Permanent magnet machines and actuators

Geraint Jewell

The University of Sheffield

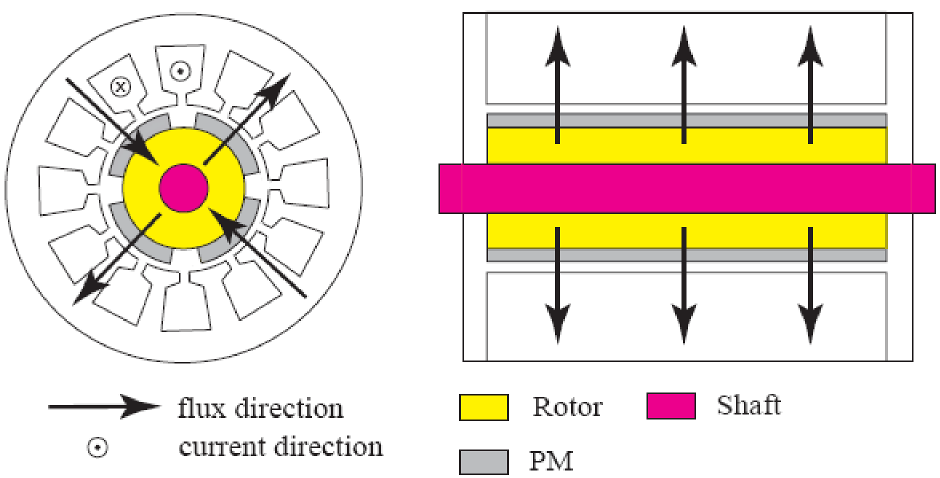
Symposium on Materials for a Sustainable Future
11/09/09

Key PM Properties for Electro-Mechanical Devices

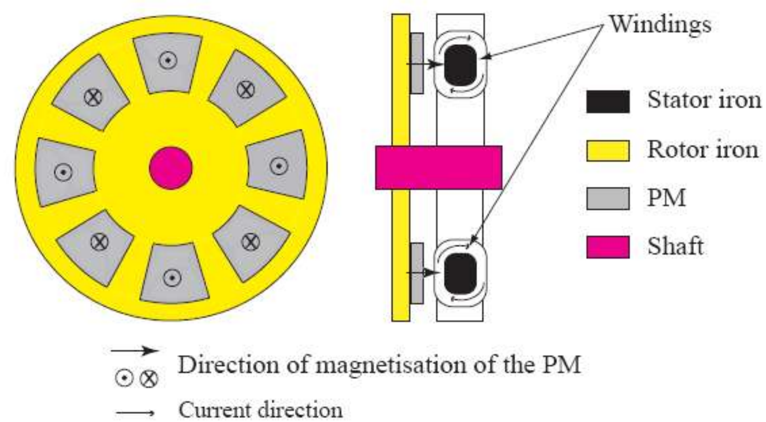
● High remanence	$\Rightarrow$	High airgap flux density
● High coercivity	$\Rightarrow$	Demagnetisation withstand
● <u>High temperature capability</u>	$\Rightarrow$	Demagnetisation withstand Environmental capability
● <u>Corrosion resistance</u>		
● High mechanical strength	$\Rightarrow$	High speed operation
● Low electrical conductivity	$\Rightarrow$	Rotor loss
● Formability	$\Rightarrow$	Ease of manufacture Scope for product integration
● Ease of magnetisation	$\Rightarrow$	Ease of manufacture
● <u>COST</u>		

Brushless PM machines

- Also called electronically commutated
- So-called brushless DC or AC operation
- Always used in conjunction with a power electronic converter
- Electronically commutated as a function of rotor position
- Can operate as motors and generator – switch between two modes very rapidly
- Arguably more competitive as motors than generators in most ‘standard’ speed applications



Radial field



Axial field

Key features of performance

- High efficiency – can be >95% even at modest powers
- High power density compared to competing technologies
- Capable of high speed operation
- Reasonably good short-term overload capability
- Well suited to very high pole numbers
  - Important feature for high torque / low-speed applications

Efficiency in Electrical Machines

Can be traded off against machine volume

up to a point where machine becomes thermally limited

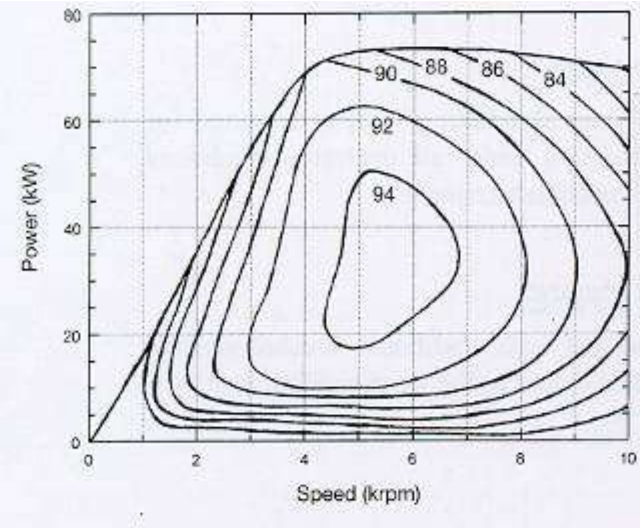
Higher airgap flux densities generally give higher efficiencies – particularly in low to medium speed applications

Highly influenced by size (larger machines tend to be more efficient)

Tends to vary over operating range of the machine

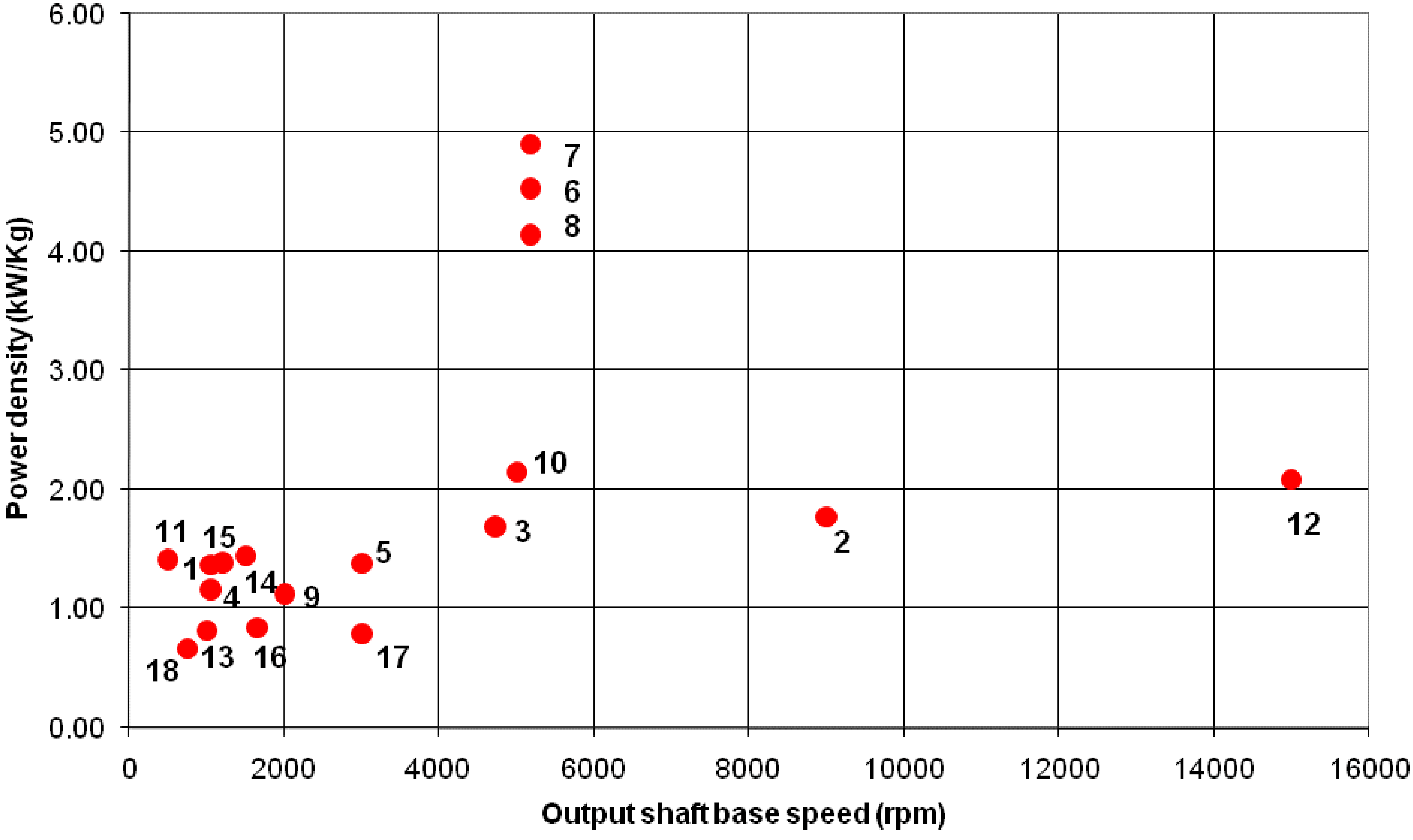
Can be >98% in some cases

High Performance PM Traction Drive



10,000 rpm maximum speed
35kW continuous rating (70 kW peak)
0.7kW / Kg continuous (2kW/kg peak)
Total weight of motor 42kg (incl 3.5kg of NdFeB)

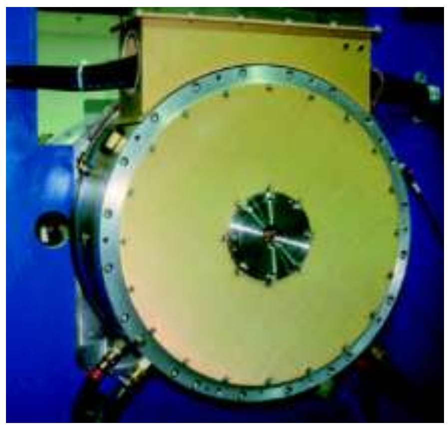
Power density of electrical machines



1MW range PM machines

- **Several impressive demonstrator machines with ratings in the 0.5-1.0 MW range**
- **Many aimed at military vehicles**
- **Very competitive power and torque densities**

DRS PA44-5W



Canopy Technologies LLC HA57-100

DRS 370kW CR32-50

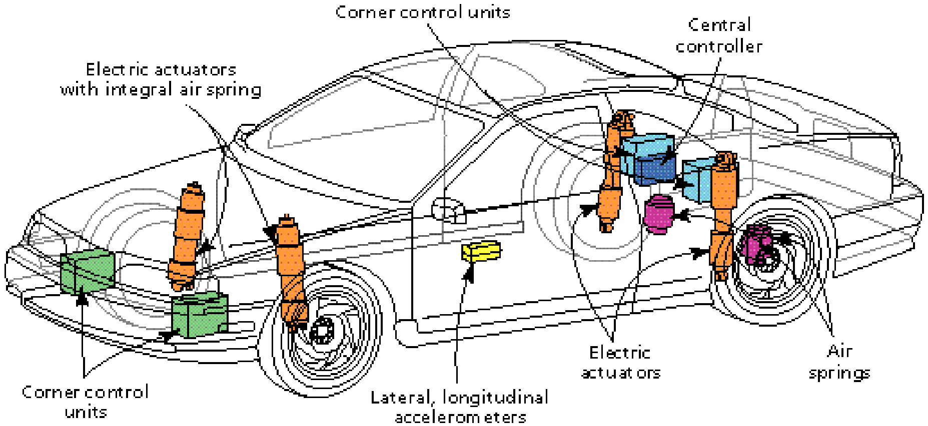
OSSA Powerlite 597kW

Key performance indicators and design parameters of a series of intermediate speed PM machines

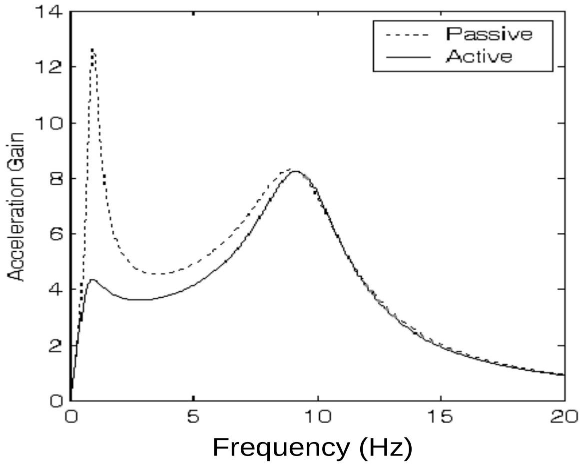
	DRS axial field [20]	Canopy Technologies HA44-45 [21]	Canopy Technologies HA57-100 [21]	DRS CR32-50	OSSA Powerlite 597KW model
Rated power (MW)	0.97	0.34	0.74	0.37	0.60
Rated torque (Nm)*	1287	1120	2712	1761	5179
Maximum speed (rpm)	**6000**	3600	4000	3600	**1100**
Topology	Axial-field	Axial-field	Axial-field	Radial-field	Radial-field
Number of poles	Not known	28	36	20	Not known
Total weight (kg)	160	195	354	227	791 (incl. converter)
Machine diameter (m)	0.61	0.65	0.78	0.48	0.55
Axial length (m)	0.16	0.22	0.26	0.44	0.60
Torque density (Nm/kg)	8.0	5.7	7.5	7.7	6.5
Torque density (kNm/m^3)	27.5	15.1	19.0	22.1	**35.5** (excl. converter)
Power density (kW/kg)	**6.1**	1.74	2.10	1.62	0.75
Power density (MW/m^3)	20.7	4.55	7.9	4.64	4.1
Peak efficiency	96%	95%	95%	95%	**98.9%**

*** rated torque is not necessarily at maximum speed**

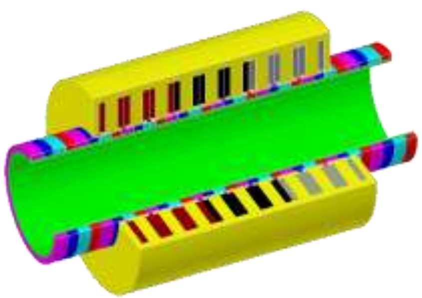
Active Vehicle Suspension



Peak force capability	5kN
Rms force capability	2kN
Nominal stroke	+/- 50mm
Maximum stroke	+/-100mm
Average output power	50W
Peak/Rms velocity	1.5/1.0m/s



Integrated active suspension unit

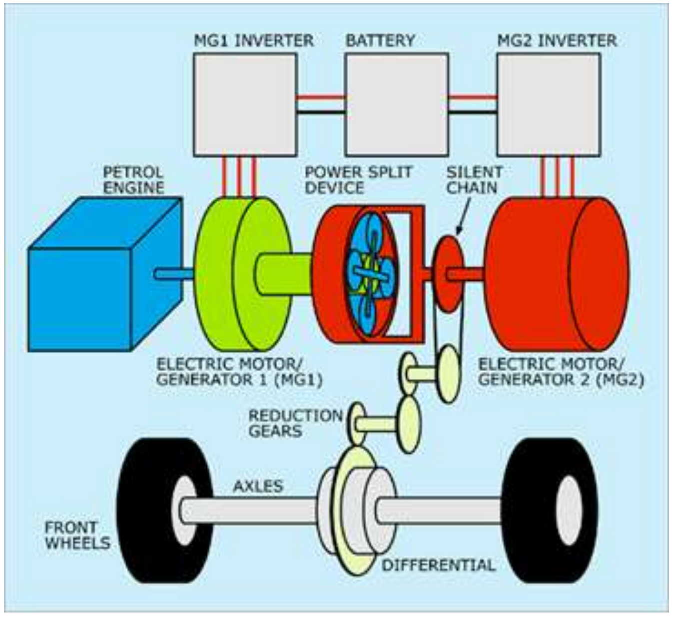


Project partners:

Loughborough University

Jaguar Land Rover Research UK Ltd

Toyota Prius



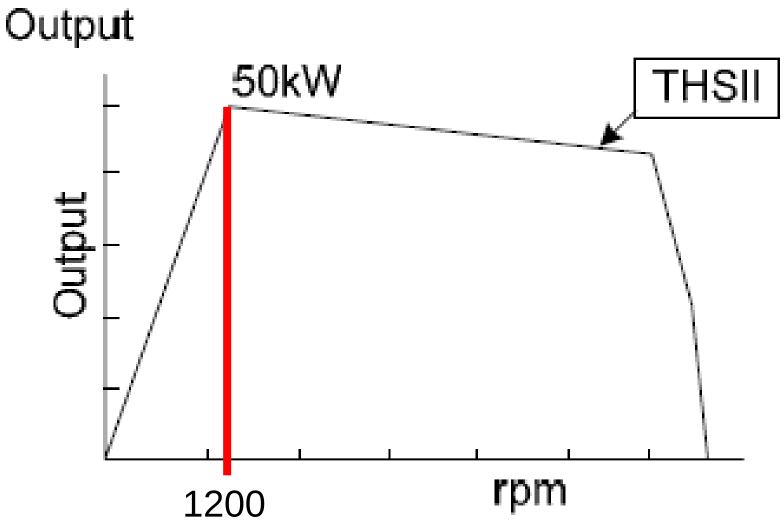
Introduced in 1997
Sales to 2006 (all models): 552,657

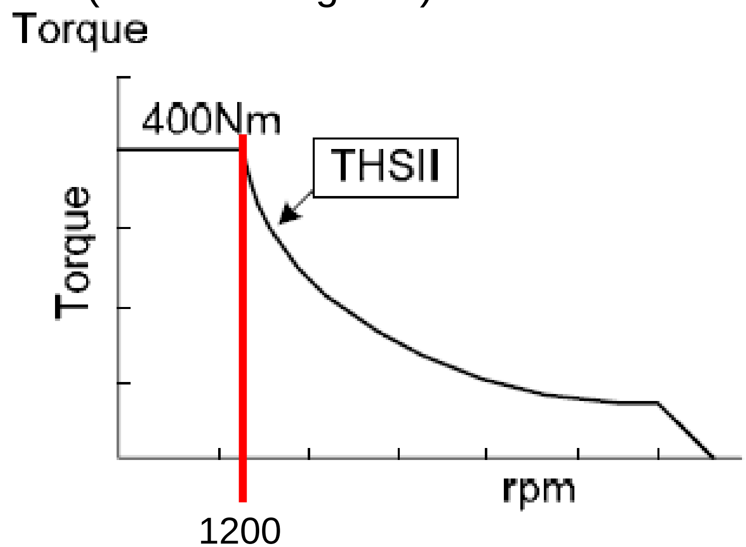
Most detailed information available for 2004 model
Two excellent and comprehensive public-domain reports from: Oak Ridge National Laboratory

- **'Report on Toyota / Prius Motor Design and Manufacturing' (ORNL/TM-2004/137)**
- **'Evaluation of 2004 Toyota Prius Hybrid Electric Drive System Interim Report' (ORNL/TM-2004/247)**

Electric Motor

Permanent magnet brushless AC synchronous motor (NdFeB magnets)

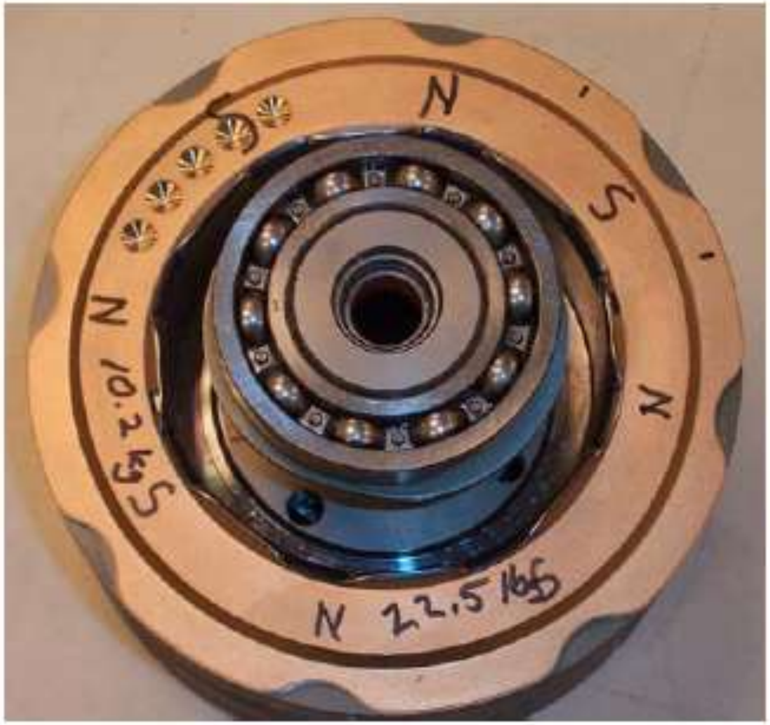




Liquid cooled (ethelyne/glycol)
Total active mass = 36.3kg
Power density = 1.37kW/kg
Torque density = 11Nm/kg

Source: Oak Ridge National Laboratory

Drive machine rotor

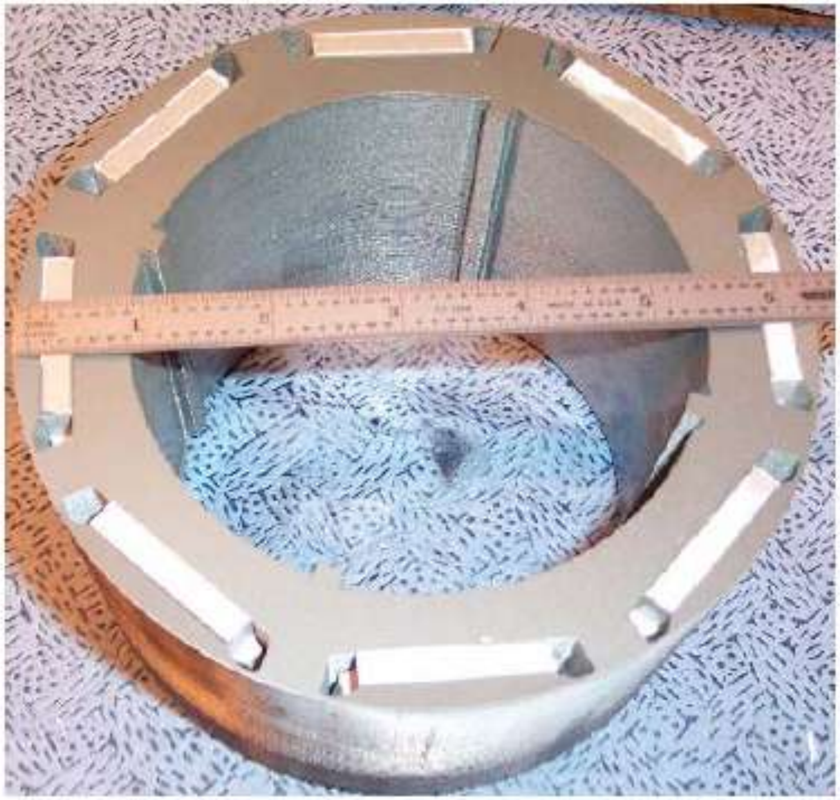


8-pole sintered NdFeB magnets (~1.8kg)

Source: Oak Ridge National Laboratory

Rotor construction

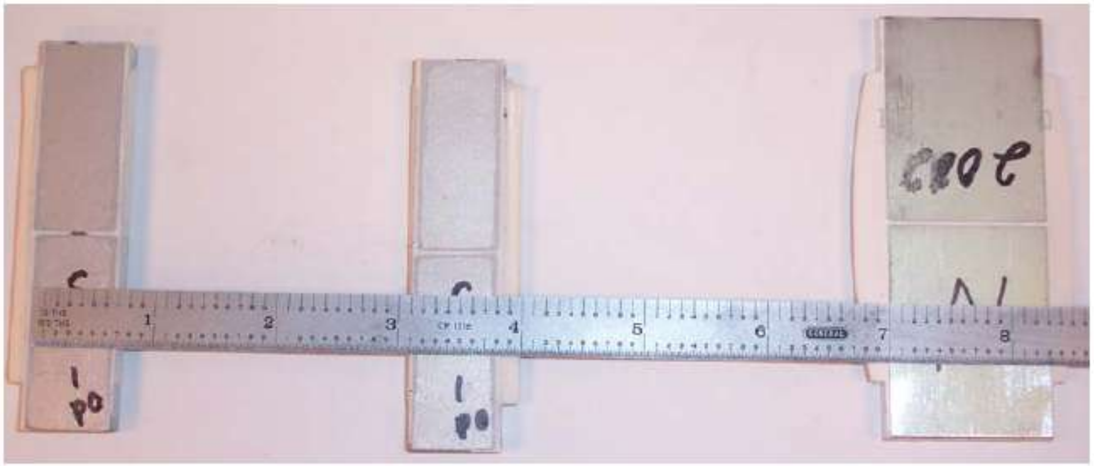
- so-called 'inset magnet rotor'



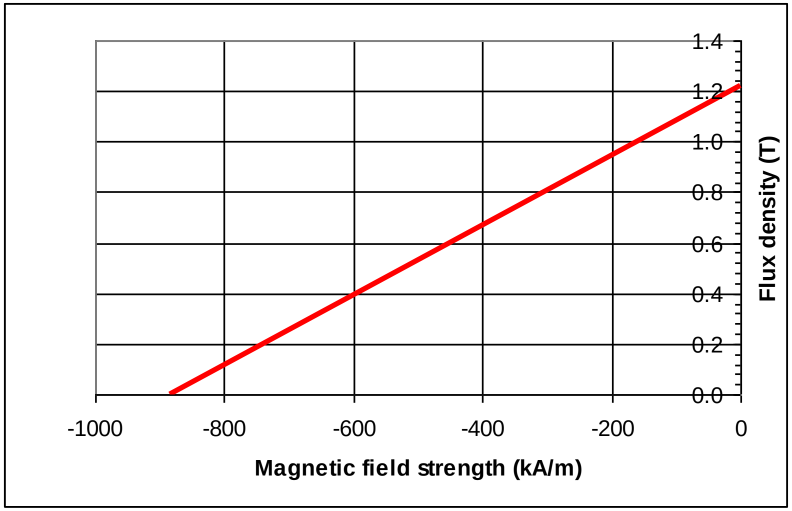
Usually requires high tolerances

Source: Oak Ridge National Laboratory

Magnet segments



2004 2003

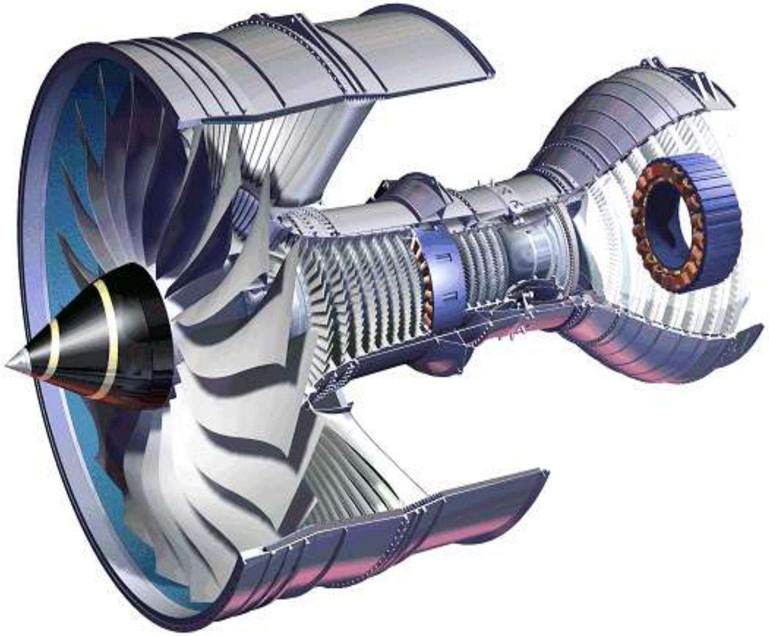


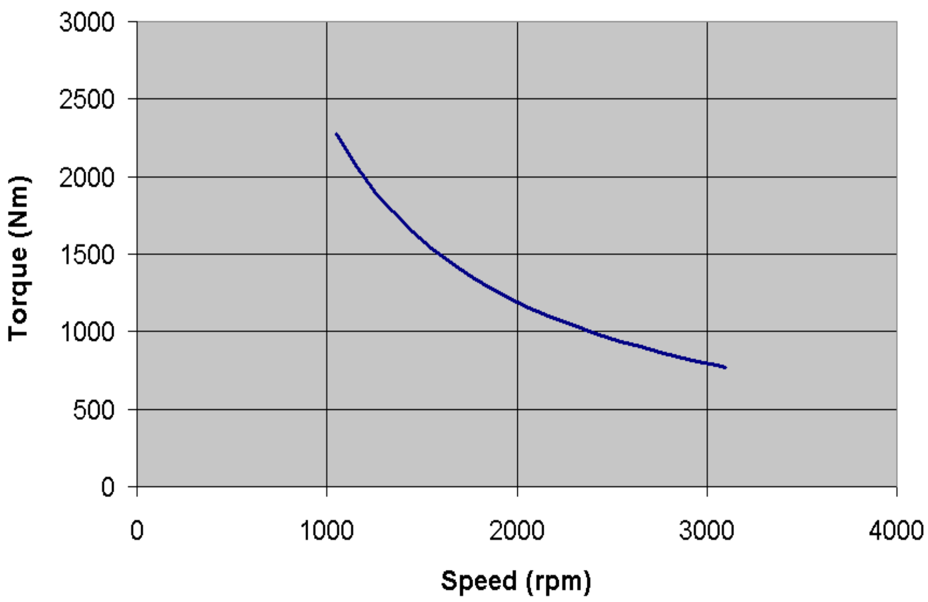
Over-mould sintered NdFeB in a polymer carrier

- tolerance on width and lock-in is achieved by polymer

Source: Oak Ridge National Laboratory

LP shaft generator

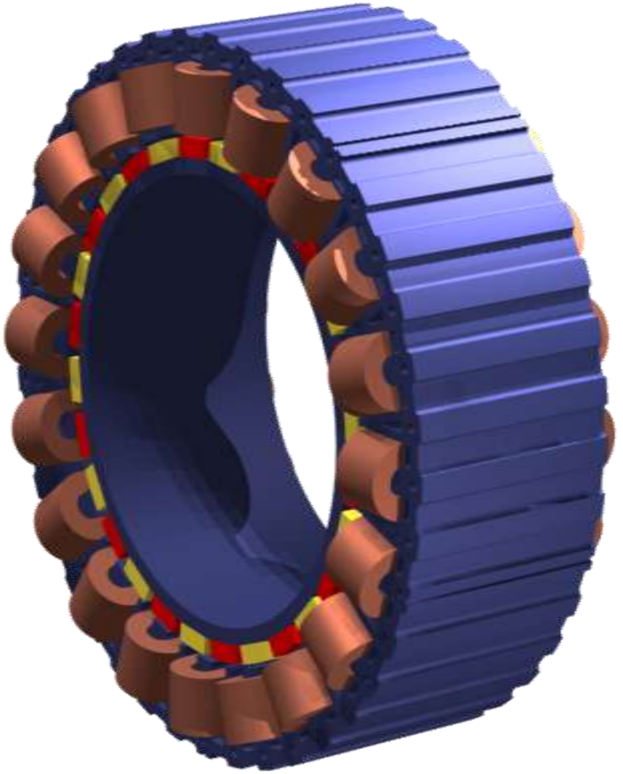




Air-cooled
Direct drive

- **Output power - 250kW over speed range 1050rpm - 3100rpm**
- **Output voltage - 350V DC**
- **High efficiency - >95%**
- **Located within tail-cone**

Finalised design

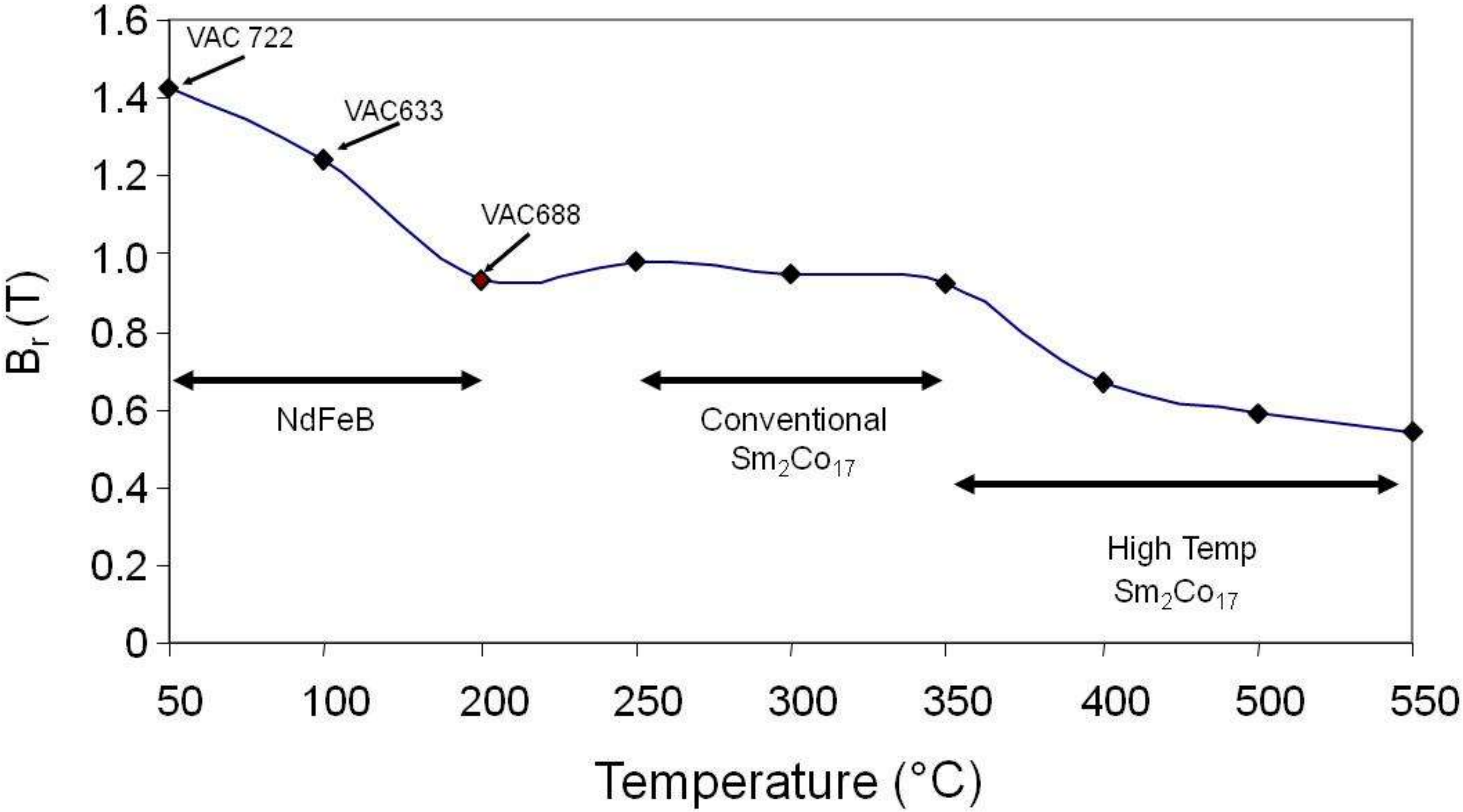


Stator core	**90kg**
Stator winding	**52kg**
Rotor magnets	**22kg**
Rotor core	**19kg**

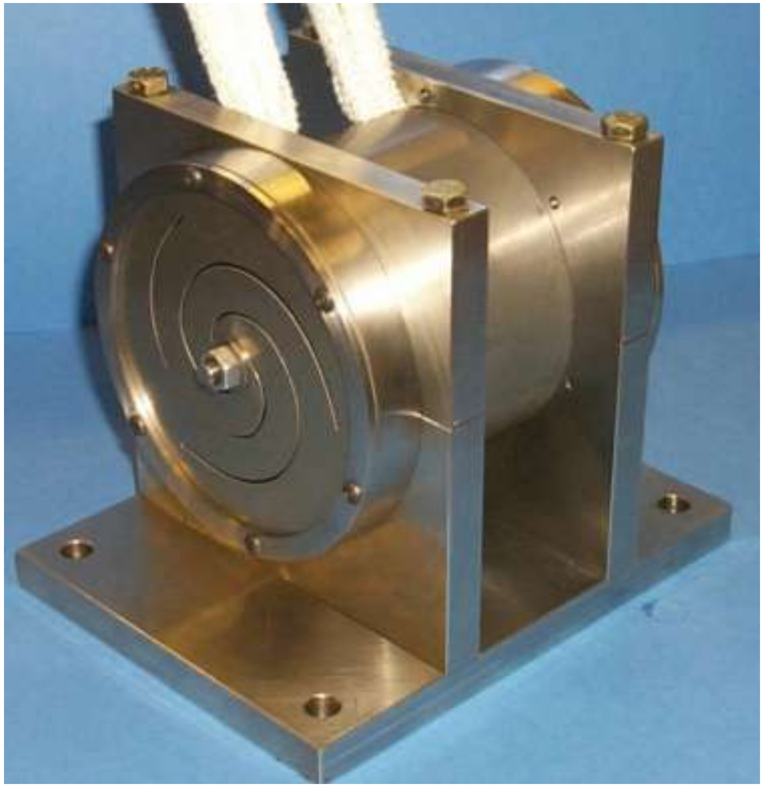
TOTAL (active weight) 183kg

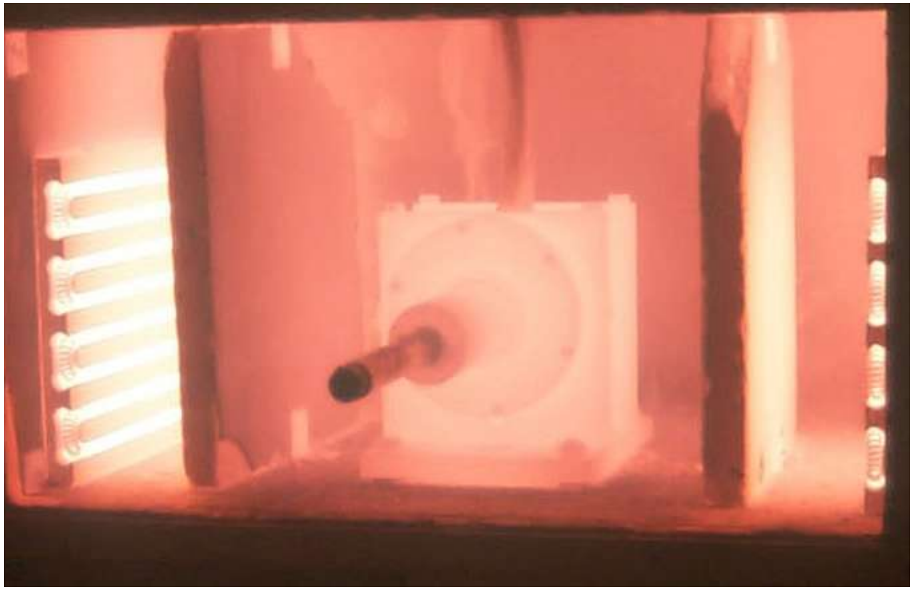
Power to weight ~ 1.36kW / kg of active mass

High temperature application of PM materials



Ultra high temperature actuator



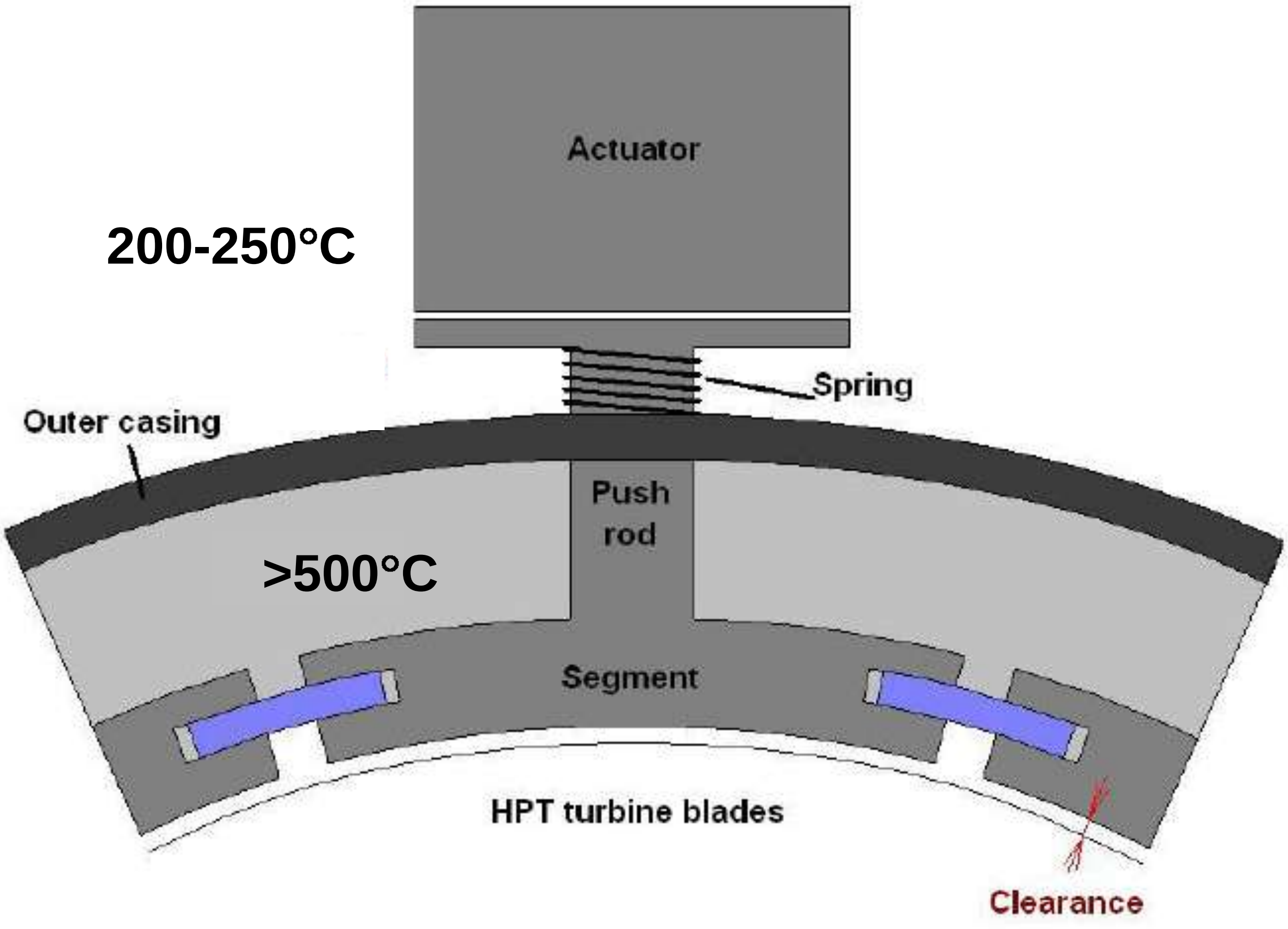


Operates in 800°C ambient
Pure reluctance actuator
24% Cobalt Iron stator and armature cores
Mica insulated wire (not viable long-term)

High temperature wires

- VonRoll Isola - SK 650
  - Mica tape wound nickel-plated copper wire (500°C)
- CGP - Cerafil 500
  - nickel-plated copper alloy wire with ceramic insulation (450°C)
- Fujikura - Fujithermo A
  - nickel-plated copper wire with convertible ceramic insulation and protective layer (400°C)

Typical turbine tip clearance actuation system



Clearance Variation - Symmetrical

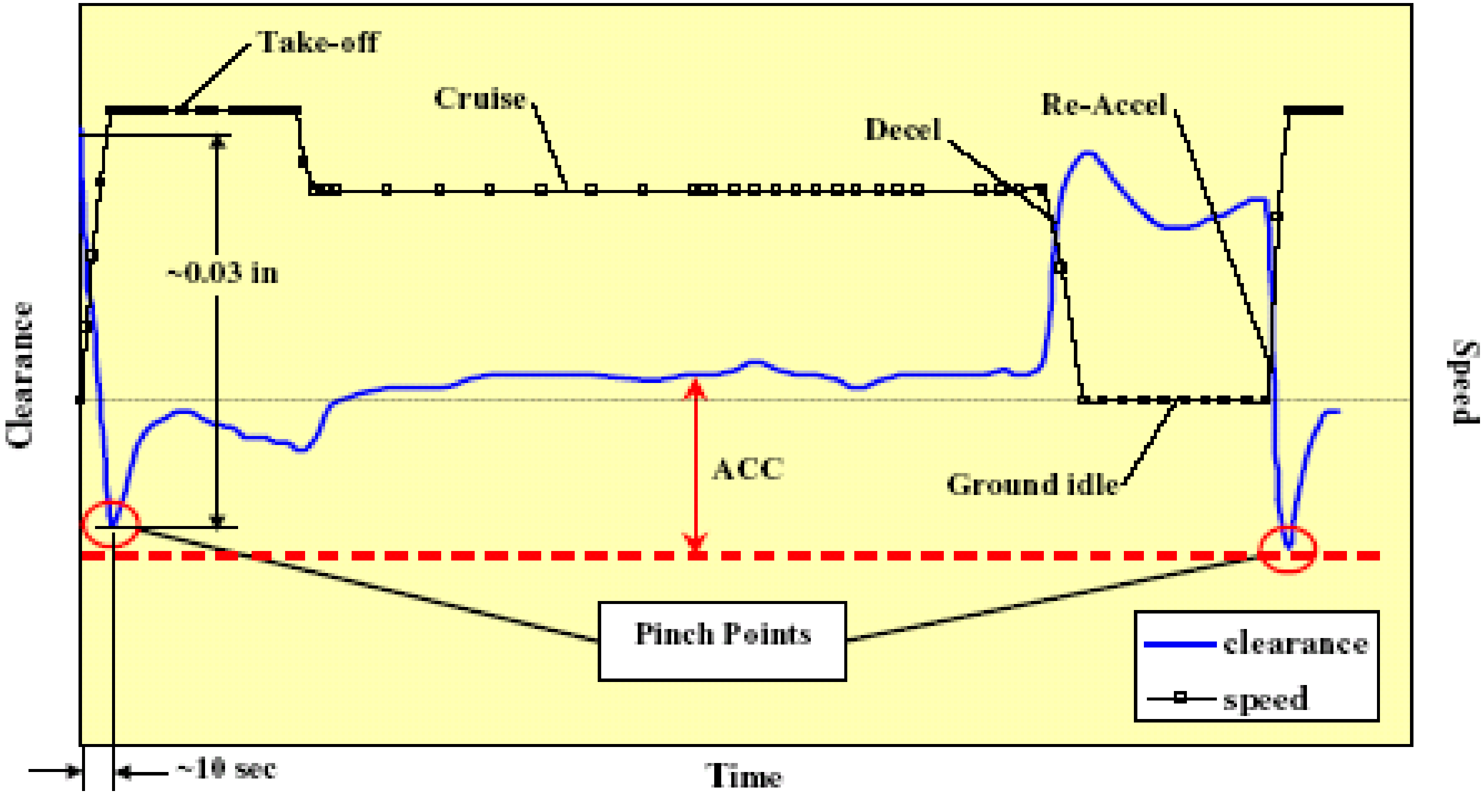


Figure 4: HPT tip clearance as a function of time over a given mission profile

Source : Lattime, S.B., and Steinetz, B.M., Turbine engine clearance control systems: current Practice and Future Directions, NASA TM-20020211794, July 2002.

Clearance Variation - Asymmetrical

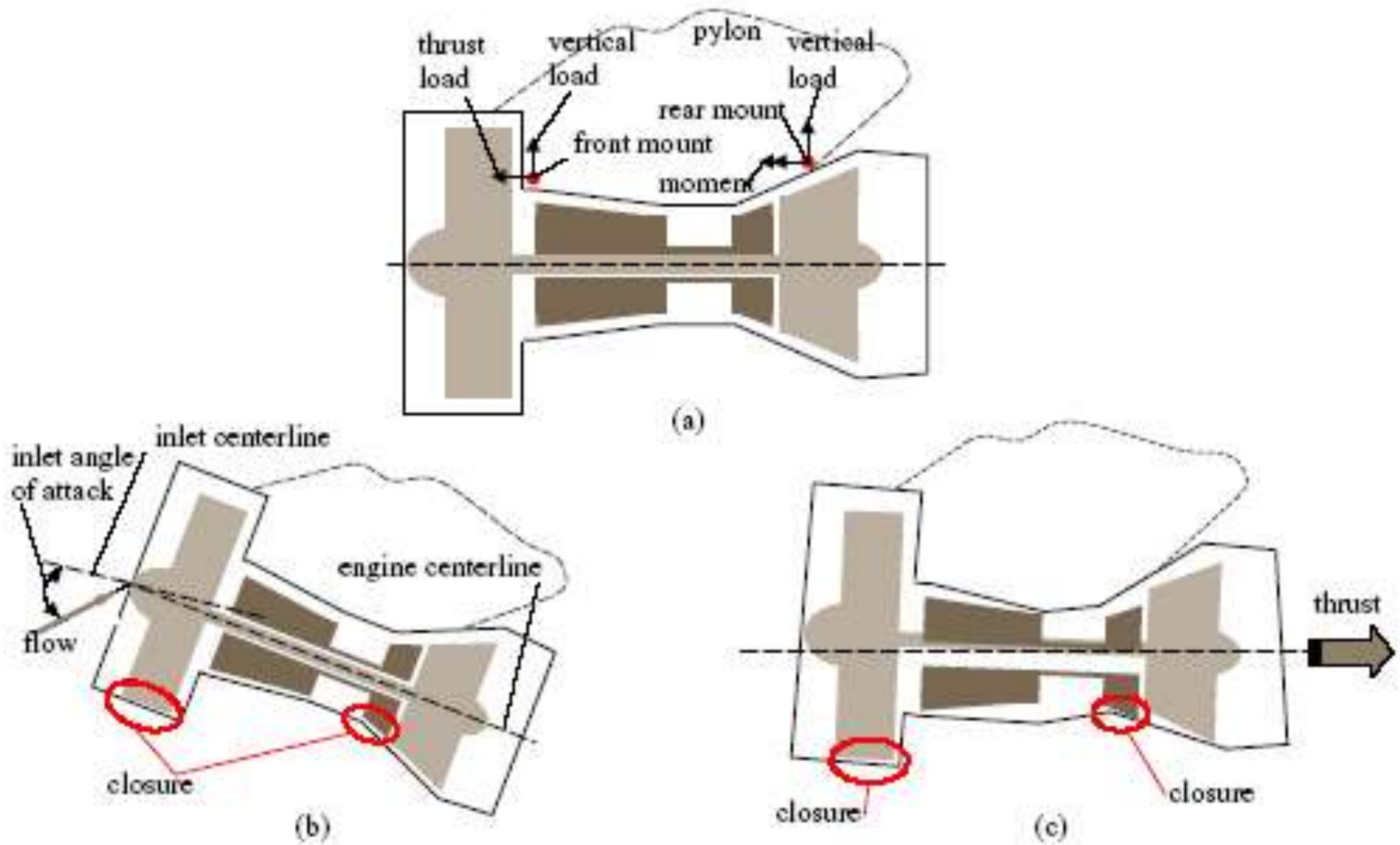


Figure 6: (A) Engine mounts and load paths, (B) Closures due to aero loads, (C) Closures due to thrust loads

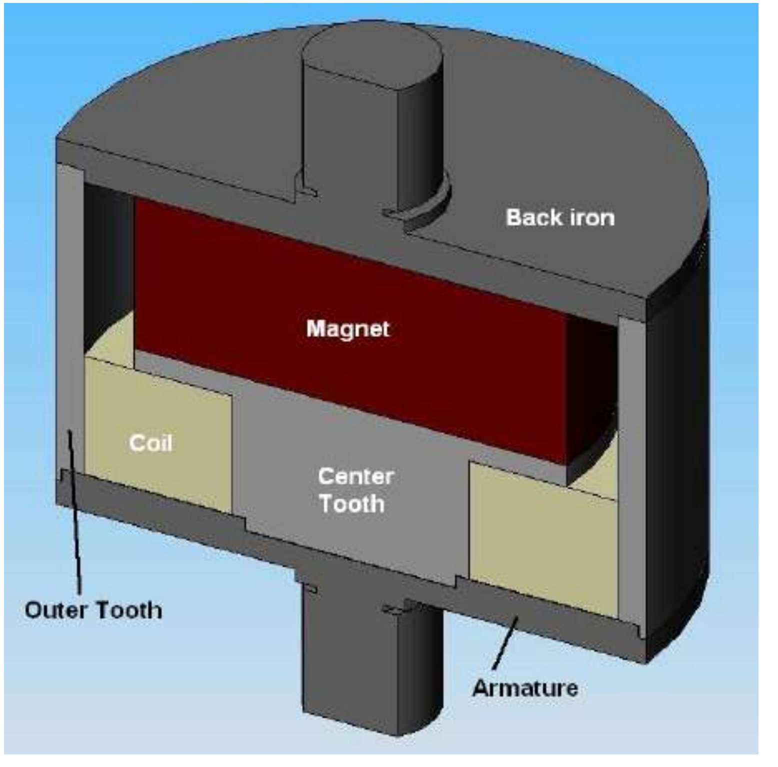
Source : Lattime, S.B., and Steinetz, B.M., Turbine engine clearance control systems: current Practice and Future Directions, NASA TM-20020211794, July 2002.

Features of application

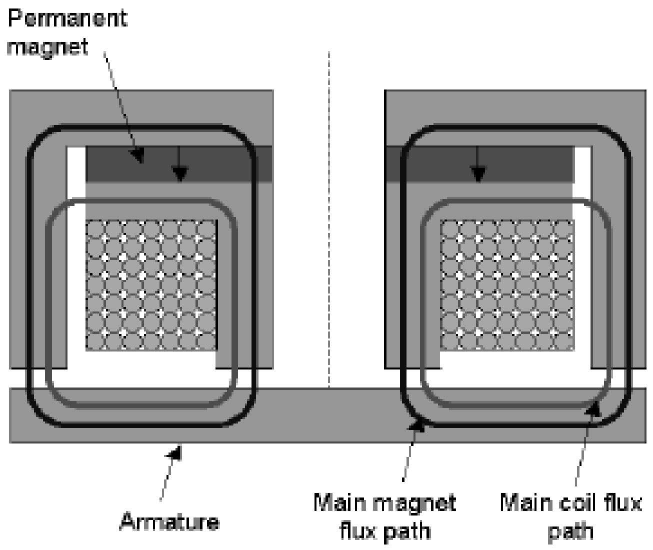
- High temperature environment – high temperature wire and modest current densities
- Modest strokes (up to a few mm) – normal force actuators may be preferred
- Relatively slow response required (100s of ms)– solid cores
- Very precise positional control required – hysteresis could be difficult to accommodate
- High forces (several kN) – highly dependant on degree of pressure balancing employed
- Predictable and benign failure mode – fail outwards in turbine
- Nominal force specification of 1kN at 2mm (part of a general study comparing different actuator technology specifications)

Permanent magnet polarised reluctance actuators

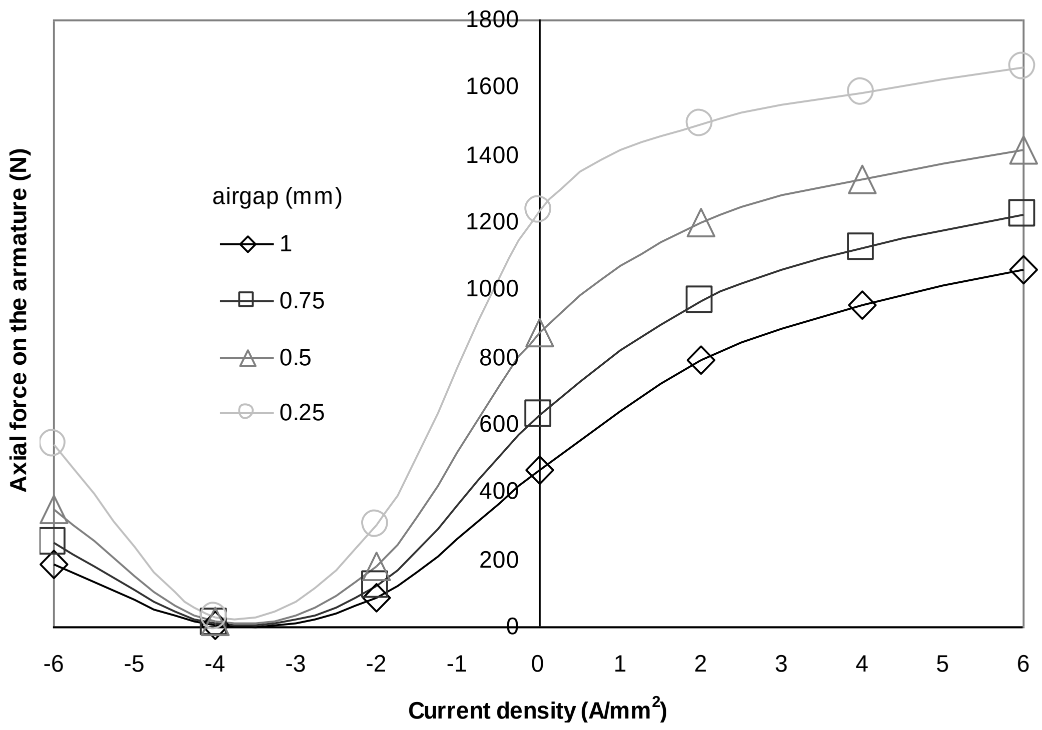
•High holding force with zero current
•Fail to closed position with zero current
•Permanent magnet is located in stator



Basic operating principle



Typical form of characteristic (not this design study)



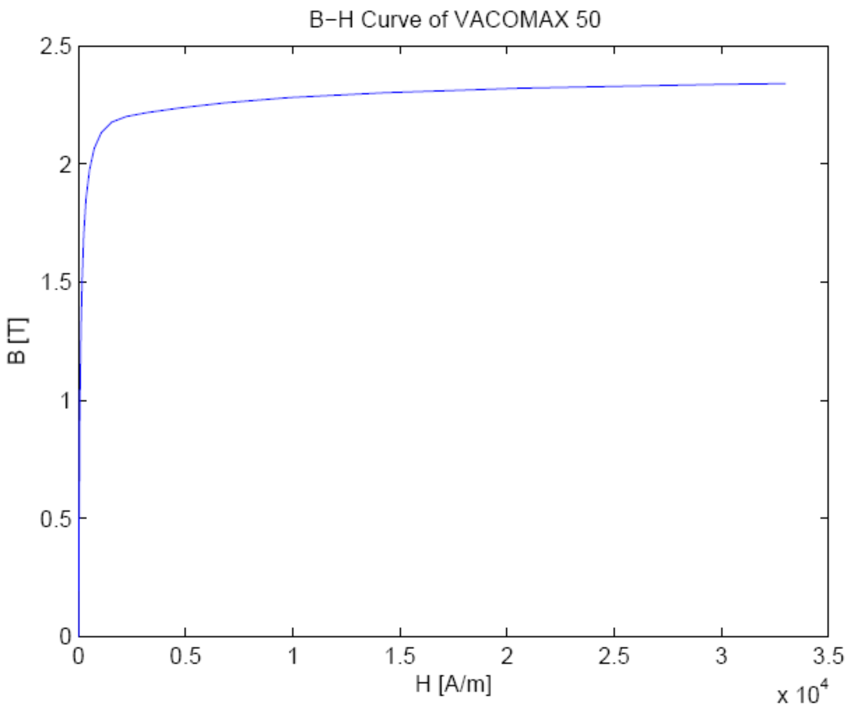
Current can aid or oppose PM flux

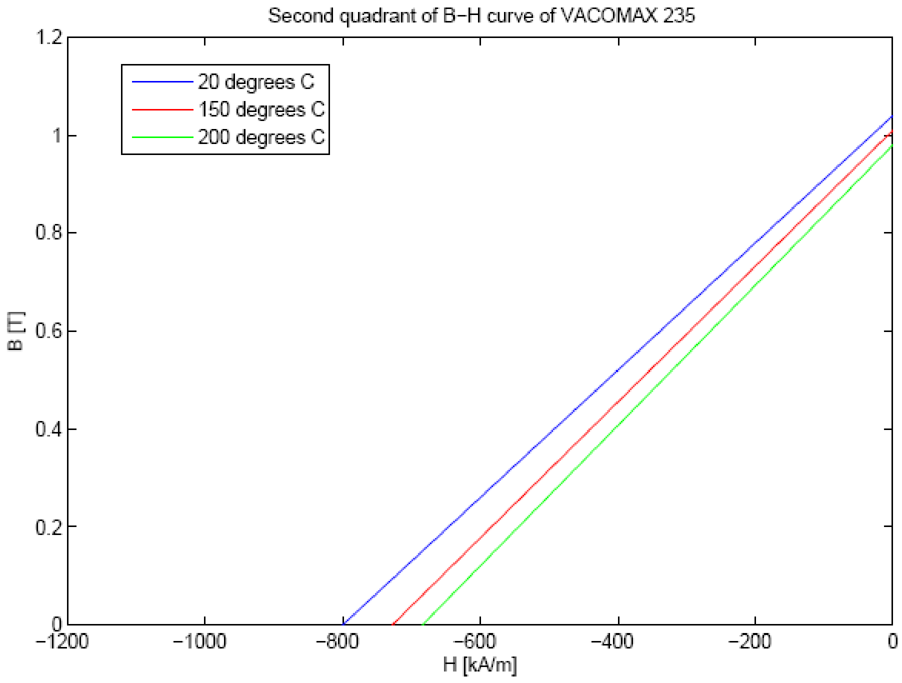
Electromagnetic design involves many trade-offs

Magnetic materials

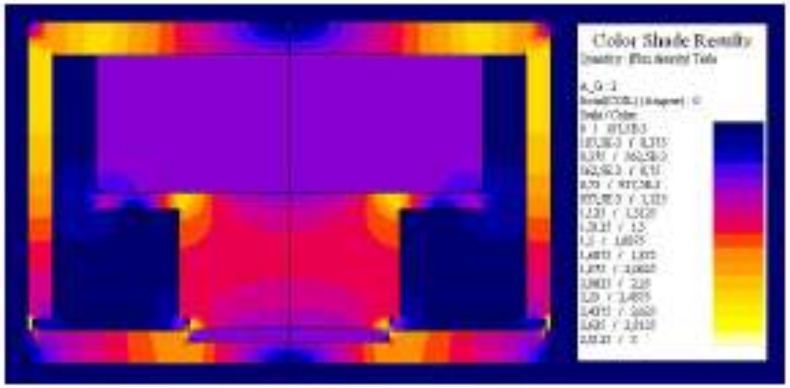
49% Cobalt Iron stator core and armature

Sm_2Co_{17} magnets

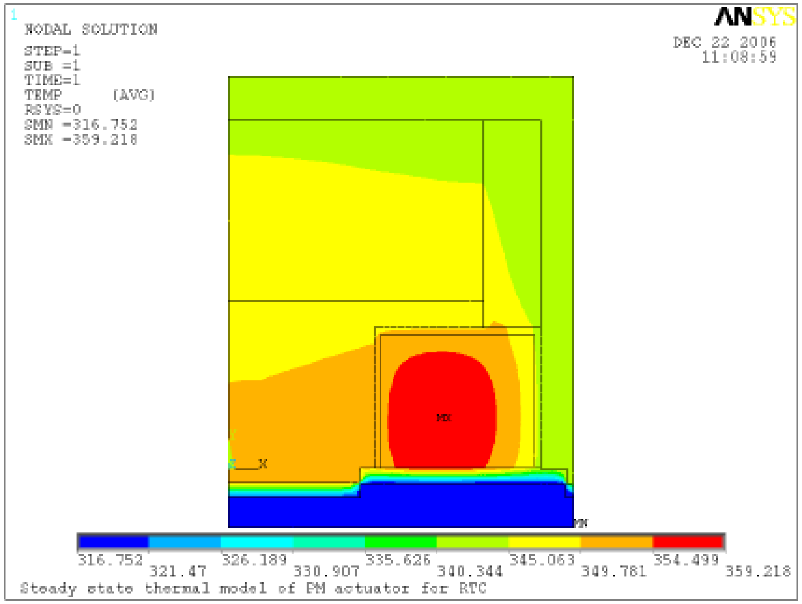




Electromagnetic and thermal design optimisation



FLUX2D

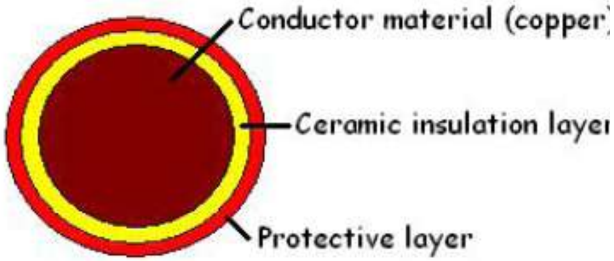


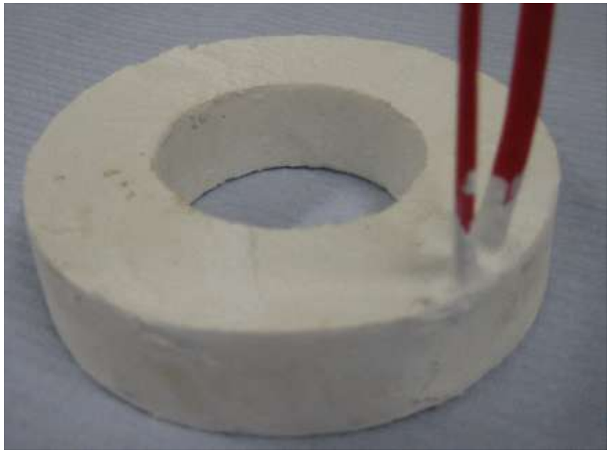
ANSYS

2.84kg – 350N/kg

Fujithermo A – high temperature wire

Ceramic coated wire
Continuous maximum temperature rating of 420°C

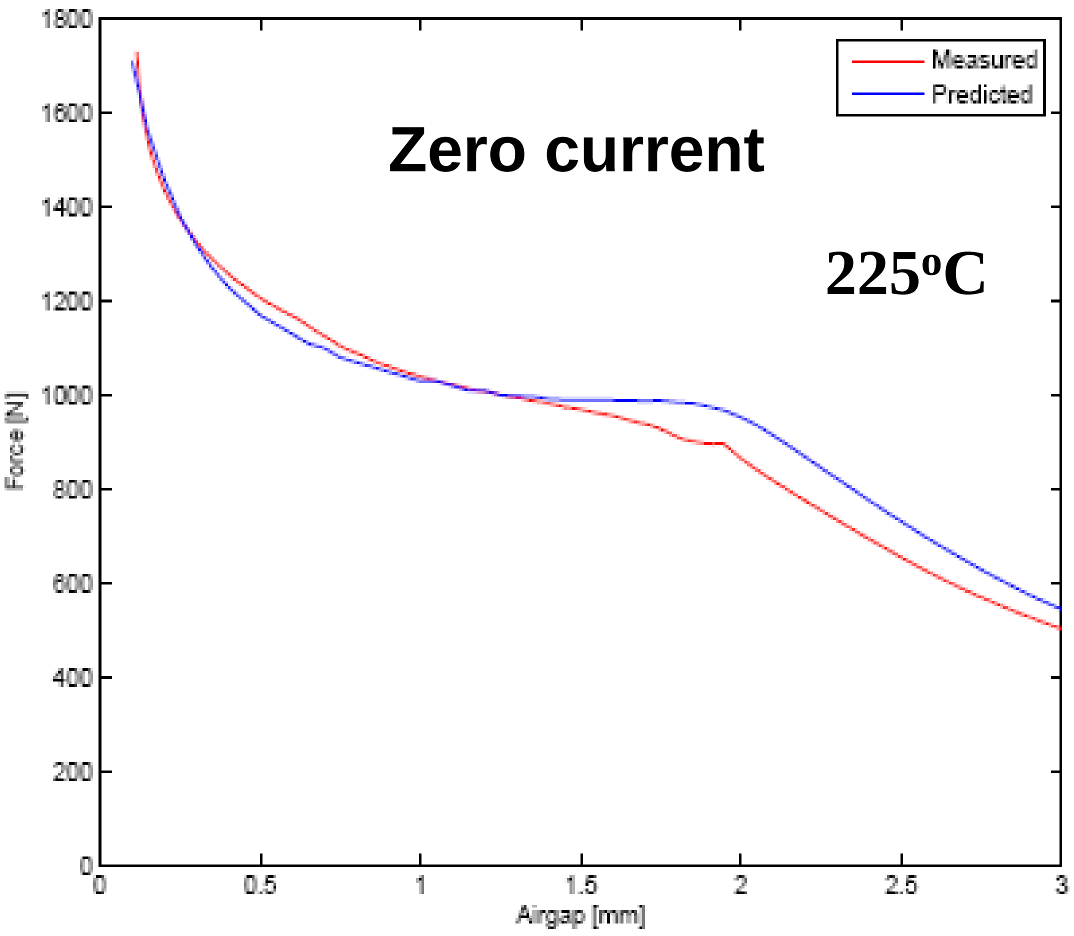




Experimental measurements

- Characterised on an Instron load-frame with 300 °C heater stage
- Eliminates the need for bearings in prototype

Experimental measurements at 225ºC ambient



Experimental measurements at 225ºC ambient