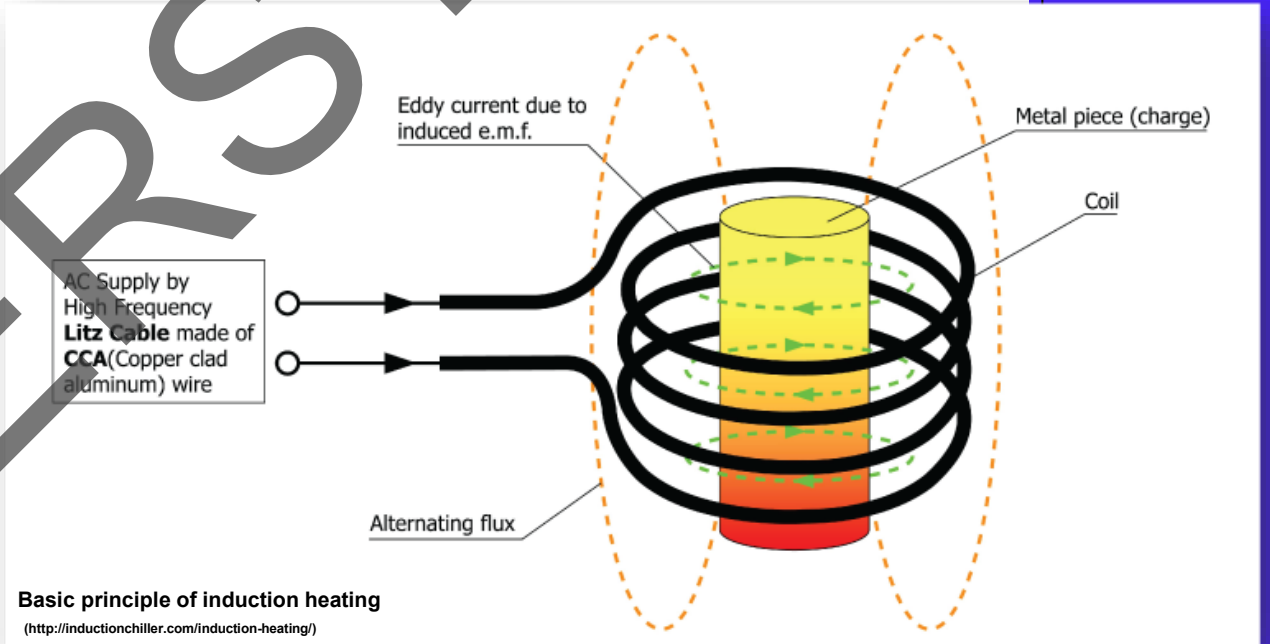
Fundamentals of Induction Heating
Electromagnetic and Thermal Effects

Electromagnetic effects

- Alternating coil current generates a changing magnetic field.
- The alternating field causes **eddy currents** in the conductive workpiece to flow.
- Eddy currents heat up the work piece.
- Penetration depth varies with frequency: lower frequencies penetrate deeper.

Thermal effects

- Heat conducts from the heated region into the component.
- Material properties change with temperature, influencing heating behaviour.
- Heating rate and temperature gradients affect distortion and residual stress.



Basic principle of induction heating

(http://inductionchiller.com/induction-heating/)

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Application of Induction Heating

- **Automotive:** Surface **hardening** of gears, shafts, camshafts and transmission parts; **shrink-fitting** bearings and rotors.
- **Aerospace:** Brazing and repairing turbine blades, preheating titanium components, and bonding composite structures.
- **Metalworking:** Heating steel or aluminium billets before forging; **melting**, **annealing**, tempering and stress relieving.
- **Energy:** Preheating and post-weld heat treatment of pipelines; hardening large wind-turbine gears and bearing rings.
- **Semiconductors:** Melting high-purity silicon, crystal growth and controlled wafer annealing.
- **Electronics:** Precision **soldering** and brazing of connectors, terminals and conductive assemblies.
- ...



Heated rotor

(https://vividmetrawattglobal.com/blogs/what-is-induction-heating-for-large-rotors/)

Main objective: Achieve a uniform target temperature with minimal energy and distortion

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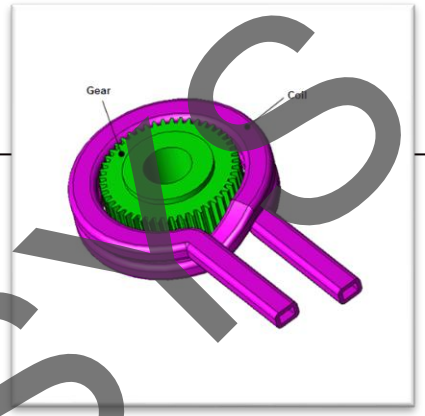
Challenges

- **Overheating:** May cause undesirable microstructural changes or surface damage.
- **Uneven temperatures:** Poor coil design can create hot and cold spots.
- **Deformation:** Rapid, non-uniform heating and cooling can deform the component.
- **Energy efficiency:** Coil position, frequency and power strongly affect losses.
- **Process costs:** Scrap, rework, cycle time and energy consumption drive total cost.

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Advantage of Simulation

Predict	Identify hot spots and uneven heating
Optimize	Refine coil geometry, position and operating settings
Reduce Risk	Reduce prototypes, overheating and development cost



Induction heating coil optimization, surface hardening

(https://www.jmag-international.com/catalog/233_ih_optimization//)

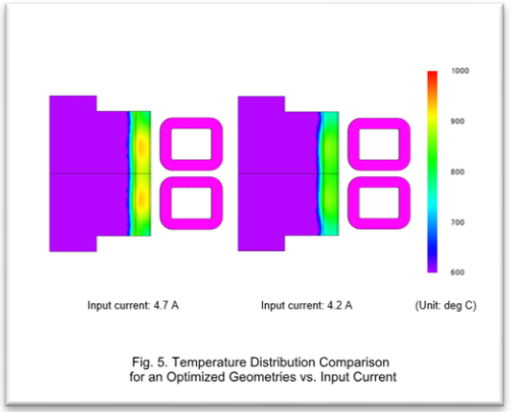


Fig. 5. Temperature Distribution Comparison for an Optimized Geometries vs. Input Current

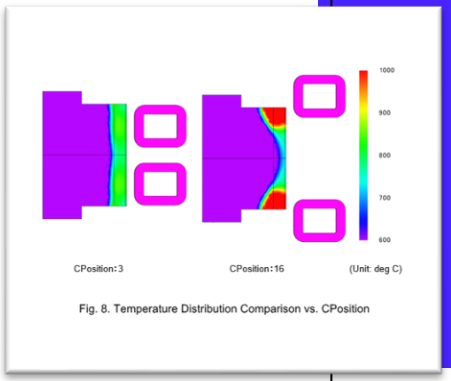


Fig. 8. Temperature Distribution Comparison vs. CPosition

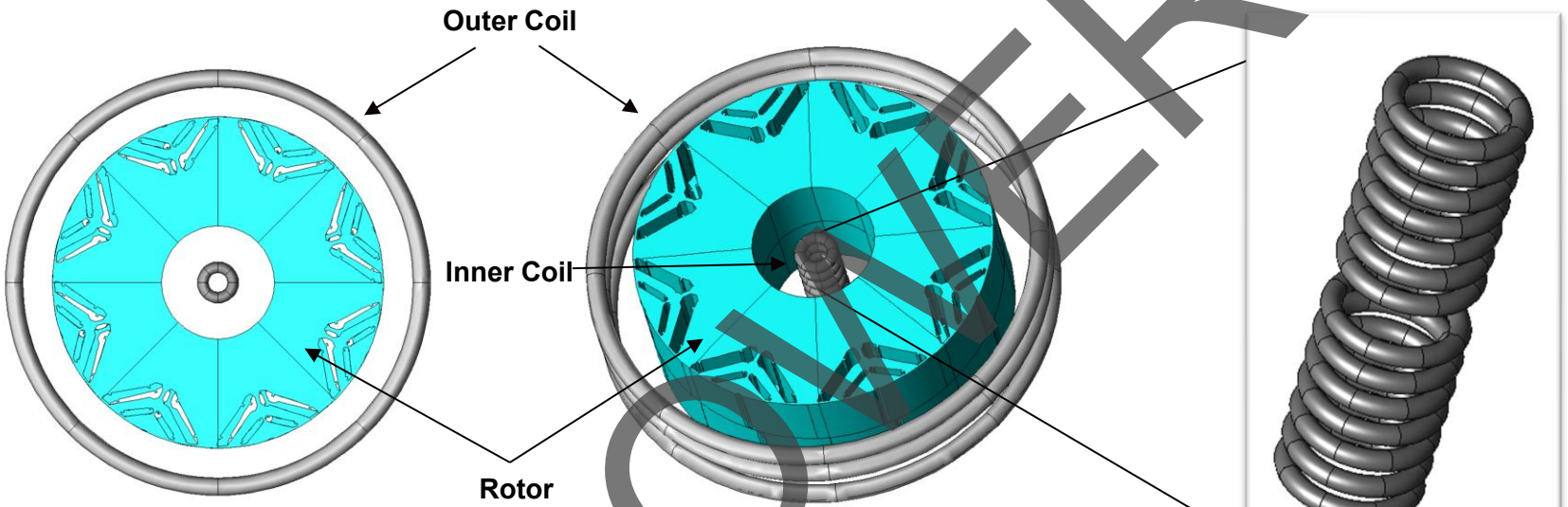
JMAG combines electromagnetic accuracy, multiphysics coupling and automated optimization in one workflow.

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Volvo Case Study

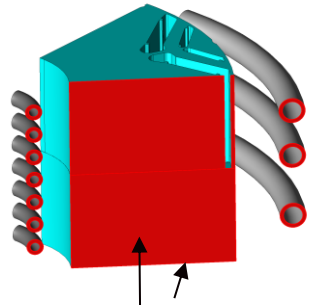
Application: Shaft press fitting

Optimization of induction heating coil to reach uniform temperature distribution at inner rotor surface



Optimization Target: Inner Coil

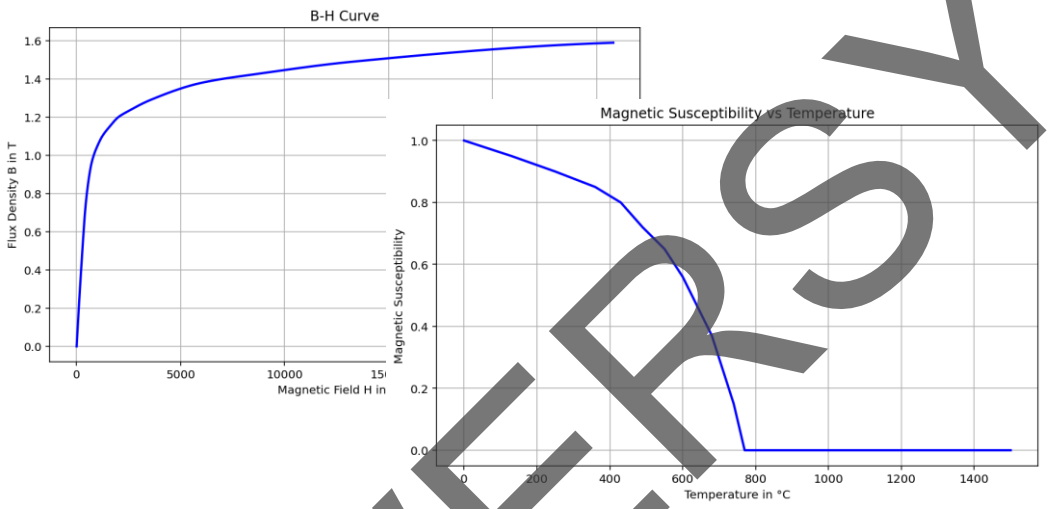
Partial model



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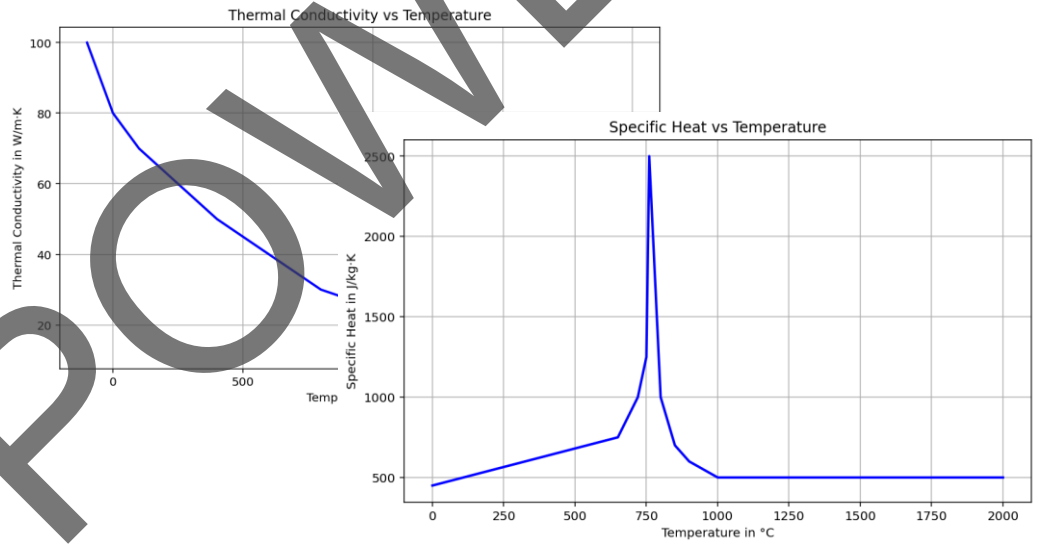
Study Setup: Custom Rotor Material

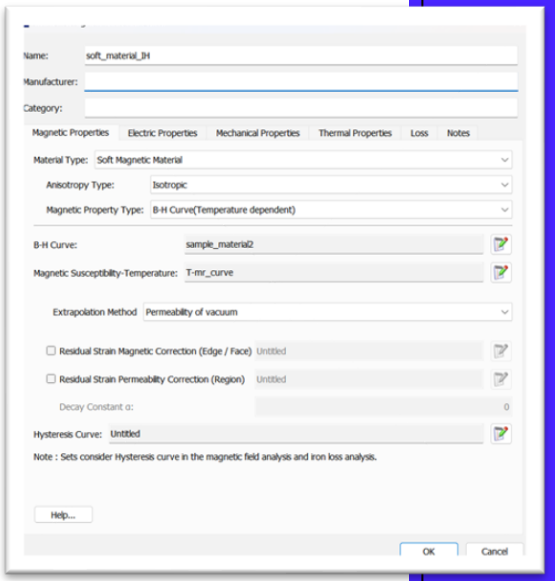
Magnetic properties:



JMAG Material Editor

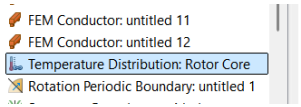
Thermal properties:





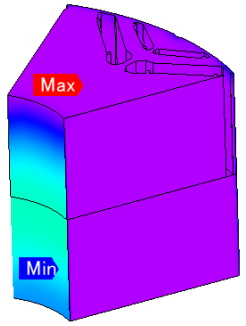
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Study Setup: Coupled Analysis Multiphysics



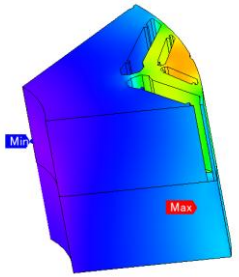
Frequency Analysis

Input Parameter:
Current Amplitude and Frequency



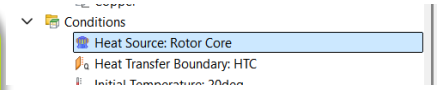
Rotor Temperature Distribution

Rotor Joule Loss Density



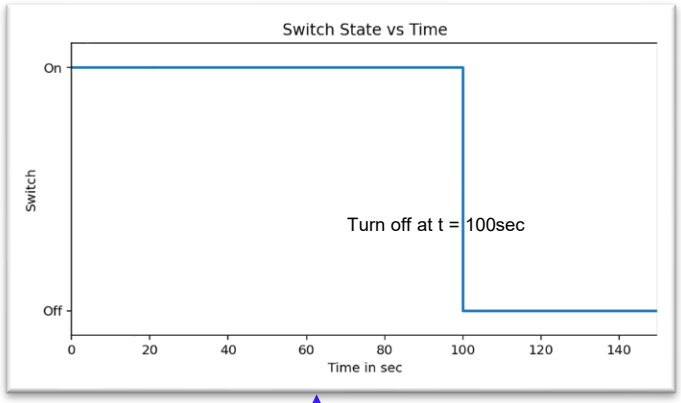
Thermal Analysis

Output Parameter:
Temperature Distribution of Rotor Core

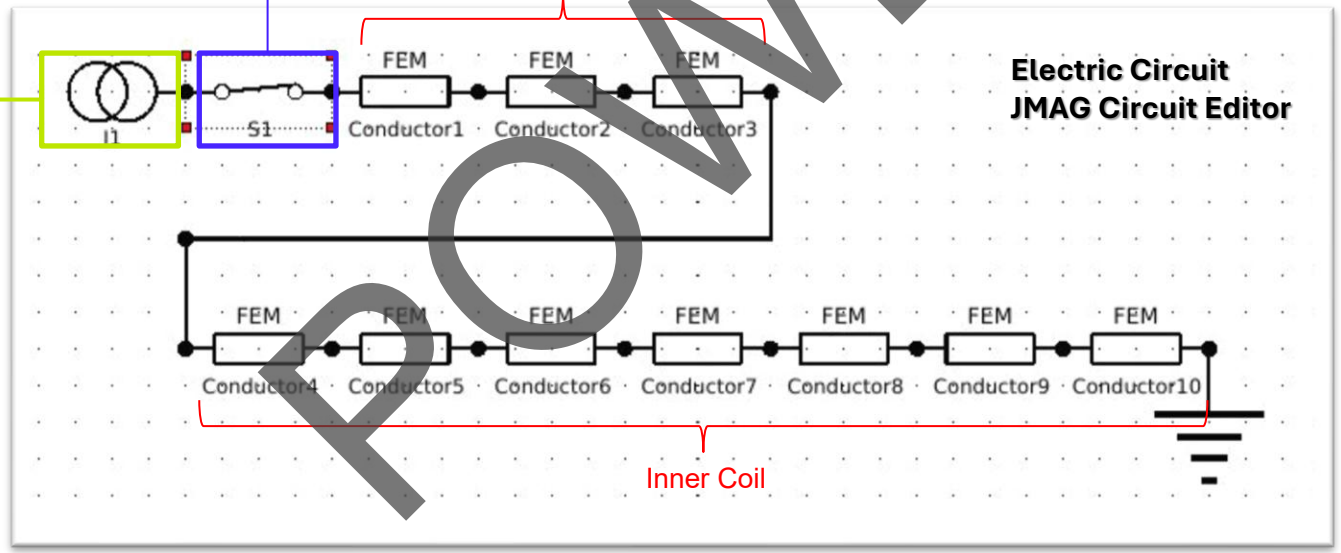


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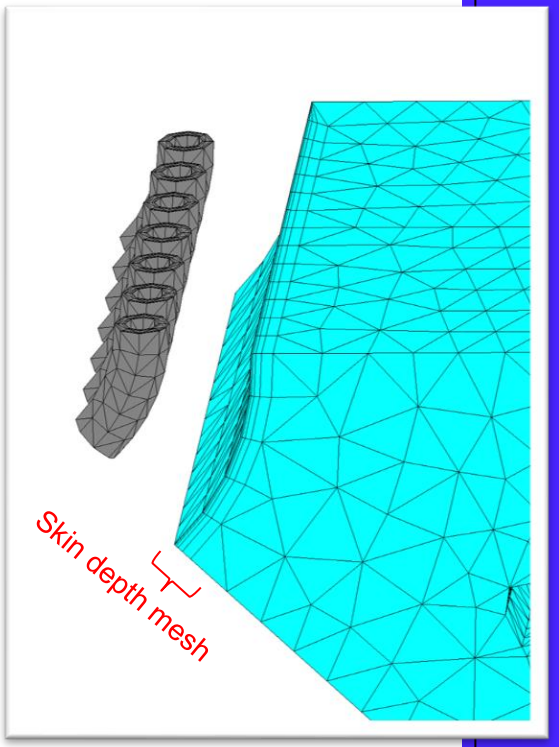
Study Setup: Frequency Analysis

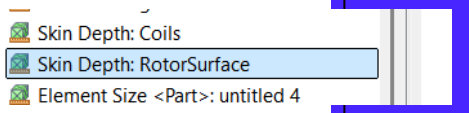


Set Current Amplitude and Frequency



Mesh Model





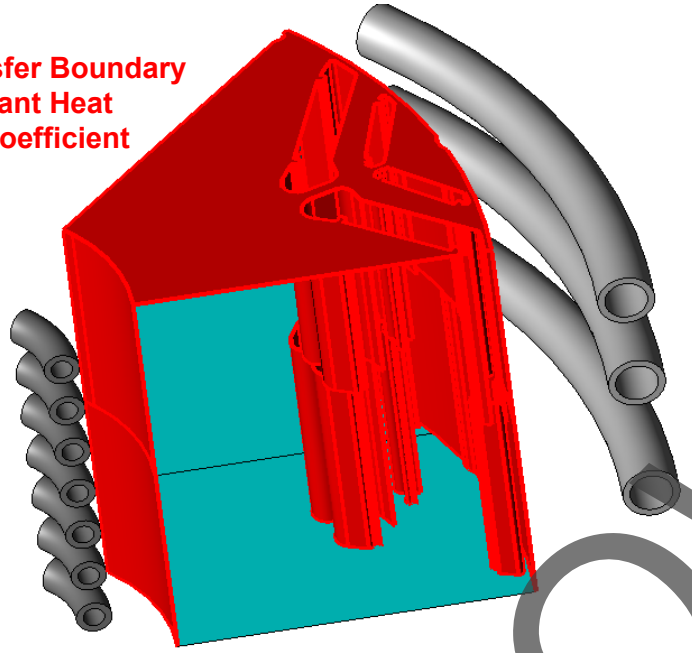
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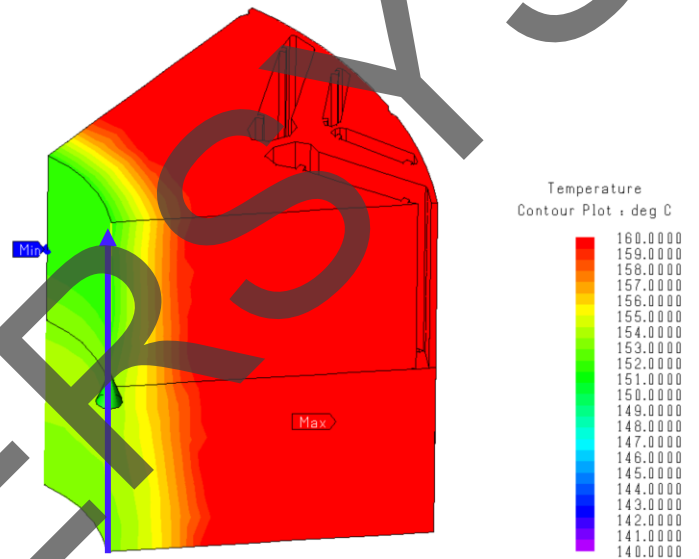
Study Setup: Thermal Analysis

Time step: 20 sec

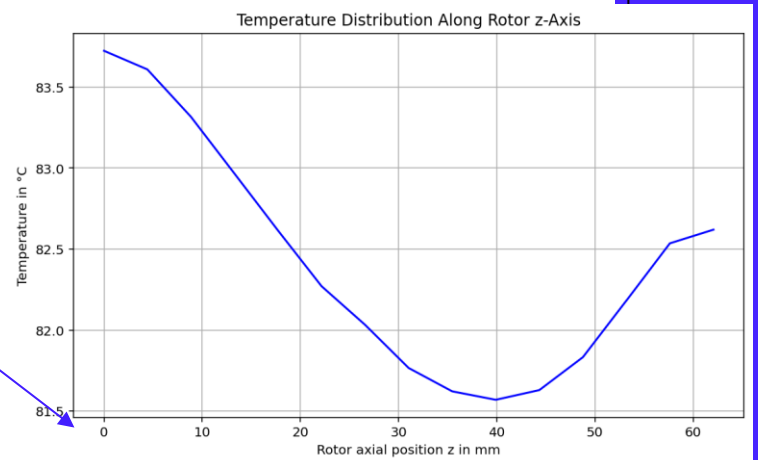
Number of steps: 6

Heat Transfer Boundary with constant Heat Transfer Coefficient





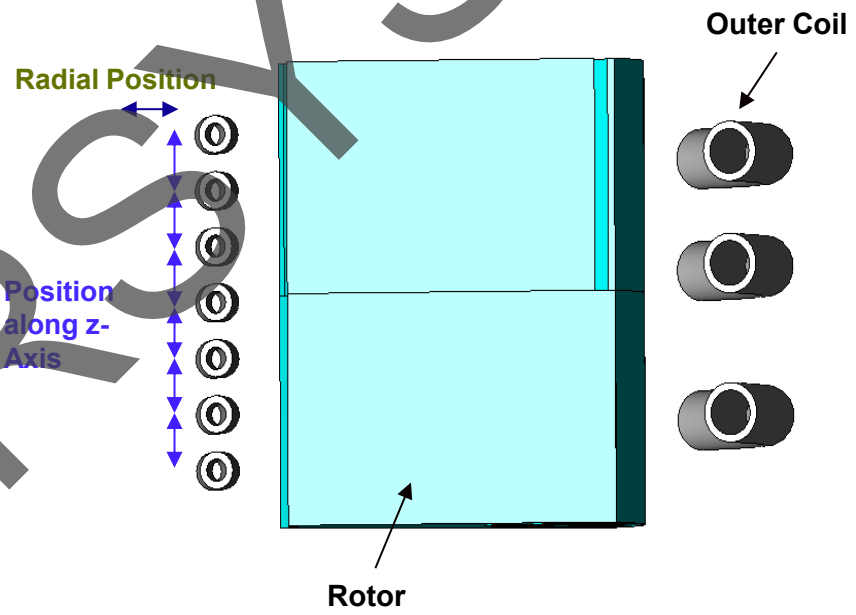
Section Graph along z-Axis



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Optimization Parameters and Objectives

- Electric Parameter
  - Frequency 20 – 50 kHz
  - Current Amplitude 400 – 900 A
- Geometrical Parameter
  - Radial Position 5.1 – 23.4mm
  - Relative Position along z-Axis 5.1 – 31.5mm



Objective:
Minimize temperature range along section at t = 120sec

Constraint:
Temperature of rotor surface > 150 °C

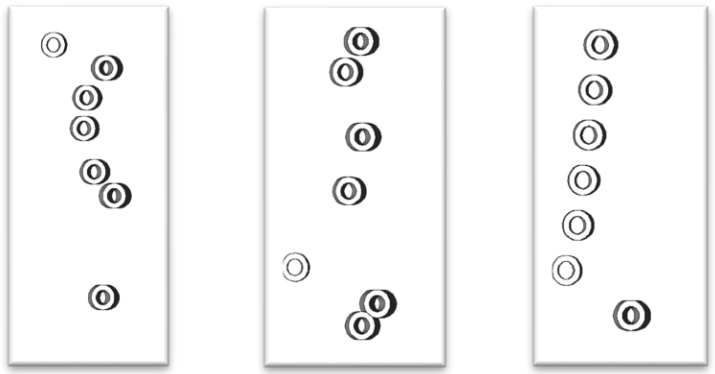
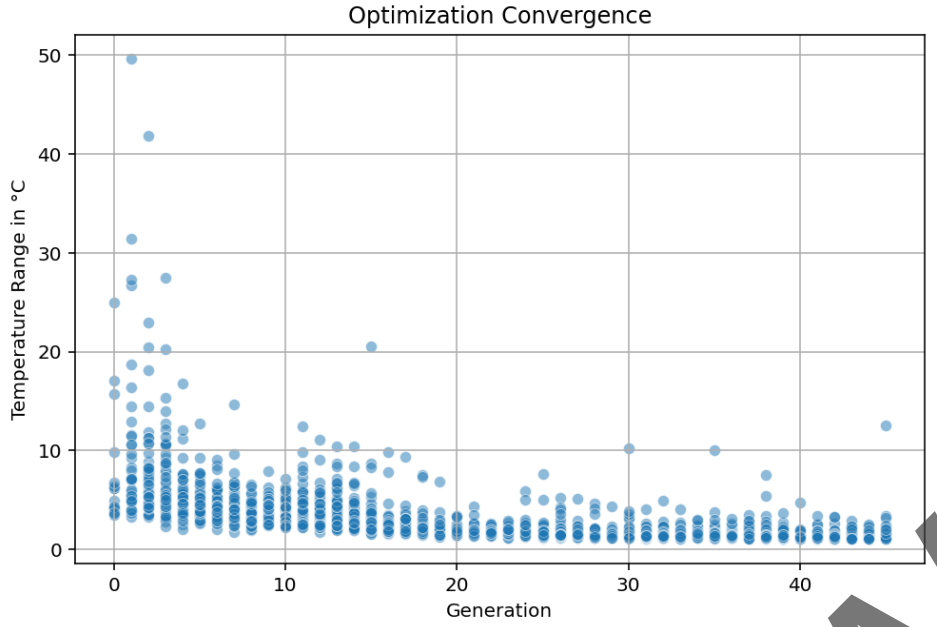


Illustration of Design Space

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Optimization: Multi-Objective Genetic Algorithm

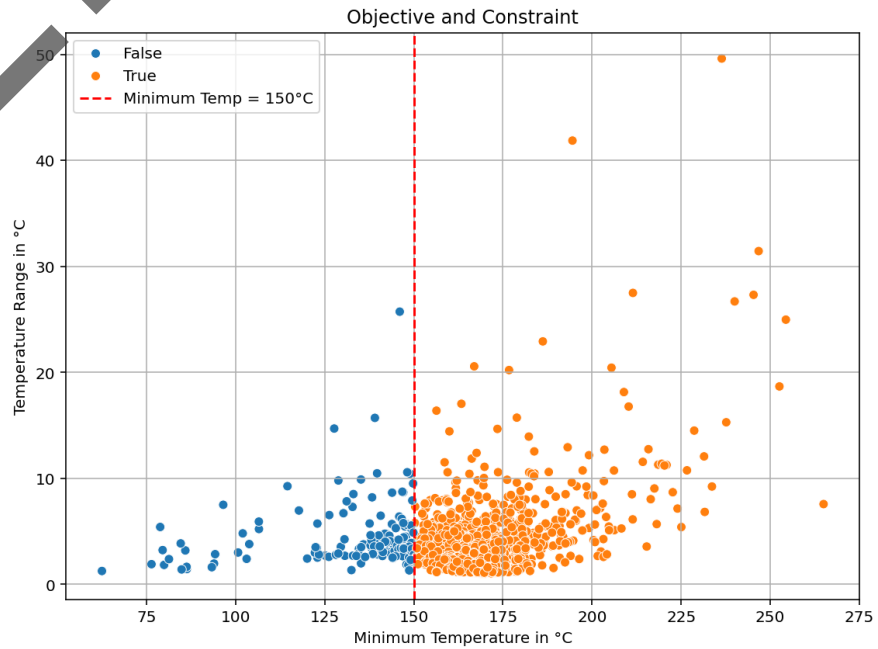


Generations 46

Population Size 56

Total Designs 2563

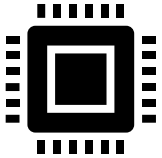
Feasible Designs 2404



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Optimization: Cluster Environment

License: PSL200

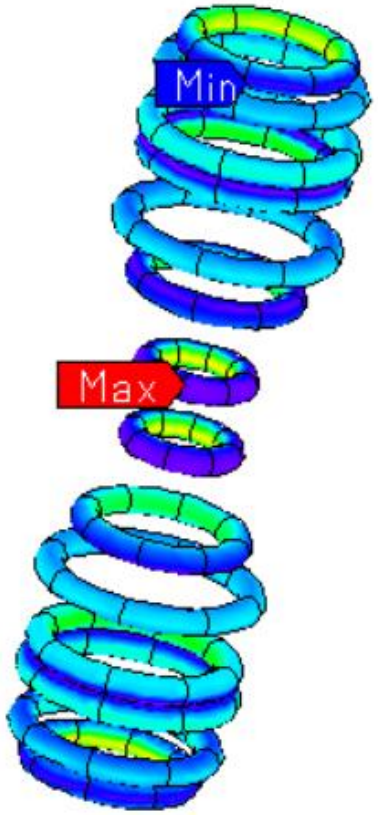


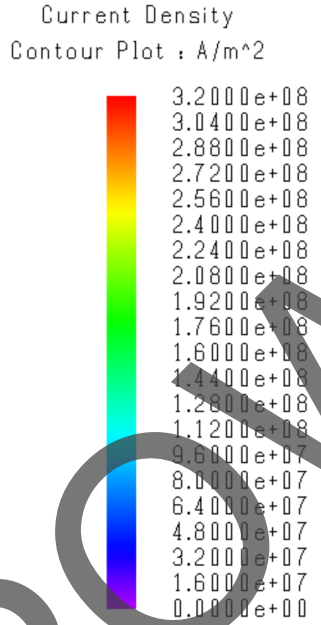


Compute Resources	Parallel Execution	Total Runtime
448 Cores	56 Designs x 8 cores each	~ 17 hours
7 Nodes x 64 cores	Simultaneously	One Design ~20min

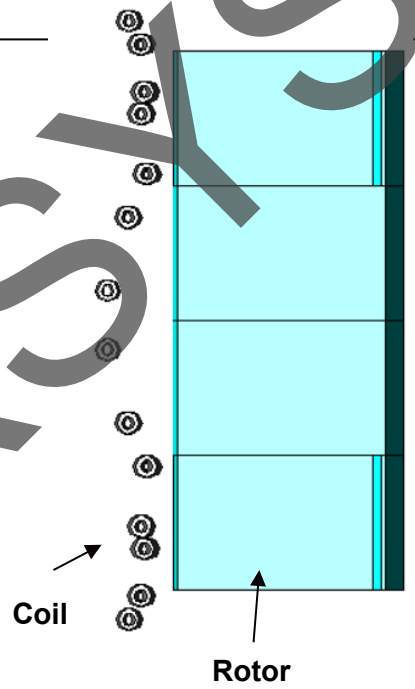
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Results: Optimized coil shape





Current density distribution in the optimized inner coil, Full model conversion on



Full model conversion on (axially)

radiusCoil1	8,9	posCoil1	6,8
radiusCoil2	13,9	posCoil2	16,9
radiusCoil3	18,3	posCoil3	10
radiusCoil4	17	posCoil4	13,9
radiusCoil5	17,8	posCoil5	5,1
radiusCoil6	16,9	posCoil6	10,9
radiusCoil7	14,1	posCoil7	5,2

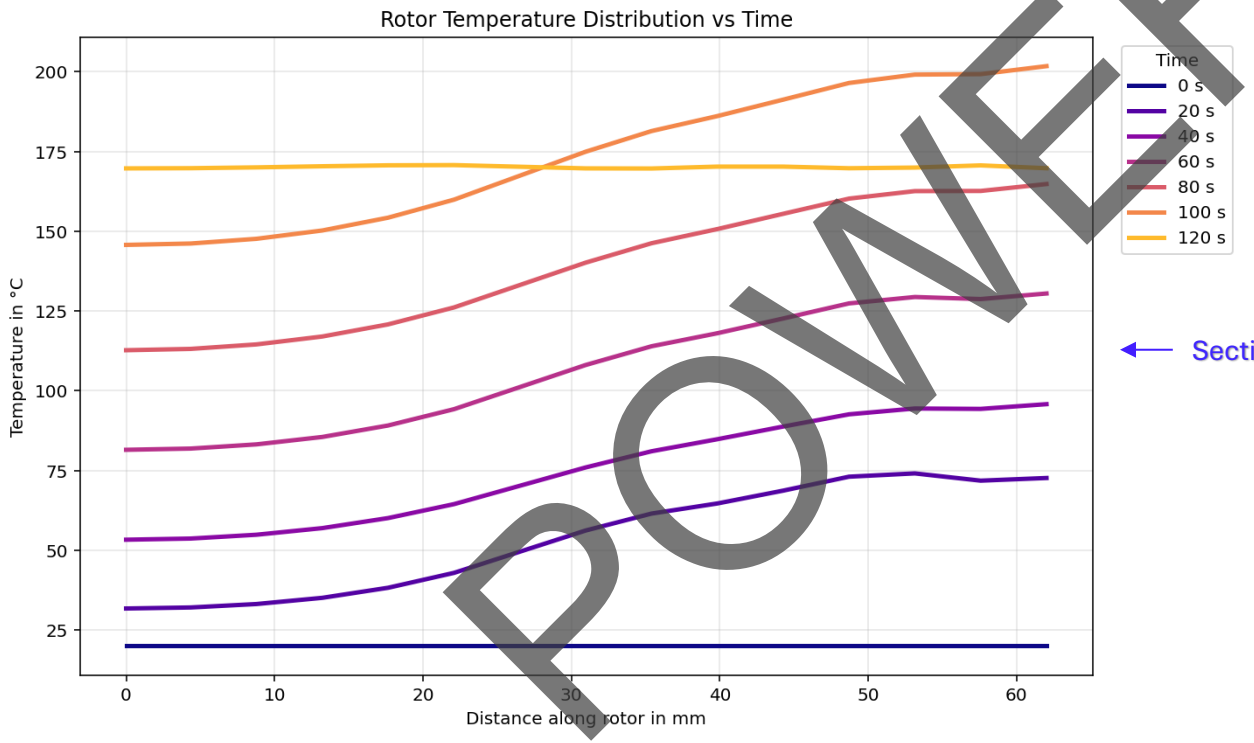
Optimized coil position relative to the rotor in mm

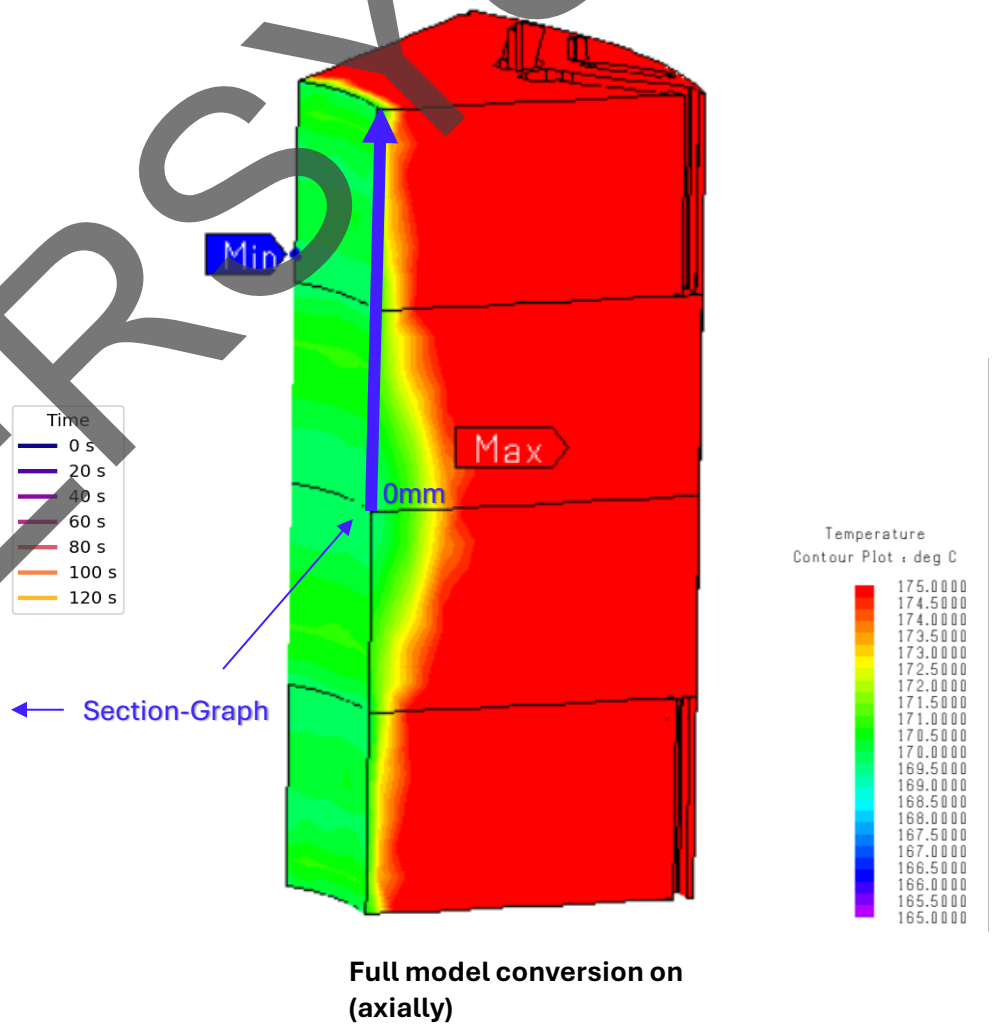
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Result: Best Case

At t = 120 sec

Minimum temperature	169 °C
Temperature range	1.03 °C
Current Amplitude	769,11 A
Frequency	26,577 kHz





Full model conversion on (axially)

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Key Takeaways and Next Steps

- ✓ **Induction heating connects electromagnetic and thermal effects.**
- ✓ **Heating quality is critical.**
- ✓ **Simulation allows coil designs to be tested before manufacturing.**
- ✓ **JMAG provides capabilities to simulate effects and optimize coil shape to enhance quality and reduce cost.**
- ✓ **Optimization varies both geometry and operating parameters.** Coil radius, axial position, frequency and current amplitude are varied to reduce temperature variation while meeting a minimum-temperature objective.

Next steps

Include Outer Coil in Optimization
Topology Optimization
Validate with measurement results

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THANK YOU

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