ReFreeDrive

Rare-Earth Free e-Drives feat. low cost manufacturing

Adoption of the Induction Motor With Copper Rotor for E-Mobility

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26 September 2018, Pordenone ,Italy

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III. Work Package structure

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V. Preliminary design analysis

VI. Optimisation

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Introduction

ReFreeDrive goals and actions

Objectives and actions

Motor Design Limited

ReFreeDrive

Main goals

- Mass production
- Low costs
- Increased performances

Which Actions??

Objectives and actions

ReFreeDrive

Motor Design Limited

Main goals

Mass production

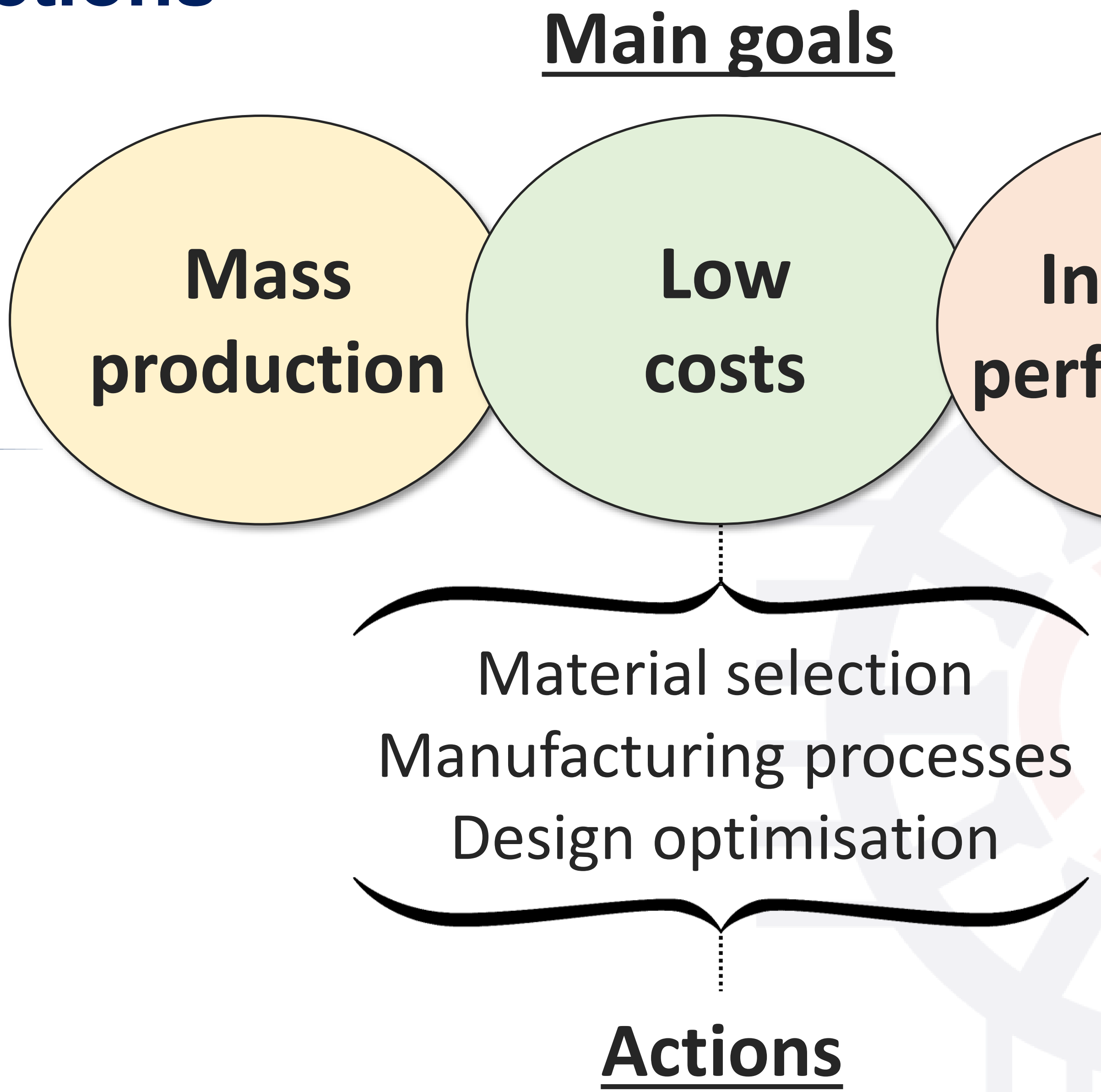
Low costs

Increased performances

Copper rotor induction motor
Die-casted or fabricated rotor

Actions

Objectives and actions



Objectives and actions

Motor Design Limited

ReFreeDrive

Main goals

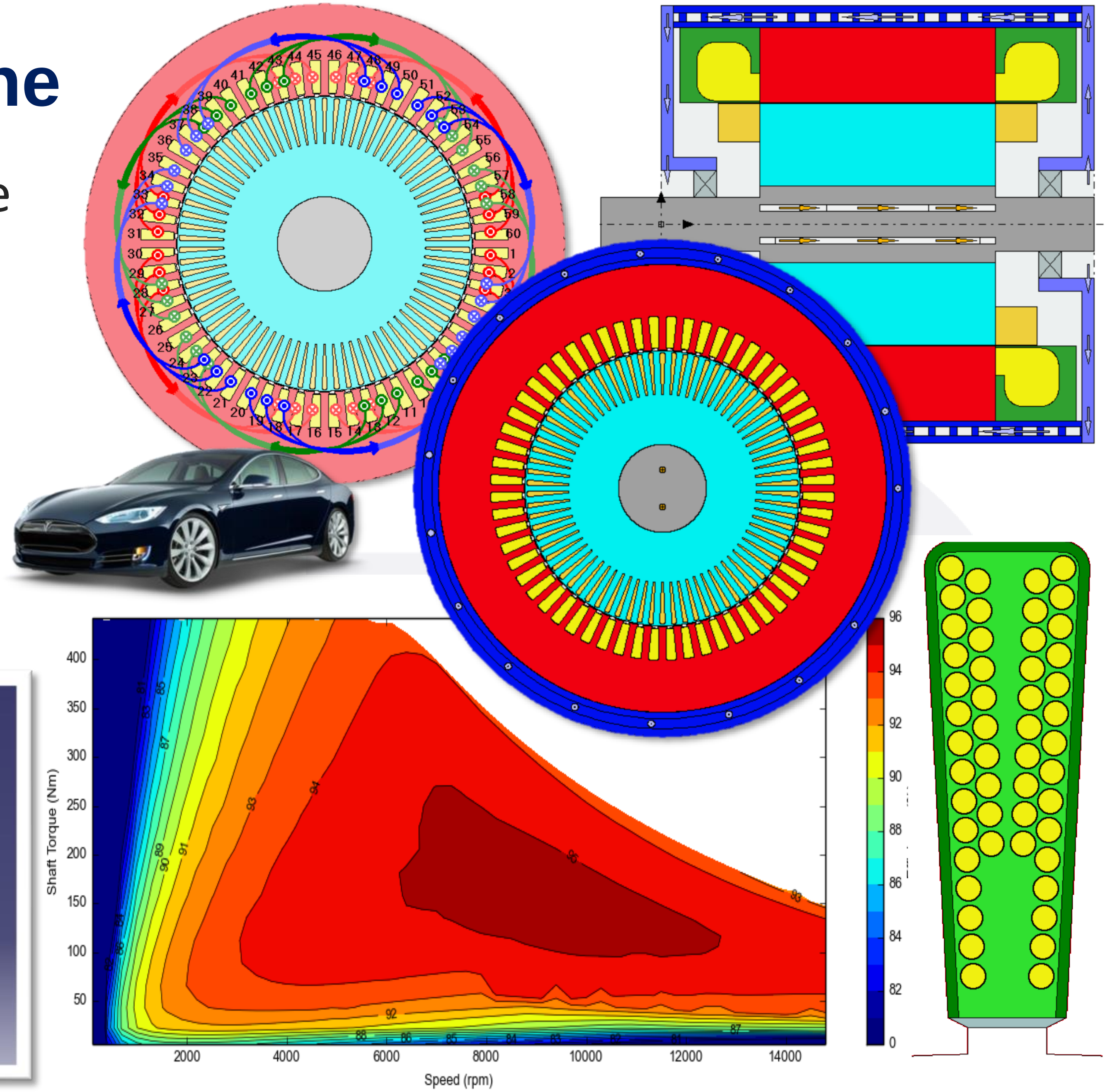
- Mass production
- Low costs
- Increased performances

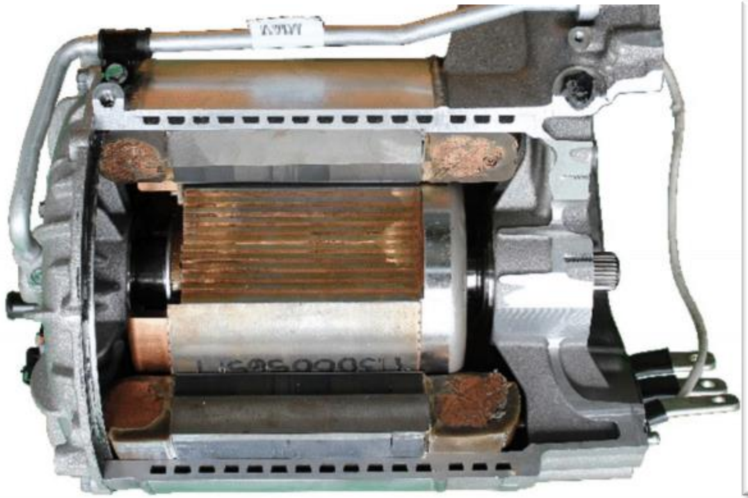
Material selection
Inner Rotor vs Outer Rotor
Hairpin winding technology
Increase speed
Innovative cooling system
Design optimization

Actions

Rotor cage induction machine

- Proven technology in industry with the Tesla model S
- Data from teardown analysis and used as a reference
- Copper preferred to aluminium for its conductivity, thermal dissipation, rigidity and strength, recyclability…

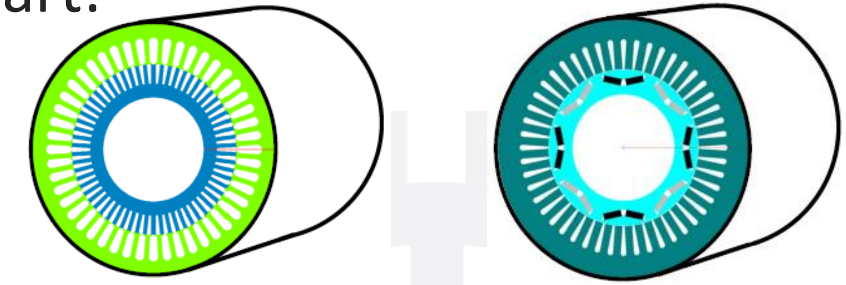


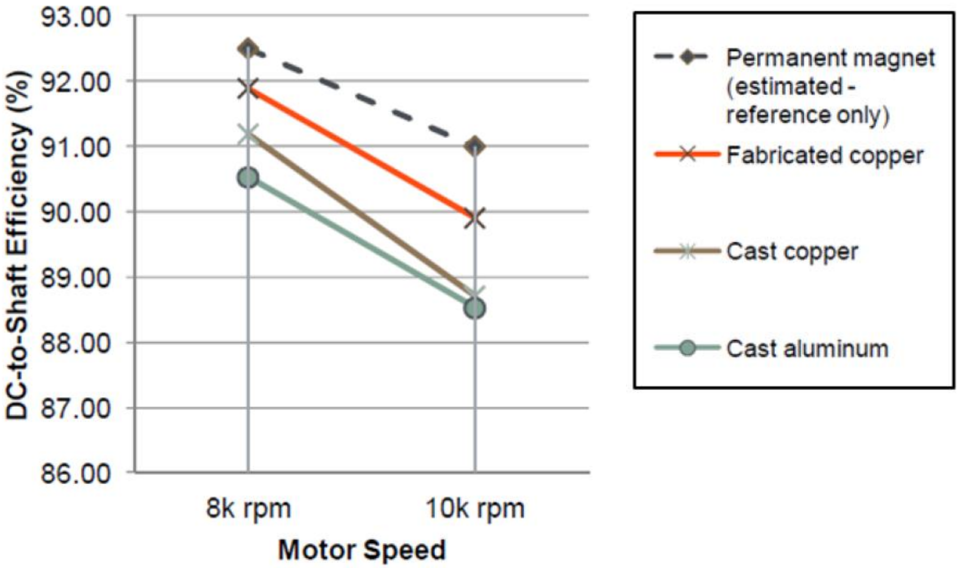


Induction machine (IM) vs PM-machine

Despite lower performances as a whole, IMs still have attractive features for EV applications compared to their counterpart:

- Simplicity, robustness, fault tolerant capability
- Efficiency can be higher over a full drive cycle
- Rare-earth PM-free machine
- Can lead to cost savings



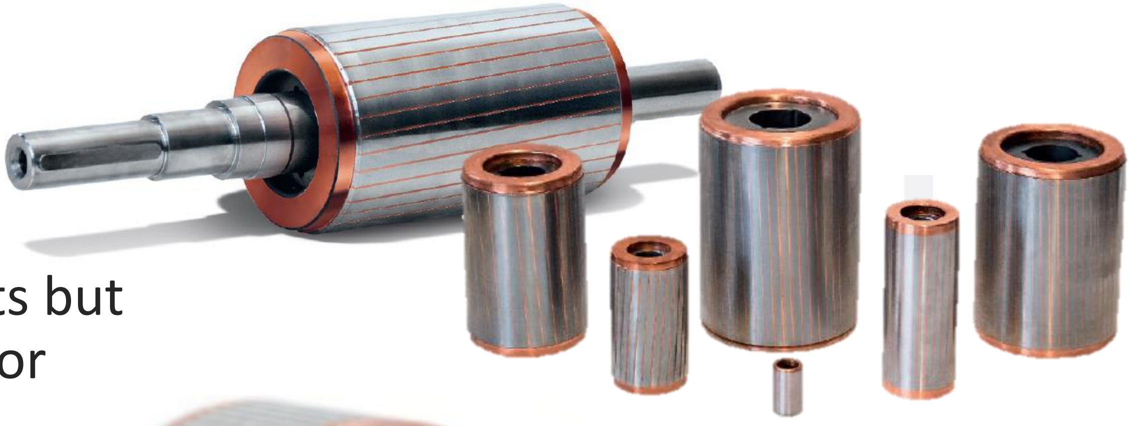


Property	Copper Rotor Induction Motor	Permanent Magnet Motor
Efficiency	88%	92%
Stator Copper Loss	940 W	780 W
Rotor Loss	230 W	0 W
Stray Load Loss	140 W	0 W
Iron Loss	180 W	100 W
Total Loss	1490 W	880 W
Coolant Temperature	105°C	105°C
Coolant Flow Rate	2.4 gallons/min	2.4 gallons/min
Maximum Winding Temp	156°C	156°C

Die-casted vs fabricated copper rotor

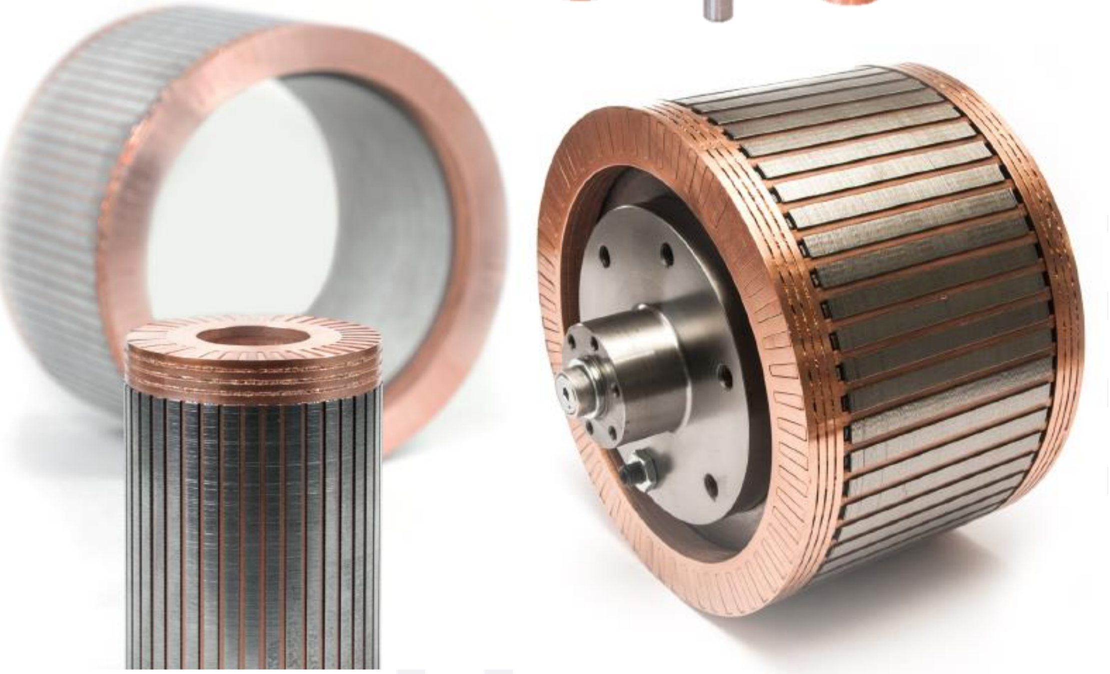
Die-casted rotor

- Mechanical rigidity for a cost effective noise solution and a better strength at higher speeds
- More flexibility for bar geometry and number
- Lower efficiency than their fabricated counterparts but can be improved with a post heat treatment and/or a lamination coating
- High melting temperature of copper: requires more expensive dies and can cause inter-bar currents and short-circuited laminations



Fabricated rotor

- Higher efficiency than their die-casted counterparts
- End-ring assembly: can be expensive, involves stress concentrations at braze joints and reduces electrical conductivity



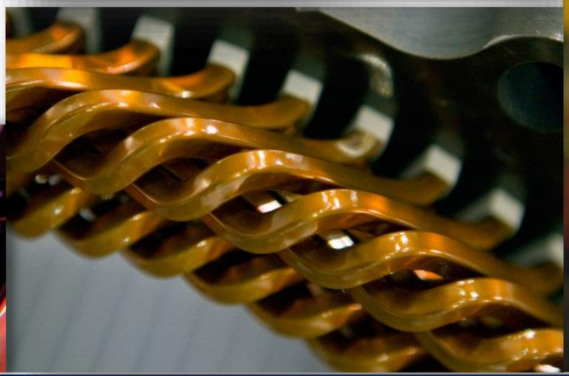
Hairpin winding

Advantages

- Repeatable manufacturing
- Well suited for distributed windings
- Robust construction at ends connections
- Heat management can be improved
- Short end-windings overhangs
- High slot fill factor

Drawbacks

- Limited number of conductors
- AC losses at high speed



High speed machine

Motivations

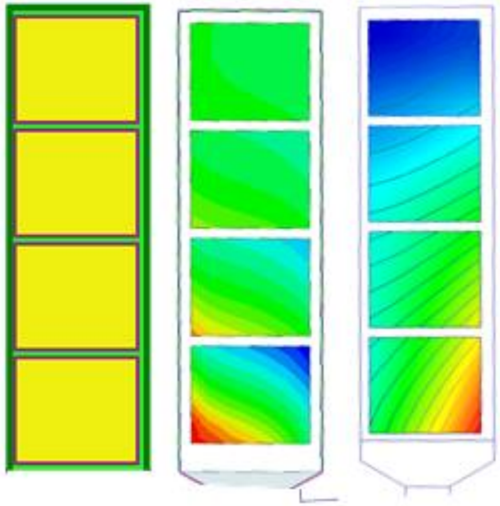
- Power density can be increased: Power = Torque × Speed
- Advances in power electronics and power controls
- Development of high strength and low loss materials

Limitations

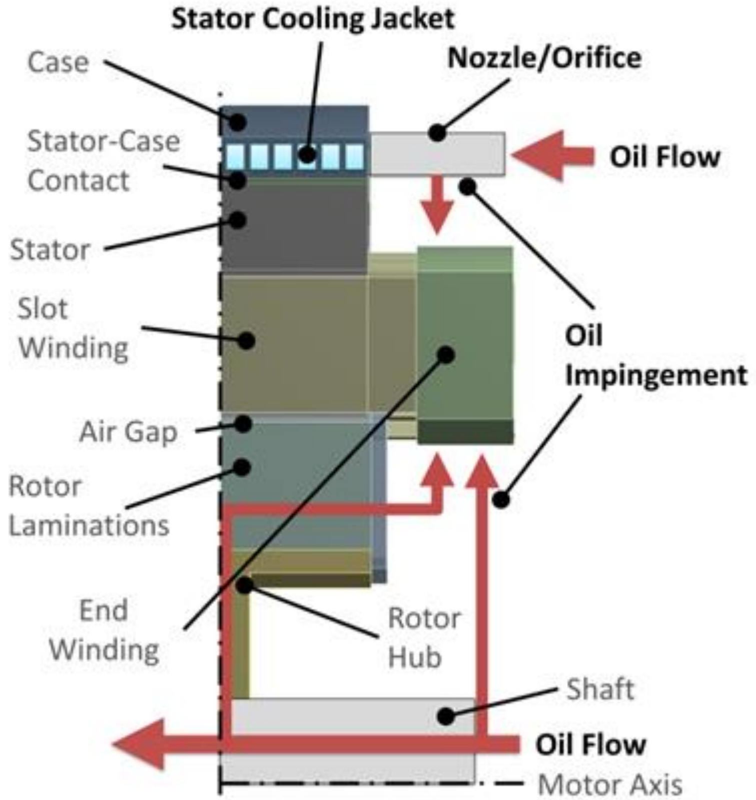
- Speed dependant losses (iron losses, AC copper losses, friction losses, windage losses…)
- Gearbox and bearings (availability, cost, dimensions…)

Requirement

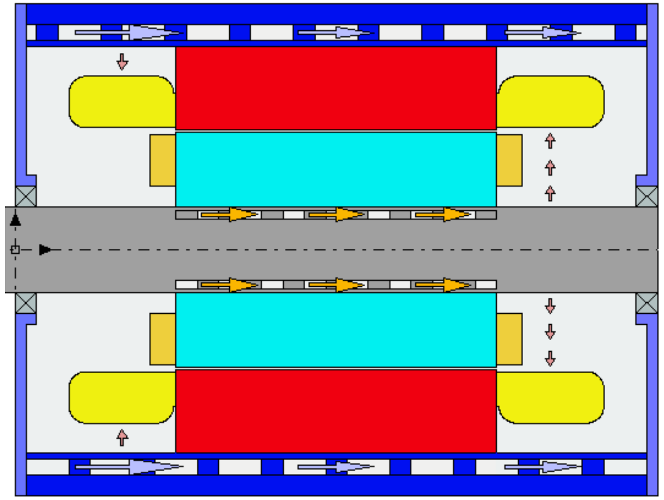
- Proper electromagnetic, mechanical and thermal design of the machine through multi-physic analysis

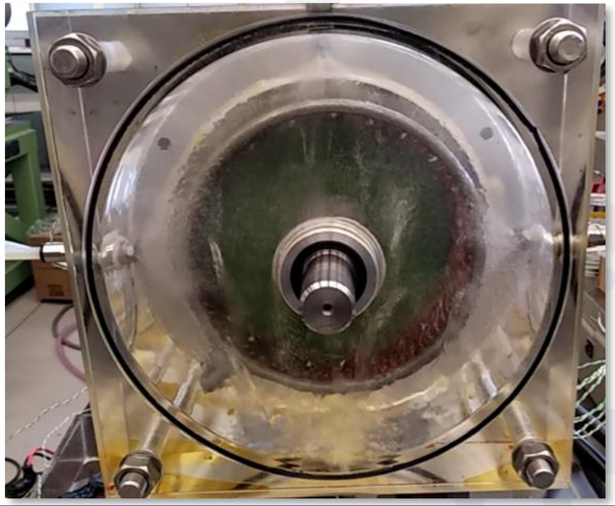
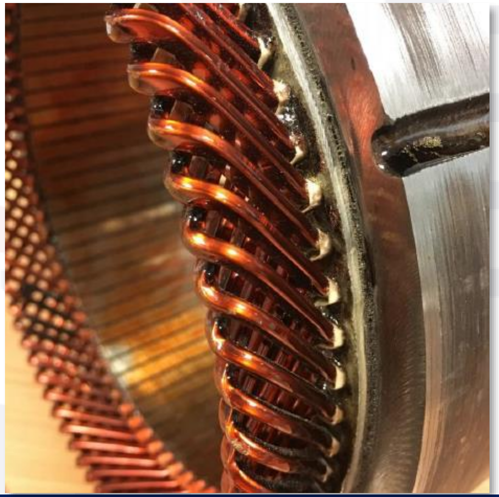


Advanced cooling system: oil spray



- Direct cooling (jet impingement) that improves heat transfers at end-winding locations
- Implemented in Motor-CAD software through correlations established from tests and experiments
- Independent nozzles can be placed on the endcaps, the housing or the shaft
- Flow can be supplied from external data or coupled with a shaft and/or a housing jacket cooling system



Specifications

Boundary Conditions & Key Performance Indicators

Boundary conditions

Machine topology

- Copper rotor IM
- Inner Rotor (IR) vs Outer Rotor (OR)

Power levels

- High power: 200kW (peak)
- Medium power: 80kW (peak)

Copper rotor manufacturing

- Die-casted
- Fabricated

→ *Medium power motor scaled from the high power motor*

→ *Specified volume includes the motor together with its cooling system*

Specification	Unit	Medium power	High power
Nominal voltage	Vdc	From scalability	720
Working voltage	Vdc	250-450	500-840
Nominal power	kW	45	120
Peak power	kW	80	200
Nominal speed	rpm	From scalability	> 6000
Maximum speed	rpm	From scalability	10000..18000
Peak torque	N.m	From scalability	> 280
Nominal current	Arms	500	500
Peak current	Arms	550	550
Volume (max)	mm	200h×300L×300W	350h×330L×550W
Cooling systems	-	Housing jacket, shaft cooling, oil spray	
Coolant type	-	Water/glycol, ATF fluid	
Insulation level	-	Class H	
IP level	-	> IP55	
Weight	kg	< 20	< 60

Key Performance Indicators (KPI)

Motor Design Limited

- Main performance indicators for an electric motor
- Defined according to APEEM 2022[1] goals and from state of the art
- Adapted for each targeted power: medium and high power

KPI	Unit	APEEM 2022 Goal	Medium power	High power
Specific power	kW/kg	1.6	> 1.6	> 2.0
Specific torque	N.m/kg	-	> 2.0	> 3.0
Power density	kW/L	5.7	> 5.4	> 6.0
Torque density	N.m/L	-	> 3.0	> 5.0
Peak efficiency	%	> 94	> 94	> 94

[1]*APEEM: Advanced Power Electronics and Electric Motors (program, DOE)*

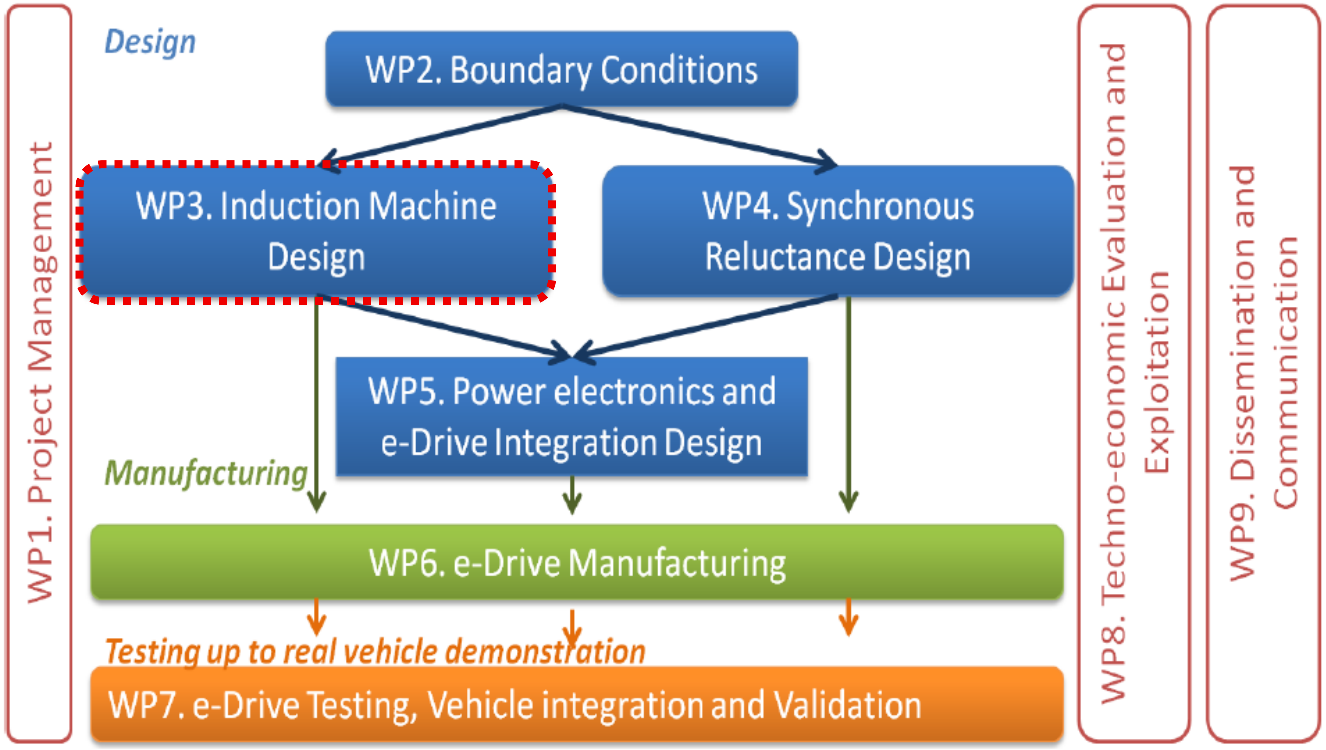
DOE: US Department of Energy

Work Package 3 (WP3)

Structure, partners & planning

WP3 in ReFreeDrive project

WP structure



Partners involved*

MDL: WP3 leader, motor design and analysis

UAQ: electromagnetic 3D FEA

CSM: electric steel definition

BREU: die-cast copper rotor technology

AUR: fabricated copper rotor technology

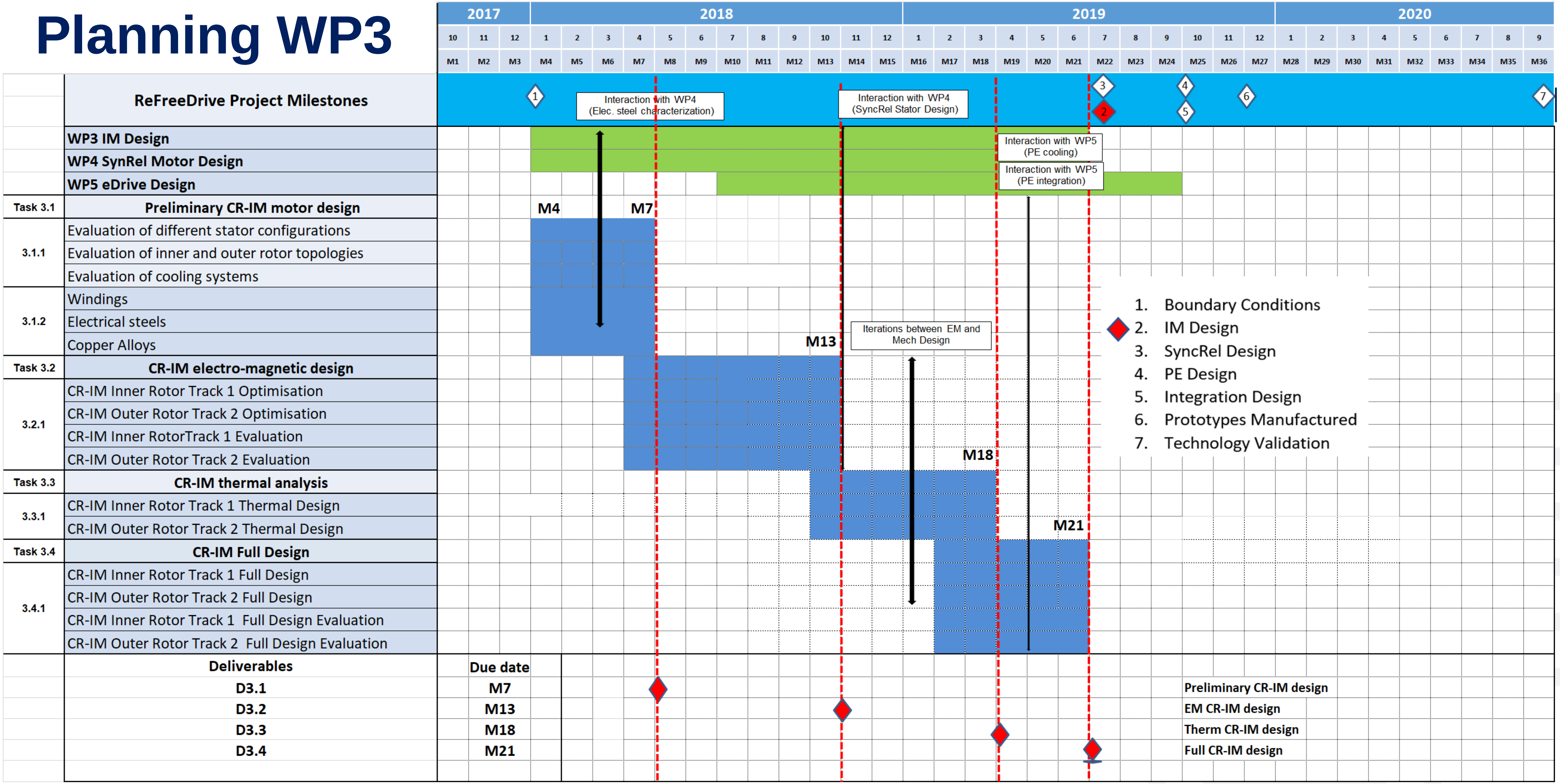
TCM: hairpin winding

CID: NVH analysis, 3D manufacture drawings

JLR, ECI, PRI: advise on manufacturability issues

*__MDL__: Motor Design Limited; **UAQ**: University of l'Aquila; **CSM**: Centro Sviluppo Materiali; **BREU**: Breuckmann; **AUR**: Aurubis;
*__TCM__: Tecnomatik; **CID**: Cidaut; **JLR**: Jaguar and Land Rover; **ECI**: European Copper Institute; **PRI**: Privé

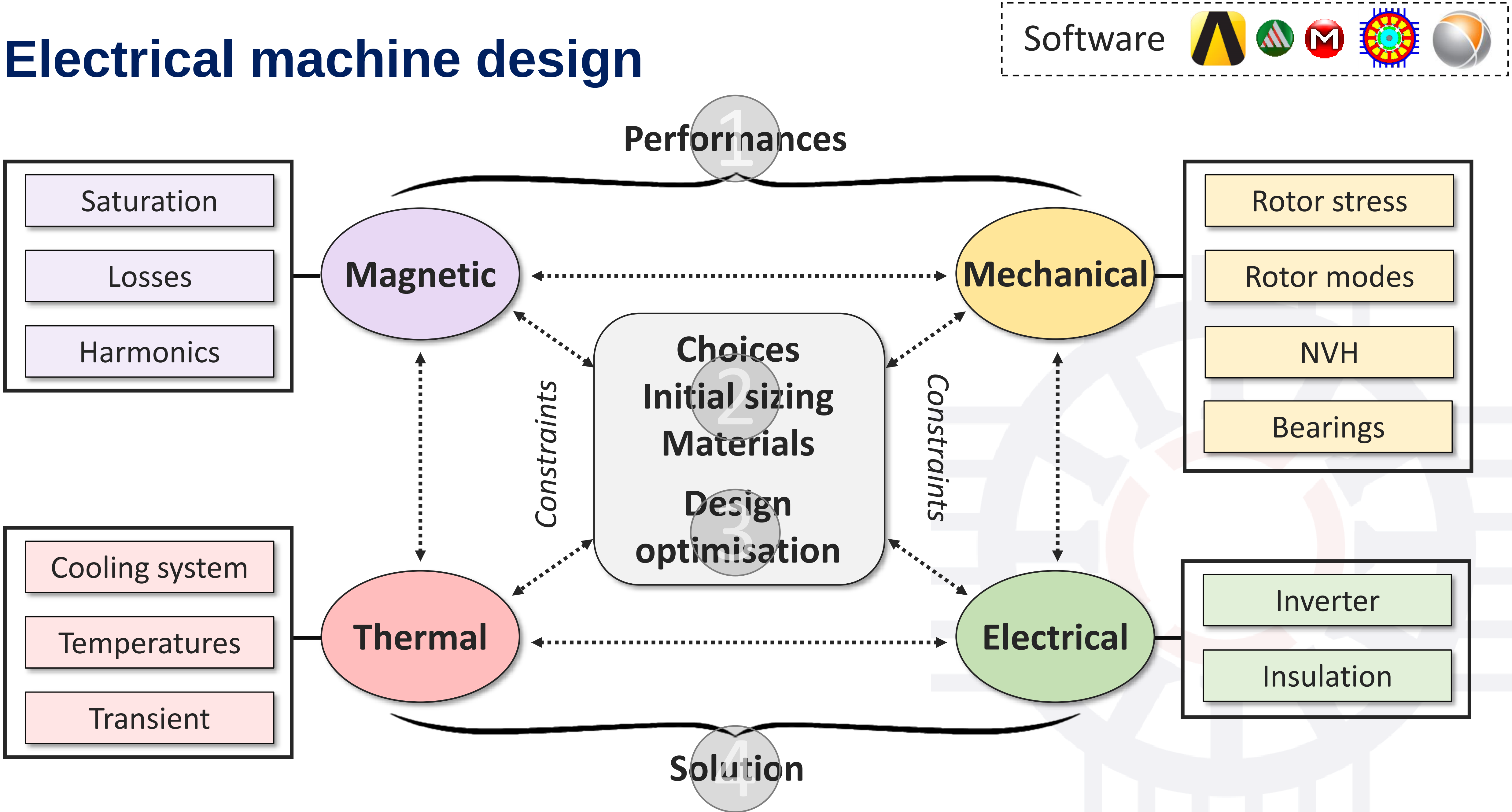
Planning WP3



Design procedure

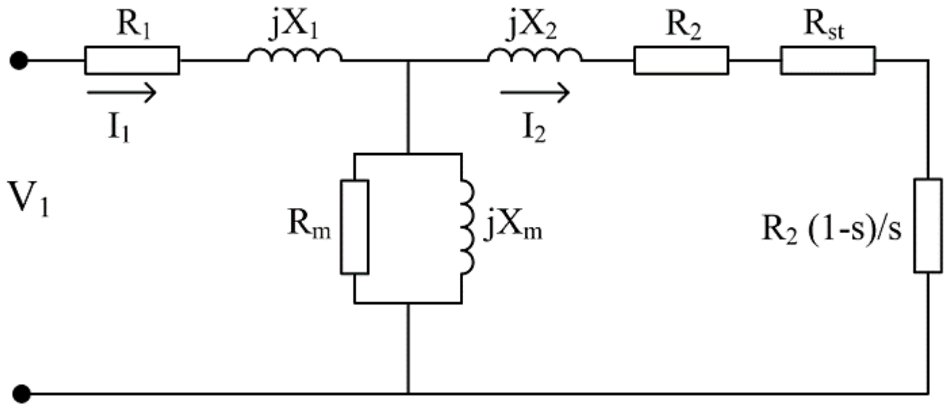
From project definitions to integration & validation

Electrical machine design



Motor-CAD software

- IM electromagnetic design analysis in Motor-CAD based on a hybrid 2D Finite Element Analysis (FEA) method and analytical magnetic equivalent circuit



- Operating point determined through a MTPA strategy:

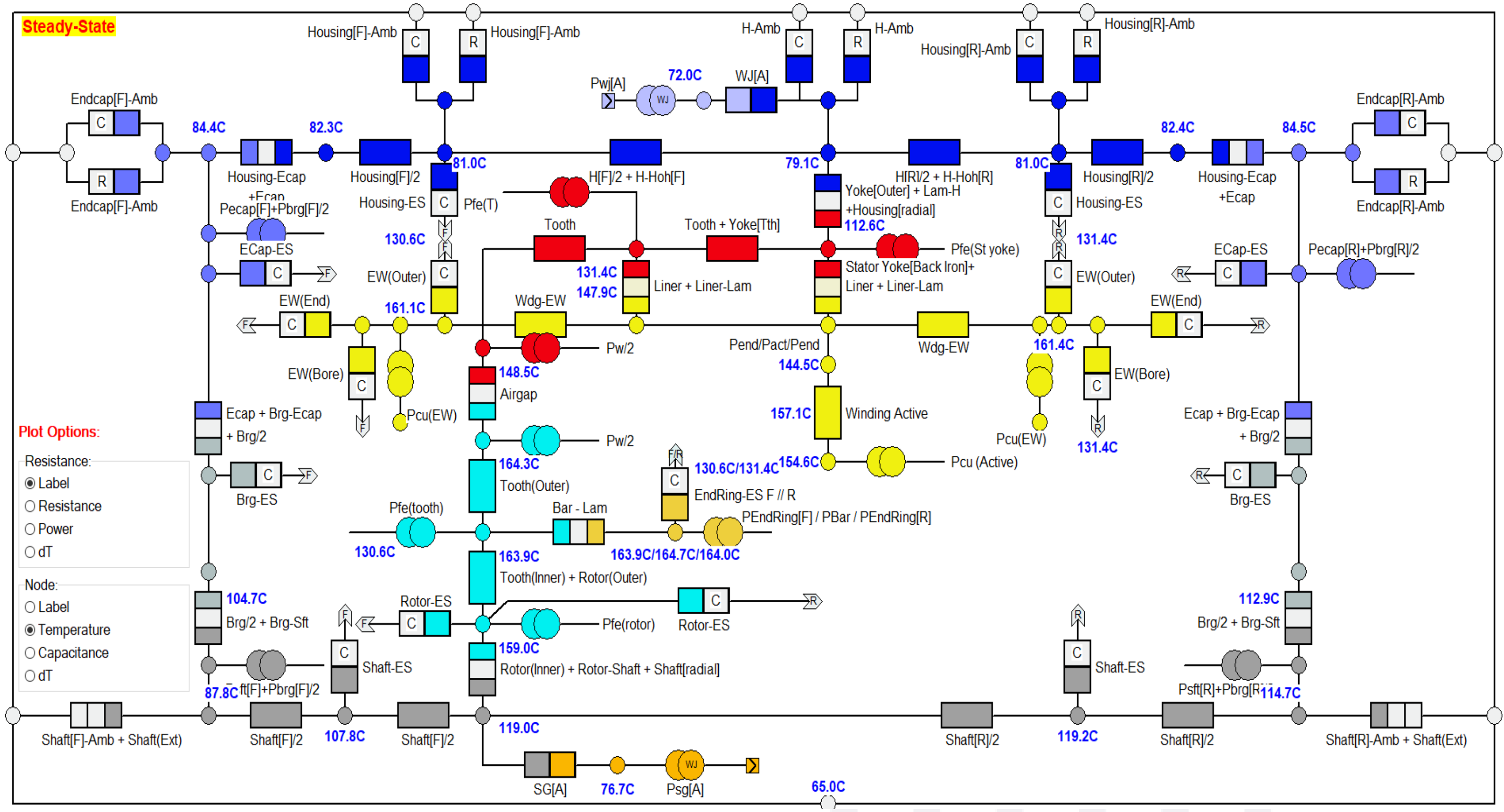
Maximum torque per amp

minimise $I_s = \sqrt{I_d^2 + I_q^2}$,

subject to $T_{shaft} - T_{demand} = 0$

and $V_{lim} \geq 2\pi f \sqrt{\psi_d^2 + \psi_q^2}$

- Thermal design analysis based on a lumped analytical thermal network

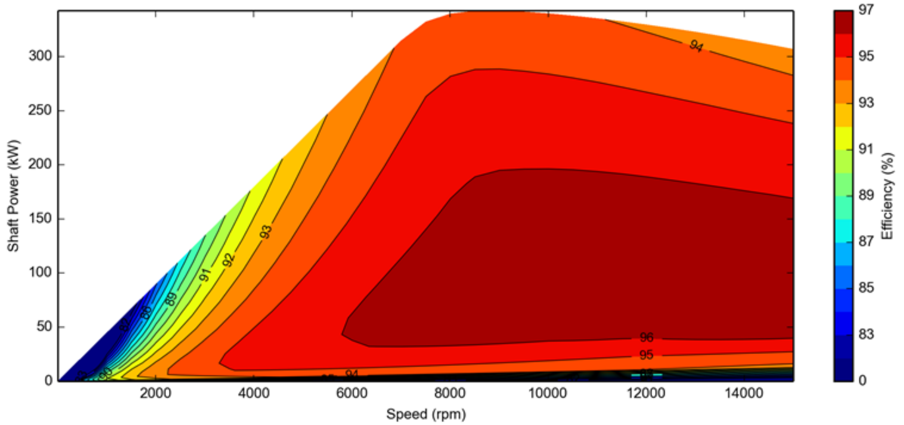


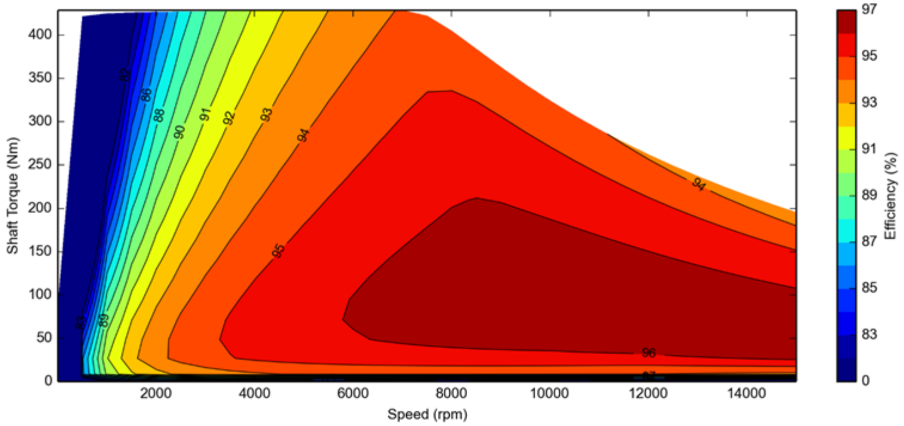
Preliminary design analysis

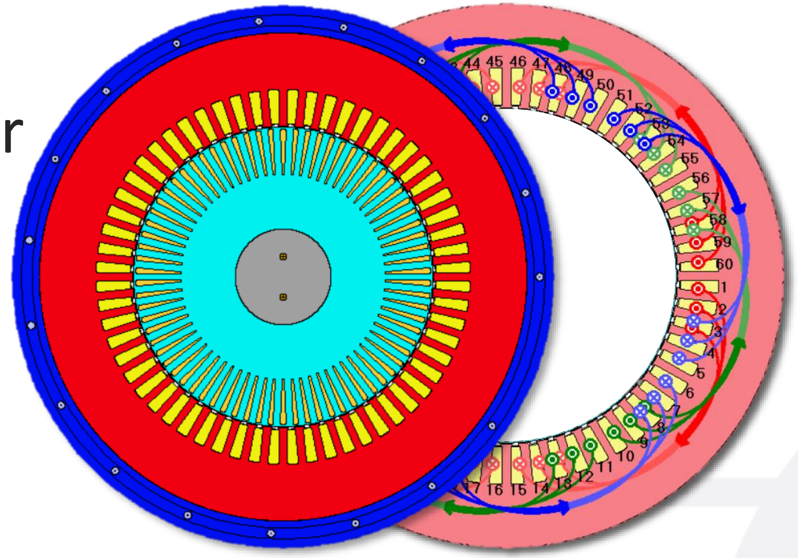
Choices, material selection & initial sizing

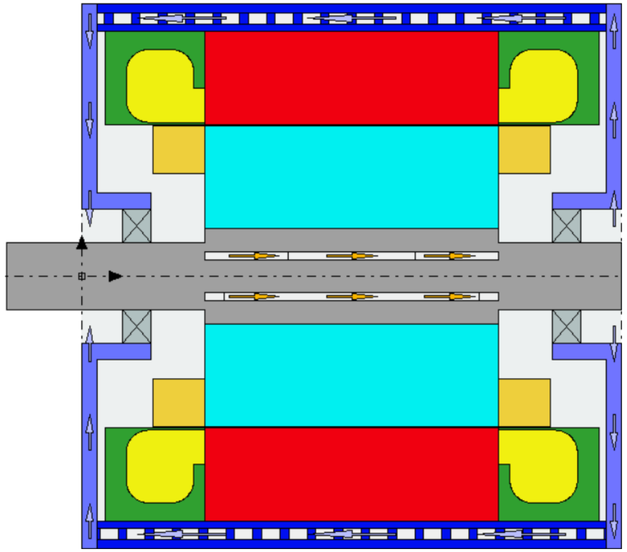
Reference design: TESLA 60S

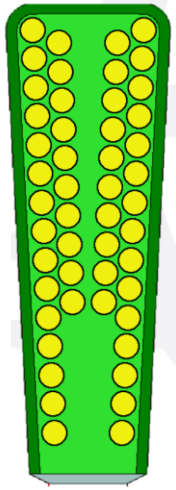
- Copper rotor IM
- Water cooled stator and rotor
- Potted end-windings









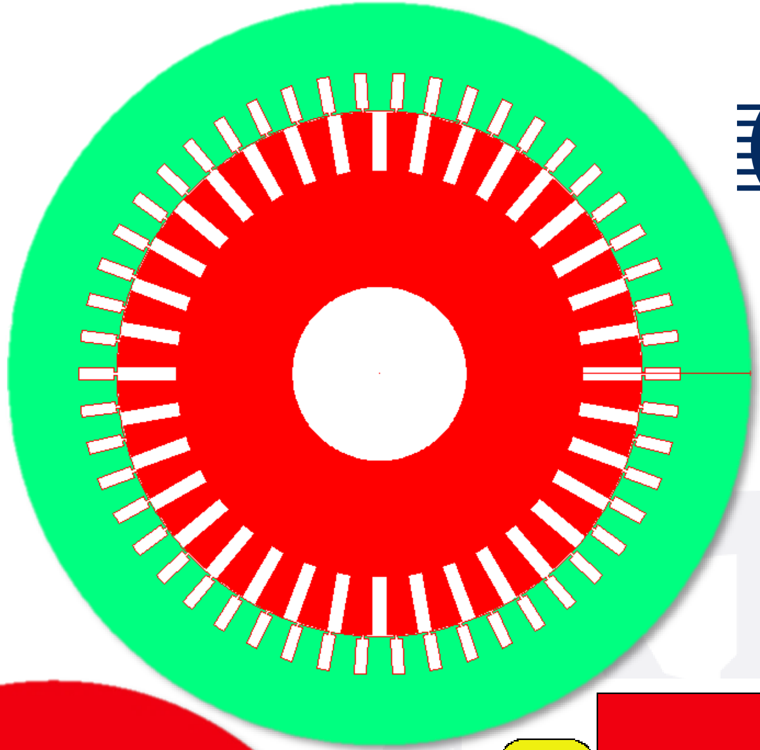


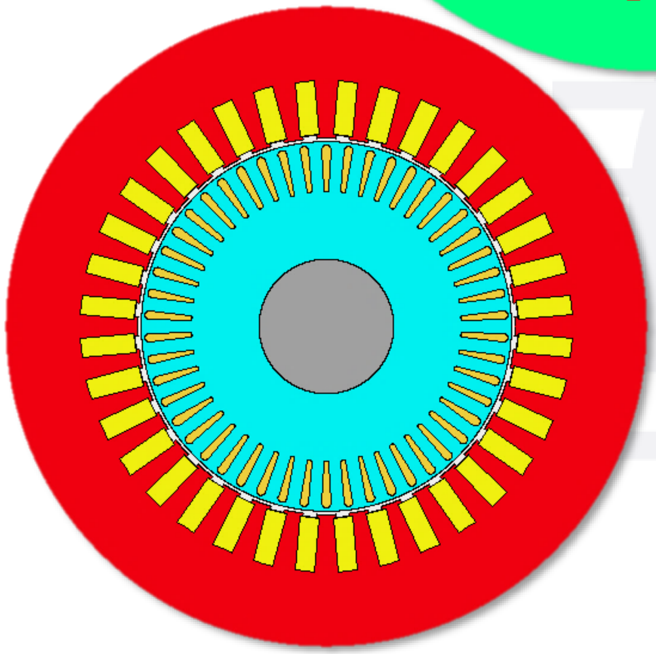
Parameters	Unit	Value
Stator slots	-	60
Pole pairs	-	2
Rotor bars	-	74
Stator diameter	mm	254
Stator bore	mm	157
Airgap	mm	0.5
Active length	mm	152
Machine length	mm	280
Parallel paths	-	2
Turns/coil	-	1 or 2
Coils/phase	-	12
DC voltage	V	366
RMS current	A	900
Maximum speed	rpm	14700

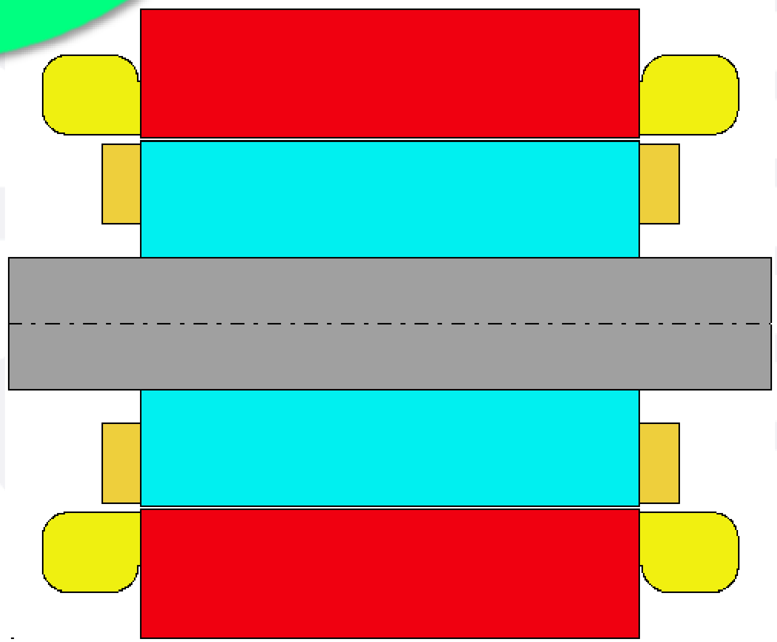
Geometry

Best candidates for IR-IM and OR-IM

Parameters	Unit	Value	
		IR-IM	OR-IM
Stator slots	-	36	36
Pole pairs	-	2	3
Rotor bars	-	50	50
Stator OD	mm	190	179
Rotor OD	mm	110	254
Airgap	mm	1	0.5
Active length	mm	150	90
Active weight	kg	~ 36	~ 48



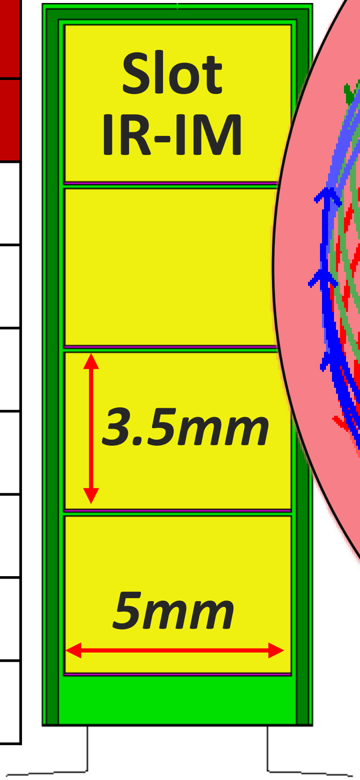


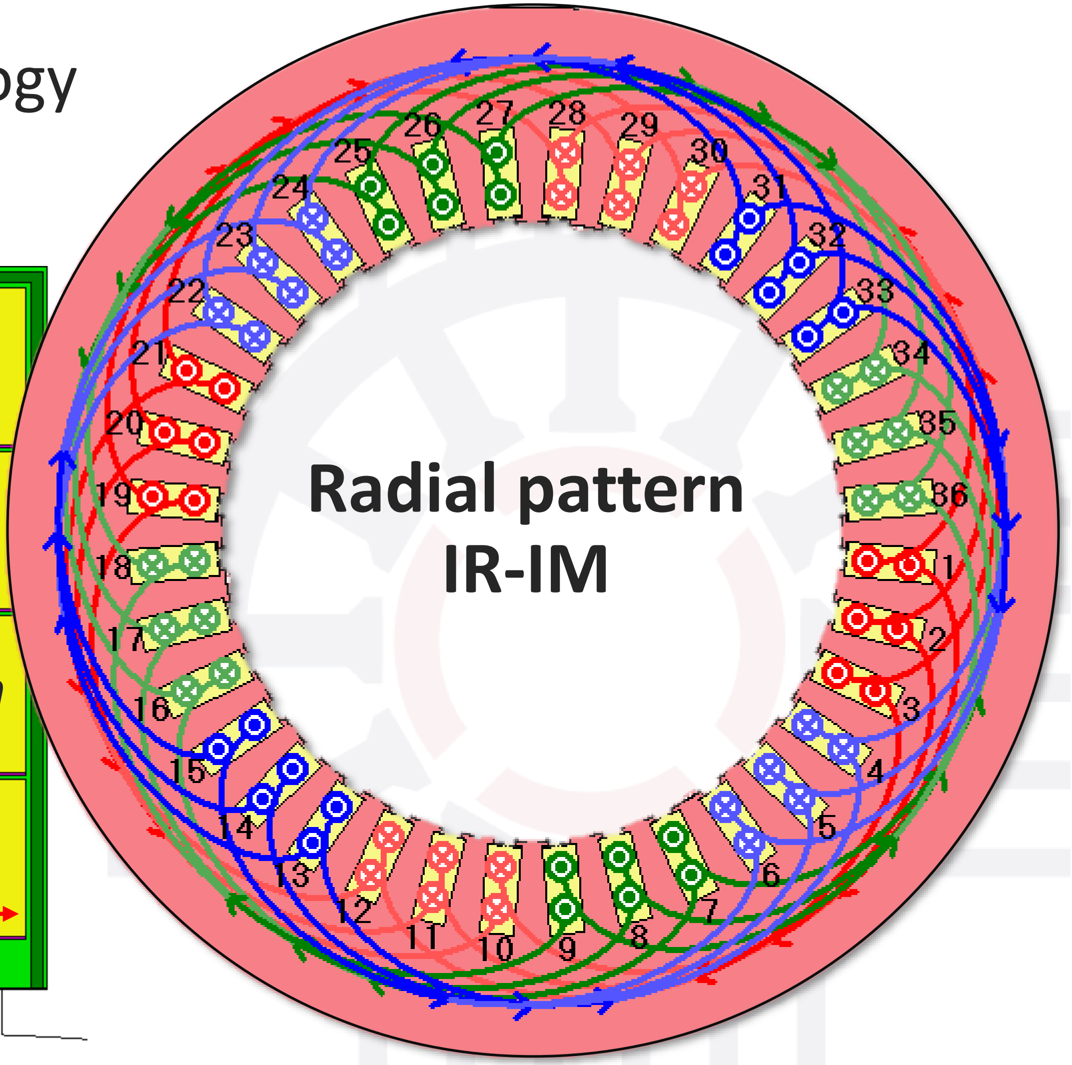


Winding

- Hairpin winding technology with rectangular wire size
- Four conductors/slot based on existing technology
- Double coil layer winding and parallel slot sided

Parameters	Unit	Value	
		IR-IM	OR-IM
Parallel paths	-	1	1
Turns per coil	-	2	2
Strand in hand	-	1	1
Slot fill factor	%	~ 73	~ 73
Turns/phase (in serie)	-	24	24
Coil pitch	slot	9	5
Winding factor (k_{w1})	-	0.959	0.933

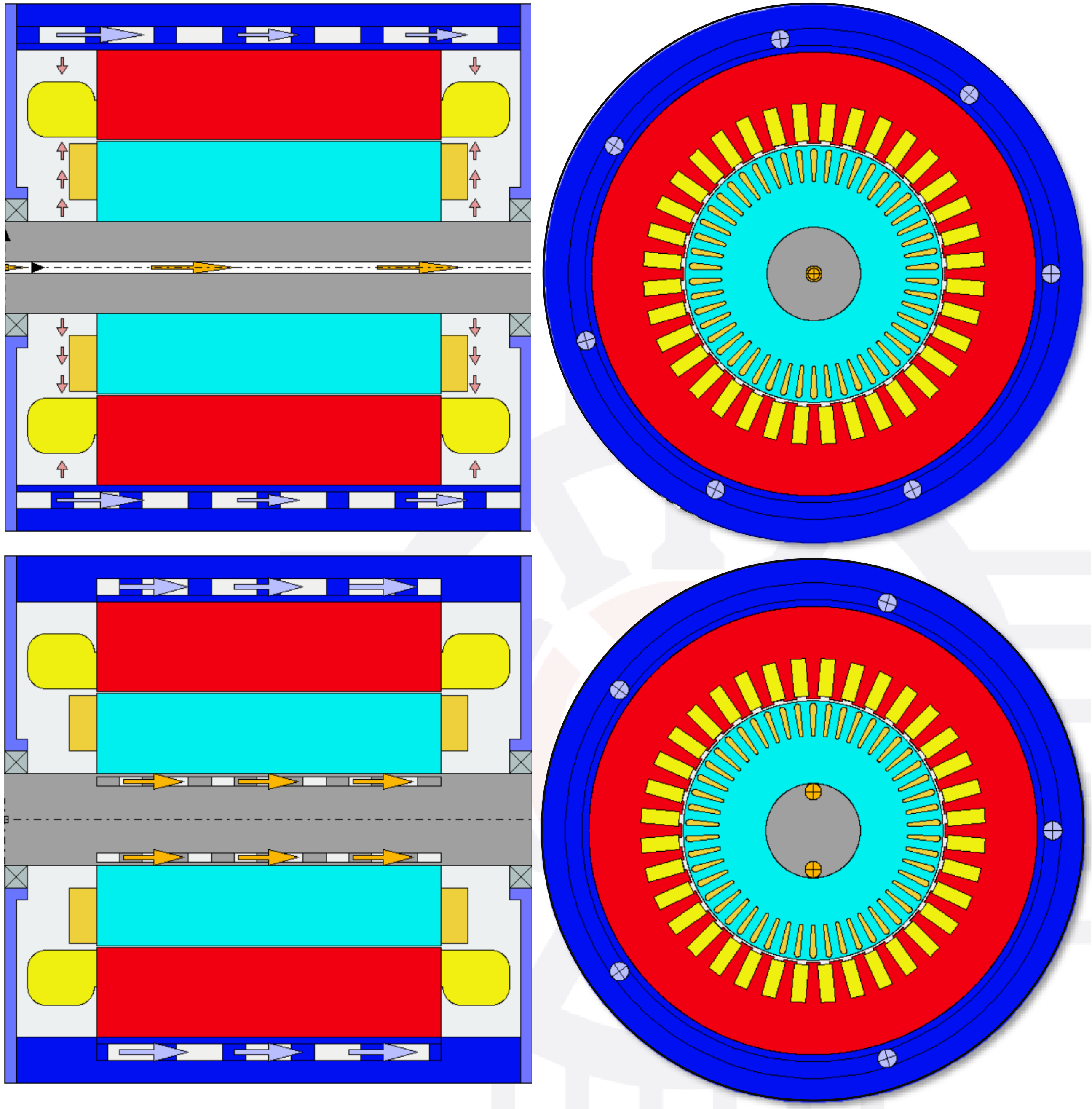




Cooling systems (IR-IM only)

- Shaft cooling required to meet KPIs
- Housing and shaft cooling systems are parallel connected
- Coolant is oil (ATF fluid) or water-glycol mixture (EWG 50/50)

Parameters		Unit	Value	
			EWG	ATF
Shaft	Flow rate	L/min	2	3
	Inlet temp.	C	65	65
	Inner diameter	mm	-	5
Housing	Flow rate	L/min	10	5
	Inlet temp.	C	65	65
	Outer diameter	mm	230	230



Materials: electrical steel

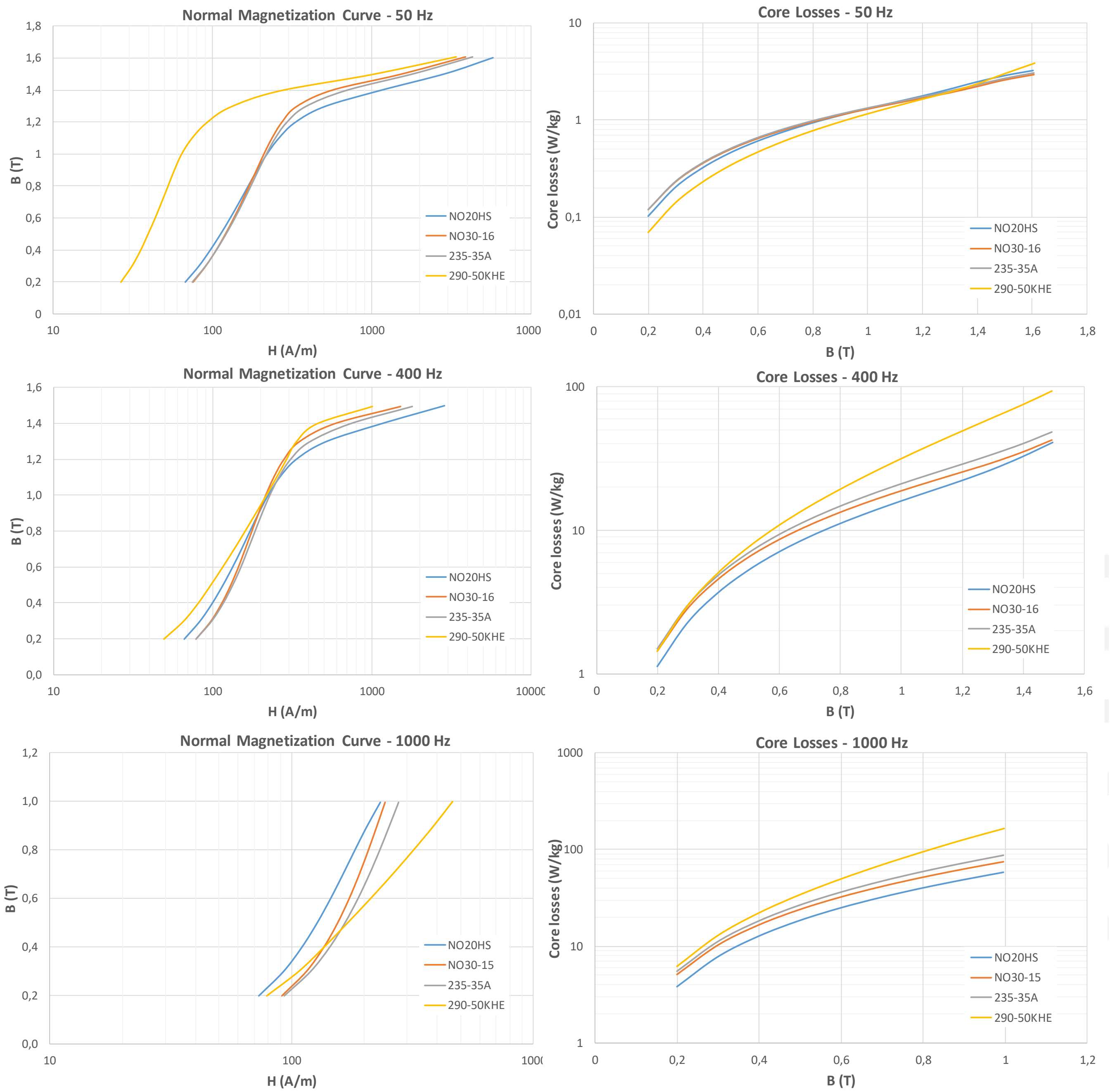
Magnetic characterization (RINA-CSM)

- Four Non-Grain Oriented materials:
  - ✓ NO-020HS (fully finished, 0.20mm thick)
  - ✓ NO-030-15 (fully finished, 0.30mm thick)
  - ✓ HP290-50K (semi-finished, 0.50mm thick)
  - ✓ M235-35A (fully finished, 0.35mm thick)
- Frequencies: 50-400-800-1000Hz
- Measurements: BH curves and losses

Material selection

- 50Hz data give the best peak torque
- Small impact on the motor efficiency
- M235-35A has the best performance to cost ratio for both IR-IM and OR-IM

→ *Mechanical characterisations on-going*



Materials: copper alloys

Fabricated rotor: CuAg0.04 alloy

- Commonly used material in IM
- Good mechanical strength (T < 200C)
- End-rings can be soldered or welded
  → trade-off cost/rotor strength

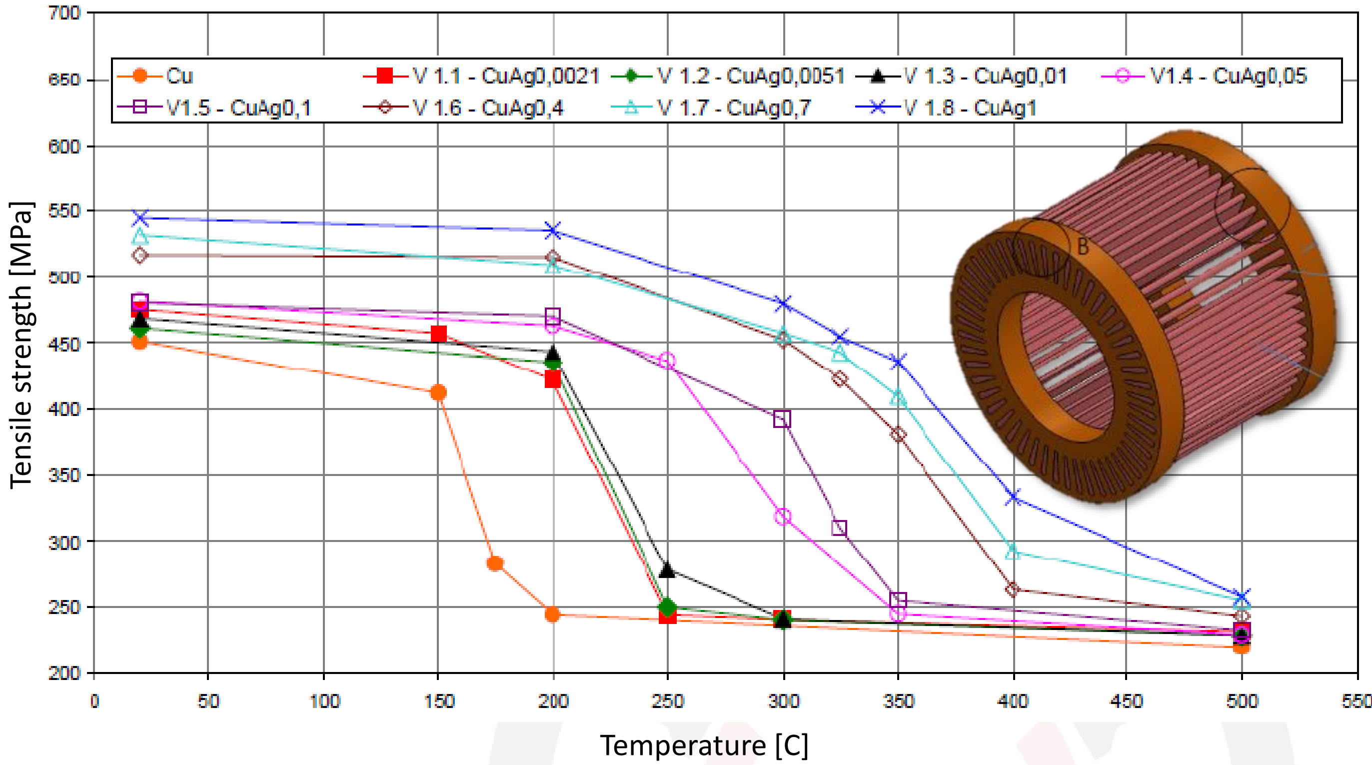
Die-casted rotor: Cu-ETP alloy

- Best electrical conductivity in the list of materials proposed (BREU)

Die-casted vs Fabricated

- Small differences observed in efficiency maps due to low variation in the referred rotor resistance
- 3D mechanical stress analysis required to select the best configuration

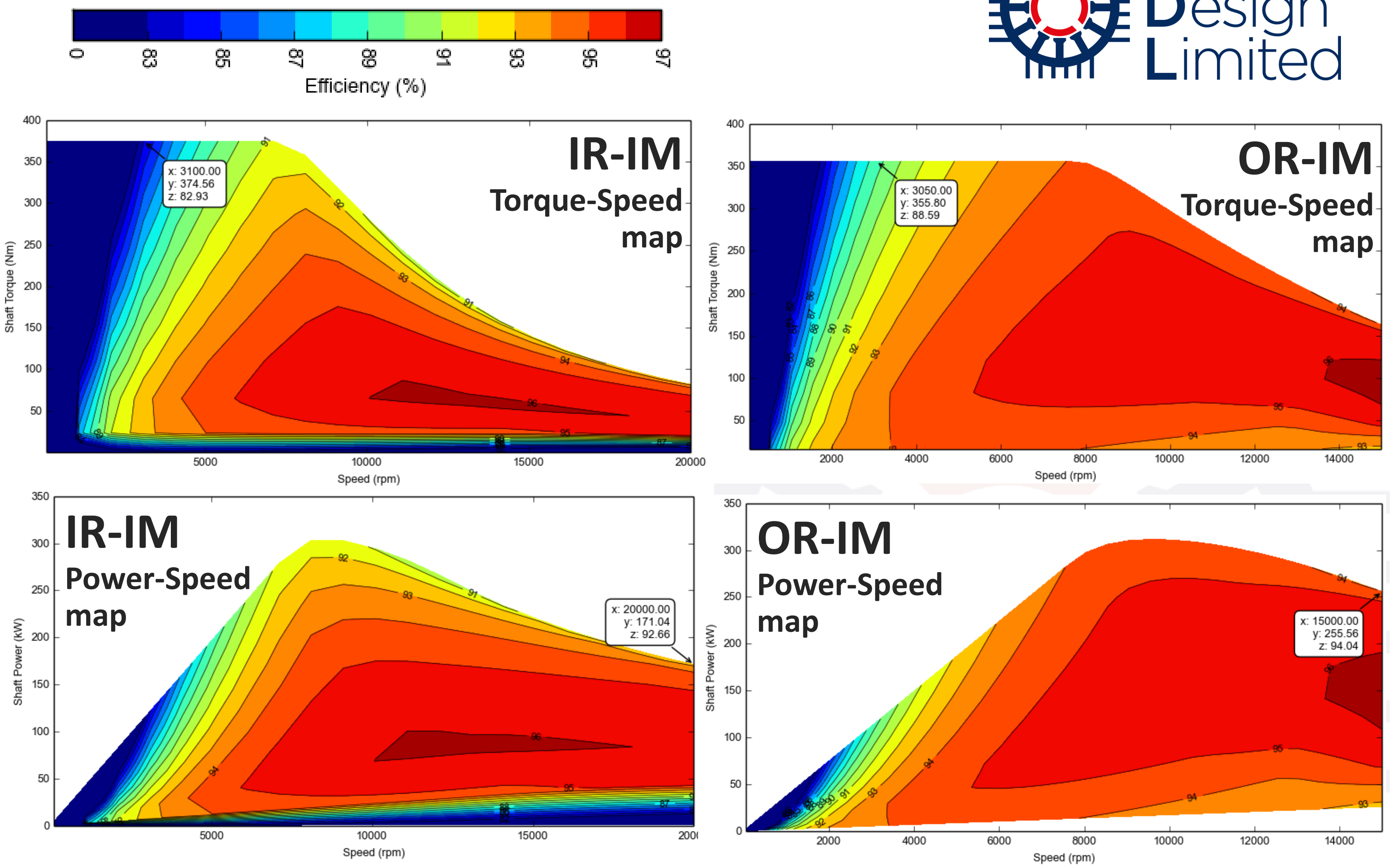
Mechanical characterizations (AUR)



Rotor type	Material type	Motor part	Resistivity $[\times 10^{-8}\Omega/m]$
Die-casted	Cu-ETP	Bars, end-rings	1.8349
Fabricated	CuAg0.04	Bars, end-rings	1.7020
	SAC305	Filler	10.4
	BercoweldK5	Filler	[5; 6.67]

Efficiency maps

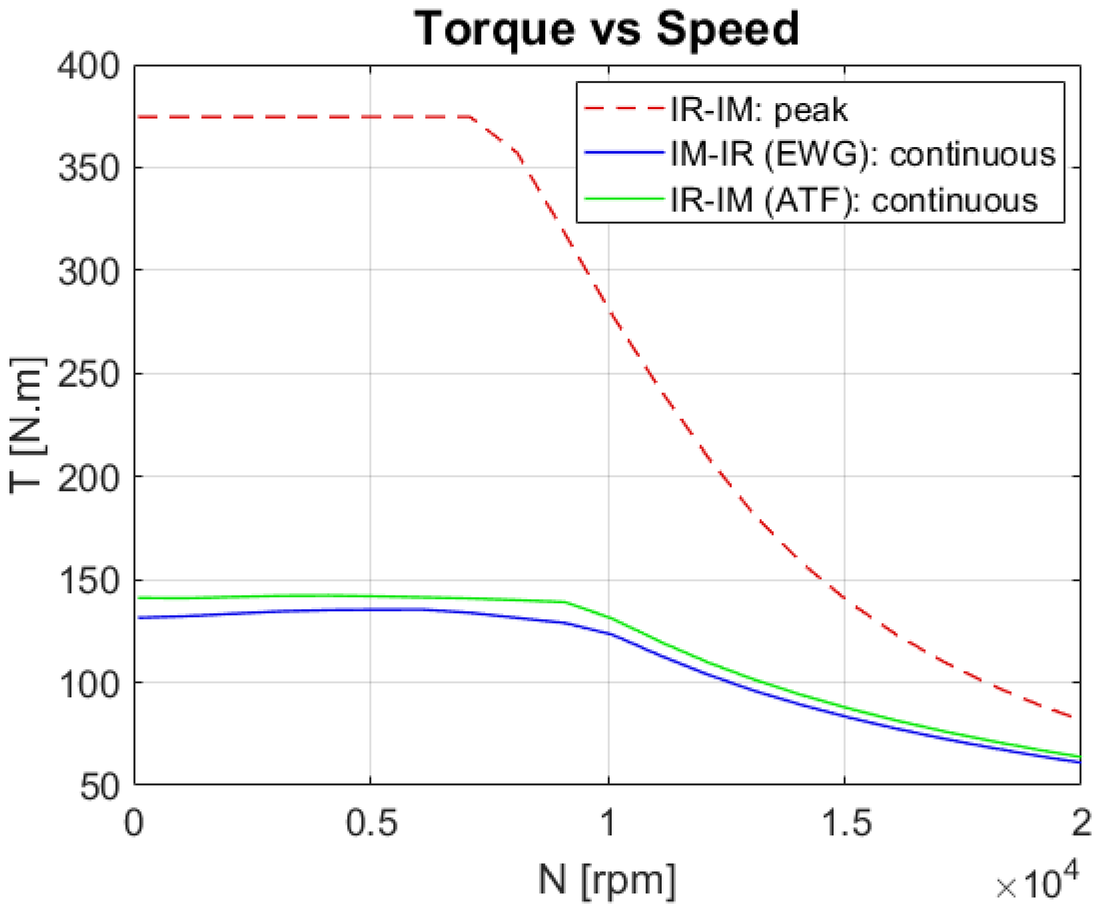
- AC losses, windage losses and friction losses not considered
- Peak efficiency of 96% for both IR-IM and OR-IM technologies
- Efficiency maps show the peak performance for a given maximum current
- Peak torque is about 375N.m and 356N.m for IR-IM and OR-IM, respectively

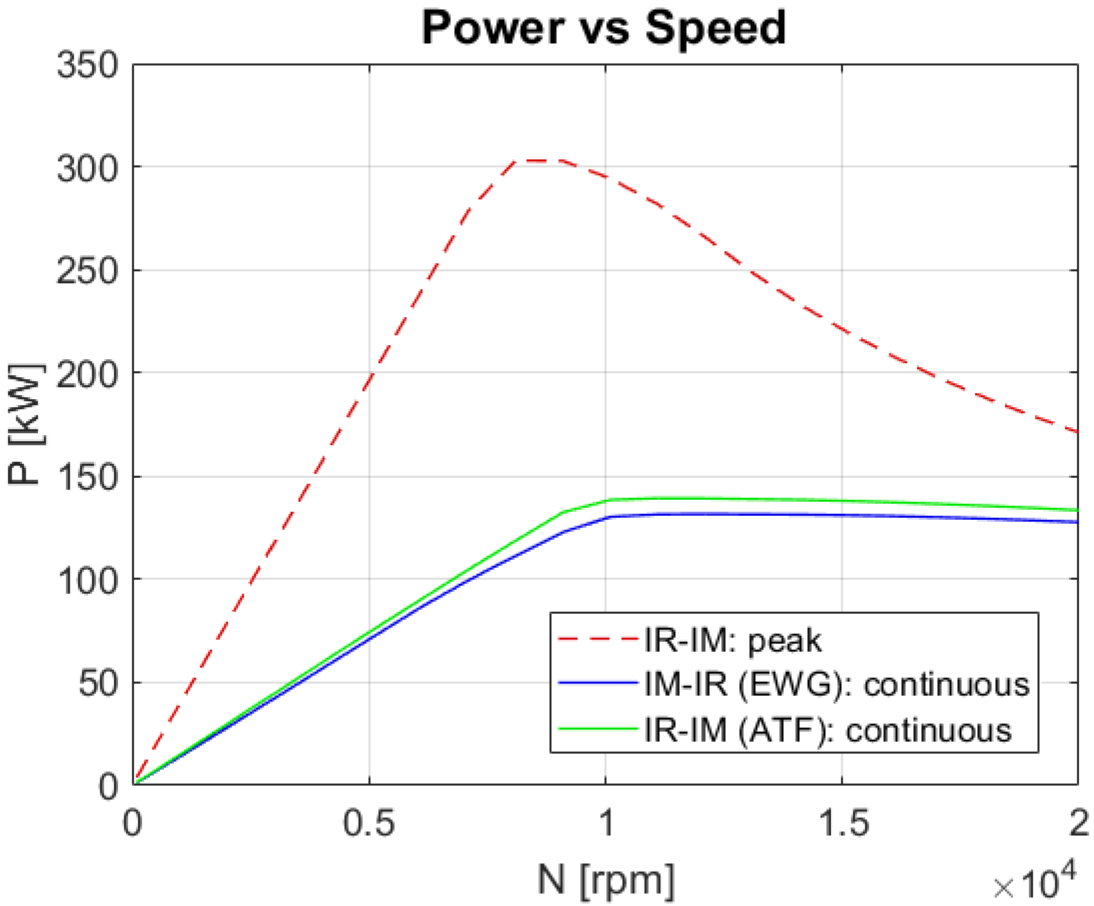


→ *AC losses, windage losses and friction losses not considered*

Thermal envelope (IR-IM only)

- Maximum thermally constrained operational envelope of the motor
- Maximum winding and rotor cage temperatures set to 180C



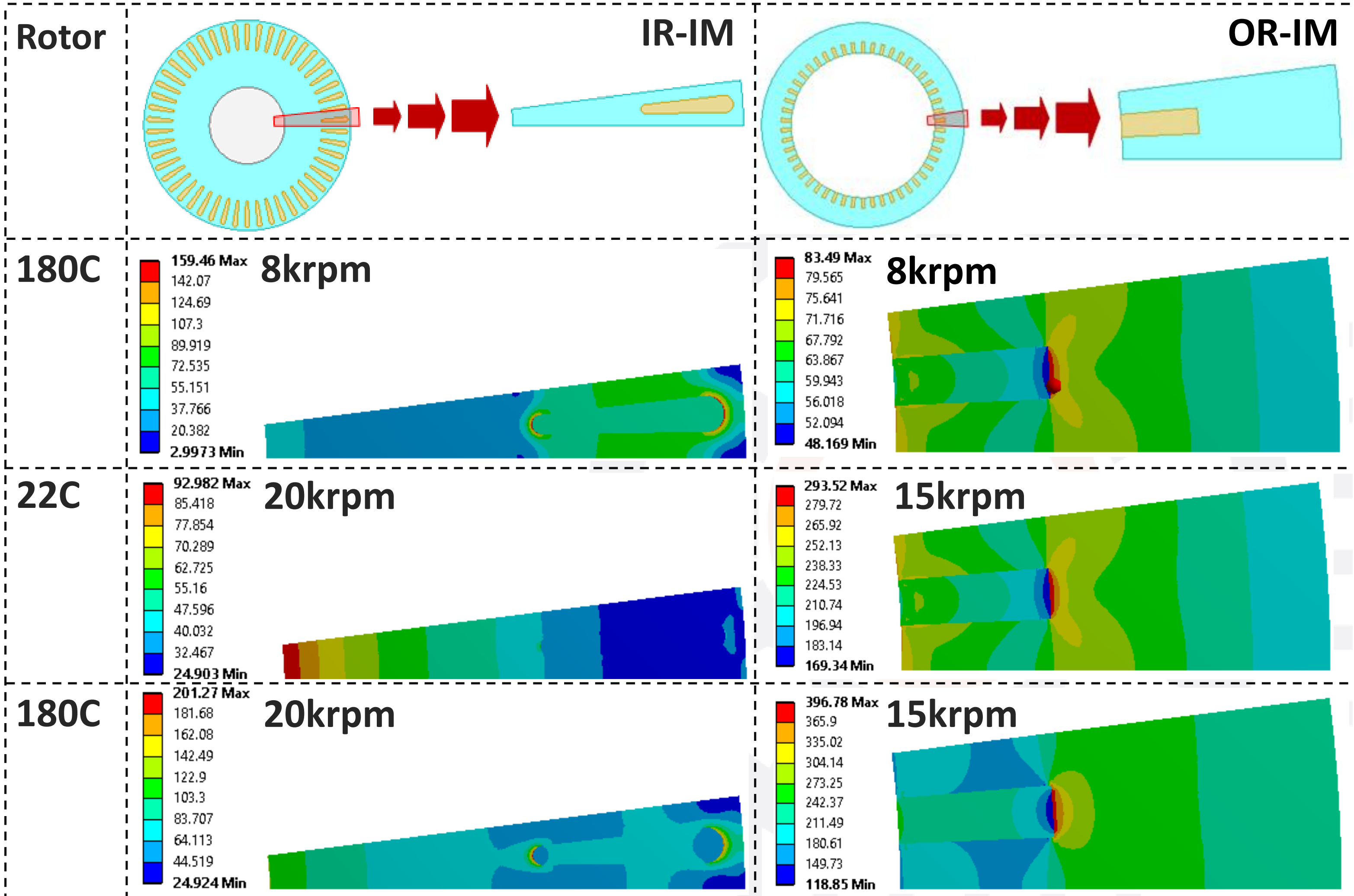


Rotor stress analysis

- **Speed** and **temperature** are sources of stress in the rotor
- **Thermal stress** comes from different material expansion rates
- **Rotational stress** is caused by centrifugal forces
- **IR-IM** is strongly impacted by thermal stress but shows good safety factors
- **OR-IM** is more affected by centrifugal stress, resulting in lower safety factors

Material	Density [kg/m³]	Elastic modulus [GPa]	Poisson ratio []	Yield strength [MPa]	CTE* [10^{-5}/C]
Copper	8933	110	0.34	280	1.8
Steel	7650	190	0.3	460	1.19

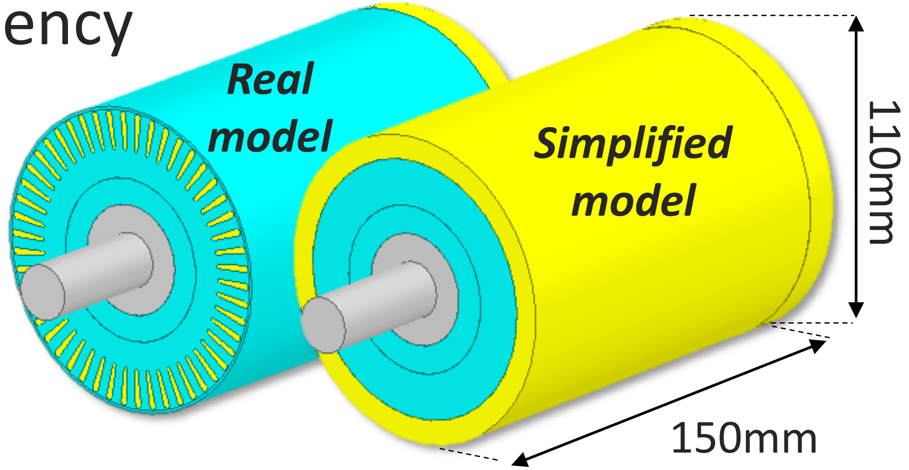
*Thermal expansion coefficient

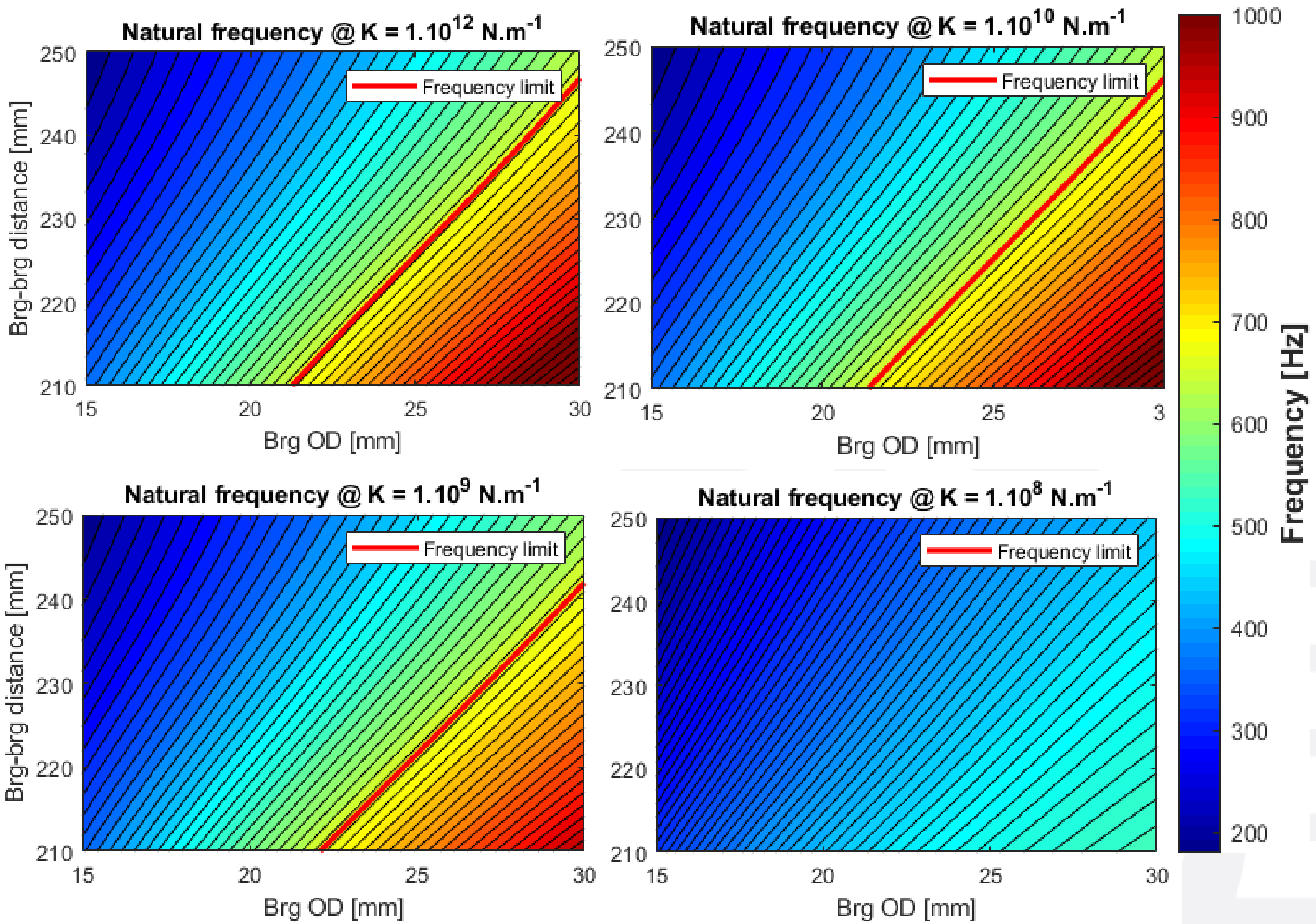


Modal analysis (IR-IM only)

When spinning the rotor is subjected to **unbalance forces** and **moments**

Resonance occurs when the excitation frequency equals the rotor natural frequency





Parametric analysis

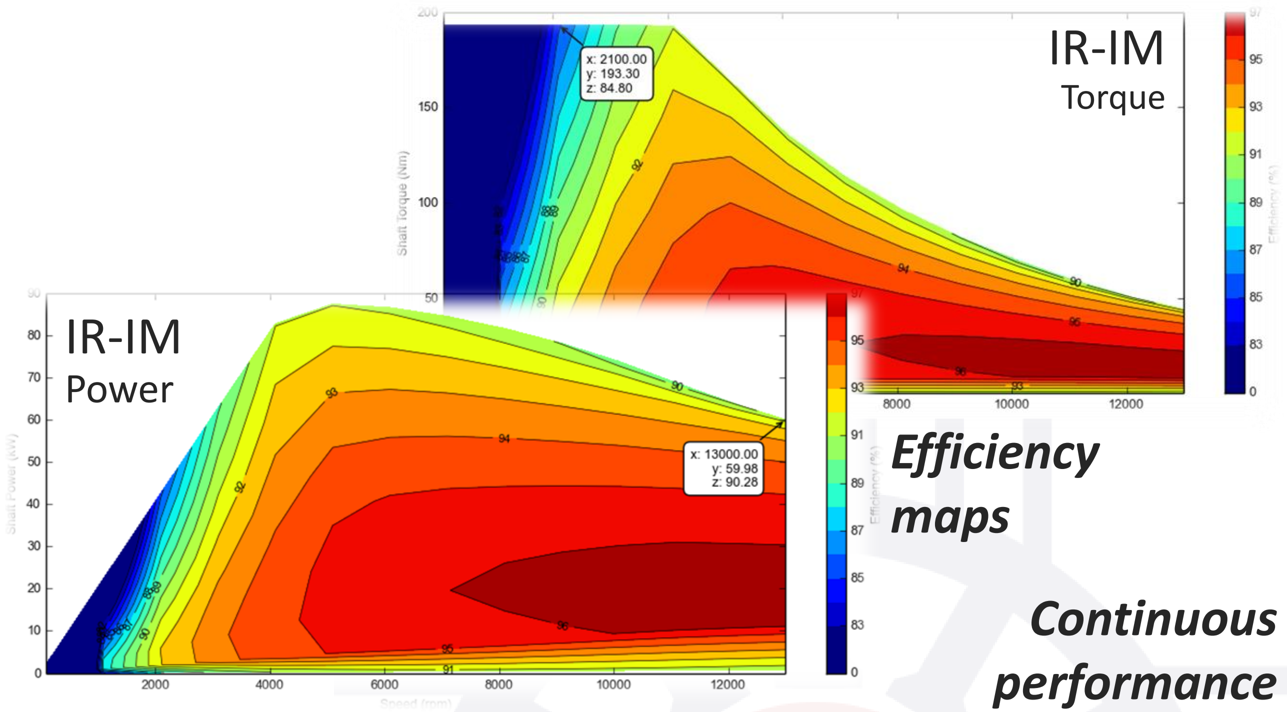
- Shaft length: 210…250mm
- Bearing OD: 15…30mm
- Bearing stiffness: $1.10^{8..12}$N/m

Bearing stiffness ↗	First critical speed ↘	Stiff bearing required
Bearing diameter ↗	First critical speed ↗	Bearing cost? Max torque?
Shaft Length ↗	First critical speed ↘	End windings dimensions?

Scalability

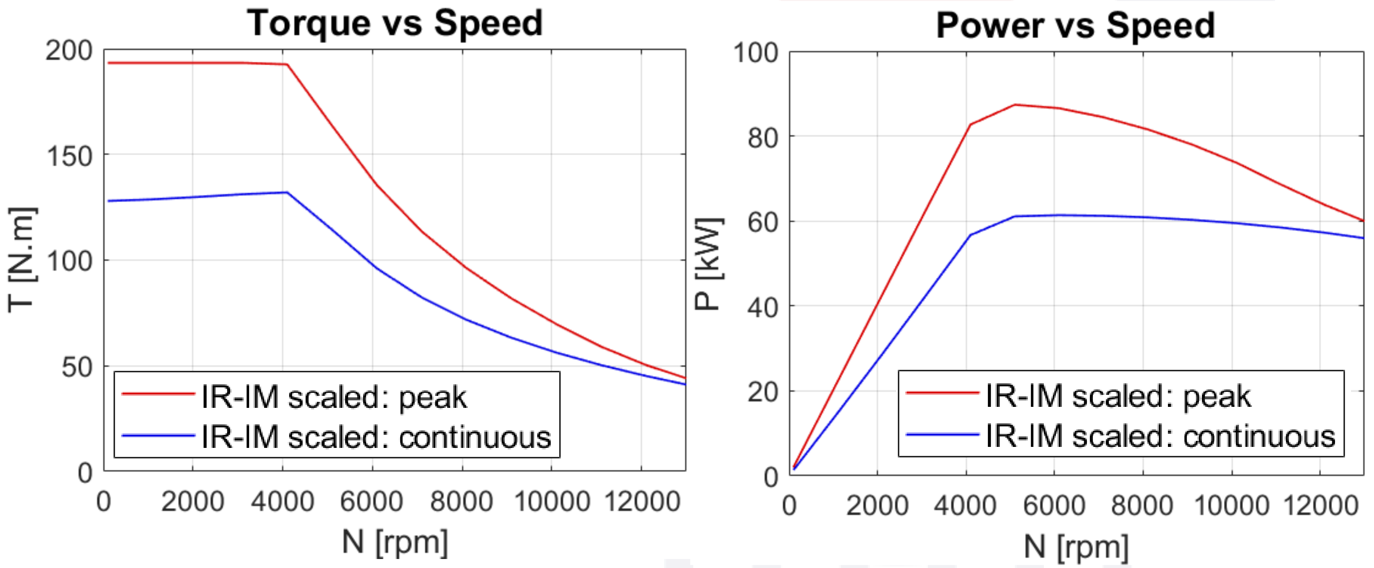
- Relies on the same radial dimensions
- The power supply is adapted based on the available current and voltage levels

Parameters	Unit	Value (IR-IM)	
		200kW	80kW
Peak power	kW	> 200	> 80
Continuous power	kW	> 120	> 60
Peak torque	N.m	375	192
Continuous torque	N.m	> 130	> 125
Peak efficiency	%	96	96
DC voltage	V	720	350
RMS Line current	A	500	275
Maximum speed	rpm	18000	13000



Efficiency maps

Continuous performance

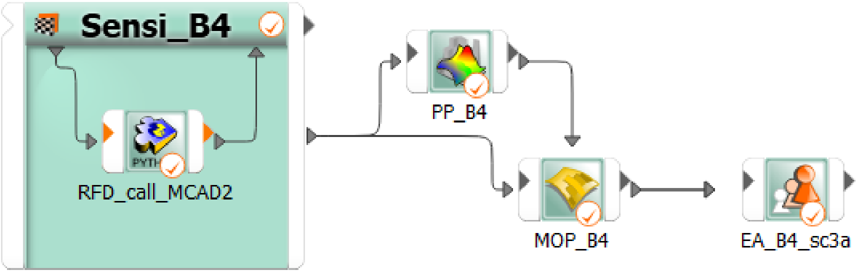


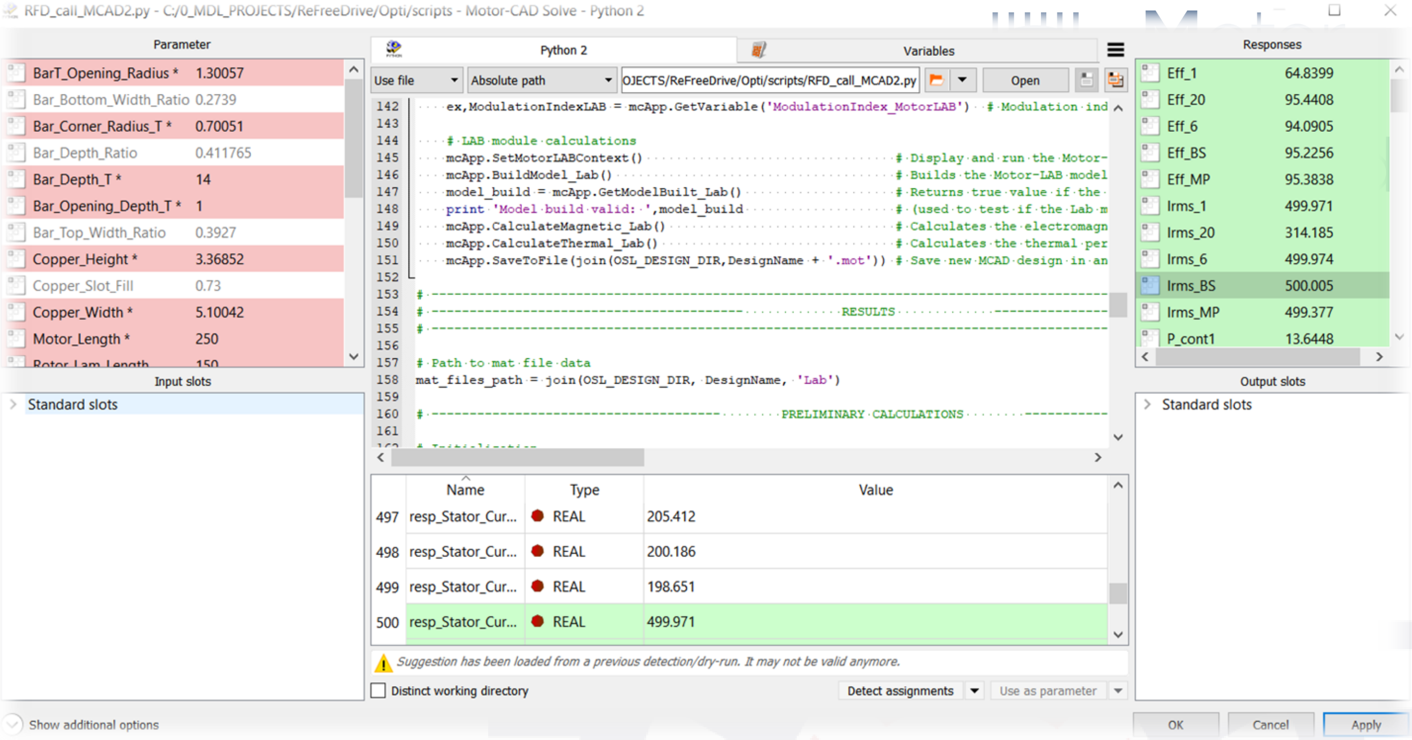
Design optimisation

Towards a better motor

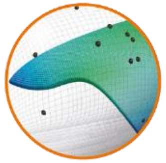
Motor-CAD & optiSlang

Coupling via customised Python scripts and the ActiveX connection

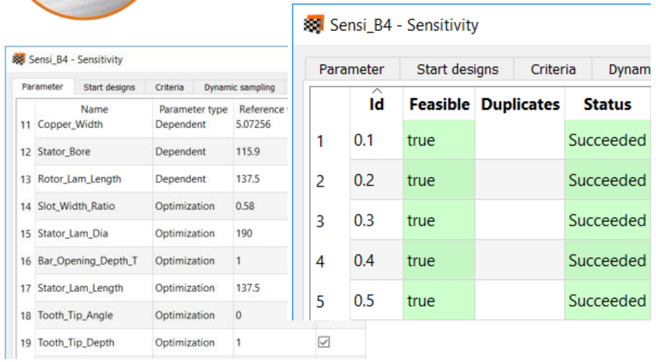


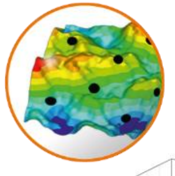


Workflow

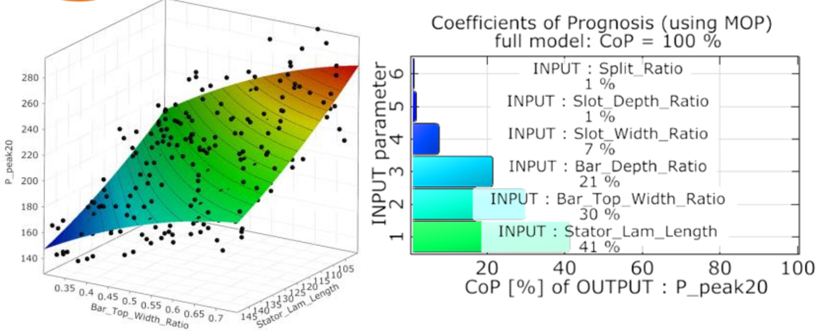


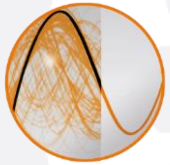
Sensitivity analysis



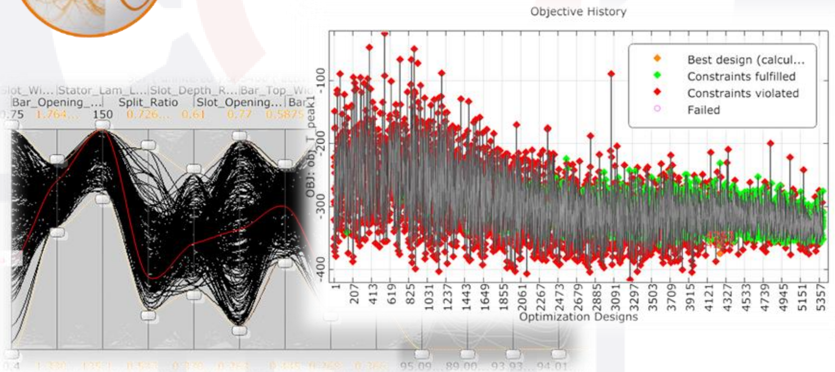


Metamodel of prognosis



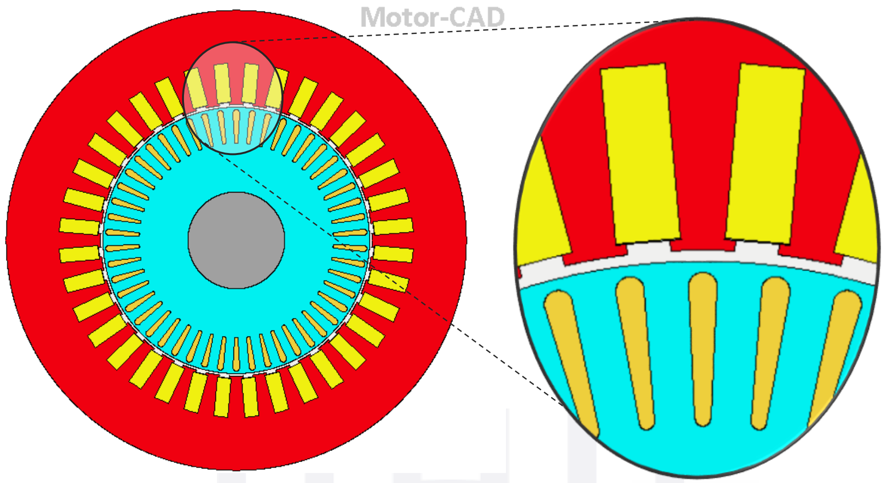


Optimisation



Setup

Fixed parameters: max. dimensions, cooling system, slot/pole/bar combination, winding, materials, drive settings, max. temperatures



Variables	Bounds
Slot width/Slot pitch	[0.45; 0.75]
Active length	[100; 150] mm
Bar opening depth	[0.5; 2] mm
Stator ID/Stator OD	[0.5; 0.75]
Slot depth/(Slot depth + Stator yoke)	[0.25; 0.7]
Bar depth/(Bar depth + Rotor Yoke)	[0.3; 0.6]
Slot opening width/Slot width	[0.2; 0.8]
Bottom bar width/Bar pitch	[0.2; 0.6]
Top bar width/Bar pitch	[0.3; 0.65]

Goal(s) and constraint(s

Scenario 1

$$\begin{cases} \max(T_{peak}@LS) \\ T_{cont}@6krpm > 130N.m \\ P_{peak}@MP > 200kW \\ P_{cont}@MP > 120kW \end{cases}$$

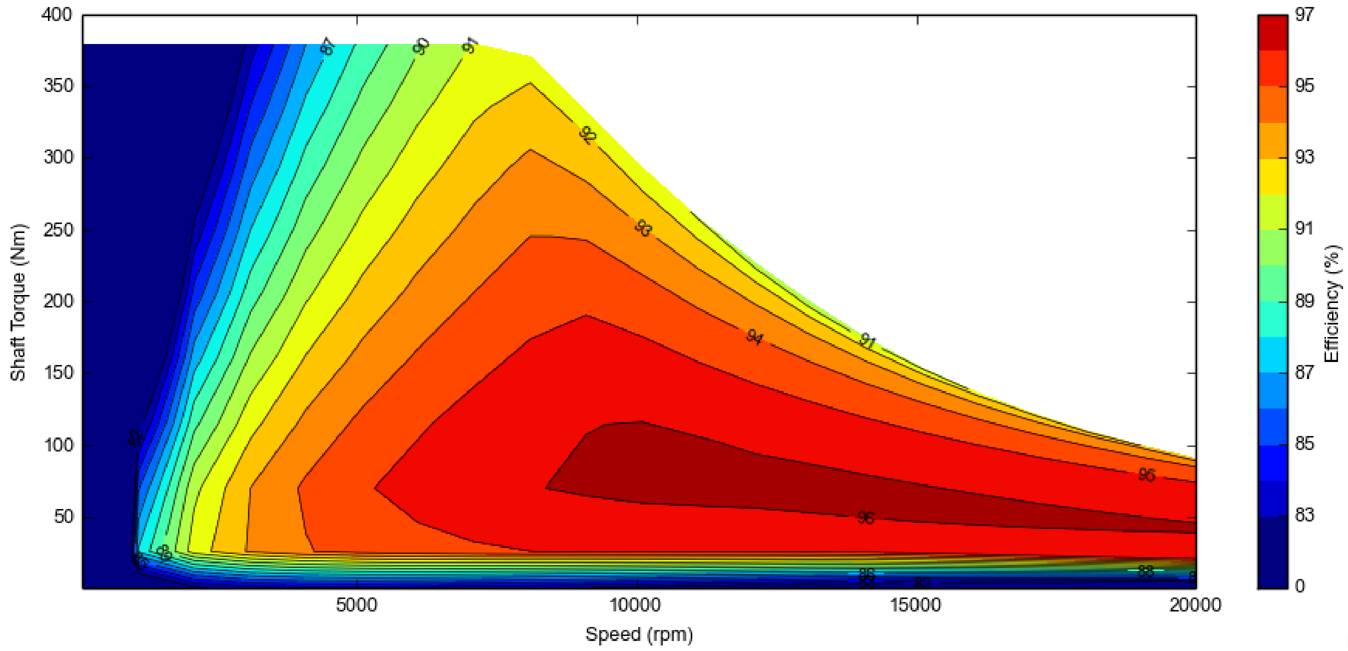
Scenario 2

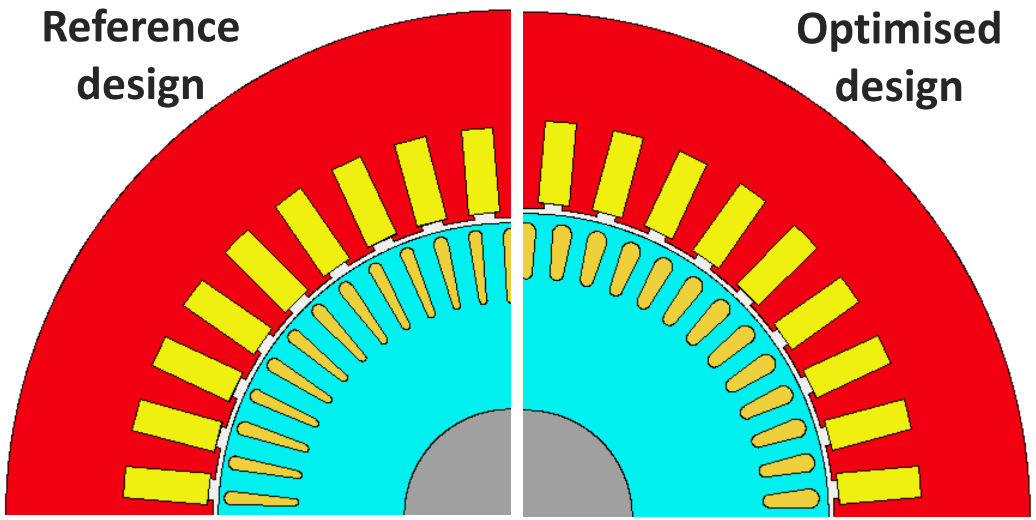
$$\begin{cases} \min(L) \\ T_{peak}@LS > 280N.m \\ P_{peak}@MP > 200kW \\ P_{cont}@MP > 120kW \end{cases}$$

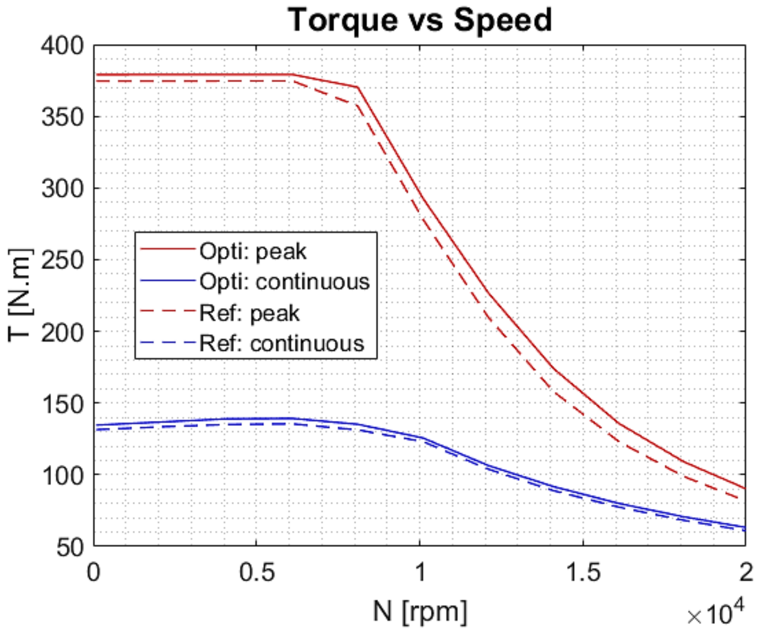
$T = Torque; L = Length; LS = Low\ Speed; MP = Max\ Power$

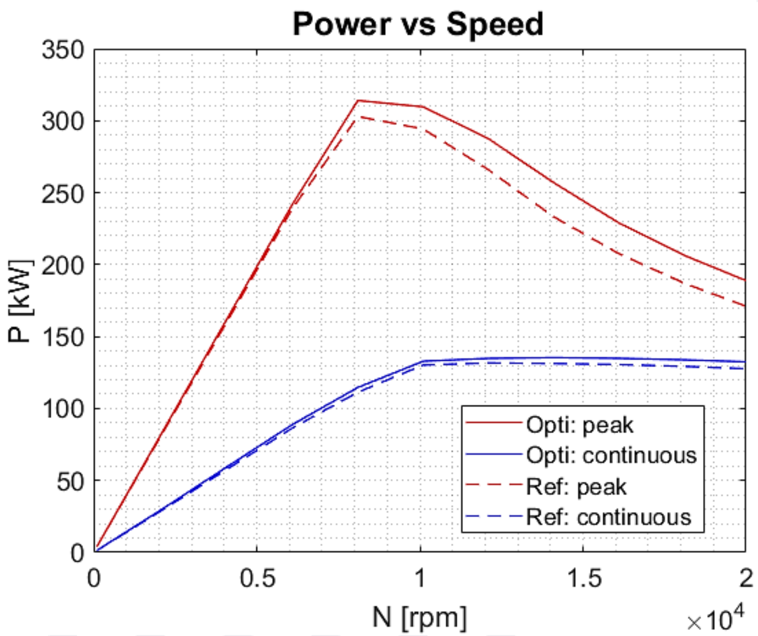
Results: scenario 1

- Better peak and continuous performance over the full speed range
- 96% peak efficiency in a larger area
- Length maximised to its max bounds
- Higher split ratio
- Bar cross sectional area increased



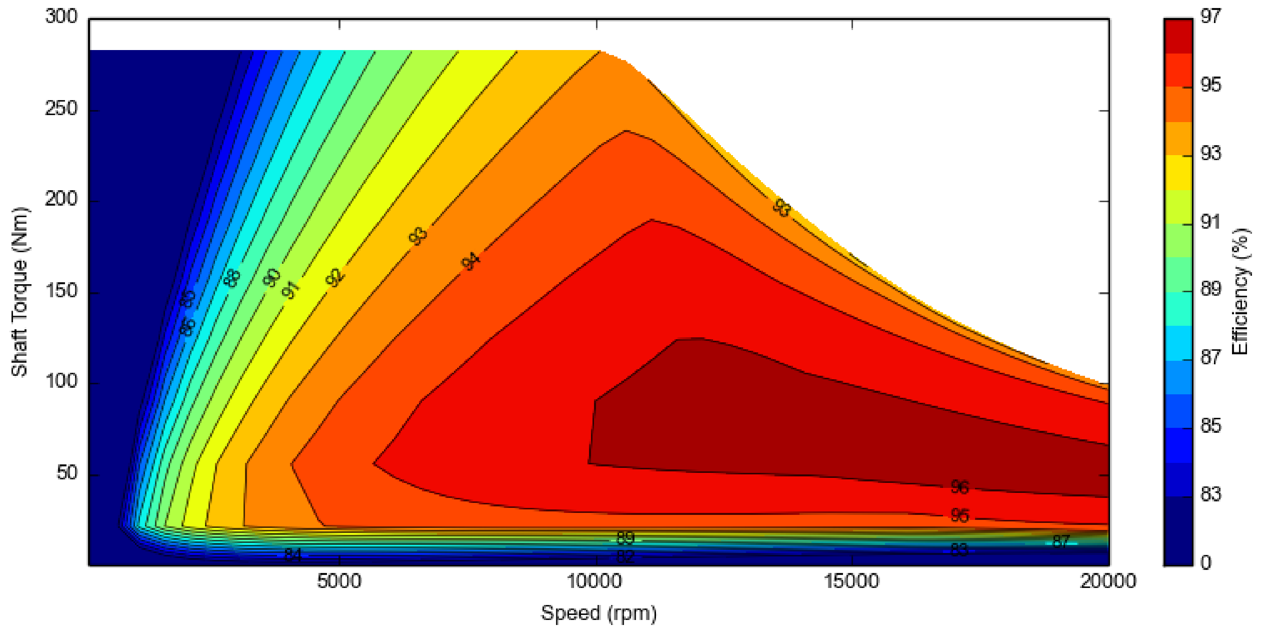


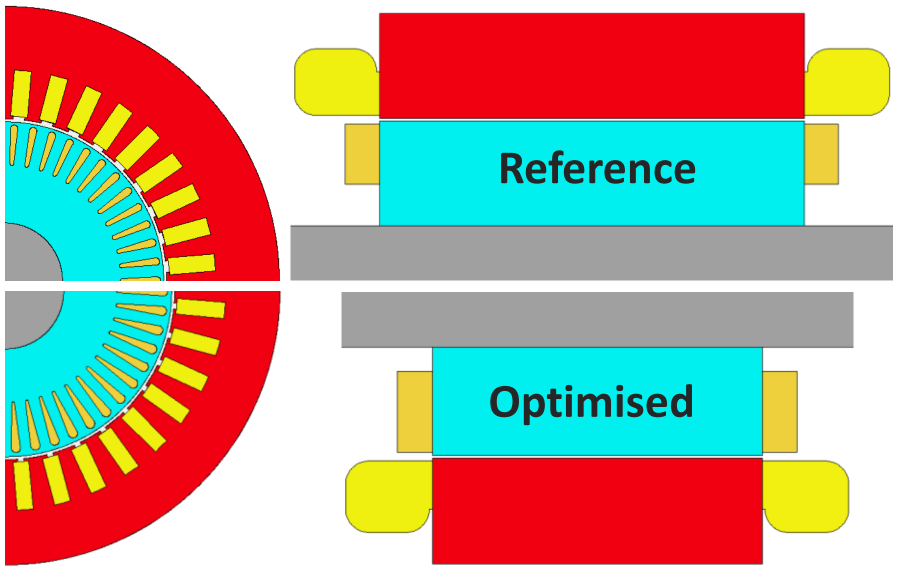


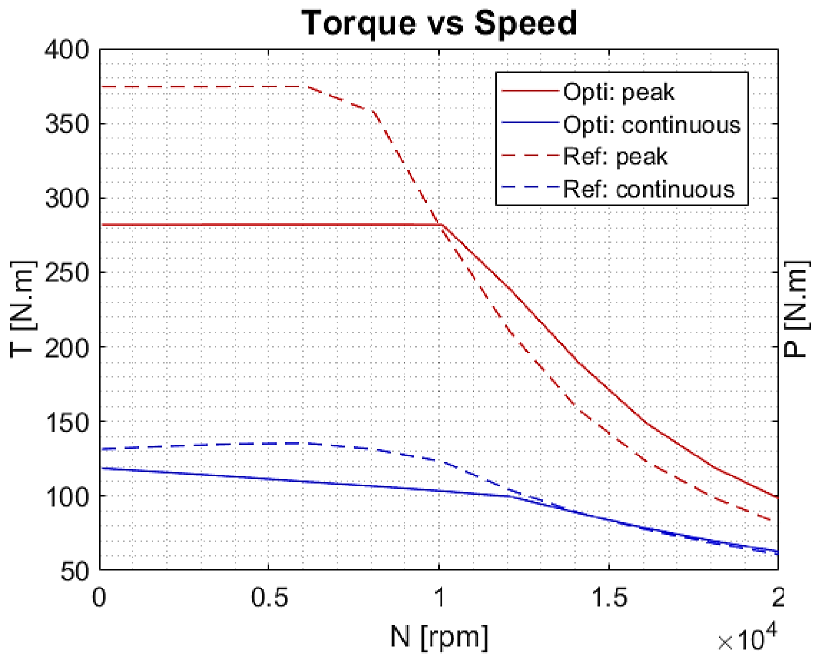


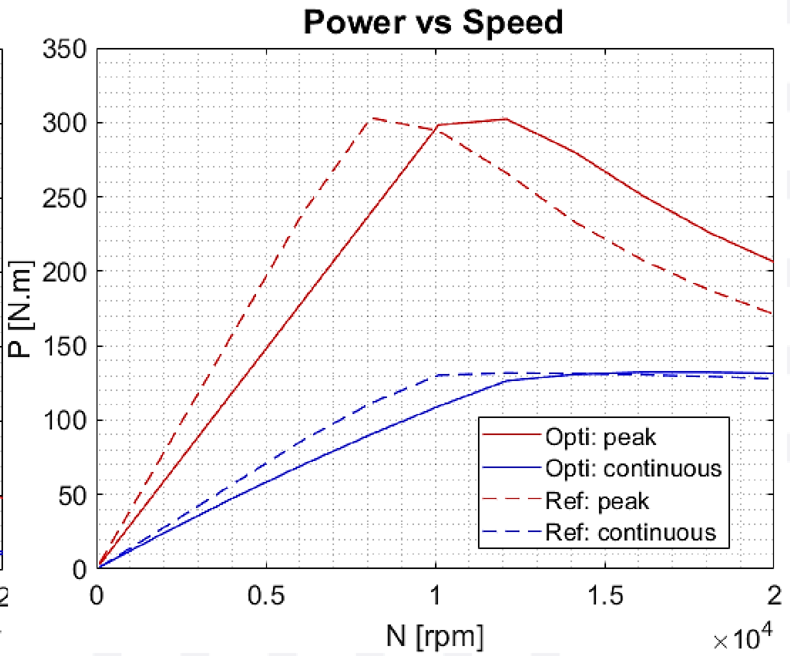
Results: scenario 2

- Length reduced by 23% compared to the reference design
- 96% peak efficiency in a large area
- Larger bar area and higher split ratio
- Continuous performance at low speed sufficient? → ***Pareto front***





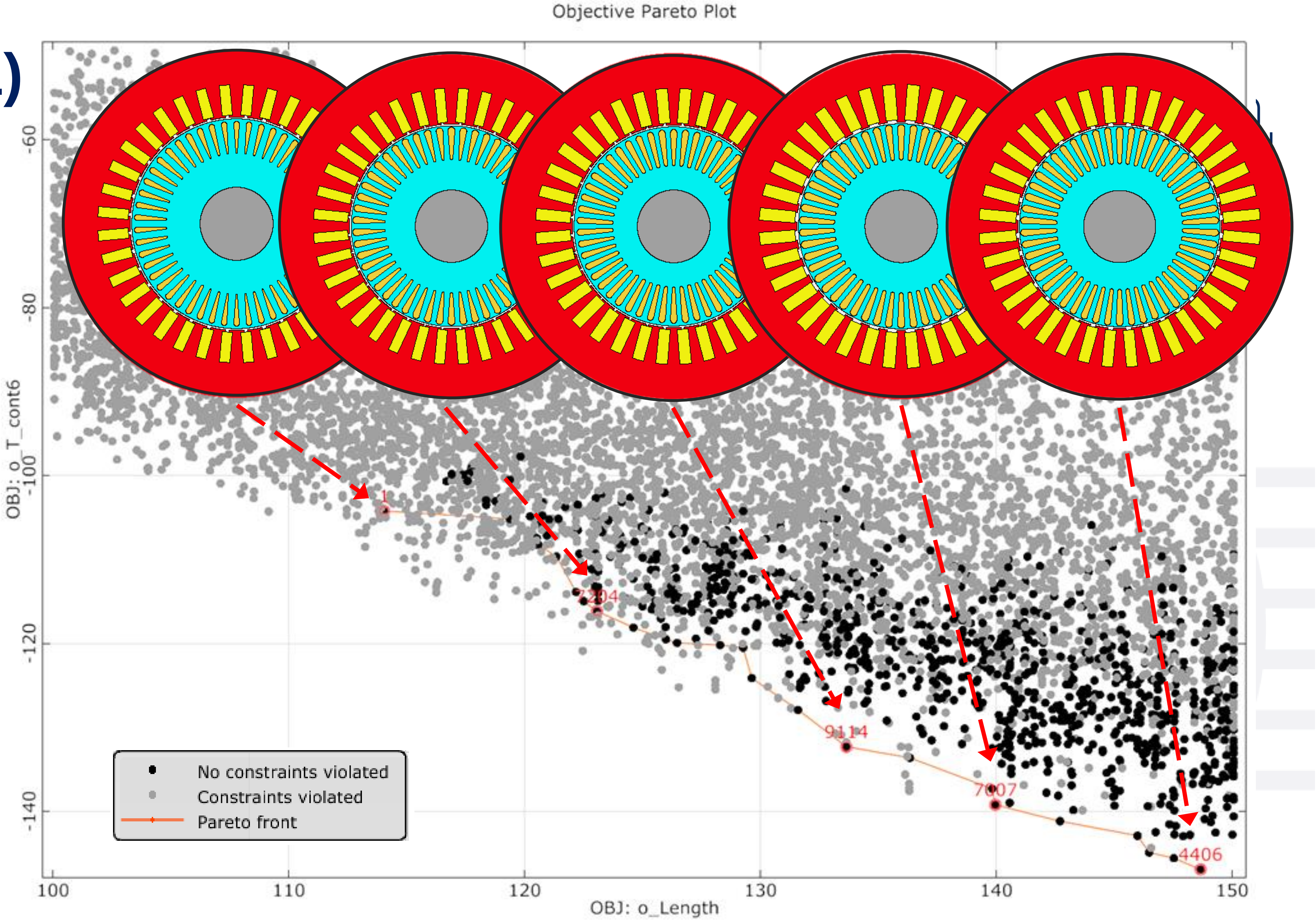




Pareto front (1)

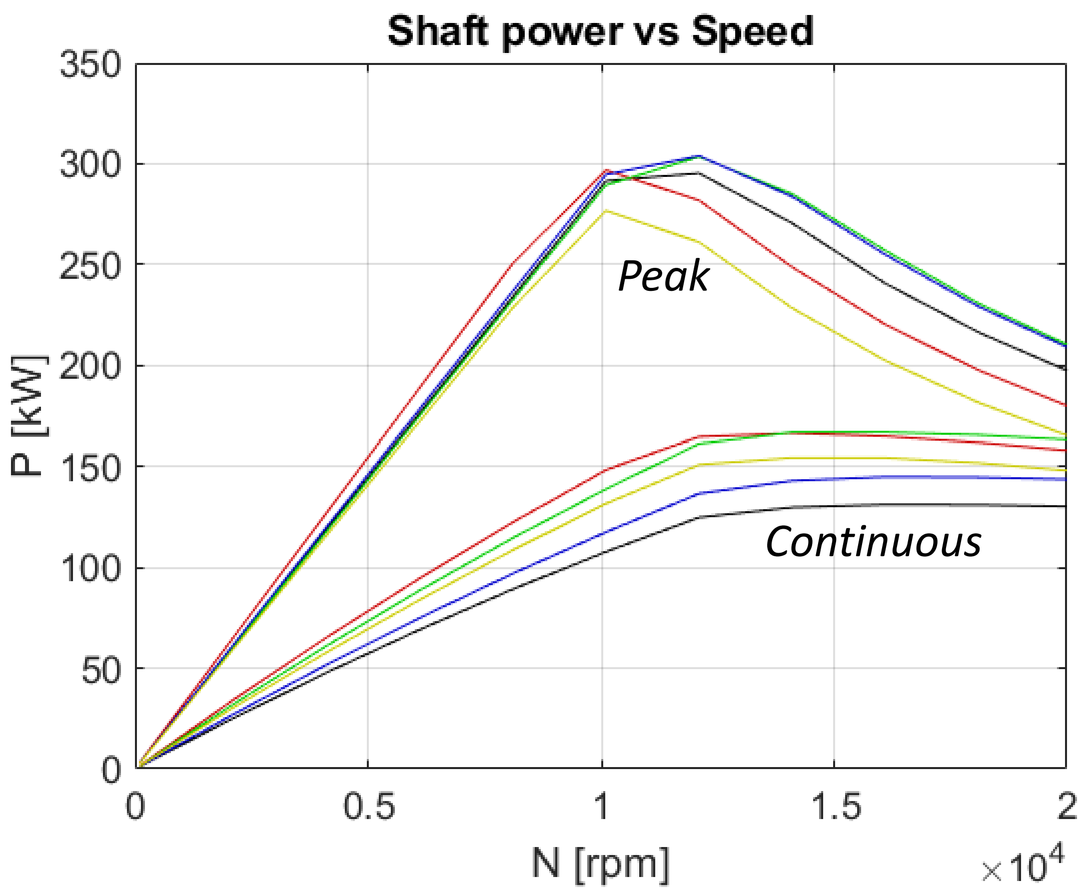
Scenario 2

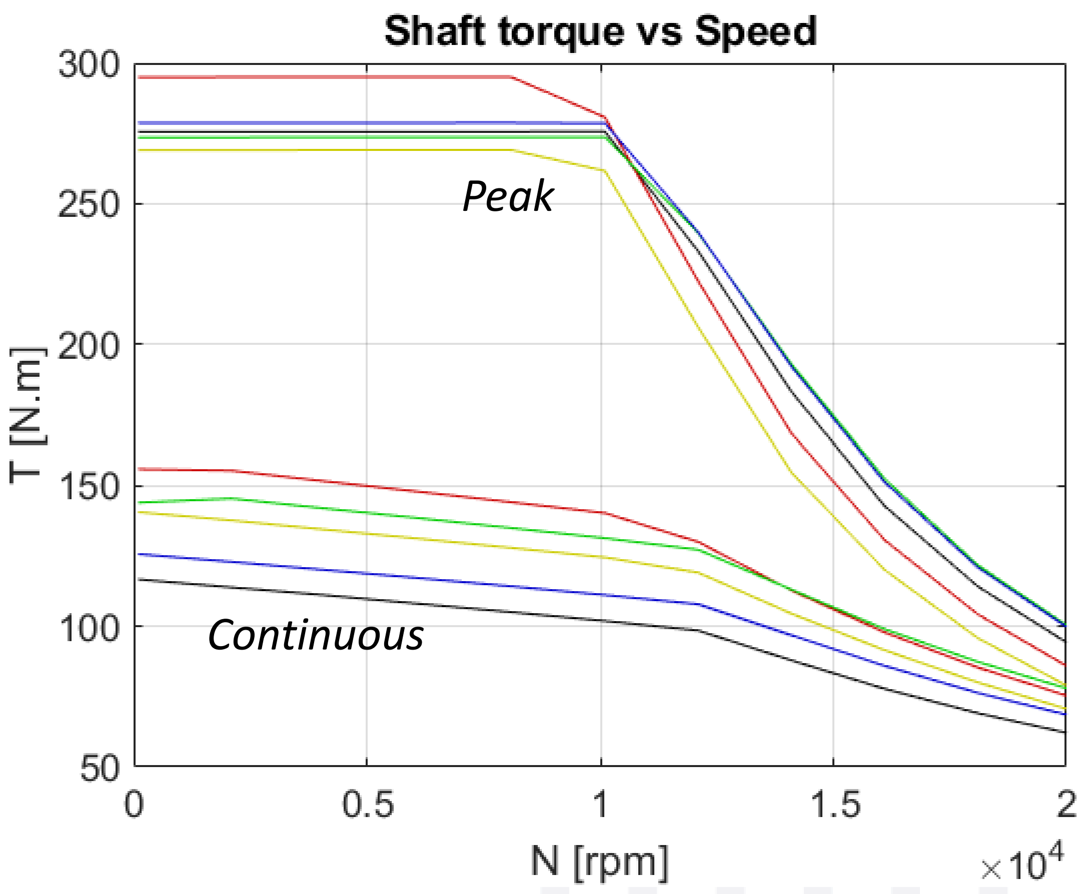
$$\begin{cases} \min(L) \\ T_{peak}@LS > 280N.m \\ P_{peak}@MP > 200kW \\ P_{cont}@MP > 120kW \end{cases}$$



Pareto front (2)

- The longer the machine the better the thermal envelope
- Different tendency for the peak operation





Conclusion

Main results & Outlooks

Conclusion

Main results (Task 3.1)

- IR-IM and OR-IM solutions are potential structures to be used for ReFreeDrive application and eMobility overall
- Mechanical stress calculations showed poor safety factors for OR-IM solution that needs for refinements
- Materials for the rotor bars and the rotor and stator cores were selected according to the best performance to cost ratio
- IR-IM was optimised to reduce the cost while meeting the power and torque requirements based on ReFreeDrive boundary conditions

Outlooks (Task 3.2)

- Sensitivity analysis, optimisation and thermal analysis on the OR-IM design
- 3D mechanical stress FEA to be performed on the fabricated copper rotor IM
- Parameters from the cooling system to be included in the optimisation for better efficiency and continuous performance
- Solution with spray cooling to be investigated
- Scalability principles to be applied to the optimal designs

Thank you for your attention!

Any questions

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