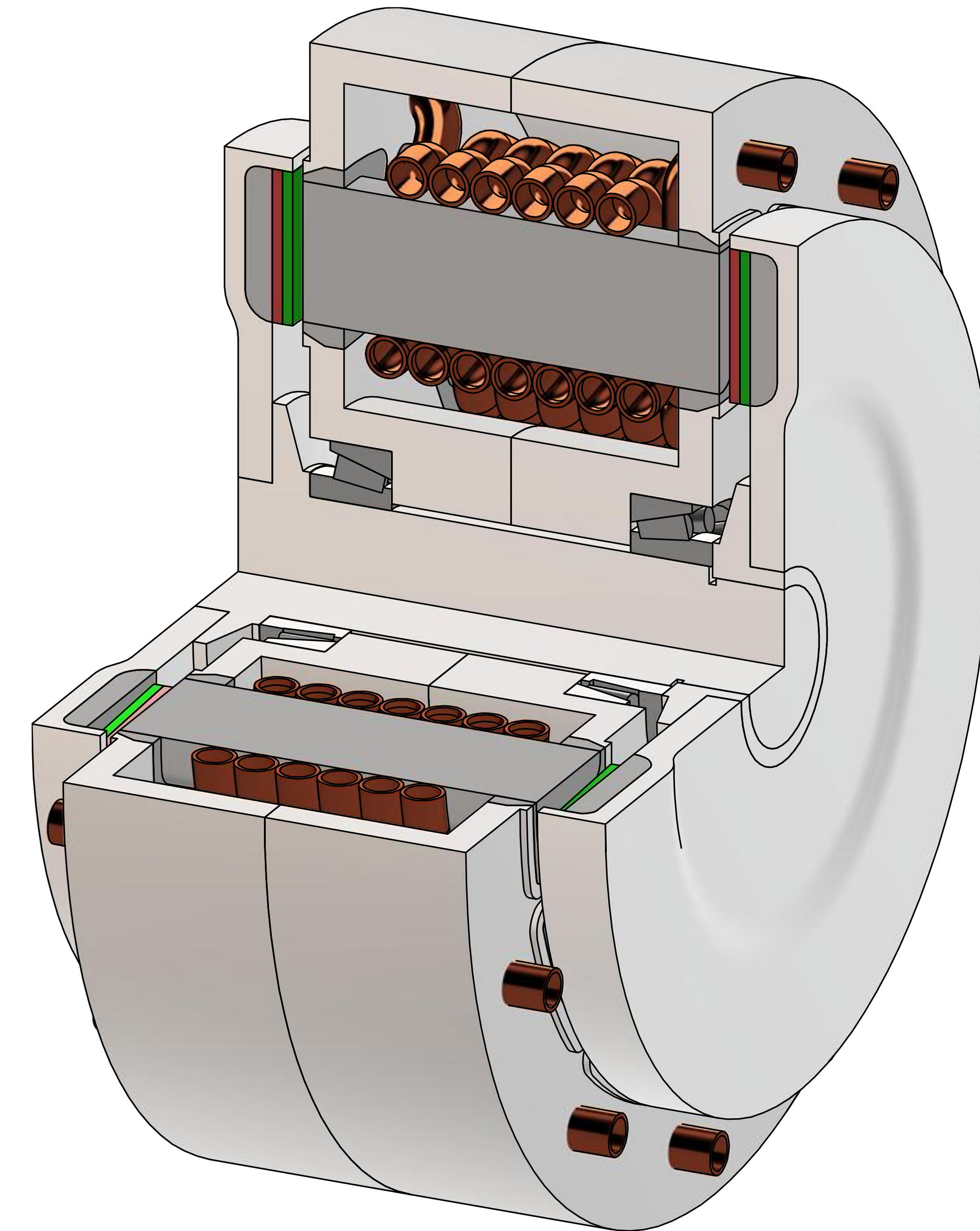


Unlocking High Power Density

Validating Novel Conductor Topologies and
Cooling Concepts for Axial-Flux Machines

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The Race to Optimal Performance

Thermal Design is Crucial

- high power density (>30kW/kg)
- high overload capability
- high efficiency
- predictable lifespan

Highest Optimization Potential: Coil Unit

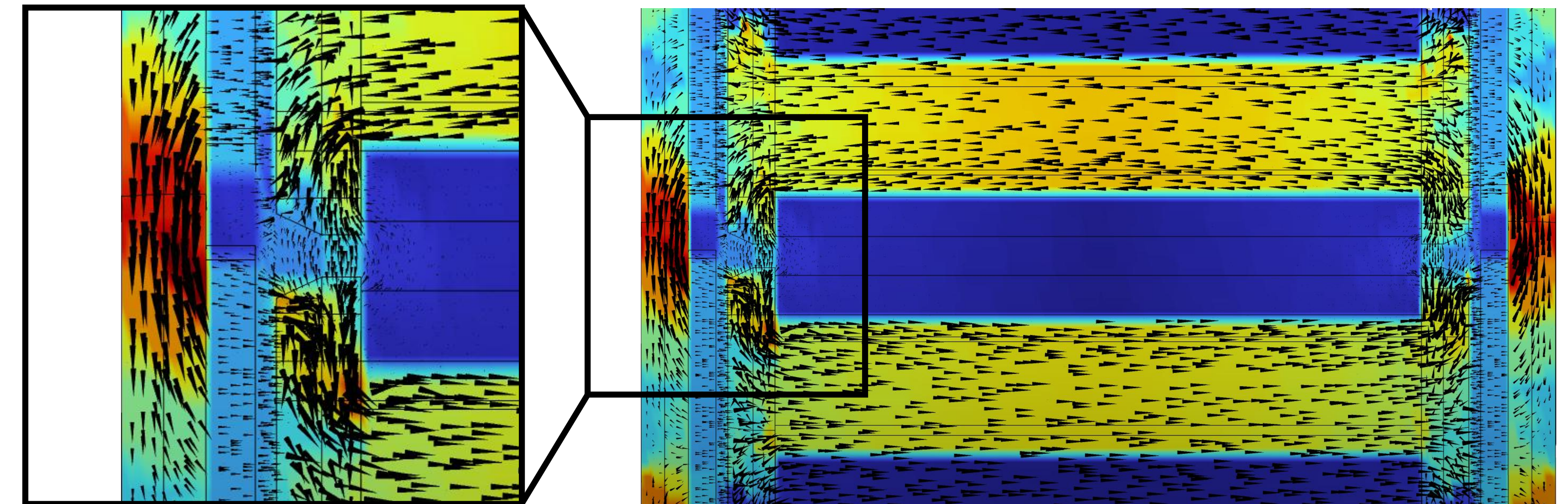
- conductor topology (wire, bar / rod, hollow, stranded)
- cooling concept
- core material
- winding material



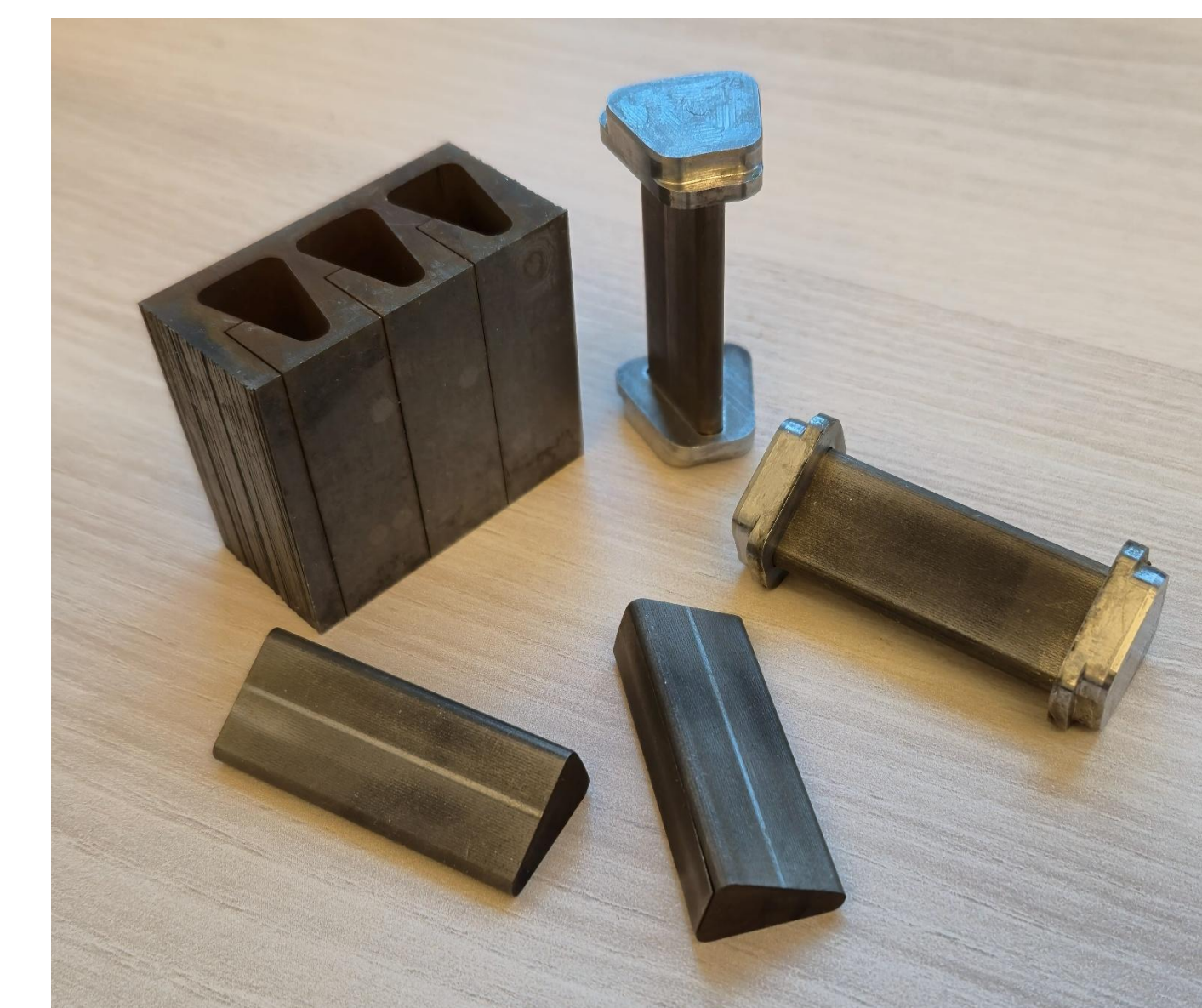
Source: [YASA smashes own unofficial power density world record pushing state-of-the-art electric motor to staggering new 59kW/kg benchmark](#)

A Multiphysical Problem

- Many physical interactions
- Many unknown quantities:
 - flux density distribution (air gap and stray flux)
 - high-frequency losses, thermal contact resistances
- Need for empirical measurements to validate and refine models and metamodels
- Real-world manufacturing processes change material characteristics:
 - stacking and baking
 - grinding and etching
 - wire EDM



Flux distribution in an axial-flux permanent magnet machine with stray flux



Manufacturing leaves a mark!

Modular System Architecture

Test Bench for Axial-Flux Coil Units

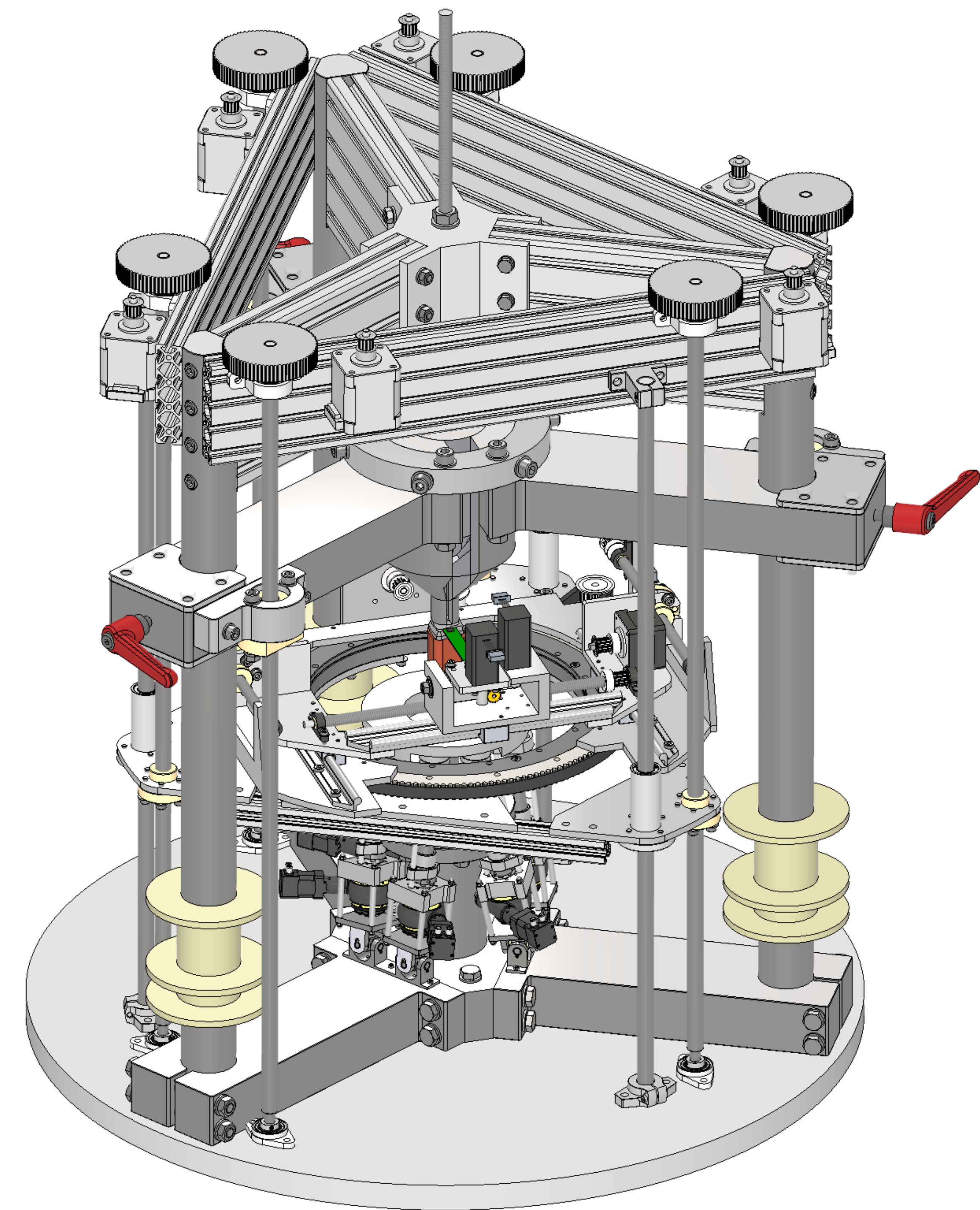
Integrated into Power-Hardware-in-the-Loop laboratory

(PHILsLab @ Hamburg University of Technology):

- 1000V DC or 300V AC power supply
- 1000V, 1.2MS/s 6-channel power analyzer
- RT HIL control and PLC control

Key facts:

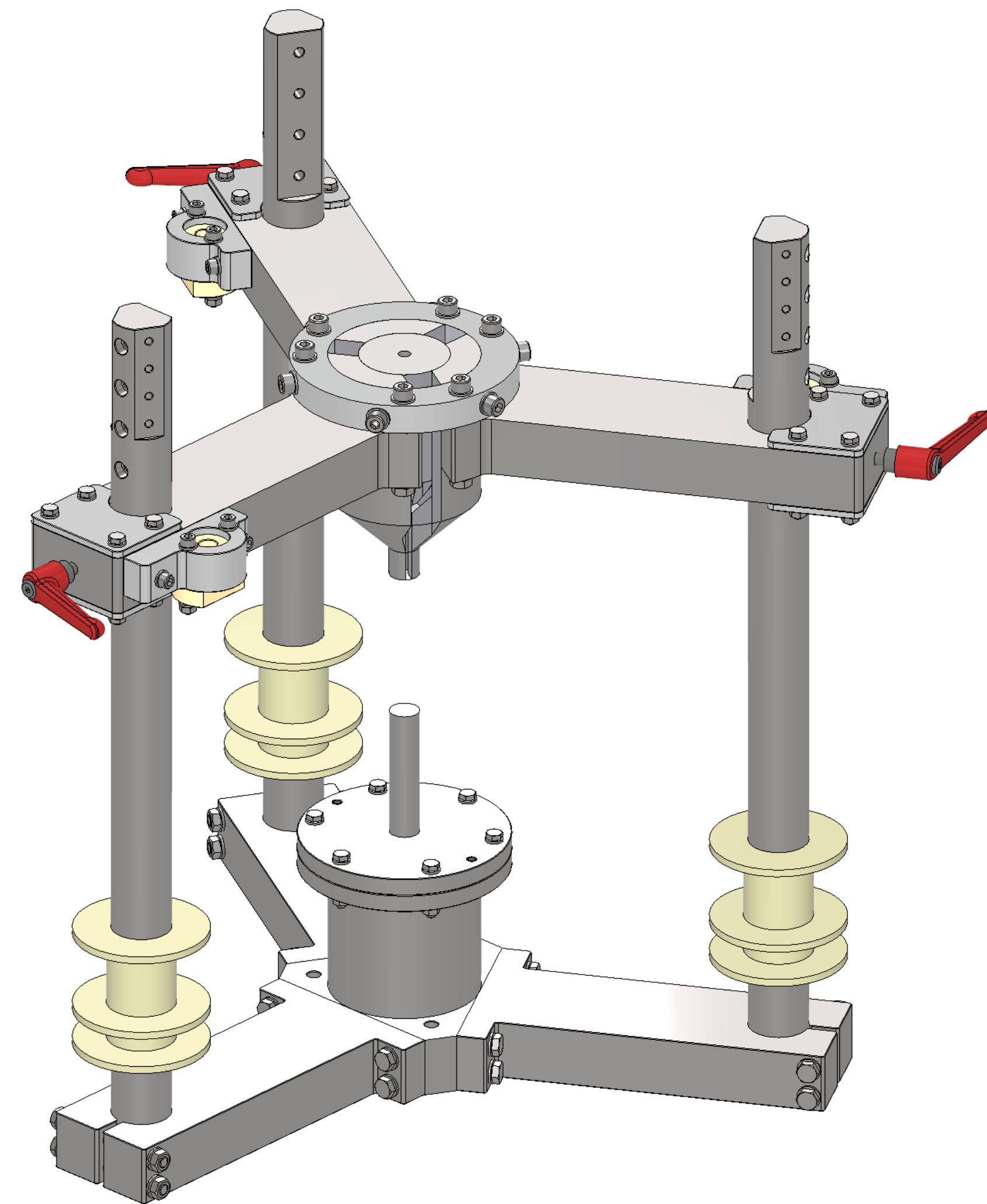
- 50mm x 50mm x 100mm coil unit size
- arbitrary excitation (up to 1000V DC, 300V AC up to 30kHz)
- up to 1.2MS/s measurements
- 4T, 3-DoF Hall probe
- 2.5kN hexapod with 6-DoF force sensor
(x/y: 50mm, z: 15mm)



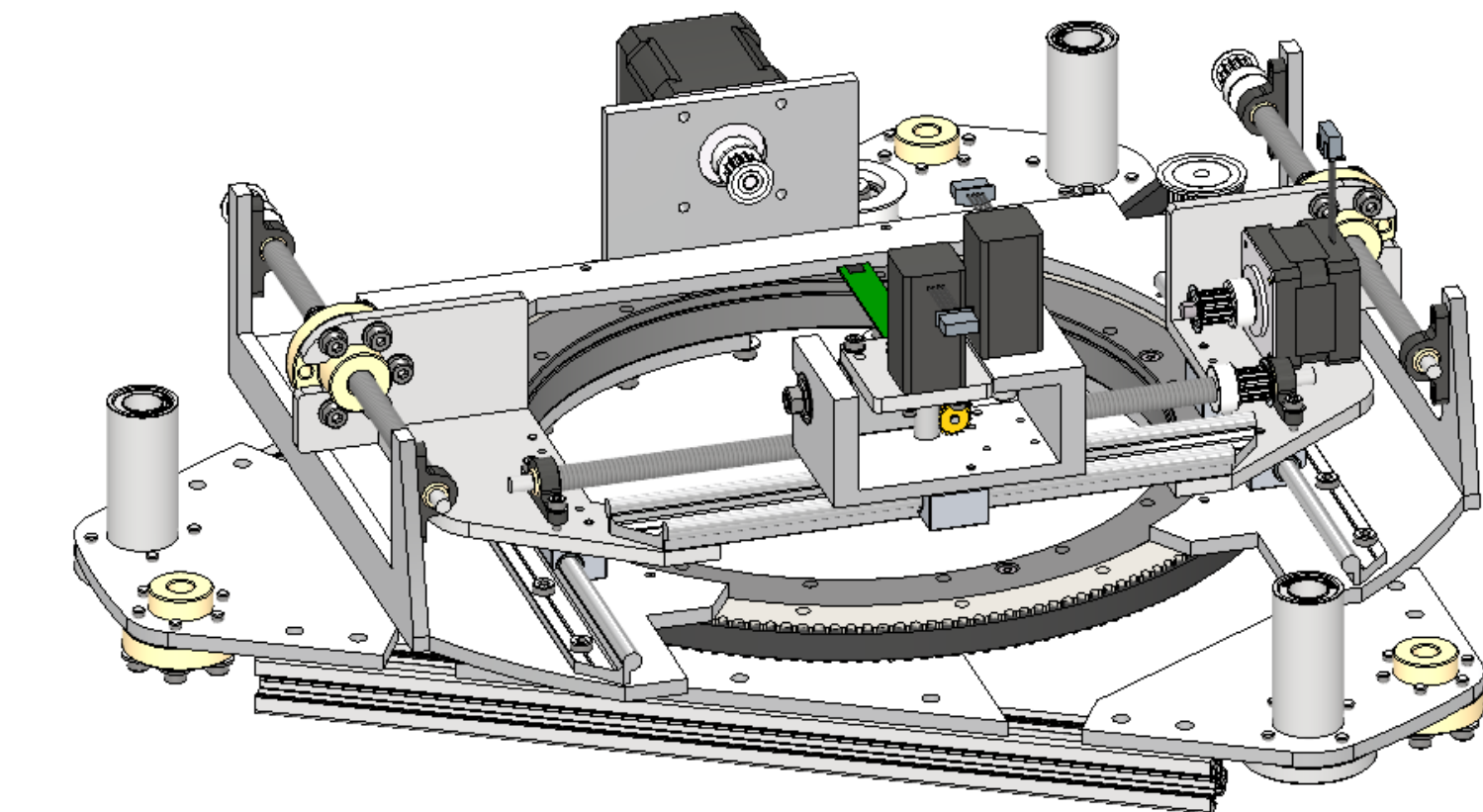
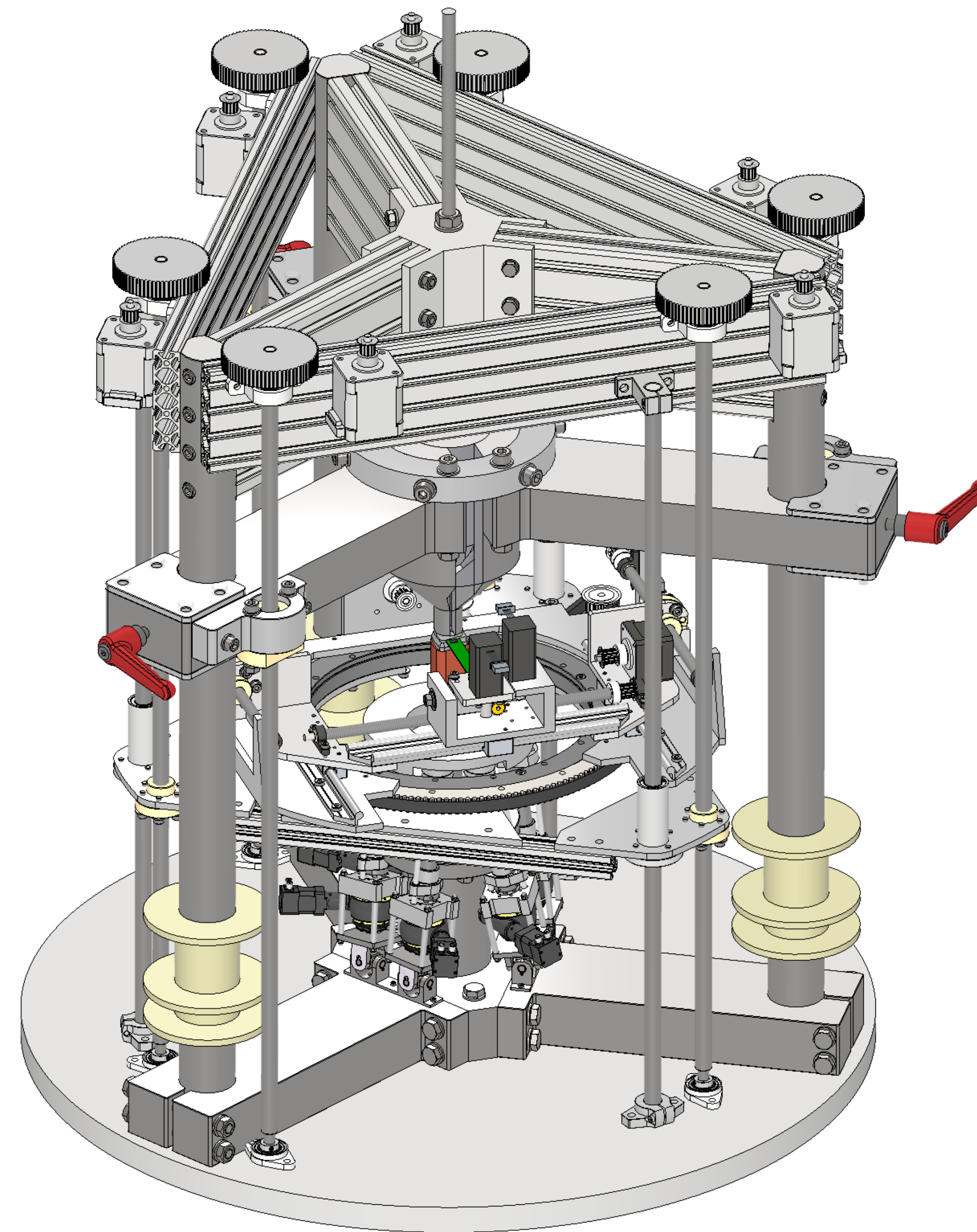
Coil Unit Test Bench with all subassemblies

Coil Unit Test Bench

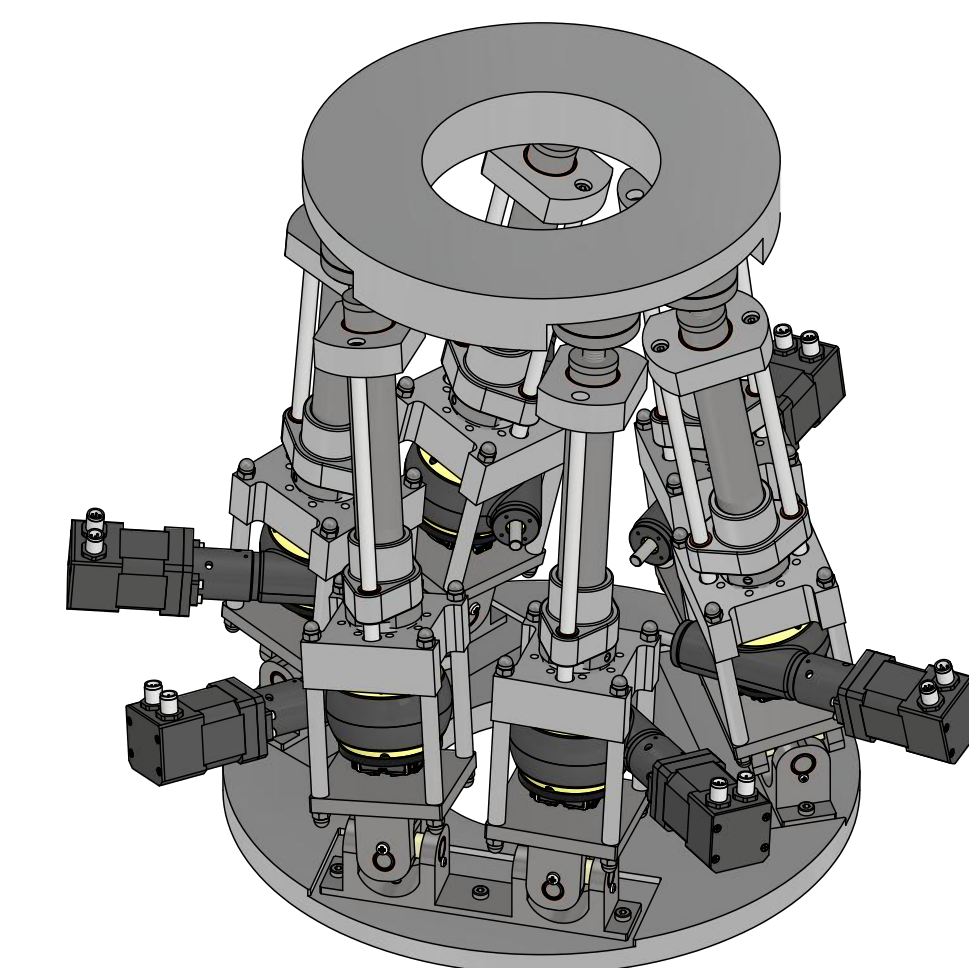
Assembly Overview



Magnetic characterization from electrical measurements



3D flux mapping

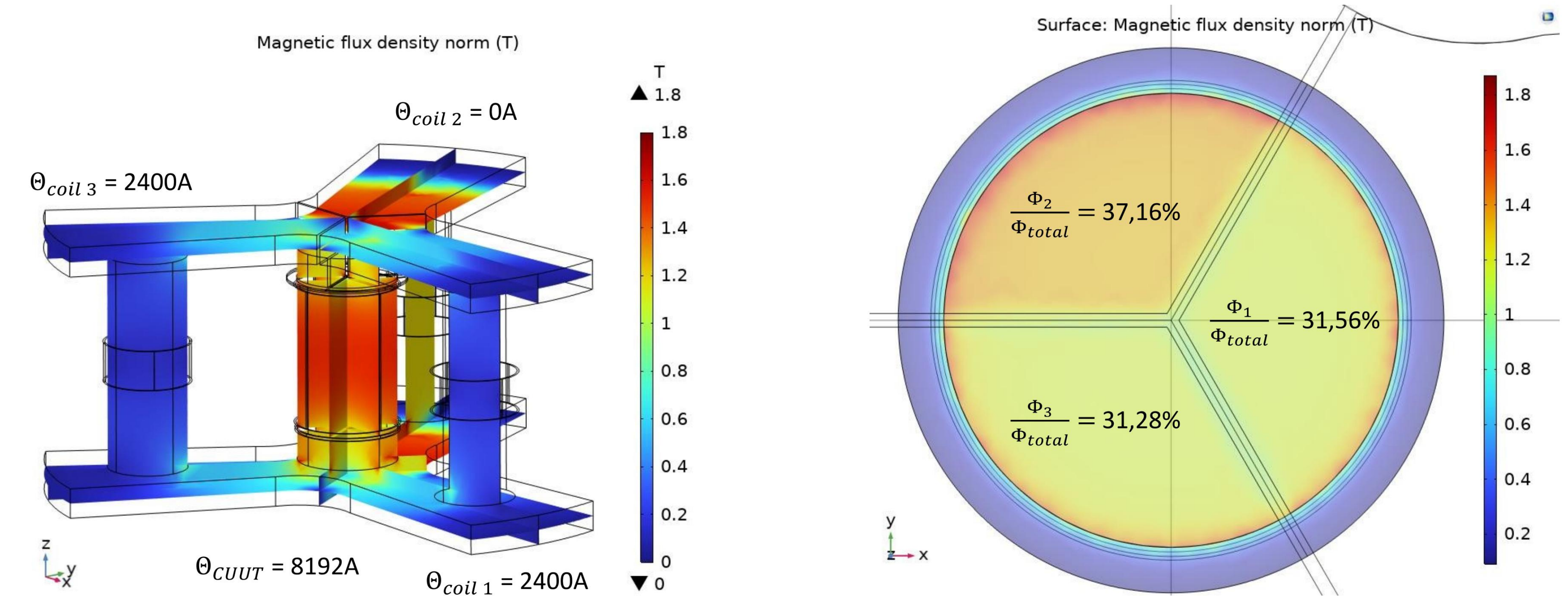


6-DoF coil unit pose manipulation and force sensing

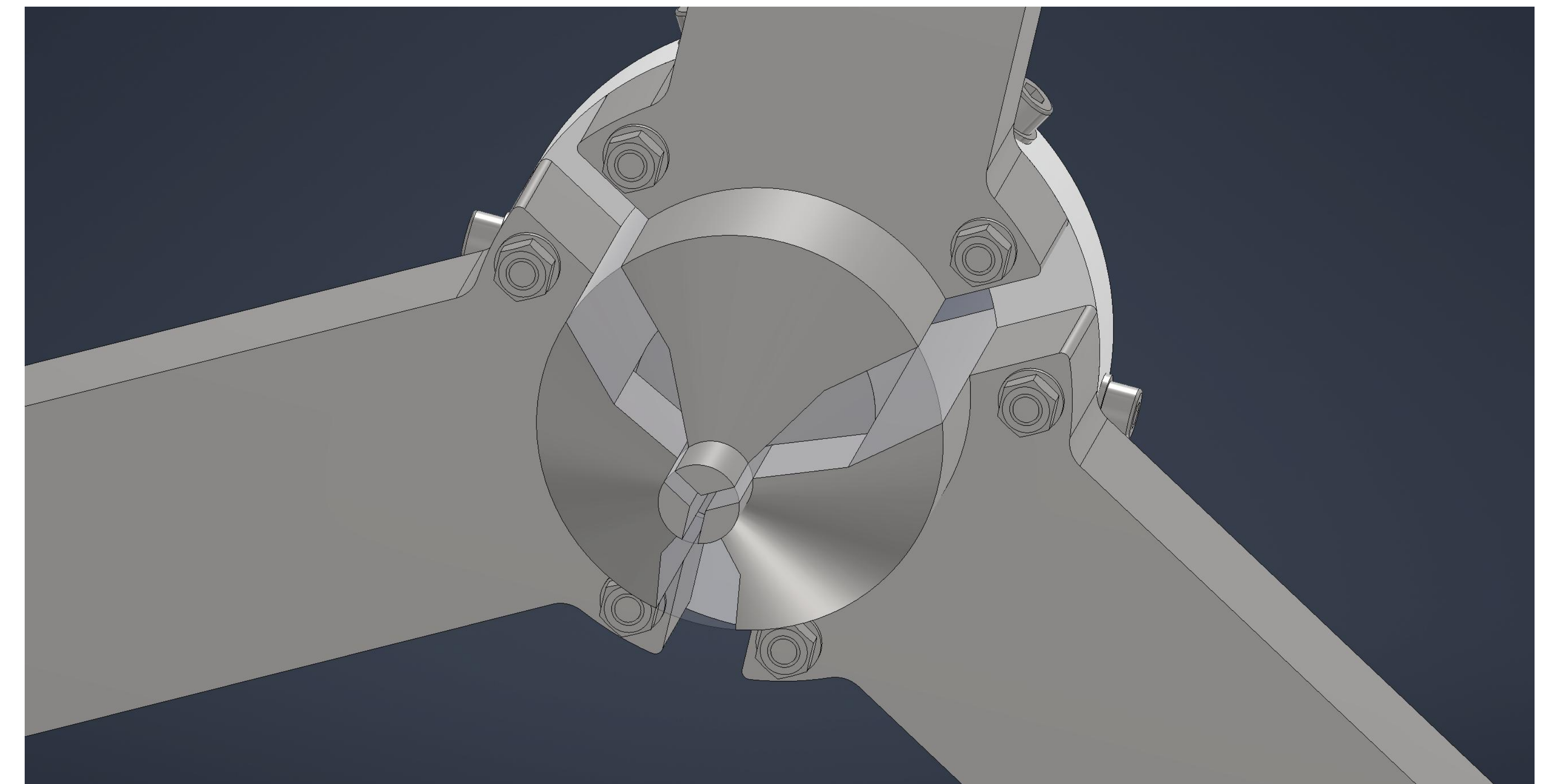
Magnetic Circuit

Active Field Emulation and Digital Twin

- Emulating rotor-stator interaction without a full physical rotor assembly
- Emulating effects in axial-flux machines (air gap flux distribution)
- Supervised by a Digital Twin (Simscape and COMSOL)



Active Field Emulation in the air gap with three magnetic paths and coils

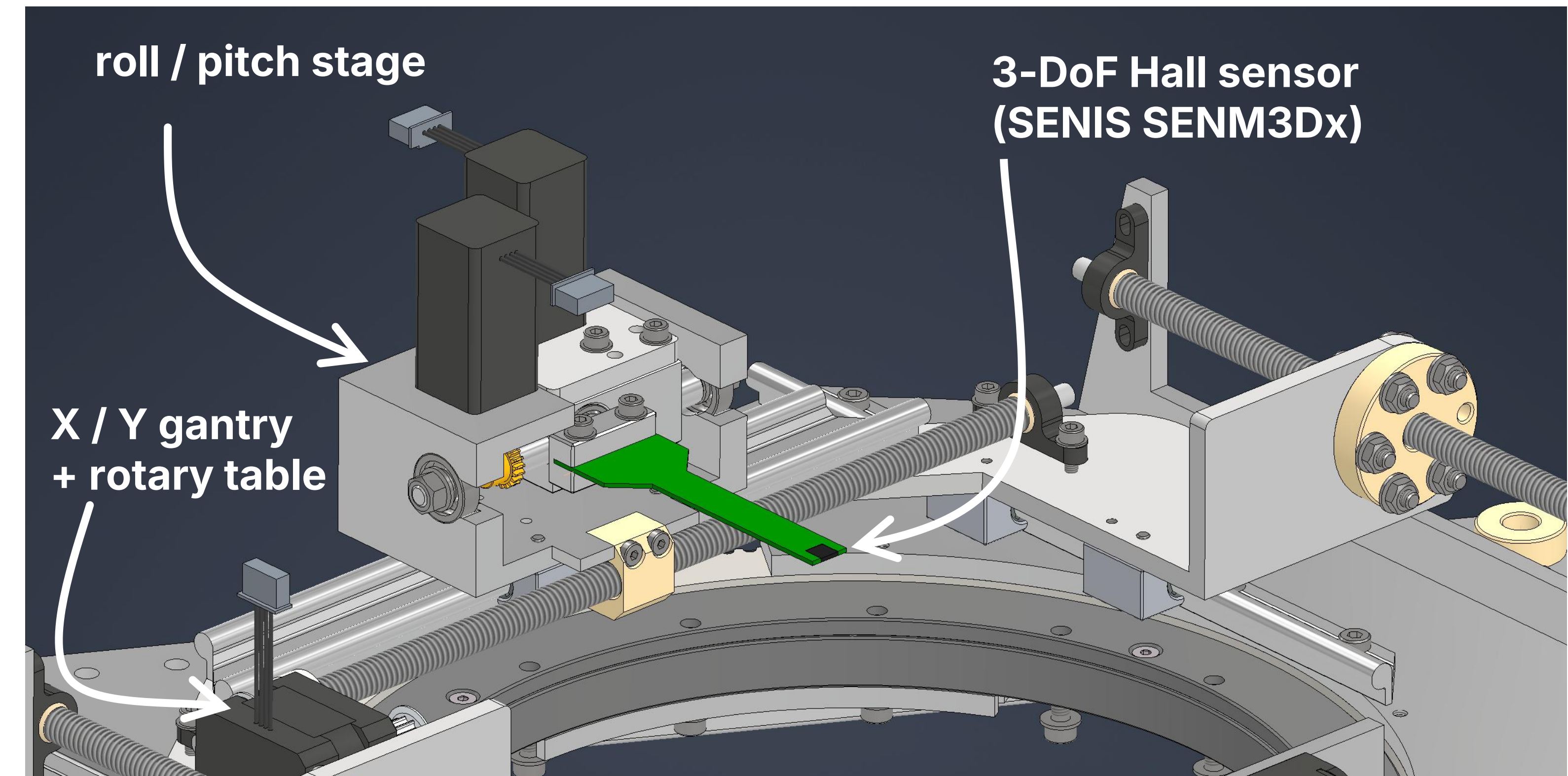
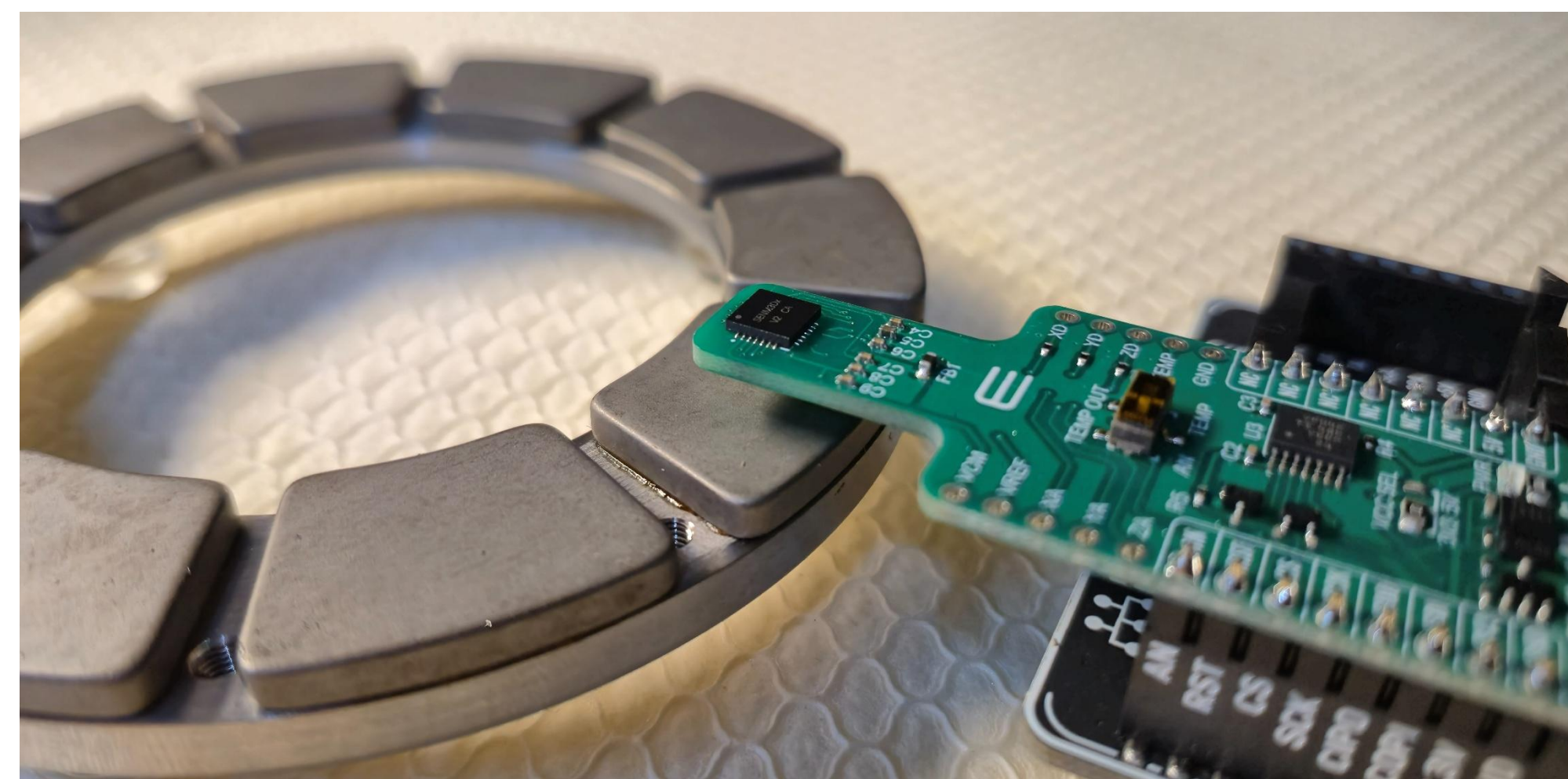


Special separated top pole shoe for Active Field Emulation

3D Flux Mapping

Air Gap and Stray Flux

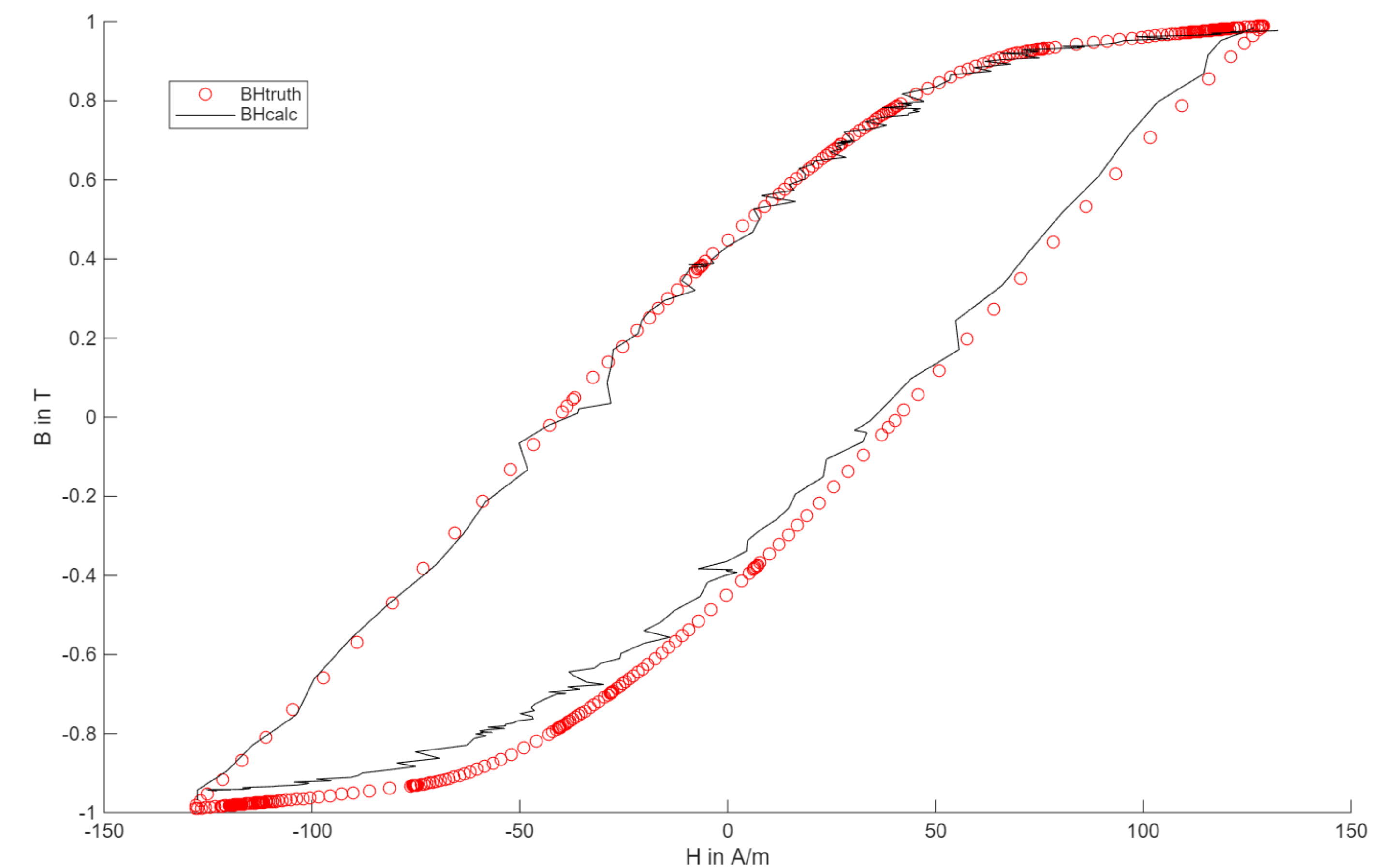
- Verification of magnetic metamodels against local flux density measurements in the 3D air gap region
- 5-axis robot and 3-DoF Hall probe system
 - up to 4T flux density
 - <1mm thick, embedded into PCB
- Also suitable for mapping an entire stator / rotor



3D flux mapping unit: rotary table, X/Y gantry, roll / pitch stage and 3-DoF Hall sensor integrated into thin PCB

Magnetic Characterization

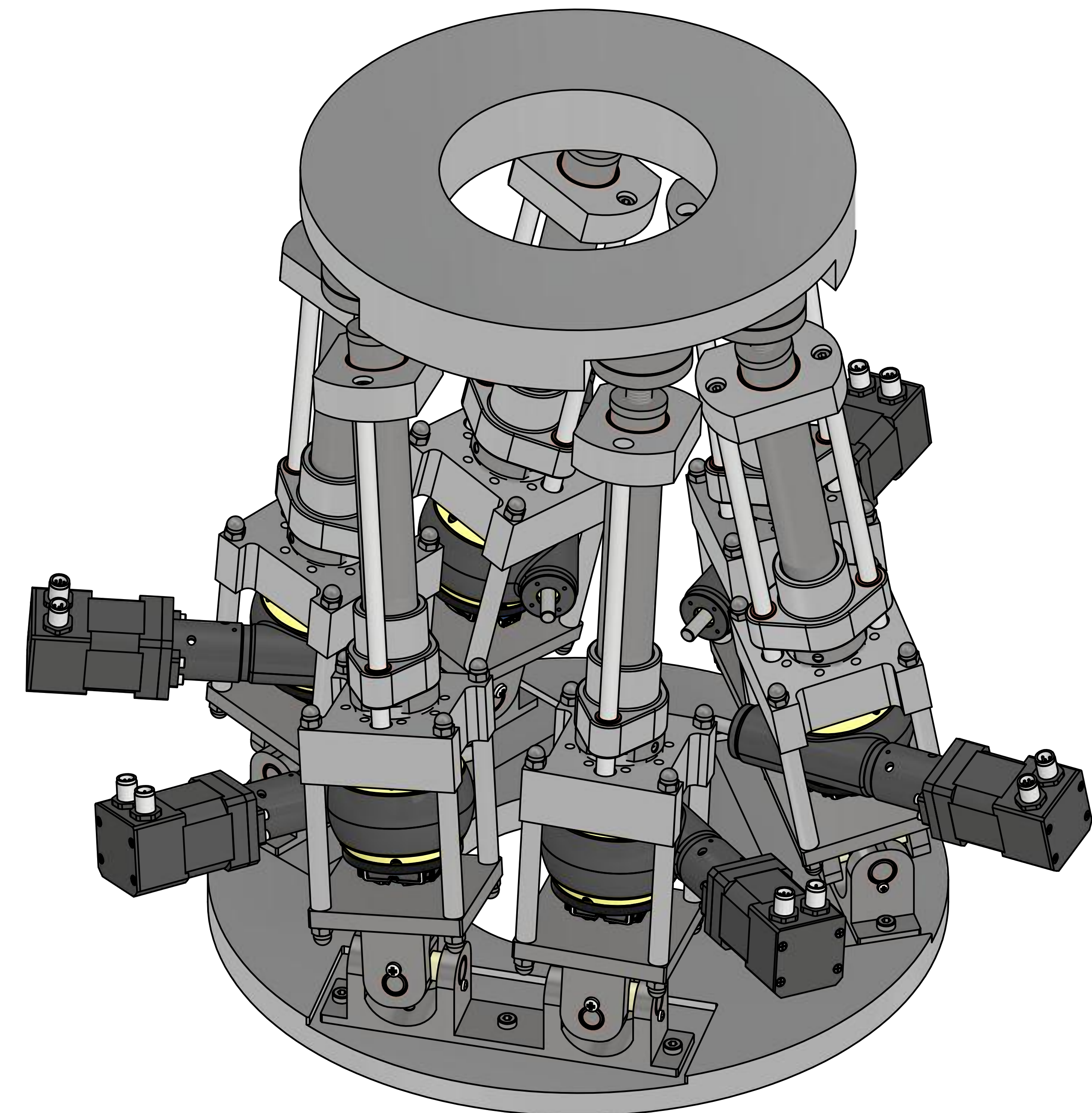
- High-precision voltage and current measurements
- Variation of excitation frequencies
- Reconstruction of B-H curves
- Measurement of coil losses (copper)
- Measurement and separation of core losses (iron)
- Coupled with a Digital Twin



B-H curve reconstruction from voltage and current measurement data
(simulation study with realistically simulated measurement data)

6-DoF Stewart Platform + Force Sensor

- Simulation of manufacturing tolerances
 - air gap width
 - eccentricity, shift
 - tilt
- 6-axis force quantification during excitation
- Parasitic forces on bearings, case, etc. (-> NVH)
- **Key figures:**
 - **2.5kN actuation force**
 - **50mm movement in x, y**
 - **15mm movement in z**
 - **<50 μ m displacement under load**



Thermal Validation

Parameter Identification of Cooling Concepts

Metrology

Measurement of:

- temperatures
 - fluid flow
 - pressure (difference)
 - voltage, current
- power, impedance

Model Refinement

Parameter identification and training using empirical data:

- LPTN
- Thermal Neural Networks

→ **Validation of models** ←

In-Situ Sensing

Different types of temperature sensing:

- surface and coolant stream
- thermocouple and RTD
- calculation of temperature from impedance

Conductor Topology Benchmarking

– Preliminary Results of an Experimental Hollow Conductor –

Conductor Topology Benchmarking

Litz Wire Hollow Conductors

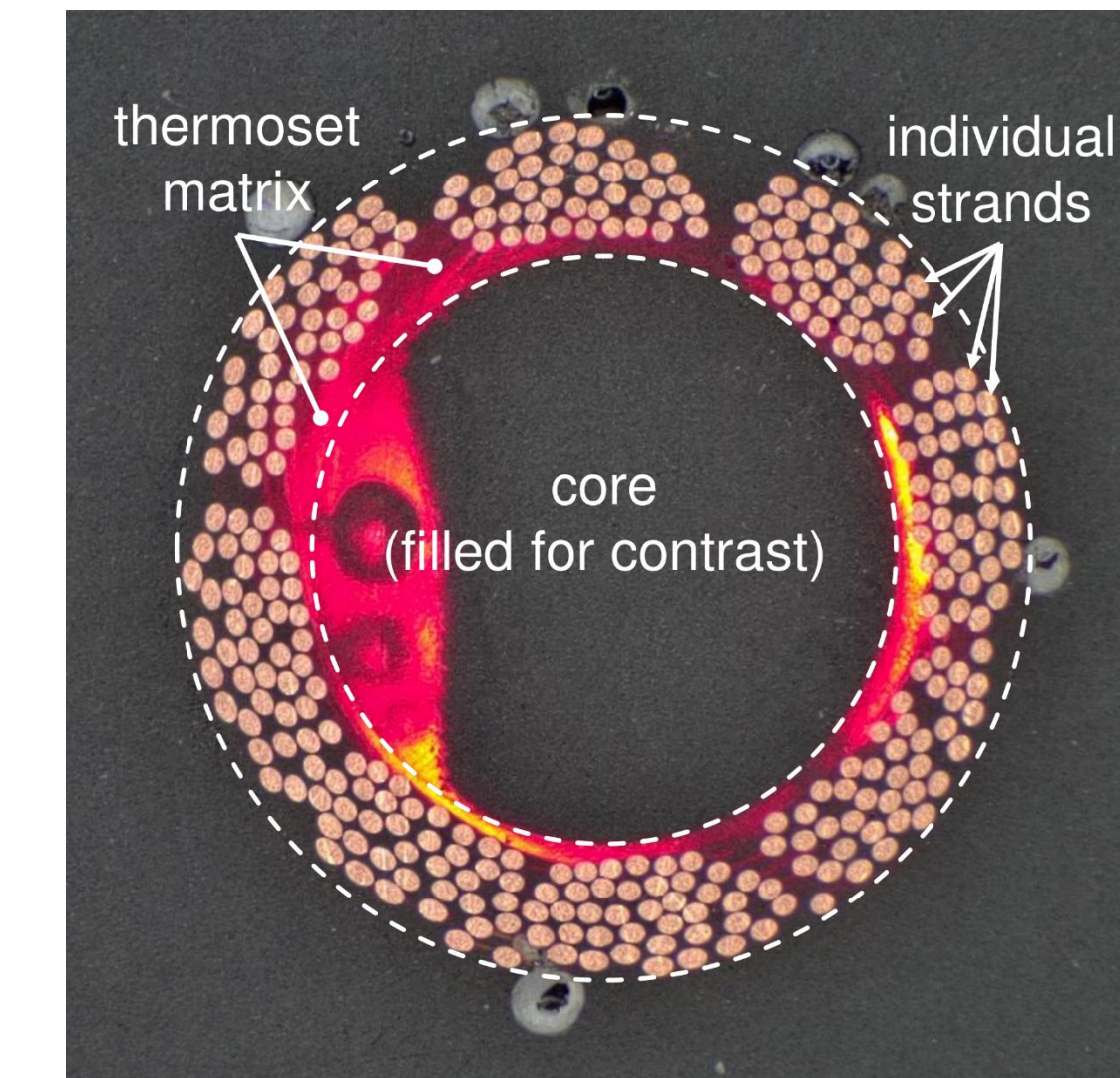
- High frequencies increase losses in the conductor
- Solution: Use litz wire!
- Problem: How do you cool litz wire?
- Investigation on litz wire hollow conductors



Prototype of a litz wire hollow conductor with a thermoset matrix for pressure testing (result: pressure tight up to the maximum tested pressure of 4.8 bar)



Prototype for thermal testing



Outside surface and cross-section of hollow conductor

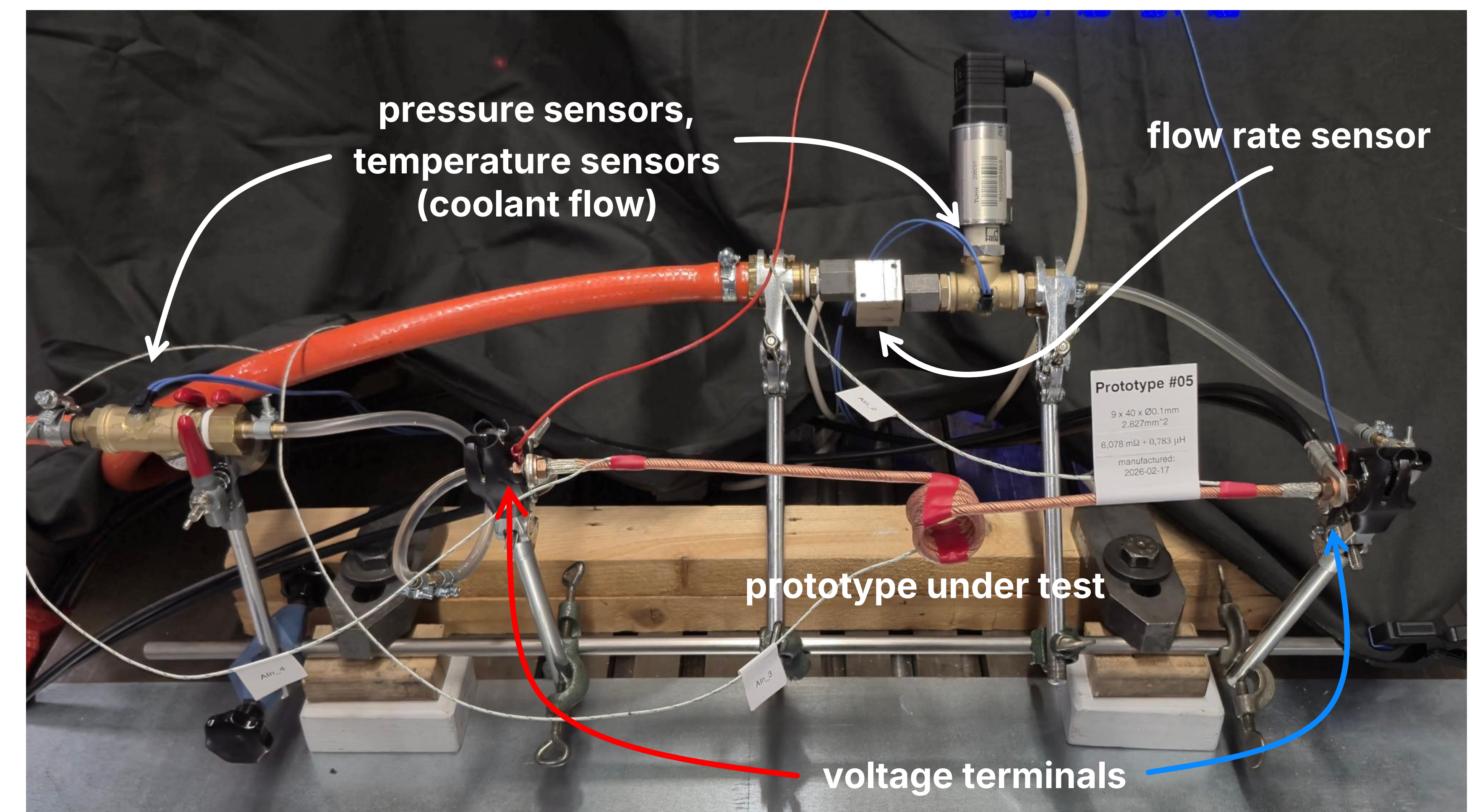
Conductor Topology Benchmarking

Litz Wire Hollow Conductors

- Measurement setup: as explained before (just not integrated into the test bench yet)
- Current densities from 32 A/mm² up to 112 A/mm²

Nr.	success?	current density [A _{rms} /mm ²]	power [W]	flow rate [L/min]	ΔT_{max} [°C]
1	yes	32	52	0.254	2.6
5	yes	32.5	55	0.105	6.2
8	no	57.0	181	0.097	41.5
10	yes	100.0	567	0.257	32.4
11	no	112.3	746	0.257	49.2

Excerpt from conducted measurements with litz wire hollow conductor prototype

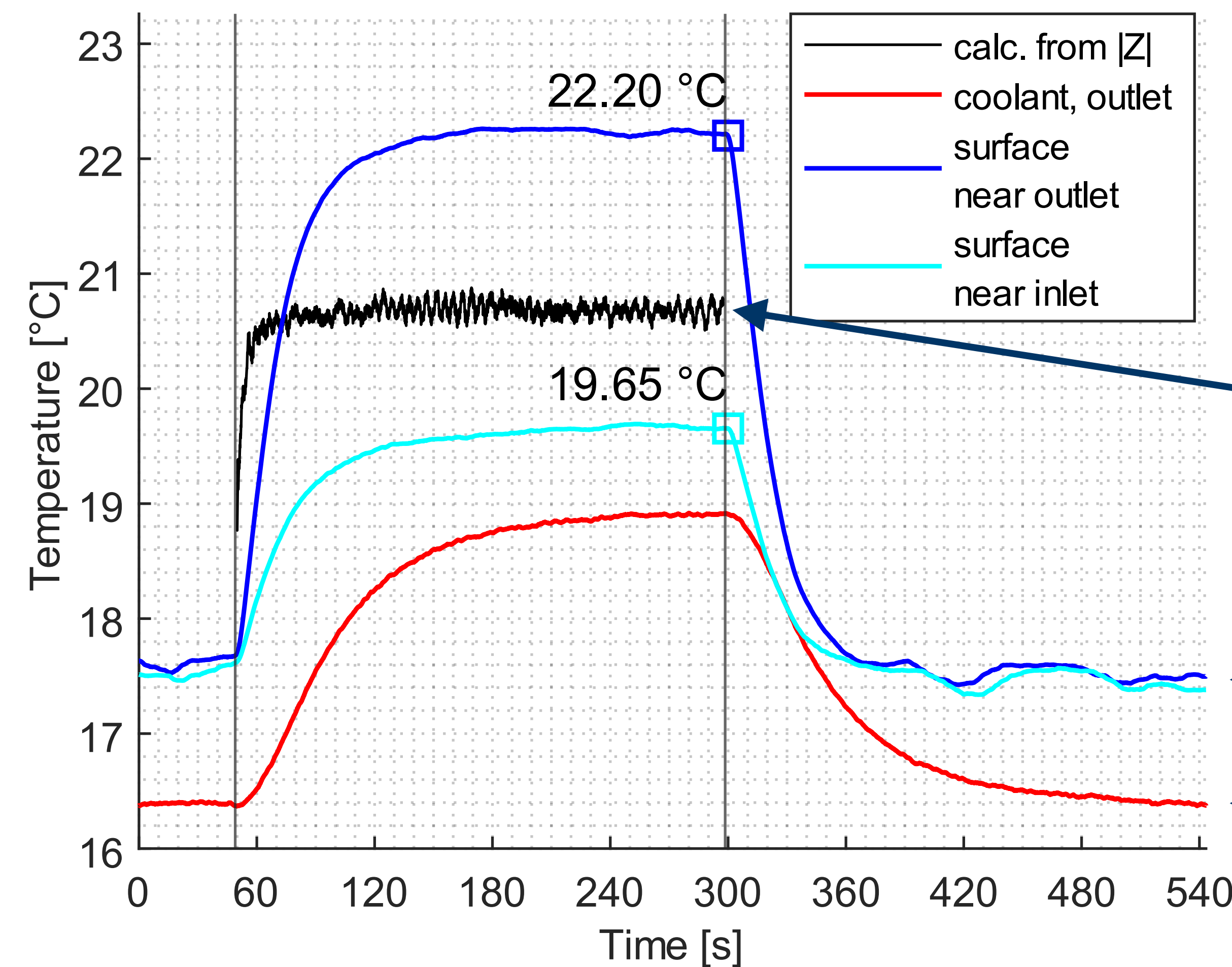


Measurement setup for thermal investigation of litz wire hollow conductors (current sensors are hidden)

Conductor Topology Benchmarking

Litz Wire Hollow Conductors

$J = 32 \text{ A/mm}^2$:



← calculated from impedance

← Type K thermocouple on surface

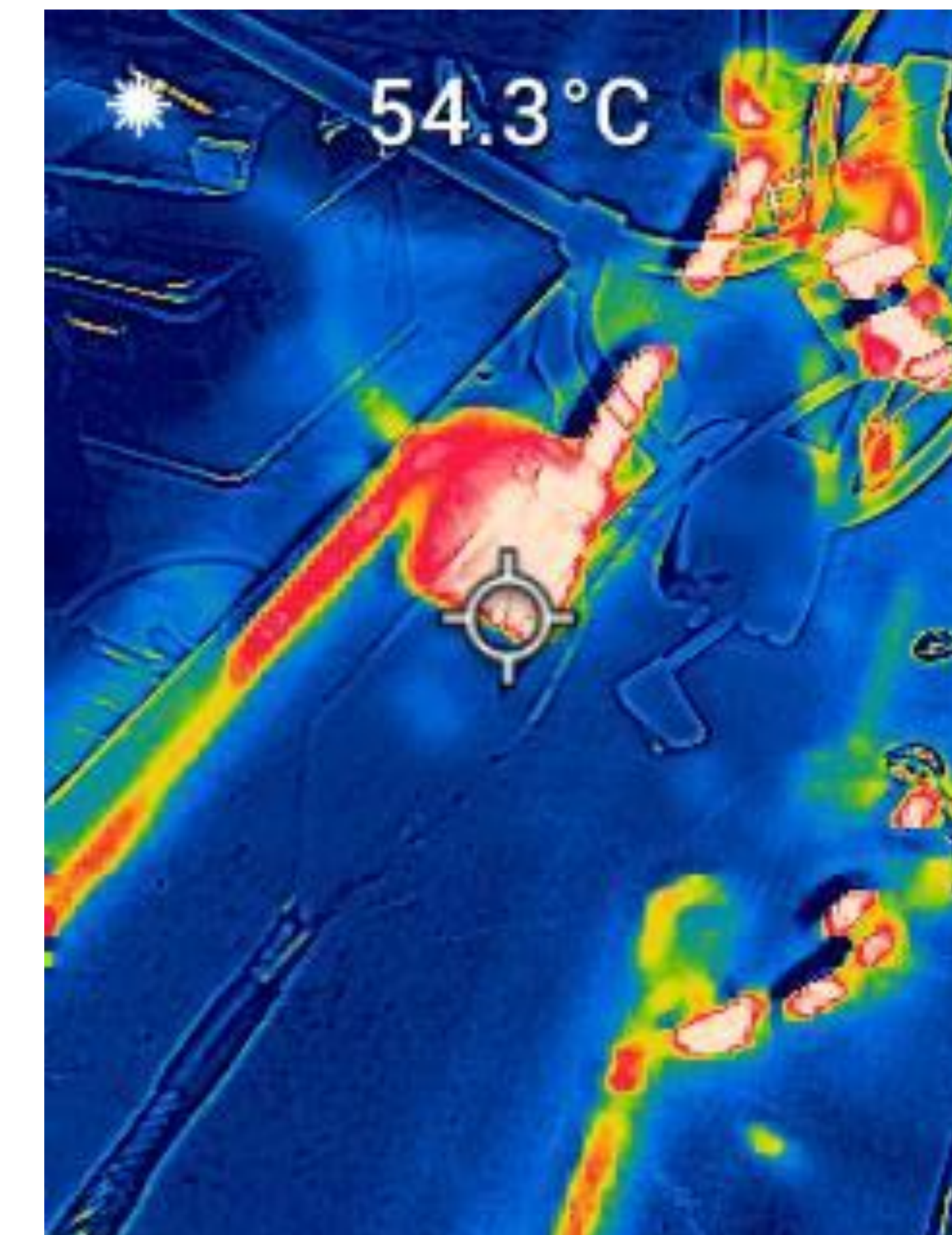
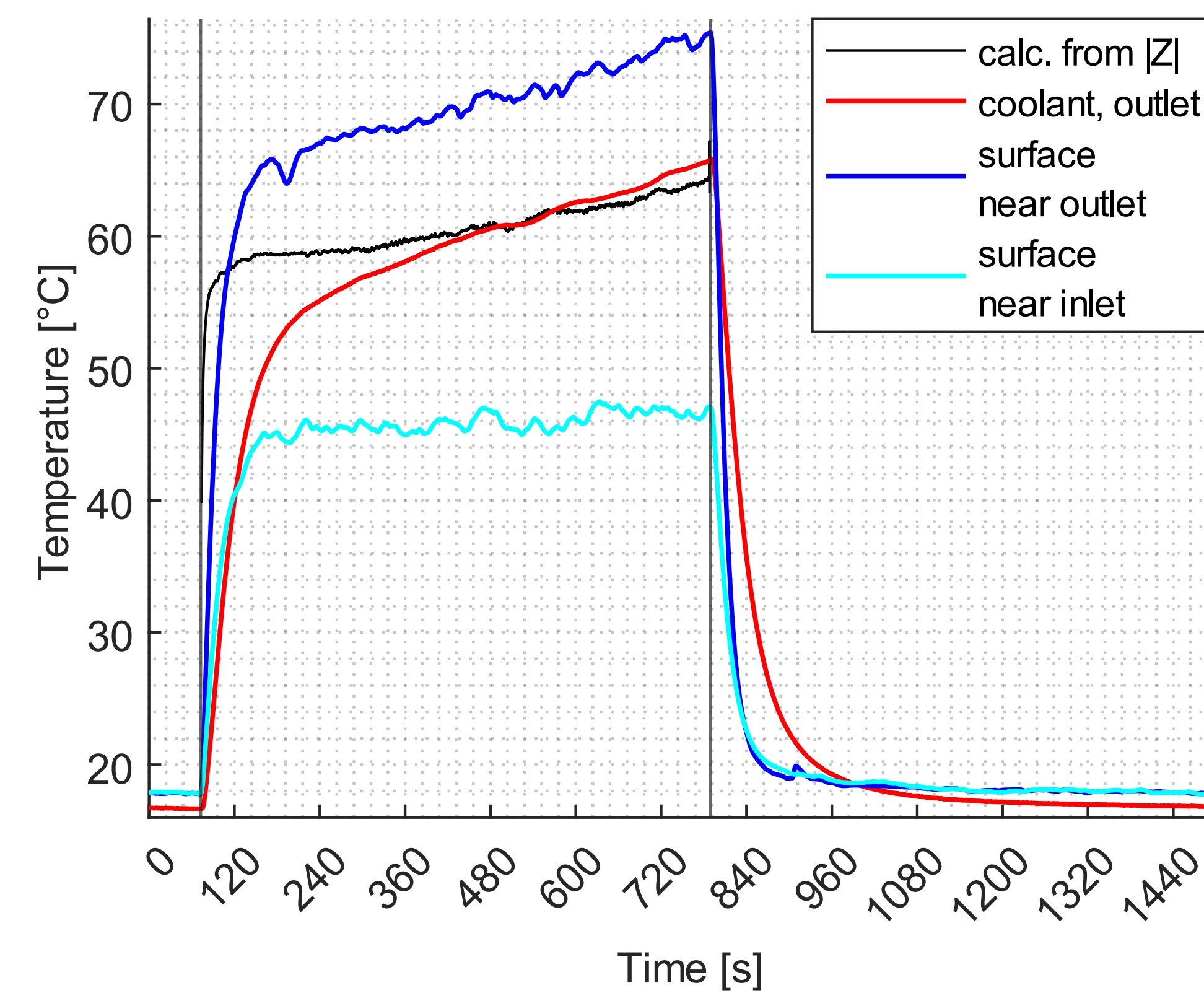
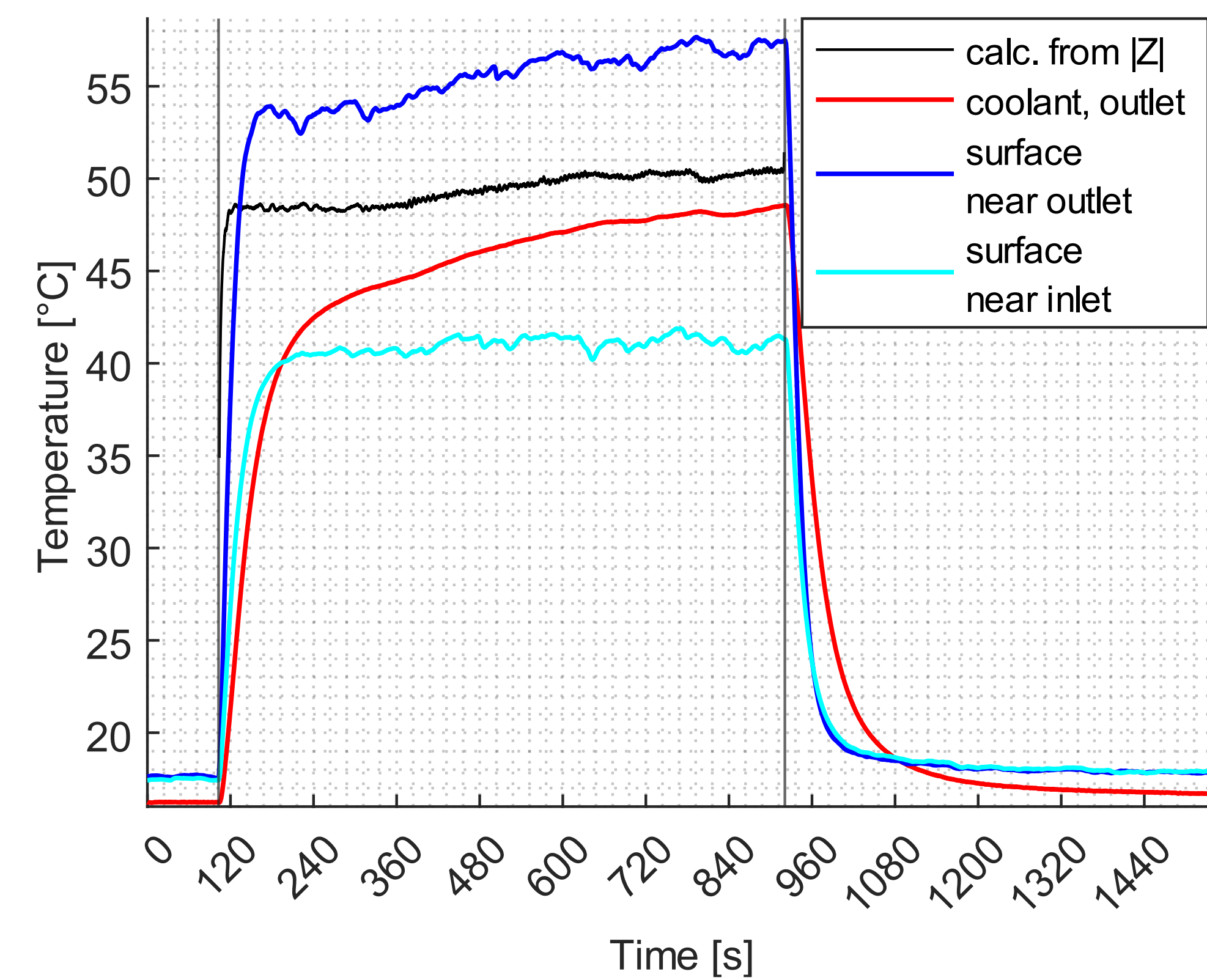
← Pt100 in coolant flow

Conductor Topology Benchmarking

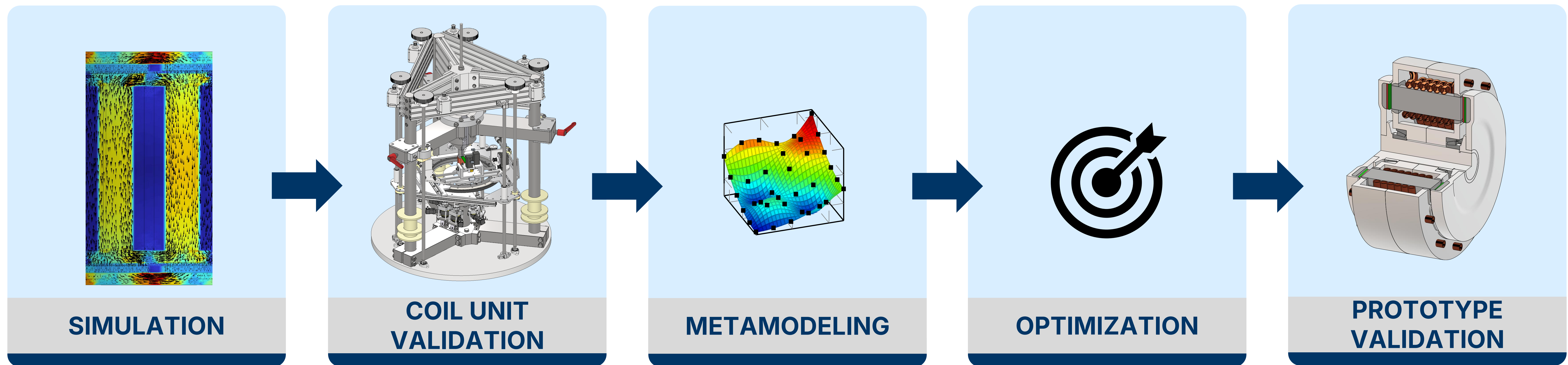
Litz Wire Hollow Conductors

$J = 100 \text{ A/mm}^2$: 

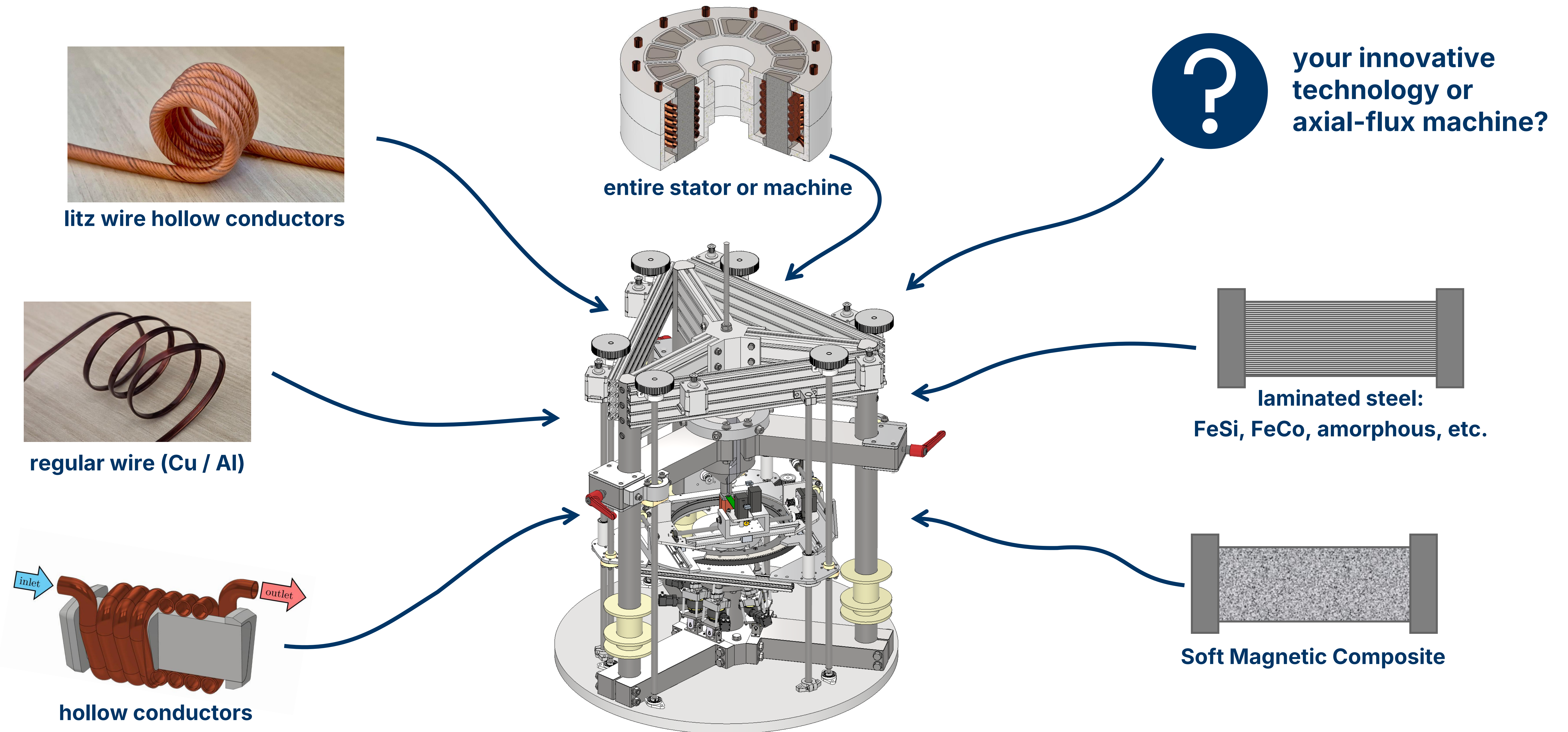
$J = 112 \text{ A/mm}^2$: 



Pipeline: from Design to Prototype



Open Validation Platform



Thank you! Questions?

How would you use the Open Validation Platform?

Do you miss a feature?

Which material would you like to have tested?



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