

PORSCHE

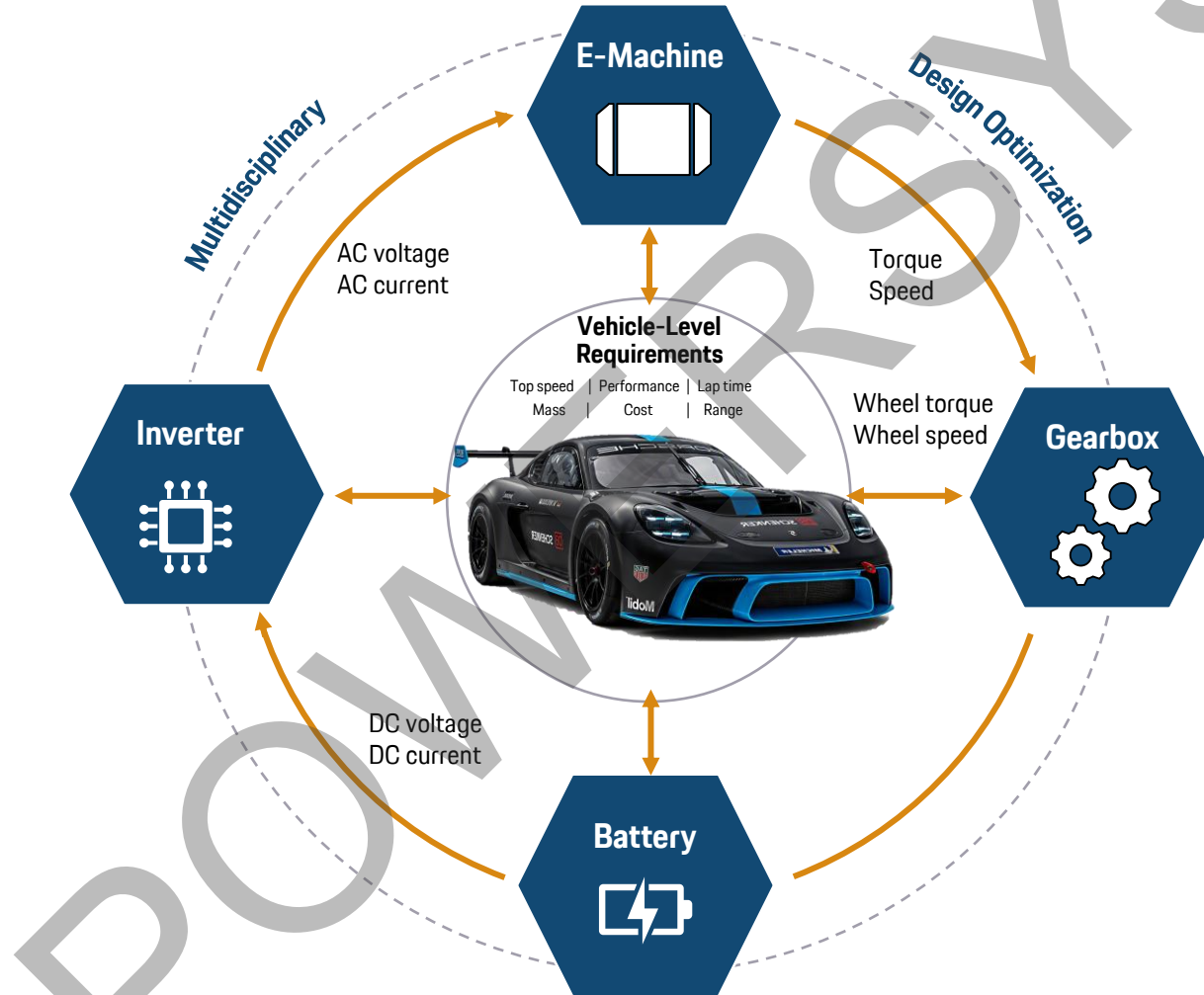
AI Accelerated Multi-Objective Optimization of High-Performance Axial Flux Powertrains Using a Holistic Data Driven Workflow

Vehicle-Level Requirements



Holistic Optimization of the Electric Powertrain

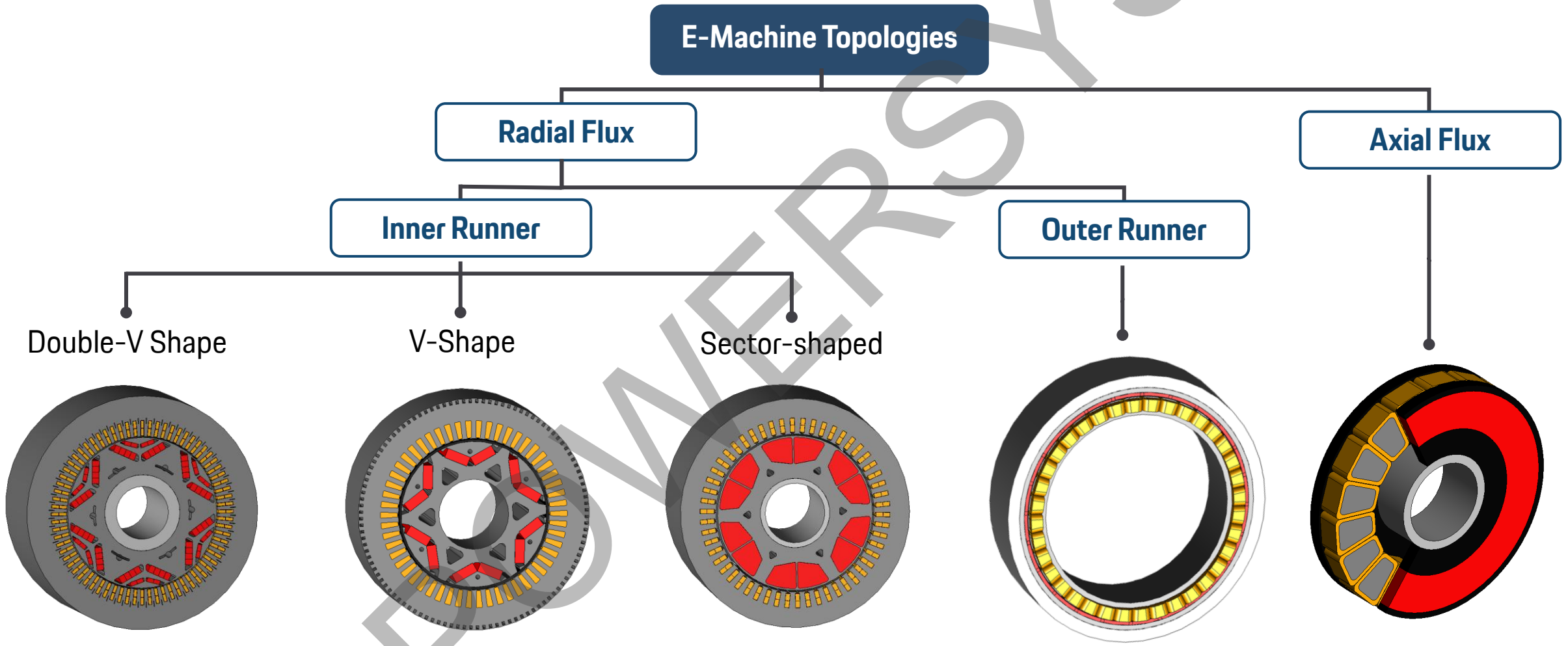
Coupled vehicle and component design based on vehicle-level requirements



Powertrain Components

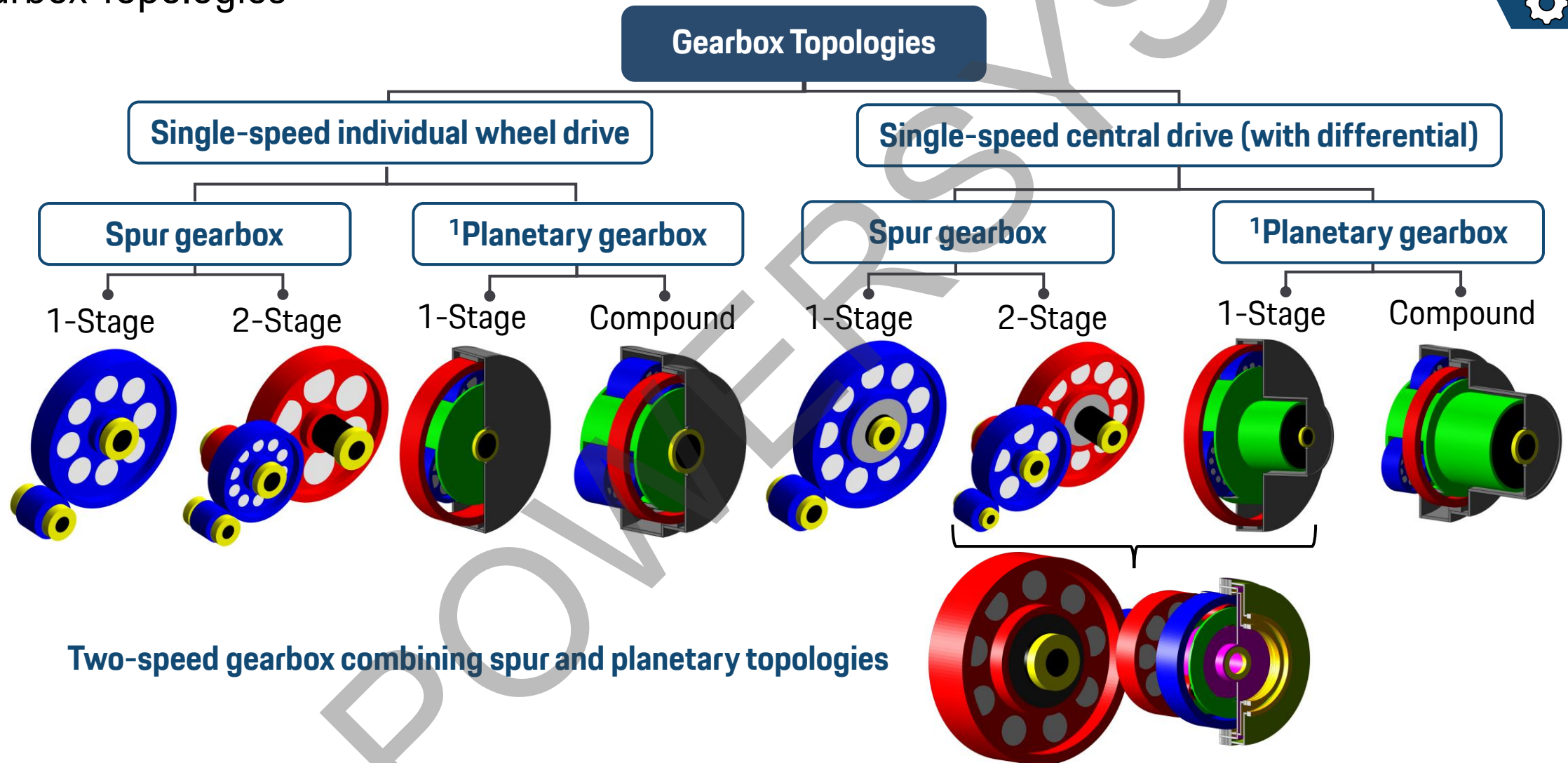
Electric Machine Topologies

E-Machine



Powertrain Components

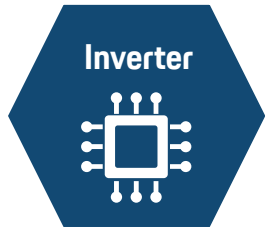
Gearbox Topologies



¹Master Thesis: Jens Hoffmann (EFA1), "Increasing Torque and Power Density of Electric Drive Systems by Means of Holistic Optimization"

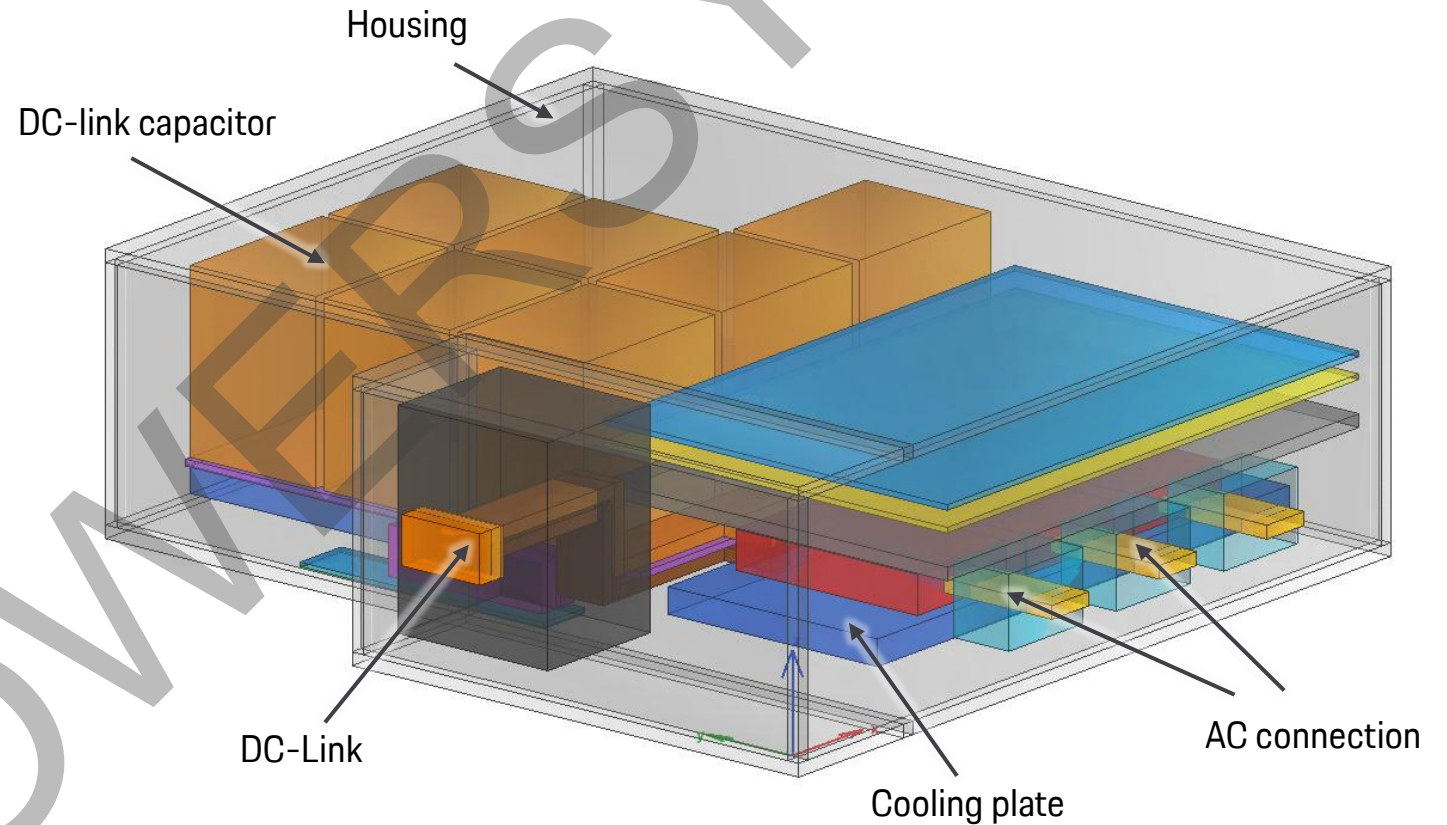
Powertrain Components

Inverter Topology



Fully parametric model:

- Power module configuration (Number and area of semiconductors)
- DC-link capacitor
- DC and AC connection
- Current sensors
- Housing
- Cooling system (cold plate or direct/immersion cooling)



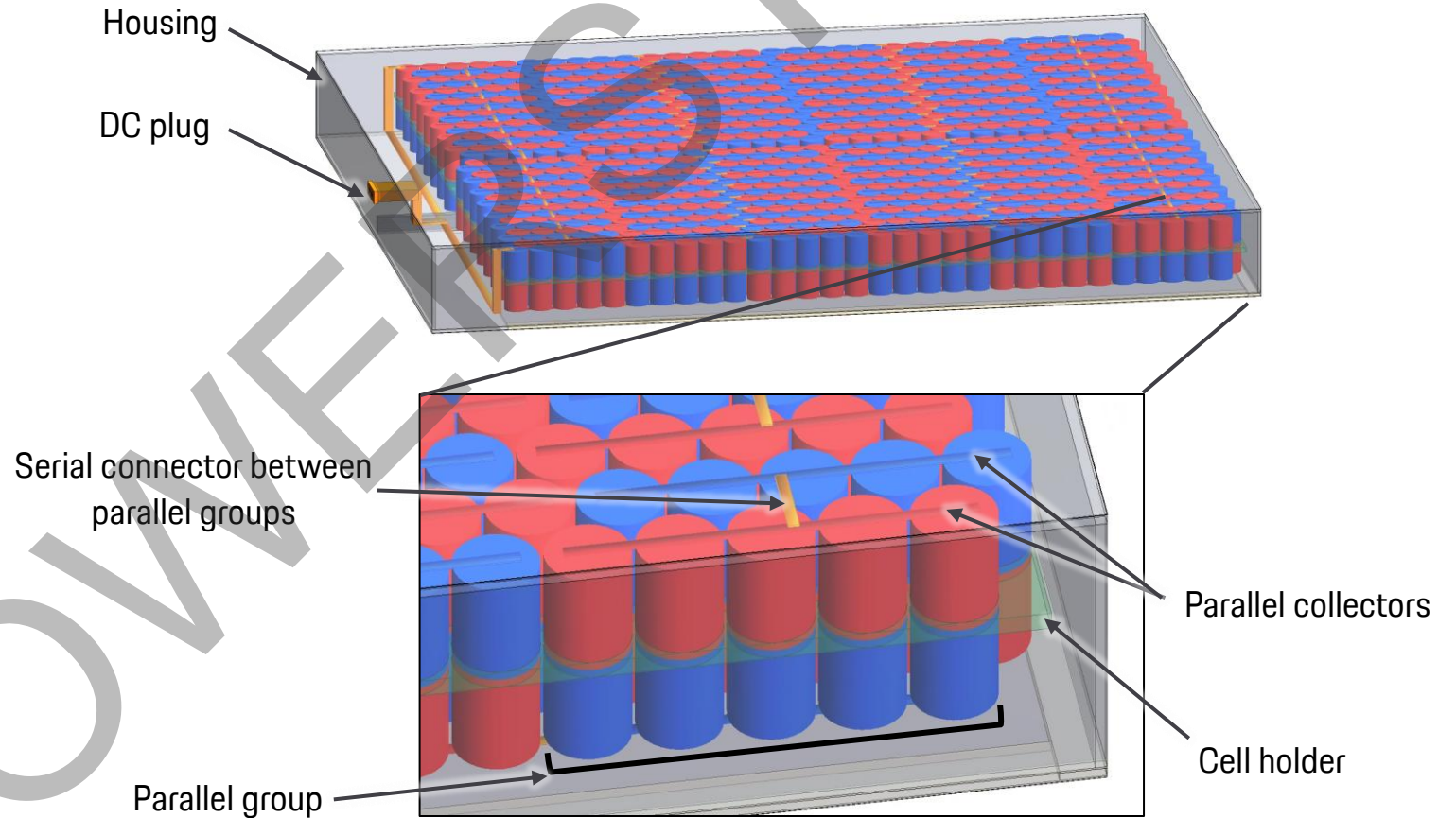
Powertrain Components

Battery Pack Topology



Fully parametric model:

- Cell configuration and electrical interconnection
- Parallel busbars between parallel cells
- Serial connectors between parallel groups
- Housing
- Cooling system (plate or immersion)
- E/E box (MSD, Pyrofuse, ...)
- BMS (BMS master, BMS slave, current & temperature sensors)



Source: Jens Hoffmann

Vehicle Dynamics Simulation

Racetrack

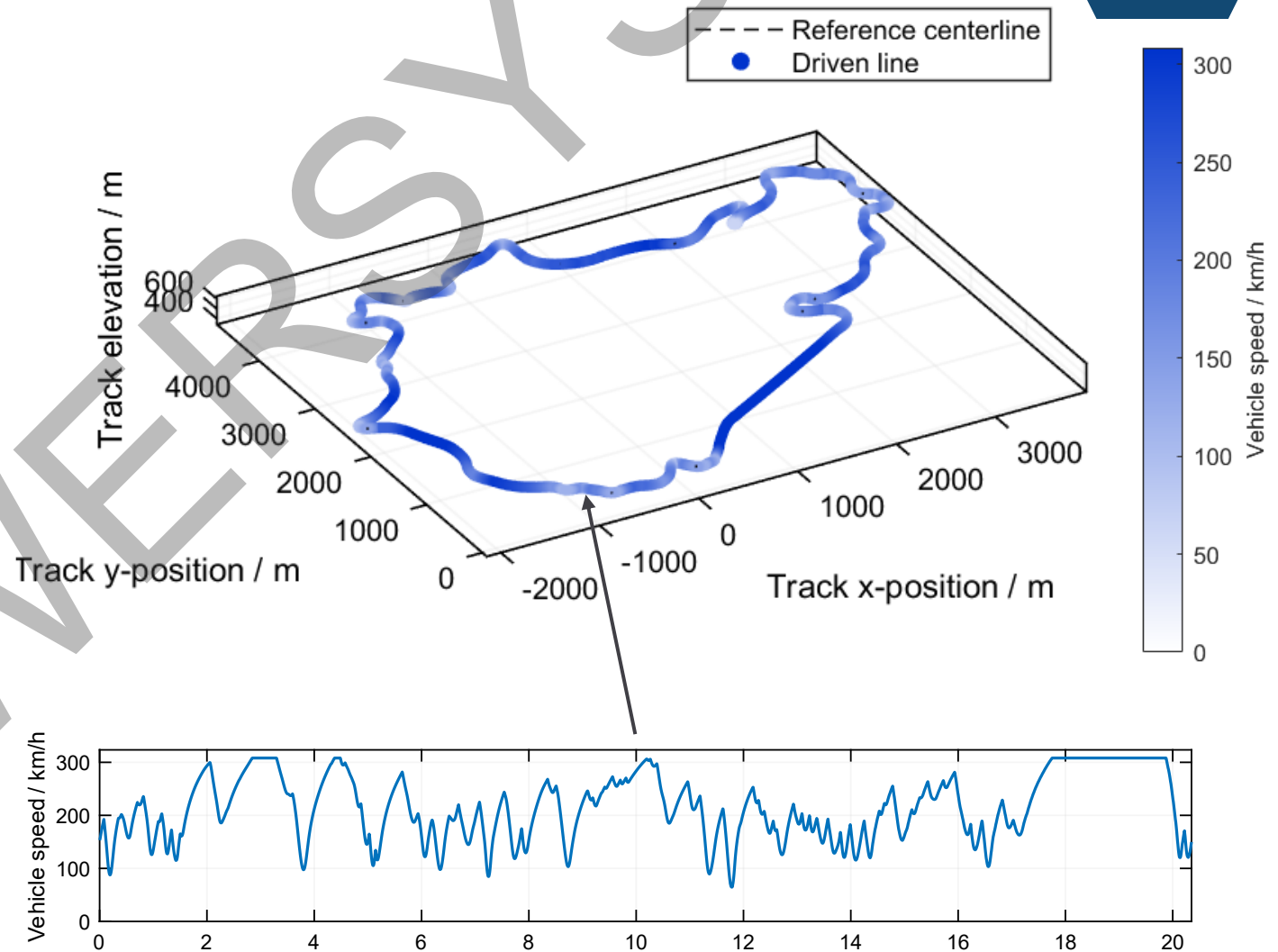
Racetrack simulation for evaluating the dynamic performance of a high-performance vehicle and determining the minimum lap time

Track data and interpolation:

Track is described using x, y, z coordinates and interpolated at constant steps Δs to ensure numerical stability

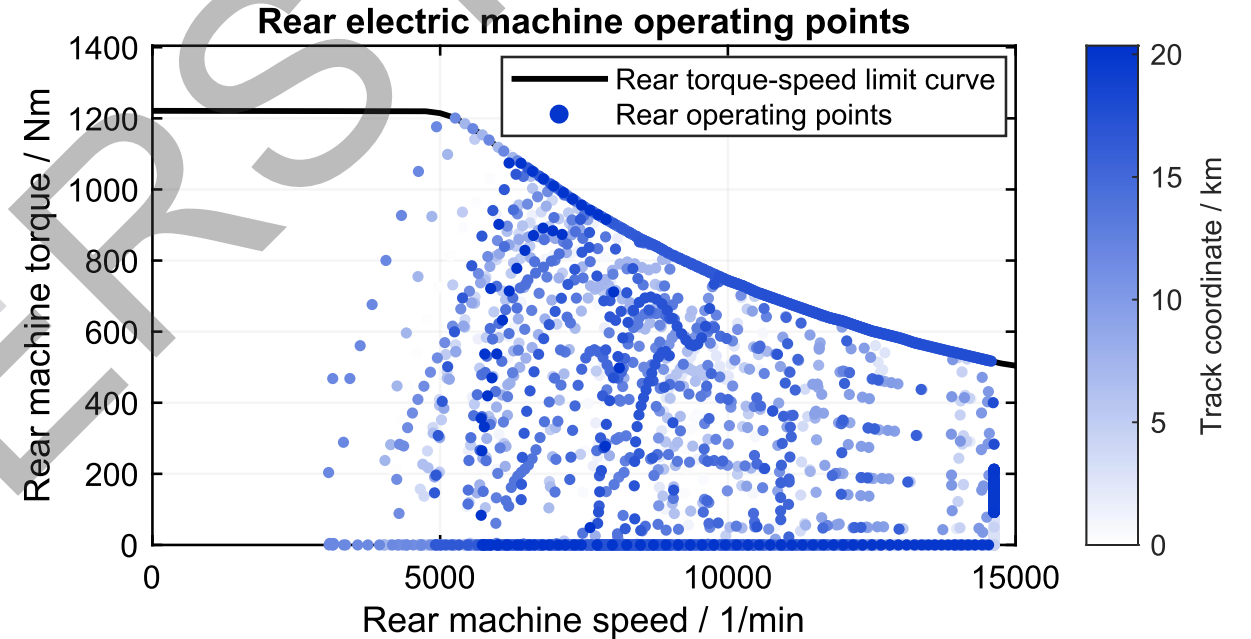
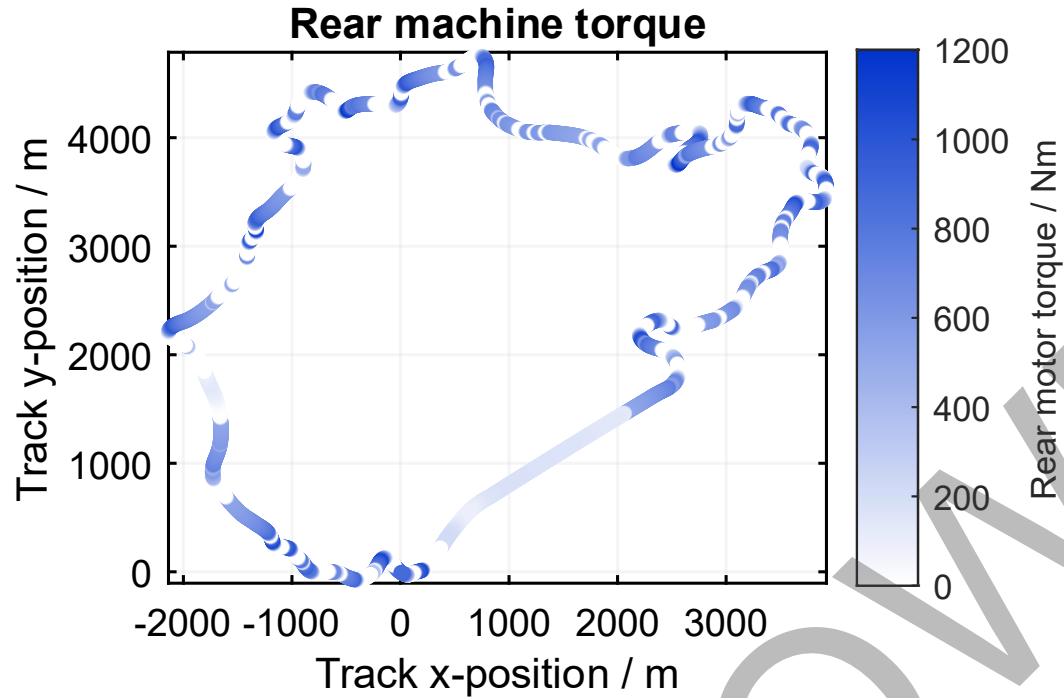
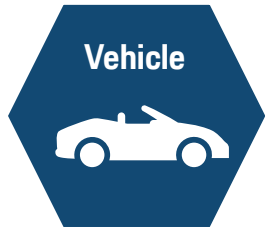
Geometric parameters:

Curvature κ , direction of travel ψ , and gradient α are derived from the coordinates and influence lateral acceleration and tire grip



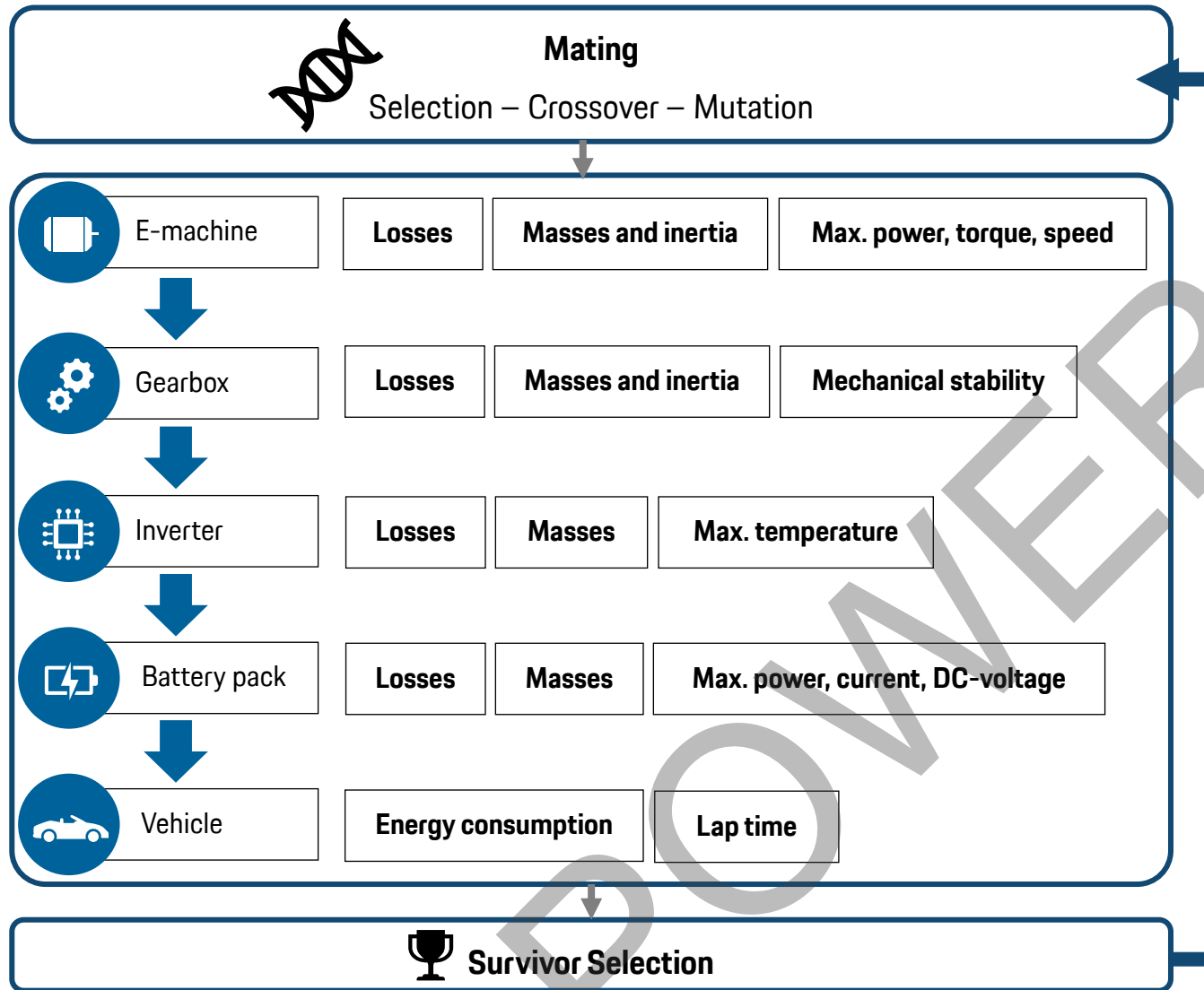
Vehicle Dynamics Simulation

Racetrack



The simulation considers the torque-speed limit curve, gearbox efficiency, and a torque-rate limit

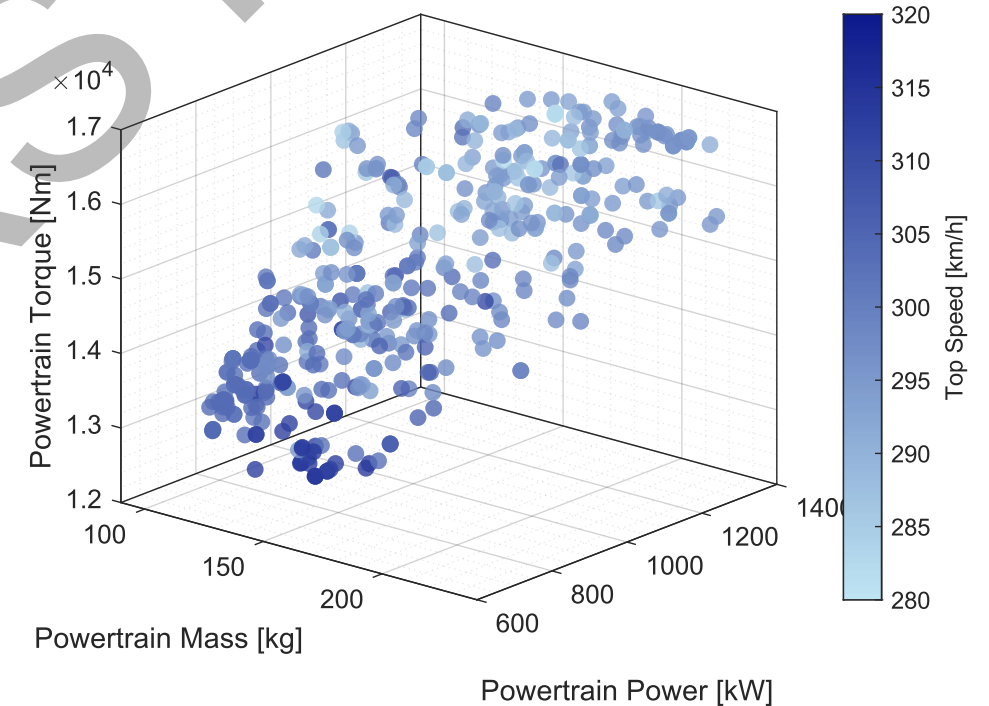
Holistic Multi-Objective Optimization at System Level



E-machine: High-speed axial flux

Gearbox: Planetary single-stage

Inverter: Three-level voltage source



Total number of evaluated powertrains: 80,000

Calculation time: 38 min on a workstation (Intel Xeon, 16 CPU cores, 4.1 GHz)

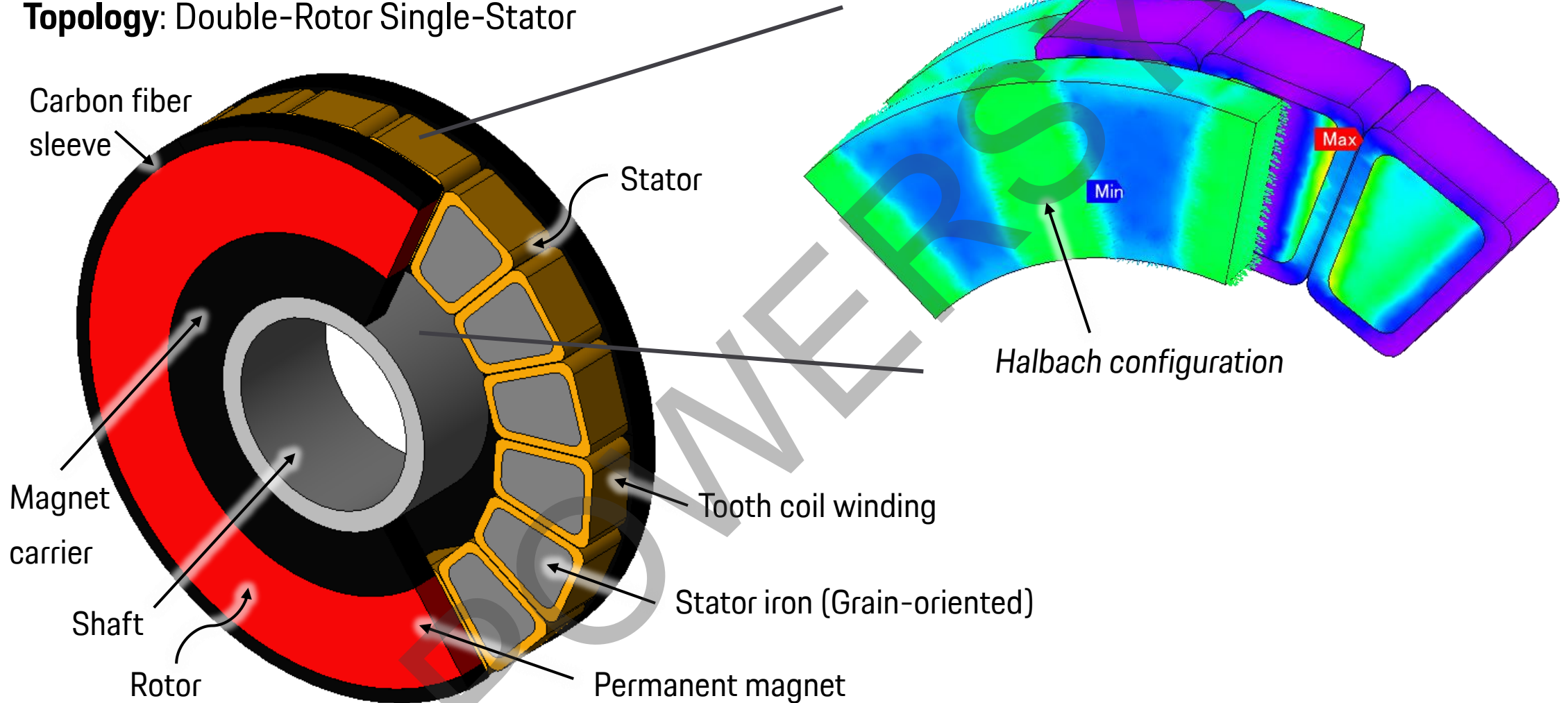
→ Evaluation of **33 powertrains per second**

Axial Flux Machine Design and Calculation Procedure

Design Overview

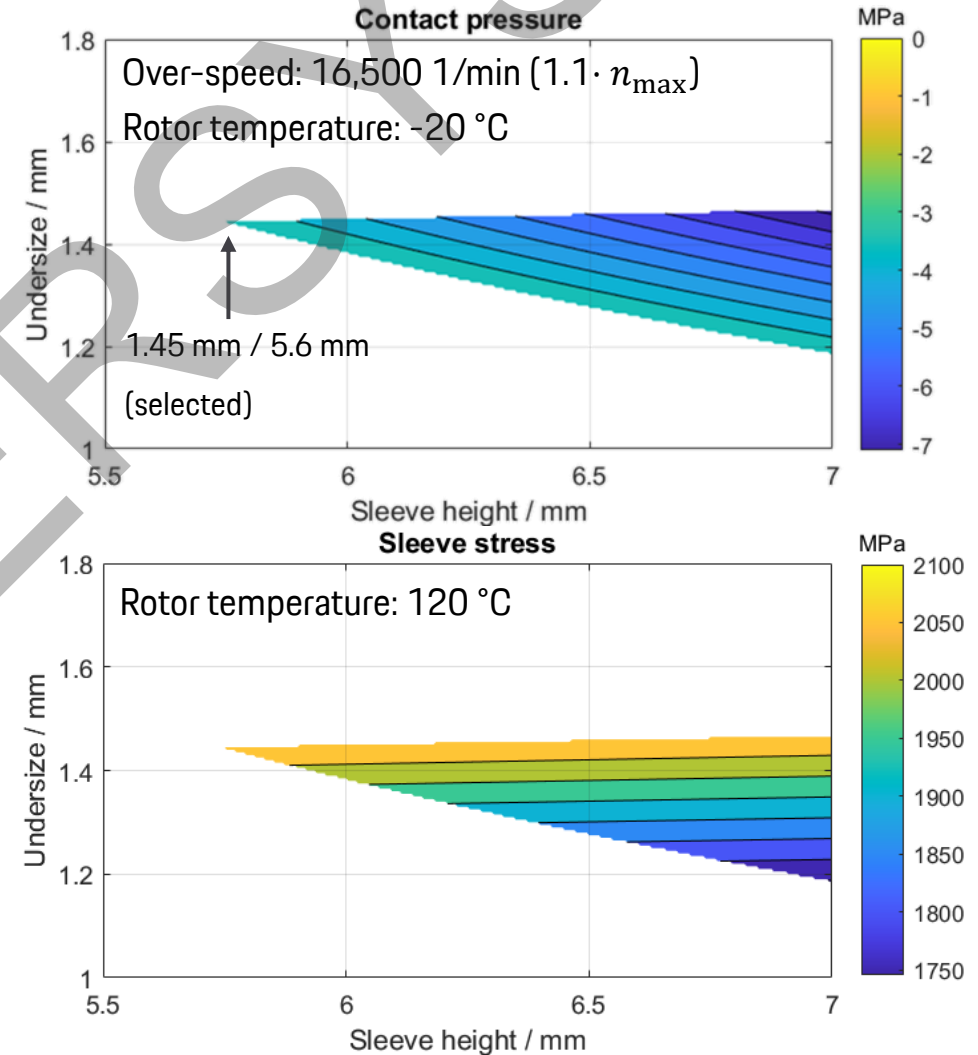
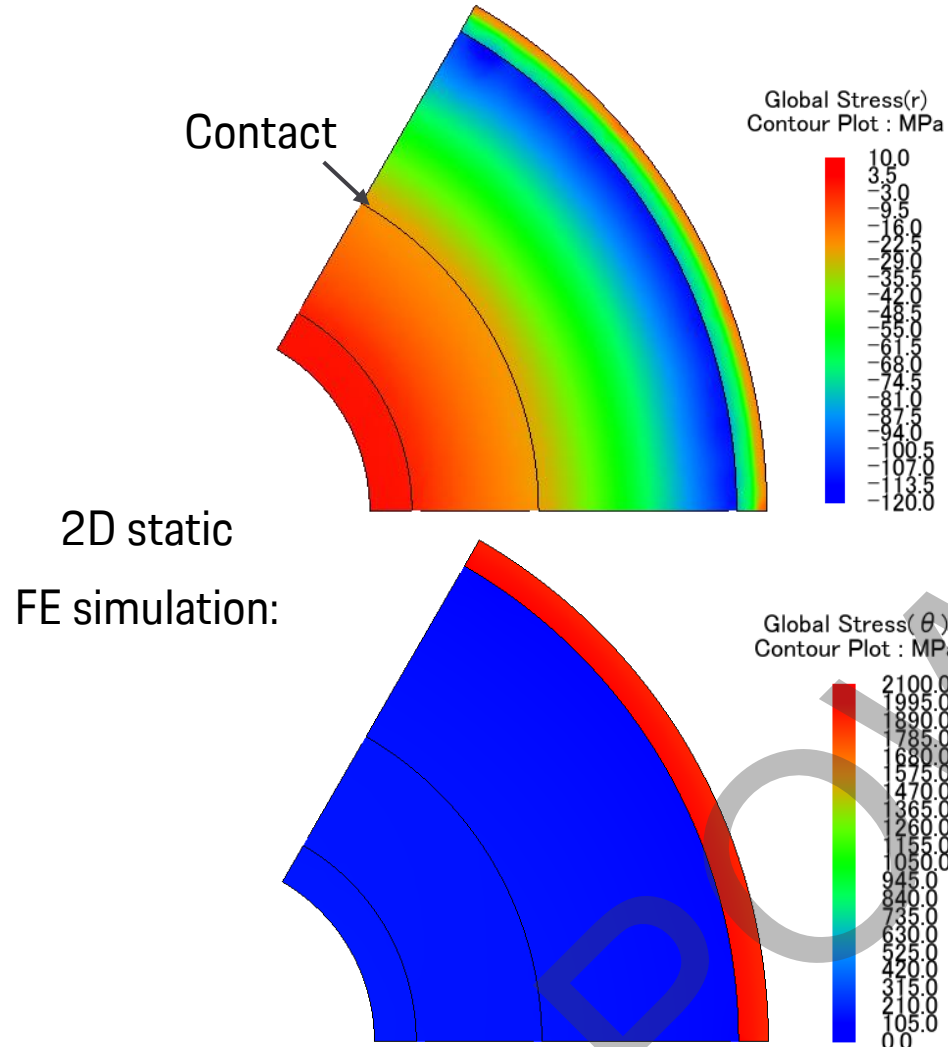
Topology: Double-Rotor Single-Stator

Full-load operating point: 775 Nm (phase current: 860 A, current angle: -4°)



Axial Flux Machine Design and Calculation Procedure

Mechanical Calculation Method



Axial Flux Machine Design and Calculation Procedure

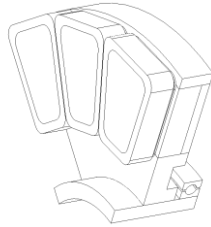
Numerical Calculation Method

Key simulation challenge: Accurately resolving eddy currents in the segmented magnets required a very high mesh density.

Simulation model

2.4 M

mesh elements



130

time steps per case

11

machine parameters

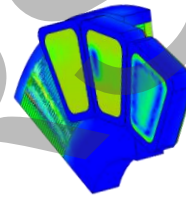
200

machine designs

Licenses 3D FEM

PSL200:TR

3D transient solver



PSL200:LS

iron-loss solver

PSL200:PP

pre-/post-processing

Parallelization: 8 cores per case and 200 cases in parallel

HPC hardware

1,600

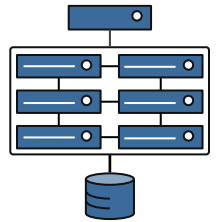
CPU cores total

2.3 GHz

clock speed

384 GB

RAM per node



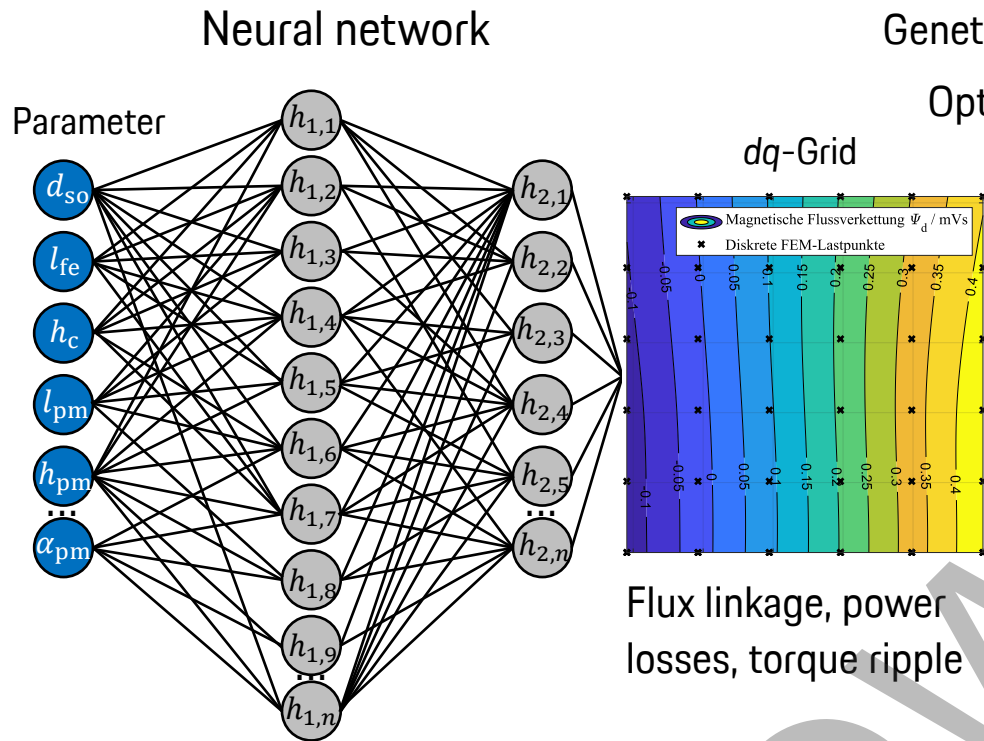
Intel Xeon Platinum 9242

InfiniBand: 100 GB/s

HPC simulation time: $\approx$ 4 days: Parametric model → 3D transient FEA → Iron-loss calculation → dq-grid data

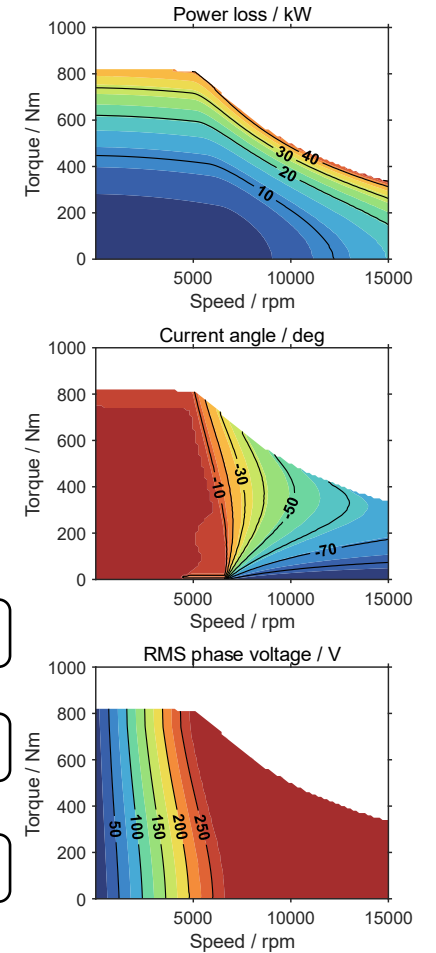
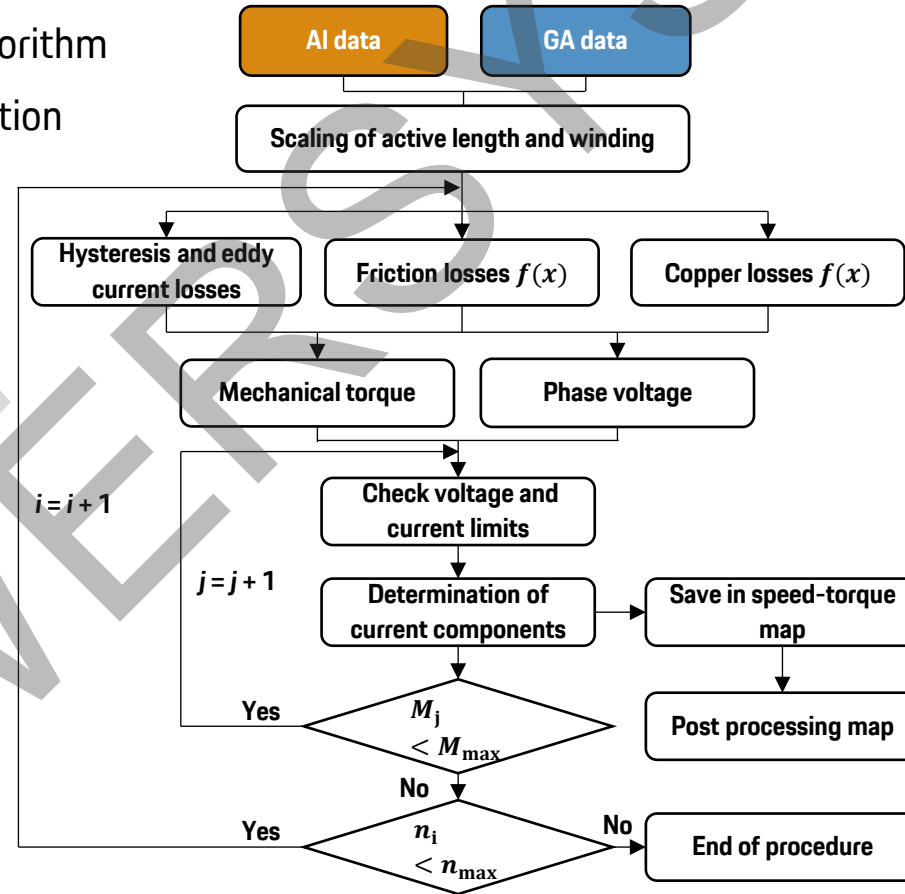
Axial Flux Machine Design and Calculation Procedure

AI Calculation Method



Design representation through multiple individual networks. Training time ≈ 20 s

Genetic Algorithm
Optimization

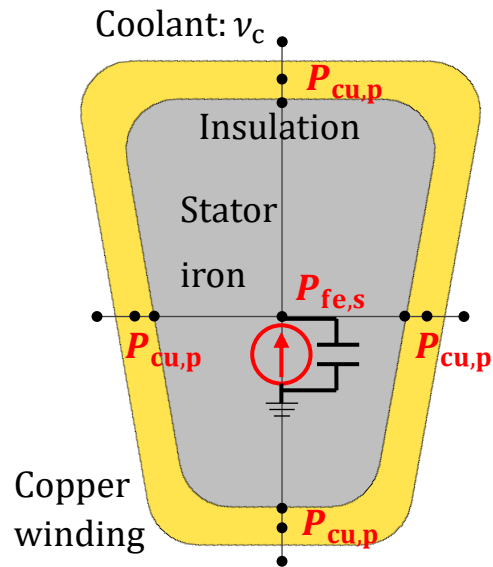


Use of a **surrogate model** for finite element data with post-processing in the fitness function of the genetic algorithm

Axial Flux Machine Design and Calculation Procedure

Thermal Calculation Method

Generation of the lumped-parameter thermal network model:



Loss:

$$P_{cu,p} = 0.25 \cdot P_{cu}$$

Thermal capacitances:

$$C_i = m_i \cdot c_{p,i}$$

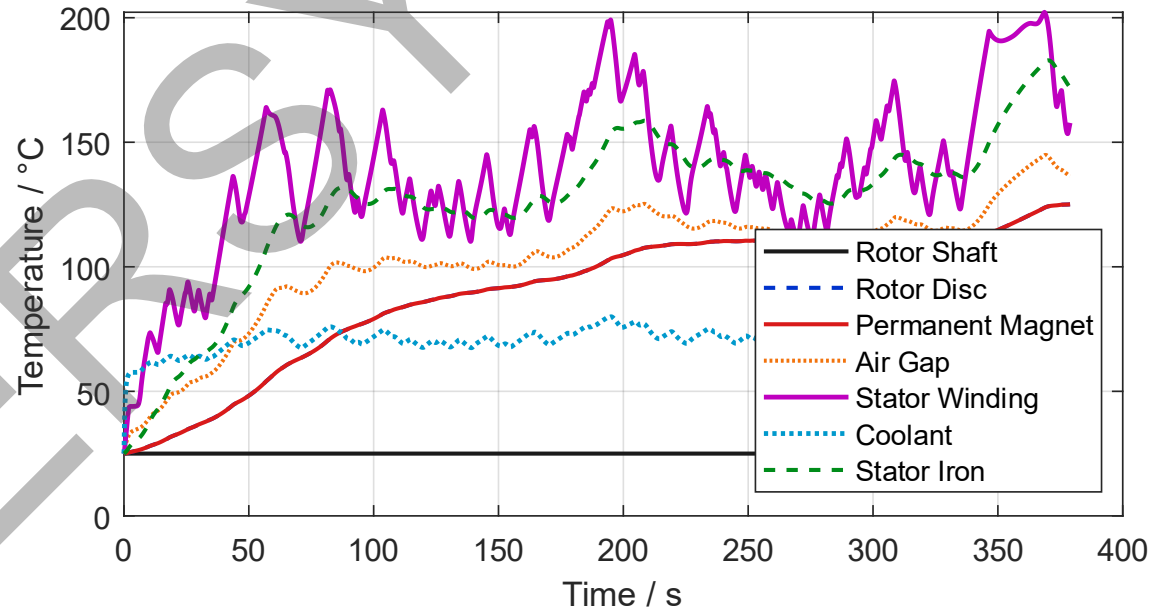
Thermal resistance:

$$R_c = \frac{1}{\alpha \cdot A}$$

$$R_{cyl} = \frac{\ln(r_a/r_i)}{2 \cdot \pi \cdot \lambda \cdot l}$$

- Analytical calculation of pressure drop, Reynolds number, Nusselt number, and heat transfer coefficient of the cooling channels
- Speed-dependent heat transfer in the air-gap based on analytical correlations

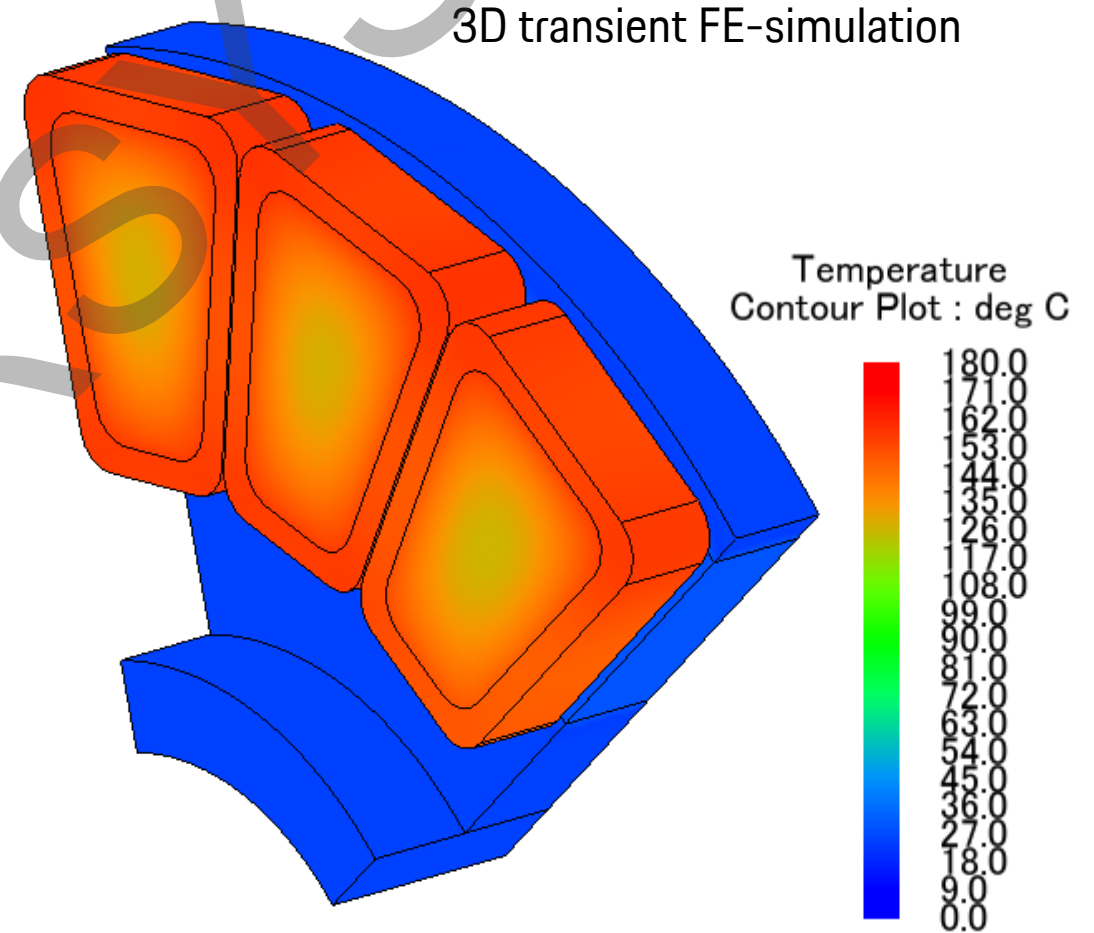
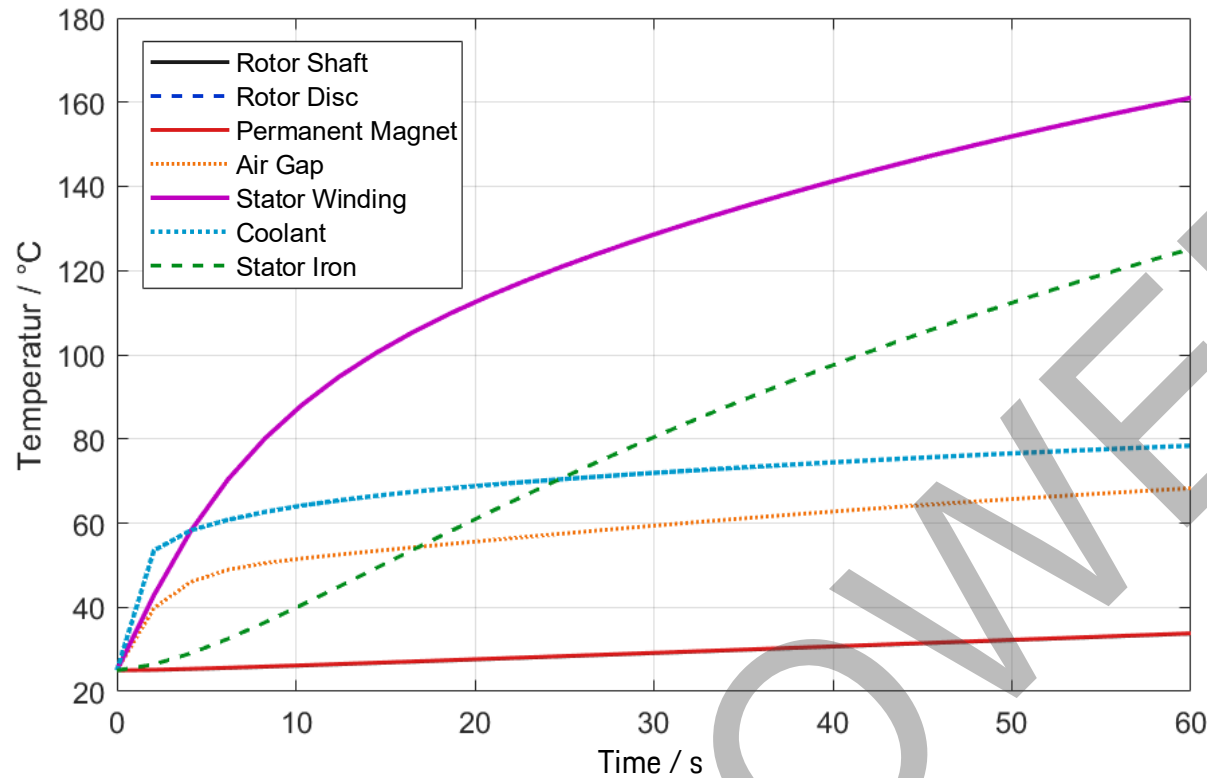
Temperature profile during a Nordschleife lap



Automatic generation of models for thermal load analysis based on analytical formulations

Axial Flux Machine Design and Calculation Procedure

Thermal Calculation Method



Comparison with the 3D thermal FE simulation shows deviations of less than 5 K

High-Performance Powertrain Optimization Study

Optimization Results

System:

Max. DC-link voltage: [650, 780] in V

Max. phase current: [900, 1080] in A

E-machine:

Stator iron length: [22, 32] in mm

Number of turns: [20, 24]

Gearbox:

Gear ratio: [6, 7]

Normal module: [1.0, 4.0] in mm

Inverter

Chip area: [5, 35] in mm²

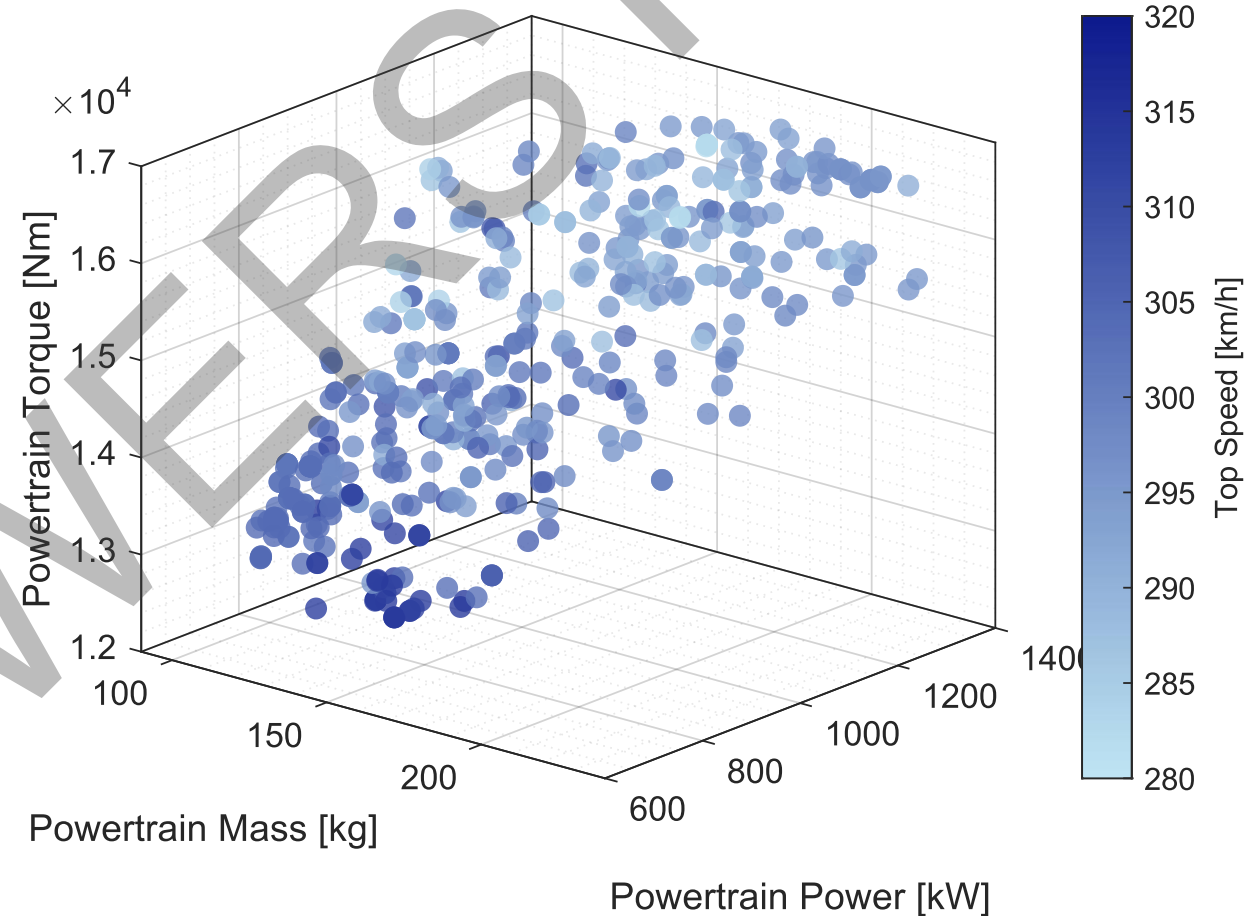
Number of parallel chips: [10, 50]

Battery pack:

Battery capacity: [90, 120] in kWh (gross)

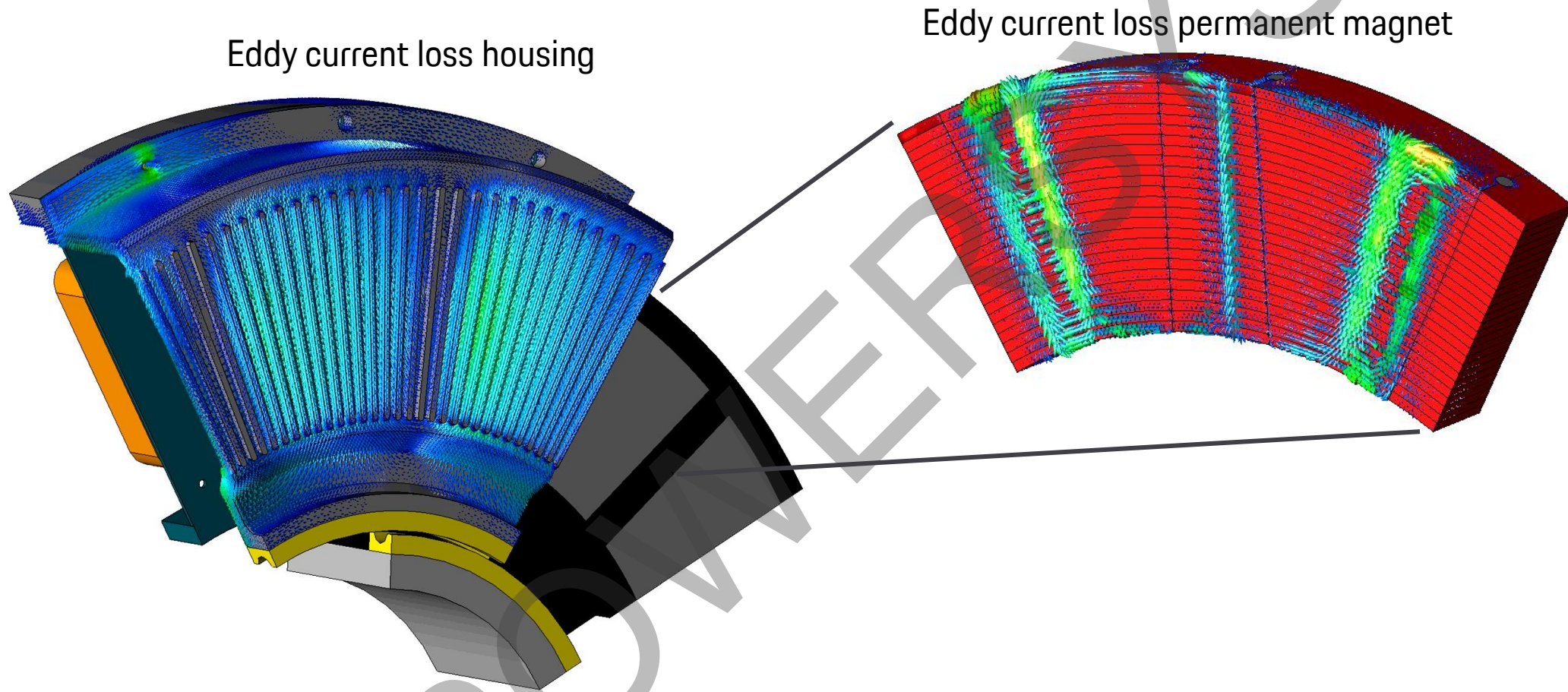
E-Machine: High-speed axial flux | **Gearbox:** Planetary single-stage | **Inverter:** Three-level voltage source

Individual rear wheel drive



High-Performance Powertrain Optimization Study

Design Validation Using 3D FEA



Automated 3D FEA calculation method for design validation

System-Level Conclusions

Takeaways

At *Porsche*, high-fidelity, large-scale simulation with *JMAG Designer* is shaping the future of powertrain development, enabling data-driven optimization across electromagnetic, thermal, mechanical, and vehicle-level domains to achieve maximum system performance.

01

Powertrain mass

<100 kg

Low machine mass combined with low gearbox mass.

02

Powertrain power density

> 10 kW/kg

High powertrain power density due to low powertrain mass.

03

Powertrain torque density

> 100 Nm/kg

High powertrain torque density due to low powertrain mass.

