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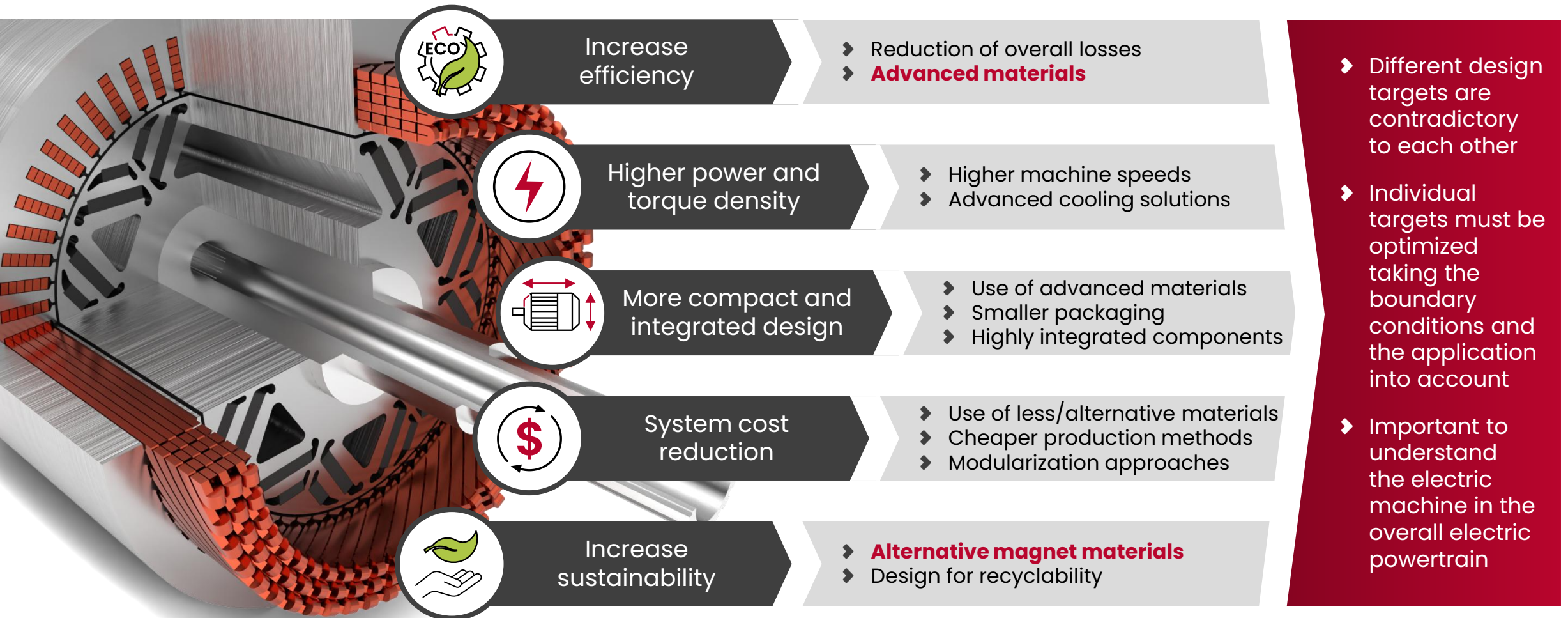
prepared for

Aachen Colloquium

Amorphous-Core Electric Machine with HRE-Free Permanent Magnets

In addition to higher efficiency and power density, the development of sustainable electric machines is focused on reducing critical raw materials

ELECTRIC TRACTION MACHINE DEVELOPMENT TRENDS



Proterial supports the automotive industry with advanced materials

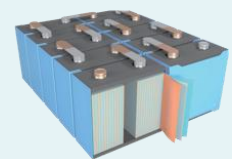
DELIVERING VALUE ACROSS A BROAD RANGE OF AUTOMOTIVE TECHNOLOGIES AND APPLICATIONS

Electric machine



Motor core Amorphous alloy Metglas™	Motor core Permendur YEP™-2V	Magnetic wedge Magnetic slot wedge	Magnet wire Inverter-surge resistant wire KMKED High-PD/IV wire KMKDF	Power supply Semi-rigid connect assy
Magnet Nd-Fe-B sintered magnet NEOMAX®	Magnet Ferrite sintered magnet NMF™	Magnet Nd-Fe-B bonded magnet HIDENSE™ NEOMAX-P		

Battery / Fuel Cell



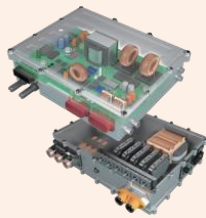
Battery terminal Clad terminals for Li-ion batteries CLAMET™	Battery current collection components Clad materials for secondary batteries	LiB cathode Cathode material production technology CALISMAT™
Bipolar plate for PEMFC Wide and thin Titanium and Nickel metal foil	Interconnector for SOFC Highly oxidation- resistant ferritic steel ZMG™232G10	

ICE



Turbocharger Turbine wheel	Piston ring Materials for piston rings	Hydraulics & Valves Materials for vanes / engine valves	Transmission CVT belt materials	Injector High-Corrosion-Resistance alloy suitable for e-fuel ACD™602N, ACD™627N
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Inverter / On-board charger



Insulating substrate Silicon nitride (SiN) insulating substrate	Lead frame Copper strip / profiled copper strip	Connection terminal Dissimilar-metal bonding material (Clad)	Power devices Silicon carbide (SiC) substrate
Isolation transformer Soft ferrite MaDC-F™	Current sensor Resistance materials (NC, NRH, MC)	Common mode choke FINEMET® common mode choke	Shielding sheet FINEMET® Magnetic Shield Sheet

Manufacturing

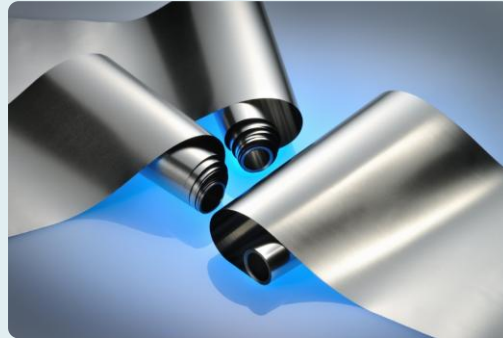
Die casting mold Die steel for gigacasting	Die casting mold SKD-type metal powders for additive manufacturing P-YDC01, P-YDC05	PVD coating PVD coating for cold-forging dies Tribec™smooth, Tribec™MX	PVD coating PVD coating for press-forming dies L-Flex™SUP	PVD coating PVD coating for precision dies Tribec™DX, Tribec™Mk-II	Manufacturing process High-performance thin film Sputtering target
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Proterial provides both soft and hard magnetic material for the use in electric traction machines

DECADES OF INNOVATION AND MASS PRODUCTION IN AMORPHOUS ALLOYS AND ND-FE-B MAGNETS

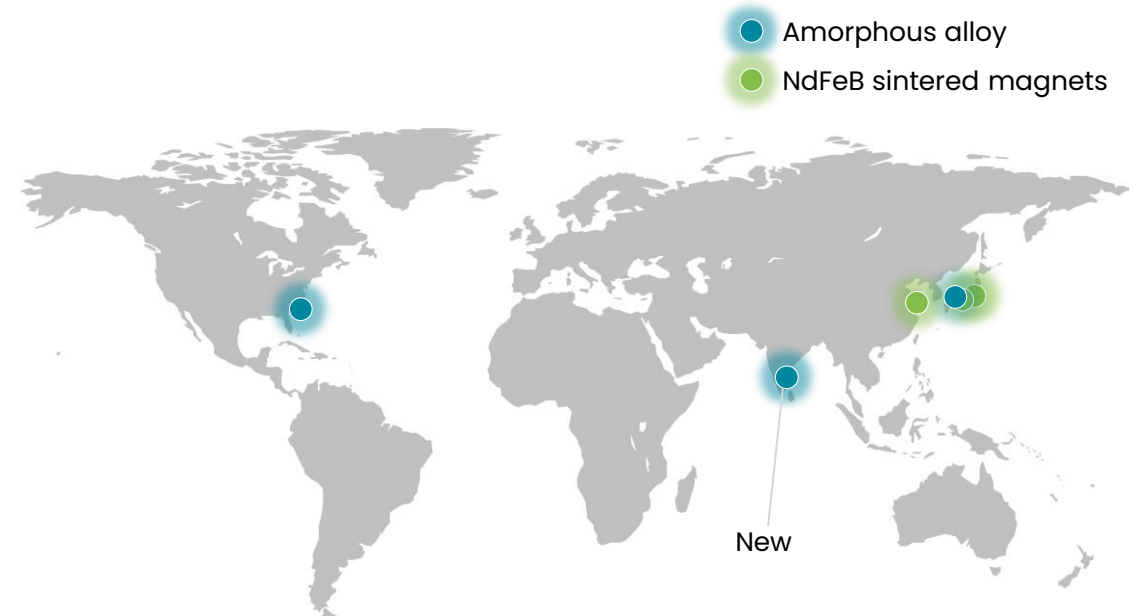
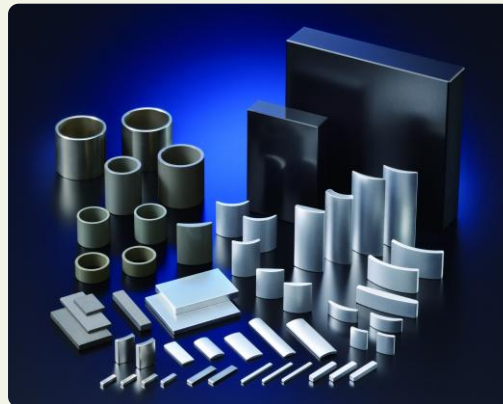
Amorphous alloy

- ▶ Start mass production at Metglas* in 1989
- ▶ Production in the United States and Japan
- ▶ New production capacity in India
- ▶ Widely used for transformer applications



NdFeB sintered magnet

- ▶ Invention by Proterial Magnetics*,** in 1982
- ▶ Global portfolio of 600+ magnet patents
- ▶ Development of heavy-rare-earth-free permanent magnets
- ▶ Widely used for various applications



excluding downstream-only companies

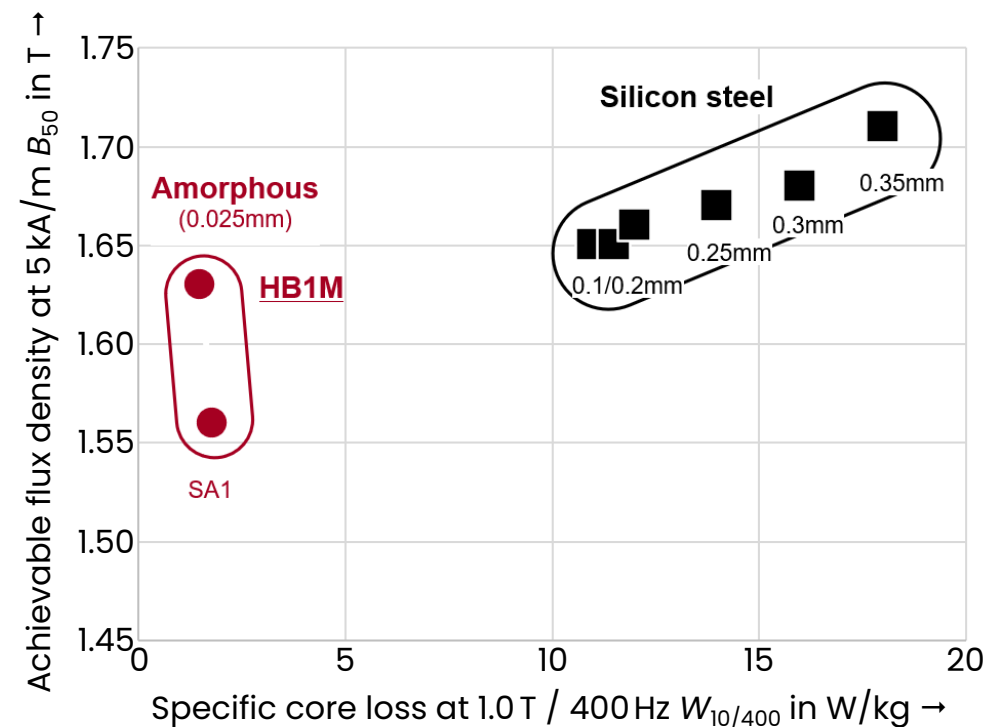
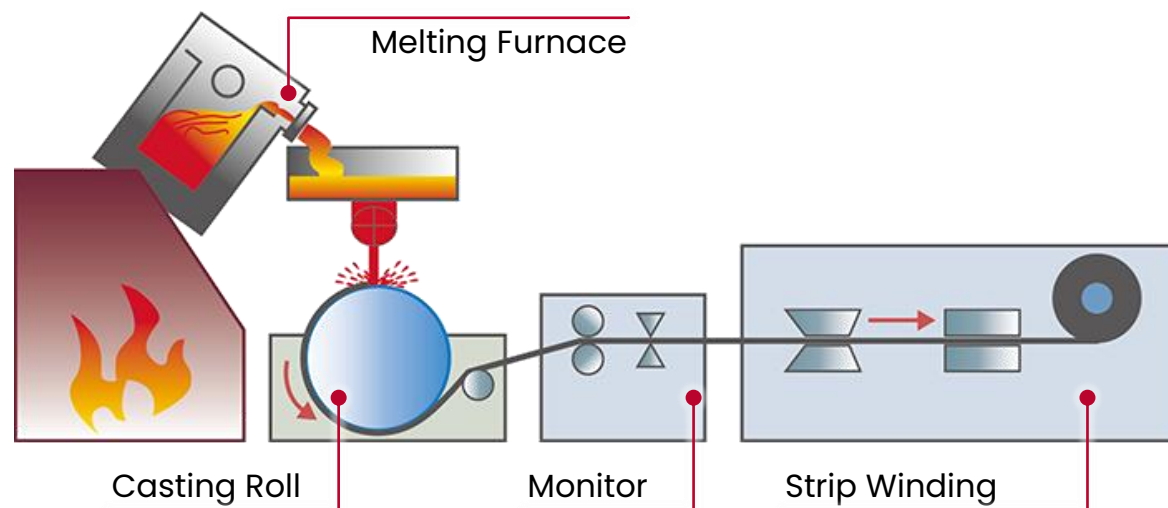
* Subsidiary of Proterial, Ltd.

** Former Sumitomo Special Metals

Amorphous alloy ribbon reduces hysteresis and eddy current losses

ITS UNIQUE METALLIC GLASS STRUCTURE CHANGES THE DOMINANT LOSS MECHANISMS

- Rapid quenching at approximately 10^6 °C/s
- Non-crystalline metallic-glass structure
- Strip thickness of approximately 25 μ m
- Higher electrical resistivity
- Lower coercivity
- Resulting in low hysteresis and eddy current losses



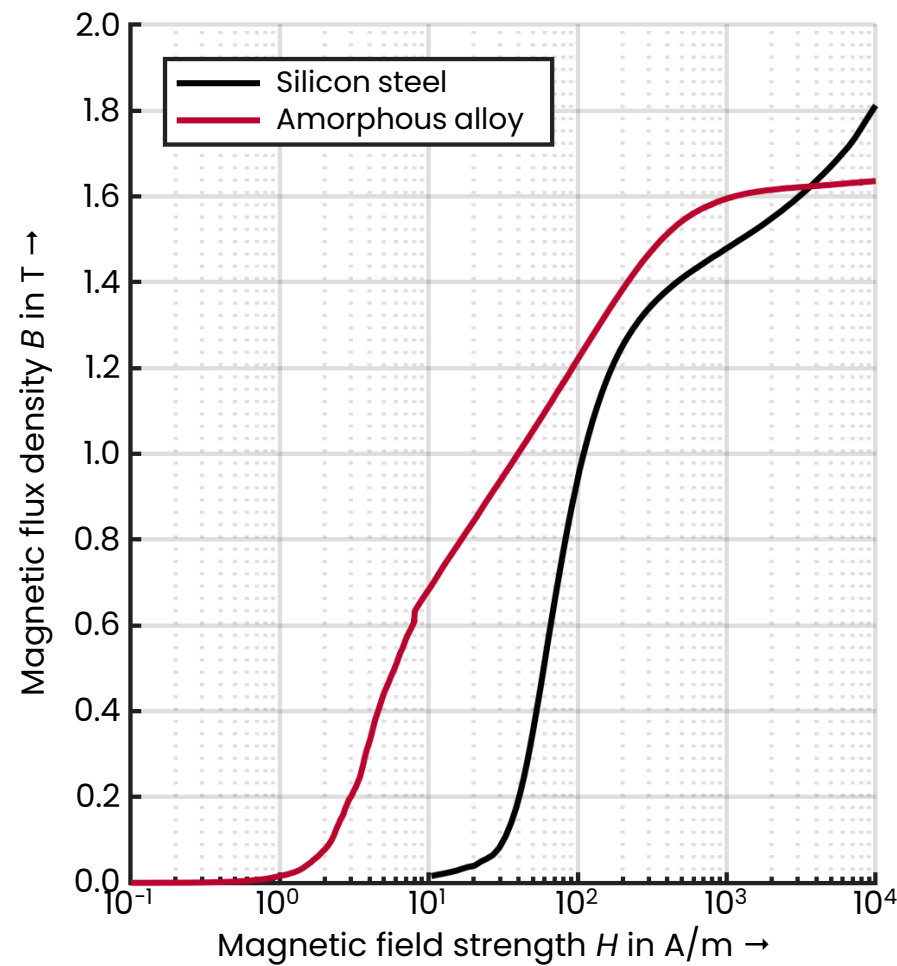
Amorphous alloy offers substantial loss advantages but requires dedicated electric machine design



MATERIAL PROPERTIES DIFFER FROM CONVENTIONAL NGO ELECTRICAL STEEL

Property	Non-oriented silicon steel	Proterial 2605HB1M™ amorphous alloy ribbon
Material type	FeSi	FeBSi
Strip thickness	0.25 mm	0.025 mm
Saturation flux density	> 1.9 T	1.63 T
Density	7.65 g/cm³	7.33 g/cm³
Specific electrical resistance at 20 °C	0.52 μΩ·m	1.2 μΩ·m

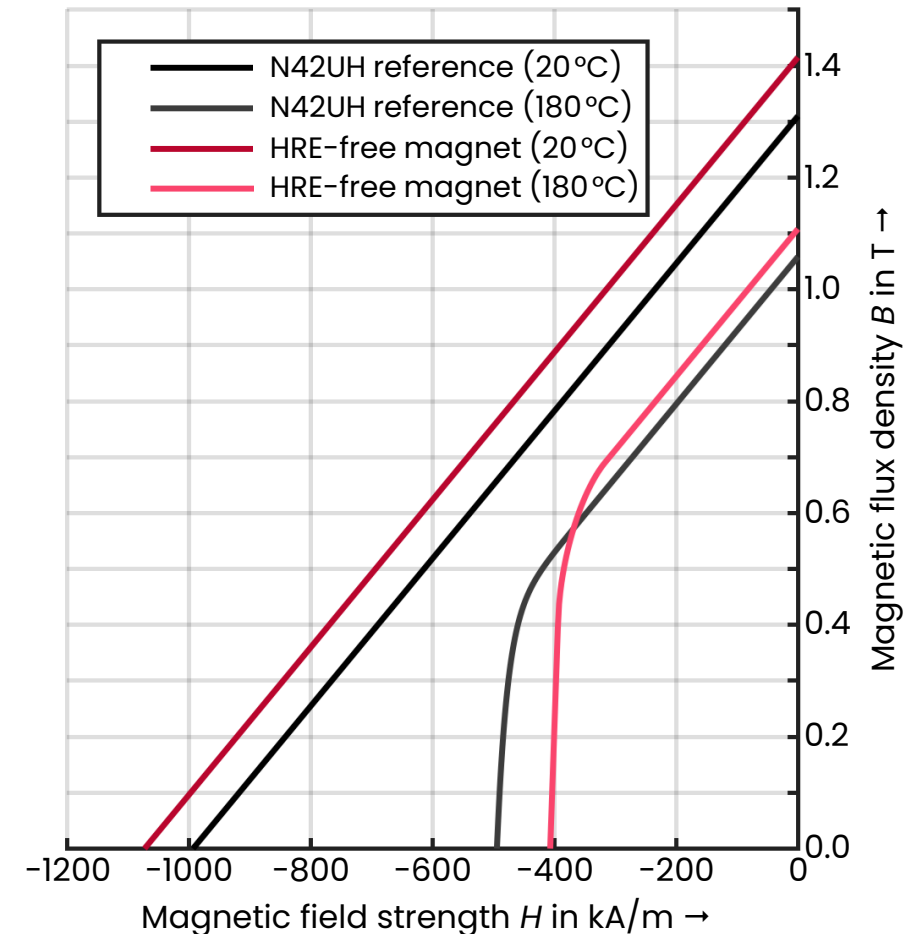
- ▶ Substantially reduced hysteresis and eddy-current losses enable higher efficiency > Allows higher frequencies/speeds
- ▶ Lower saturation flux density limits maximum magnetic loading > Requires increased tooth and yoke cross-sections
- ▶ Higher permeability enables target flux densities at lower magnetizing field strength
- ▶ Optimized electromagnetic design is required to balance efficiency and torque density



HRE-free magnets reduce critical raw materials without sacrificing traction performance

ADVANCED ND-FE-B TECHNOLOGY ELIMINATES DYSPROSIUM AND TERBIUM

- Eliminates dysprosium (Dy) and terbium (Tb)
- Reduces dependence on critical raw materials
- Comparable or higher remanence preserves traction-relevant torque capability
- Reduced intrinsic coercivity requires dedicated demagnetization-safe machine design
- Optimized electric machine design and operating strategy maintain high-temperature robustness
- Rotor geometry and flux barriers must be optimized to limit reverse magnetic fields



A benchmarked EV drive unit provides the foundation for the concept study

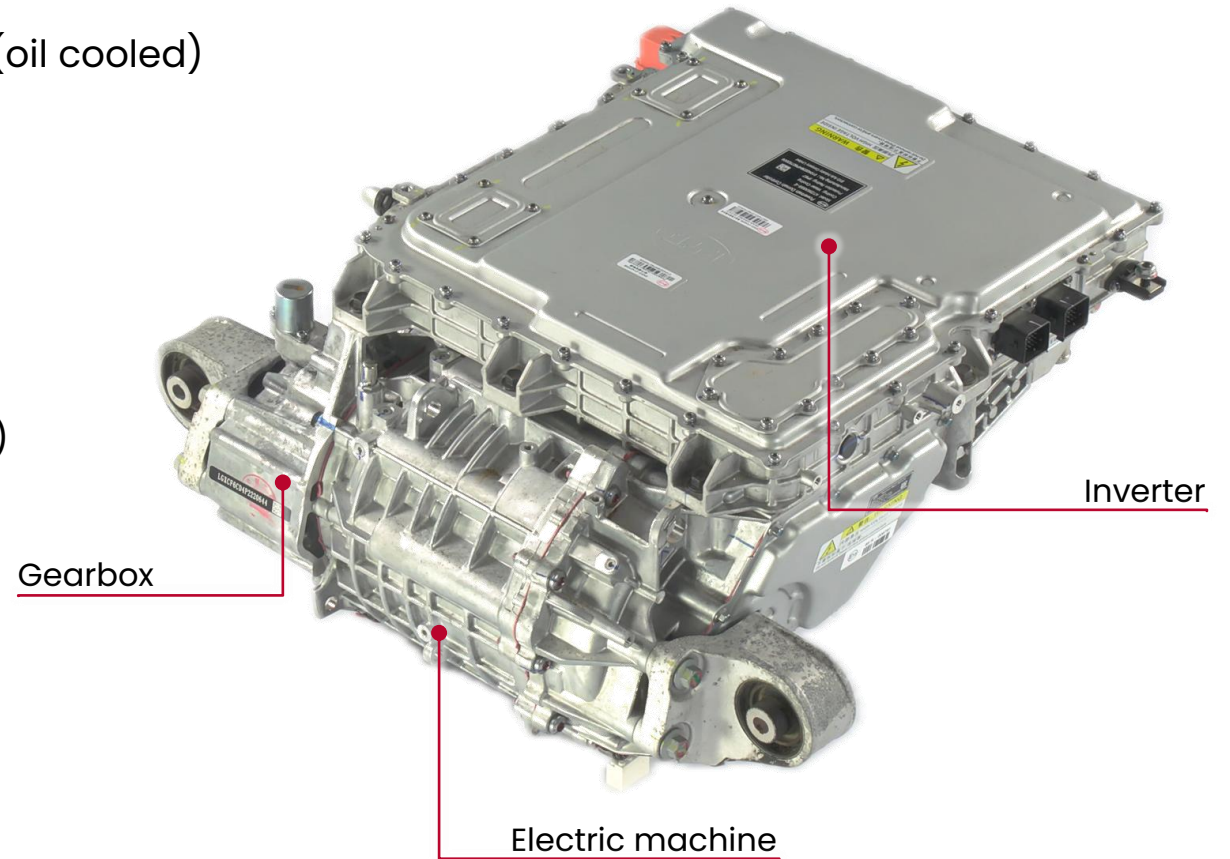
VEHICLE PERFORMANCE TARGETS REMAIN UNCHANGED THROUGHOUT THE REDESIGN PROCESS

Reference:

- Rear-axle electric drive unit of a battery electric vehicle (oil cooled)
- 800 V system voltage
- Permanent magnet synchronous machine (PMSM)
- Maximum power: 230 kW
- Maximum torque: 360 Nm
- Maximum speed: 180 km/h at 14,900 rpm (gear ratio: 10.8)

Objectives:

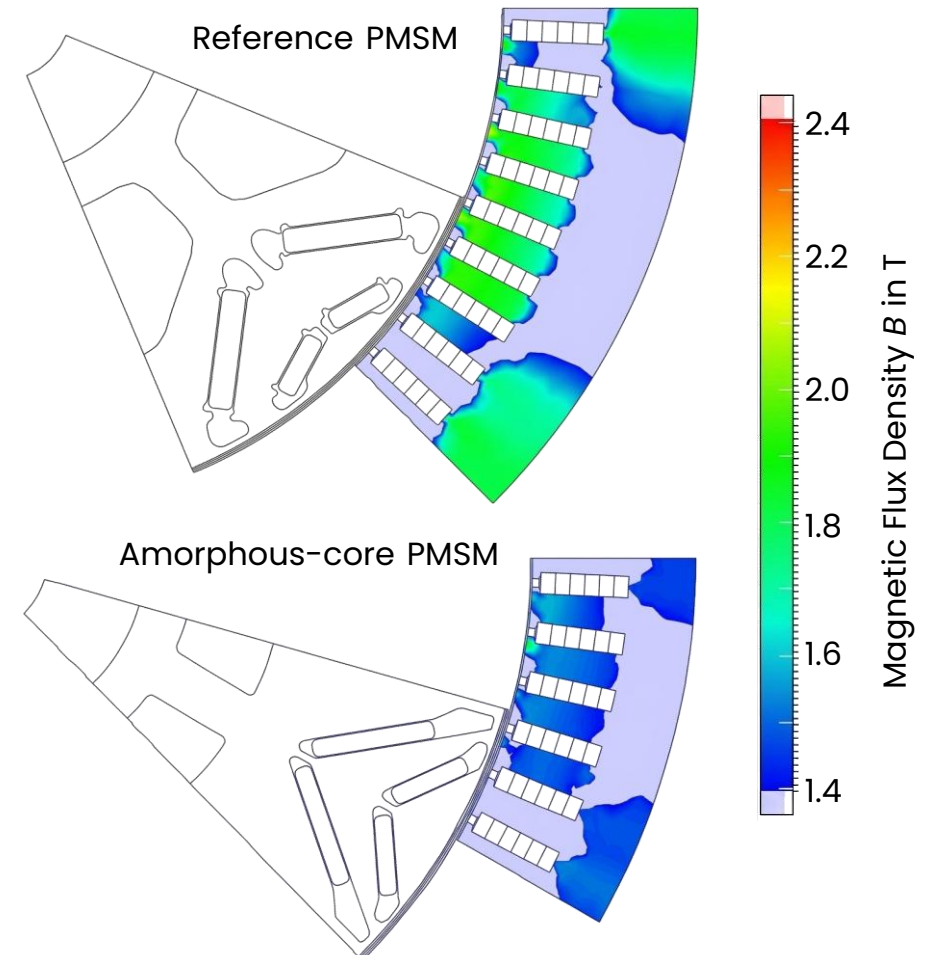
- Exploit amorphous steel advantages
- Reduce critical raw materials
- Keep vehicle performance
- Keep maximum electric machine outer dimensions



Amorphous materials introduce electromagnetic, mechanical and manufacturing challenges

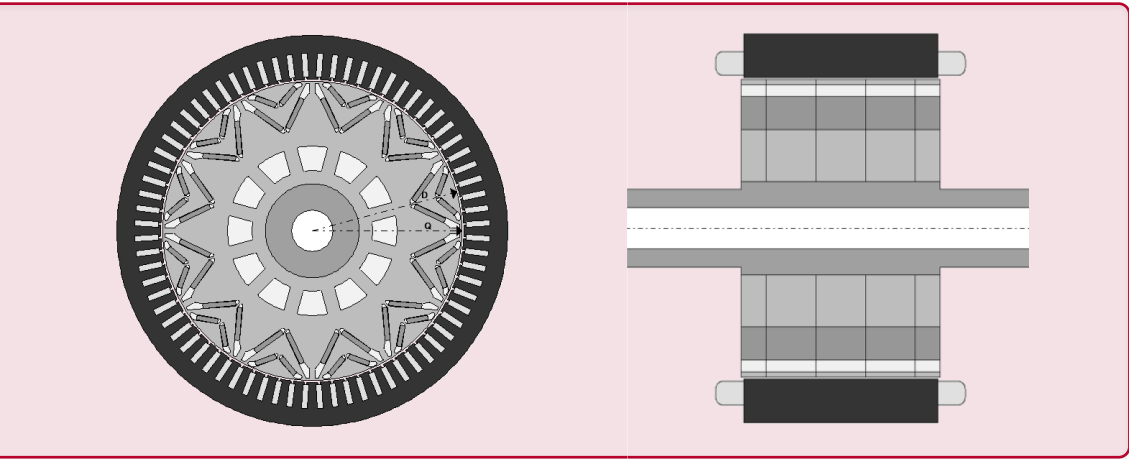
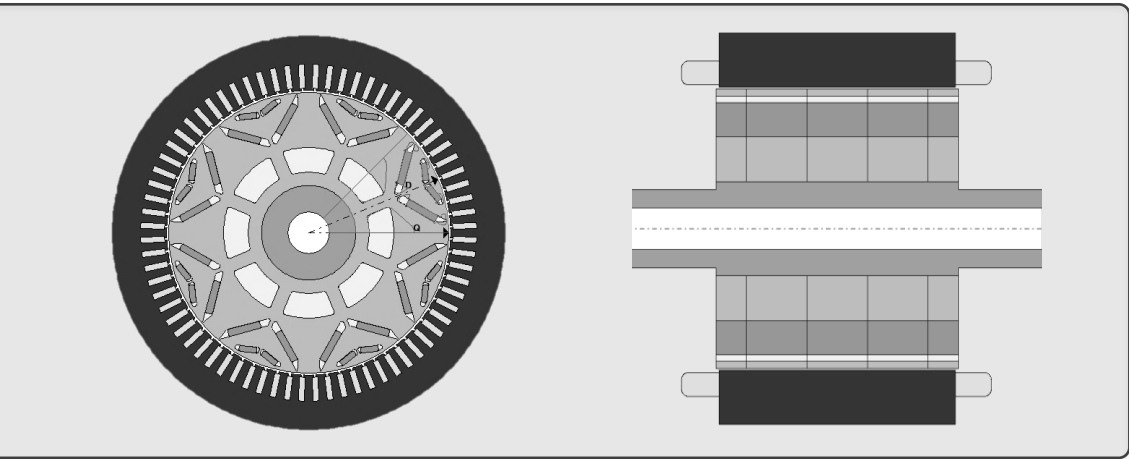
LOWER SATURATION LEVELS AND STRESS SENSITIVITY REQUIRE DEDICATED ENGINEERING SOLUTIONS

- Lower saturation flux density requires an adaptation of the magnetic circuit
- The maximum speed is increased from 14,900 rpm to 20,000 rpm to exploit the low iron losses at high electrical frequencies, which increases the power density
- A higher pole count enables a thinner stator back yoke, while the inner radius increases by 7.2 %
- Reduced slot depth and tooth width increase the current density by 8.7 %
- Pre-laminated and bonded strip assemblies improve handling and achieve a stacking factor of approximately 90 %
- 23 % shorter active length due to increased power density
- Bolted stator mounting avoids potentially critical shrink-fit stresses
- Manufacturing remains challenging due to the thin ribbon geometry, high layer count, and increased tool wear



The electric machine is redesigned to fully exploit amorphous alloy ribbon benefits

HIGHER SPEED, MORE POLES AND A SHORTER ACTIVE LENGTH ENABLE THE NEW CONCEPT



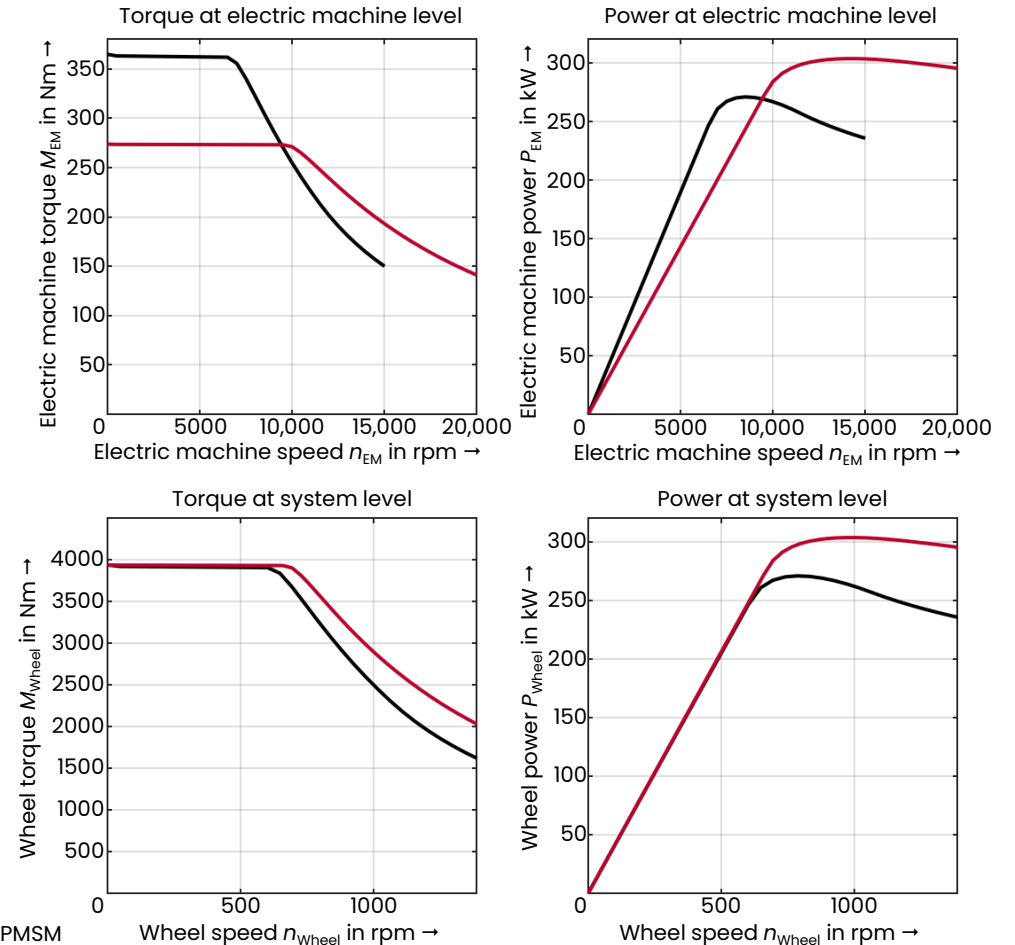
	Reference PMSM	Amorphous-core PMSM
Stator lamination material	Non-oriented silicon steel	Amorphous alloy ribbon
Rotor lamination material	Non-oriented silicon steel	Non-oriented silicon steel
Stator lamination stacking factor in %	96	90
Magnet type	NdFeB	HRE-free NdFeB
Maximum speed in rpm	14,900	20,000
Slots	72	72
Poles	8	12
Stator outer diameter in mm	200.0	200.0
Rotor outer diameter in mm	142.6	153.0
Max. circumferential speed in m/s	112	160
Active length in mm	138.7	107
Motor weight in kg	31.28	22.77
Magnet weight in kg	1.45	1.42
Stator lamination weight in kg	12.37	7.08
Rotor lamination weight in kg	10.41	8.74
Copper weight in kg	3.99	2.69

The redesigned amorphous-core electric machine achieves vehicle performance comparable to the reference drive

ACCELERATION CAPABILITY AND TOP SPEED ARE MAINTAINED DESPITE MAJOR DESIGN CHANGES

- Comparable wheel torque with increased gear ratio from 10.8 to 14.4
- Comparable launch performance
- Improved maximum power in the upper speed range

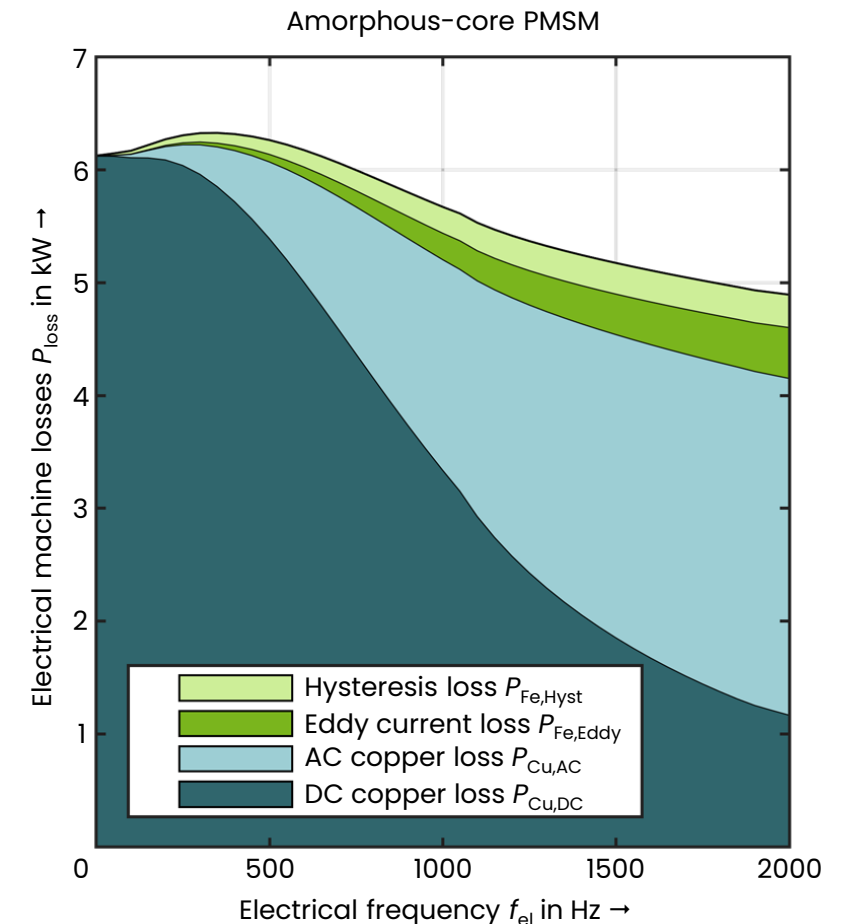
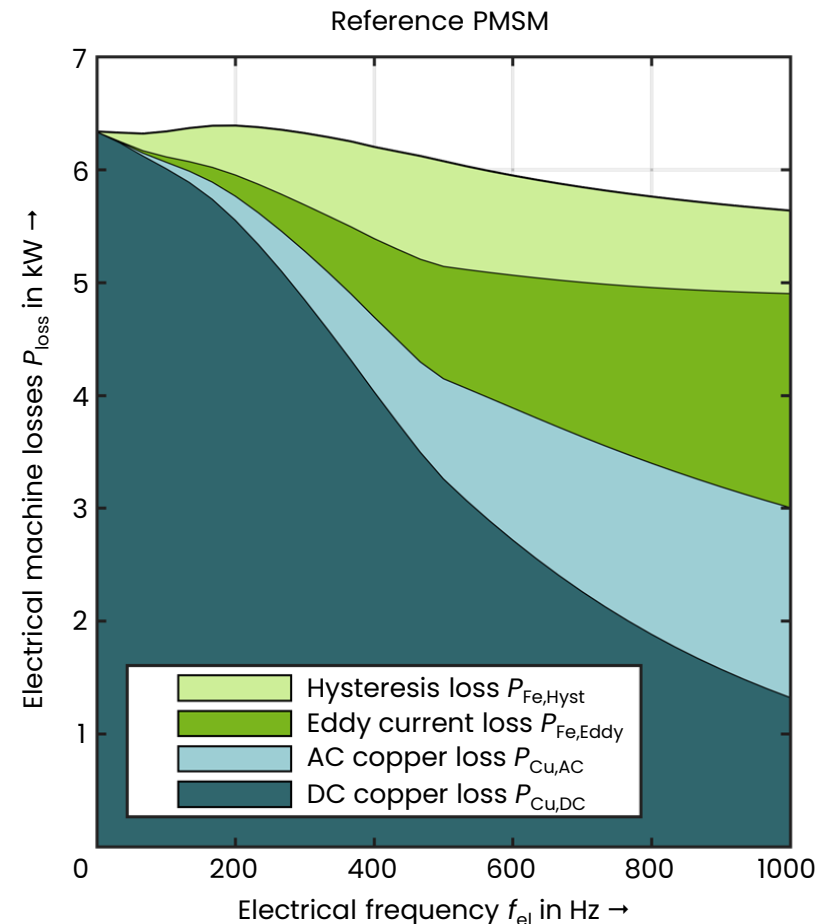
	Reference PMSM	Amorphous-core PMSM
Stator lamination weight in kg	12.37	7.08
Copper weight in kg	3.99	2.69
Rotor lamination weight in kg	10.41	8.74
Magnet weight in kg	1.45	1.42
Peak power density in kW/kg	9.6	15.1
Peak torque density in Nm/kg	12.9	13.5



Iron losses are significantly reduced across the entire high-speed operating range

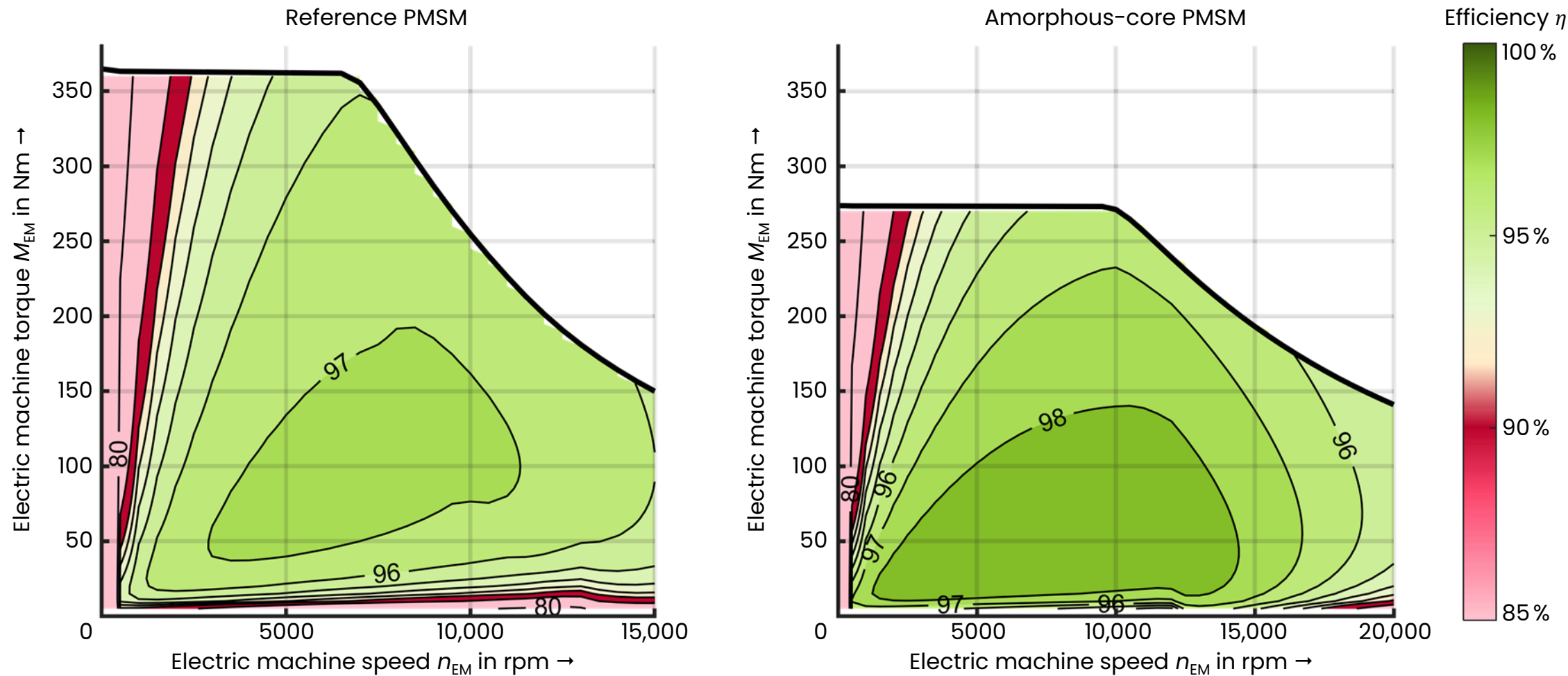
IRON LOSS REDUCTION BECOMES INCREASINGLY PRONOUNCED AS ELECTRICAL FREQUENCY RISES

- Main differences between the reference machine and the amorphous design occur in the loss distribution
- Amorphous material structure significantly reduces **hysteresis and eddy-current losses**, particularly at high electrical frequencies in the upper speed range
- At the same time, the reduced slot area and higher electrical frequency increase frequency-dependent **copper losses**, partially offsetting the iron-loss benefit
- Nevertheless, total losses are reduced compared with the reference machine



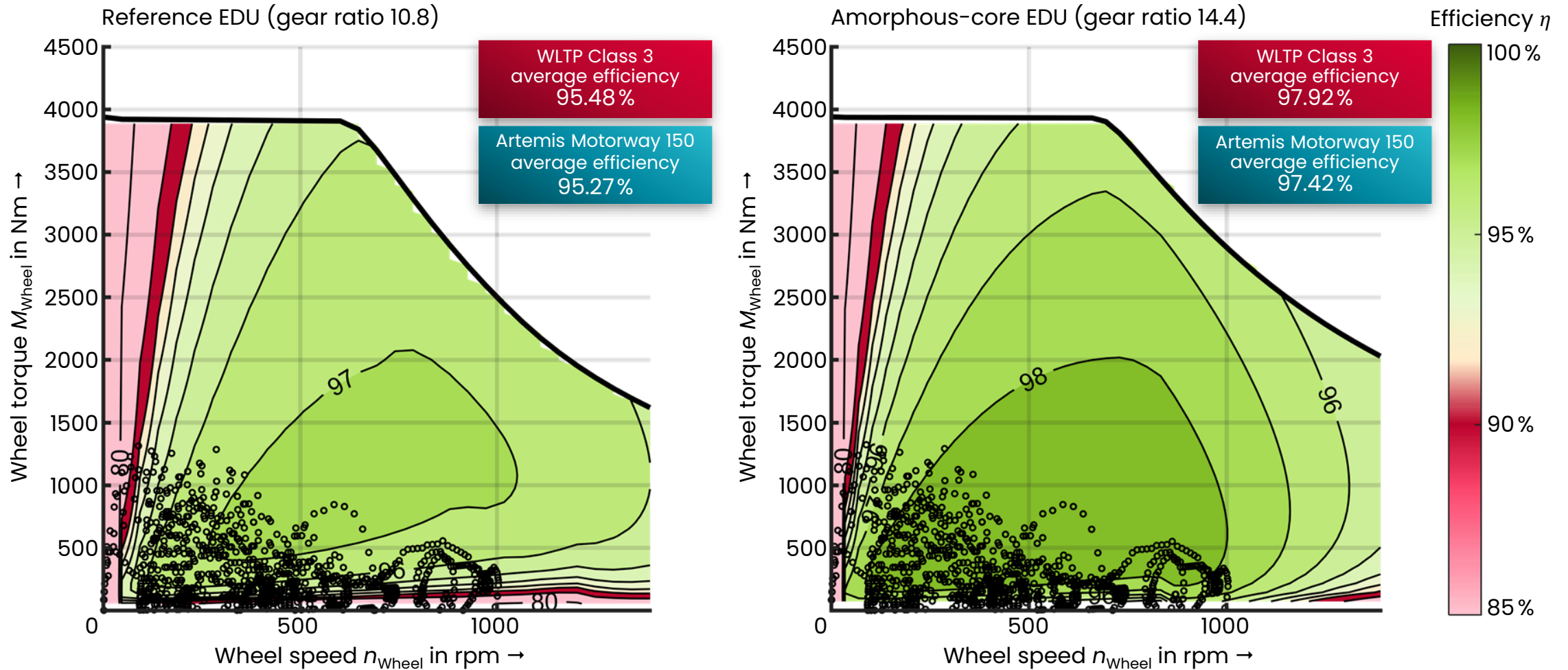
The amorphous-core PMSM exceeds 98 % peak efficiency and expands the high-efficiency region

EFFICIENCY IMPROVEMENTS ARE ACHIEVED ACROSS A BROAD OPERATING RANGE



Efficiency gains translate directly into measurable vehicle-level benefits

WLTP AND ARTEMIS DRIVE CYCLES SHOW HIGHER AVERAGE EFFICIENCIES



Amorphous alloy and HRE-free magnets unlock a new generation of efficient and resource-efficient electric drives

Key findings

- Significantly reduced iron losses enable higher efficiency and higher speeds
- Vehicle performance targets can be improved with the amorphous-core design
- Higher efficiency creates vehicle-level benefits through reduced battery energy demand
- HRE-free magnet technology reduces dependence on critical rare earth elements without compromising traction capability
- A demonstrator is intended to serve as the basis for industrial evaluation and customer-specific development activities

Next steps

- Thermal and demagnetization robustness assessment
- Mechanical and NVH validation
- Validation testing of the demonstrator machine
- Evaluation of rotor-side amorphous material applications
- Industrialization and manufacturing roadmap

Vehicle-level impact

- Reduced battery energy consumption
- Potential for battery downsizing
- Lower dependency on critical raw materials
- Attractive pathway toward lower total vehicle cost

