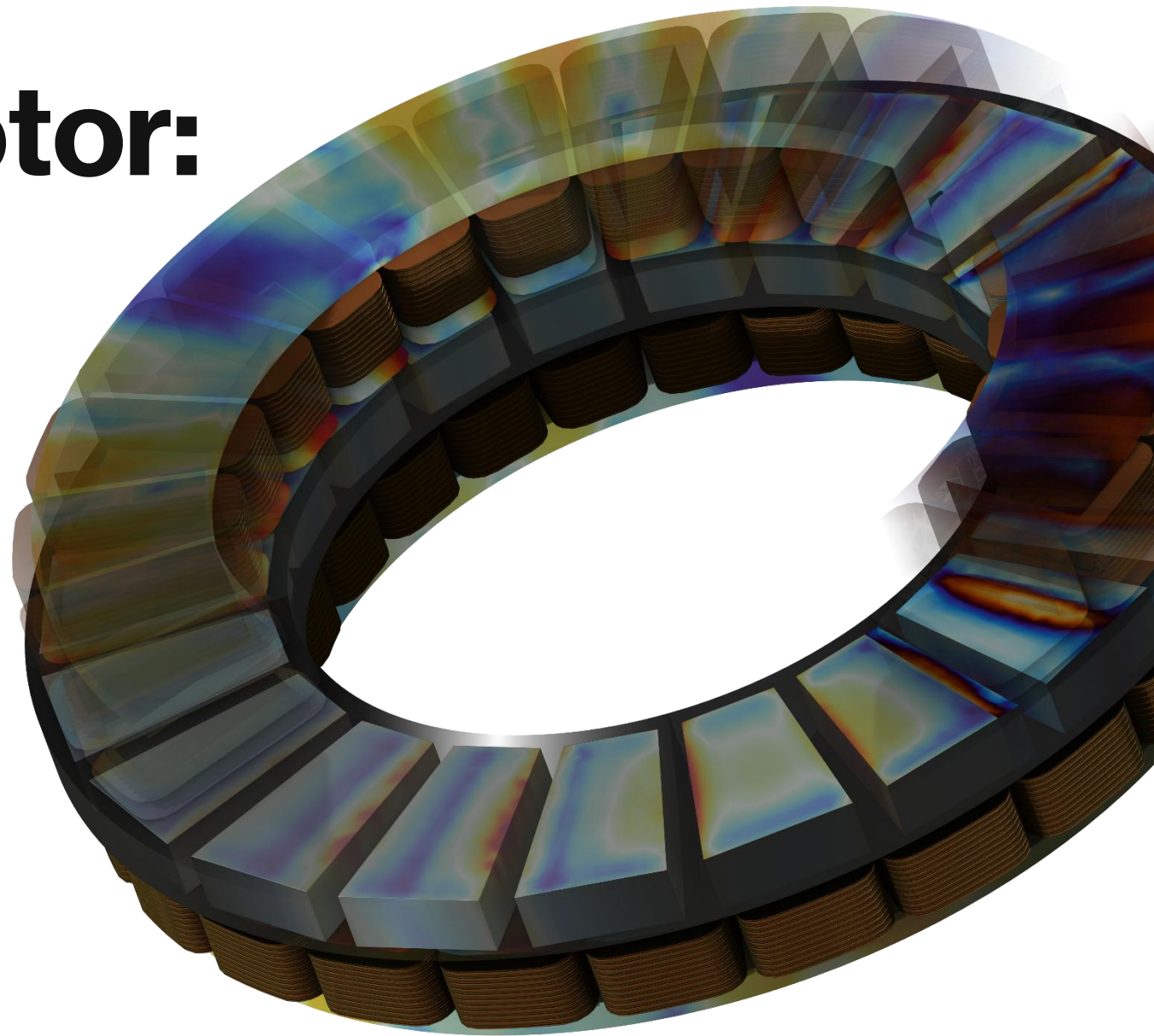


3D Axial Flux Motor: Electromagnetic Simulation & Parametric Optimization

Haixiao Wang

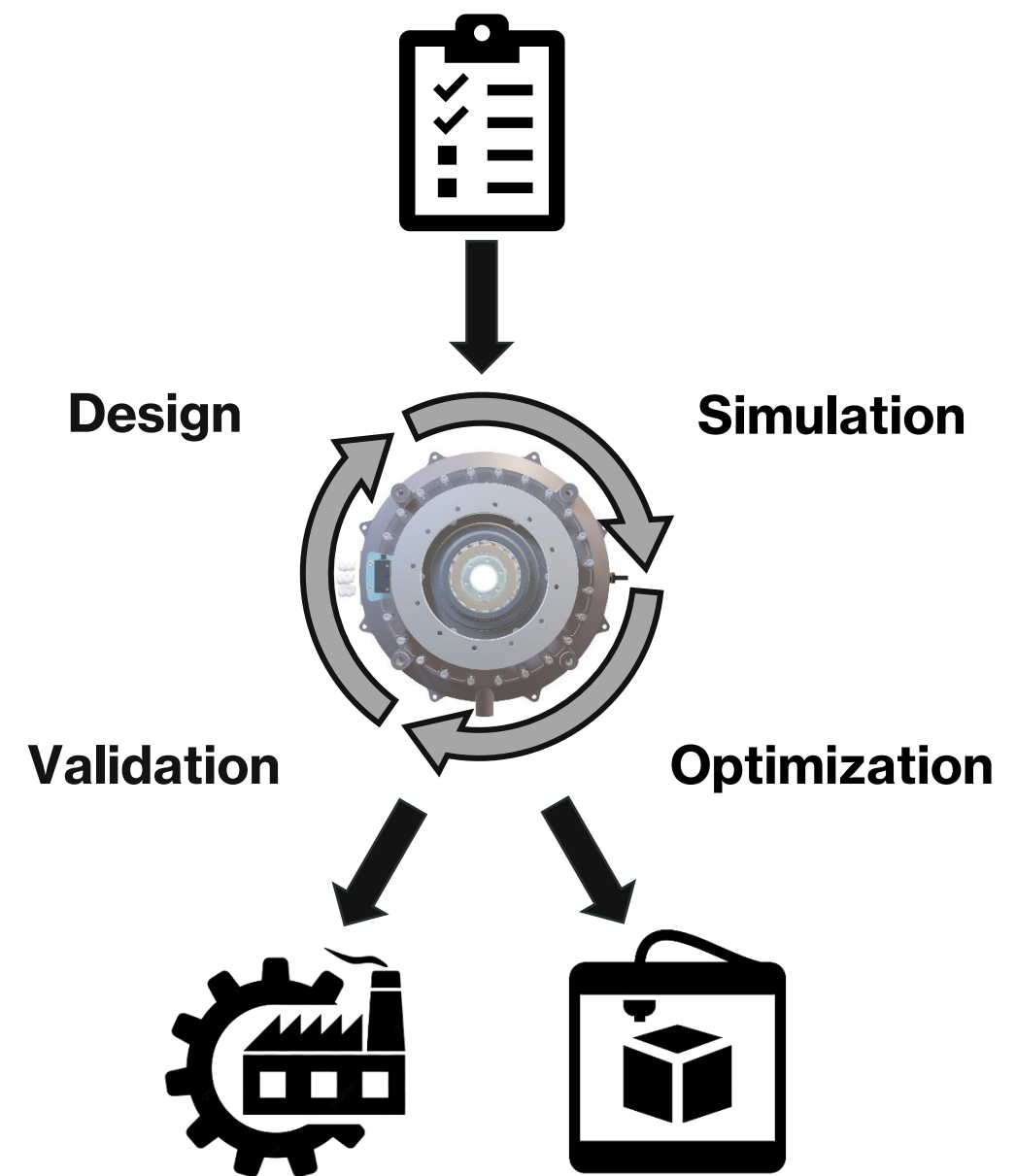
AMflux, Advanced Manufacturing Lab, ETH Zurich





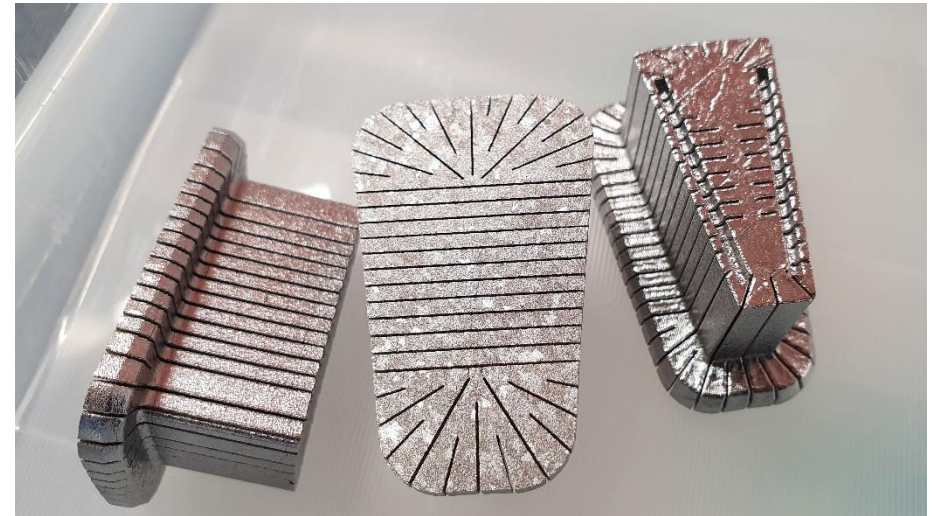
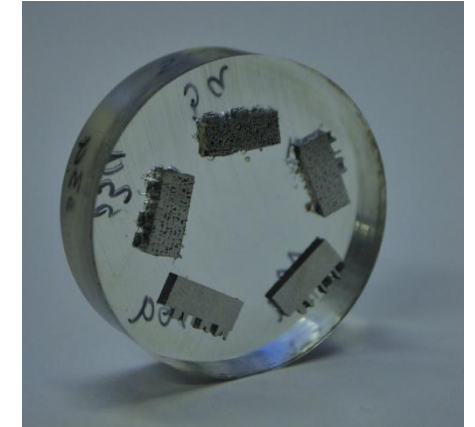
Amflux' Mission

- Build a **rapid-development pipeline** for **axial flux** motors based on custom demand
- Explore manufacturing process using custom additively manufactured **Ferrosilicon wt. 6.5%** for quick prototyping
- **Parametric design** of motor geometry for fast adaptations
- **Simulation and Optimization using COMSOL Multiphysics®**
 - Construction initial simulation model
 - Algorithmic optimization according to requirement
 - Validation of final model



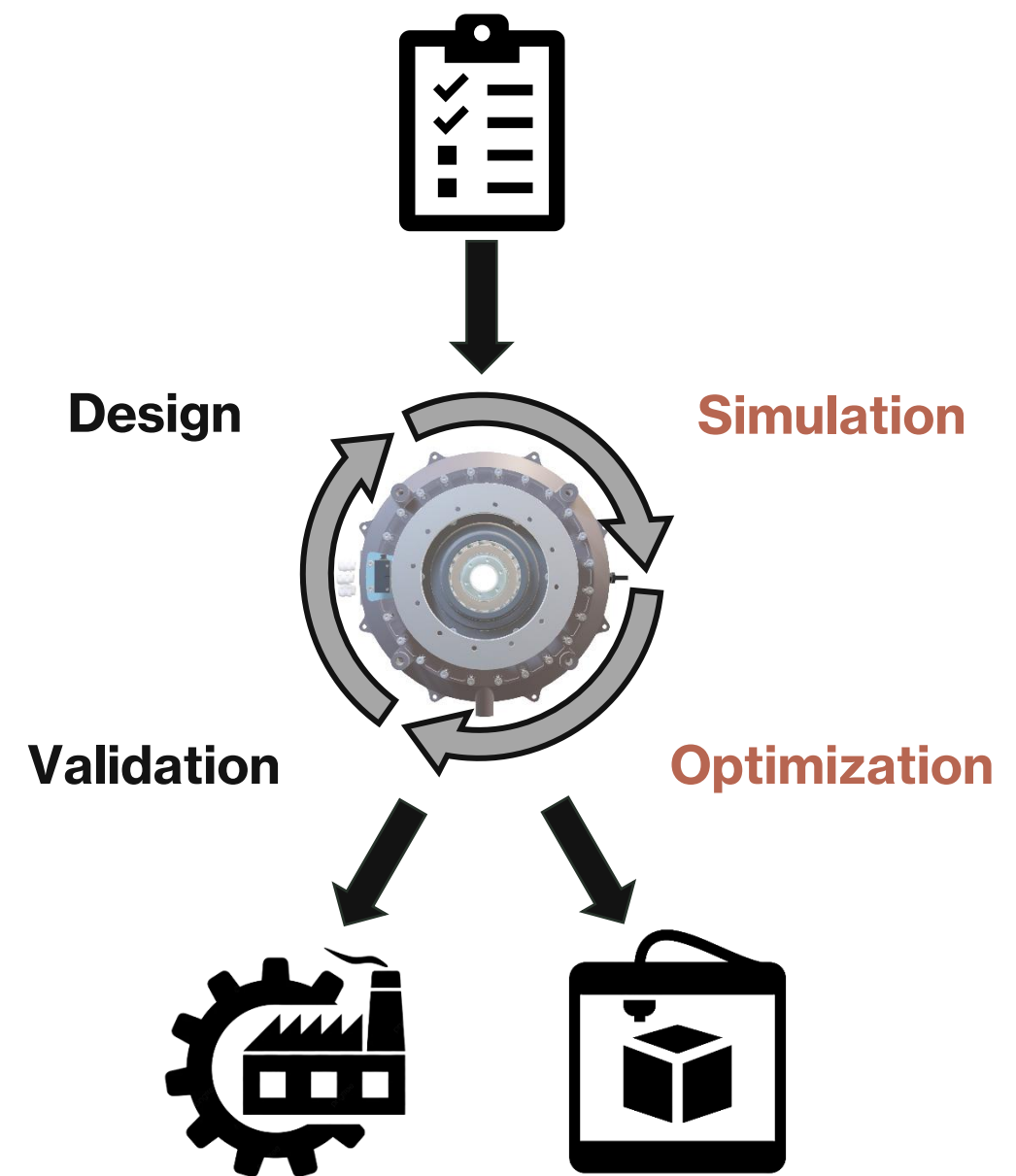
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Radial vs. Axial Flux Motors

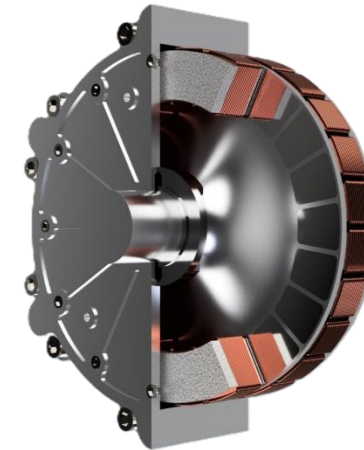
RADIAL FLUX

- $T \propto r^2$
- Large form factor (Cylindrical)
- Low Power/Torque density
- Refined manufacturing methods
- Holds **>99%** of E-motor market share



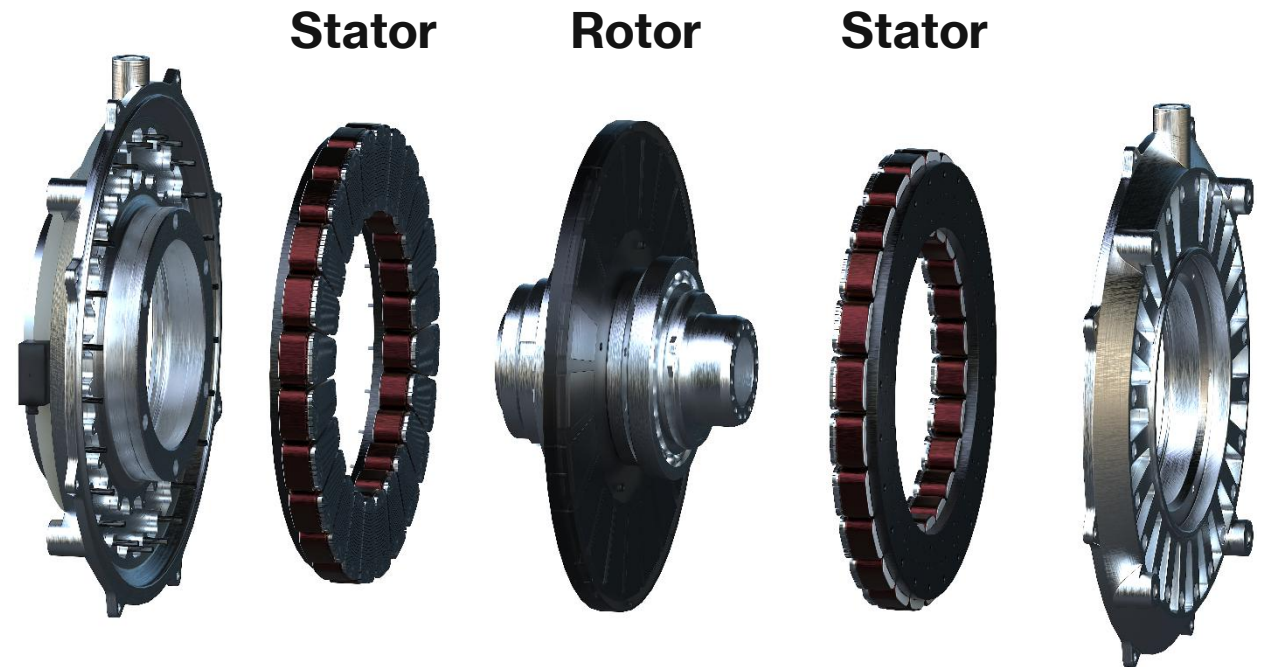
AXIAL FLUX

- $T \propto r^3$
- Small form factor ("Pancake" Shape)
- High Power/Torque density
- Difficult to manufacture with conventional methods
- Holds **0.74% to 0.88%** of market share



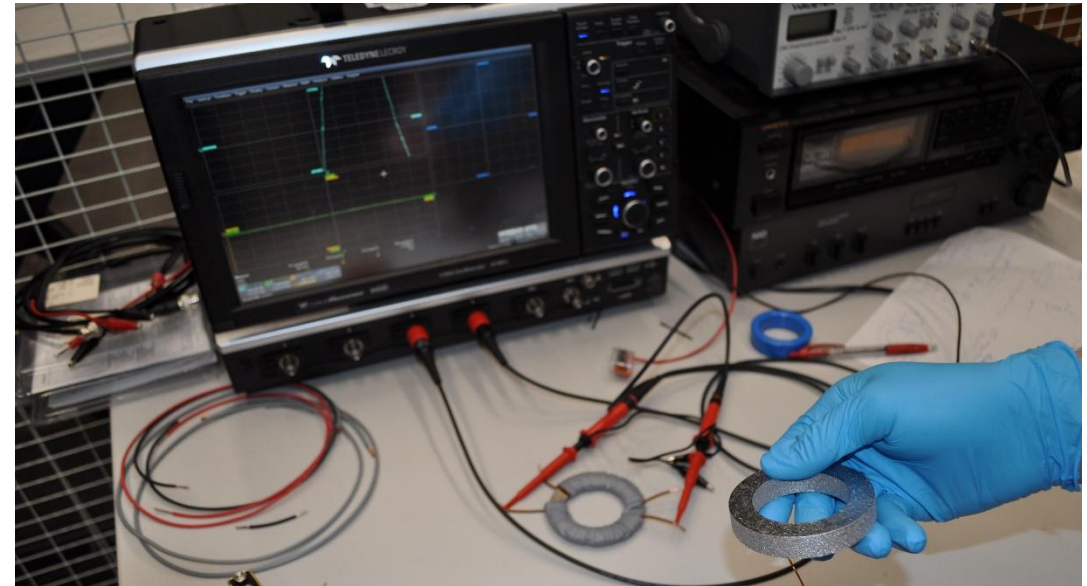
Simulation Set-up

- Only the core components are considered for the simulation
 - **Stator + Copper windings**
 - **Rotor + Permanent magnet**
- Model is set up parametrically using Design Module
 - Based on actual CAD initial model
 - **24 Slots, 20 Poles, Dual Stator Single Rotor**
- Electromagnetic simulation using
 - Rotating Machinery, Magnetic (rmm)
 - Moving Mesh



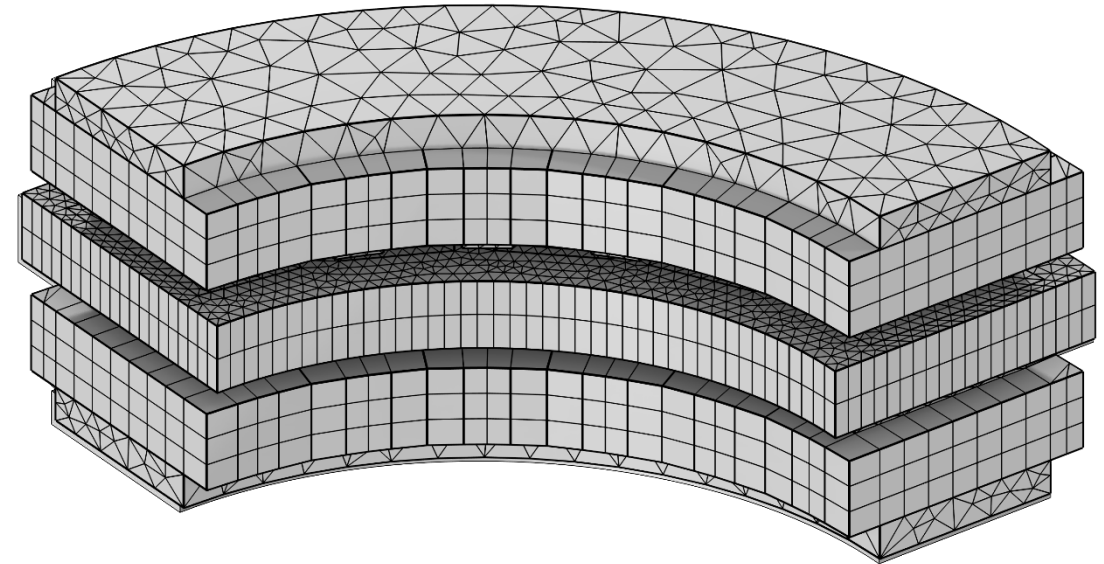
Simulation Details

- Custom B-H curve to adapt to custom Ferrosilicon wt. 6.5%
 - Based on **measured B-H curve**
 - Using **Laminated Steel, Ampere's Law** module
- Modelling improvements to increase computational efficiency
 - **Symmetry condition** of motor with periodic condition
 - Simplify mesh using targeted **swept meshing**
- Implemented studies:
 - Coil Geometry Analysis
 - Stationary
 - Time-dependent
 - Frequency-to-Losses



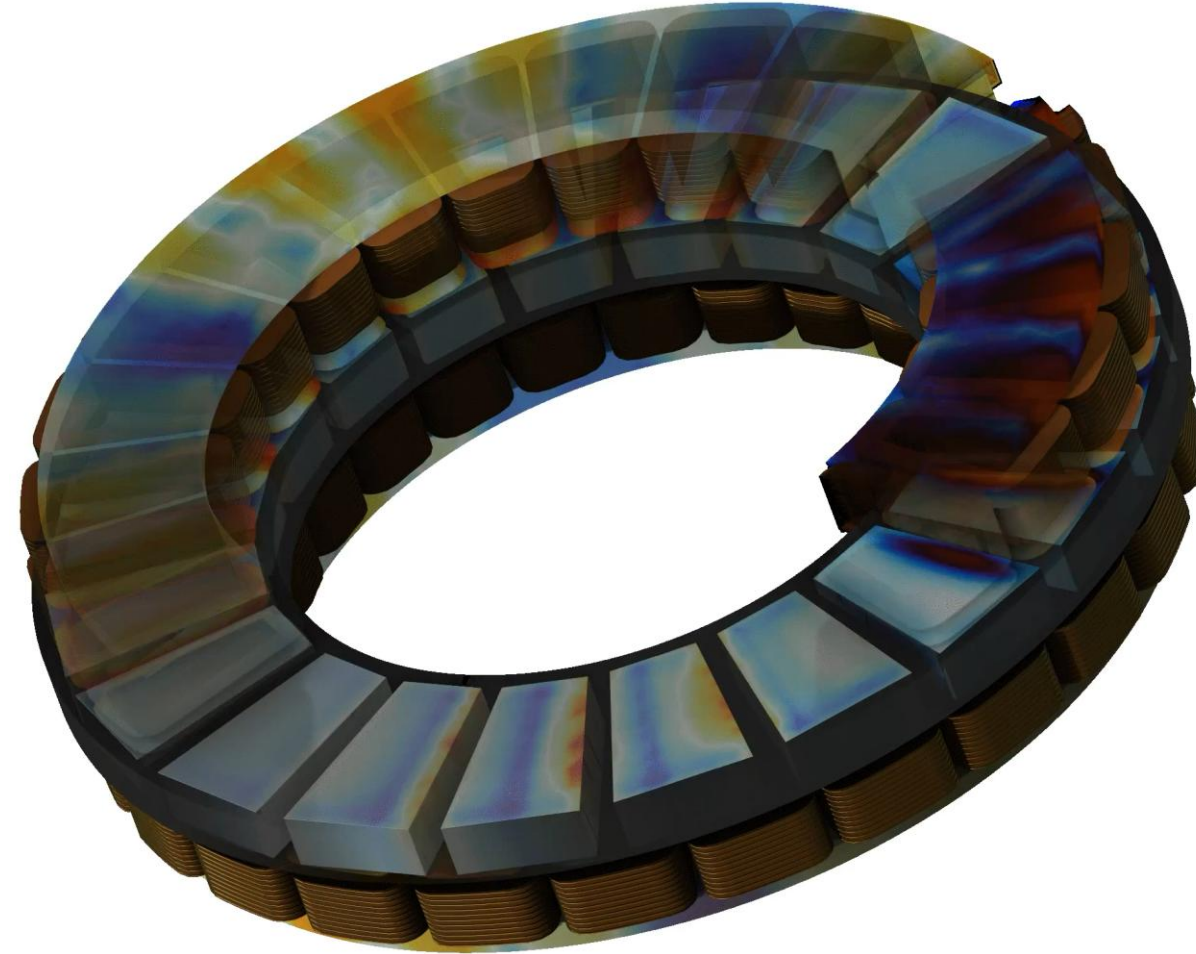
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Simulation Output & Validation

- Simulation Output:

- Torque (Maxwell Stress Tensor)
- Motor related constants
- Energy consumption
- Resistive and inductive losses
- Ripple harmonics
- Mass estimation

$$T_{z\phi} = \frac{B_z B_\phi}{\mu_0}$$

$T_{z\phi}$: azimuthal shear stress

B_z : axial component of magnetic flux density

B_ϕ : azimuthal component of magnetic flux density

μ_0 : permeability of free space

Maxwell Shear Stress

$$T = \frac{\iiint_{\text{gap}} (T_{z\phi} \cdot r) dV}{d_{\text{airgap}}}$$

T : total electromagnetic torque

$T_{z\phi}$: azimuthal shear stress

r : radial position

d_{airgap} : airgap thickness

Torque Integration

$$\tau_m = \frac{T}{m}$$

τ_m : torque density [N m/kg]

T : electromagnetic torque

m : active mass of the motor

Torque Density

$$K_m = \frac{T}{\sqrt{P_{\text{loss}}}}$$

K_m : motor constant [N m/ $\sqrt{\text{W}}$]

T : electromagnetic torque

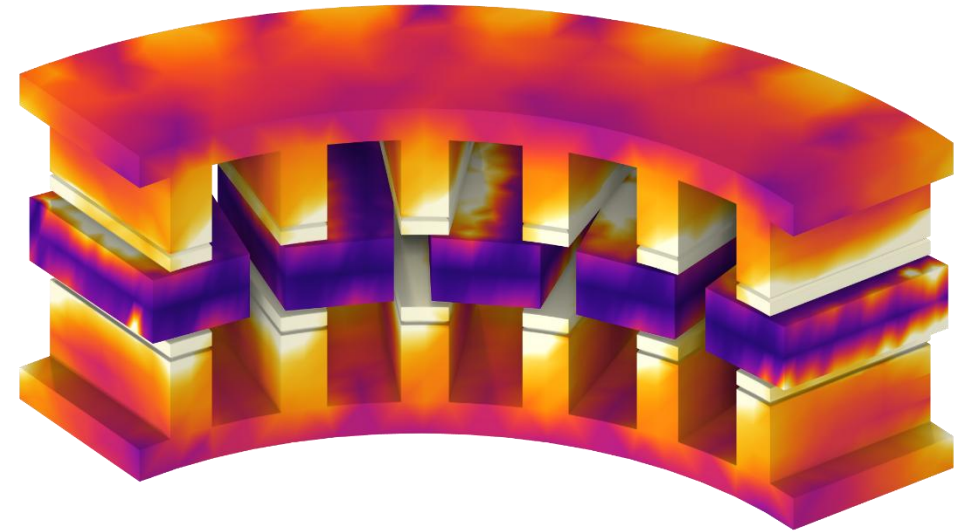
P_{loss} : resistive power loss

Motor Constant

Simulation Output & Validation

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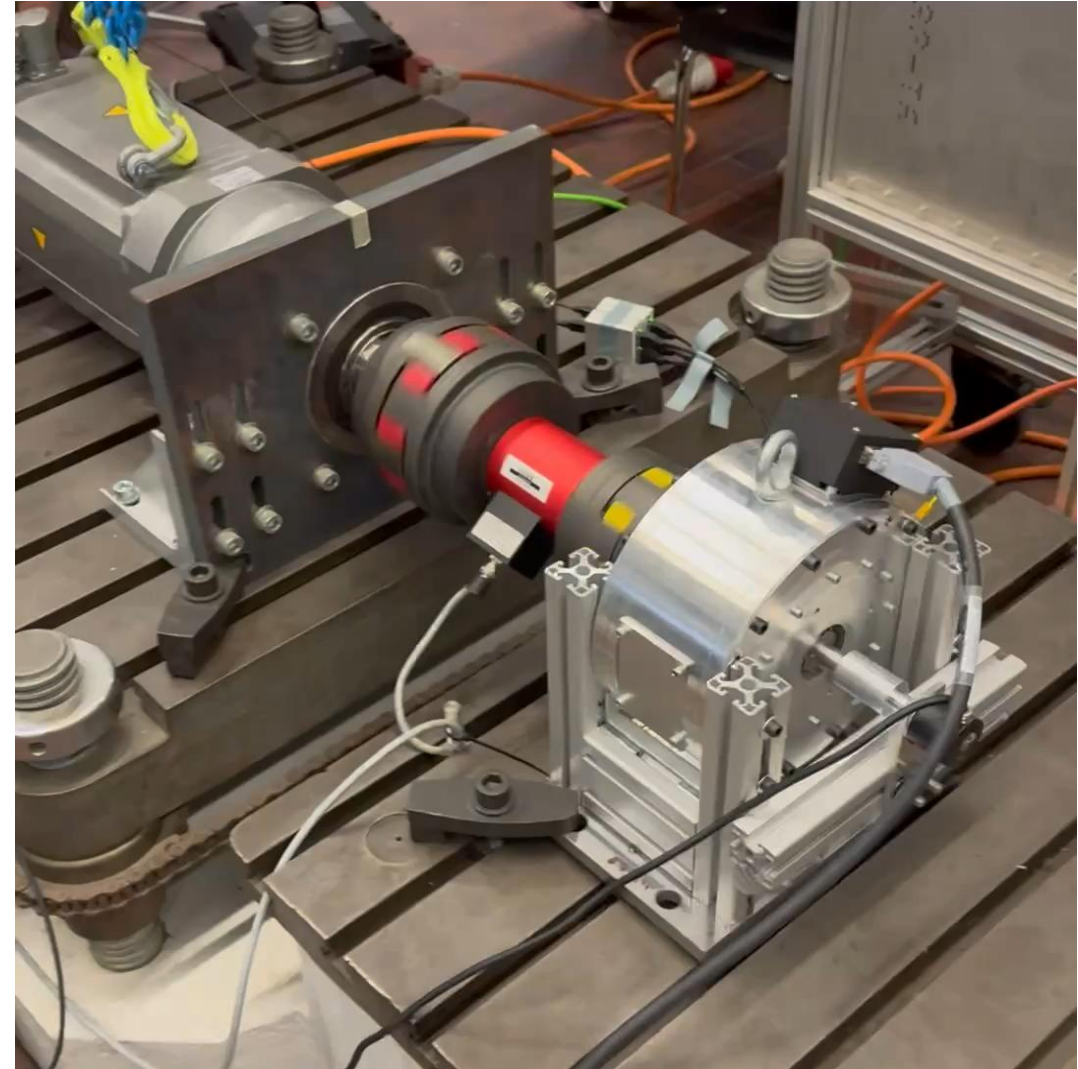
Volume: Volumetric loss density, electromagnetic (W/m³)



▼ 0.0364 2 4 6 8 ×10³ ▲ 2.09×10⁴

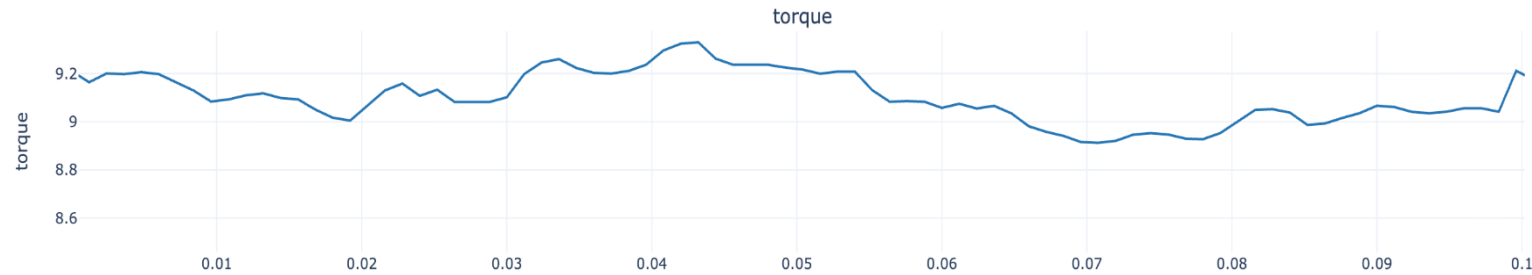
Simulation Output & Validation

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- **Validation** through physical twin
 - Manufacturing and testing of base model

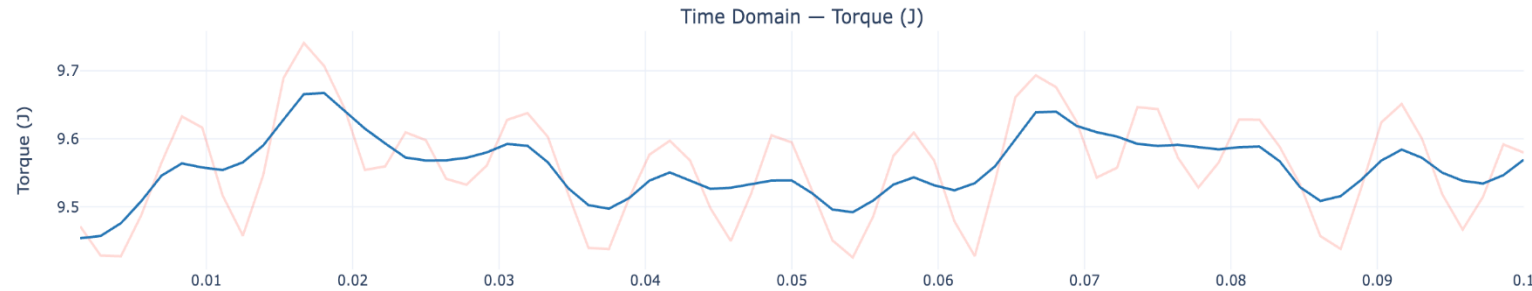


Simulation Output & Validation

- Simulation Output:
 - Torque (Maxwell Stress Tensor)
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- **Validation** through physical twin
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 - Comparison of **nominal dynamic torque**
 - **1.13%** deviation at nominal current
 - **0.89%** deviation at peak current



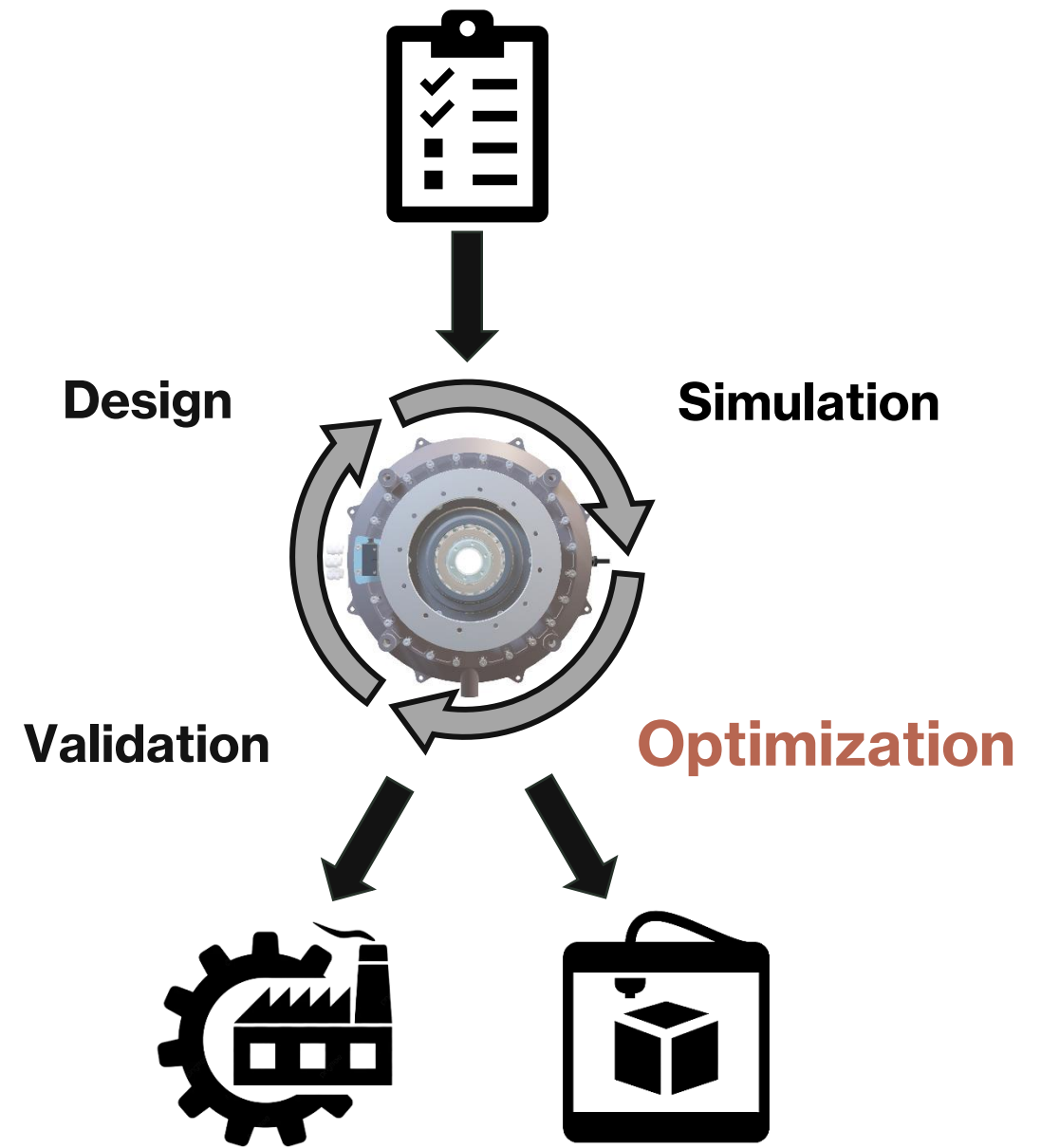
Measured Torque after noise filtering



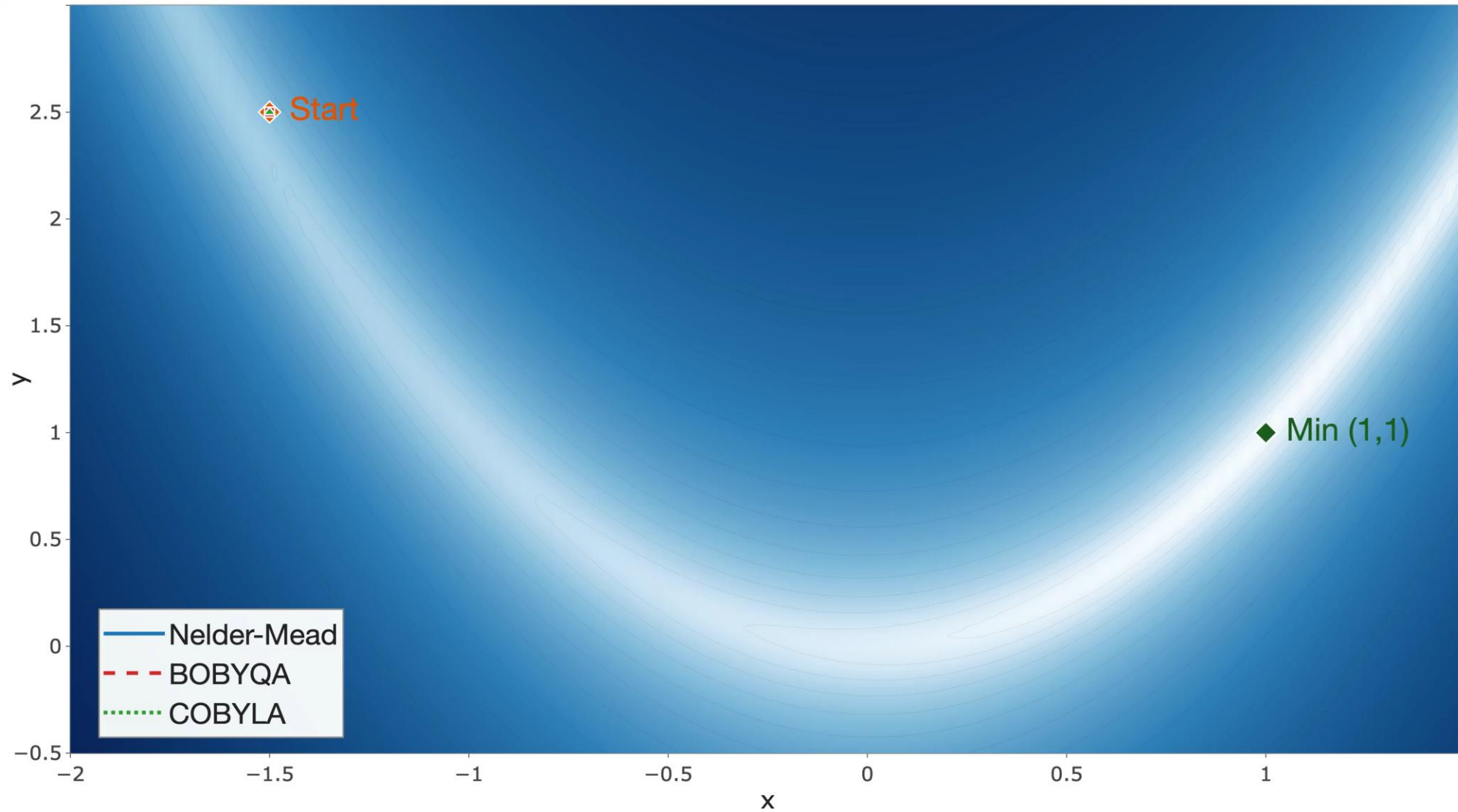
Simulated Torque after noise filtering

Parametric Optimization Set-up

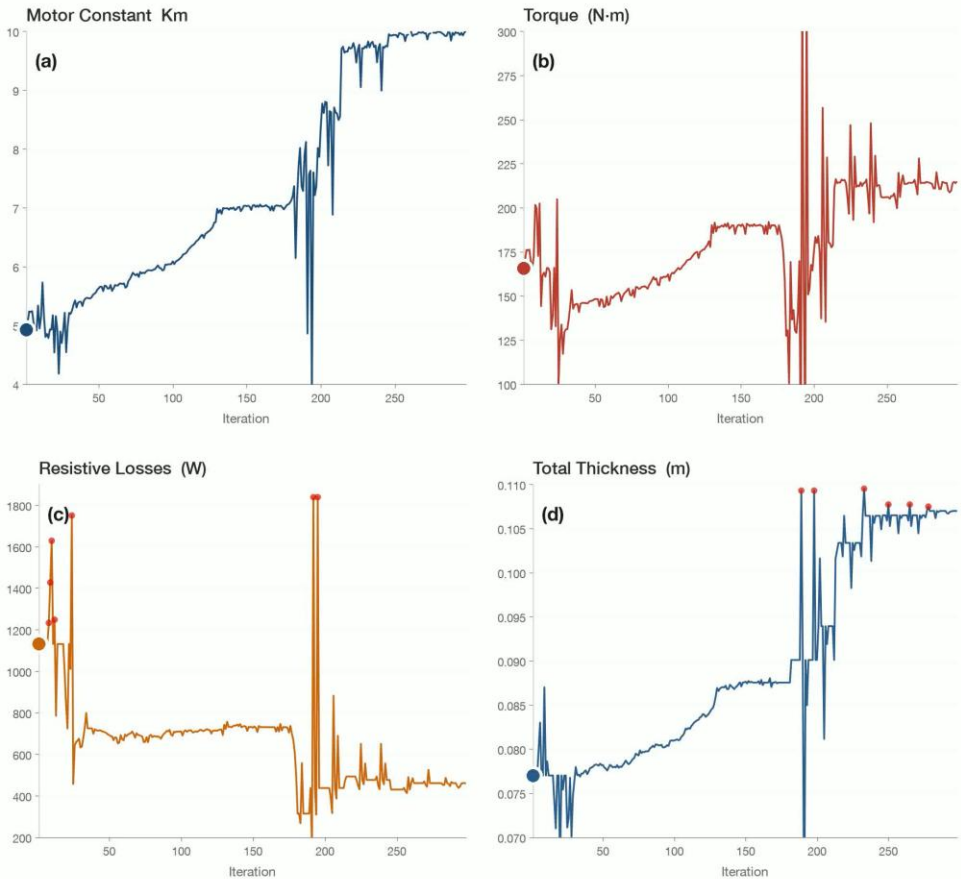
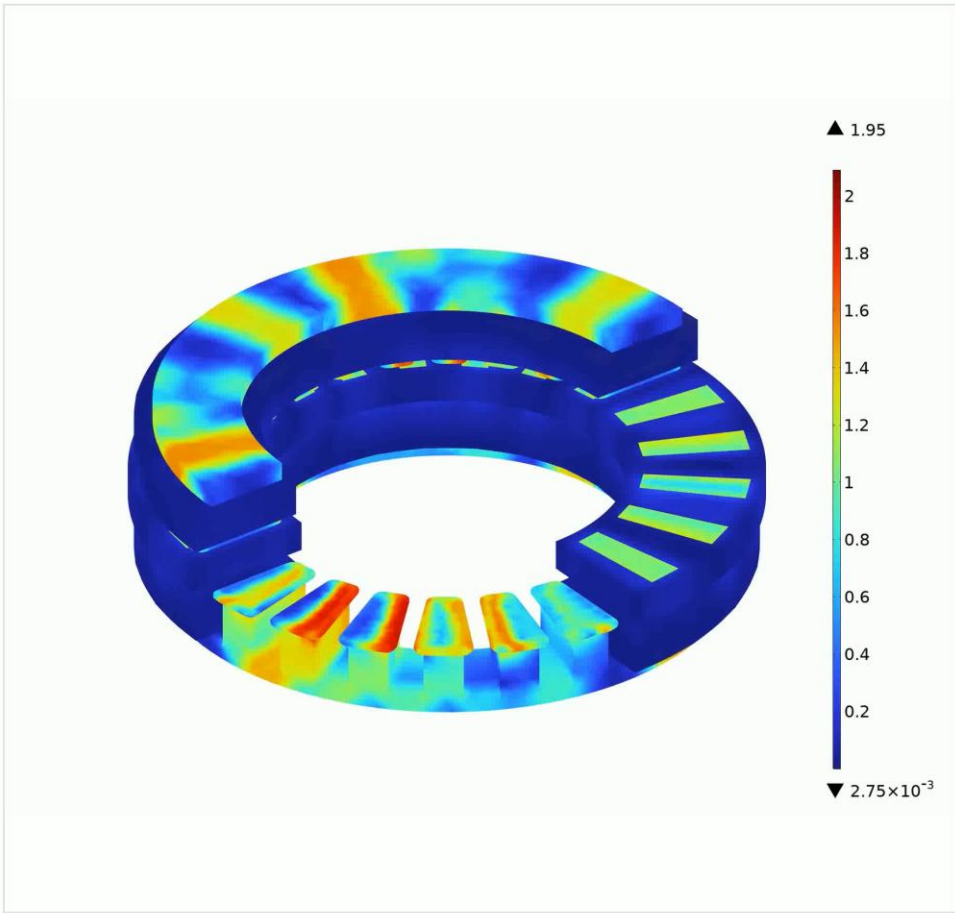
- Implementing the **parametric optimization** module
- Targeting **11 geometric and 2 electrical** parameters
- Chosen by customers:
 - **Objective function**
 - Motor constant
 - Torque density
 - **Constraints**
 - Thickness
 - Total heat loss
 - Radius



Algorithm



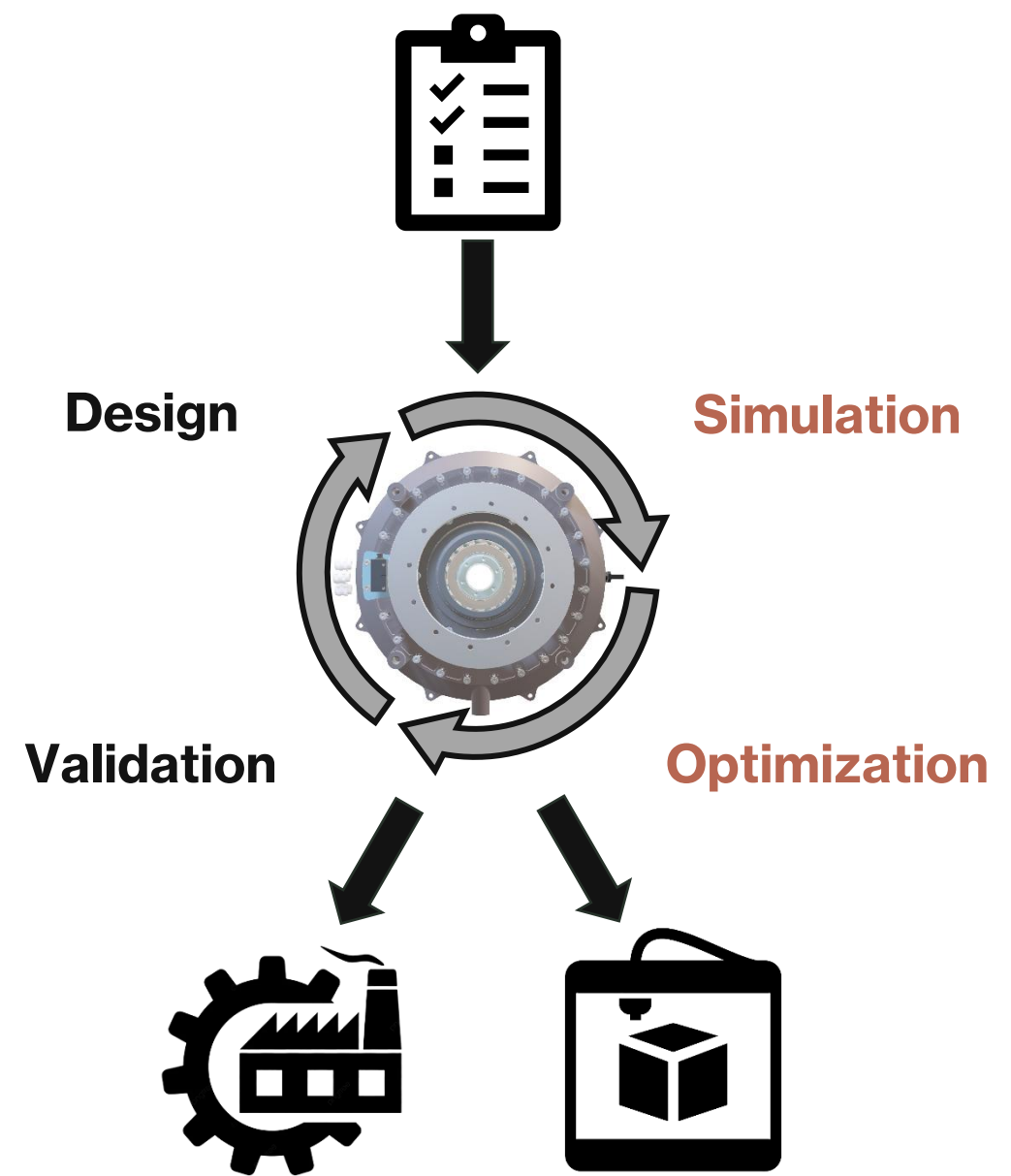
Optimization Demonstration



ITERATION	MOTOR CONSTANT	TORQUE	LOSSES	THICKNESS
1 of 298	4.922 Km	165.5 N-m	1130.9 W	77.00 mm

Conclusion

- Simulation output **verifiable and validated**
- Integration of **additively manufactured material** using existing models
- **BOBYQA** works effectively as primary optimization algorithm
- Implementation of COMSOL Multiphysics© in development pipeline



Questions?

Thank you for your attention

Presented by: **Haixiao Wang**

Supervisor: **Dr. Michael Tucker, Prof. Dr. Bambach**

Special thanks to **Dr. Sven Friedel** and **Alyona Friedel**
for their continuous support of **AMflux**

