

Preocupări actuale privind realizarea unor mașini electrice cu densitate mare de putere pentru electrificarea sistemelor de transport

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2017 – Grupul U. S. DRIVE (DOE + 13 parteneri), a publicat: "Foaia de parcurs a cercetării și inovației în domeniul tehnologiilor electrice și electronice pentru eficiența vehiculelor și a sustenabilității energetice" [1]. Pentru motoarele electrice de tracțiune sunt preconizate următoarele performanțe:

Anul	2020	2025	Schimbarea
Costul (\$/kW)	4,7	3,3	reducere de cost 30%
Densitatea de putere (kW/L)	5,7	50	reducere de volum 89%

Căile de obținere a unor valori mari ale densității de putere la mașinile electrice:

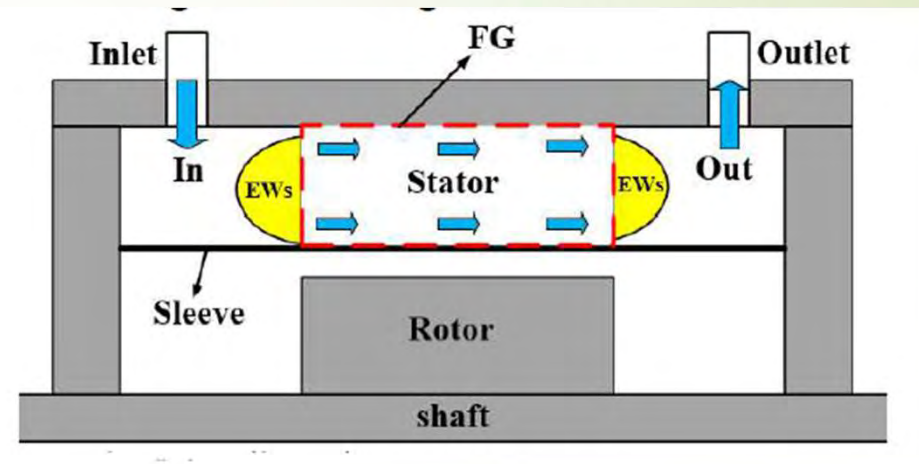
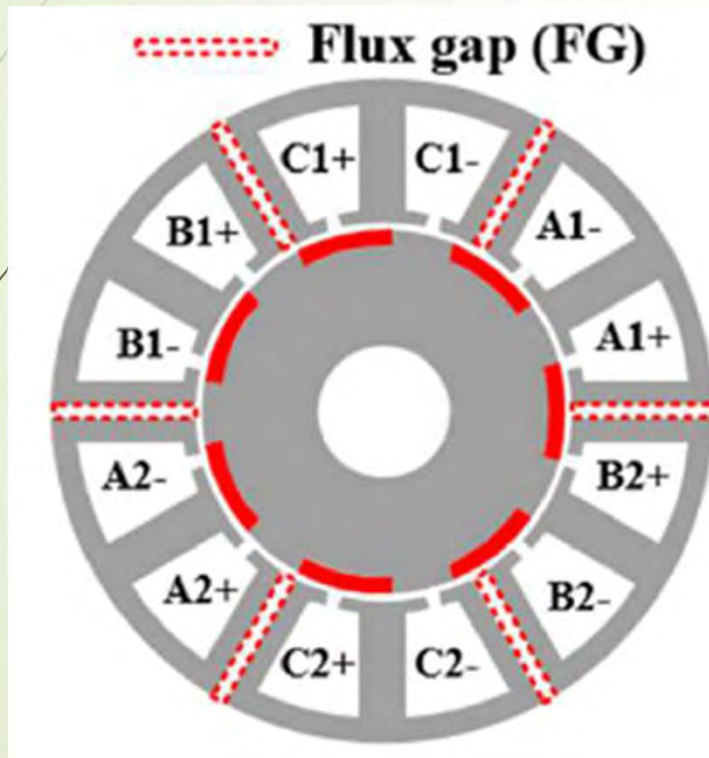
1. Efectuarea unui management termic eficient:
 - a. Răcirea creșturilor
 - b. Răcirea capetelor de bobine
 - c. Răcirea miezului statoric
 - d. Răcirea rotorului
2. Folosirea unor topologii noi de mașini electrice și a unor materiale speciale

3

Exemple de sisteme de răcire

4

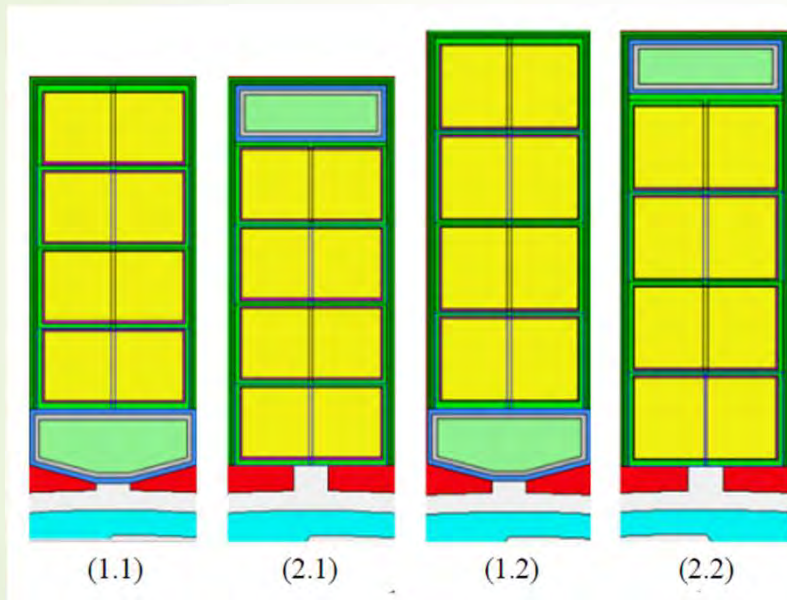
Răcirea forțată a statorului în construcție modulară, cu goluri de flux



Motor sincron cu 14 poli, și 12 creștături, cu MP consecvenți, cu stator modular, cu goluri de flux cu lățime mai mare de 2 mm, cu rol de canal pentru răcirea forțată cu ulei și manșon din fibră de carbon de 0,5 mm pentru izolarea rotorului [2].

5

Răcire forțată a statorului cu canale de apă introduse în creștături



1.1 și 2.1 – cu reducerea înălțimii conductoarelor; 1.2 și 2.2 – cu creșterea înălțimii creștăturii. (motor de 260 kW, 40 kg, 22.000 rpm, 720 V, 500 A, 190 mm/160 mm diametru/lungime activă – Jaguar XJMY21

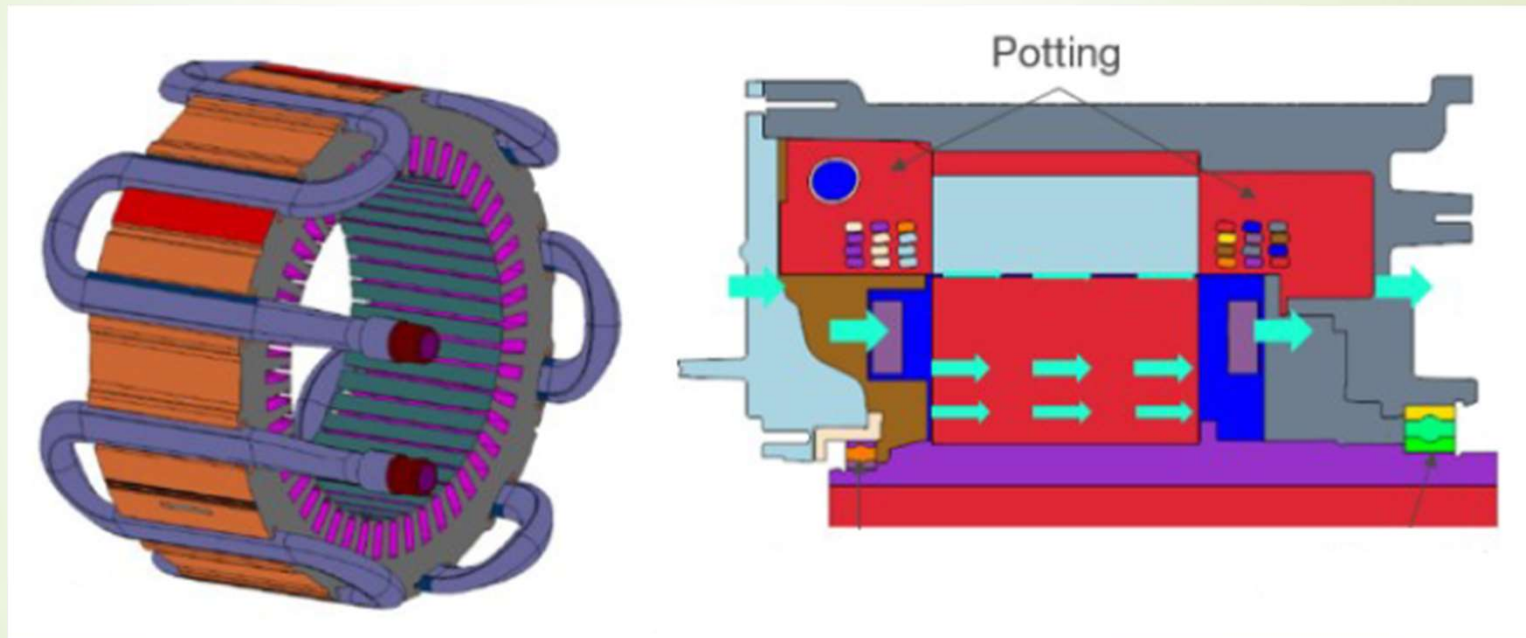
IPM				
Value	1.1	1.2	2.1	2.2
Average magnet temperature [°C]	108	110	119	124
Average winding temperature [°C]	106	109	116	121
Max. continuous torque [Nm]	123	133	111	119
Max. continuous speed [rpm]	8700	8100	7000	6600

IM				
Value	1.1	1.2	2.1	2.2
Average cage temperature [°C]	131	128	140	137
Average winding temperature [°C]	115	111	123	119
Max. continuous torque [Nm]	55	57	52	54

Concluzii: 1.1 și 1.2 plasează elementul de răcire în apropierea punctului fierbinte; 1.1 – bun pentru IMP, 1.2 – bun pentru IM. [3]

6

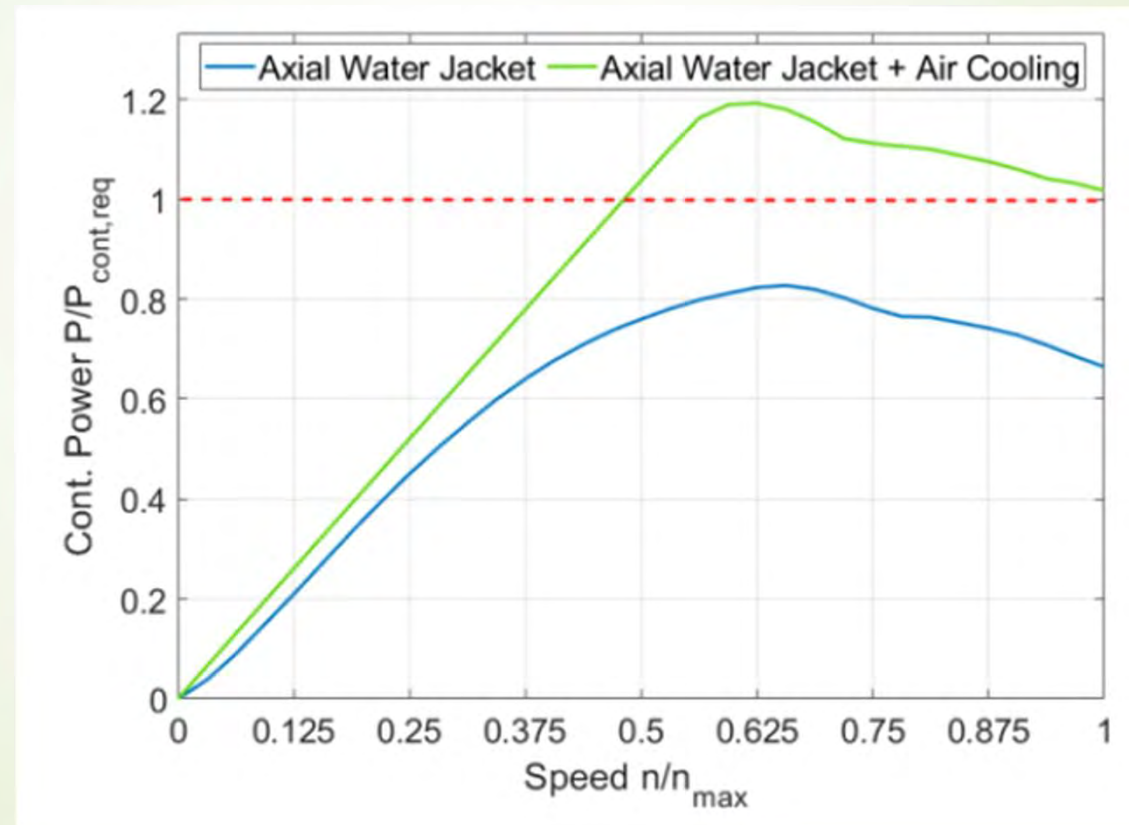
Sistem hibrid de răcire forțată cu tuburi cu apă integrate în stator și cu curenți de aer



Motor sincron cu excitație electromagnetică, [4]

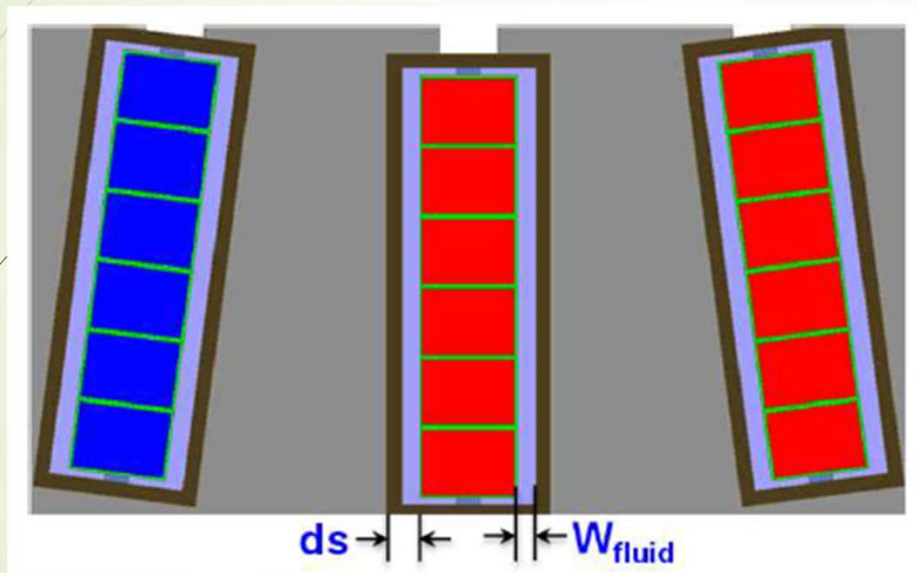
7

Sistem hibrid de răcire forțată cu tuburi cu apă integrate în stator și cu curenți de aer

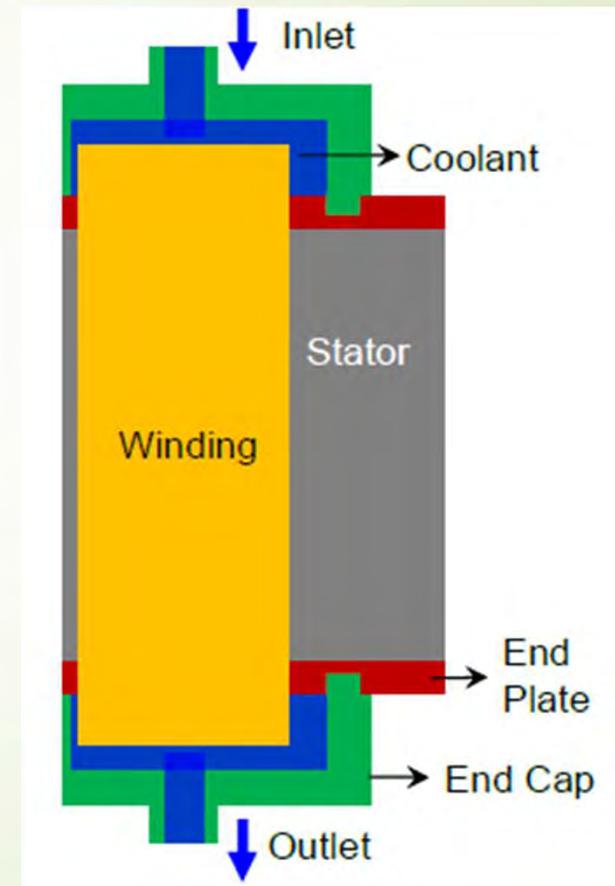


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Răcirea directă a conductoarelor din creștăturile mașinii electrice (Ford+Ohio univ.)

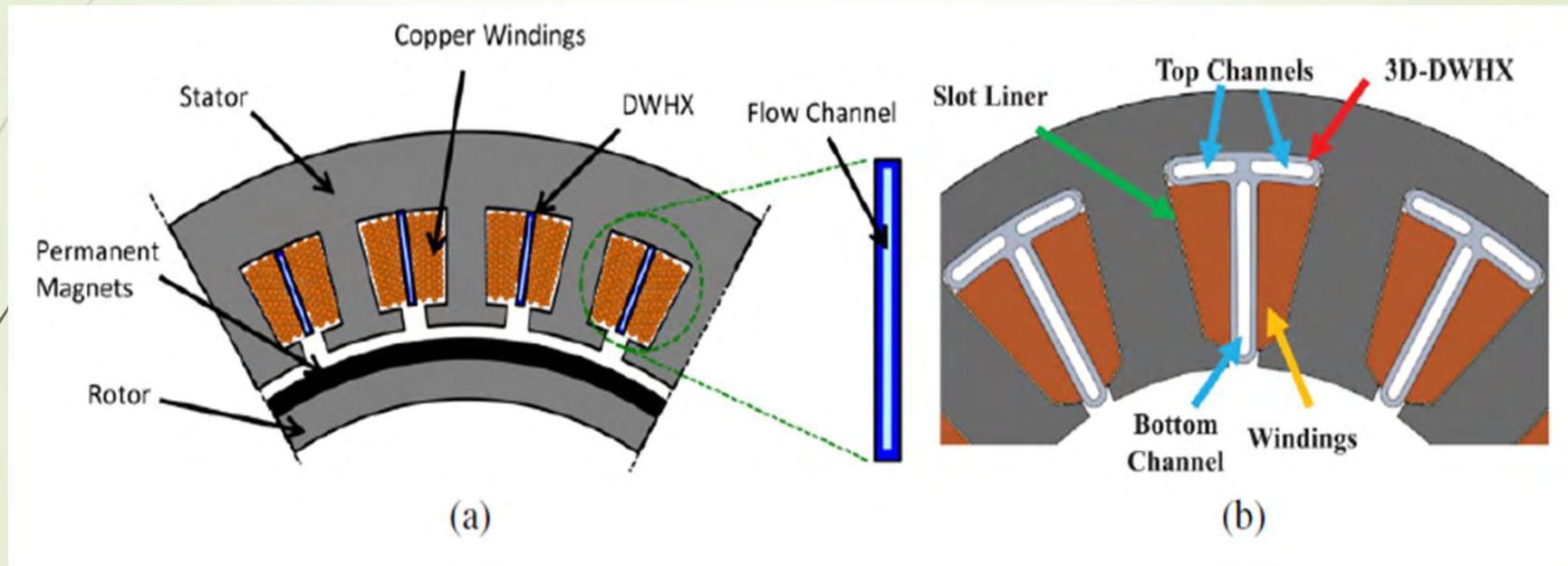


La 100 Nm și 2500 rpm, are pierderi de putere mai mici cu 6,6% și o temperatură mai mică cu 20 grade Celsius. Punctul termic apare în miezul statoric la 15.000 rpm [5].



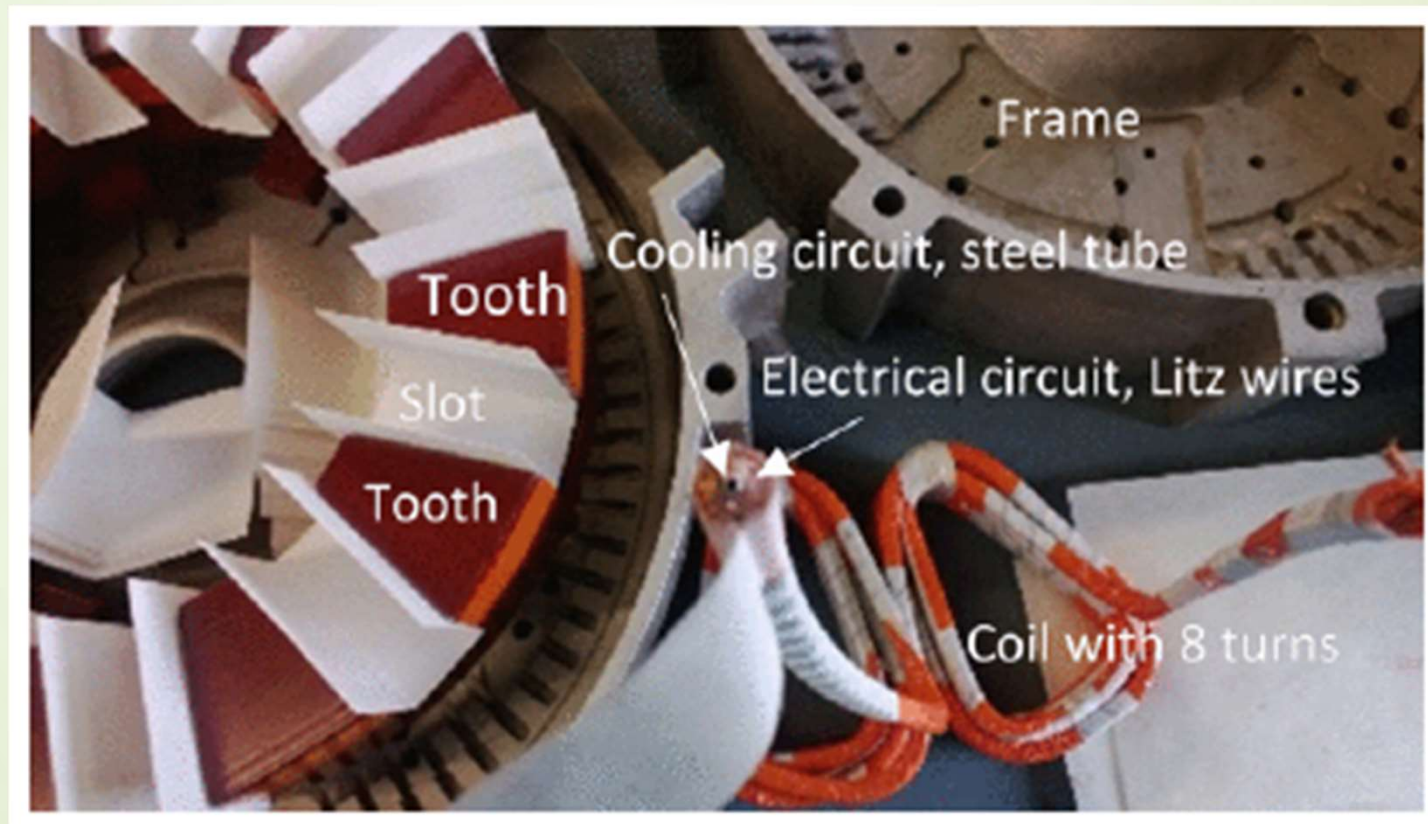
9

Metode de răcire directă a creștăturilor:
 a) cu canale 2-D; b) cu canale 3-D [6]



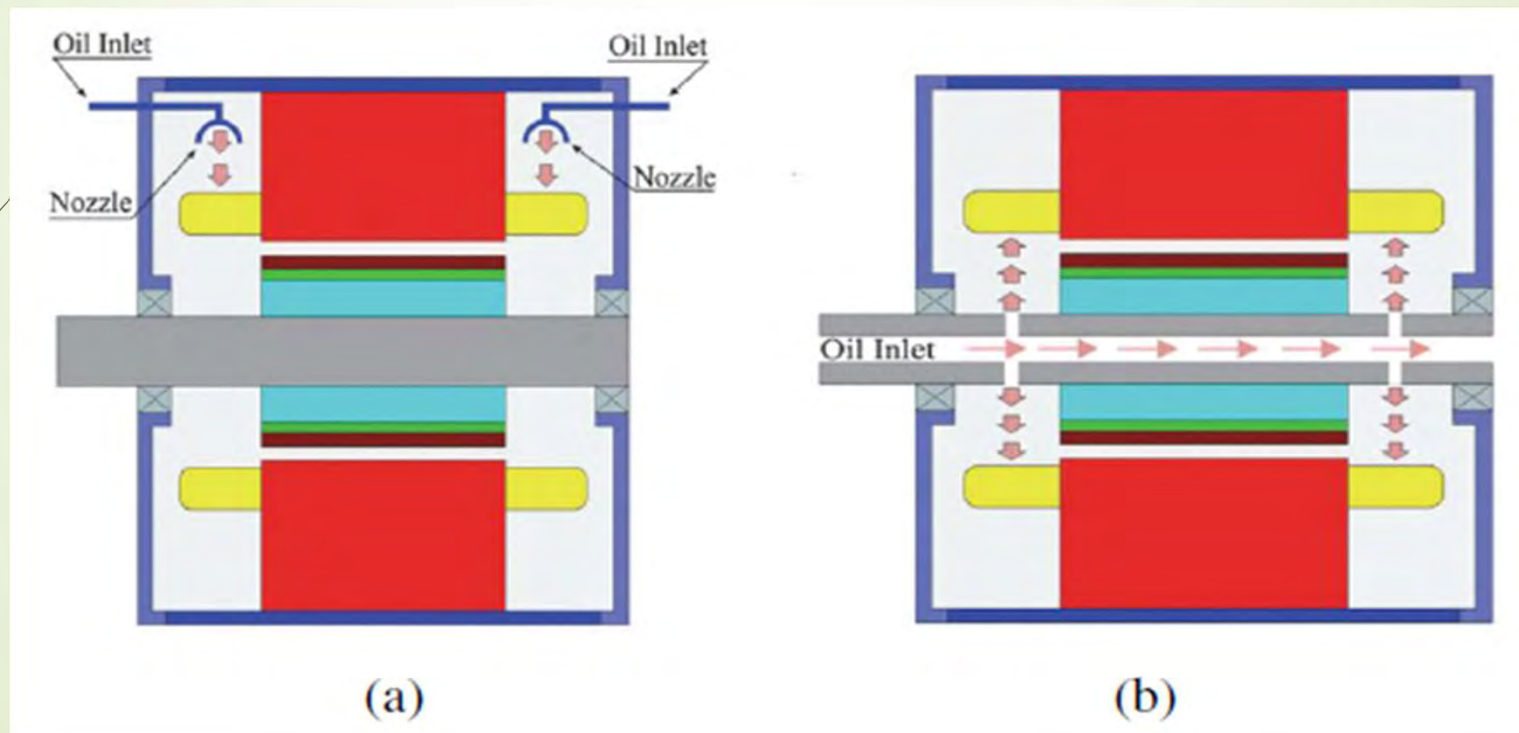
10

Metode de răcire directă a creștăturilor: cablu Litz cu tub de răcire [6]



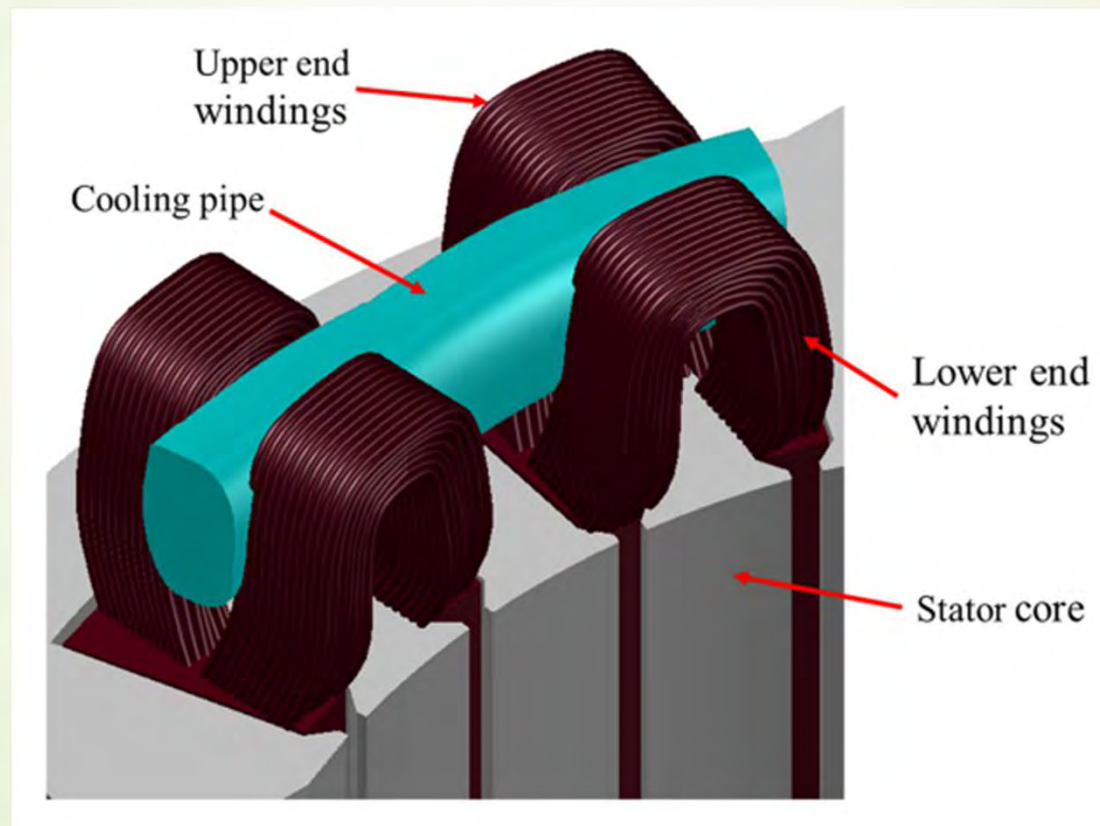
11

Metode de răcire a capetelor de bobine:
a) stropire cu duză; b) stropire prin arbore tubular [6].



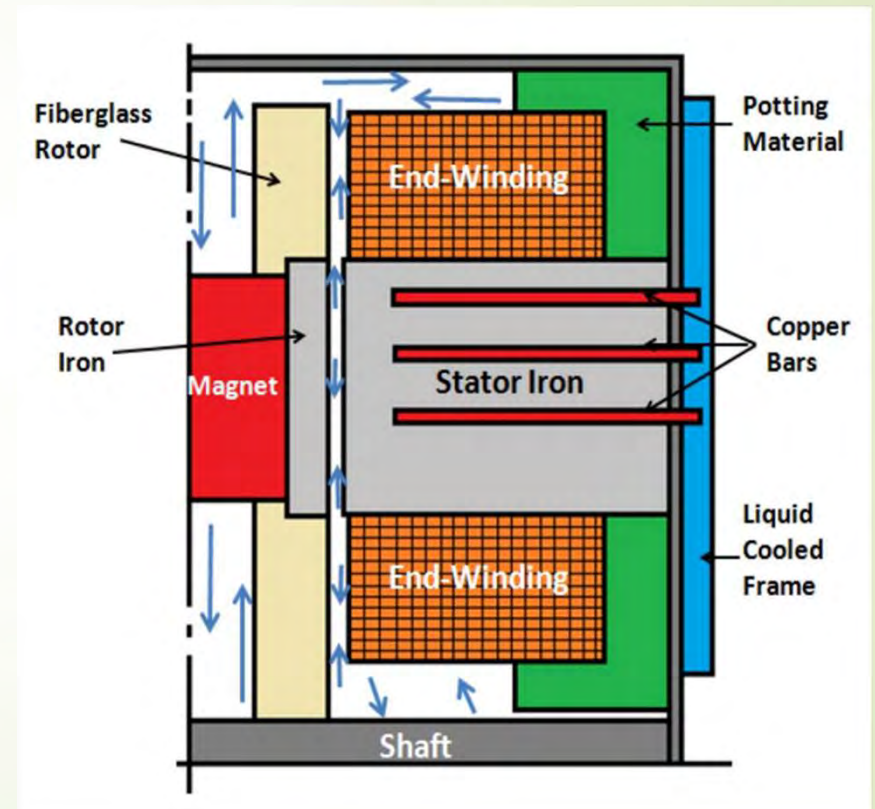
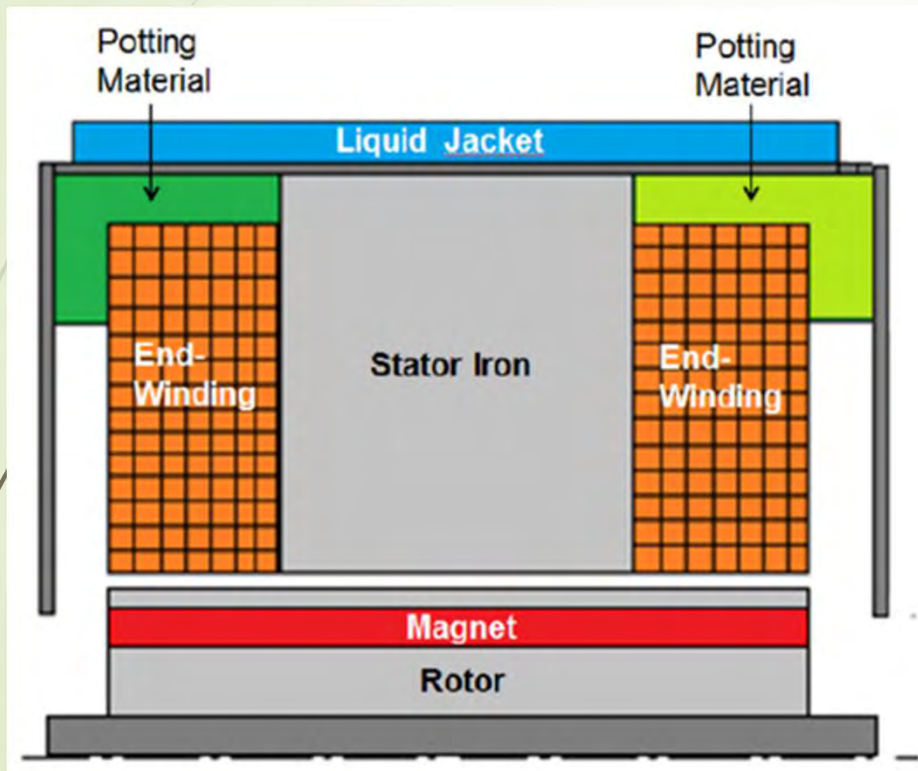
12

Metode de răcire a capetelor de bobine: cu conducte de căldură (cooling pipe) [6.a].



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Metode de răcire a capetelor de bobine: cu cămașă de apă, manșon termoconductor și bare de cupru [6]



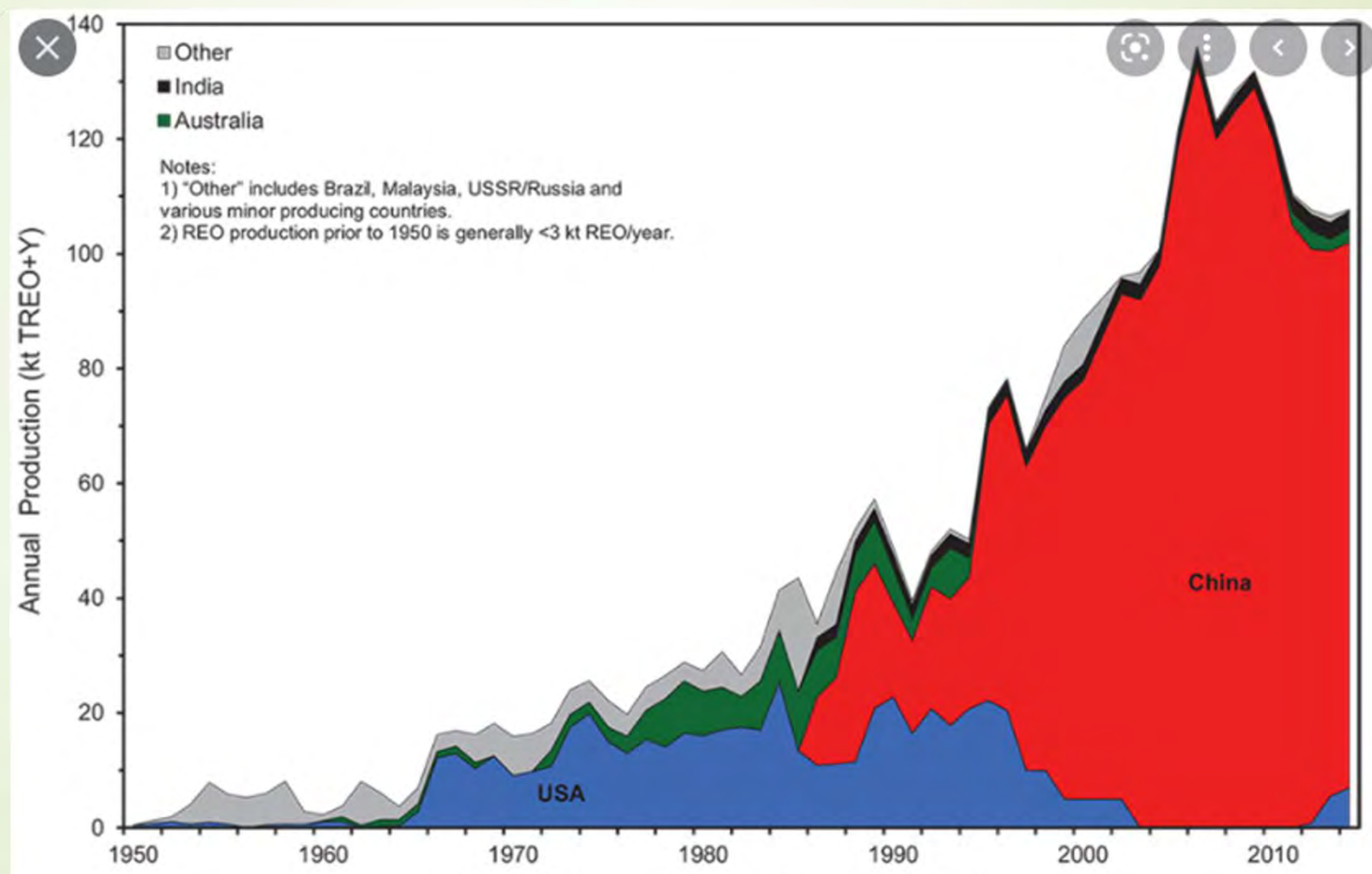
14

Mașini cu magneți permanenți cu cost redus

Cu magneți din ferită și cu NeFeB dar fără pământuri rare grele (Dysprosium / Terbium)

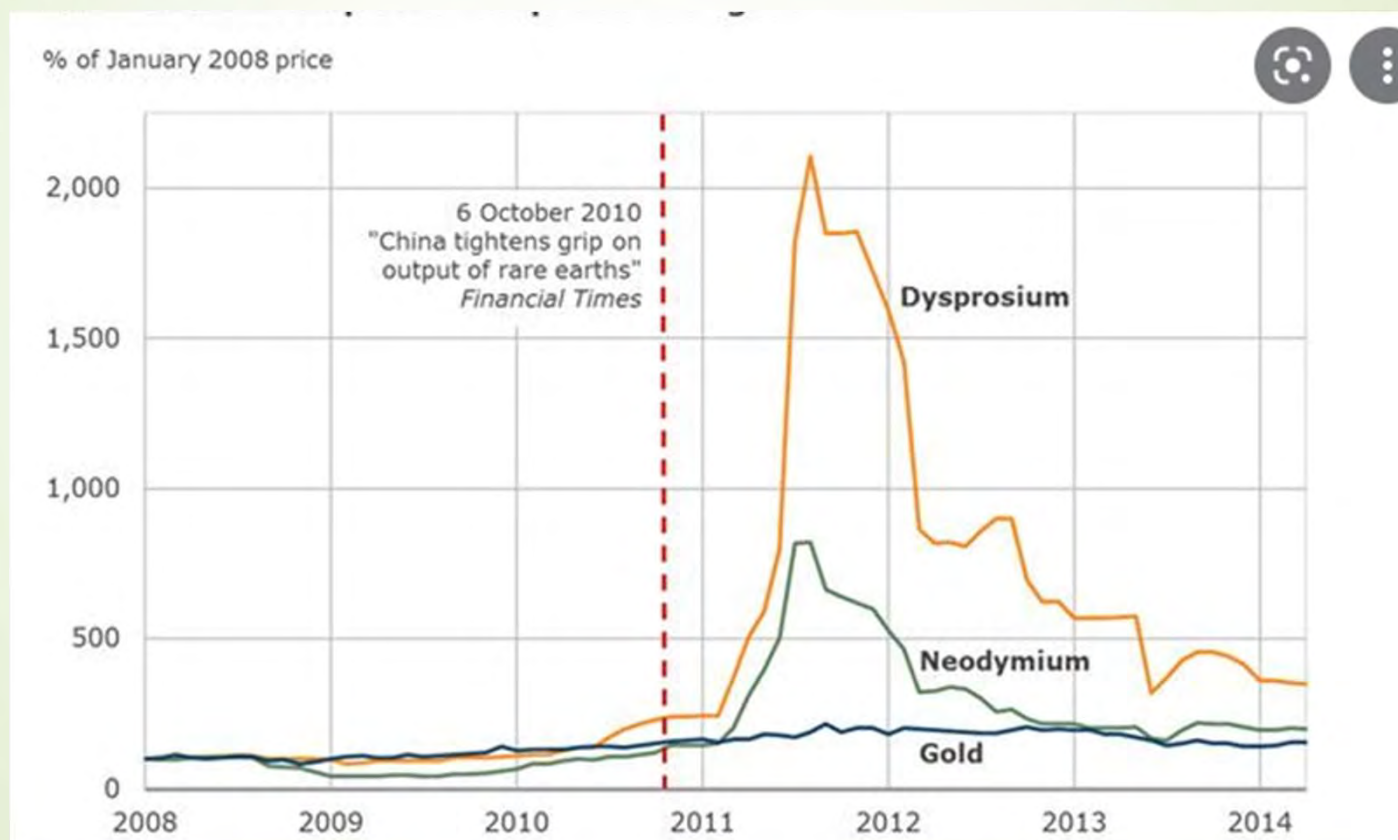
15

Producția anuală de Neodim, în ktone



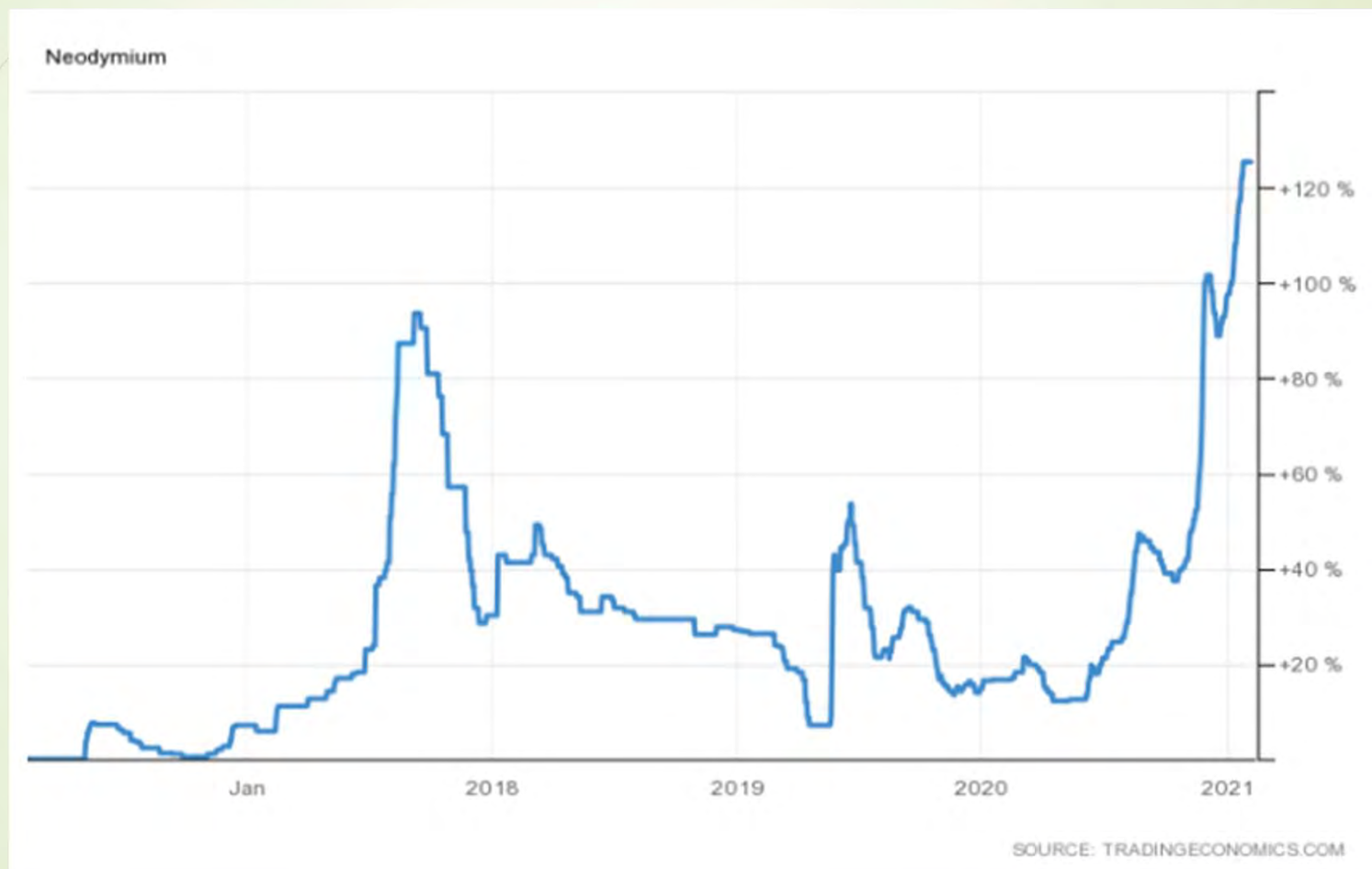
16

Evoluția prețurilor aurului, neodimului și disprosiului, în % față de ianuarie 2008



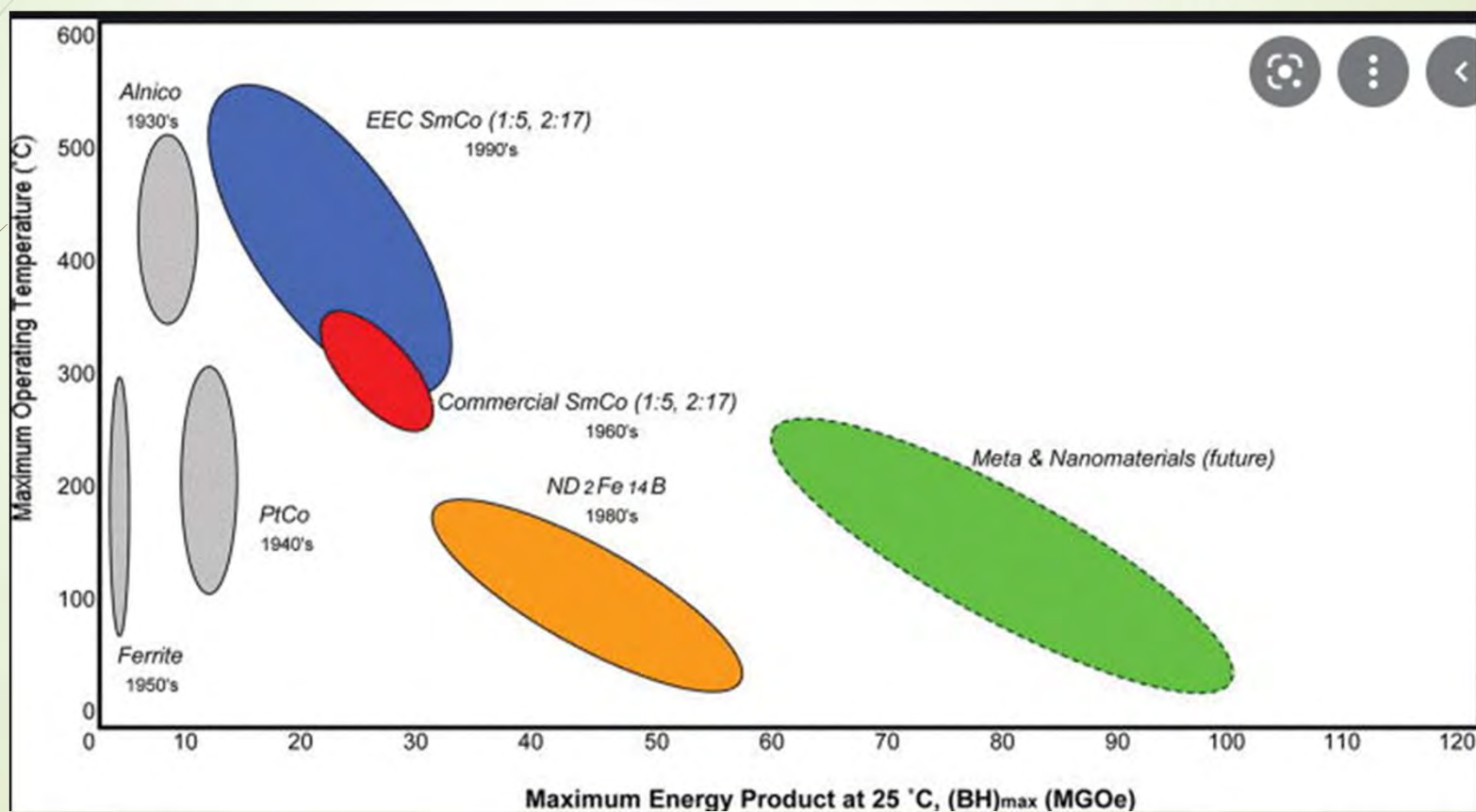
17

Evoluția recentă a niodimului

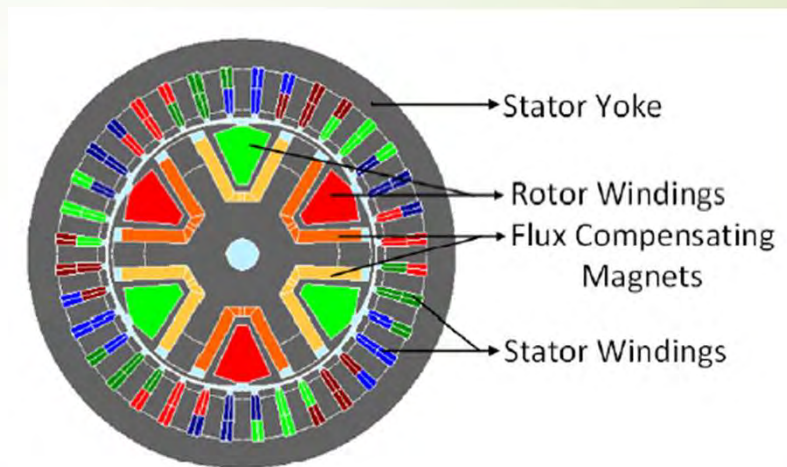
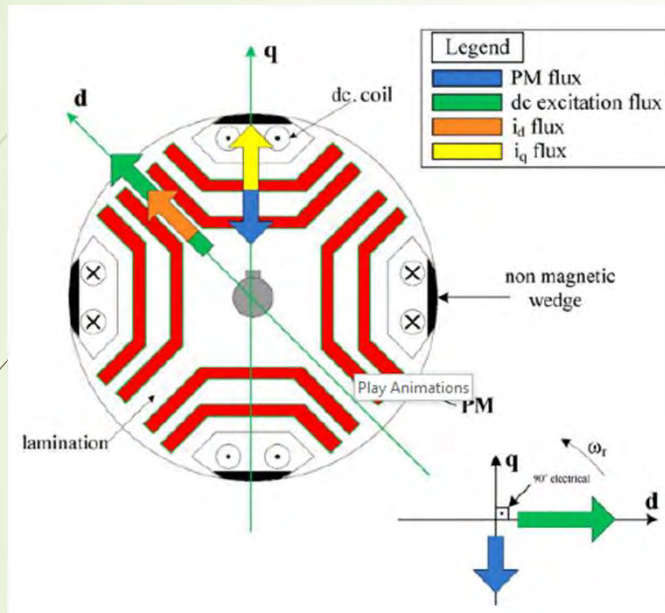


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Energii maxime și temperaturi maxime de funcționare pentru diferiți magneți



Motor sincron cu excitație bi-axială [7]



MOTOR DESIGN SPECIFICATIONS

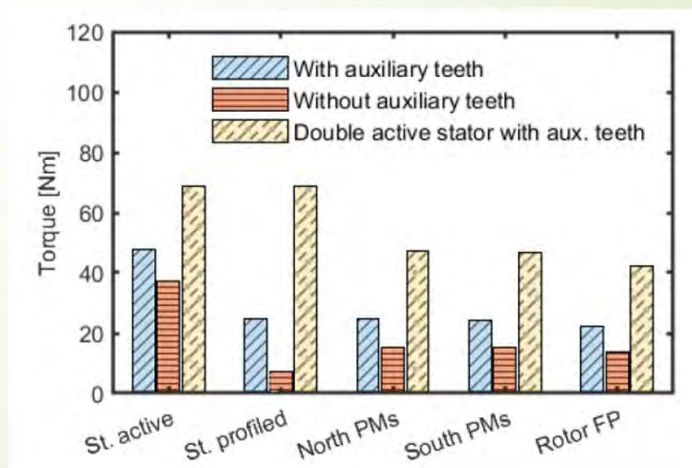
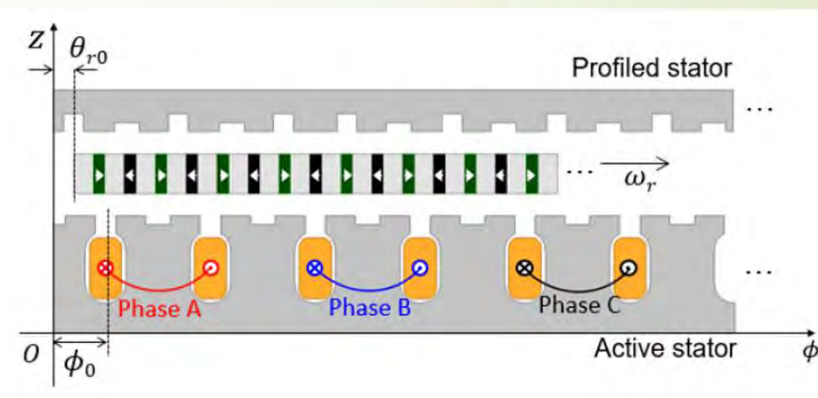
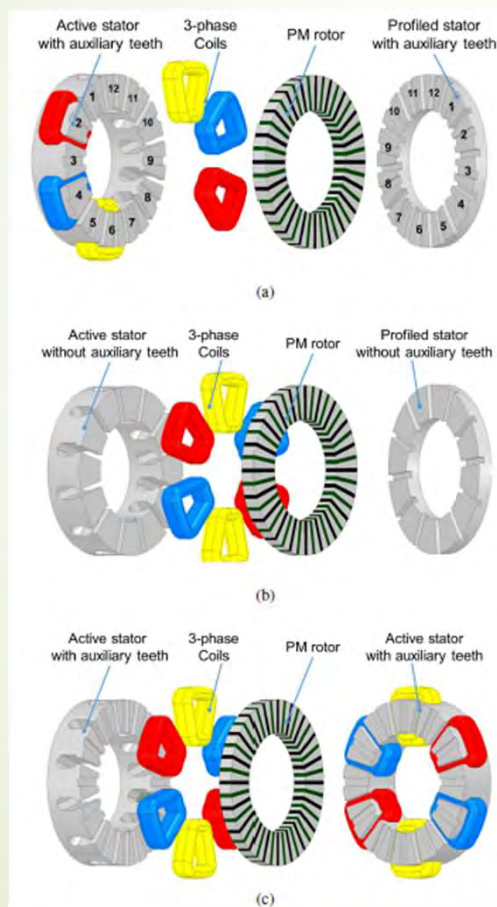
Specification	Value
Peak Power	100 kW
Base Speed	6670 rpm
Peak Torque	143 Nm
Stack Length	80 mm
Stator OD	270 mm
Pole Number	6
Stator Current Density	$\leq 20 A/mm^2$
Rotor Current Density	$\leq 8 A/mm^2$

BEGA (Bi-axial excitation generator for automobile)
 BEGA cu MP din ferită, ($\cos \phi = 0,89$) – costul motor+invertor redus cu 13% față de motorul cu reluctanță asistat cu MP din ferită și MS cu bobine de excitație, BEGA cu MP din NdFeB are $\cos \phi = 0,99$. La viteze mari, eficiența BEGA excede pe cea a motoarelor sincrone cu MP interiori uzuale.

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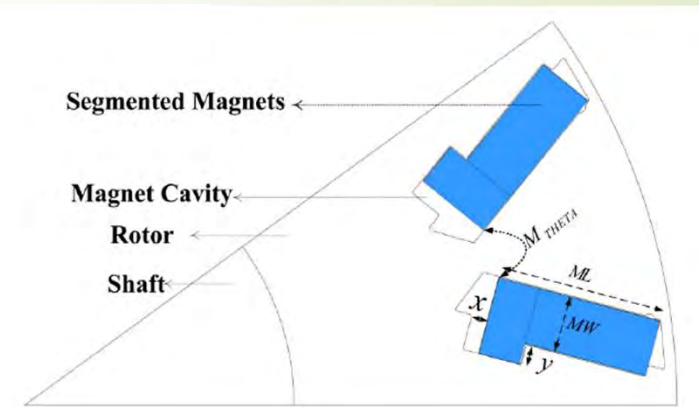
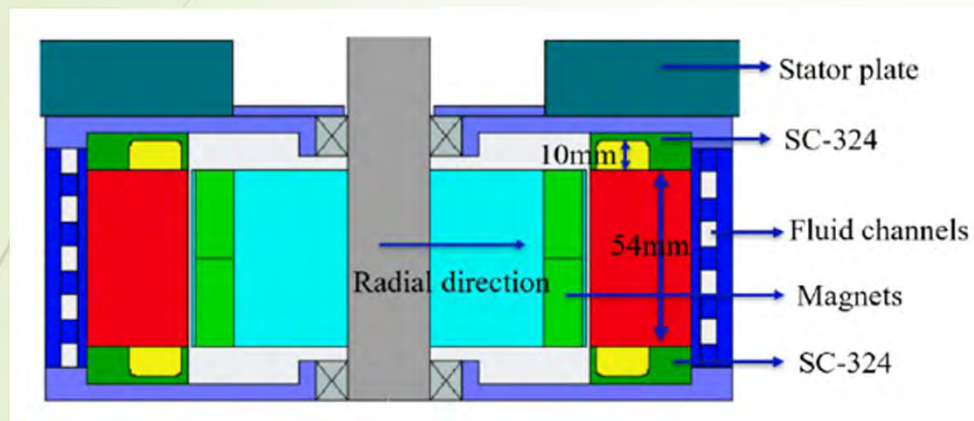
Motor sincron cu MP, cu flux axial și reducere magnetică de turație, cu 40 poli - MAGNUS [8]

Cei doi dinti auxiliari realizati pe polii statorici au marit cu 60% cuplul



21

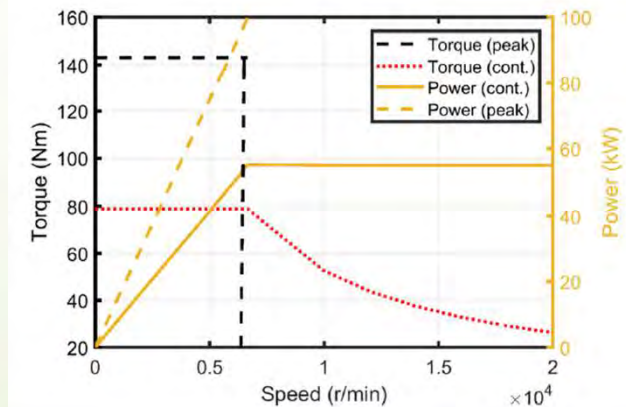
Motor sincron fără pământuri rare grele (Dy / Tb), cu densitatea de putere de 50 kW/litru [9].



- 24 crestături,
- 10 poli,
- 2 kHz
- SC – manșon conductor termic

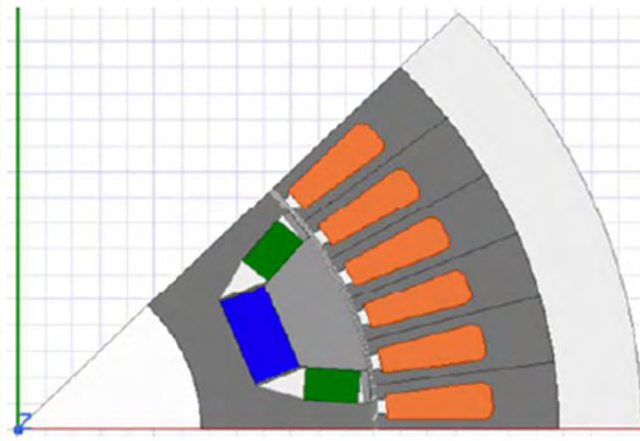
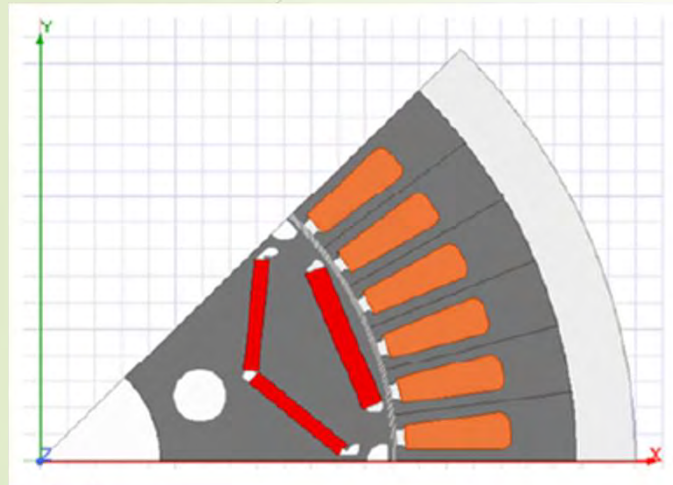
DESIGN SPECIFICATIONS

Parameters	Values
Outer diameter (mm)	185
Active length (mm)	54
Rotor outer diameter (mm)	121
Magnet B_r (T)	1.27 @ 65 °C
Lamination (0.15mm)	Hiperco
Turns, wire in hand, AWG	10, 10, 22.50



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Eliminarea pământurilor rare grele pentru motoarele de tracțiune cu densitate mare de putere [10].



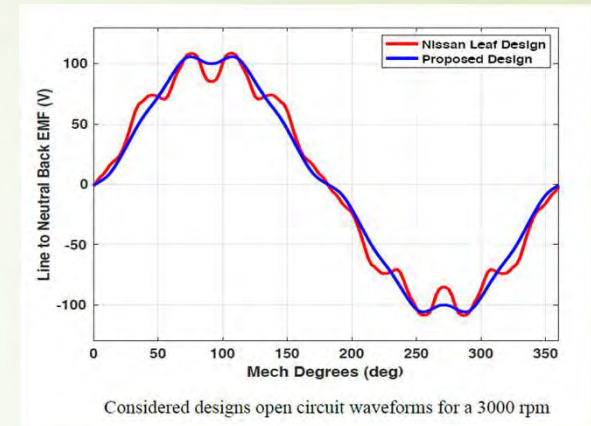
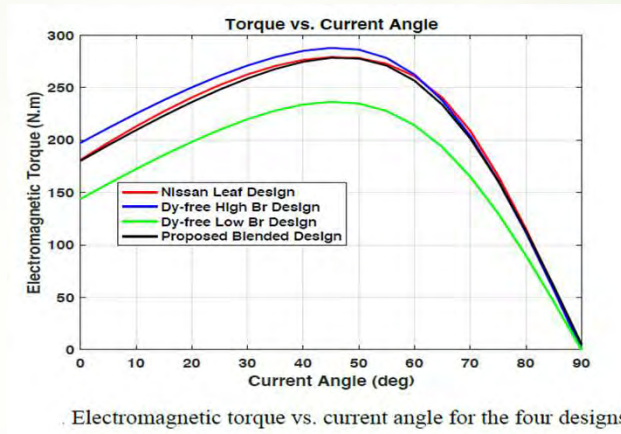
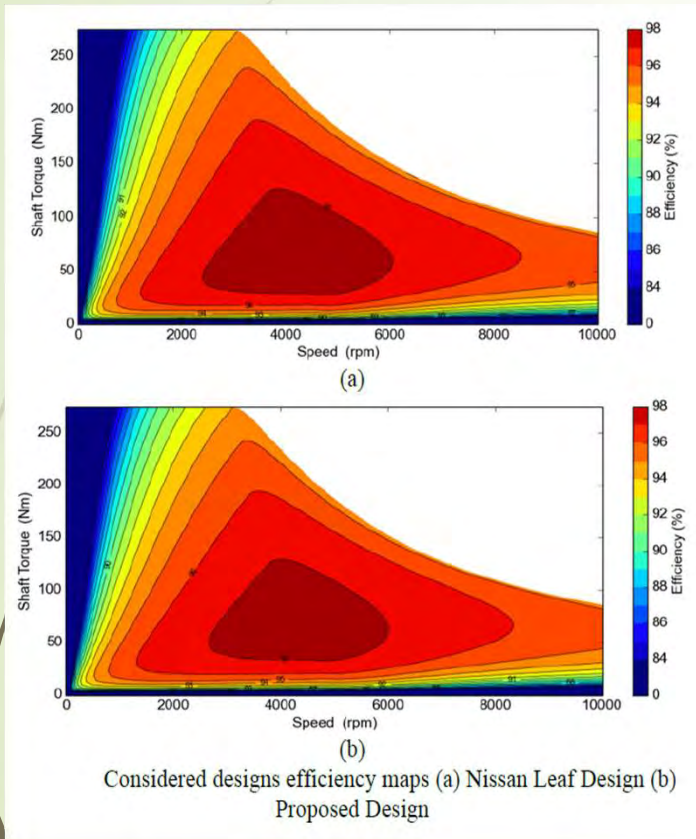
BASELINE DESIGN SPECIFICATIONS

Item and Unit	Value
Outer Rotor Radius (mm)	65
Outer Stator Radius (mm)	99
Stack Length (mm)	150
PM Mass (kg)	1.94
Motor Rated Torque (N.m)	280
Rated Mechanical Power (kW)	80
Corner Speed (rpm)	2750
Maximum Speed (rpm)	10400
Motor Rated Current (Arms)	339.5
DC Bus Voltage (V)	375
Turns/coil (Turns)	6
Windings Parallel Path Number	2

MAGNETIC PROPERTIES FOR VARIOUS PM TYPES AT 140°C

PM Type	Commercial Name	B_r (Tesla)	H_c (kAmp/m)	B_{demag} (Tesla)	Mass Density (kg/m ³)	Assumed Price (\$/kg)
Dy-NdFeB	Arnold Magnetics N30UH	0.95	-730	-0.1	7650	100
Dy-free high B_r NdFeB	TDK NEOREC45MHF	1.18	-638	0.37	7650	80
Dy-free low B_r NdFeB	Molycorp Magnequench MQ2-12-14	0.69	-720	-0.38	7650	15

Eliminarea pământurilor rare grele pentru motoarele de tracțiune cu densitate mare de putere [10].



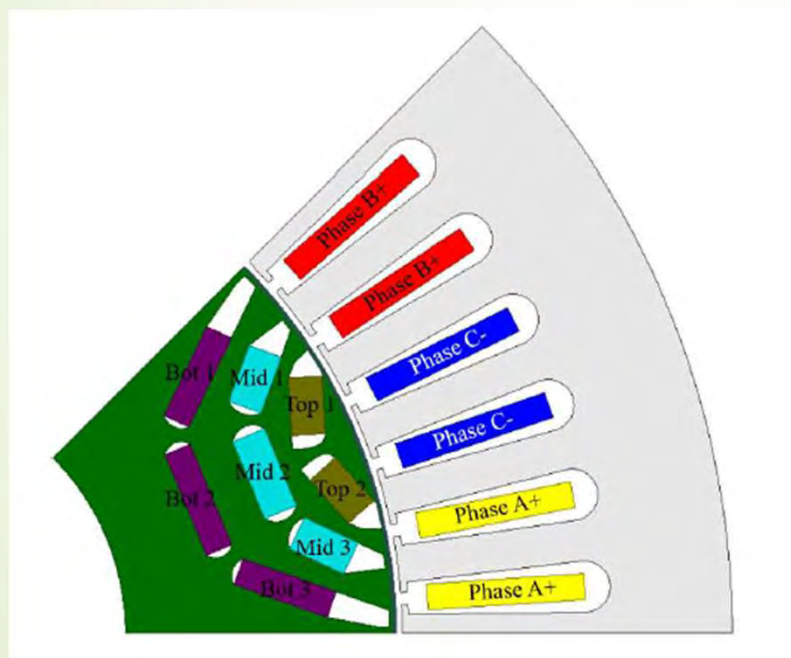
ELECTROMAGNETIC TORQUE AND TORQUE RIPPLE

Item	Nissan Leaf Design	Proposed Design
Electromagnetic torque (N.m)	274	273.6
Peak-to-peak torque ripple (%)	9.78	8.21

PM MASS FOR VARIOUS DESIGNS

Design	PM Type/Price (\$)	Torque/ PM price
Nissan Leaf	N30UH /194	1.44
Proposed Design	NEOREC45MHF/108 MQ2-12-14/ 17.25	2.22

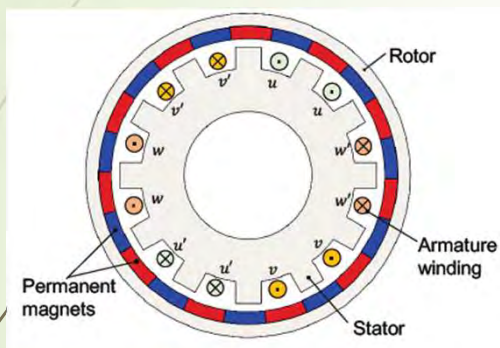
Motor sincron cu reluctanță asistat cu un grup hibrid de magneți permanenți [11].



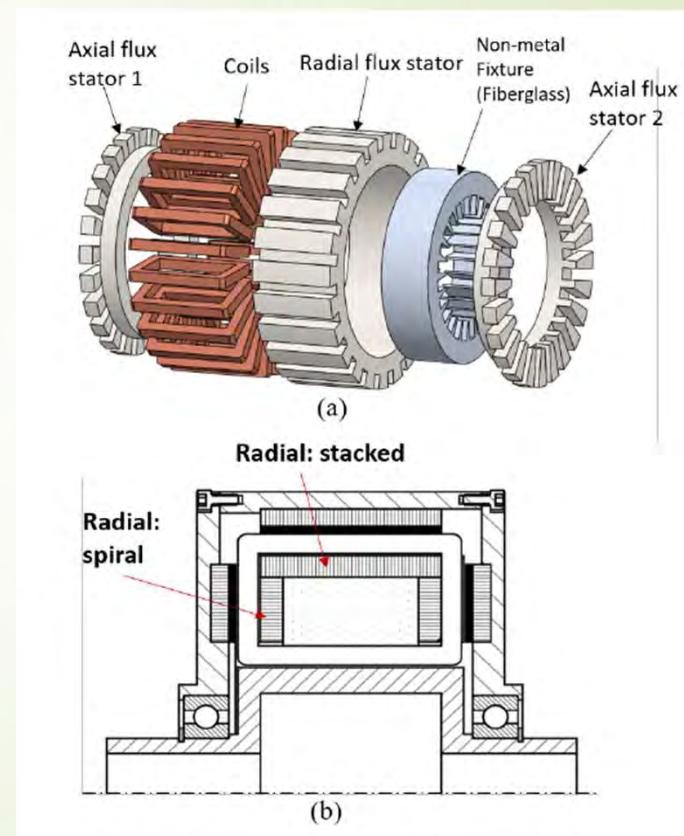
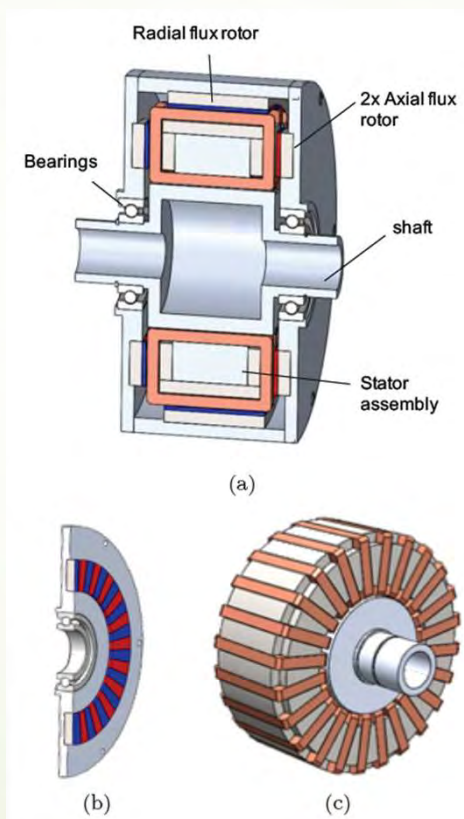
- 32 combinații analizate și comparate cu motorul Toyota Prius – cuplu maxim, costul, densitatea de cuplu, lungimea pachetului, demagnetizarea, la 10.000 rpm, 250 A max.
- Combinația optimă: Top – NeFeB, Mijloc – ferită, Interior – ferită și NdFeB
- La același cuplu maxim, cu 12,6 \$ mai ieftin, 0,47 Nm/\$ mai mult cuplu, 17,5% mai mică densitatea de cuplu, funcționare sigură la 12.000 rpm.

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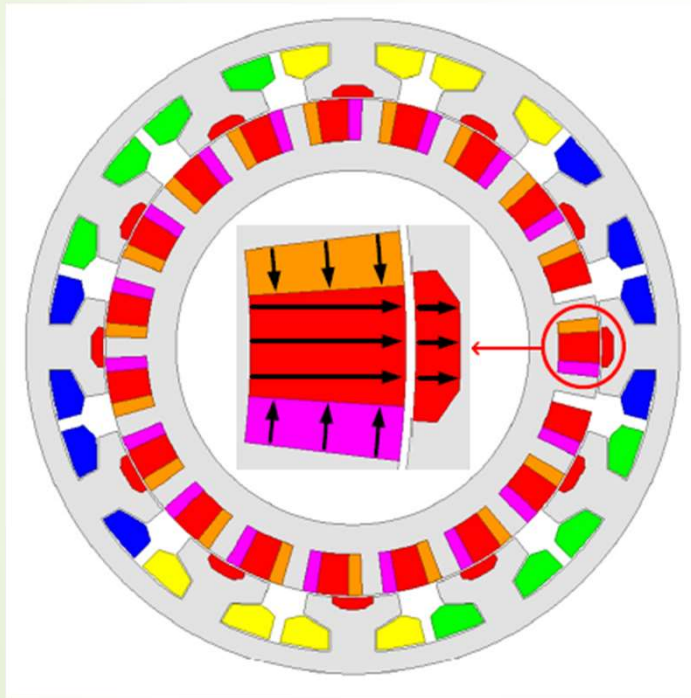
Motor sincron cu MP, cu flux axial și flux radial, și cu reducere magnetică de turație [12].



Sporul de cuplu este de 50% față de alte motoare cu acelaș gabarit.



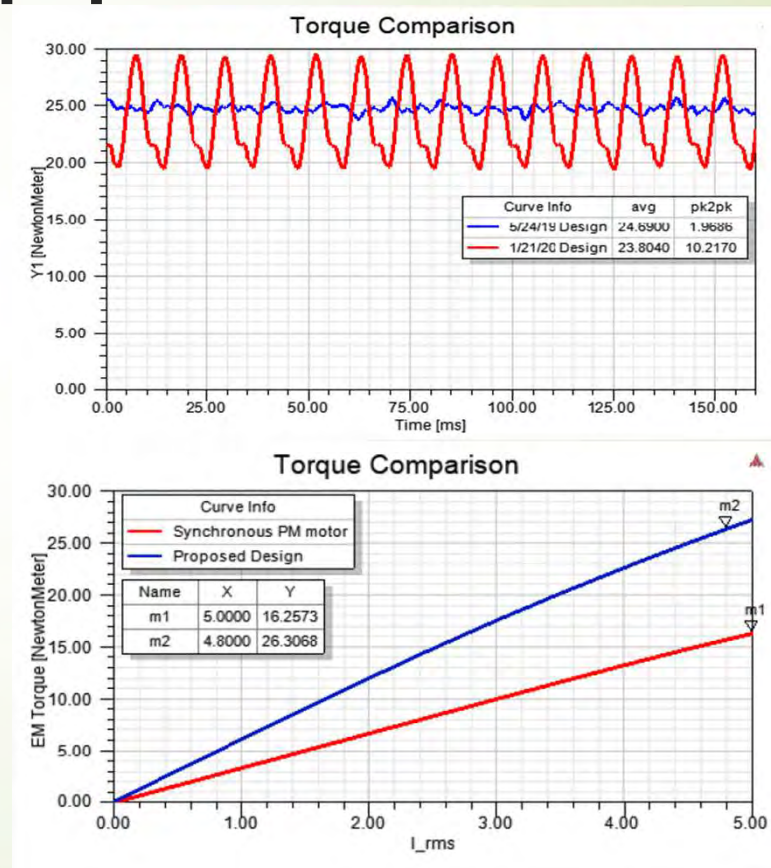
Motor tip Vernier cu poli statorici despicați și rotor cu poli consecvenți, cu magneți permanenți din ferită, în configurație Halbach [13], [14]. (Whirlpool - USA)



- Mașinile vernier cu MP anterioare au flux mare de scăpări și factor de putere redus.
- Modificarea propusă folosește poli consecvenți în rotor (se reduce nr. de magneți), în configurație Halbach (concentreză fluxul către întrefier), magneți suplimentari în dinții statorici care ghidează fluxul magnetic (reduce fluxurile de scăpări) și crește densitatea de cuplu.
- S-a redus riplul de cuplu de la 40% la 4% alegând o combinație a numerelor de poli stator/rotor
- Față de o mașină sincronă cu MP, cu același volum, are 34% mai mult cuplu 20% mai puține pierderi și un factor de putere 0,63, rezonabil

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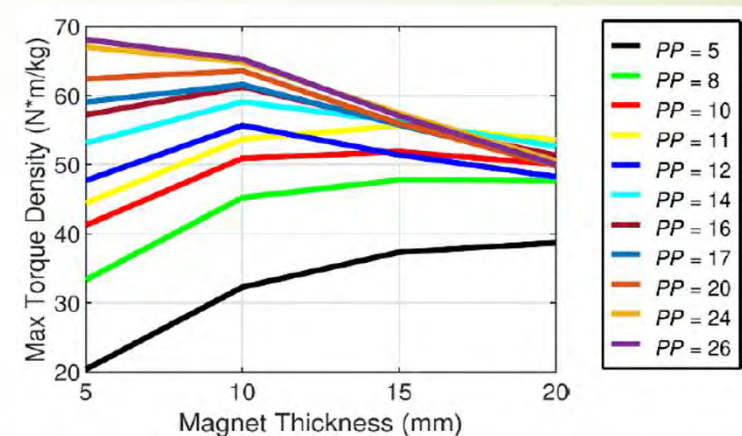
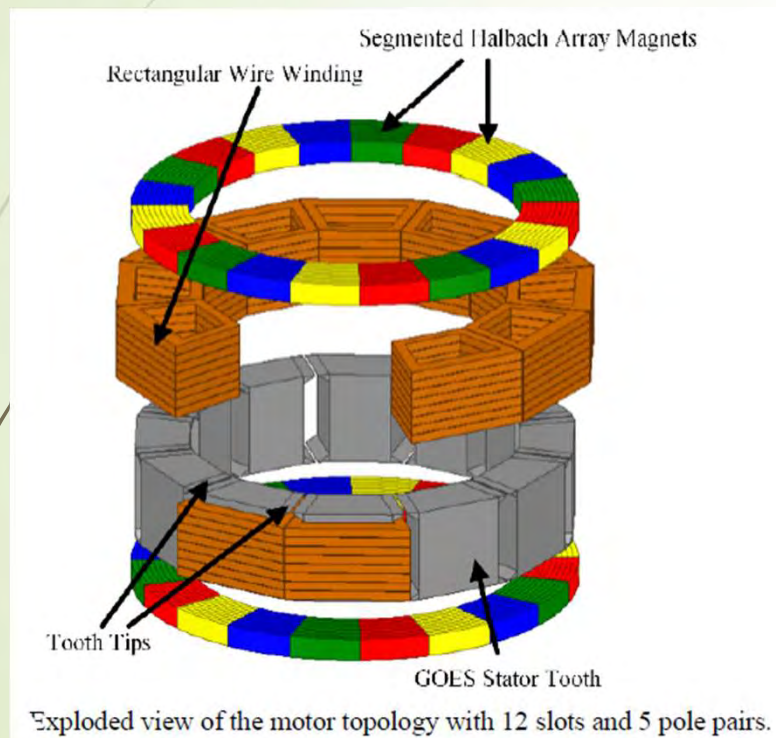
Motor tip Vernier cu poli statorici despicați și rotor cu poli consecvenți, cu magneți permanenți din ferită, în configurație Halbach [13], [14].



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Motoare speciale pentru sistemele de propulsie ale aeronavelor

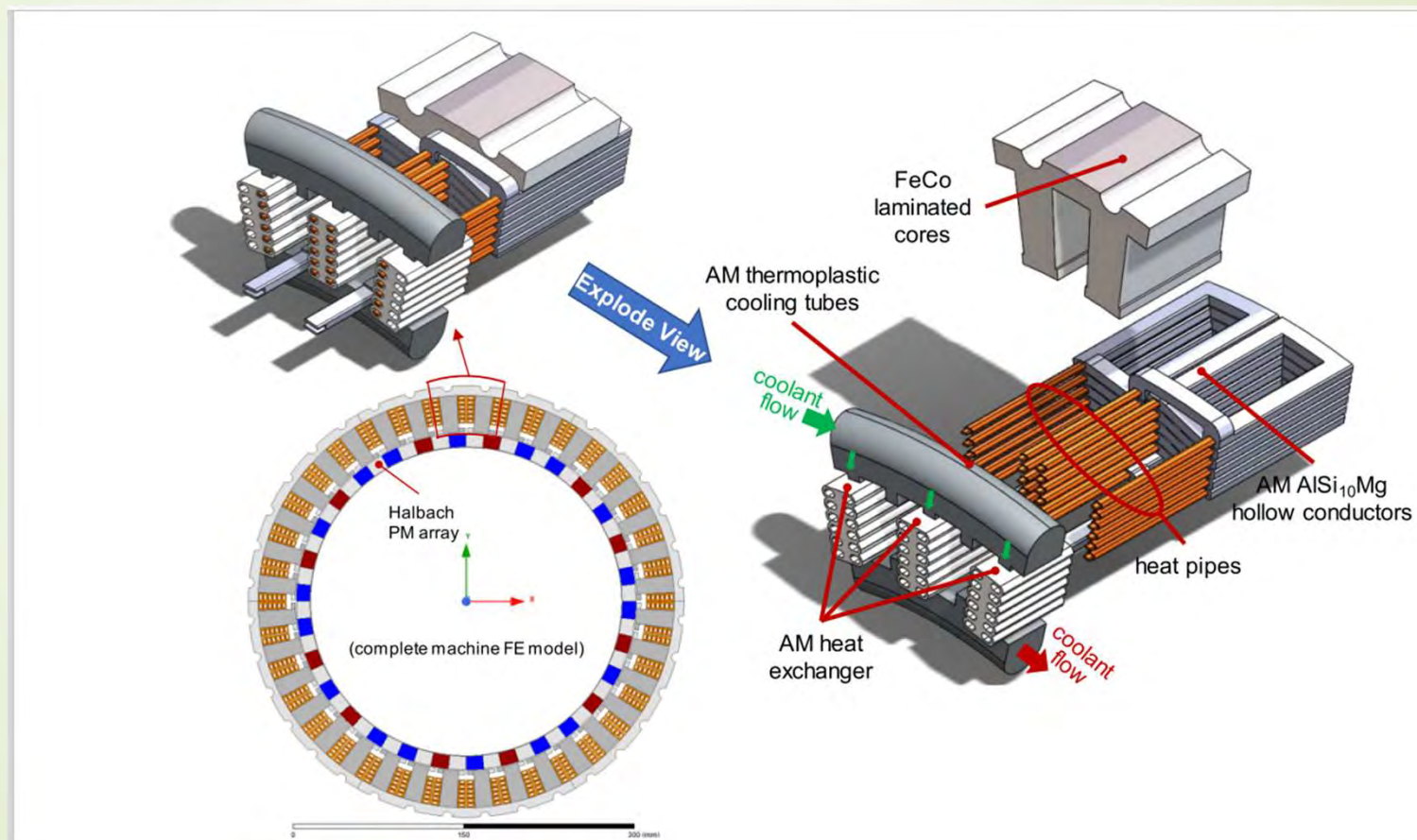
Motorul YASA cu configurație Halbach pentru propulsia avioanelor – analiză de variante [15]



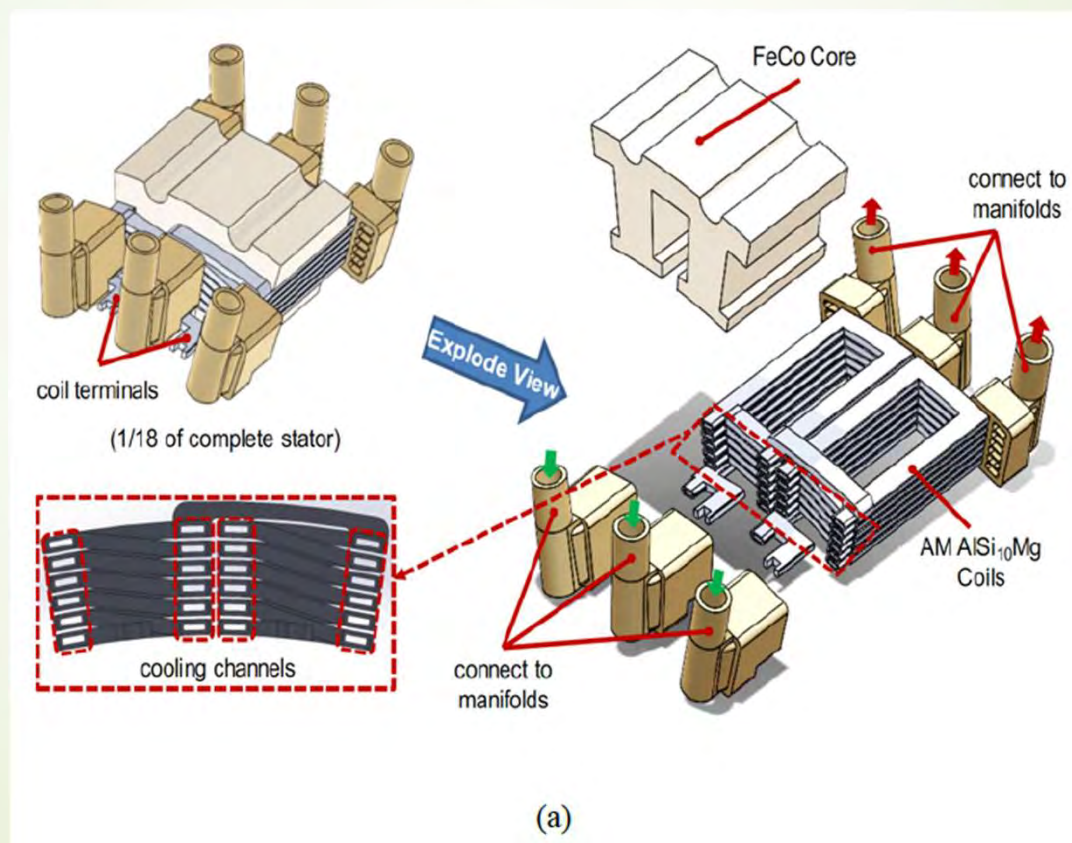
ASCEND PROGRAM SYSTEM TARGETS

Takeoff mechanical shaft power output	≥ 250 kW
Maximum rotational speed at takeoff	5,000 RPM
Specific power at takeoff and climb	≥ 12 kW/kg
Takeoff and climb average efficiency	$\geq 93\%$
Cruise mechanical shaft power output	≥ 83 kW
Cruise rotational speed	3,500 RPM – 4,500 RPM
Average cruise efficiency	$\geq 93\%$

Structura segmentată a statorului cu înfășurări și conducte de căldură în mașina cu MP [16]



Sisteme de răcire cu conductoare tubulare [16]



Sisteme hybrid serie de propulsie [17]

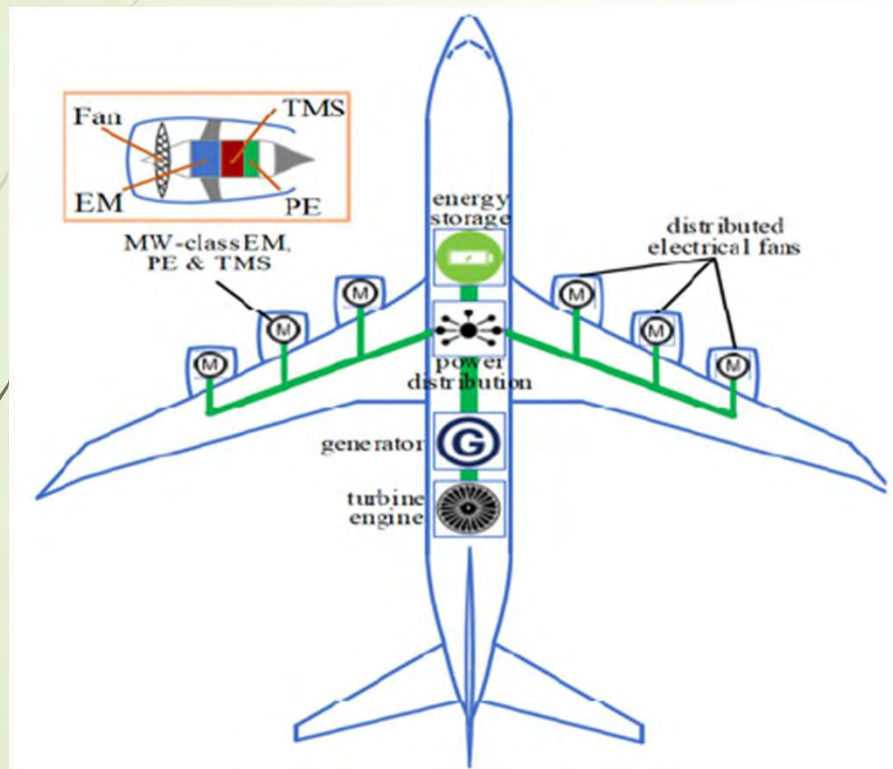



TABLE. I. DESIGN SPECIFICATIONS AND PARAMETERS

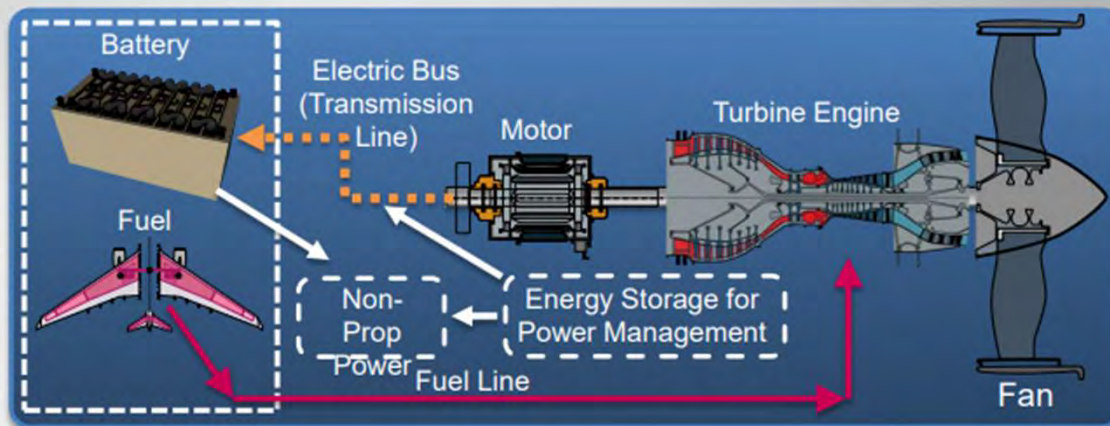
Item	Value
Machine Specifications	
Machine SP	20 kW/kg
Machine Efficiency	>95%
System SP	>12 kW/kg
Peak Power	250 kW
Continuous Power	83 kW
DC Bus Voltage	1200 V
Phase Current	~240 Arms
Design Parameters	
Slot/pole combination	36-slot/30-pole (SSP=2/5)
Tip speed	75 m/s
Rotor outer radius	143 mm
Stator outer radius	178.7 mm
Materials	
Winding material	AlSi ₁₀ MG (2700 kg/m ³)
PM material	Recoma 35E (7600 kg/m ³)
Core material	Vacoflux 48 (8120 kg/m ³)

Programul NASA pentru propulsia electrică a aeronavelor [18].

Possible Future Commercial Large Transport Aircraft Architectures

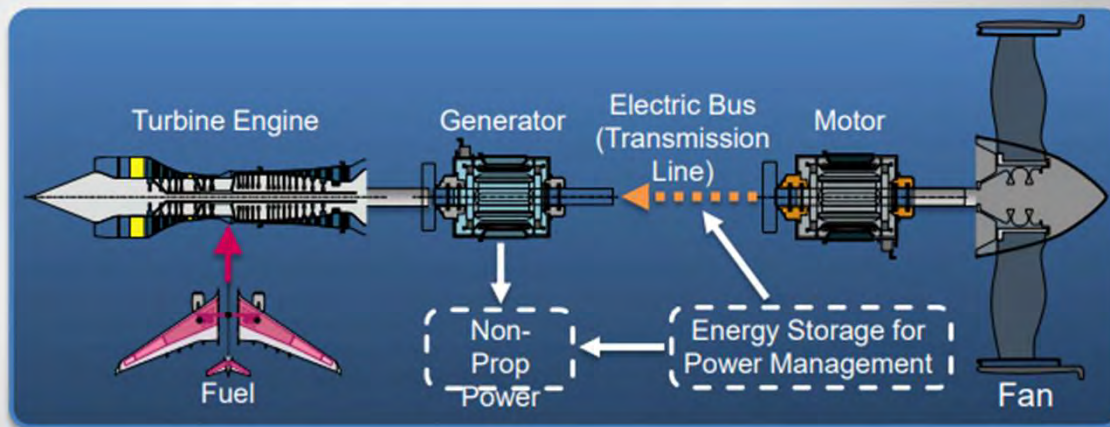


Hybrid Electric



Both concepts can use either non-superconducting motors or cryogenic superconducting motors

Turboelectric





Estimated Benefits From Systems Studies

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SUGAR (baseline Boeing 737–800)

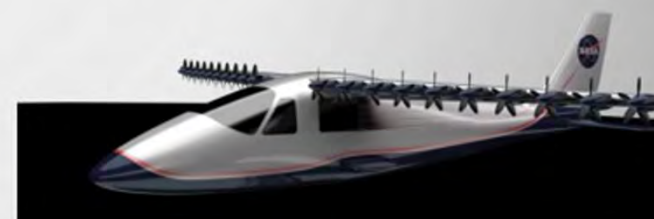
- ~60% fuel burn reduction
- ~53% energy use reduction
- 77 to 87% reduction in NO_x
- 24-31 EPNdB cum noise reduction

N3–X (baseline Boeing 777–200)

- ~63% energy use reduction
- ~90% NO_x reduction
- 32-64 EPNdB cum noise reduction

CEPT (baseline Tecnam P2006T)

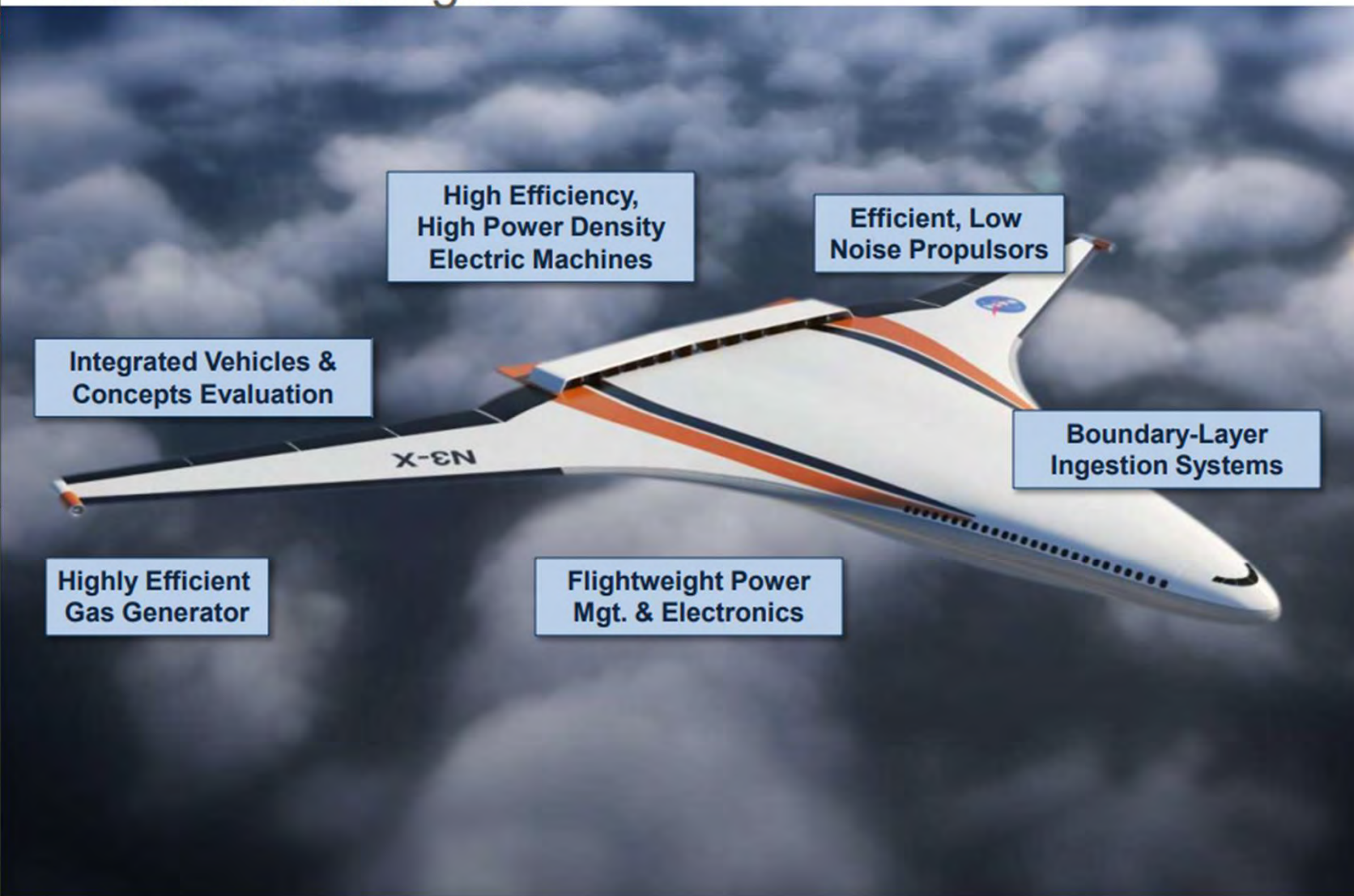
- 5x lower energy use
- 30% DOC Reduction
- 15 dB lower community noise
- Propulsion redundancy, improved ride quality, and control robustness



Investment in Hybrid and Turbo-Electric Aircraft Technologies



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High Efficiency, High Power Density Electric Machines



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- Develop High efficiency, high specific power electric machines
 - Cryogenic, superconducting motors for farther term
 - Non-superconducting motors for near and intermediate term
- Advance Materials and manufacturing technologies
- Design and test 1 MW non-superconducting electric motors starting in FY2015

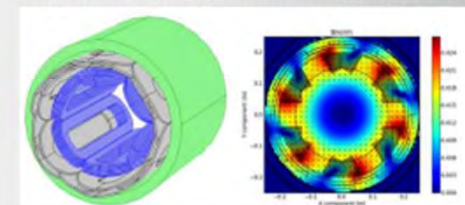
Low A/C loss
superconducting filament



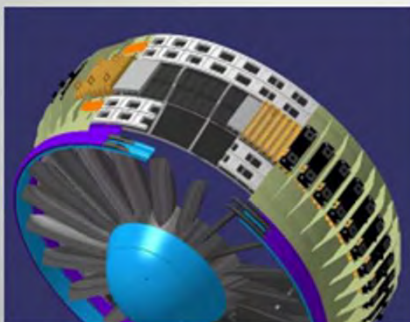
High thermal conductivity
stator coil insulation



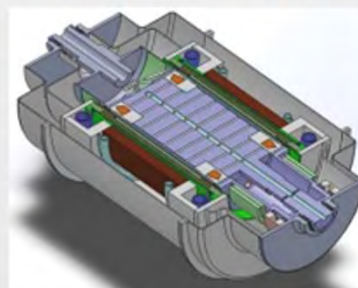
Superconducting electromagnetic model



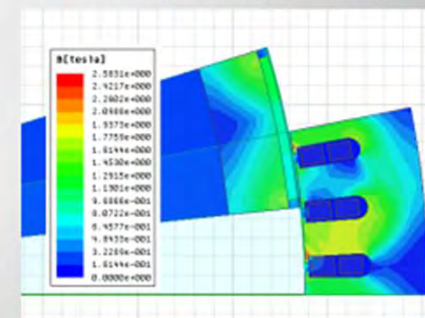
Normal conductor 1-MW rim-driven motor/fan



Fully superconducting motor



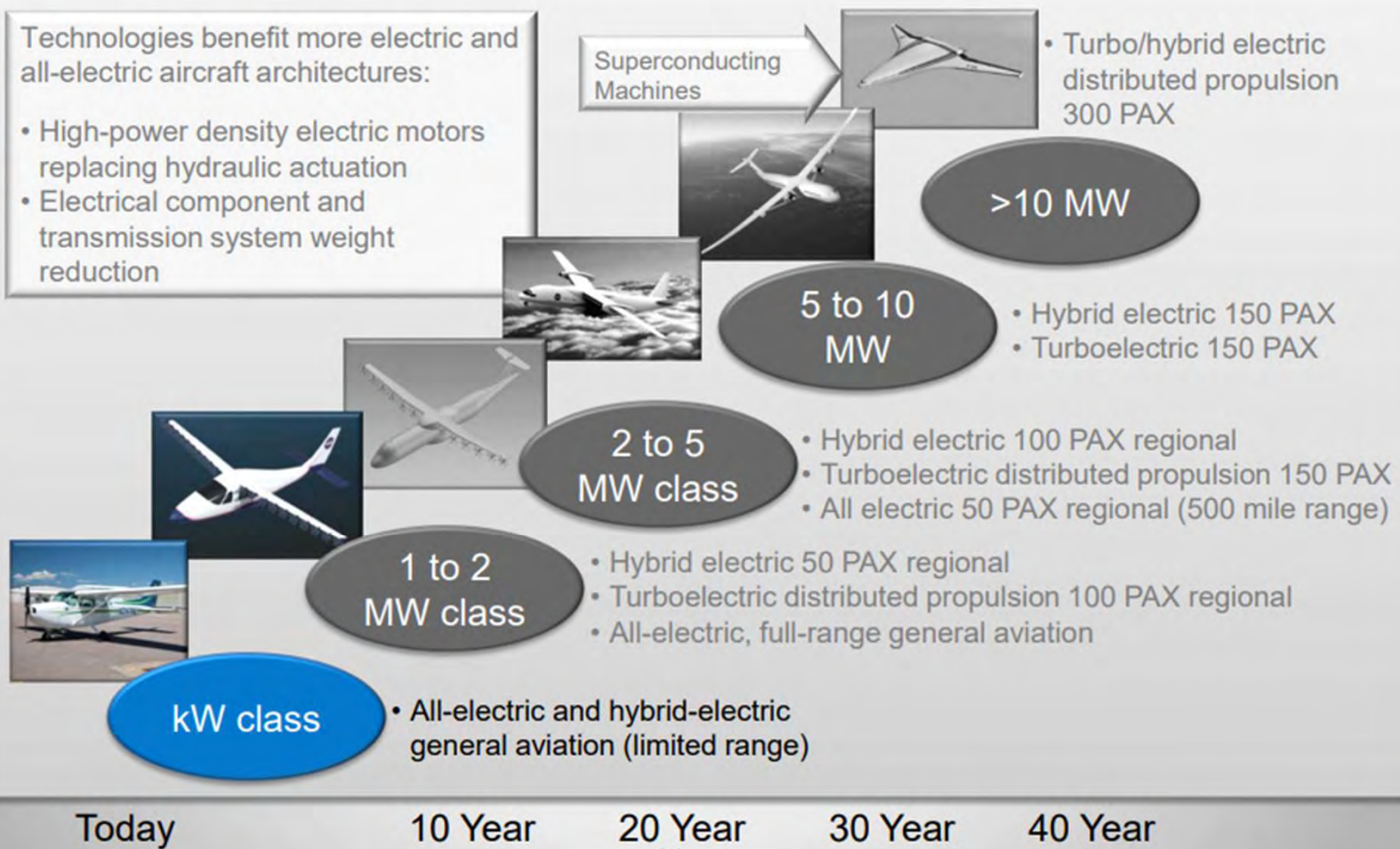
Flux density for rim-driven motor





Projected Timeline to Tech. Readiness Level 6

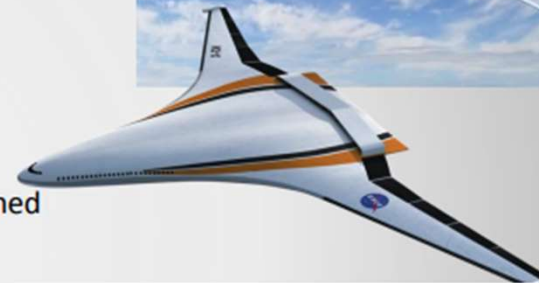
Power Level for Electrical Propulsion



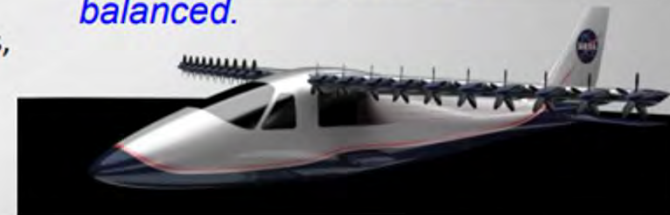
Technologies that can enable or accelerate hybrid, turbo- and all electric Aircraft



- Electric Machine Topologies:
 - Higher efficiency designs: reduce the losses in the motor through better topologies without sacrificing power density
 - Ironless or low magnetic loss
 - Concepts which allow motor to be integrated into the existing rotating machinery (shared structure)
 - Concepts which decouple motor speed and compressor speed
- Electric Machine Components and Materials
 - Flux diverters or shielding to reduce AC loss or increase performance
 - Composite support structures
 - Improvements in superconducting wire: especially wire systems designed for lower AC losses
 - Rotating Cryogenic seals
 - Bearings: cold ball bearings, active & passive magnetic bearings; hydrostatic or hydrodynamic or foil for systems w/ a pressurized LH2 source
 - Flight qualification of new components
- Cryocoolers
 - Flight weight systems for superconducting and cryogenic machines, converters and transmission lines



Vehicle and thermal management concepts need to be defined alongside propulsion systems to assure that the full system is lightweight and thermally balanced.



Technologies that can enable or accelerate hybrid, turbo- and all electric Aircraft



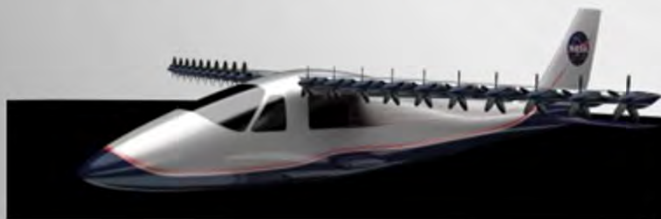
- Power electronics
 - More efficient topologies
 - Compact, highly integrated controller electronics
 - Flight certifiable, high voltage devices
 - Cryogenic compatible devices
- Power transmission
 - Light weight, low-loss power transmission
 - Light-weight, low-loss protection and switching components
- Better conductors
 - Carbon nano-tube or graphene augmented wires
 - Robust, high temperature superconducting wires
- Energy storage
 - increased battery energy density
 - multifunctional energy storage
 - rapidly charging and/or rapidly swappable



- Thermal Management

Transport class HE aircraft will need to reject 50 to 800 kW of heat in flight

- Cooling for electric machines with integrated power electronics
- Advanced lightweight cold plates for power electronics cooling
- High performance light-weight heat exchangers
- Lightweight, low aerodynamic loss, low drag heat rejection systems
- Materials for improved thermal performance
- System-level enablers
 - Flight-weight, air cooled, direct shaft coupled turbo-electric generation in the above 500kW range
 - Regenerative power absorbing propeller and ducted fan designs (efficient wind-milling)



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