Light-weighting in electrical machines - opportunities and challenges

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FUTURE Electrical Machines Manufacturing Hub
EPSRC Future Manufacturing Hub

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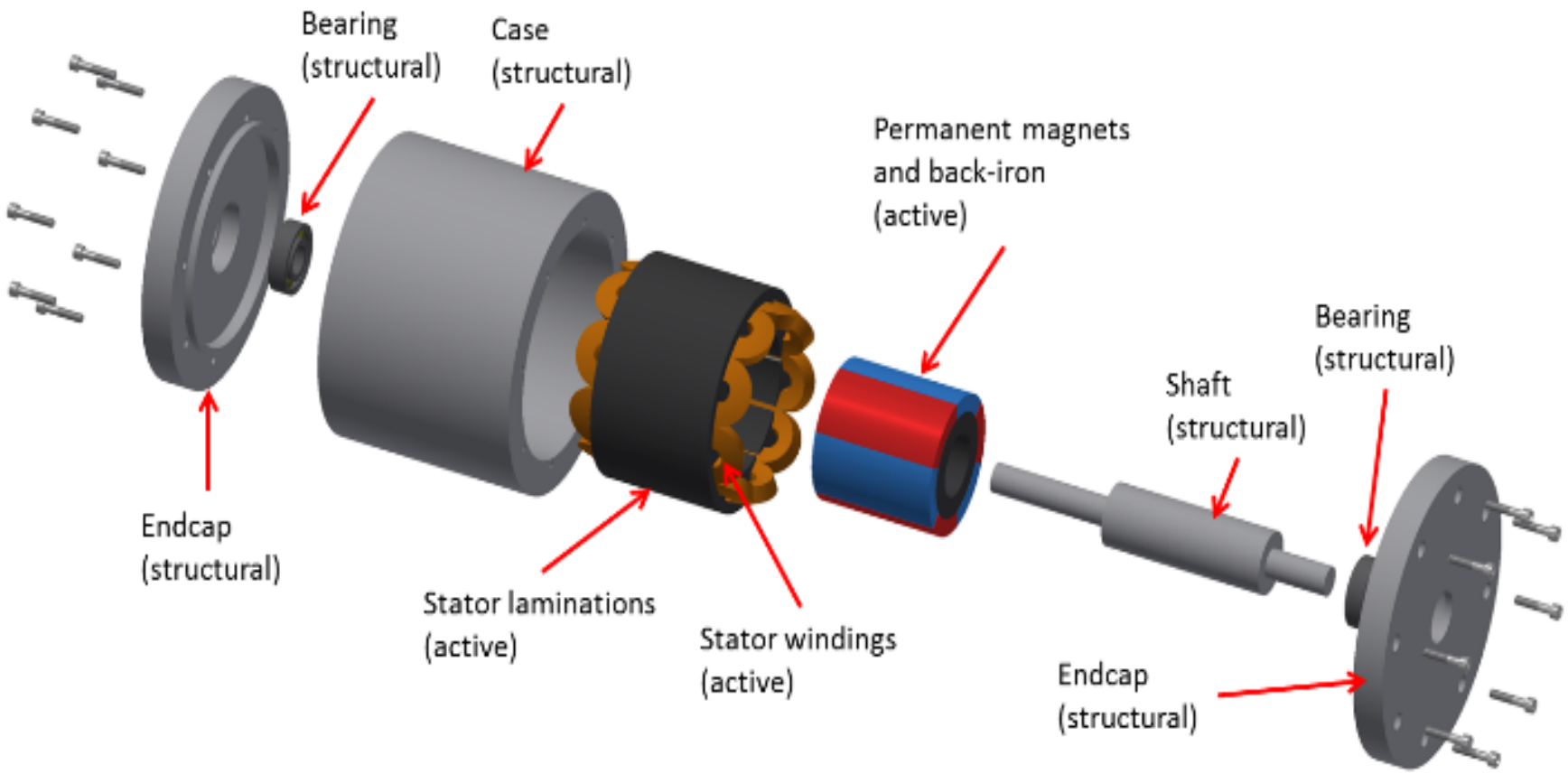
£27.7m Future Manufacturing Hub -
£10m EPSRC, £13.0m from industry and £4.7m from institutions
7 year programme from 2019-2026

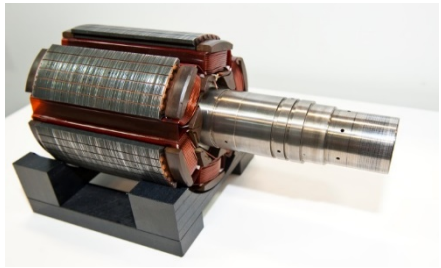
Our vision:

- To put UK manufacturing at the forefront of the electrification revolution in aerospace, energy, high value automotive and premium consumer sectors.
- Address key manufacturing challenges for high integrity and high value electrical machines.
- Assist UK manufacturing to capture significant value in the supply chain, improve productivity and deliver the cleaner growth at the heart of the UK's industrial strategy.

Official launch event – 12th June, Factory 2050
Register - http://bit.ly/2VwgXI8

Basic anatomy of a high performance electrical machine



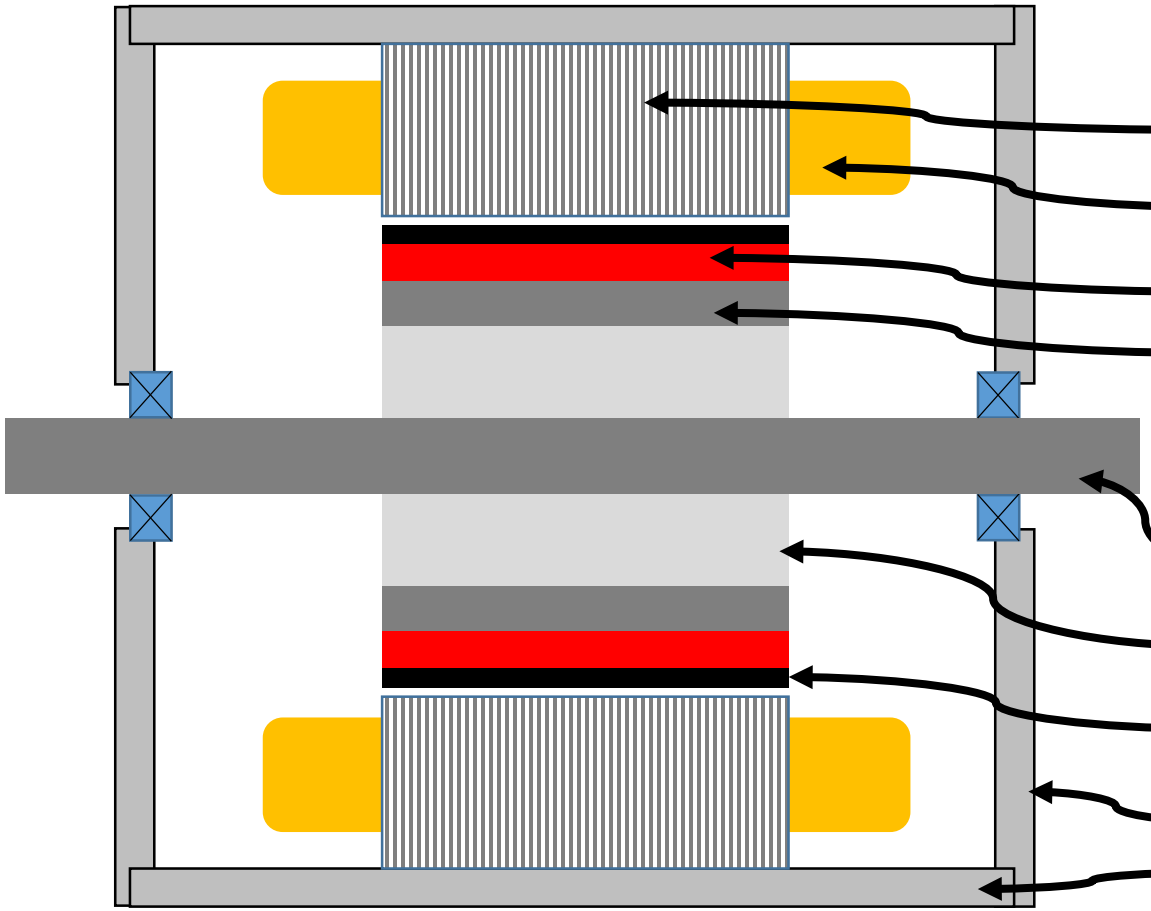


Boeing 787 starter-generator

250kVA with a mass of ~98 kg (dry)

~2.5kW/kg – achieved through sophisticated cooling with parasitic weight penalty

Typical materials



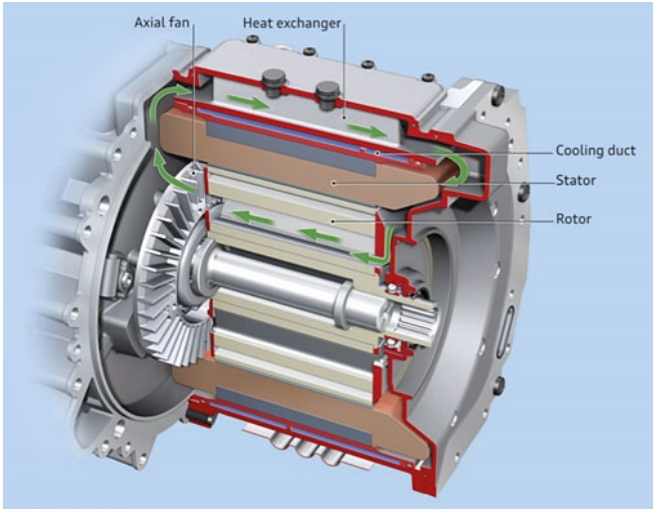
Electromagnetically active elements	
Stator core	SiFe, CoFe
Stator winding	Cu (very occasionally Al)
Rotor magnet	NdFeB / SmCo
Rotor core	SiFe/CoFe

Electromagnetically active elements	
Rotor shaft	Shaft steel
Rotor Hub	Al/Ti
Rotor containment sleeve	Carbon fibre /Inconel
Casing end-plates	Al
Tubular section of casing	Al

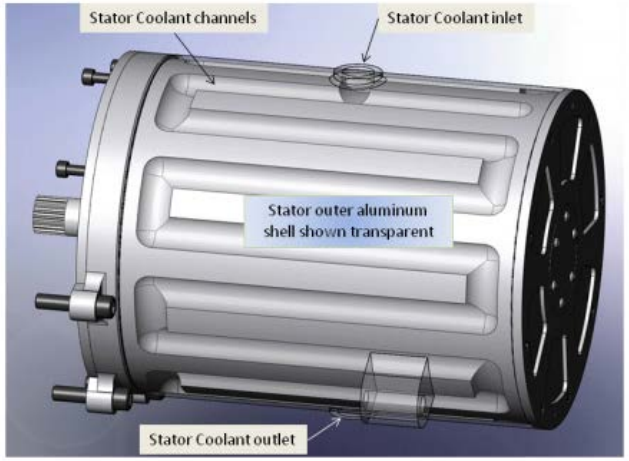
Functions of the casing

All or some of the following:

- Environmental protection, e.g. debris, dust, moisture
- Support bearings
  - Provide stiffness and damping to manage rotor-dynamics
  - Provide stiffness and damping to manage vibration
- Act as heatsink (in most but not all machines)
  - Flood-cooled machines – casing plays little role other than to contain liquid in a liquid tight space
  - Liquid jacket – critical heat transfer from core to casing
  - Forced air cooling of casing
- React electromagnetic torque to stationary structure



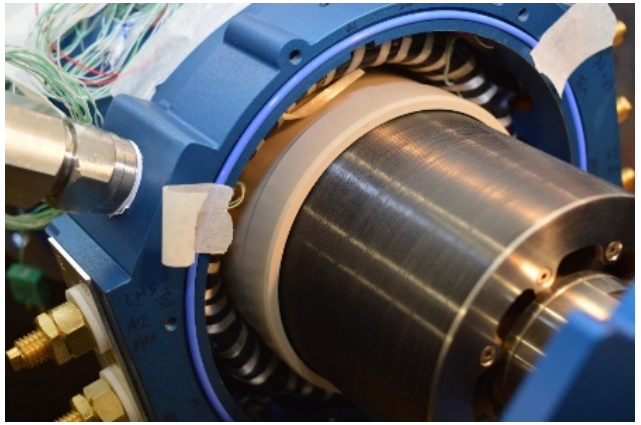
Source: Zytek



Casing material requirements

- Good conductor of heat - critical in some configurations
- Compatible with liquid coolants: water/glycol, oil, bespoke thermal fluids etc
- Stator core temperatures potentially up to 180-200°C
- Provide a reasonable CTE match to core materials
  - CoFe: $9.5\times10^{-6}K^{-1}$
  - N020 grade SiFe: $12\times10^{-6}K^{-1}$
- Small premium on being non electrically conducting

Example – high performance aerospace starter-generator



174mm stator diameter
100kW continuous, 135kW peak in generator mode
22.75kg which corresponds to 3.96kW/kg
Oil flood-cooled stator (PEEK sleeve in airgap)
Electrical feed-thoughs into oil-filled stator cavity

Cobalt Iron stator core
Aluminium stator casing
Titanium spoked rotor hub
Steel shaft
Carbon fibre rotor over-wrap

Mass breakdown

Active component	Mass (g)
Stator Lamination stack	4673
Rotor lamination stack	1287
Stator windings	4627
Magnets and carbon fibre over-wrap	1560
Total mass	12147

47% of mass contributed by non-active components even in this compact machine

Proportion will tend to increase as size and split ratio (airgap diameter : overall diameter) increases

Non-active components	Mass (g)
Rotor shaft, washer and captive nut	1790
2 rotor endplates	181
Rotor titanium hub	1027
Casing	3689
DE Endplate	1216
NDE Endplate	1181
6 brass terminals	315
6 PTFE inserts	117
PEEK sleeve	266
12 hex bolts	44
Aluminium terminal plate (x2)	54
Thermocouple pass through connectors (x2)	632
bearings	86
Total mass	10602

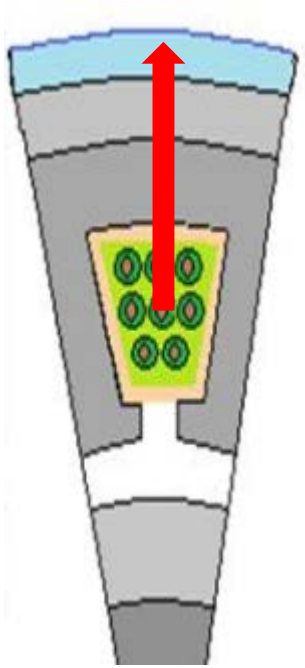
Active materials – scope for light-weighting

- Very mature materials in even the most high performance machines
  - Stator core – Vacoflux 50 Cobalt Iron – essentially a tweak on Permendur (1932)
  - Rotor magnets Sm_2Co_{17} – early 1970s
  - Drawn copper wire – Theophilus the Monk in 12th century
  - Insulation coatings of wire – Polyimides 1990s
- Very little prospect in medium term of alternatives with the requisite functional properties
  - Aluminium wire – lighter coils but knock-on effect of lower conductance per unit volume is a major obstacle to competitiveness – adoption (which is still modest) being driven by cost
- Increasing power density beyond 10kW/kg (continuous) will come from improved thermal mass and light-weighting of structural elements

Fibre reinforced composite casings

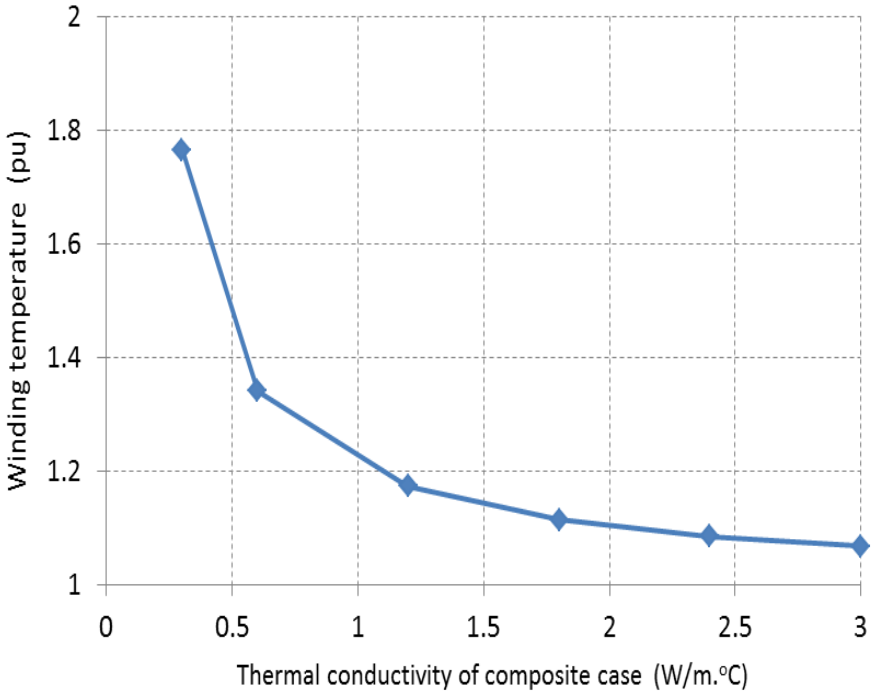
- Two potential performance issues
- CTE matching with stator core
  - Stator OD of starter-generator shown previously grows by 0.33mm between -55° and 150°C (CTE of Vacoflux 50: $9.5\times10^{-6}K^{-1}$) – often need to maintain good thermal performance at interface
- Modest thermal conductivity
  - OK for flood cooled subject to chemical compatibility with cooling fluid
  - But doesn't need much enhancement in some cases even when conduction to external cooling medium is key to heat-flow

Insensitivity of peak winding temperature to casing thermal conductivity



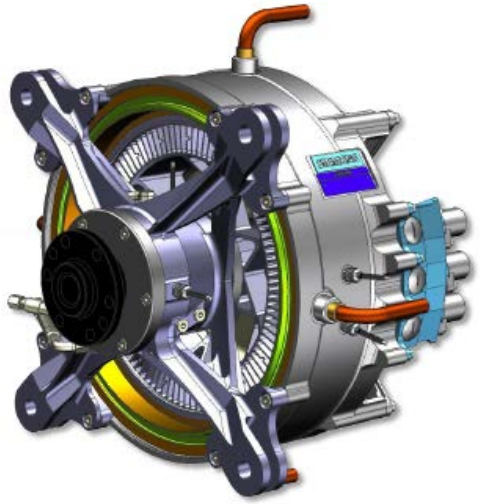
- Several thermal resistances between main source of loss (copper conductors) and the cooling fluid
- Transferring heat within the slot and across slot-liner is a key challenge
- Diminishing return on peak coil temperature from improving casing thermal conductivity

Normalised peak winding temperature compared to Al casing for a 6-phase aerospace actuation machine



Other potential solutions for structural elements

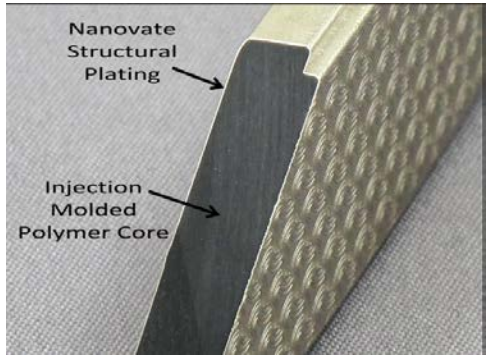
Design features in combination with ‘new’ materials



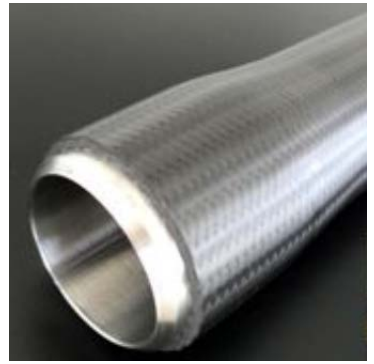
Composite bearing spider in place of traditional 10kg end-cap
Source: Siemens

‘New’ materials

Electro-clad polymers for casings



MMCs for shafts and hubs



Conclusion

- Light-weighting of structural components has a significant role in driving up electrical machine power density to levels need for greater adoption in aerospace
  - Comparable to improved thermal management
  - Greater than electromagnetics