# Electrification: Need for innovative solutions in electrical machines for automotive traction units

**Mircea Popescu, Motor Design Ltd, UK**

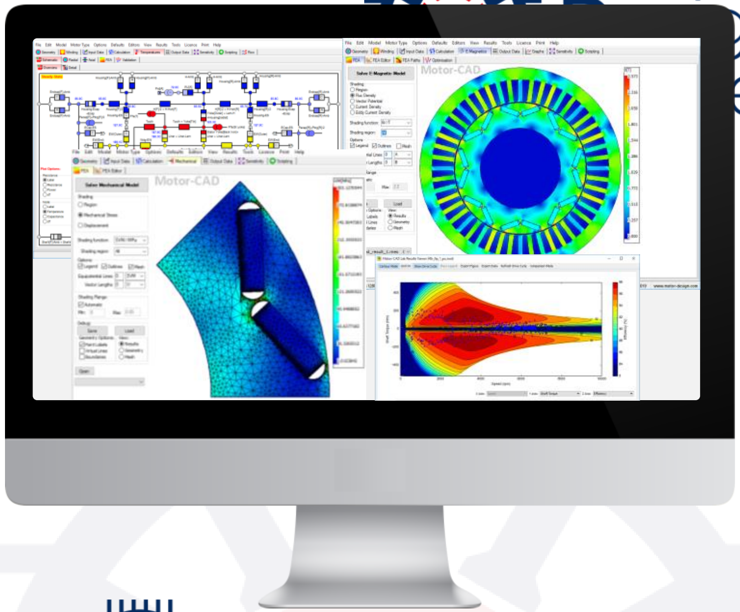
26 June 2020, CADFEM Technology Day

# Topics

- About MDL
- Electrified Systems
- Electrical Machines Innovation (Materials)
- Electrical Machines Innovation (Designs)

# About Motor Design Ltd

- **Software developers: Ansys Motor-CAD**
  - Developers of Ansys Motor-CAD – world-leading tool for the design and analysis of electric motors.
  - High level of customer support and engineering know-how.
  - Developed with expert electric machine designers.
- **Consultancy**
  - Design, analysis & training.
  - Led by motor design experts with significant industry and academic experience.
- **Research**
  - Involved in collaborative government/EU-funded research projects.
  - Collaborate with Universities worldwide to develop electric machine modelling techniques and create validation data.



Motor-CAD
MOTOR DESIGN SOFTWARE BY MOTOR DESIGN ENGINEERS

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# About Motor Design Ltd

Motor Design Limited

## Worldwide Customers

Customers in **33 countries** and over **470 companies** worldwide.

**MDL Headquarters**
Wrexham, UK

**MDL Asia**
Shanghai, China

**MDL USA**
Ohio, USA

Customers across 6 industry sectors
**Automotive, aerospace, rail, renewables, industrial & appliances.**

43% of the team are **design engineers**

30% of the team are **software developers**

47% of the team **have a PhD**

Developing Motor-CAD software since **1998**

MDL has OEM software partnership with **Ansys**

# E-Machines: The need for rapid design

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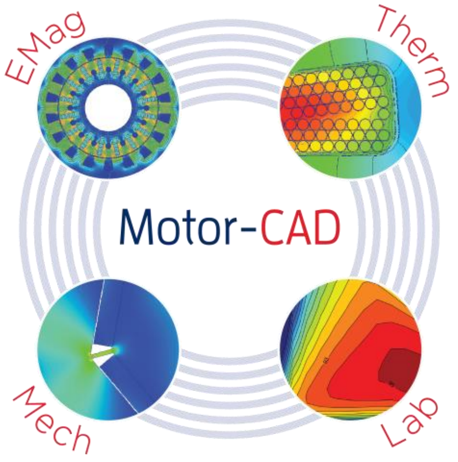
## Electric Machine Design Tool




**Rapid multiphysics design tool** providing analysis across the full torque/speed operating range

## Enables:

- Comprehensive design space exploration
- Better design and topology decisions
- More optimised designs
- Complete multiphysics evaluation of design candidates against the full specification
- Reduced risk of costly problems in the later development stages.

DESIGN → ANALYSIS → OPERATION

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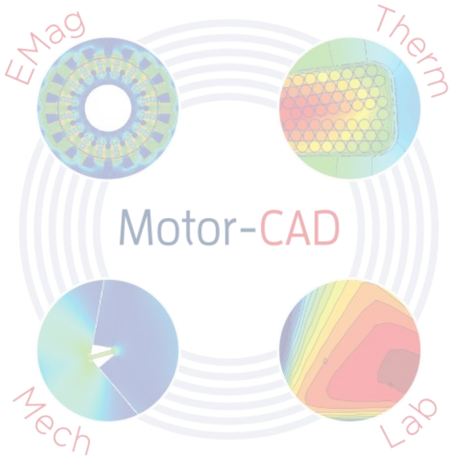
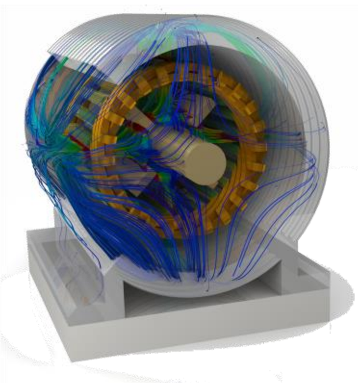
# E-Machines: The need for design, analysis validation

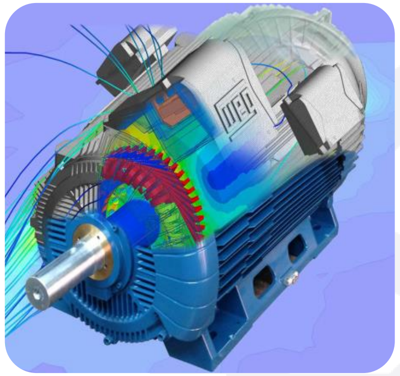
## Electric Machine Design Tool

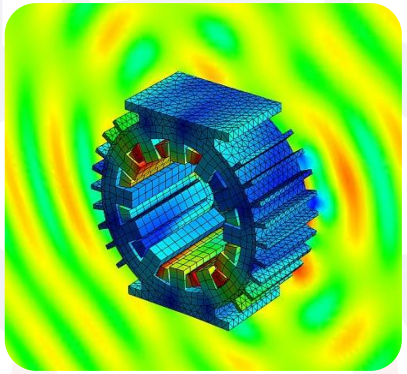



**Rapid multiphysics design tool**
providing analysis across the full torque/speed operating range

## Specialist physics-based numerical tools for multiphysics analysis







- Detailed physics based numerical simulation
- Coupled specialist tools for multiphysics analysis

DESIGN → ANALYSIS → OPERATION

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# Ansys Motor-CAD: Motor design types and templates

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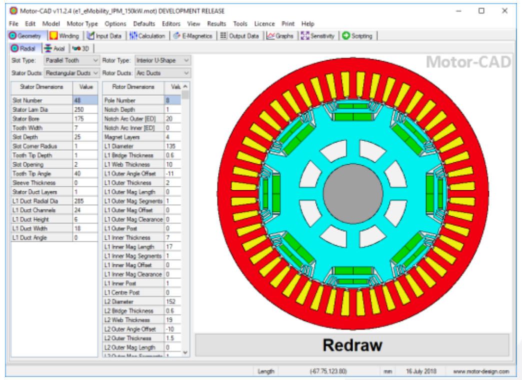
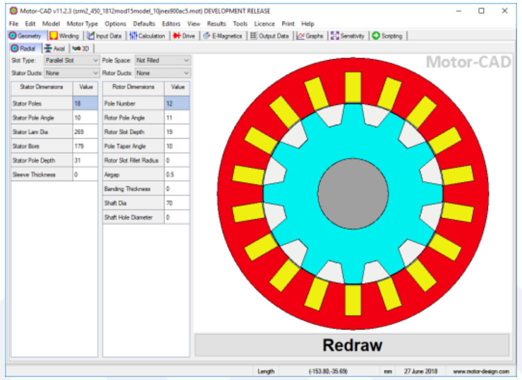
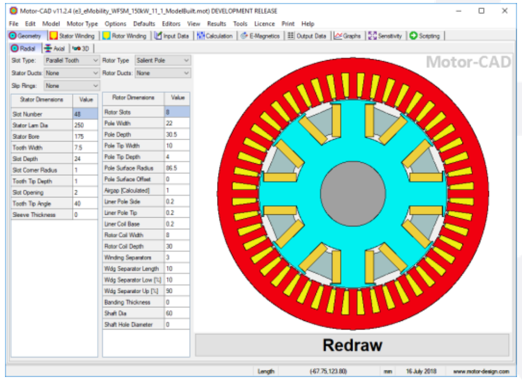
- Covers all typical types of radial flux rotating electric machines.
- Motor Types:
  - Brushless permanent magnet (inner & outer rotor)
  - Induction
  - Synchronous reluctance
  - Switched reluctance
  - Synchronous wound field
  - Permanent magnet DC
  - Single phase induction.
- Extensive range of parametrised templates & geometries.



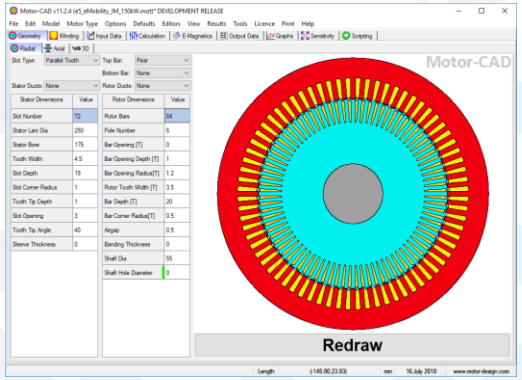

*Interior PM machine design*




*Switched reluctance machine design*




*Synchronous wound field machine design*




*Induction machine design*

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# Challenges of Designing Electrified Systems

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- **Development Costs** – prototyping & physical testing are expensive
- **Complexity** – multiple physical domains, HW/SW integration, multiple scales
- **Energy Efficiency** – a 1% improvement in energy usage is significant
- **Reliability** – how does the system respond in the event of faults?
- **Certification** – for Safety & Electromagnetic Compatibility (EMC)

**SIMULATION IS ESSENTIAL**

Courtesy of Ansys © 2020

# Technology Drivers for Aerospace Electrification

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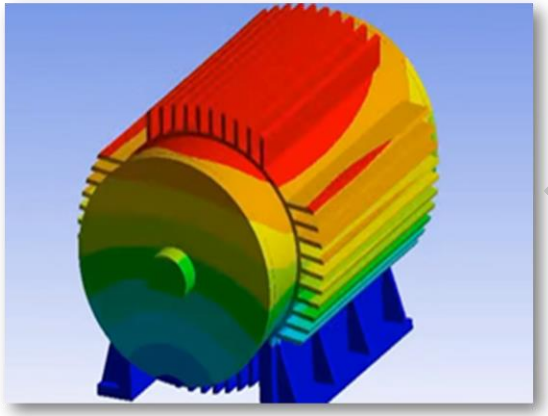
## Electric Machines

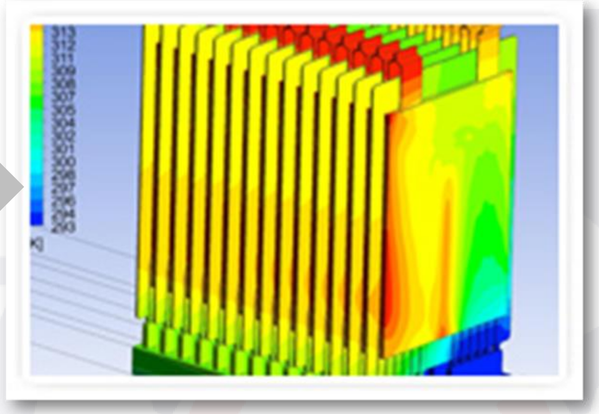


- Motors
- Generators

## Power Conversion

- AC/DC Converters (TRUs, ATRUs)
- DC/DC Converters
- Chargers

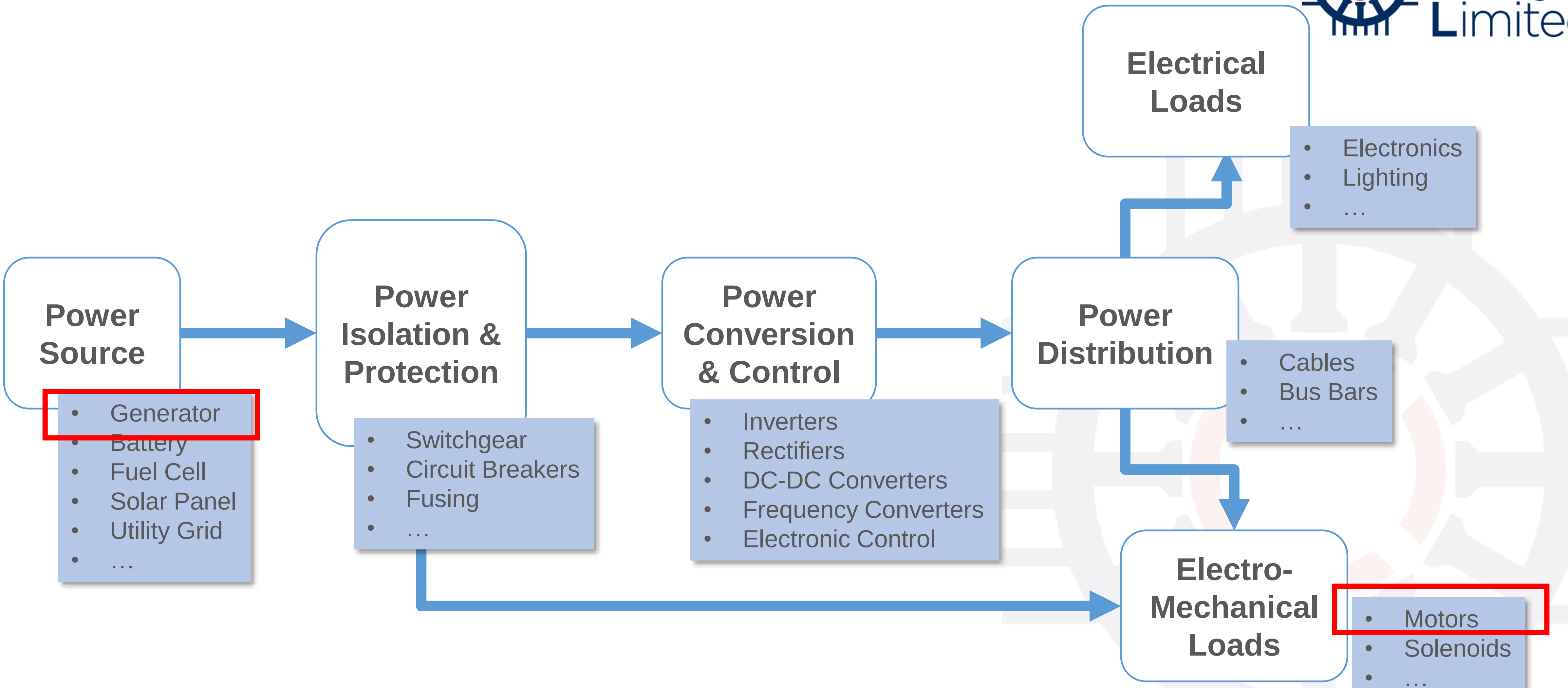
## Energy Storage



- Batteries
- Fuel-Cells

Courtesy of Ansys © 2020

# Elements of an Electrified System




Courtesy of Ansys © 2020

# Technical Challenges for Electrical Machines Design

## System Requirements in Aerospace Applications

Technical challenges associated with propulsion in aerospace are significant including **safety, mass and performance**.

Particular **safety challenges** include:

High availability for motoring or generating functions.

Bi-directional power for ‘always on’ permanent magnet machines. **1 x 10^-9 for fire**.

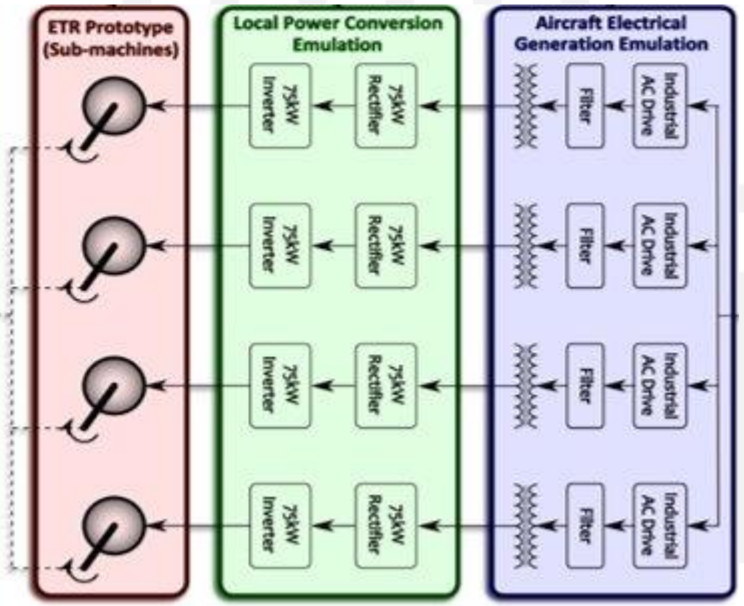
Typical requirements:

- Power between 20 kW to 2MW
- Voltages from 600V to 1000V, 3kV ongoing
- Motoring and generating
- Air cooling

# Electrical Machines Innovation

## Fault Redundancy

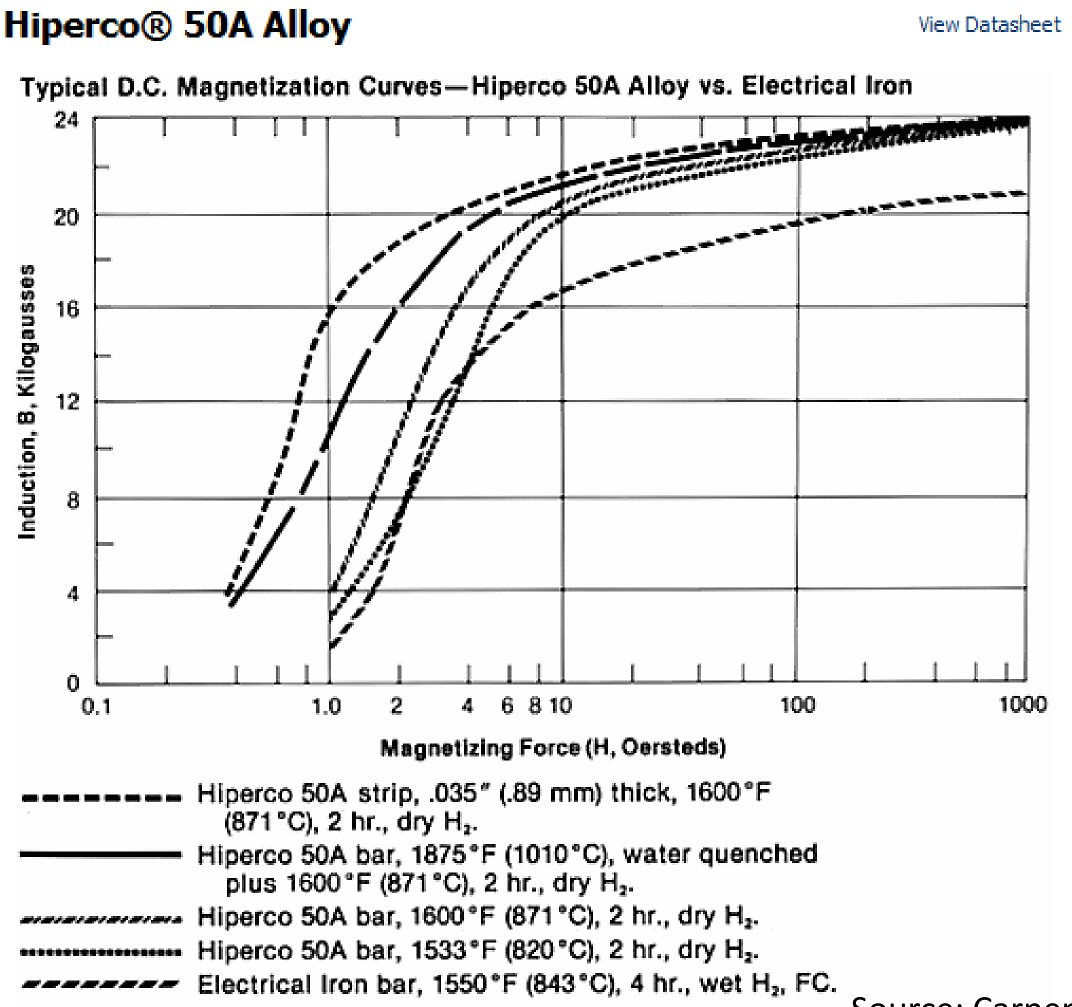
- Multiplex system, comprising multiple nominal balanced three-phase motor drive units
- Motor units share a common housing and a common output shaft
- Motor units are electromagnetically independent
- Minimal thermal interaction between motor units



# Electrical Machines Innovation

## Electric Steel - > Cobalt iron

- Higher magnetic permeability
- Benefit in achieving higher peak torque (~ 20 - 25%) in the same volume and power supply
- Designs to be done with limited field weakening region, i.e. base speed/max speed ratio < 1
- Requires careful processing (annealing)
- Carpenter
- VAC



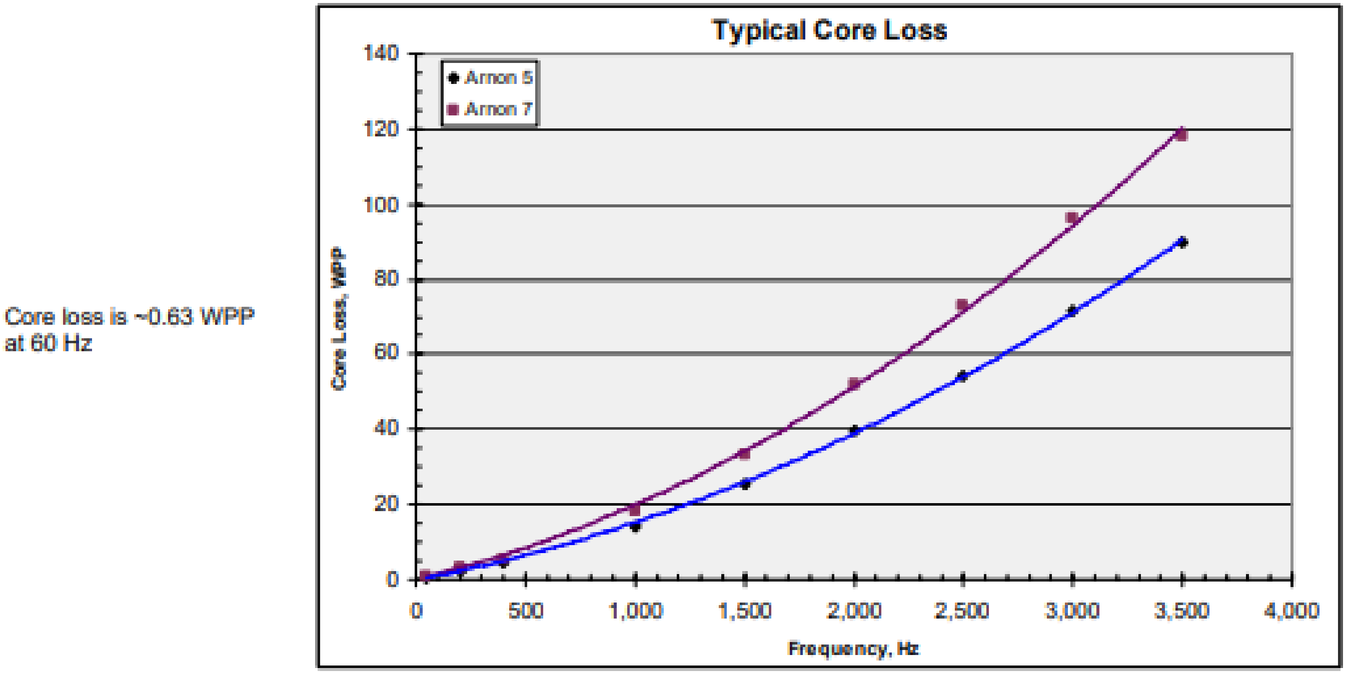

Source: Carpenter Specialty Alloys.

# Electrical Machines Innovation

- **Electrical Steel - > Silicon iron** more silicon and thinner laminations to reduce iron losses
- Due to lower losses, become preferred solution in high power density traction motors (Ampere, Canoo, Bolt)
- Arnon 4, 5 and 7
- Cogent Hi-Lite: NO10 to NO35
- JFE Steel 10JNEX

**Arnon 5 and 7 Core Loss**

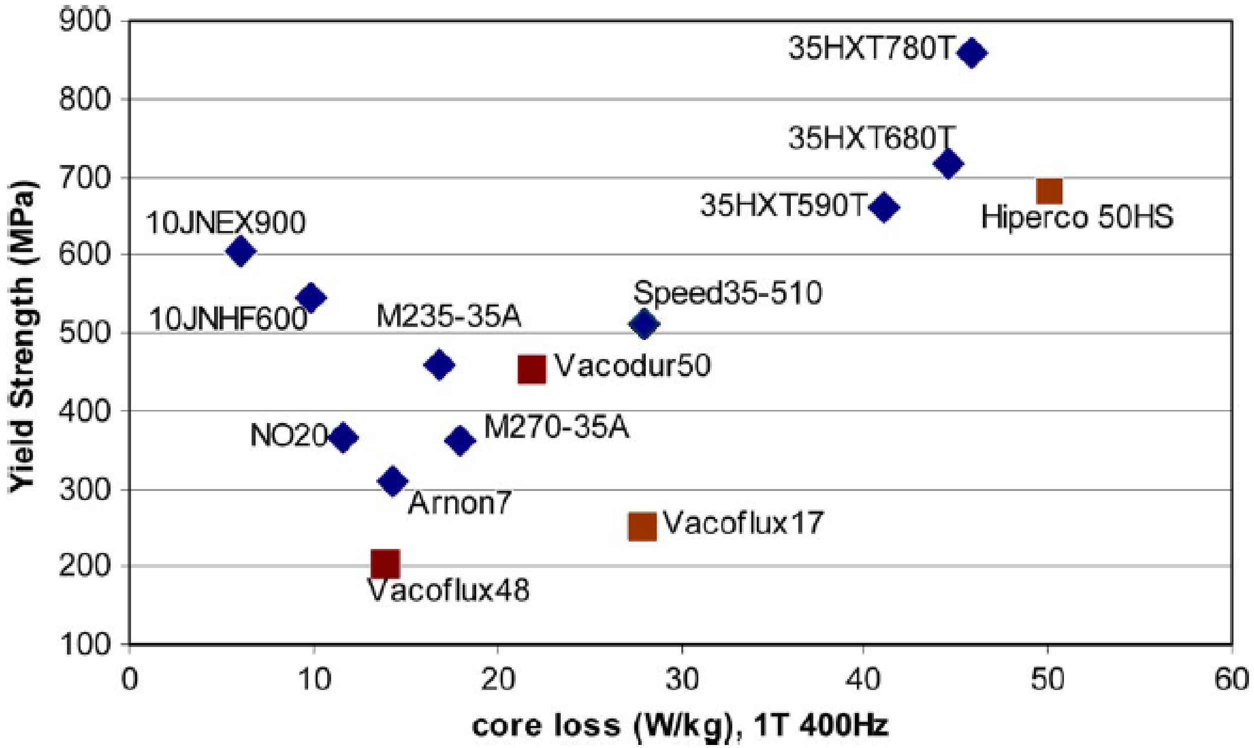
**Non-Grain Oriented, 5 and 7 mil Fe-Si**




Source: Arnold Magnetics

# Electrical Machines Innovation

- Square symbol denotes CoFe steel type
- Diamond symbol denotes SiFe steel type.
- M270-35A and M235-35A are common 0.35-mm thickness SiFe grades with a typical yield strength of around 350MPa and 450MPa, respectively.
- SiFe thinner grades than 0.35mm, such as NO30 and NO20, which have 0.30mm and 0.20mm respectively thickness.




Source: D. Gerada et al, IEEE, 2015

# Electrical Machines Innovation

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New materials – copper bars coated with nano-carbon

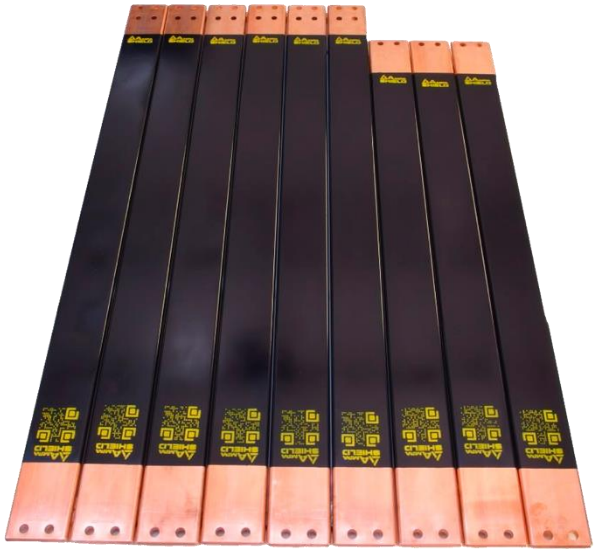
| | INCREASED AMPACITY | ELECTRICAL CONDUCTIVITY | THERMAL CONDUCTIVITY | CORROSION PROTECTION | ADHESION STRENGTH | FLEXIBLE | EASINESS OF APPLICATION | FLAME RESISTANCE |
|---|---|---|---|---|---|---|---|---|
| THERMAL | 5 | 0 | 5 | 3 | 5 | 4 | 5 | 4 |
| PLUS | 4 | 5 | 4 | 3 | 5 | 5 | 5 | 4 |
| PROTECT | 4 | 0 | 4 | 5 | 5 | 2 | 3 | 4 |
| FLEX | 4 | 0 | 4 | 3 | 5 | 5 | 3 | 4 |

AMPASHIELD®
NANO-CARBON ENABLED COATING SOLUTIONS

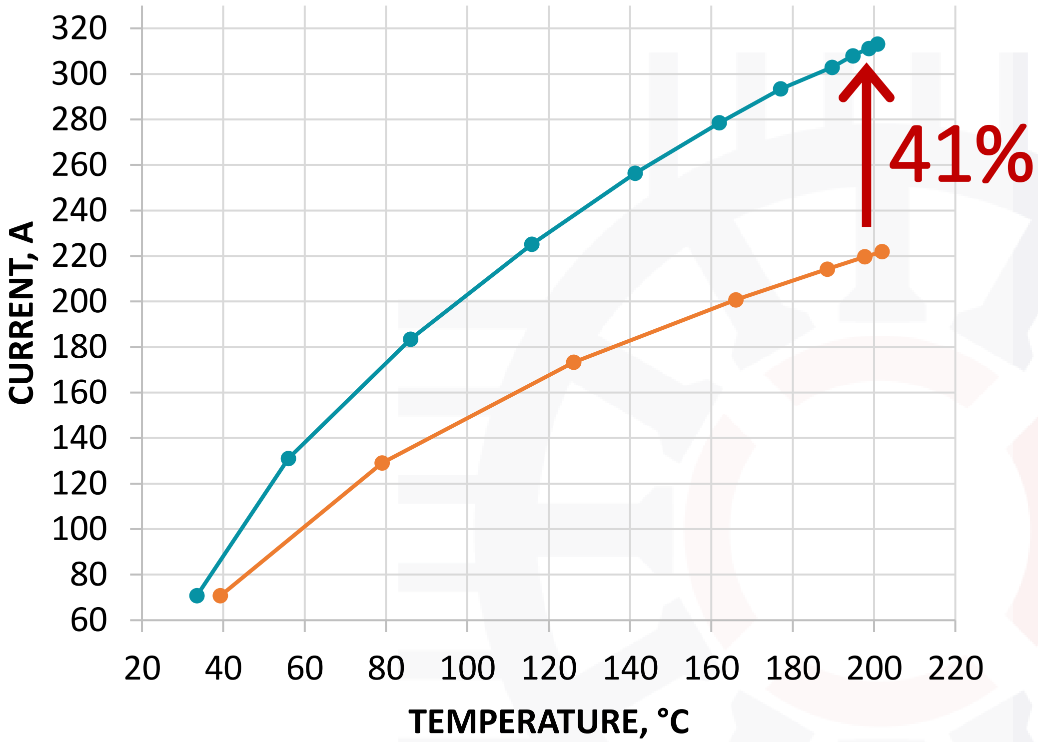
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| BEST PERFORMANCE | 5 | 4 | 3 | 2 | 1 | 0 | POOR PERFORMANCE OR LACK OF PROPERTY |

# Electrical Machines Innovation

Coated bus bars



AMPACITY Cu @ 200°C




Conductor size **22 x 0.7mm**

# Electrical Machines Innovation

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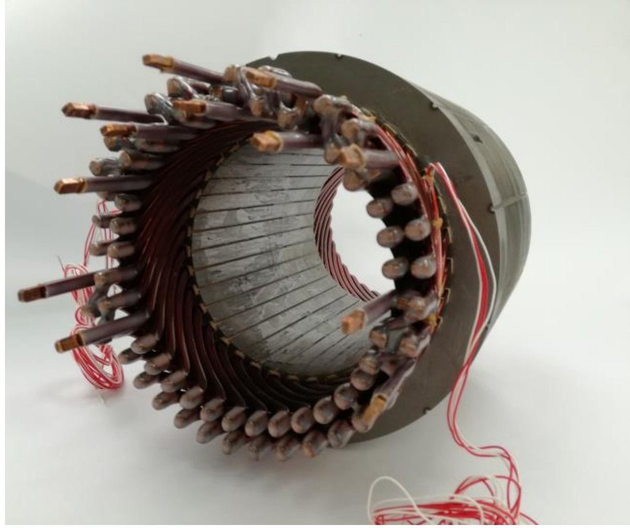
## Hairpin Winding

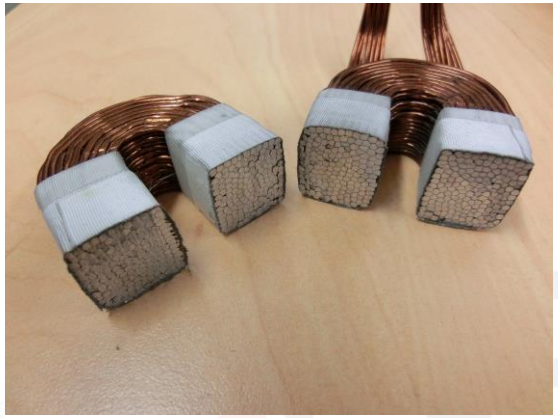


Tecnomatic

## Additive Manufactured Coils

AM CuCrZr, insulated,

AM AlSiMg, uninsulated,



AM CuCrZr shaped profile electrical machine winding,

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# Electrical Machines Innovation

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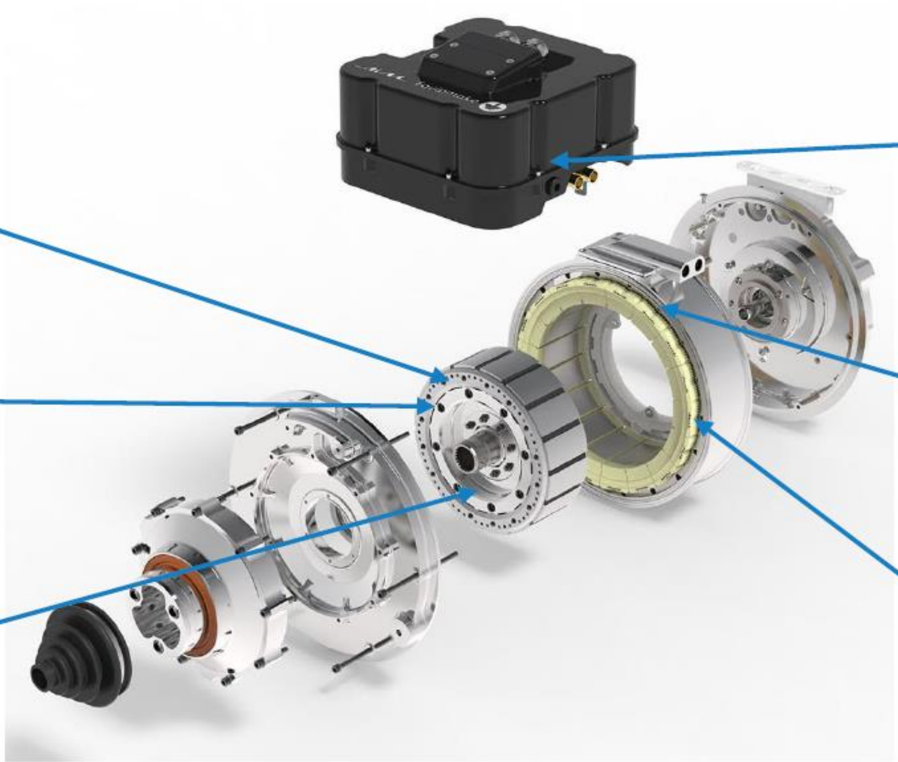
AM processing of magnetic materials (eg NdFeB)

Internally cooled magnets and rotor

Topology optimised low-inertia rotor



Integrated cooled power electronics

Cooled stator and housing

Integrated oil/water heat exchanger

APM 200 - Equipmake

# Electrical Machines Innovation

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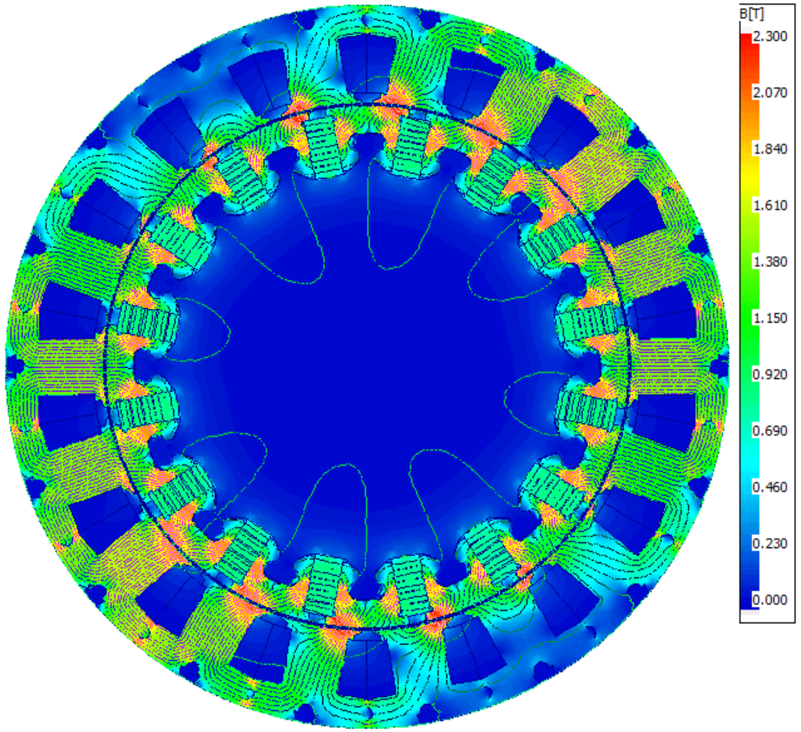
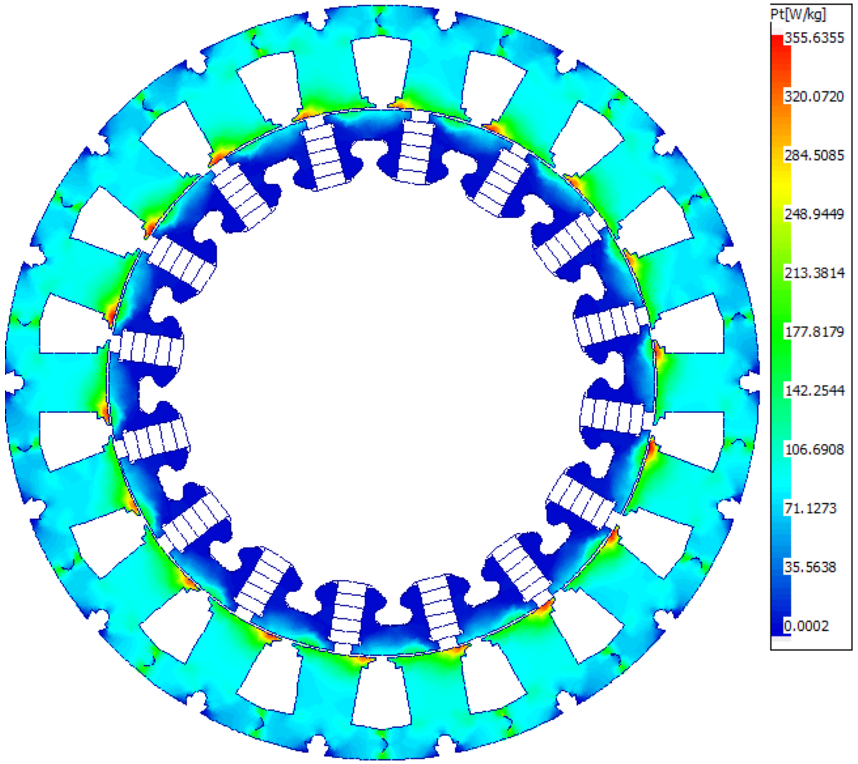



Flux density plots for APM 200




Core loss density for APM 200

# Electrical Machines Innovation

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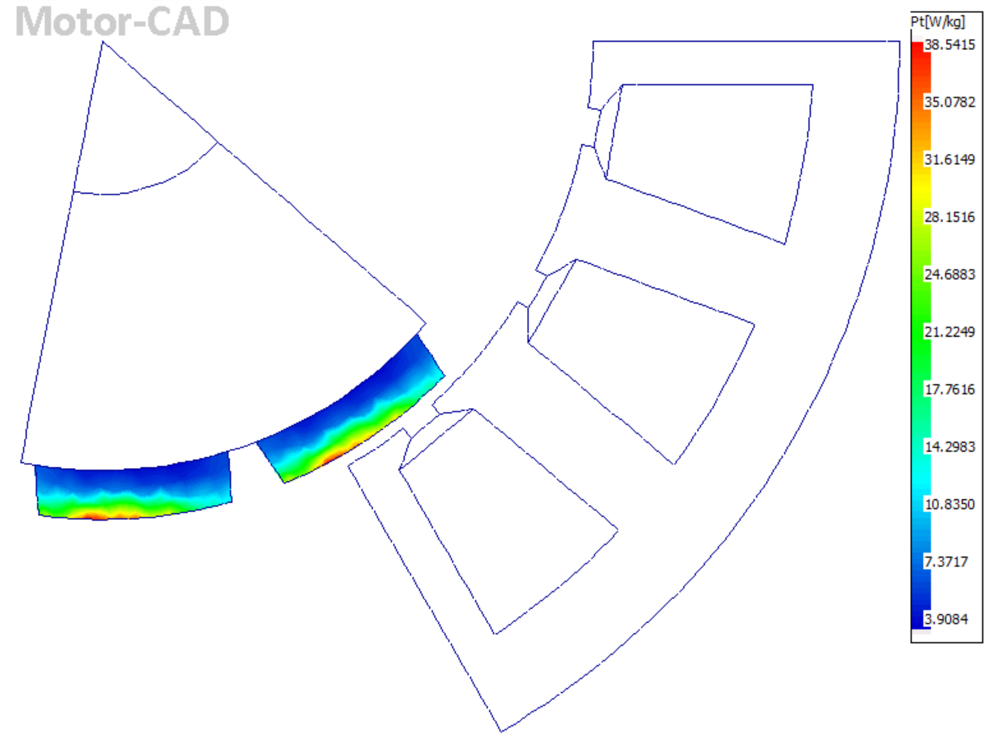
## Laminated Magnets

- Increases efficiency through further reduction of eddy currents
- Thinnest available insulating layers <20 microns for maximum energy density
- Performance at temperatures up to 200° C
- Magnet layers from ½ mm and up in custom shapes/sizes to suit your design
- Developed to solve a customer need
- Can use SmCo or GBD Neo

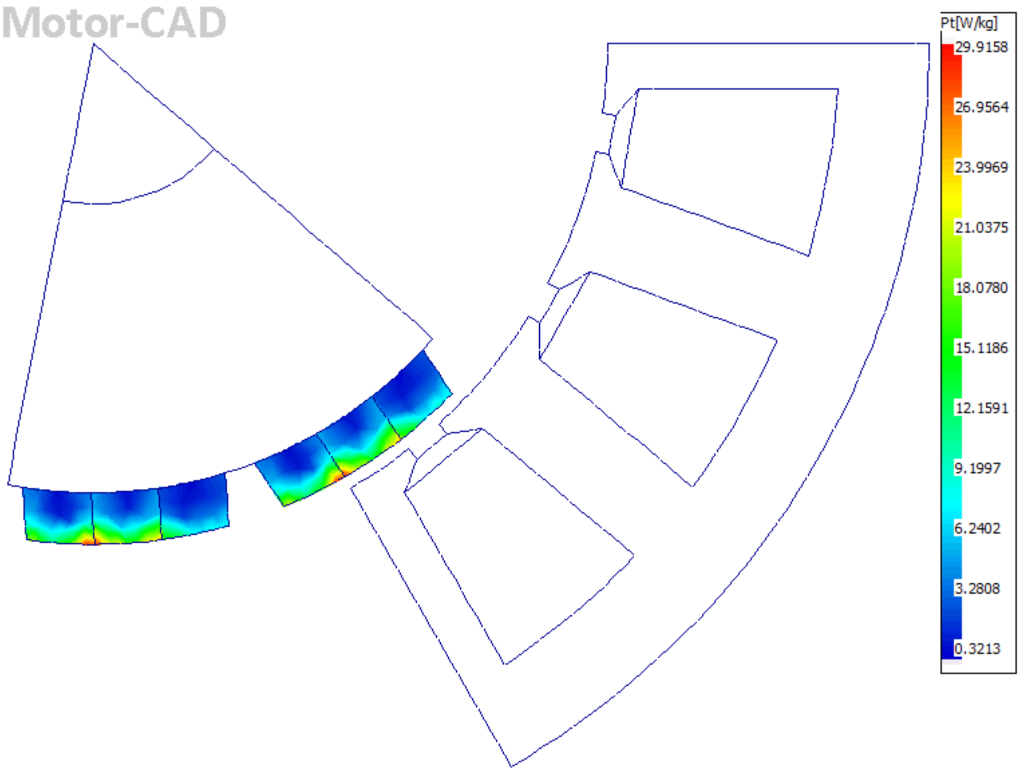
Arnold Magnetics

# Electrical Machines Innovation

## Laminated Magnets



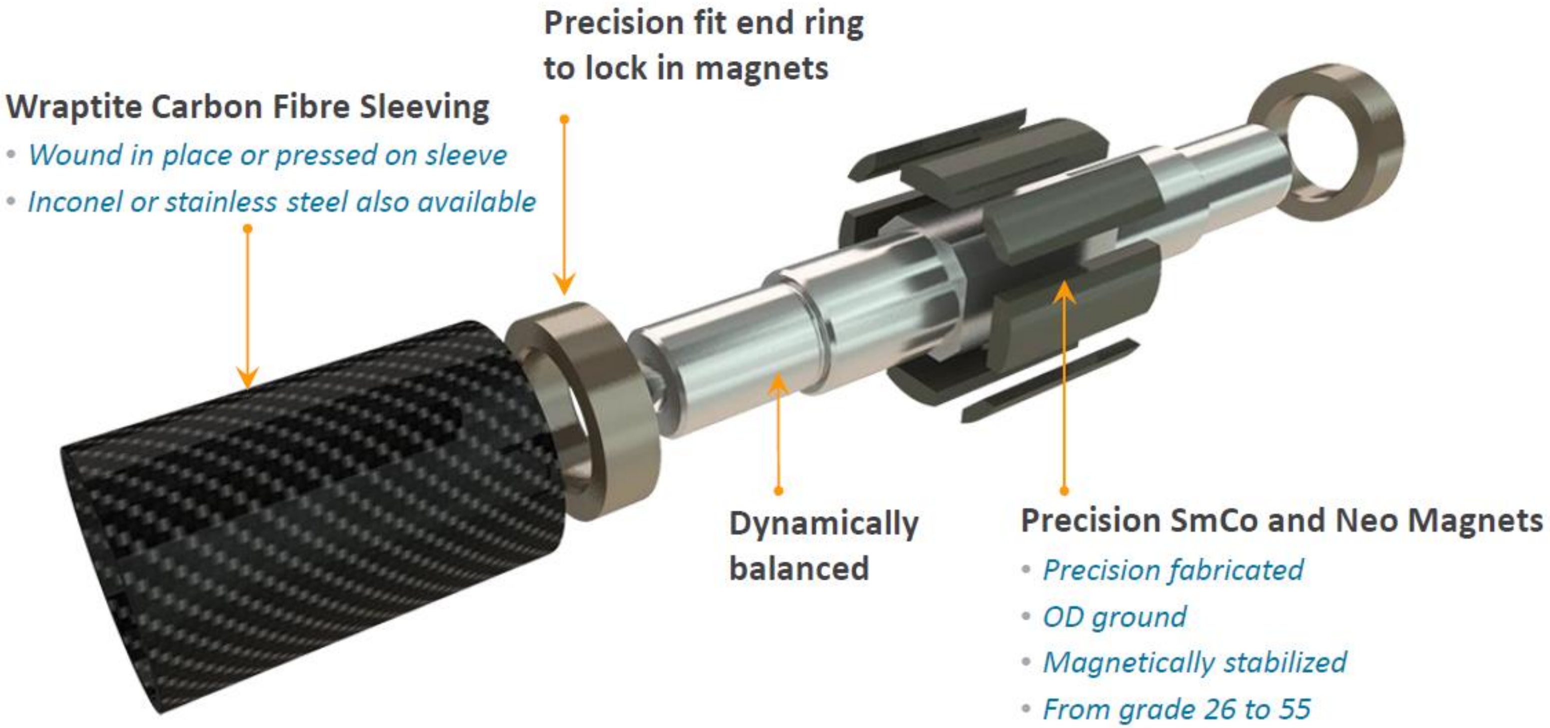

Magnet loss density with monolithic magnets (1 segment/pole)




Magnet loss density with laminated magnets (3 segments/pole)

# Electrical Machines Innovation

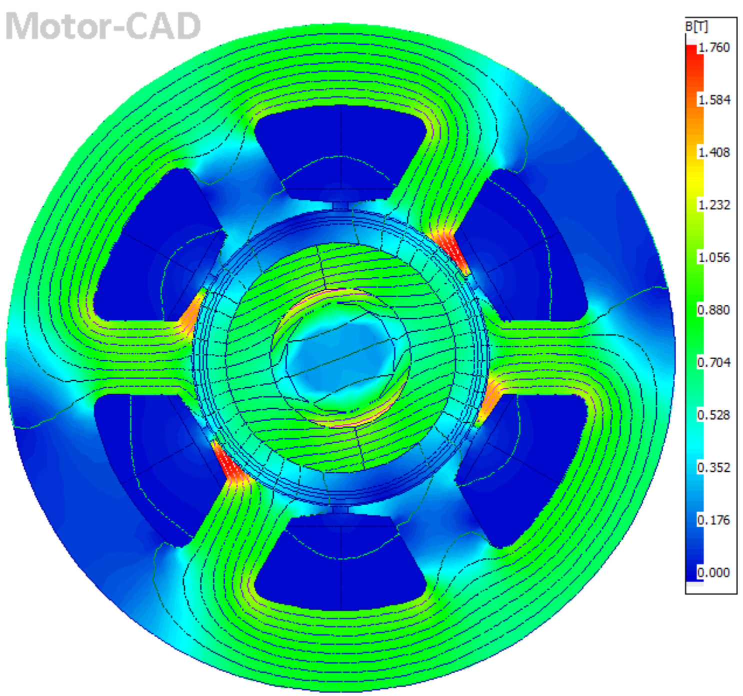
## Carbon Fibre Sleeving



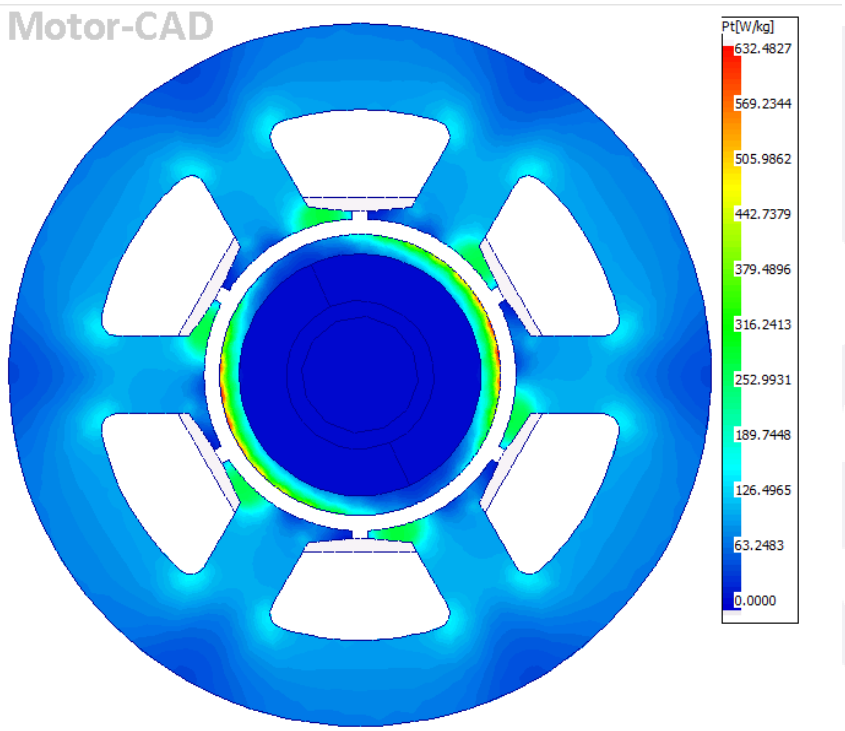

Arnold Magnetics

# Electrical Machines Innovation

## Carbon Fibre Sleeving




Flux density plots for high-speed generator (120krpm)




Magnetic Loss density plots for high-speed generator (120krpm)

# Electrical Machines Innovation

## Air-gap winding composite development


- Composite matrix of
  - 1.7 mm dia. aluminium wires
  - 0.7 mm reinforcing glass fiber rods
  - 1.25 mm Kevlar thread weave
- Structure vacuum impregnated with a high temperature grade of epoxy and cured
- First sample achieved a 27% conductor fill

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# Electrical Machines Innovation

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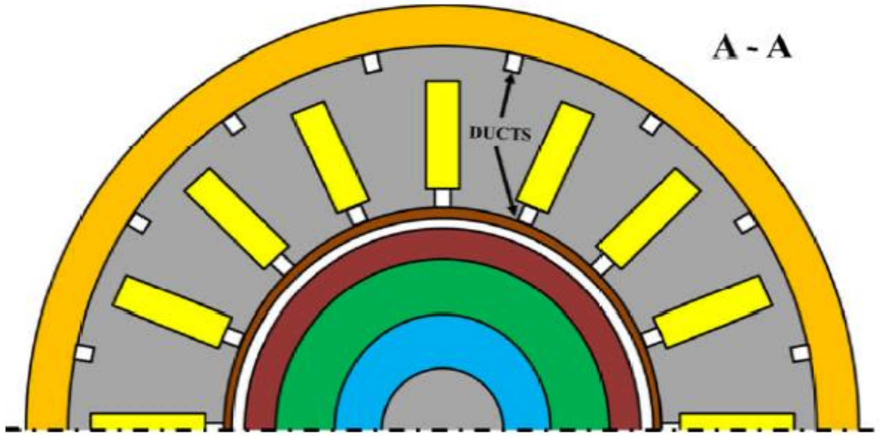
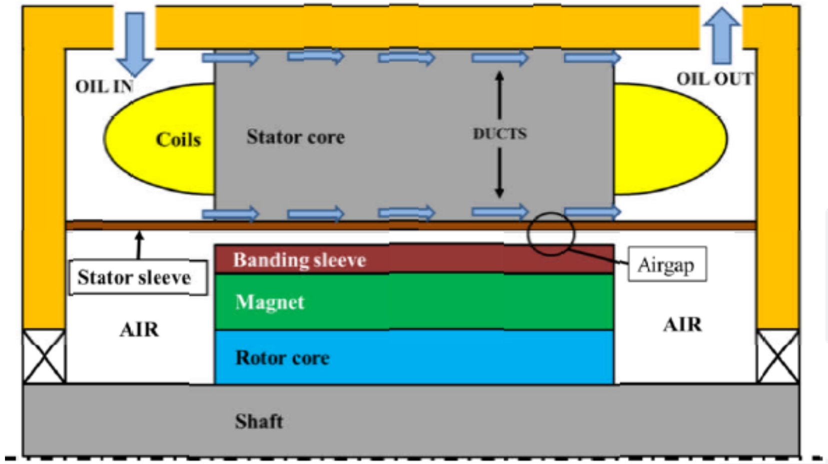
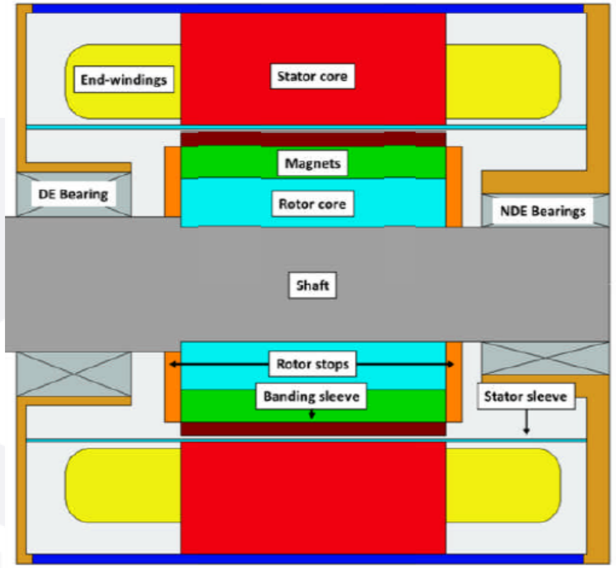
## Sleeve flooded stator cooling



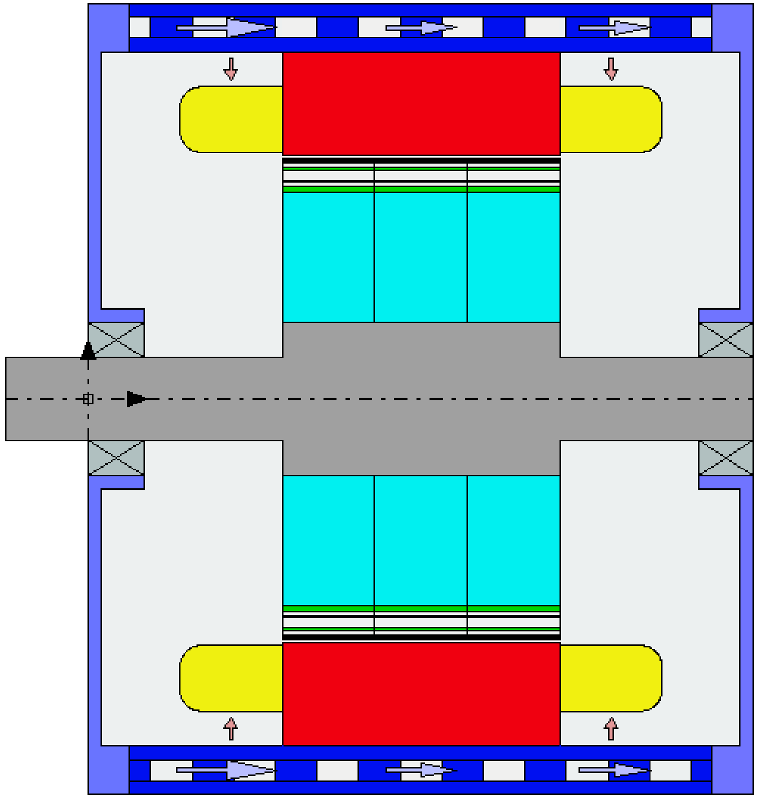




- a stator sleeve is introduced in the airgap to isolate the stator from the rotor.
- Stator is flooded with oil, passing through the cooling ducts at slot opening and stator back iron
- intensive direct cooling to the machine but at the same time could prevent any liquid from entering the airgap.

# Electrical Machines Innovation

## Oil spray cooling

- Housing water jacket is a common cooling solution.
- Copper loss at end winding can be substantial.
- Heat flow path of end winding is relatively longer when compared to active winding.
- Hot spot is usually located at the end winding.
- Improvement solution, the end winding can be cooled by oil spray.
- Direct cooling method.
- An active cooling that gives very high convective heat transfer coefficient (HTC).



For example, HTC can reach up to about 10,000 $W/m^2/K$ at Jet Impingement Velocity of 10 m/s by using automatic transmission fluid (ATF), Bennion and Moreno [2015]

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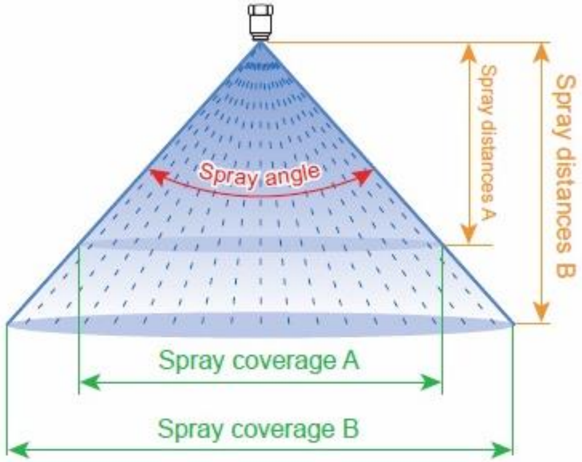
## Oil spray cooling

For oil spray cooling, oil is gone through two processes:

1) Oil is atomised and breaks into small droplets;
2) Oil drops are directed onto a target surface.




Oil spray nozzles:

- Oil spray – spray angle > 0°
- Oil jet – concentrated jet with spray angle of 0°
- Oil mist
- Oil droplets

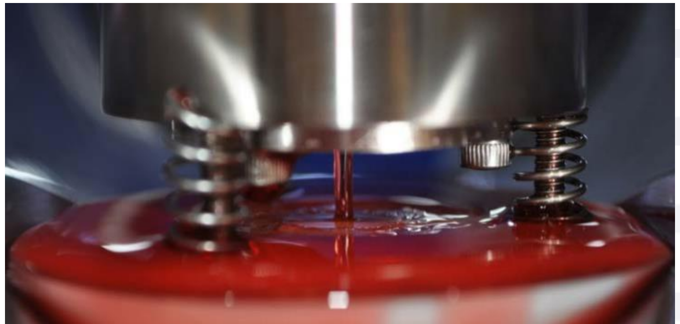
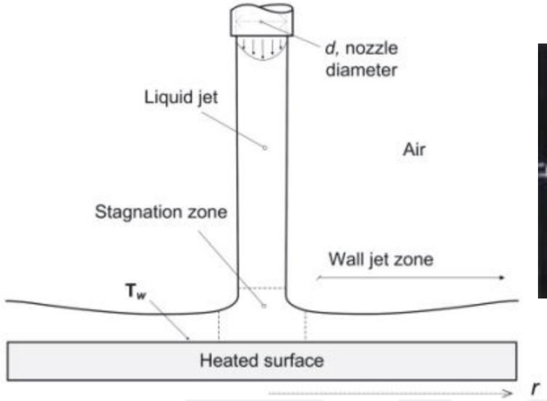


Photo Credit: Jana Jeffers, NREL

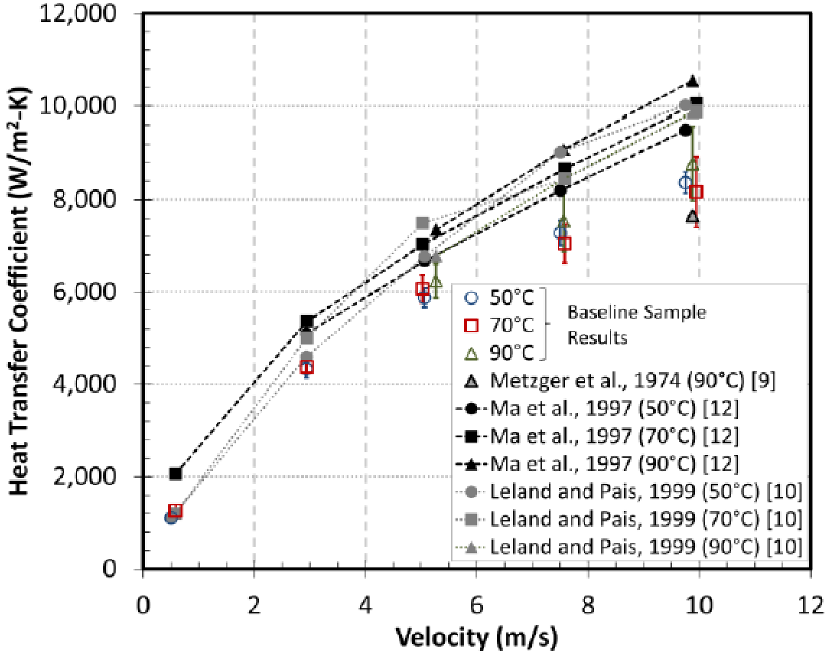



# Electrical Machines Innovation

## Oil spray cooling

- To remove the undesired heat from electrical machines, the cooling mechanism relies ultimately on the convective cooling.
- provide the highest convective heat transfer coefficient.
- up to about 10,000 W/m$^2$/K at nozzle hole flow velocity of 10 m/s by using automatic transmission fluid (ATF)
- direct oil cooling as it cools heat generating components directly (stator/rotor end winding, rotor end ring, magnet)

- Air Natural Convection
  - h = 5-10 W/(m$^2$.C)
- Air Forced Convection
  - h =10-300 W/(m$^2$.C)
- Liquid Forced Convection
  - h = 50-20000 W/(m$^2$.C)




[K. Bennion and G. Moreno, “Convective heat transfer coefficients of automatic transmission fluid jets with implications for electric machine thermal management,” in *ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK2015)*, 2015, pp. 1–9.

# Electrical Machines Innovation

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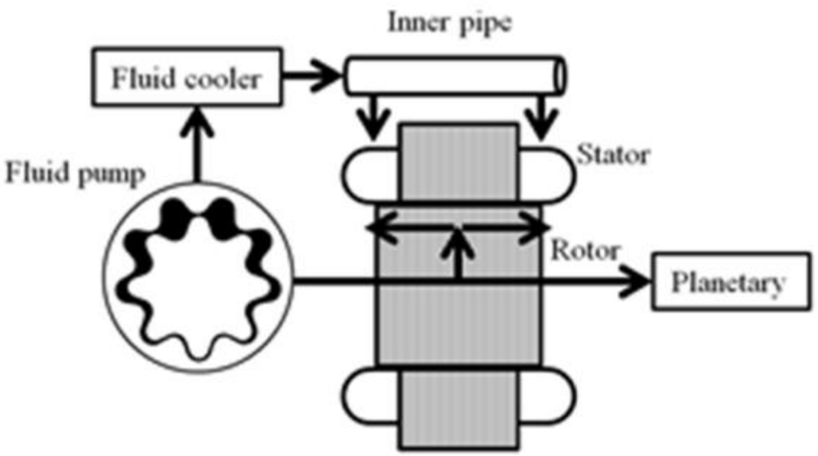
## Oil spray cooling

- ATF is supplied from oil pump to cool the stator and coil end winding through the inner pipe.
- The oil passed through rotor core to cool the magnet actively
- Thus, the motor is cooled efficiently and increased the current density up to 58% compared to Toyota Prius 2009 motor.

Toyota Prius 2017




S. Sano, T. Yashiro, K. Takizawa, and T. Mizutani, “Development of New Motor for Compact-Class Hybrid Vehicles,” *World Electr. Veh. J.*, vol. 8, no. 2, pp. 443–449, 2016.

# Electrical Machines Innovation

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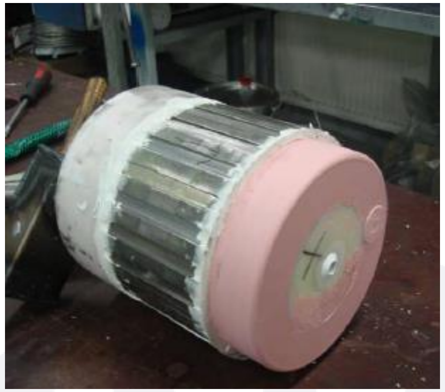
## Impregnation Materials

TABLE I
COMPARISON BETWEEN THE IMPREGNATION MATERIALS STUDIED

| Materials | Varnish | Epoxylite | SbTCM |
|---|---|---|---|
| Thermal conductivity (W/mk) | ≈0.25 | ≈0.85 | 3.20 |
| Dielectric strength (kV/mm) | ≈80 | ≈20 | ≈10 |
| Volume resistivity at 25°$C$ (Ω·cm) | $> 10^{15}$ | $> 10^{14}$ | $> 10^{14}$ |
| Viscosity (Pa·s) | - | 3.5 | 25 |
| Price (Pu) | 1.0 | ≈2.0 | ≈4.0 |

S. Nategh, A. Krings, O. Wallmark, and M. Leksell, "Evaluation of impregnation materials for thermal management of liquid-cooled electric machines," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 5956–5965, 2014.

- impact of the thermal conductivity of different potting materials
- high-performance liquid-cooled electric machines
- k varies from 0.25 to 3.2 W/mK

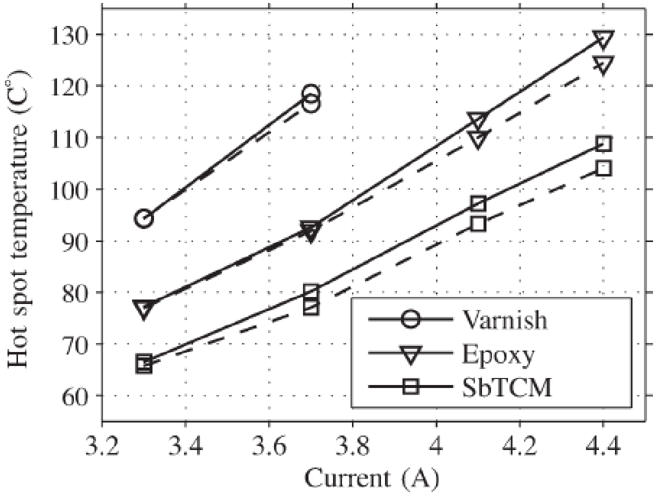
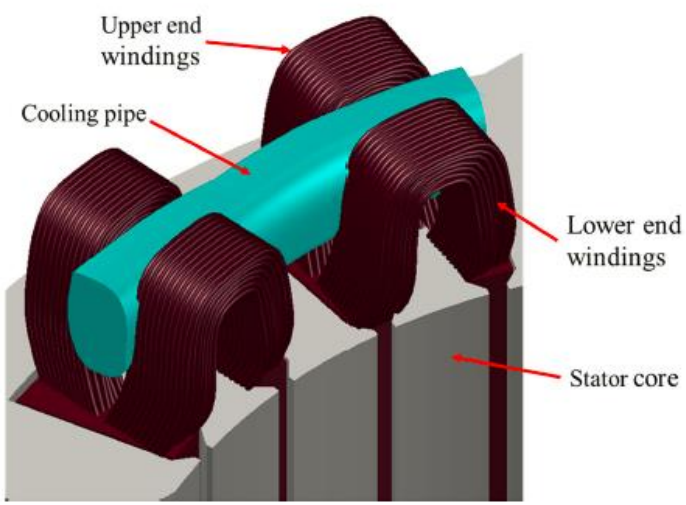



Fig. 14. Comparison between the hot spot temperatures of the machines. The inlet coolant flow rate is 3.0 L/min. The solid and dashed lines represent the experimental and simulation results, respectively.

# Electrical Machines Innovation

## Cooling pipes system



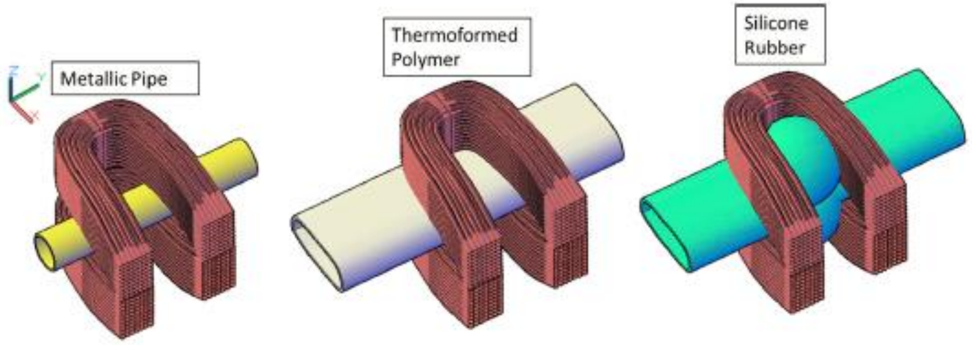




TABLE I

LIST OF POTENTIAL COOLING PIPE MATERIALS AND THEIR PROPERTIES

| Material | $\sigma$ [MS/m] | $\vartheta_{Max}$ [°C] | $k_{pipe}$ [W/K/m] | $E_{pipe}$ [GPa] | $t_{pipe}$ [mm] | $cf$ [-] |
|---|---|---|---|---|---|---|
| PVC | Diel. | 100 | 0.19 | 2.4–4.1 | 2 | 0.2 |
| ABS | Diel. | 100 | 0.17 | 2-2.6 | 2 | 0.2 |
| PTFE | Diel. | 260 | 0.25 | 0.4-1.8 | 2 | 0.25 |
| Silicone Rubber | Diel. | 200 | 1.22 | 0.001-0.05 | 0.5 | 0.5 |
| Nylon | Diel. | 70 | 0.25 | 2–4 | 2 | 0.2 |
| Copper (square) | 58.5 | >500 | 385 | 117 | 2 | 0.15 |
| Copper (round) | 58.5 | >500 | 385 | 117 | 1 | 0.1 |
| Stainless Steel | 1.35 | >500 | 12–45 | 190-203 | 1 | 0.1 |
| Aluminium | 36.9 | >500 | 204 | 69 | 1 | 0.1 |
| Ceramic | Diel. | >500 | 5-15 | 360 | 1 | 0.1 |
| Glass | Diel. | >500 | 1.05 | 50-90 | 2 | 0.1 |
| Carbon Fibre | Diel. | 100 | 5-7 | 150 | 1 | 0.1 |

MADONNA *et al.*: IMPROVED THERMAL MANAGEMENT AND ANALYSIS FOR STATOR END-WINDINGS OF ELECTRICAL MACHINES, Trans. On Ind Electronics, 2018

# Electrical Machines Innovation

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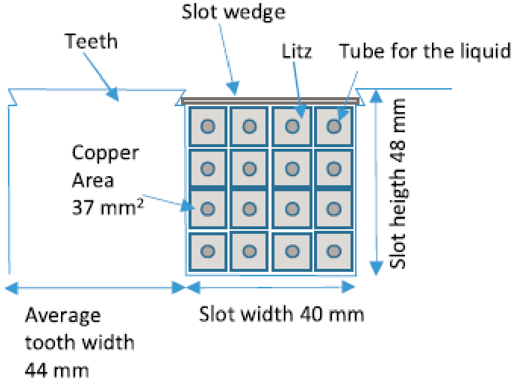
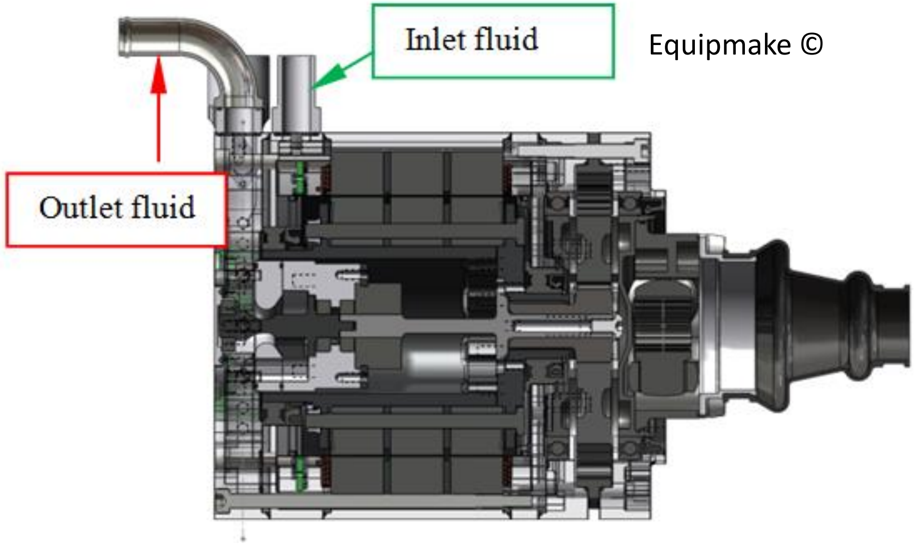
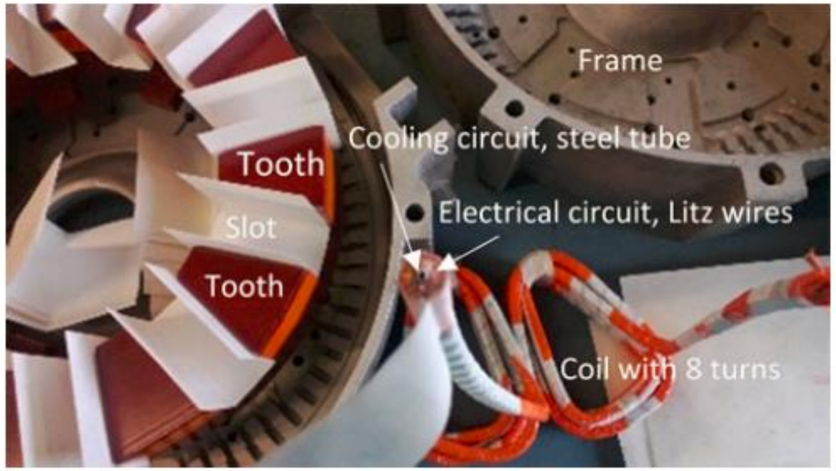
Through slot/conductors liquid cooling




Equipmake ©




Power traction EV – liquid and forced air cooled motor

P. Lindh *et al.*, “Direct liquid cooling method verified with an axial flux permanent-magnet traction machine prototype,” *IEEE Trans. Ind. Electron*. 2017.

# Heat extraction through convection

Power traction EV – liquid and forced air cooled motor

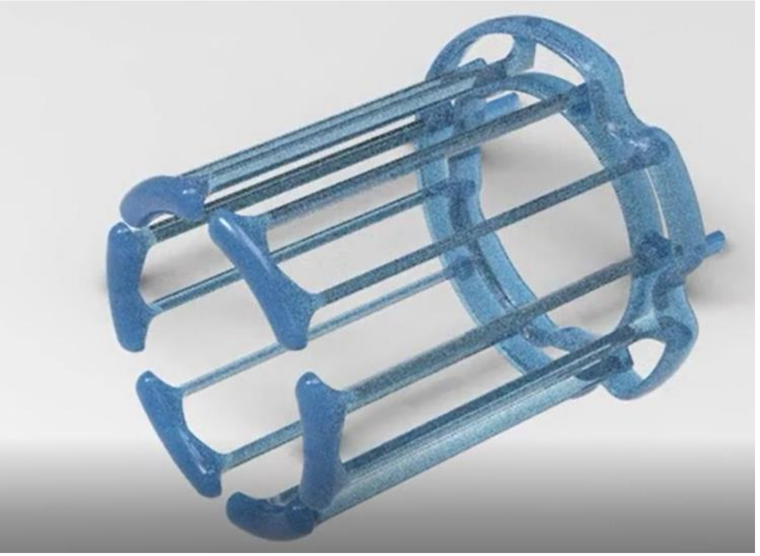
Porsche ©

Protean Electric ©

In-wheel BPM motor

# Electrical Machines Innovation

Power traction: BPM liquid cooled stator package and rotor shaft (Fraunhoffer)



# Electrical Machines Innovation

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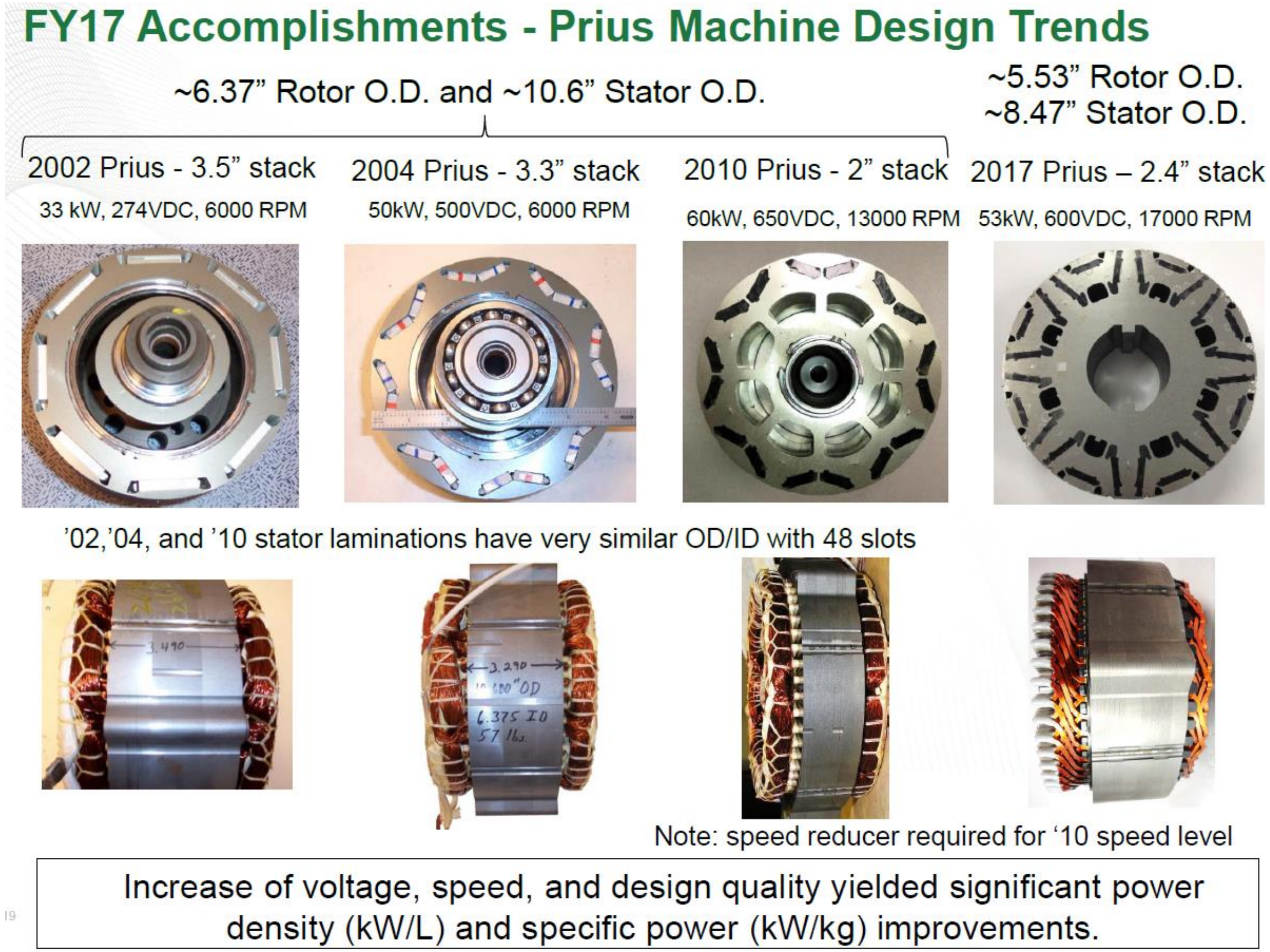
## Design evolution

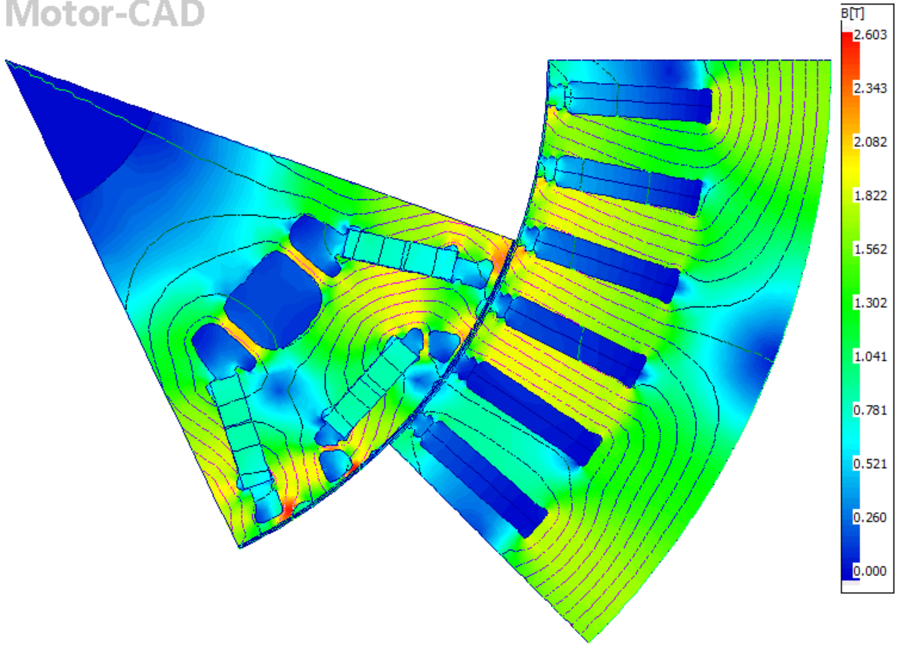


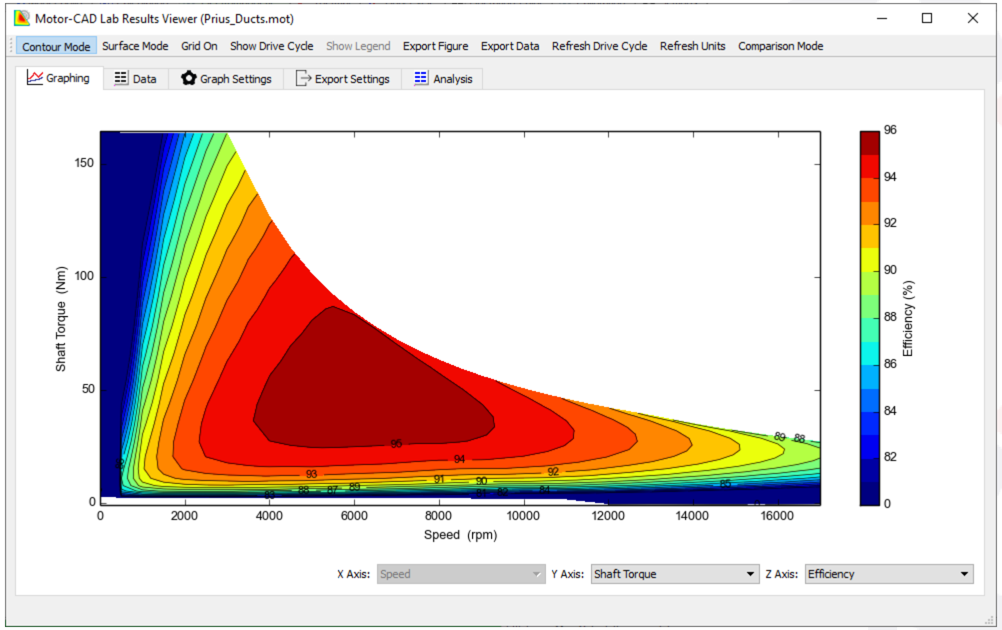

Oak Ridge National Laboratory
www.ornl.gov

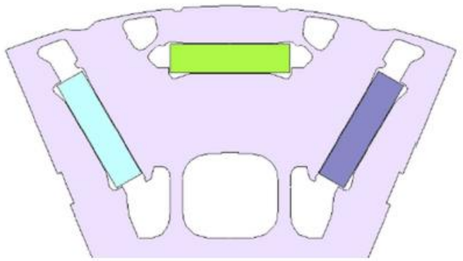
# Electrical Machines Innovation

- Prius 2017 - Dimensions can be approximated
- Assumed magnet (N42UH) and electrical steel grades (M250-35A)

Motor-CAD



P610

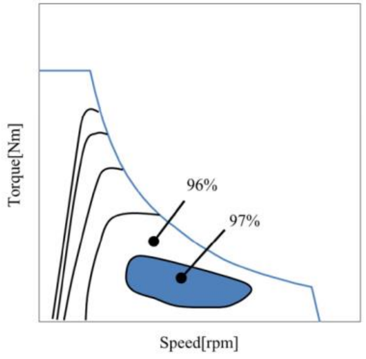



Figure 14: Motor Efficiency map of P610

*EVS29 Symposium*
*Montréal, Québec, Canada, June 19-22, 2016*

**Development of New Motor for Compact-Class Hybrid Vehicles**

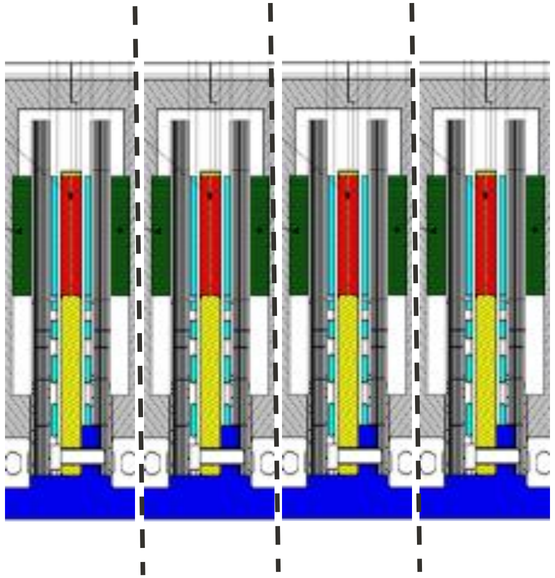
Shinya Sano, Takahisa Yashiro, Keiji Takizawa, Tatsuhiko Mizutani,

# Electrical Machines Design

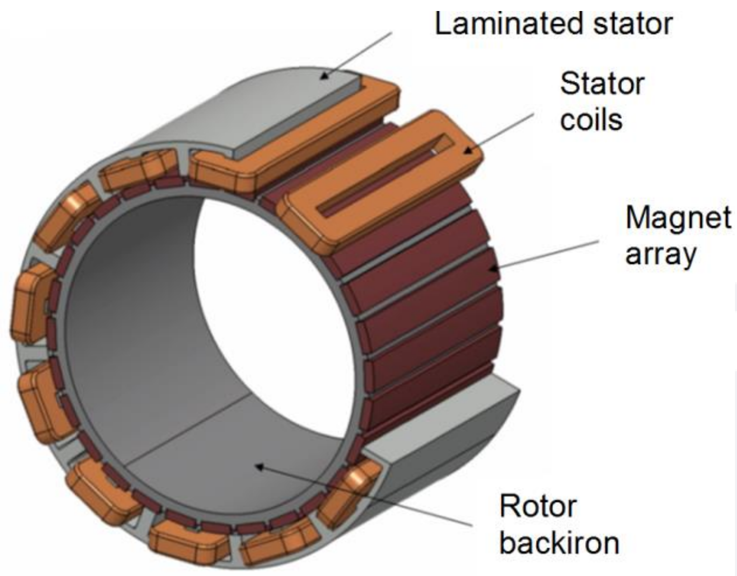
Motor Design Limited

## Brushless Permanent Magnet Machines

Dual stator
Axial-flux



Internal rotor
Radial-flux

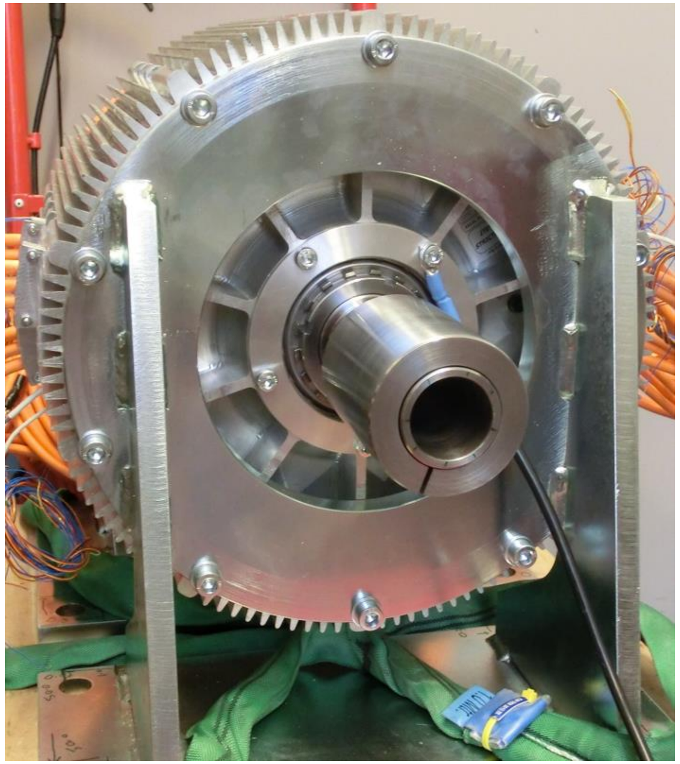



CleanSky, www.eletad.eu

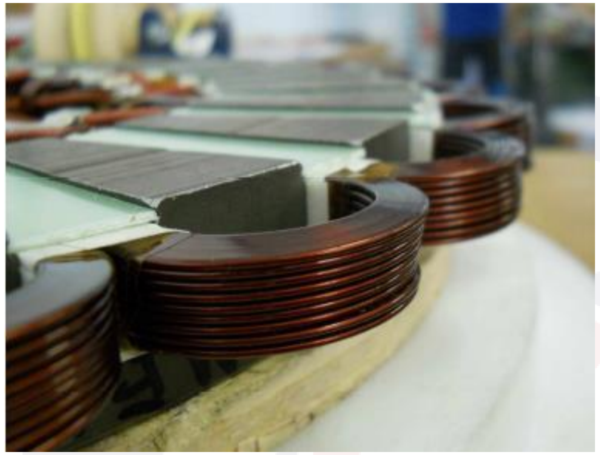
- Axial separation with 4 electro-magnetically independent stages
- Limited axial thermal interaction between stages
- Four separate rotors on a common shaft

- Circumferential separation with minimal winding mutual coupling
- Thermal interactions via back iron and casing
- Design uses a single shared rotor

# Axial-flux machine prototype



*Pre-formed Stator winding*



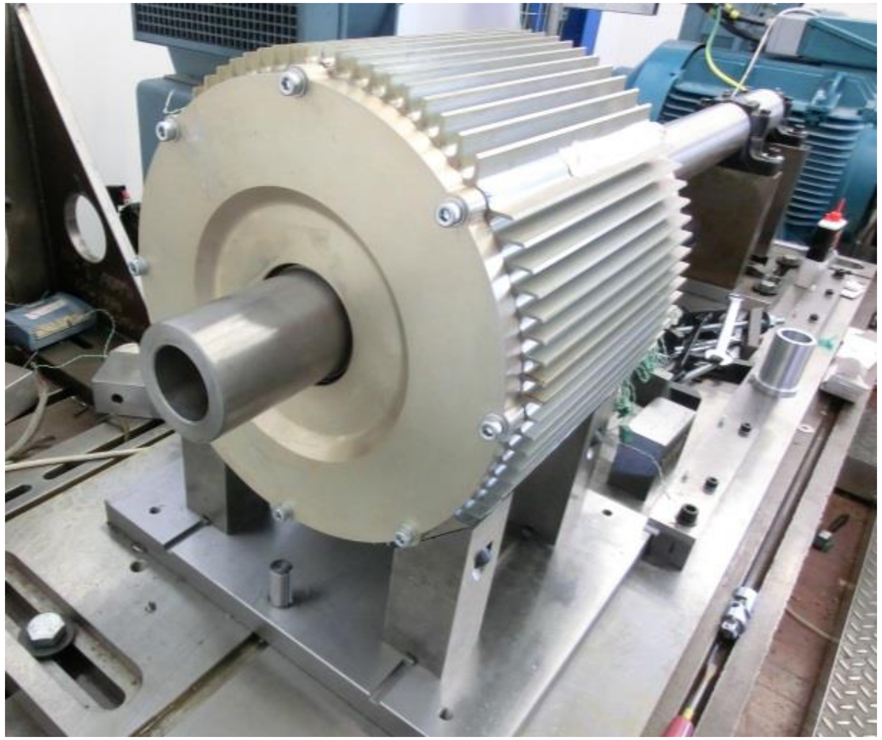
CleanSky, www.eletad.eu

*Rotor magnets and carrier*

Lucchi R. Elettromeccanica s.r.l.

# Electrical Machines Design

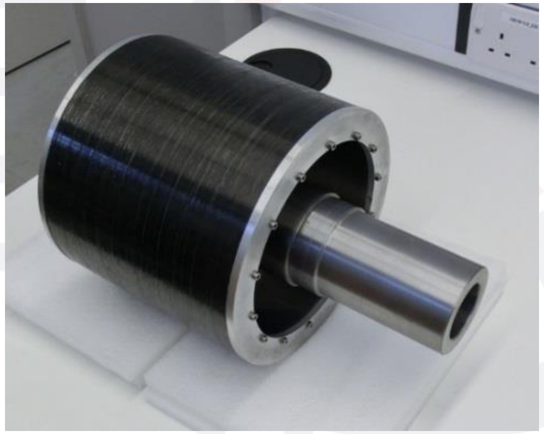
## Radial-flux machine prototype



*Wound stator*
*(prior to varnishing)*

CleanSky,
www.eletad.eu

*Rotor assembly*



University of BRISTOL

# Electrical Machines Design

## Radial-flux machine prototype

Phase coils individually terminated
(and instrumented with thermocouples)


CleanSky,
www.eletad.eu

Neighbouring coils grouped into four
star connected 3-phase motor units

University of BRISTOL

# Electrical Machines Design

## Radial-flux machine prototype

Phase coils individually terminated
(and instrumented with thermocouples)

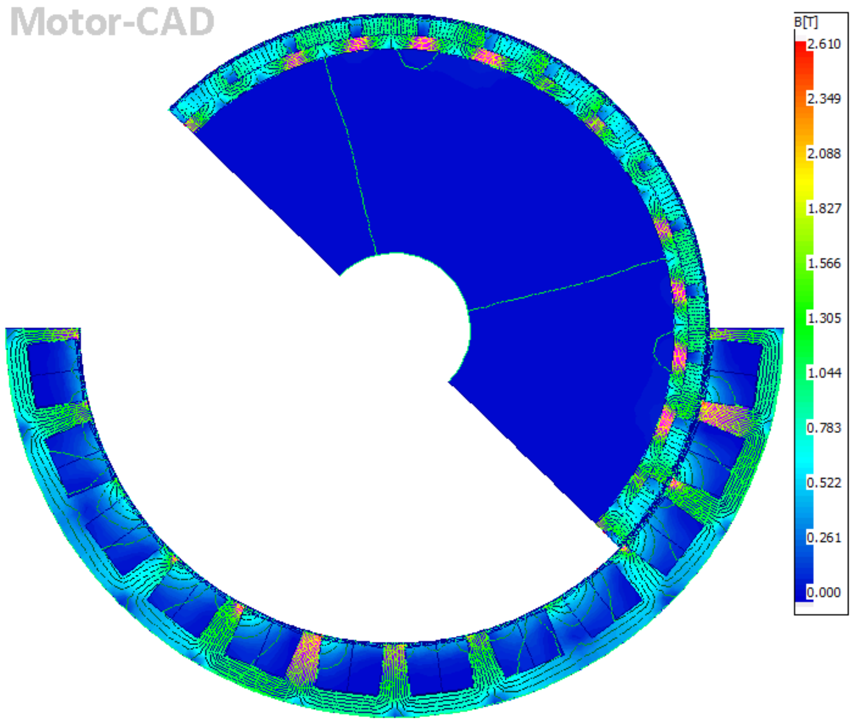

Neighbouring coils grouped into four star connected 3-phase motor units

CleanSky,
www.eletad.eu

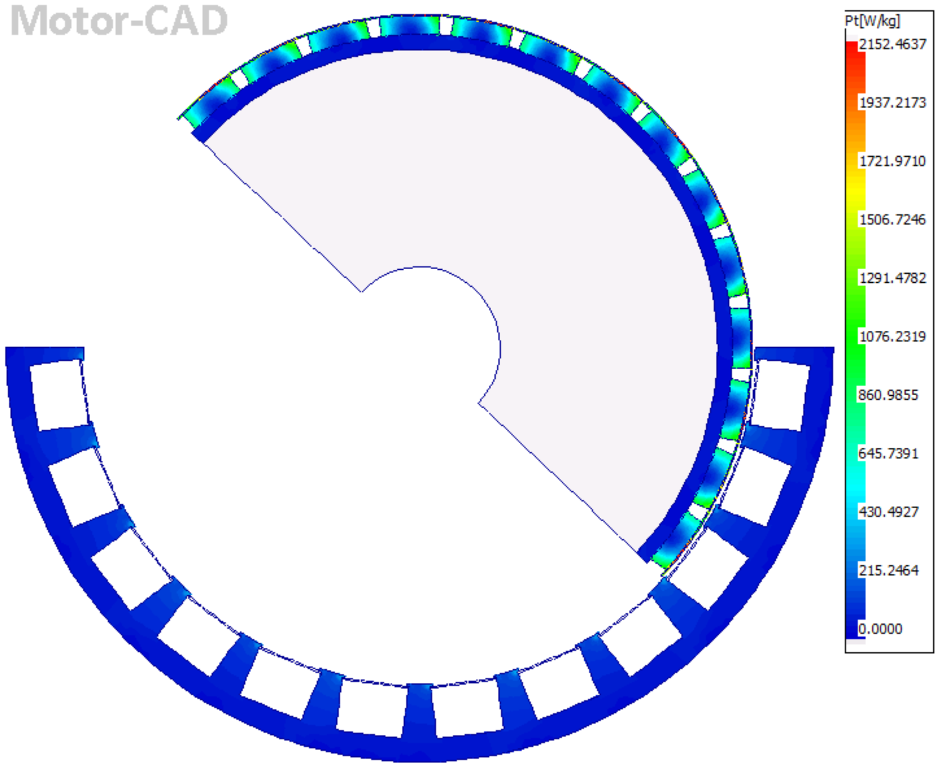
University of BRISTOL

# Electrical Machines Design

## Radial-flux machine model




Flux density plots

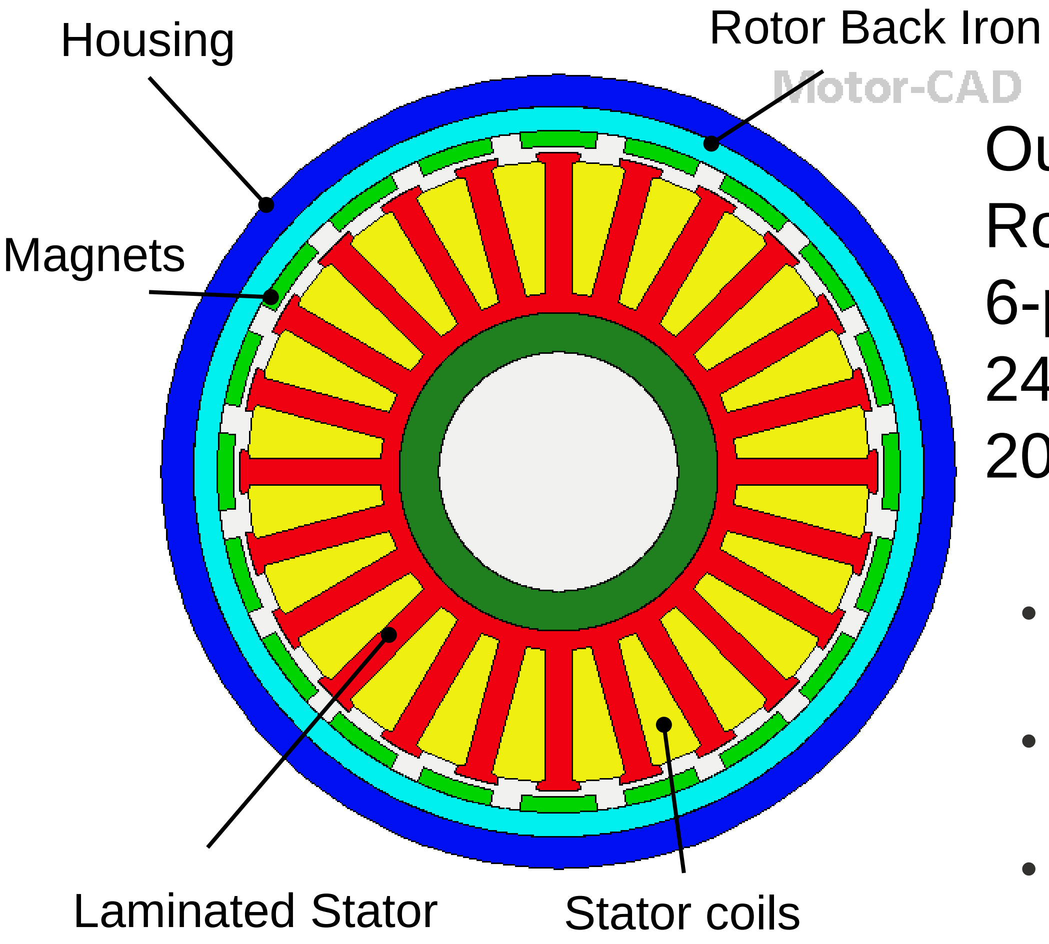



Magnetic loss density plots

CleanSky,
www.eletad.eu

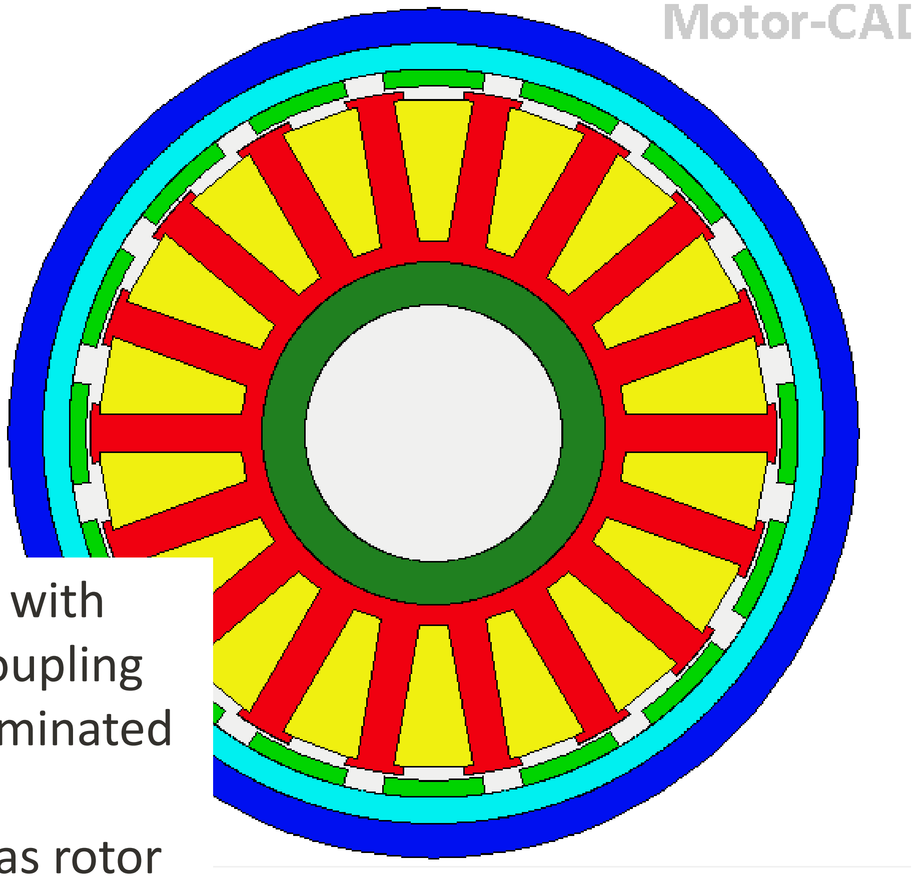
# Electrical Machines Design

## Brushless Permanent Magnet Machines




Outer
Rotor
6-phase
24 slots
20 poles

Outer
Rotor
9-phase
18-slots
16-poles




- Circumferential separation with minimal winding mutual coupling
- Thermal interactions via laminated steel and axle
- Design uses propeller hub as rotor casing

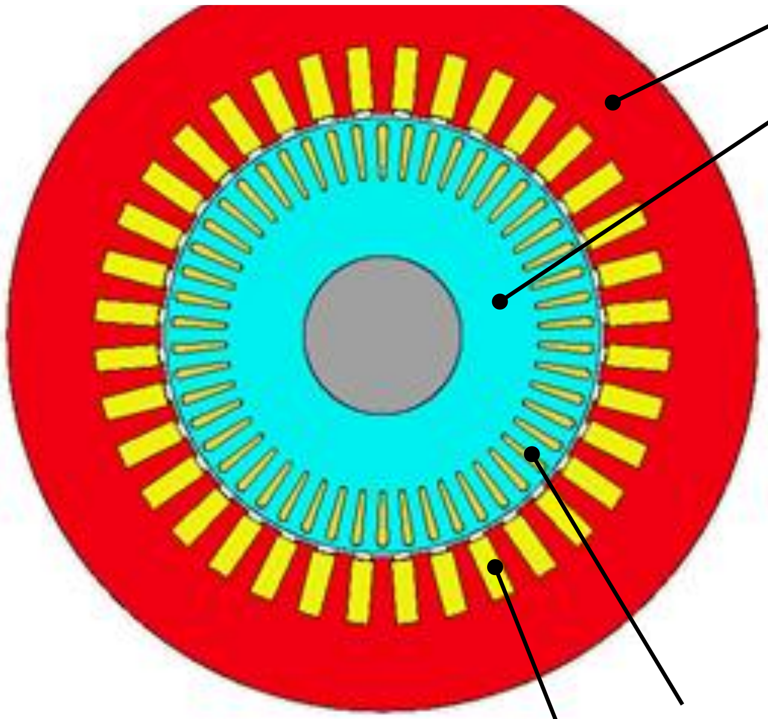
# Electrical Machines Design

www.refreedrive.eu

Motor Design Limited

## Induction Machines

- Design couples via gearbox shaft to propeller axle

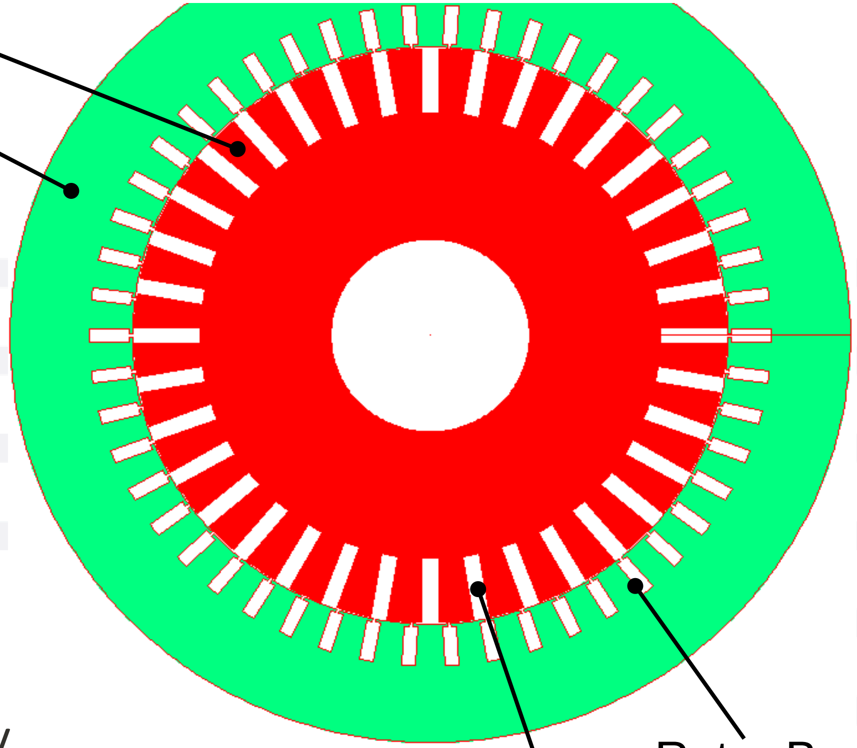



Inner Rotor
6-phase
36 slots
50 bars
4 poles

Outer Rotor
6-phase
36 slots
50 bars
6 poles

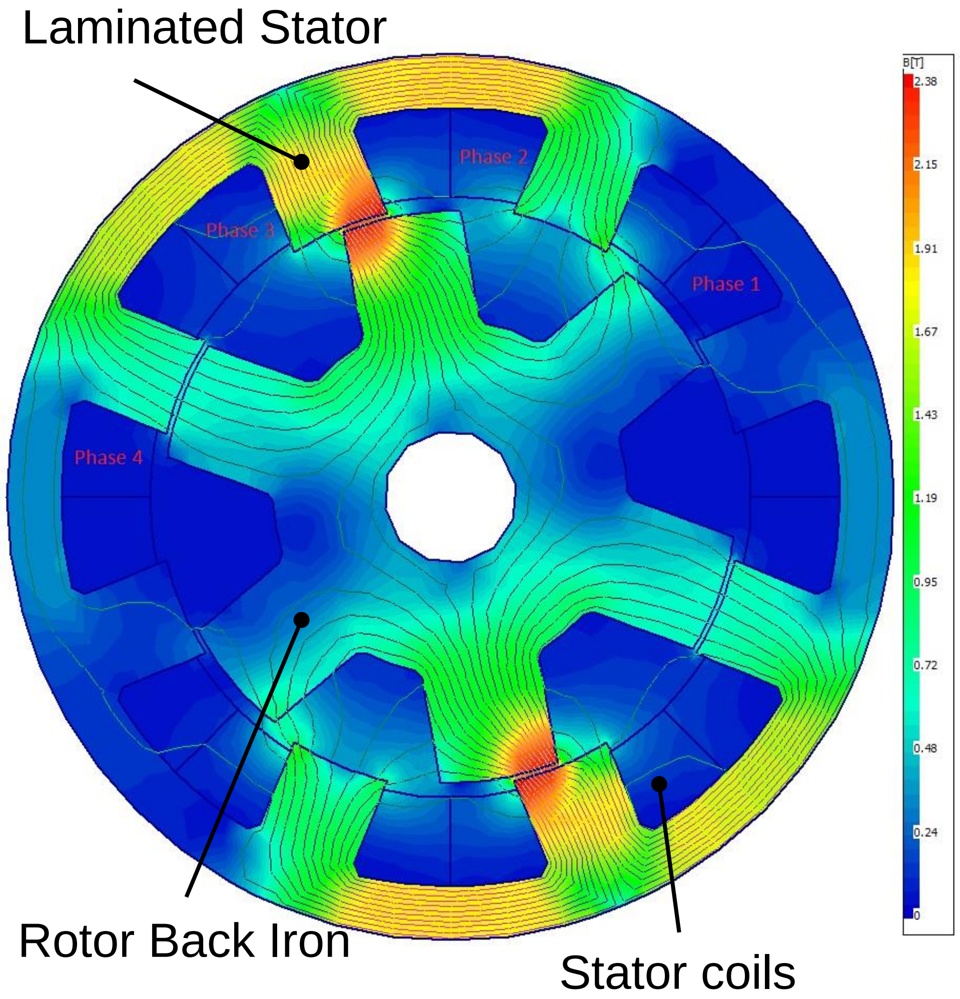
- Hairpin winding
- Thermal interactions via laminated steel and casing / axle

- Design uses propeller hub as rotor casing



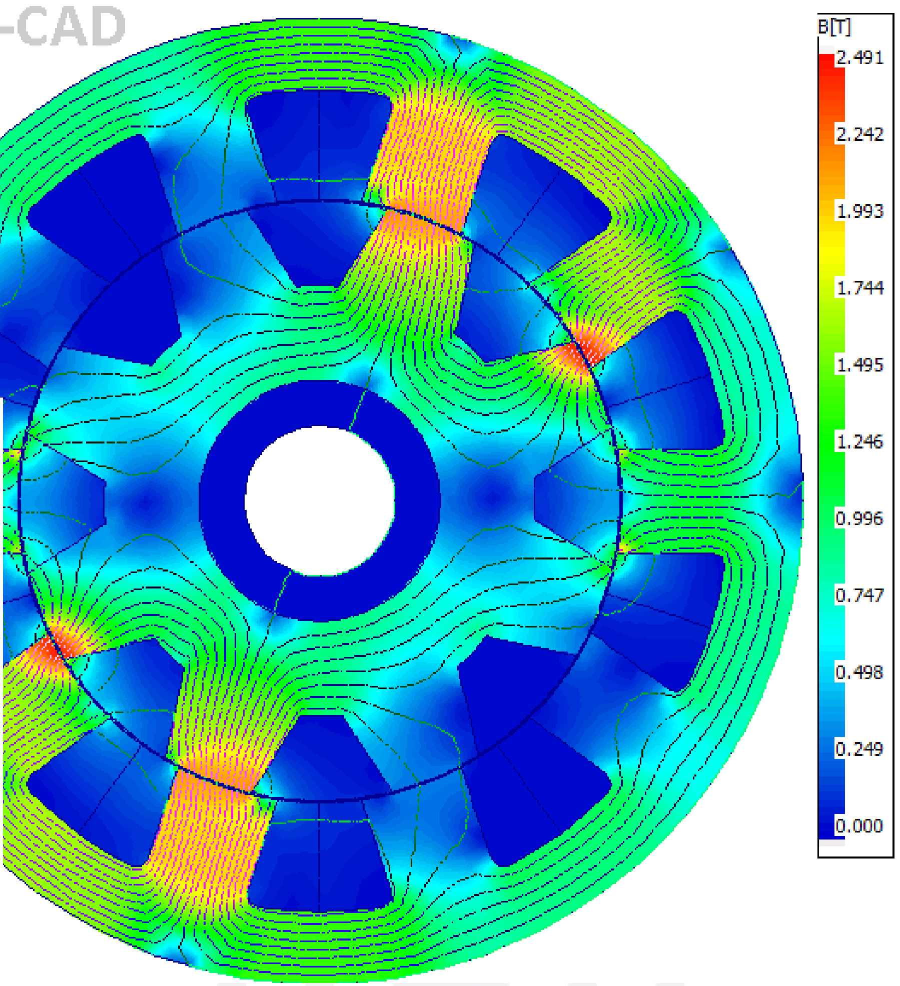
# Electrical Machines Design

## Switched Reluctance Machine




Inner
Rotor
4-phase
8 teeth
6 poles

Inner
Rotor
5-phase
10 teeth
8 poles




- Circumferential separation with minimal winding mutual coupling
- Thermal interactions via laminated steel and casing
- Design uses shaft coupled via gearbox to propeller axle

# Summary

- Electrical motors for high-performance applications have to comply with:
  - High safety factor (fault tolerant operation)
  - High power density (low mass)
- Key to potential solutions:
  - Advanced materials: CoFe, NGO steel, special additive coils, coatings
  - Multiplex systems
  - Liquid cooling systems
- Various topologies can be used depending on operating range and supply
  - Brushless PM or Reluctance PM assisted machines
    - Radial and Axial flux
    - Inner and Outer rotor
  - Induction machines
    - Inner and Outer rotor
  - Switched reluctance machines
    - Inner and Outer rotor

# Thank You for Your Attention!
# Contact Details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