Solutions and Challenges - Electric Machines for Aerospace and Automotive Applications

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Introduction

Motivation:

- Transport electrification is seen as main solution to reduce CO2 emissions
- Increased demand of mechanical energy can be provided by electrical energy
- Best energy conversion systems: electrical machines + power electronics + batteries

Solutions:

- Aerospace, automotive and marine propulsion to become hybrid and full electric
- Automotive industry most advanced, all larger OEMs and Tier 1 companies involved
- Aerospace industry less details on advances, players such GE, Boeing, Airbus, Rolls-Royce, Siemens, NASA are involved
- Main problems:
  - Battery capacity – how much electrical energy can we store?
  - Weight (aerospace only)
  - Market demand/cost

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PENETRATION OF ELECTRICAL SYSTEMS BY AIRCRAFT TYPE

Many aircraft now employ electric systems, and/or a mix of hydraulic and electric systems.

	Boeing 737	A380	Boeing 787	A350	F-35 JSF
Environmental Control System	P	P	E	P	P
Flight Control System	H	E H	H	E H	E
Landing Gear	H	H	H	H	H
Wheels & Brakes	H	H	E	E	H
Ice Protection	P	P	E	P	E
Thrust Reverser	H	E	H	E	F

E Electric H Hydraulic P Pneumatic F Fuel

Source: Airbus, Boeing, Lockheed Martin, Roland Berger

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ELECTRICAL PROPULSION ARCHITECTURES

There are three main architectures for Electrical Propulsion.

Hybrid-electric

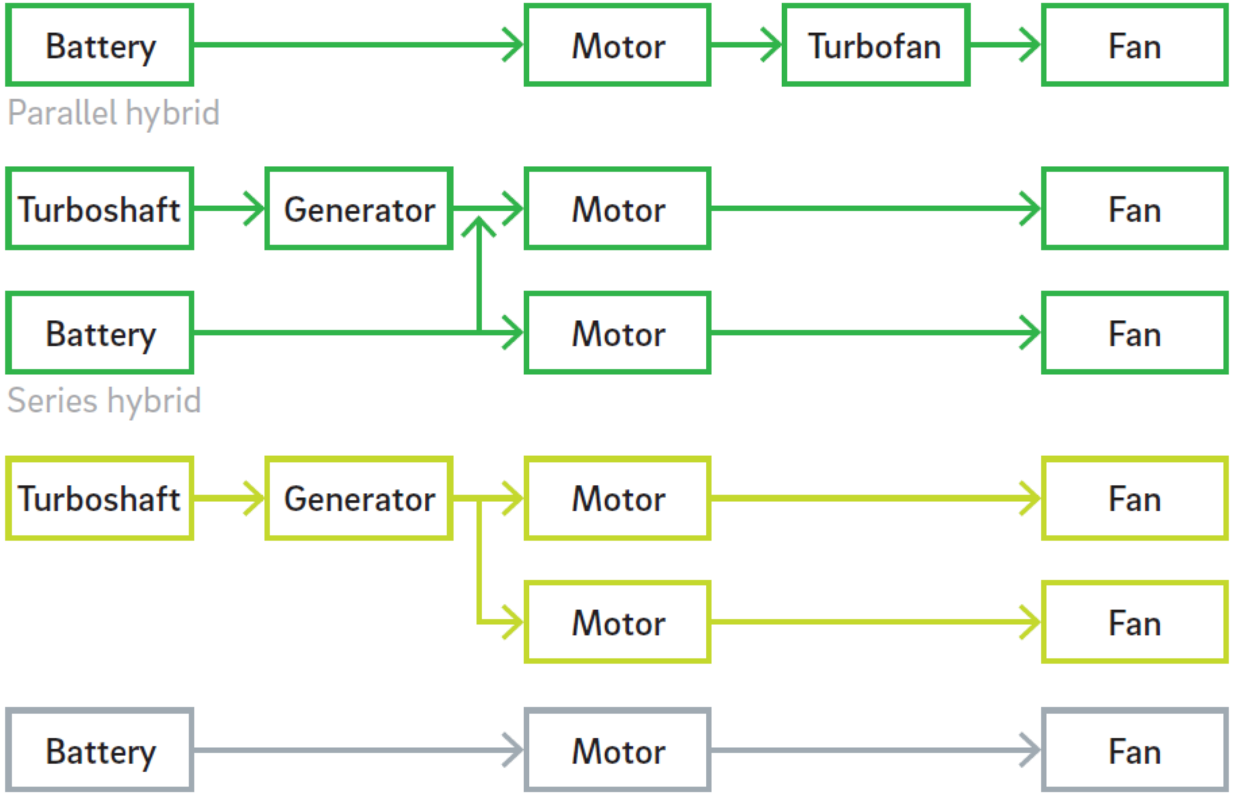
Hybrid-electric is one of two architectures – Parallel or Series hybrid. Additional electric energy can be used for acceleration and in times of high power demand, and bi-directional flow of power is possible between the generator and battery.

Turbo-electric

The kinetic energy of a turbo shaft is transformed into electric energy via a generator to drive multiple, distributed fans, with the fans driven by electric motors.

All electric

One, or multiple, fans are driven by electric motors with energy stored in a battery.



Source: NASA, Roland Berger

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Electrification of aircraft systems brings benefits across market segments

	Vertical Take-Off and Landing	Fixed Wing
Non-Propulsive Energy - improved performance & mandatory step for hybridization	• Manage aircraft loads and engine offtakes in real-time • Load balancing and optimisation • Simpler system with improved reliability	
	• Assist engine during transient operation through power injection	
Hybrid-Electric Propulsion - new missions, new markets, & improved performance	• Urban operation through system redundancy and low noise • Competitivity through lower cash operating cost • Simplified tilt-wing for longer range	• Higher efficiency – opens up aircraft design space – BLI / distributed propulsion • Lower cost – elimination of high cost component • Higher utilisation – lower noise

Source: Glen Llewllyn, Airbus, 2017, Koln

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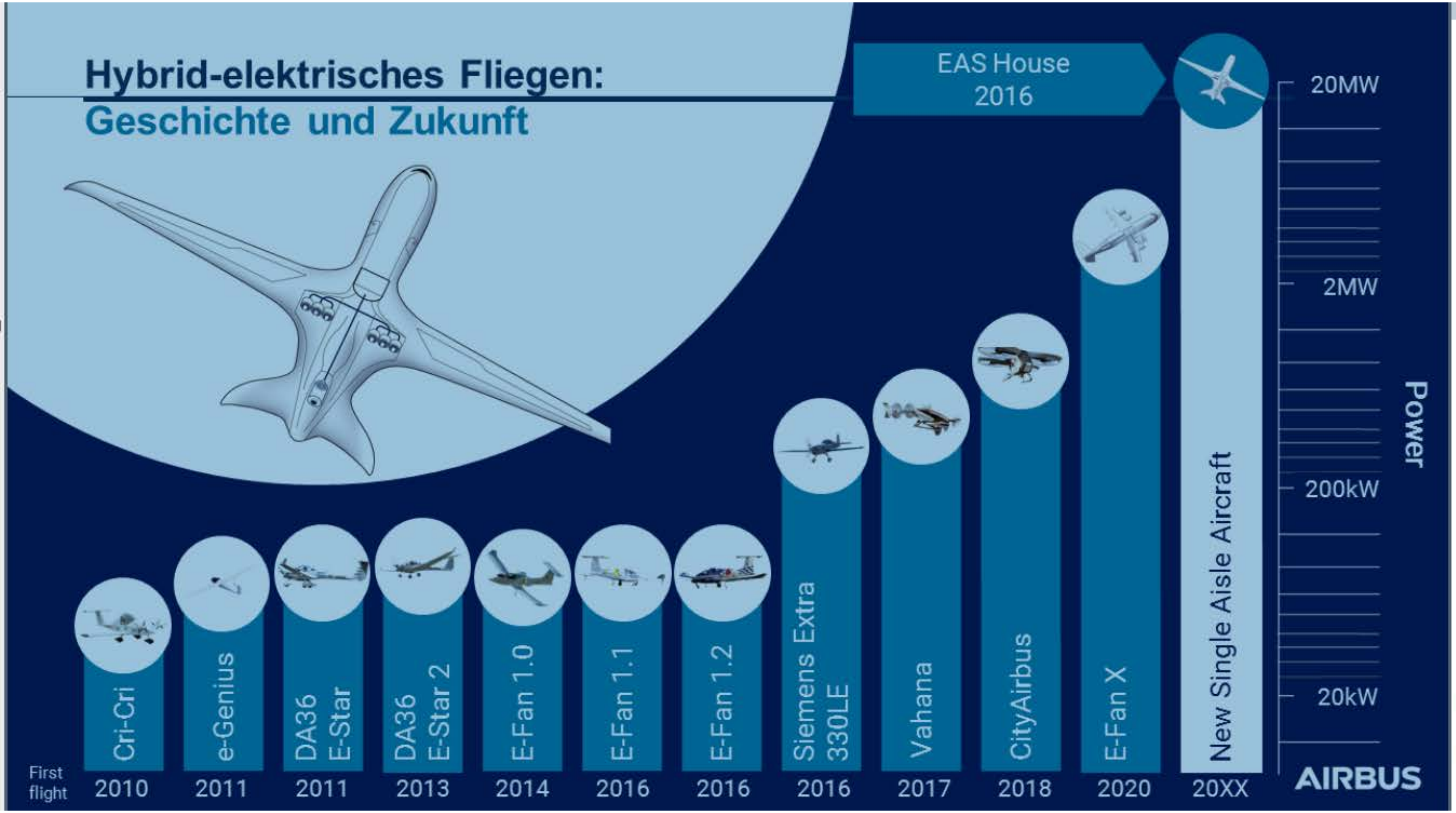
Airbus-Siemens Collaboration Hybrid- electric propulsion roadmap



Source: Paul Eremenko's keynote address at the 2017 AIAA AVIATION Forum in Denver, June 2017

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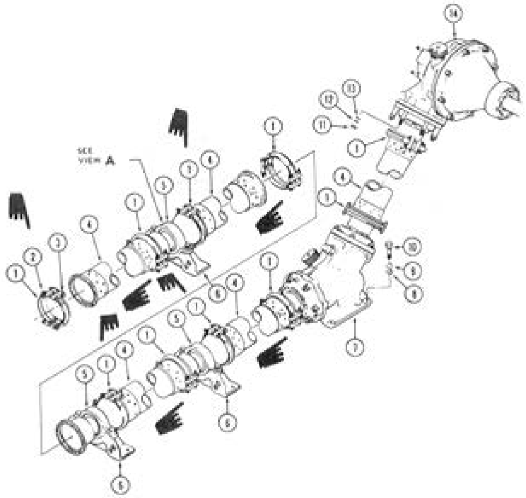
Airbus-Siemens Collaboration Hybrid- electric

	SP260D 2015		SP200D 2017
Continuous Power	260 kW		204 kW
Rotational Speed	2500 RPM non-geared		1300 RPM non-geared
Continuous Torque	**1000 Nm**		**1500 Nm**
Mass	50 kg		49 kg
Torque to Mass Ratio	**20 Nm/kg**	**Increase by 50%**	**30.6 Nm/kg**
Inverter Type	Si		SiC

Source: Dr. Frank Anton, Siemens AG eAircraft, 2017, Koln

Fault-tolerant aircraft propulsion motor



Mechanical power transmission:
Two gearboxes, supercritical shaft

Electrical power transmission:
Direct drive electrical machine and cable

Source: ELETAD, Cleansky 2012-2014 program

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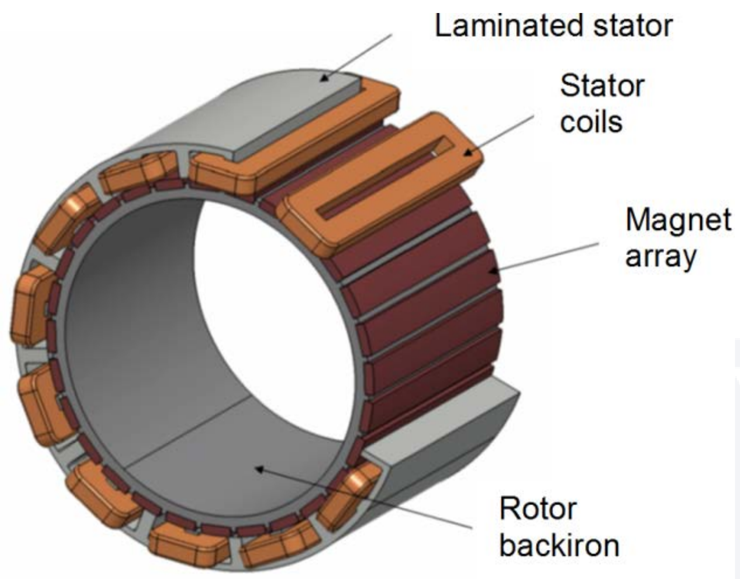
Fault-tolerant aircraft propulsion motor

Dual stator
Axial-flux

Source: ELETAD, Cleansky 2012-2014 program

Internal rotor
Radial-flux



- 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

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Fault-tolerant aircraft propulsion motor

- Axial- and radial-flux prototypes realisations have near identical active mass

Active component	Axial-flux	Radial-flux
Stator core	40 %	34 %
Winding copper	36 %	32 %
Permanent magnet	24 %	25 %
Rotor back iron	N/A	9 %

- Radial flux has configuration benefits: lower outer diameter and a large central void to accommodate pitch mechanisms

Source: ELETAD, Cleansky 2012-2014 program

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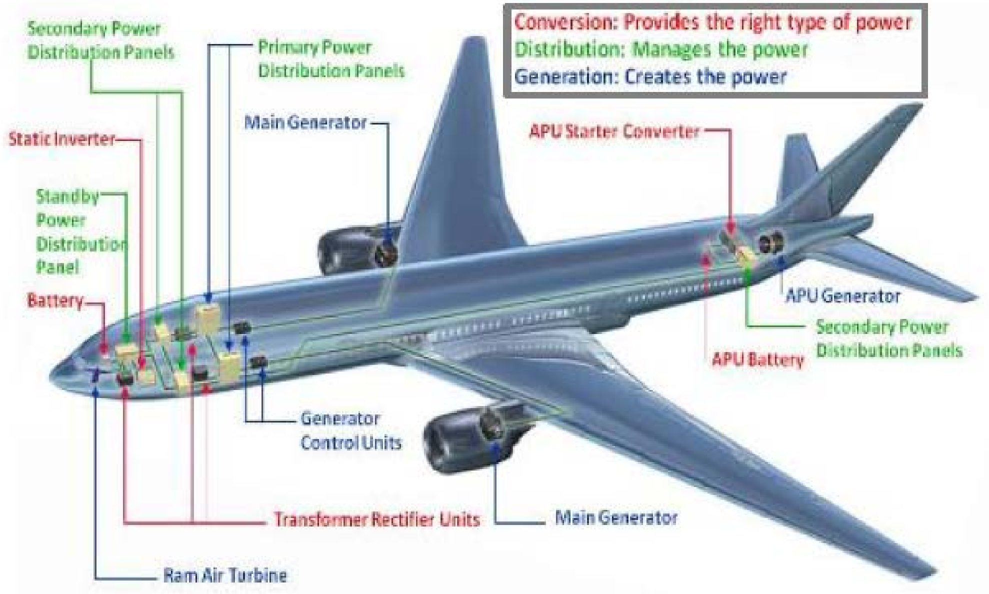
Honeywell Turbine Engines and Electric Power Products



Source: C. Anghel, Honeywell, 2017, Koln

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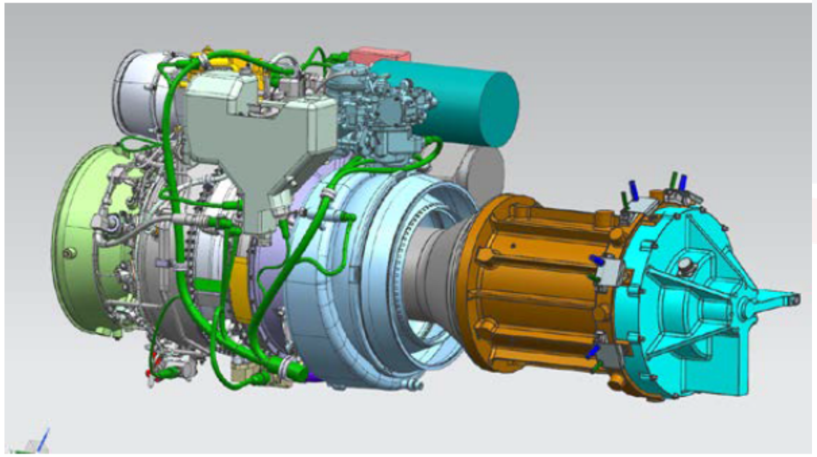
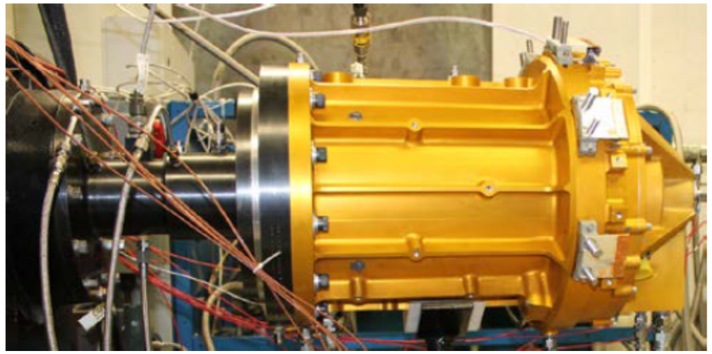
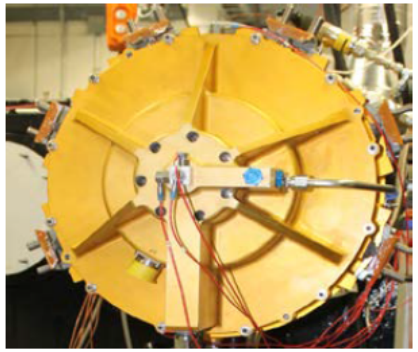
Honeywell 1MW Aerospace Generator

- High power, high efficiency generator ideal for turbo-electric applications
- Tested to high power levels, more testing underway

Rating	1 MW continuous (after rectification)
Voltage	234 Vac or 300 Vdc or 600 Vdc (after rectification)
Speed	19,000 rpm (20,000 rpm overspeed)
Weight	126.5 Kg (279 lbs) (generator only)
Design efficiency	98% at rated load
Cooling	Oil conduction and spray
Type	Wound field synchronous with rotating rectifiers
Poles	8 (main machine)
Output winding	2 X 3-phase Y with 30° electrical shift
Rectification	Passive external







Source: C. Anghel, Honeywell, 2017, Koln

Automotive Electrical Solutions

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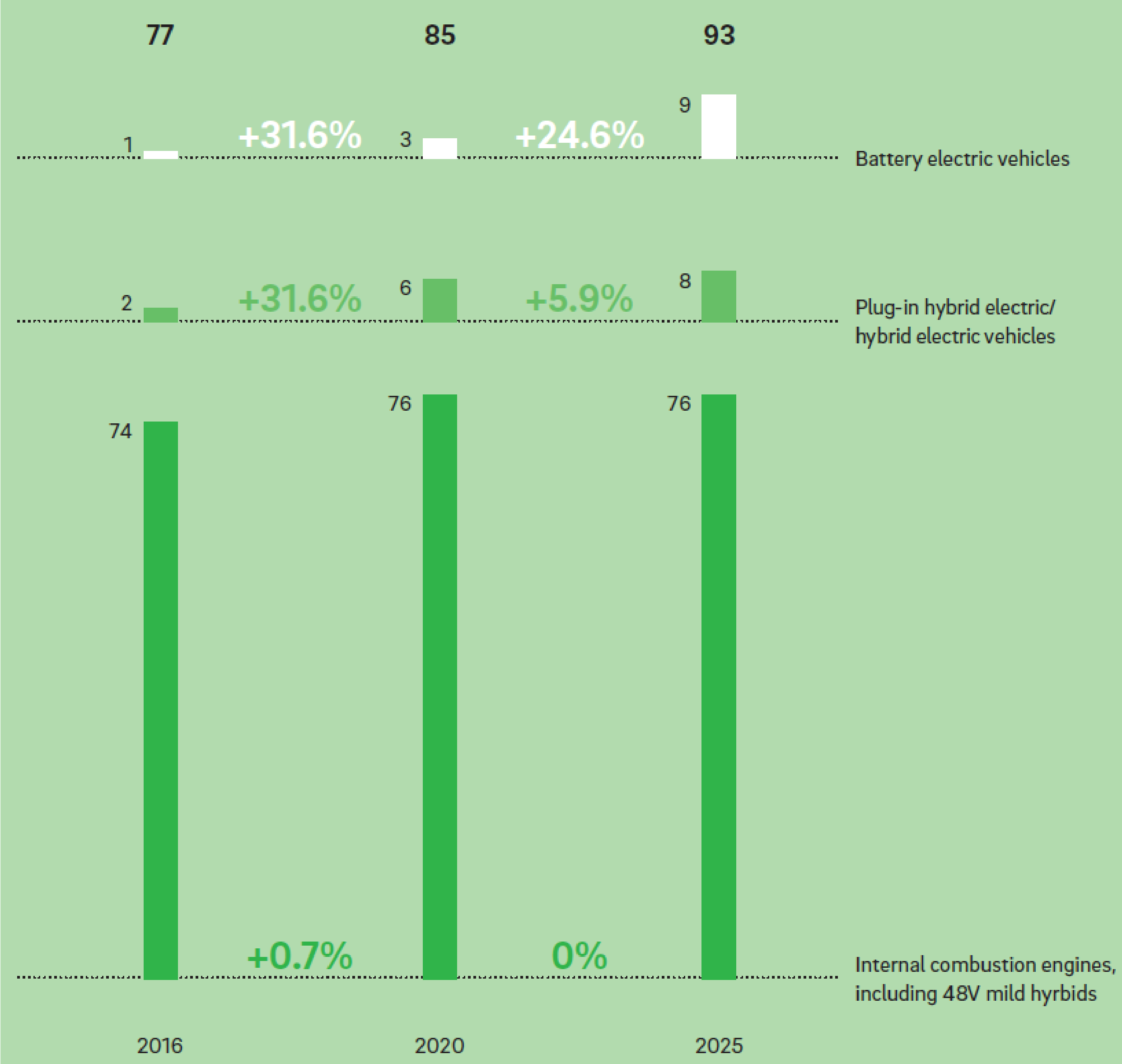

Global light vehicle production [m vehicles]

Automotive Electrical Traction

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- Range of configurations under development
  - Mild, Series, Parallel and Plugin Hybrid
  - Battery Electric and Range Extender
- Main design drivers:
  - Efficiency
  - Power Density
  - Cost
- To make optimum designs we need to quickly calculate the efficiency map and then allow fast complex drive cycle transient thermal analysis






Automotive Electrical Traction

E. Grunditz and T. Thiringer – IEEE Transactions on Transportation Electrification, VOL. 2, NO. 3, SEPTEMBER 2016, p. 270 - 289

Model	EM Motor type	EM Max. Torque (Nm)	EM Max. Power (kW)	EM Cont. Power (kW)	EM Speed at max. Torque (rpm)	EM Speed at max. power (rpm)	EM Max. Speed (rpm)	EM Cooling	Transm. Ratio
fortwo	PM [106]	130 [106]	55 [106]	35 [106]				Water [108]	9.922 [181]
BRABUS	PM [109]	135 [109]	60 [109]	35 [109]					
iQ EV	PMSM [110]	163 [35]	47 [35]					Air [35]	
500e	PMSM [182]	200 [112]	83 [112]				12,800 [67]	Water [67]]	9.59 [112]
C-ZERO	PMSM [113]	196 [113]	49 [113]		300 [113]	4,000-8,800 [113]			
iOn	PMSM [115]	196 [115]	49 [115]	35 [115]	300 [115]	4,000-8,800 [115]	9,500 [115]		
i-MiEV	PMSM [117]	196 [117]	49 [117]		300 [117]	4,000-8,800 [117]	9,900 [117]	Water [117]	7.065 [117]
e-Up!	PMSM [118]	210 [118]	60 [118]		2,800 [118]	2,800 [118]	12,000 [118]		8.162 [119]
Spark EV	PMSM [43]	444 [43]	105 [43]					Liquid [43]	3.87 [43]
Bluecar			50 [83]	35 [83]					
MiniCab	PMSM [122]	196 [121]	30 [121]	25 [121]	3,000 [122]	2,500-6,000 [122]			7.065 [121]
i3	HPMSM [29]	250 [77]	125 [77]	75 [77]	5,000 [65]		11,400 [29]	Liquid [65]	9.7 [77]
Zoe	SM, w.r. [46]	220 [46]	65 [46]		2,500 [46]	3,000-11,300 [46]	11,300 [46]		9.32 [183]
C30 El.		250 [78]	89 [78]						
e-Golf	PMSM [125]	270 [125]	85 [125]	50 [184]	3,000 [185]	3,000 [185]	12,000 [125]		9.747 [125]
Leaf'15	IPMSM [56]	254 [127]	80 [127]		3,008 [127]	3,008-10,000 [127]	10,500 [127]	Water [56]	8.1938 [127]
Leaf'16	SM [128]	254 [128]	80 [128]		3,008 [128]	3,008-10,000 [128]	10,500 [128]		8.1938 [128]
FIT EV	PMSM [130]	256 [130]	92 [130]		3,056 [130]	3,695-10,320 [130]	10,320 [130]		8.058 [130]
Fluence.	SM, w.r. [60]	226 [60]	70 [60]	35 [63]	2,500 [164]	3,000-8,900 [164]	11,000 [48]		9.34 [60]
Focus EV	PMSM [103]	250 [133]	107 [133]			5,500 [155]		Liquid [49]	7.82 [155]
Soul El.	IPMSM [55]	285 [134]	81.4 [97]		2,730 [134]	2,730-8,000 [134]		Liquid [97]	8.206 [134]
B-Class El.Dr.	IM [135]	340 [135]	132 [135]	65 [135]		9,900-12,500 [135]		Liquid [57]	9.73 [136]
e6	PMSM [137]	450 [137]	90 [137]				7,000 [186]	Liquid [98]	6.844 [186]
e-NV200	IPMSM [140]	254 [90]	80 [90]				10,500 [140]		7.938 [90]
RAV4 EV	IM [84]	370 [84]	115 [84]					Liquid [70]	9.73 [84]

Automotive Electrical Traction

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Model	EM Motor type	EM Max. Torque (Nm)	EM Max. Power (kW)	EM Cont. Power (kW)	EM Speed at max. Torque (rpm)	EM Speed at max. power (rpm)	EM Max. Speed (rpm)	EM Cooling	Transm. Ratio
ModelS 60	IM Cu. [187]	430 [188]	283 [189]		5,000 [188]	5,000-8,000 [190]	16,000 [28]	Liquid [28]	9.73 [187]
ModelS 70	2 IM Cu. [59]	441 [59]	285 [59]					Liquid [59]	
ModelS 70D	2 IM Cu. [59]	525 [59]	F,R:193 [59]					Liquid [59]	
ModelS 85	2 IM Cu. [59]	441 [59]	285 [59]		5,800 [188]	6,000-9,500 [190]	16,000 [28]	Liquid [59]	9.73 [187]
ModelS 85D	2 IM Cu. [59]	658 [59]	F,R:193 [59]		5,800 [188]		16,000 [28]	Liquid [59]	9.73 [187]
ModelS P85D	3 IM Cu. [59]	967 [59]	F:193 [59] R:375		5,100 [188]	5,000-8,600 [190]	16,000 [28]	Liquid [59]	9.73 [187]
ModelX 90D			F,R: 193 [142]						
ModelX P90D			F:193 [142] R:375 [142]						
Roadster	IM [143]	370 [143]	225 [143]		5,400 [143]	5,000-6,000 [143]	14,000 [143]	Air [143]	8.28 [143]
Concept One	4 PMSM [96]	1600 [96]	800 [96]		6,500 [96]		12,000 [96]	Oil [96]	3.5 [174]
SLS AMG El.Dr.	4 PMSM [68]	1000 [68]	552 [68]				13,000 [68]	Liquid [85]	
Lightning GT	2 EM [74]	4000 [74]	300 [74]						5.5 [176]
SP:01 Pure		280 [31]	150 [31]						
SP:01 Perf.		280 [31]	210 [31]						
Fetish	PMSM [148]	380 [148]	220 [148]						
America	2 PMSM [149]	480 [150]	300 [150]		6,000 [149]		10,500 [149]		
Coupe	2 Ax.Flux [61]	1355 [61]	368 [61]						
R8 e-tron	2 EM [37]	920 [30]	340 [30]						
LAMPO 3	3 HSM [152]	900 [152]	420 [152]		4,500 [152]			Water [152]	6.4 [152]

Automotive Electrical Traction

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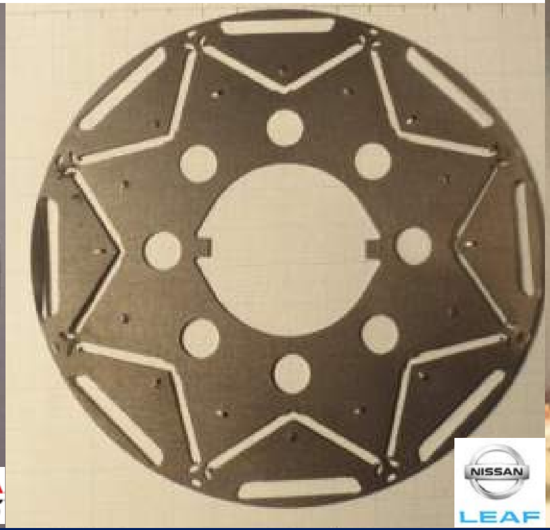
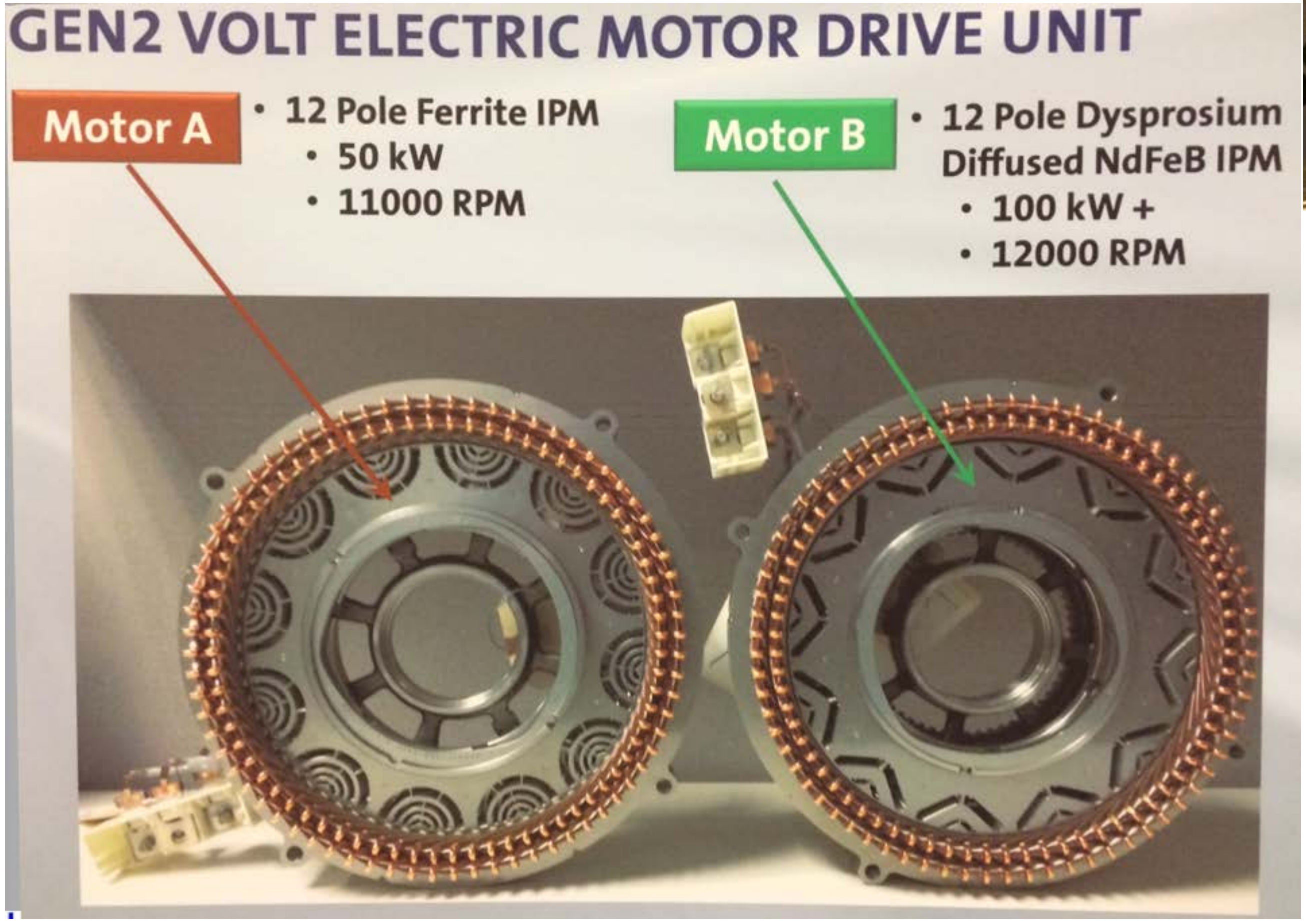
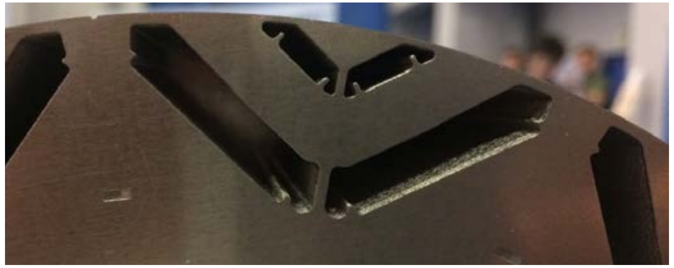
- Many choices to be made when designing a motor:
  - BPM, Induction, Synchronous Reluctance, SRM ….
  - Design Variables
    - Slots/poles, Magnet Type, IPM design, Dimensions ……
  - Winding Type
    - Distributed, Tooth Wound, Bar/Hairpin, Litz, Cu/Al …..
  - Cooling Type
    - Air, Water Jacket, Rotor Fluid, Slot Oil, Oil Spray ……



Chevrolet Volt (Generation 2)

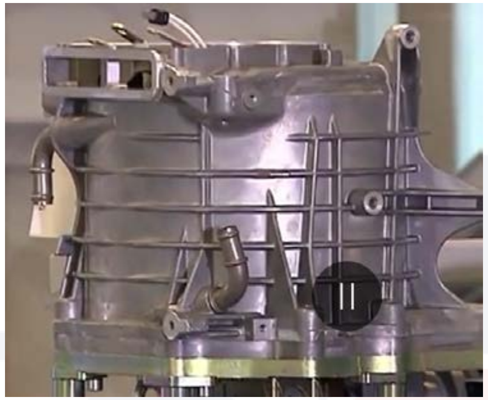
- 50kW Ferrite and 100kW Nd-Fe-B IPM motors
- Hairpin windings
- EV range over 50 miles but no fast charge

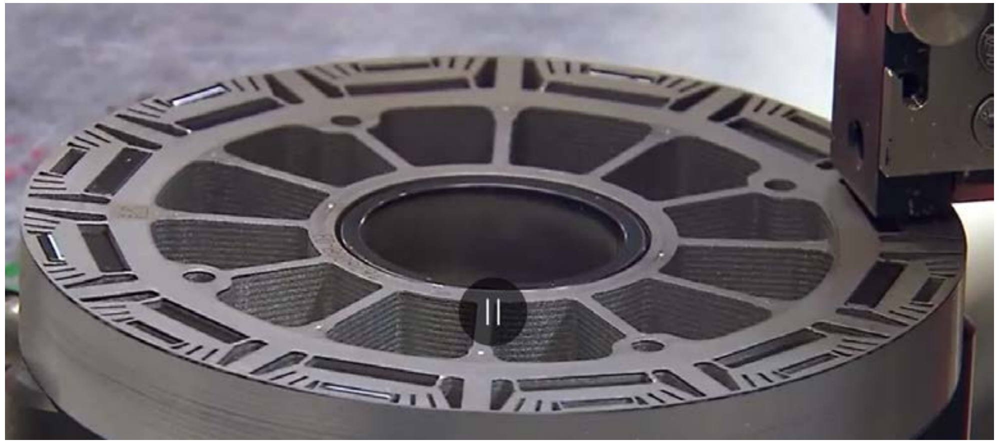




BMW i3

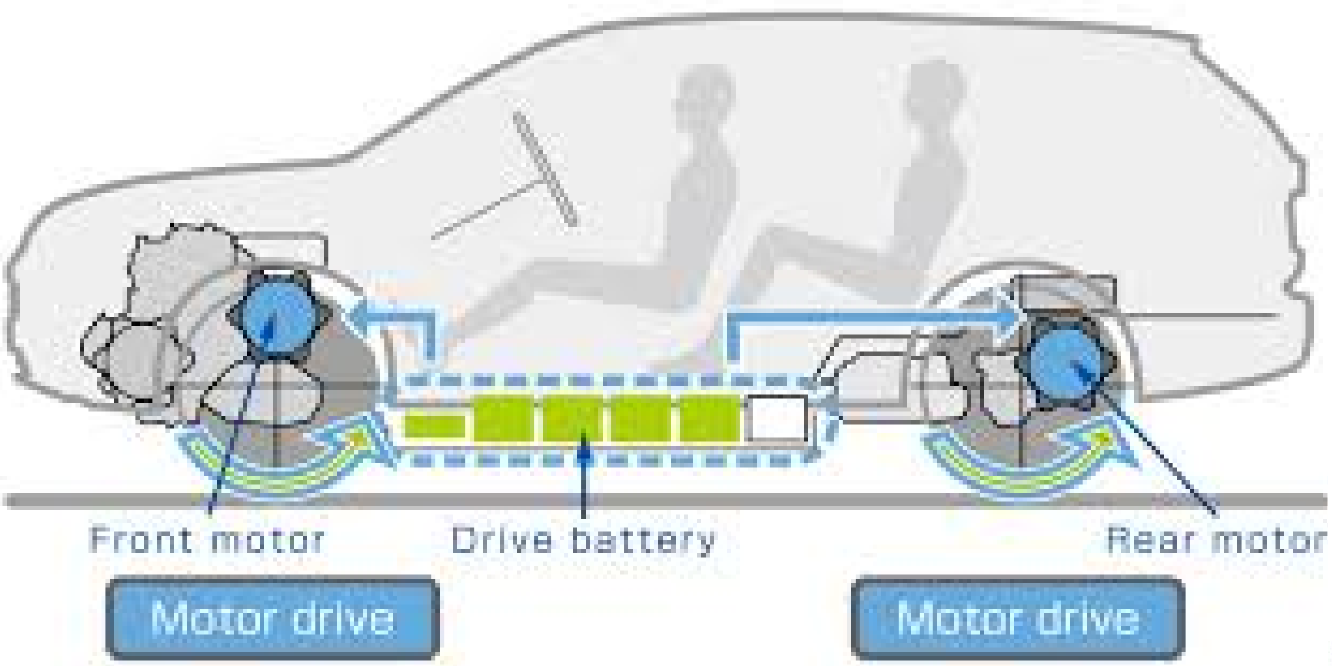
- 125kW NdFe-B- IPM Motor
- 18.8 kWh lithium iron battery (range extender option)
- Around 80 mile range
- New model has 1.5 range with larger battery

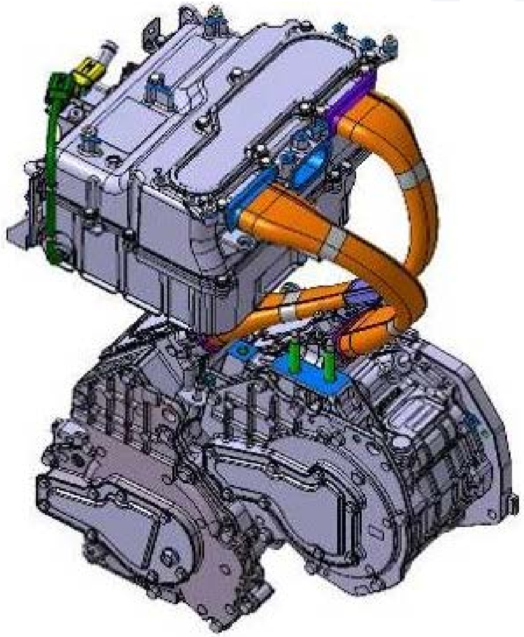




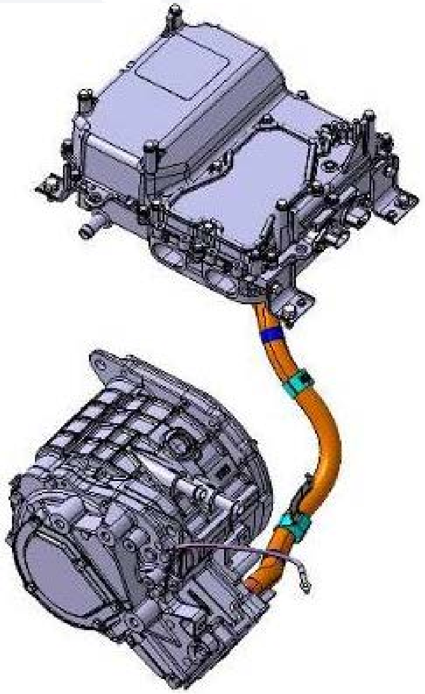
Mitsubishi Outlander PHEV

- Twin 60kW electric motor 4WD with 2.0-liter gasoline engine
- Around 30 mile range on electric - published value (less in practice)
- Can work in pure EV, series hybrid and parallel hybrid modes





Power Drive Unit, Electric generator, Electric motor + inverter (60 kW/82 ps - 137 Nm)



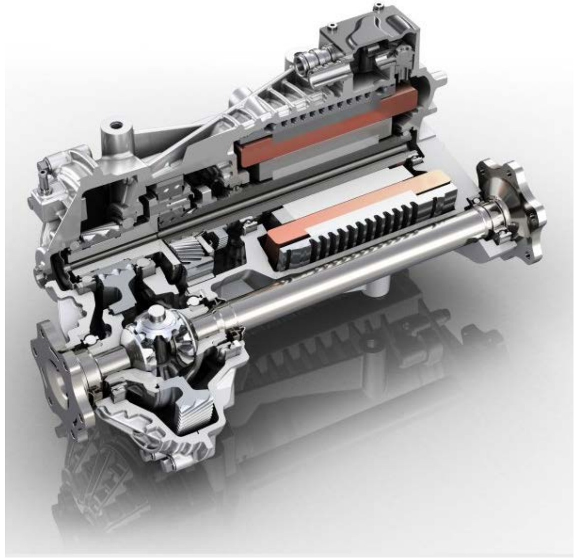
Rear Motor Control Unit, Electric motor + inverter (60 kW/82 ps - 195 Nm)

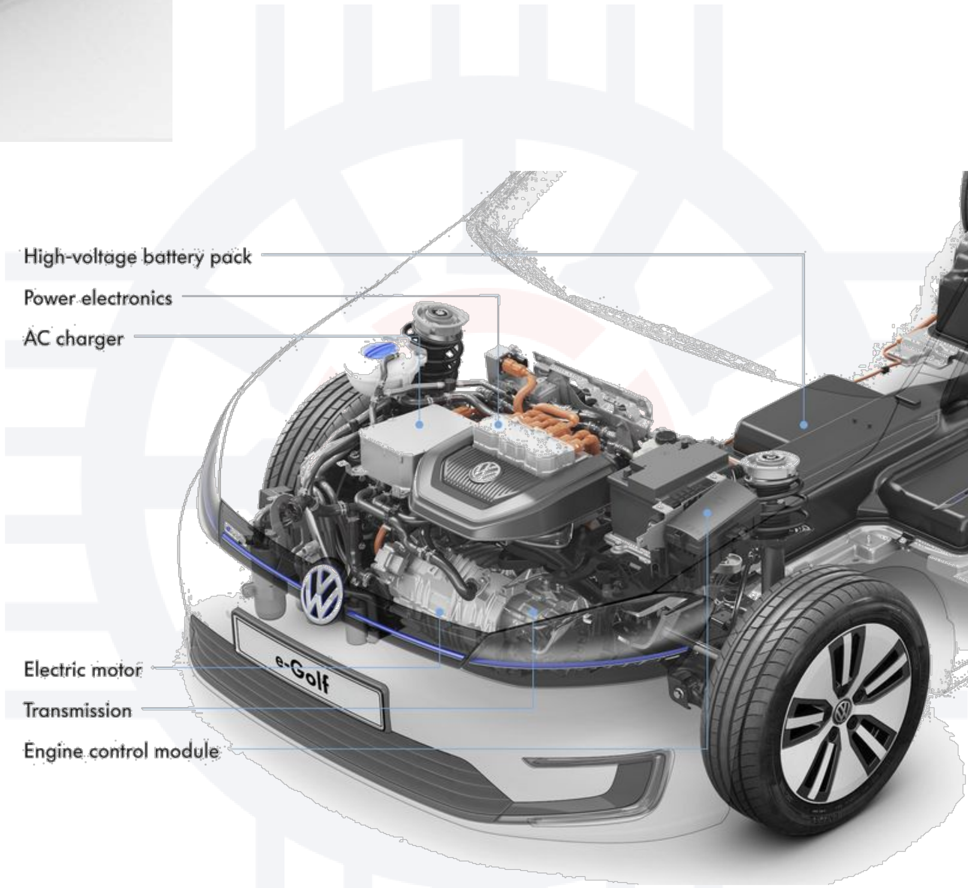
Renault Zoe

- Small low cost all electric EV
- Battery hire rather than purchase
- Around 100 mile range
- 65kW wound field synchronous motor

VW e-Golf

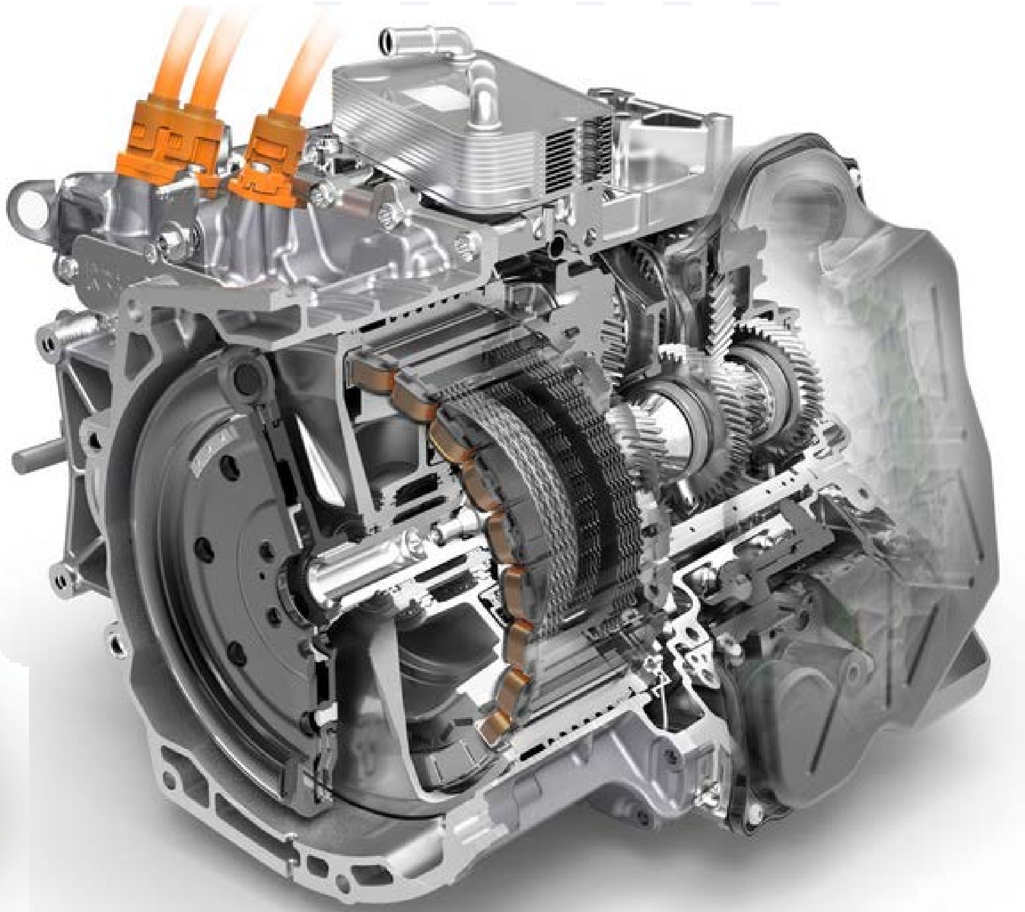
- All electric BEV
- 118 mile range
- 85 kW 12,000rpm PM motor
- 0 to 60 km/h within 4.2 seconds
- up to 100 km/h 10.4 seconds
- top speed electronically limited to 140 km/h (87 mph)
- single-speed gearbox





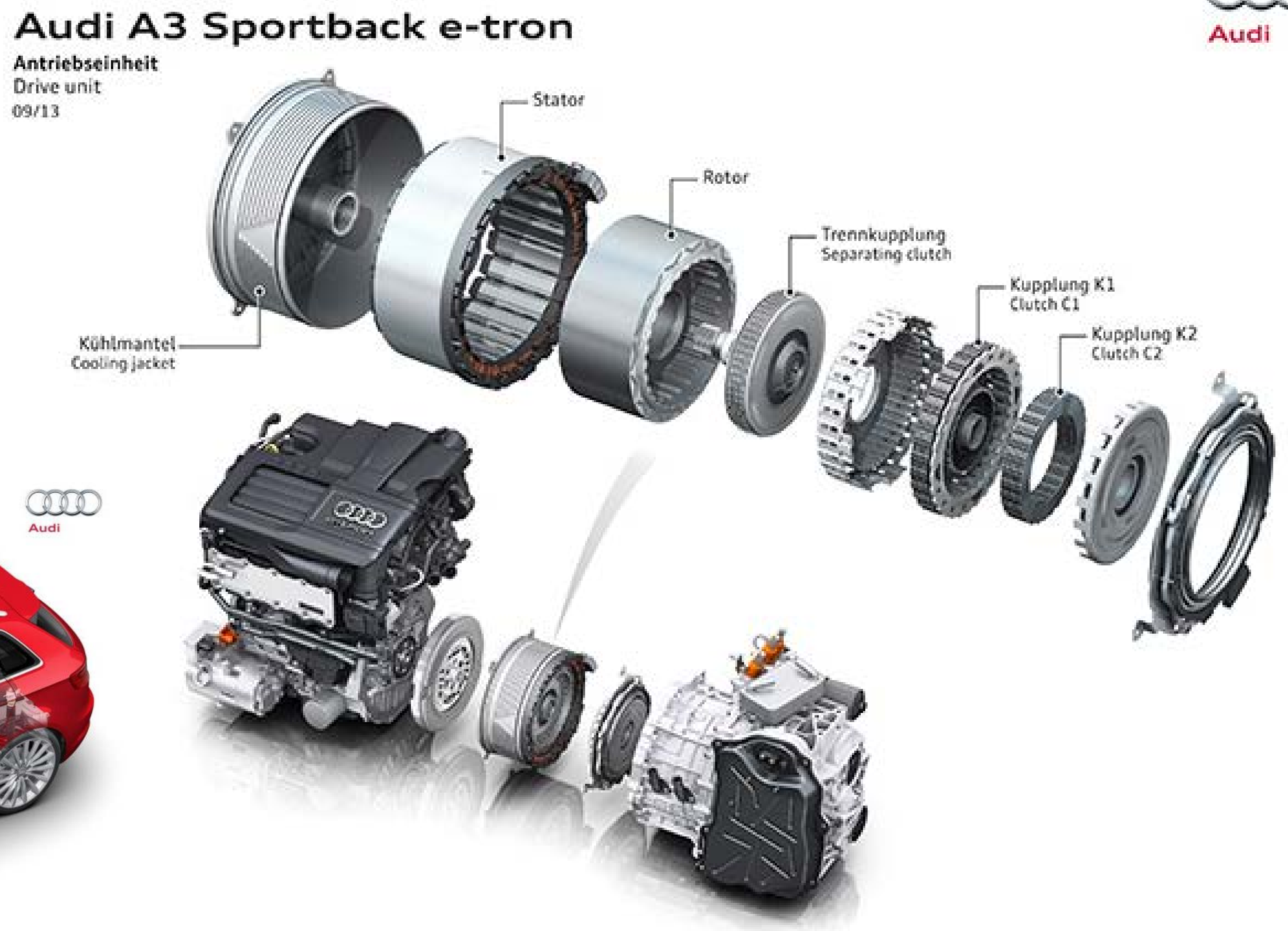
VW GTE

- 31 mile electric mile range PHEV
- 75-kW three-phase, permanent magnetic electric motor
- 1.4-litre petrol engine



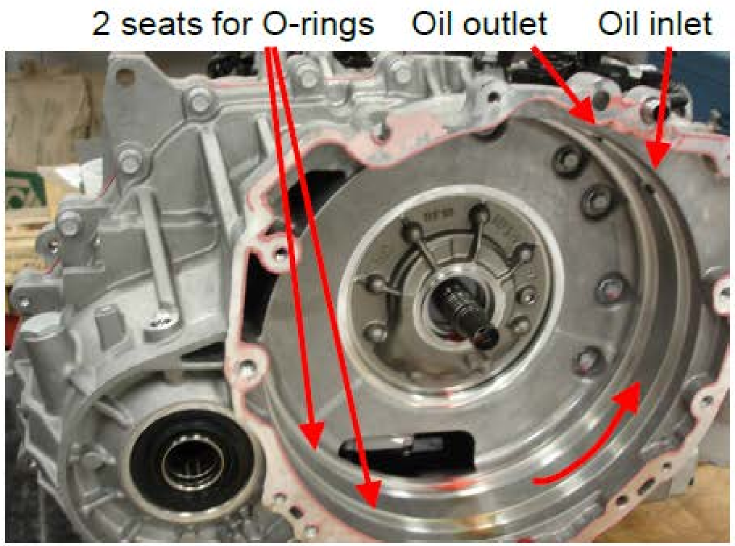
Audi A3 e-tron

- ➢31 mile EV range PHEV
- ➢multi-speed transmission
- ➢102-hp electric motor

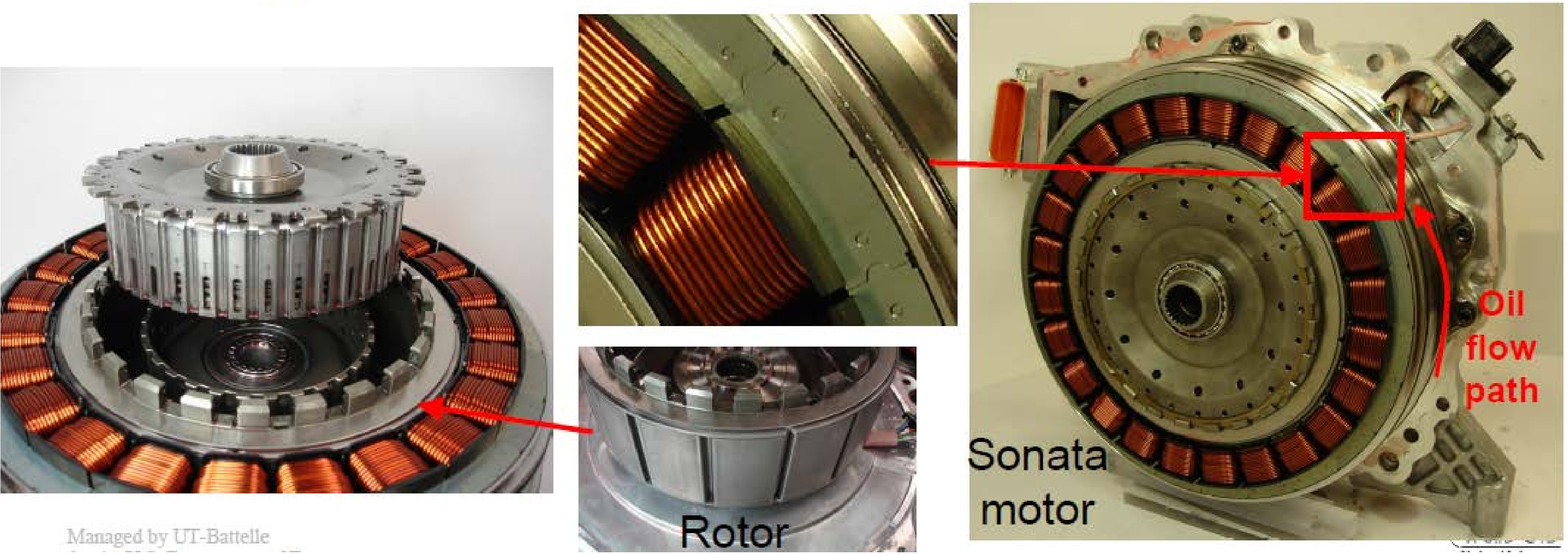


Hyundai / Sonata

- **Sonata transaxle/transmission**
  - Conventional 6 speed transmission
  - Motor replaces torque converter
    - But not simply interchanged
  - Primary motor: 205 Nm and 30 kW ratings
    - Approximate corner speed: 1400 rpm
    - Motor very similar to Honda hybrids
    - 24 stator teeth and 16 rotor poles
  - Resolver similar to Toyota/Honda
  - 3-phase oil pump
  - Clutch integrated into motor rotor
  - Oil cooling path around stator



- Radial Flux PM Motor



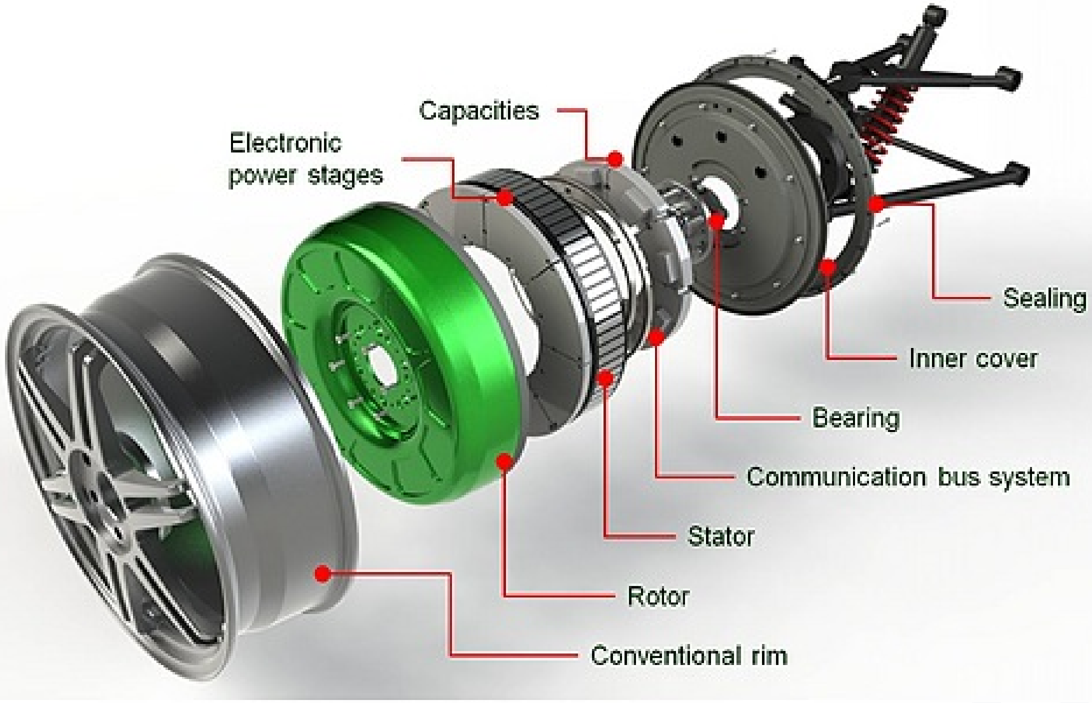
Source: ORNL, US DE report 2012

EM-Motive (information in public domain)

- Joint venture Bosch – Daimler
- Dimensions and weight
  - Stator diameter 138 mm
  - Length of active parts 80 mm
  - Casing diameter 162 mm
  - Housing length 185 mm
  - Weight 14 kg
- Performance
  - Operating voltage max. 300 V
  - Mechanical Power max. 20 kW
  - Torque max. 55 Nm
  - Speed max. 18,000 1/min

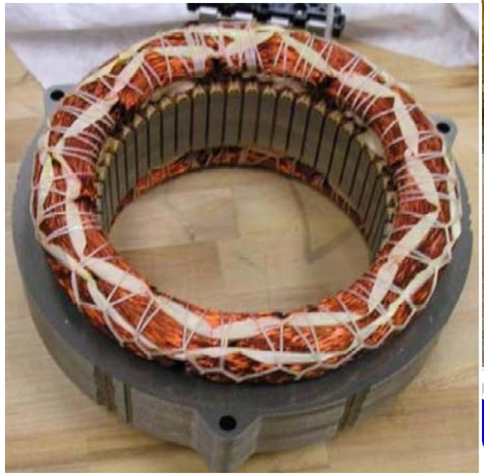
Protean Electric – In Wheel Motor

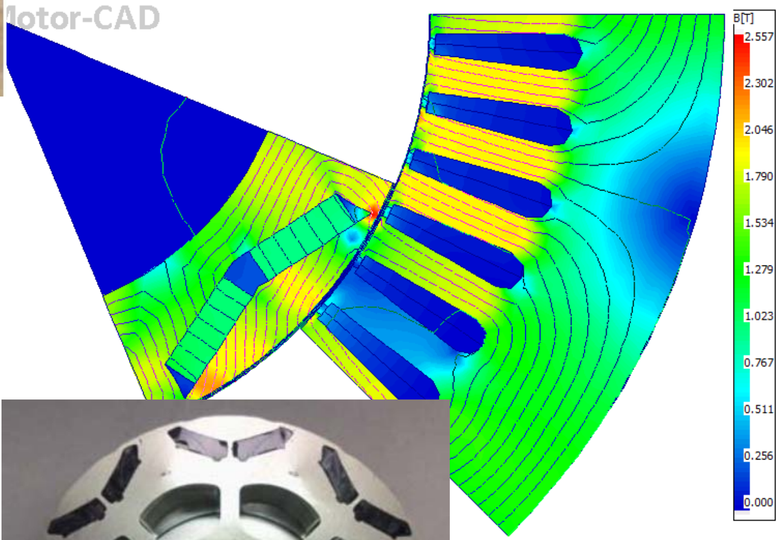
- Direct drive solution
- Outer-rotor BPM motor
- 75kW Peak, 54kW Cont.
- 420mm OD, 115mm long
- Each motor is controlled independently
- Retrofit possible
- Mahle PHEV shown

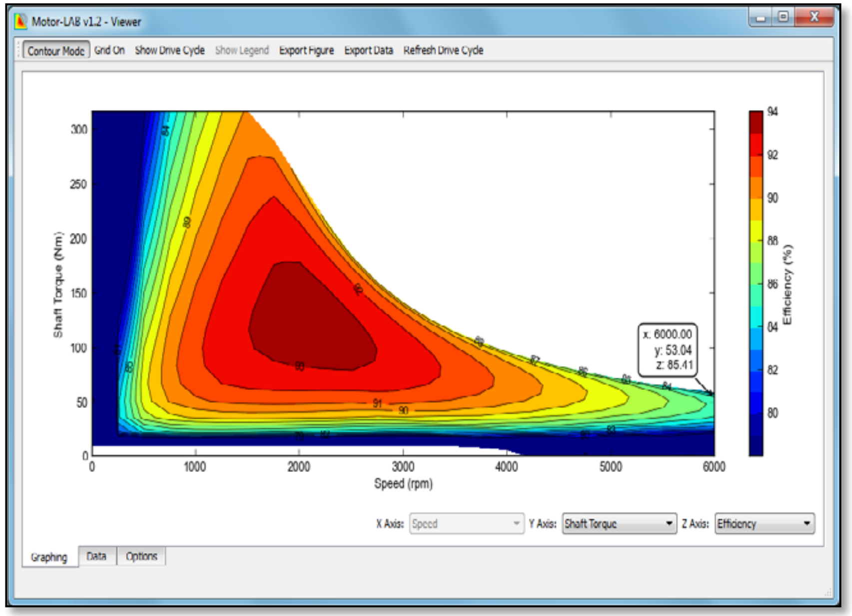


Toyota PRIUS

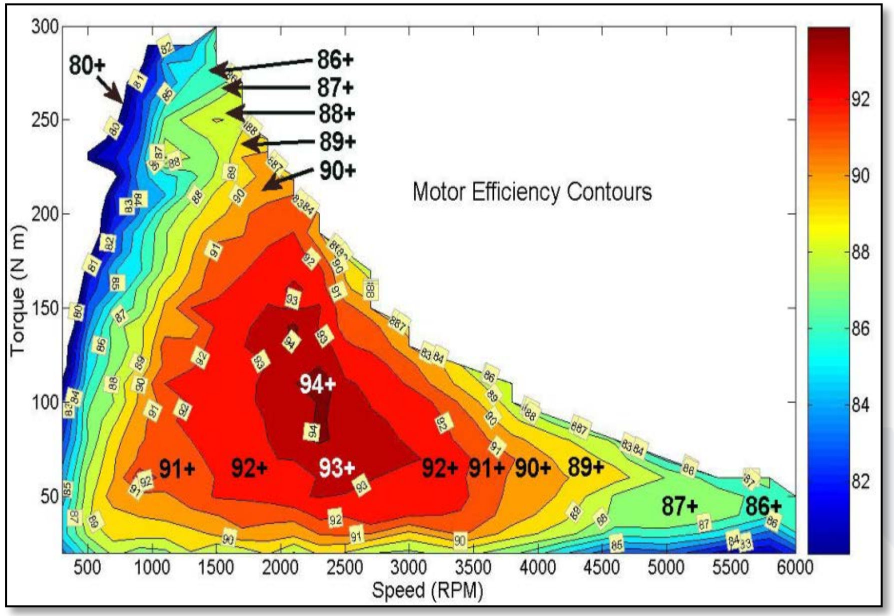
- Validation based on Toyota 2004 Prius test data from ORNL published at between 2004 -2012







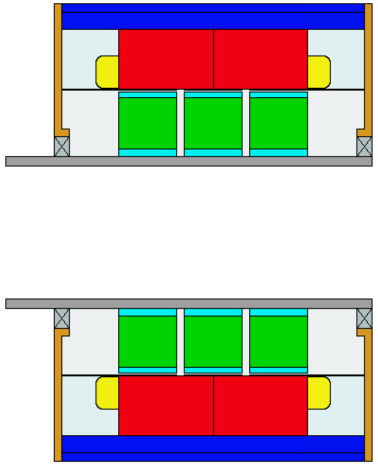
Motor-LAB Calculation

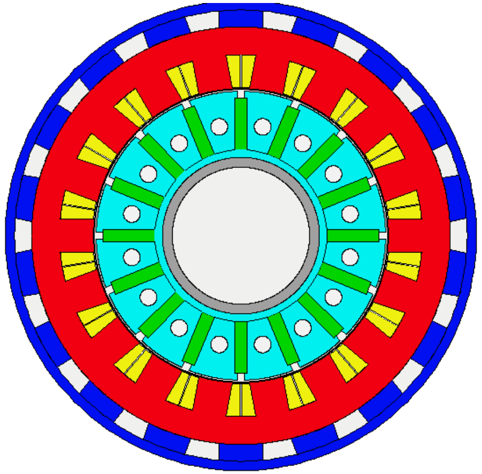


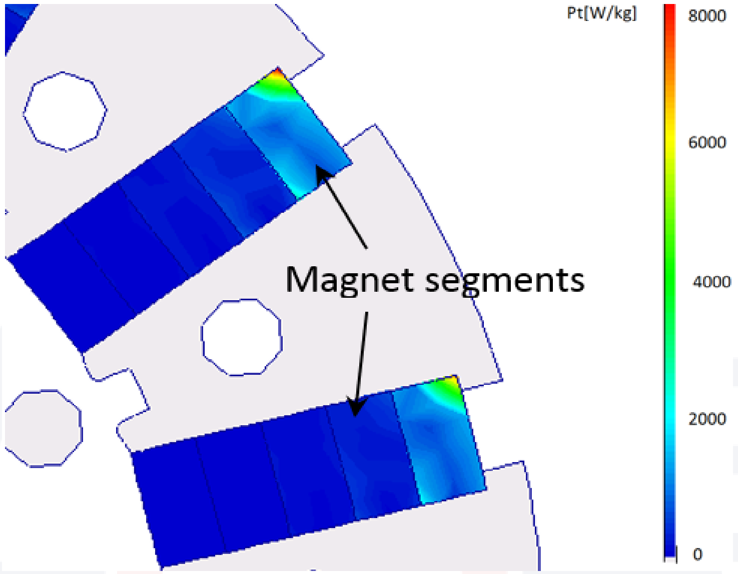
Measured Efficiency Map

High Performance Motorsport Motor

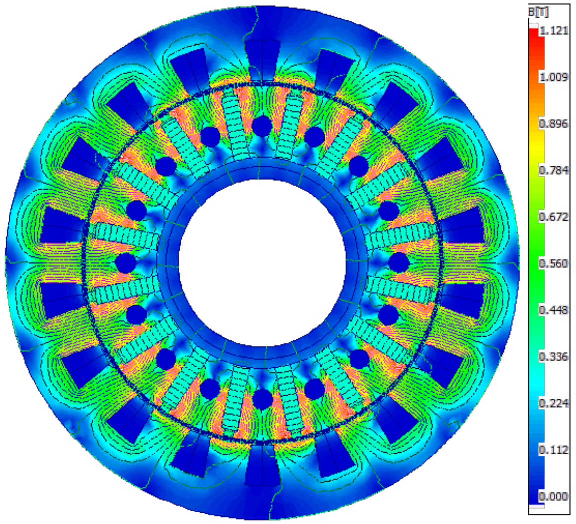
➢High torque density motor for motorsport



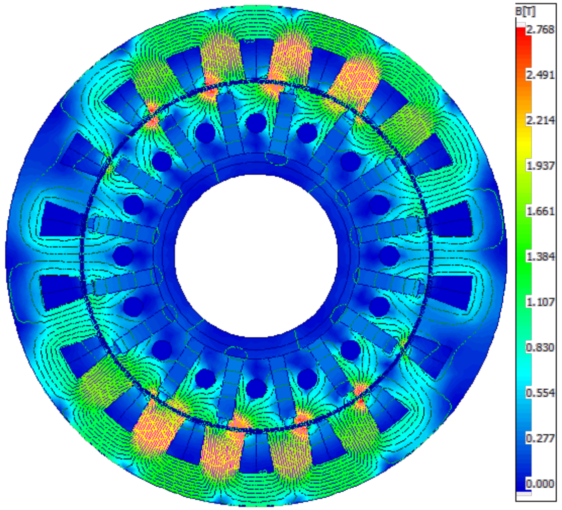




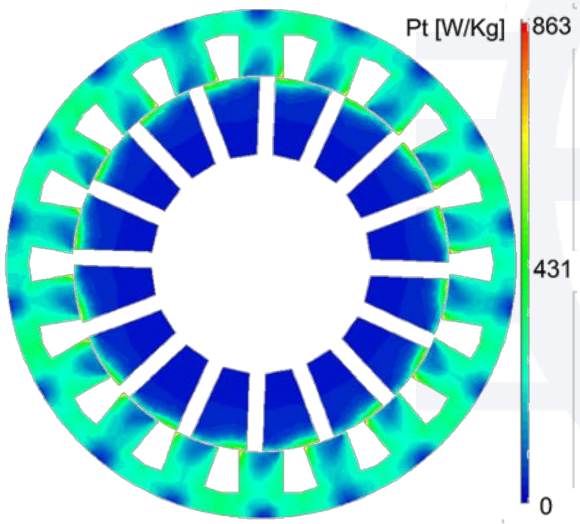
Magnet Loss (Over One Cycle)



Open Circuit



On-Load



Iron Loss (On-Load)

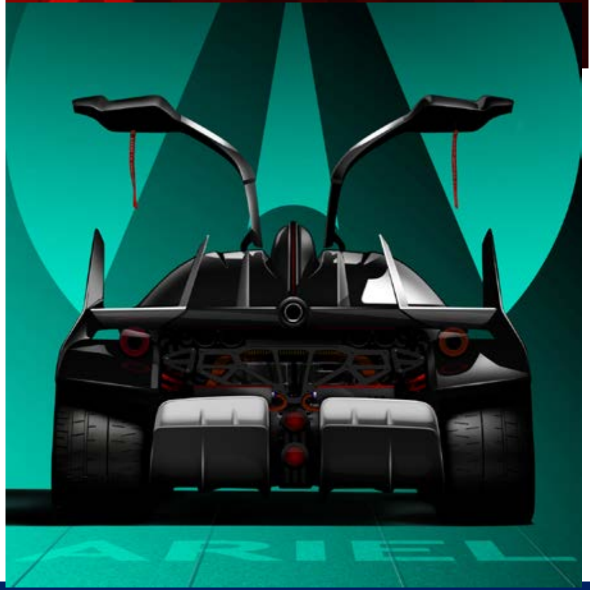
Equipmake

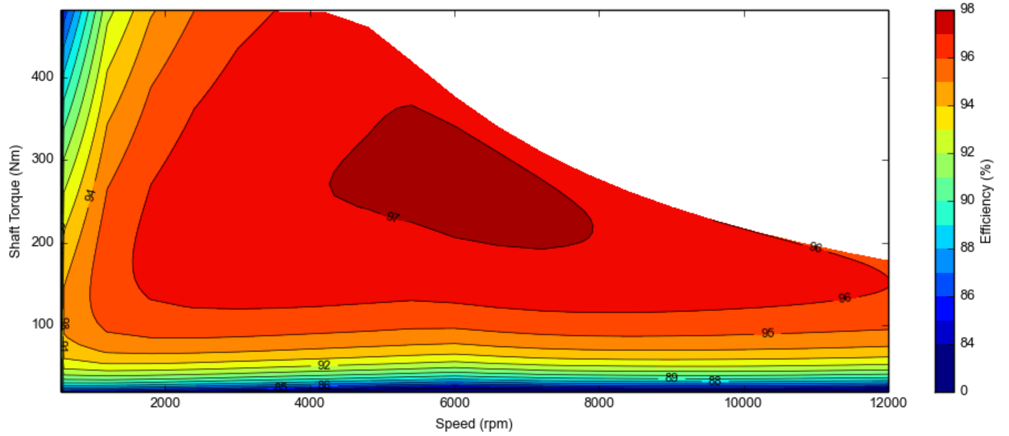
High Performance Motorsport Motor

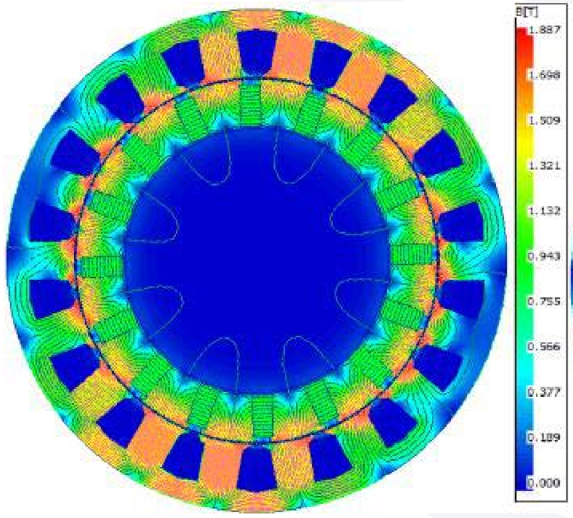
Equipmake

Motor Design Limited

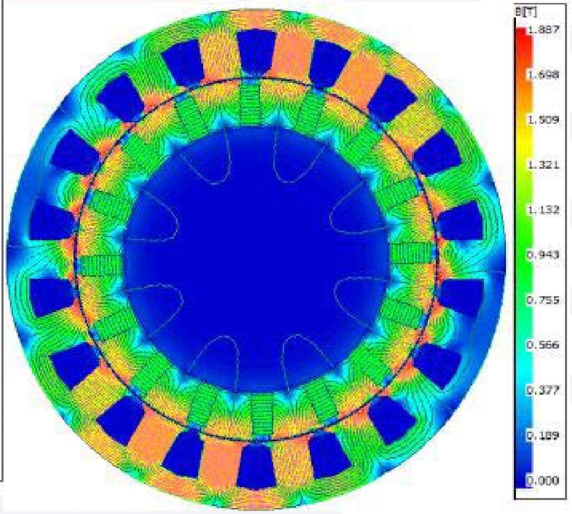
- High torque density motor for Motorsport
- Used in Ariel Hipercar







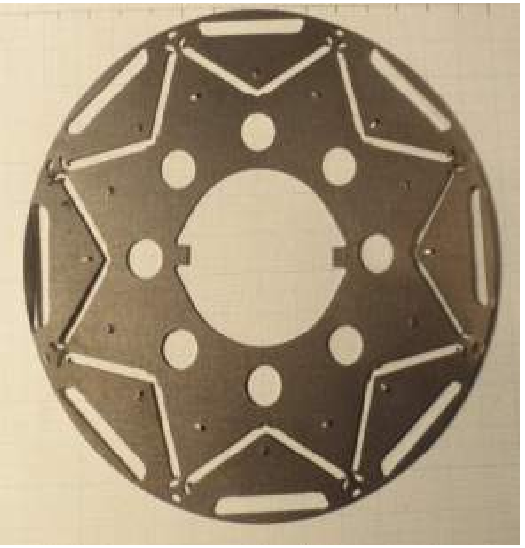
Open Circuit

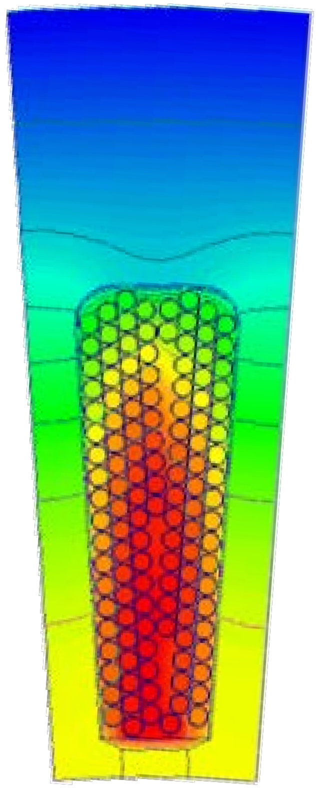


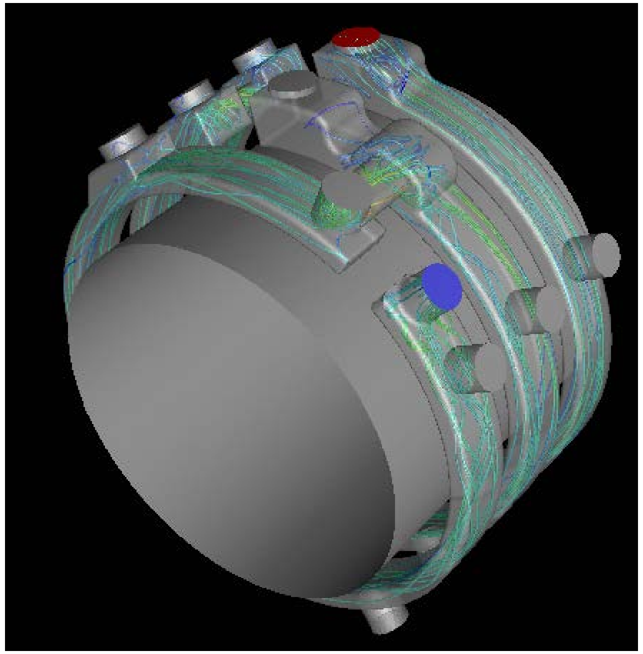
On-Load

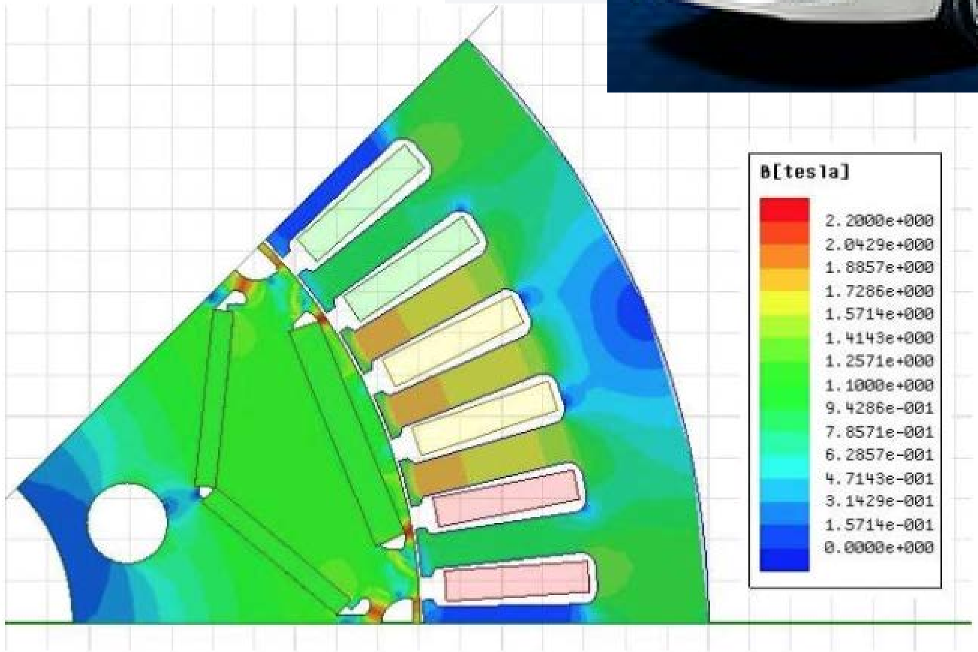
Nissan LEAF

- All electric BEV
- 124 mile range
- 80kW IPM Motor



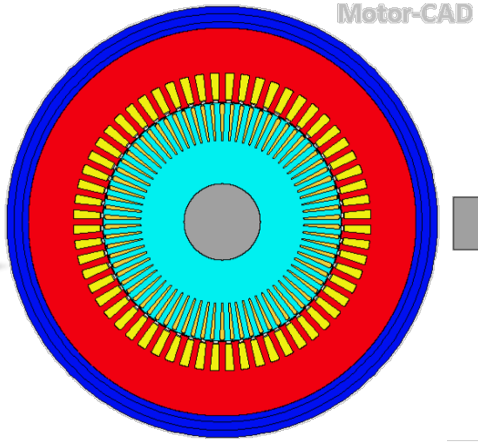


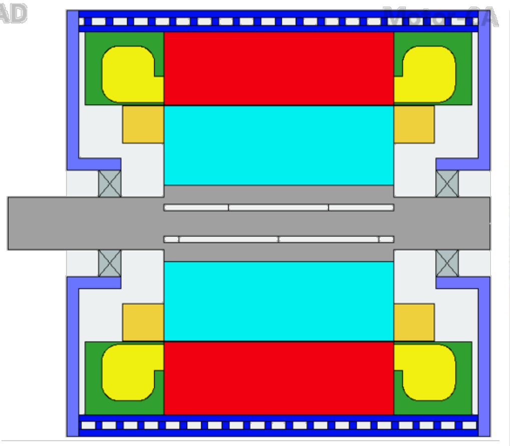


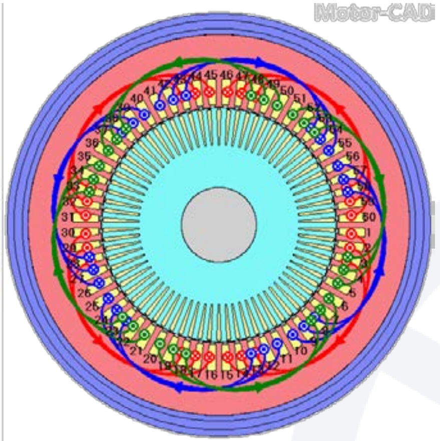


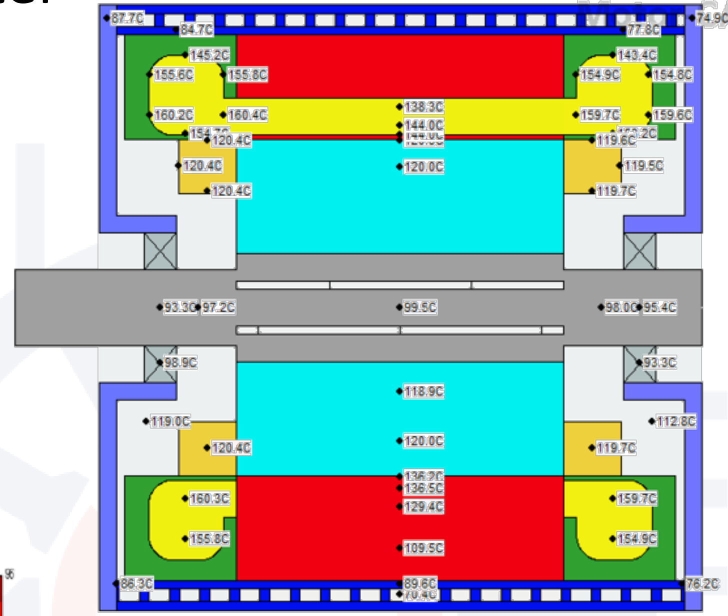
TESLA Model S

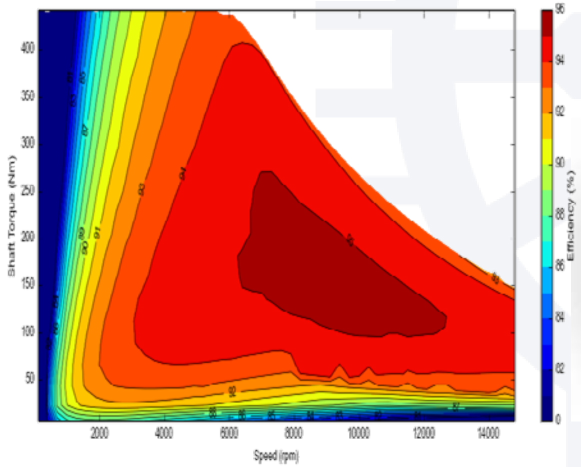
- Data from teardown analysis of the Tesla Model S electric motor
- Copper rotor induction motor with potted end windings and water cooled stator and rotor

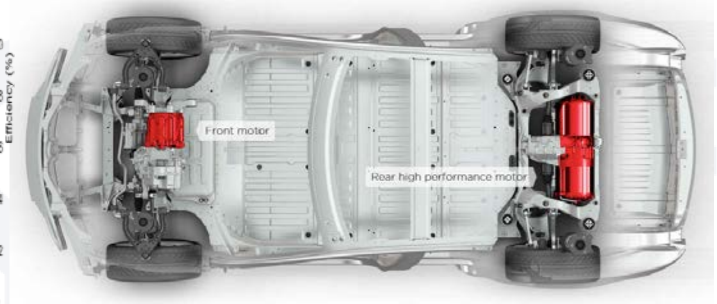












Summary

- Electrification is driving forward the development of innovative designs for electrical machines
- Automotive HEV more dynamic and easier to implement – mass production in most OEMs by 2020-2030
- Aerospace more restrictive due to technology risks (battery limitation) and market demands.
- Traction, power generation and auxiliaries in aerospace, automotive are possible applications
- Mainly permanent magnet technology is currently developed, but significant interest in induction and reluctance machines
- Copper, as best solution cost and electrical conductivity is part of design process in windings with high fill factor (all) and cage rotors (induction machines only)

Joint Motor Actions ECI – proposals from MDL

- Tutorials on electrical motors and copper element at various expos and conferences
- Series of white papers on copper role in energy conversion systems
- How can we link industrial knowledge with academia curriculum? Open sessions/seminars at Universities?
- Edit a book on electrical machines with focus on copper element: windings, rotor cage, superconducting, banding; multiple authors/experts

Thank You. Questions?

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