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Concept for a GaN-Based Intelligent Motor Controller with Integrated Failure Prediction for the Inverter and the Drive

Fraunhofer IISB

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1. Concept

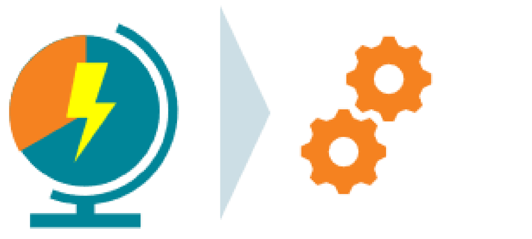
Motivation – Reliable Electrification for Industrial Drives

Efficiency: GaN in FOC controlled motors

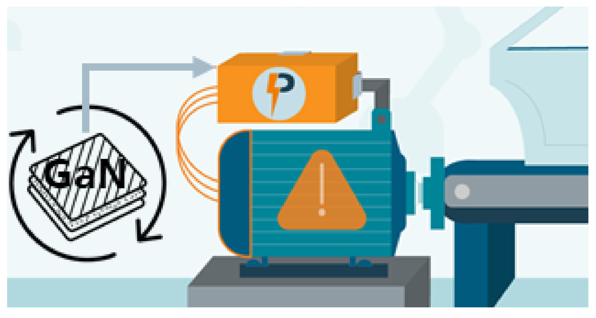
- Reduced power losses in motors and less heat
- Smaller passive elements (higher current-carrying capacity and switching frequencies)
- Improved power quality (fewer harmonics) [1]

Reliability: Major challenges for Industry

- Reliability and maintenance costs as main industrial restriction for novel power devices [2]
- Semiconductors and capacitors are most failure-critical, accounting for > 50% of unplanned maintenance costs) [3]



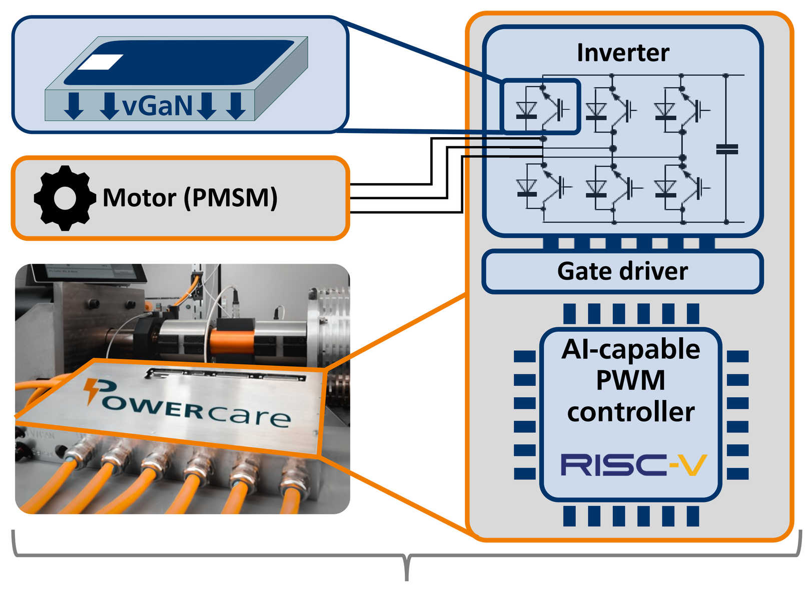
Driving industrial motors takes **30% of global electricity use**

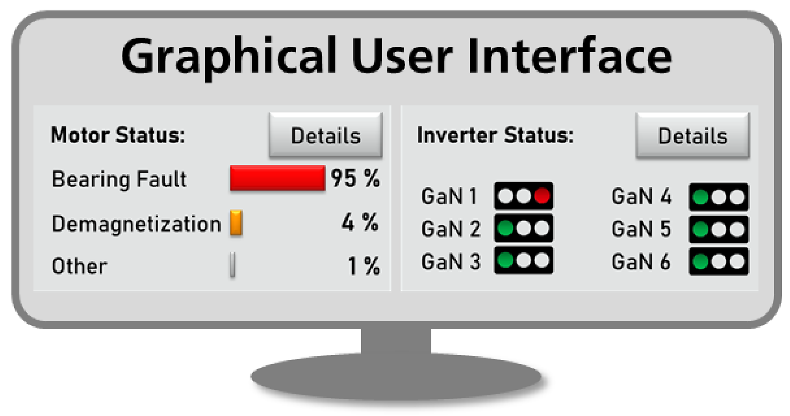


Potential **savings of 124 megatons CO_2e per year** through GaN drive inverters [4]*

Concept with Three Goals

1. **Novel, vertical GaN** trench MOSFETs and their behavioral models,
2. **Embedded AI** models for failure prediction of electric motors and GaN power semiconductors,
3. **System demonstration** of GaN MOSFETs and **intelligent motor control**





Embedded AI Models for Failure Prediction

- Development of two failure models with implementation on a RISC-V based power module for real-time execution
- Various approaches were evaluated for their ability to detect anomalies, classify failures, and their feasibility on memory-constrained microcontrollers

Electric motor AI model

- Uses a hybrid approach combining specific pre-processing of sensor data, a compact model component and a machine learning model
- Tracks changes in load current and other data like vibration and rotation rate to detect faults such as bearing damage, demagnetization, and winding faults

Transistor and inverter failure models

- Use life test data and parameter measurements for training failure
- Employ SPICE-based simulations to manage data size and incorporate system-level effects, with outcomes empirically validated and adjusted

AIfES

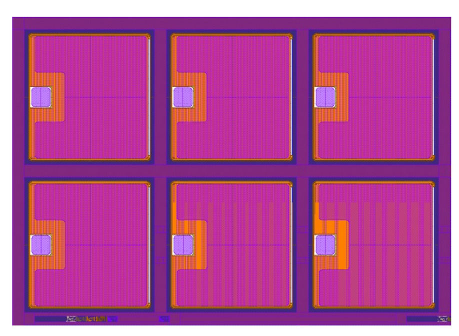
- Edge AI framework by Fraunhofer IMS
- Supports on-device training and inference, enhancing privacy and reducing energy consumption by avoiding data transfer to more powerful devices
- Ensures sufficient memory during operations and outperforms other solutions in terms of execution time and memory usage, offering significant memory savings

AIfES

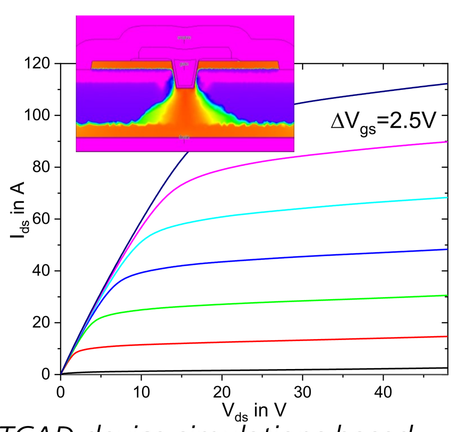
Vertical GaN Design, Manufacturing & Characterization

Design & simulation

- System technology co-optimization (STCO) using TCAD process and device simulations
- Creation and optimization of behavioral models for system design
- Implementation of degradation mechanisms in behavioral models
- Thermal and mixed-mode simulations



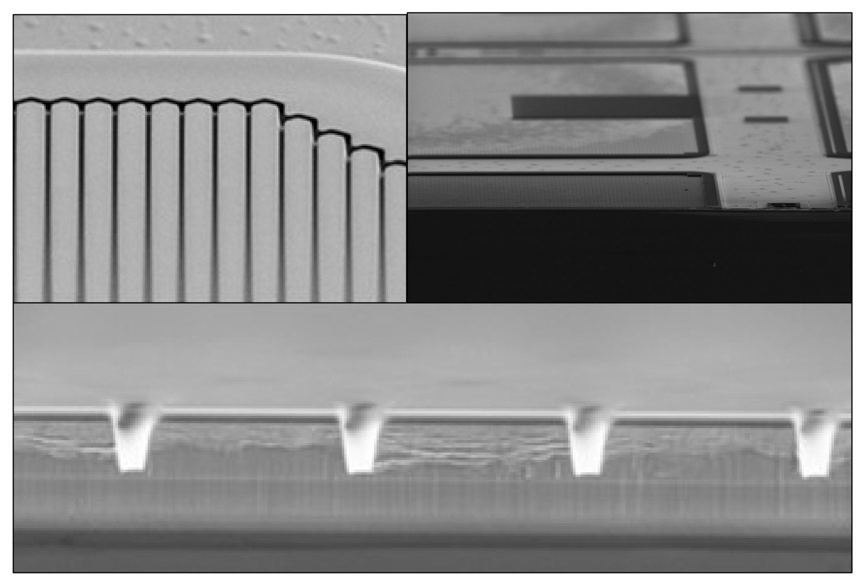
Exemplary design variations.



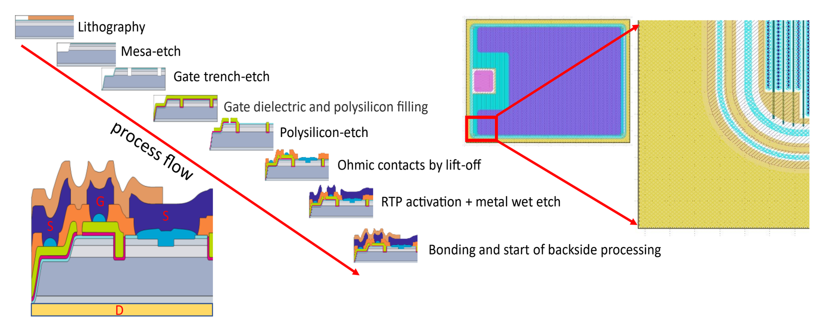
TCAD device simulations based on processing flow and design.

Processing

- In an 8" post-CMOS process line
- Trench-based device design
- Membrane stabilization by carrier wafers
- Complete substrate removal
- Device termination with recess etch
- Scalable GaN epitaxy on QST



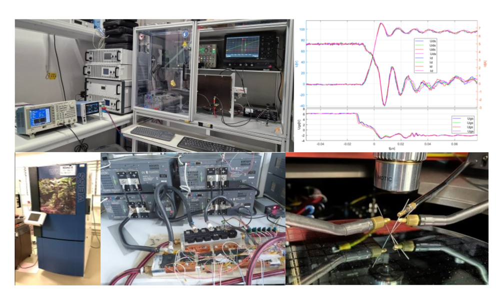
Insights into process development for vGaN.



Schematic overview of the vGaN process modules.

Characterization

- Establishment of high-performance probe stations for double pulse and PIV
- Reliability: Power cycling, thermal and voltage stress tests
- Static and dynamic waferlevel tests



Impressions of various test benches for testing and reliability of power components.

1. M. Wattenberg, E. A. Jones and J. Sanchez, "A Low-Profile GaN-Based Integrated Motor Drive for 48V FOC Applications," PCIM Europe digital days 2021.
2. J. Endrenyi and G. J. Anders, "Aging maintenance and reliability: Approaches to preserving equipment health and extending equipment life", IEEE Power Energy Mag., vol. 4, no. 3, pp. 59-67, May 2006.
3. J. Falck, C. Felgemacher, A. Rojko, M. Liserre and P. Zacharias, "Reliability of power elec-tronic systems: An industry perspective", IEEE Ind. Electron. Mag., vol. 12, no. 2, pp. 24-35, June 2018.
4. Infineon, "Industrial drives: overview and main trends", 2020.

* Assumption: efficiency increase of 3 % (Si-FET to vert. GaN)

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POWERcare
Cognitive power electronics with integrated failure prediction

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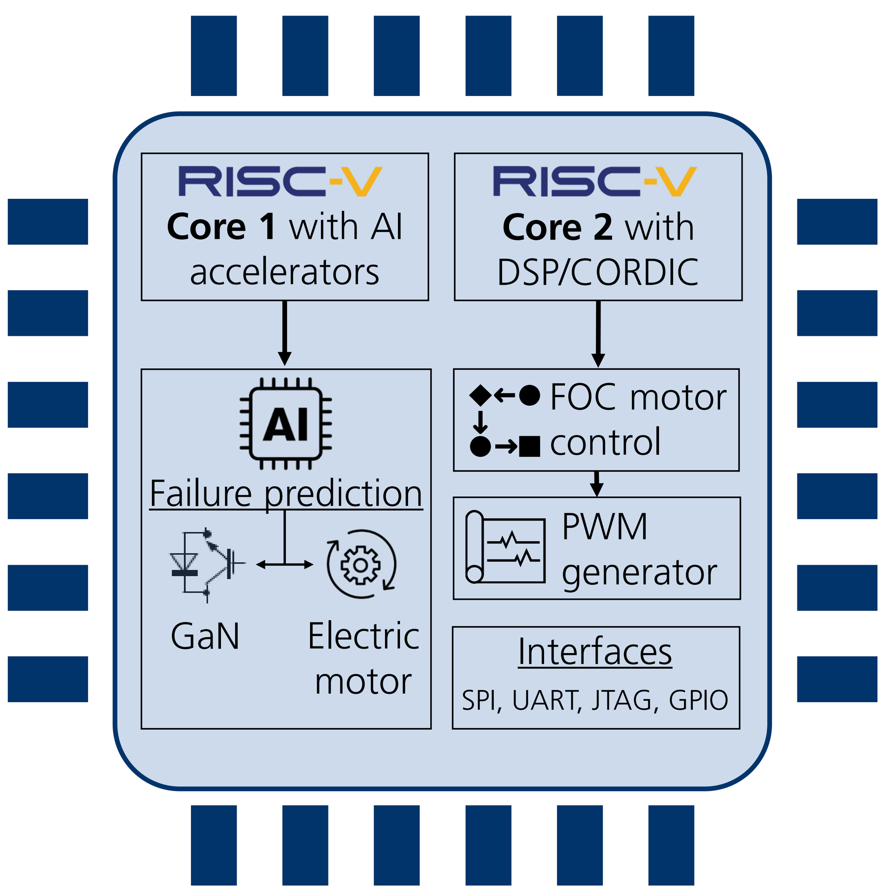
2. Steps towards Implementation

AI-Capable PWM Controller – Dual-Core FPGA on RISC-V Basis

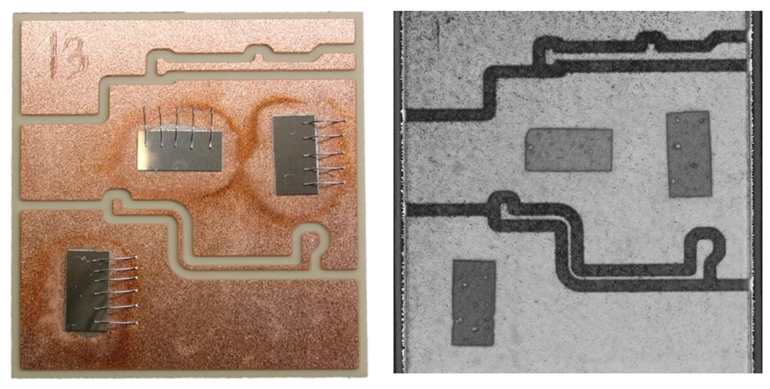
- Core 1 (AI) for local calculation of complex neural networks (CNNs/FCNNs) on the controller, extended by dedicated AI hardware accelerators
- Core 2 (FOC) for motor control, to increase performance with dedicated hardware accelerators (e.g., filtering and trigonometric functions)
- Functional safety available as "ASIL-D ready" automotive standard



Inverter System based on Vertical GaN semiconductors

- Development and prototype realization of a 3-phase inverter system for electric drives based on vertical GaN semiconductors
- Technical specification:

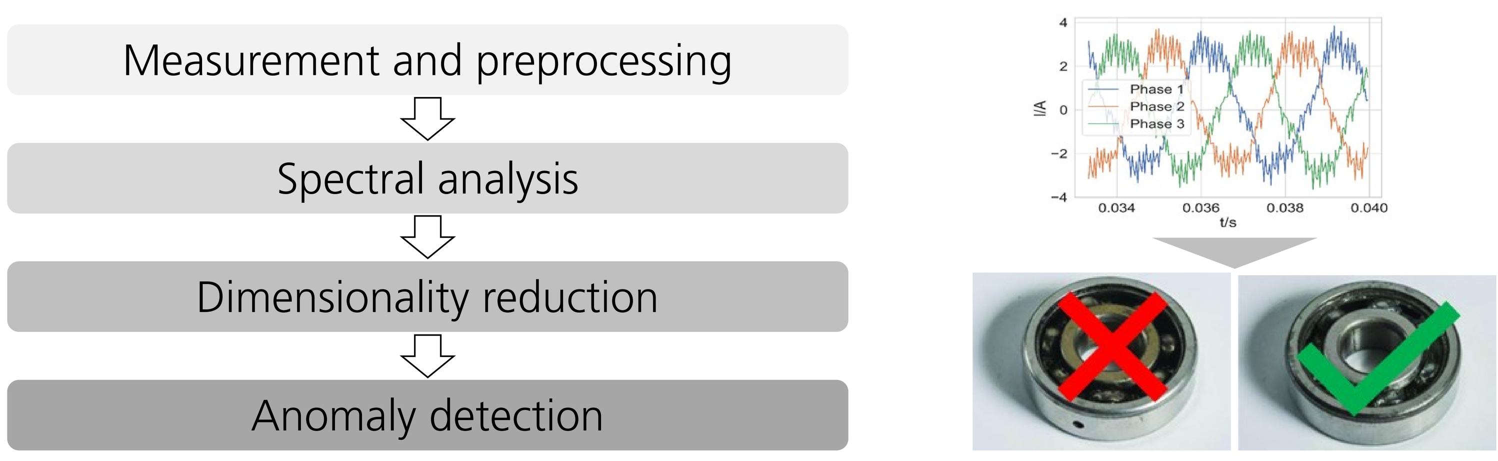
Topology	3-phase B6
DC-voltage	48 V
Peak output power	20 kVA
Phase current	475 A_{rms}
Switching frequency	max. 20 kHz



- Test-bench characterization and benchmarking with inverter systems based on lateral GaN HEMTs

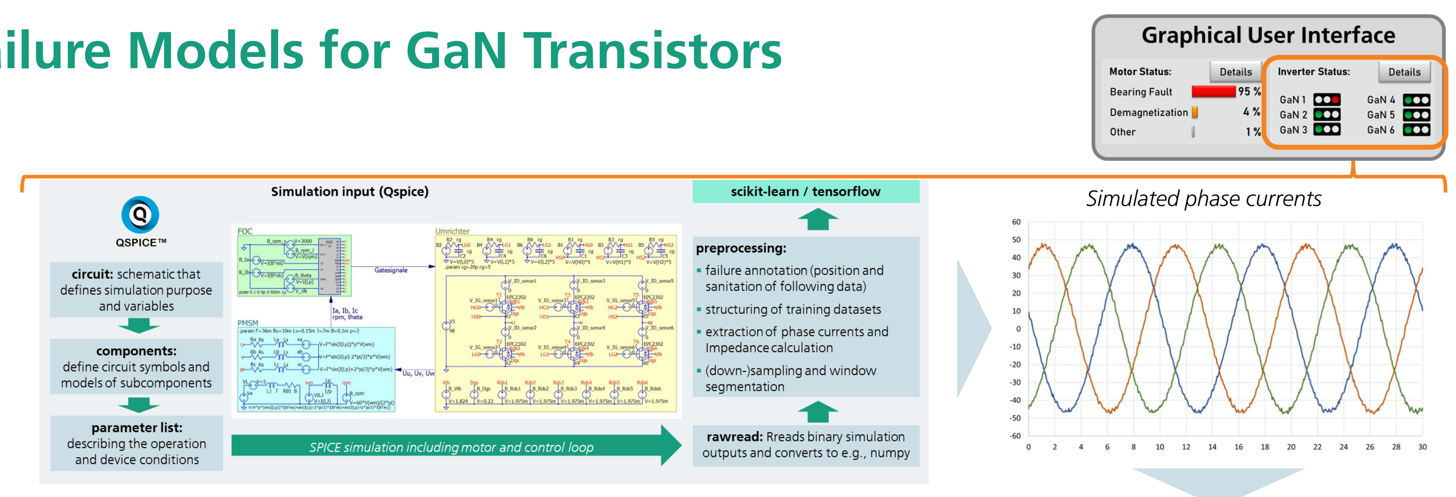
Failure Models for Electric Motors

- Objective: Detecting failures in electric motors using current sensors already present in inverters, aligning with the Cognitive Power Electronics (CPE) concept for condition monitoring
- Initial motor failure detection approach: Semi-supervised, trained only with data from healthy motors to identify deviations from normal conditions

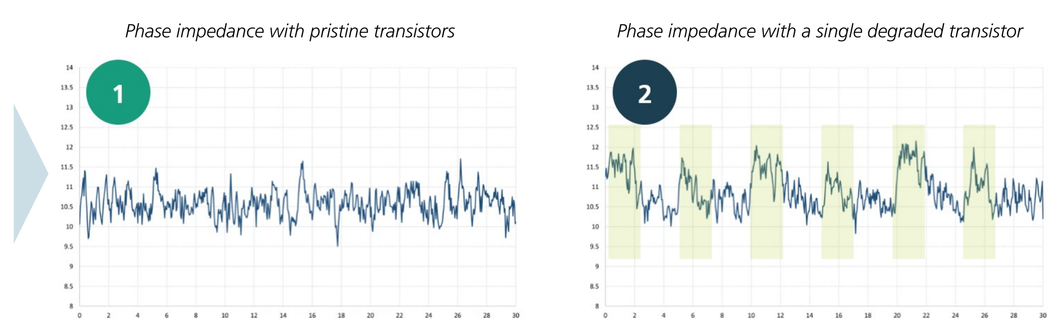


- First results:
  - Initially, the models required significant memory
  - Models were optimized to function efficiently on RISC-V-based motor controllers, reducing memory usage substantially after optimization and conversion using AIfES.

Failure Models for GaN Transistors

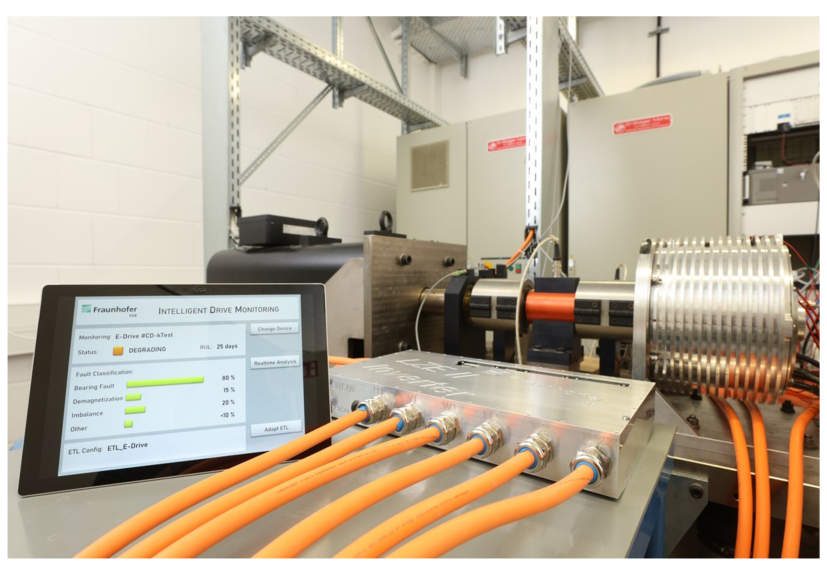


- Deduction of power electronic health based on phase current and control loop parameters only
- AI-based models to overcome challenging signal to noise ratio in real-world applications
- Exemplary impedance time traces for healthy (1) and degraded (2) transistors are shown below



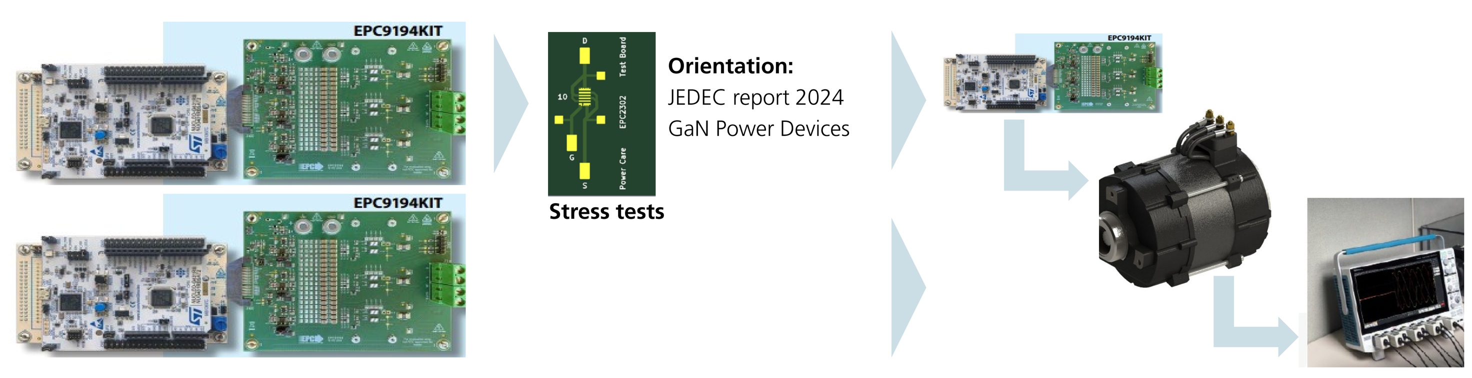
Project Demonstrator

- Realization of the PowerCare project demonstrator at a motor-test bench
- Experimental validation of the developed failure prediction methods for the power electronics and the electric machine
- Testing and characterization of the inverter based on vertical GaN semiconductors



Motor-test bench (© Kurt Fuchs, IISB)

Stress Tests for GaN Transistors



- EPC9194KIT:
  - Evaluation board is a 3-phase BLDC motor drive inverter featuring the EPC2302 eGaN FET 1.8 mΩ maximum RDS(ON), 100 V max. device voltage
- Process for producing real data:
  - Gate, thermal, cycling stress tests on the EPC HEMTs
  - Demo setup with engine + brake + original/stressed EPCKIT + oscilloscope

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