3. Electric Motors and Hybrids

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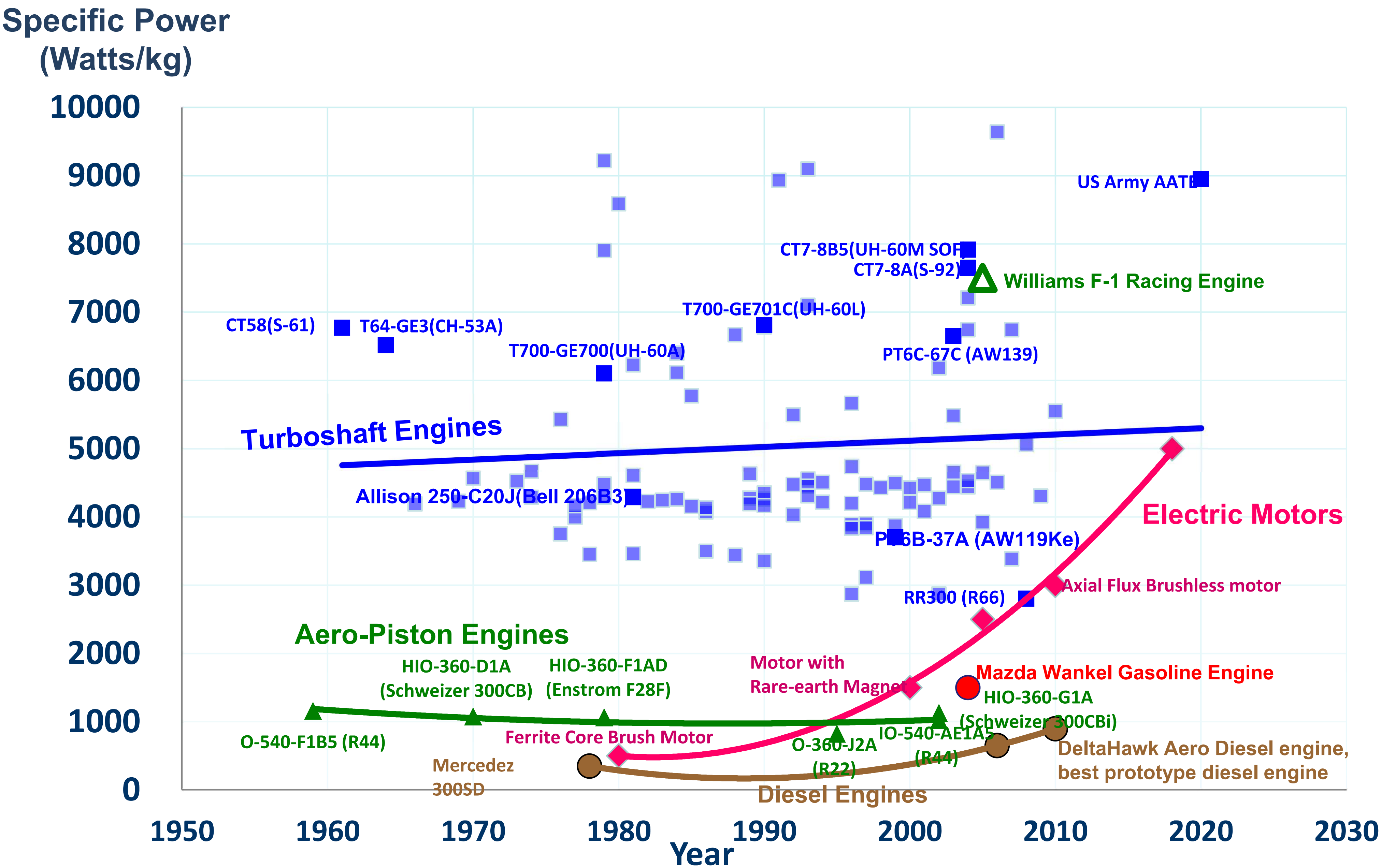
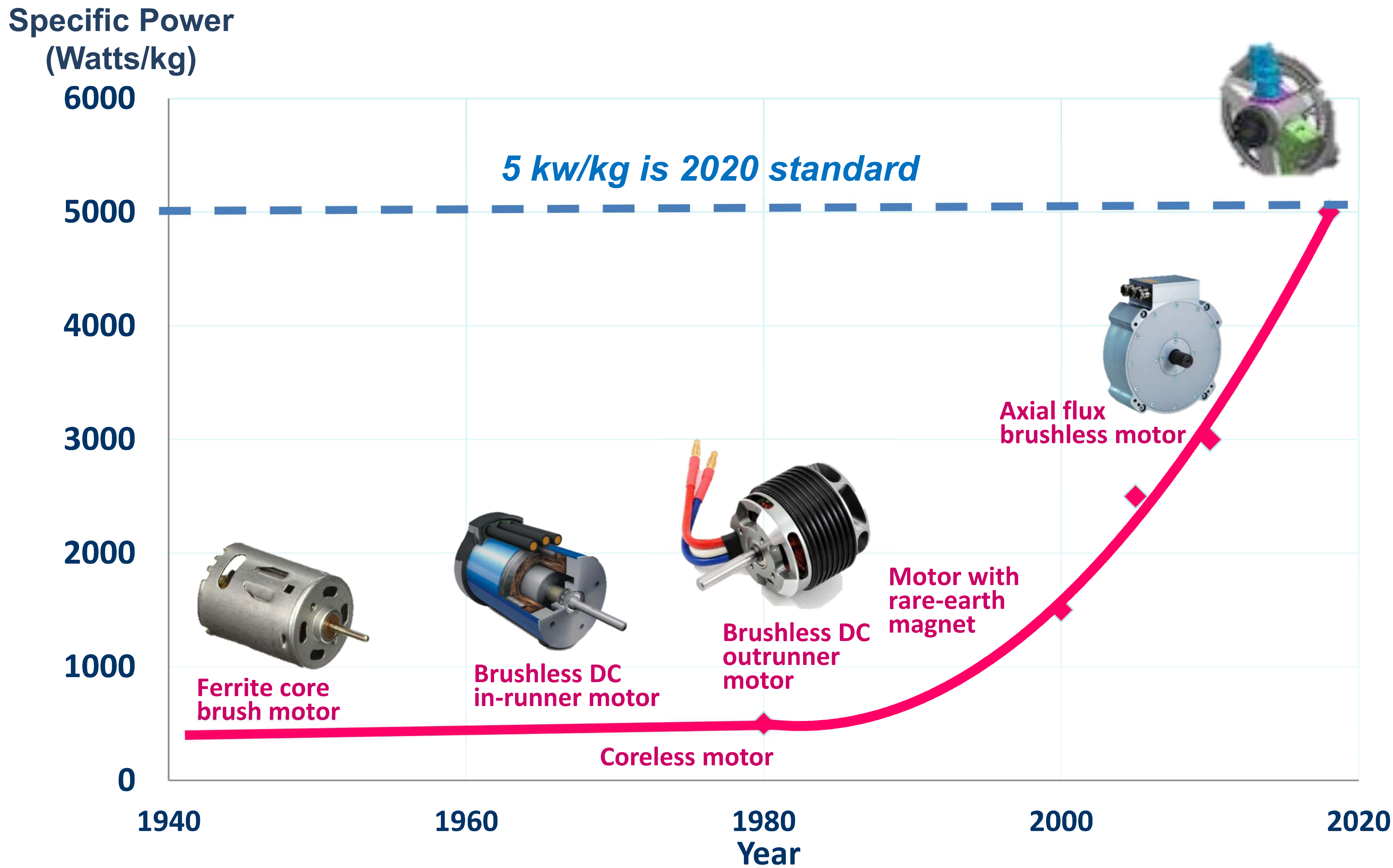
Propulsion Specific Power Trend



Note, 746 watts = 1 horsepower

Electric Motor Specific Power Trend



Note, 746 watts = 1 horsepower

Direct Electric Drive Has Many Benefits

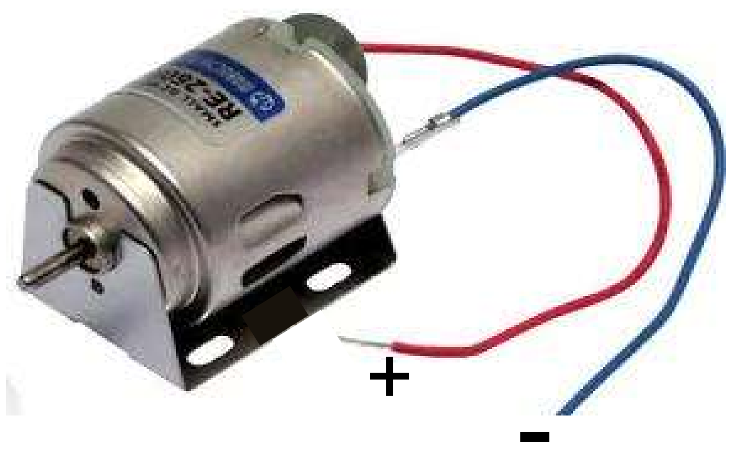
- 92-95% efficiency continuously
- 30% overpower for few min.
- No gearbox needed
- Easy to vary rotor rpm
- Instantaneous response
- Few moving parts
- Low noise
- No polluting exhaust
- Low thermal signature
- No oxygen combustion, altitude independent

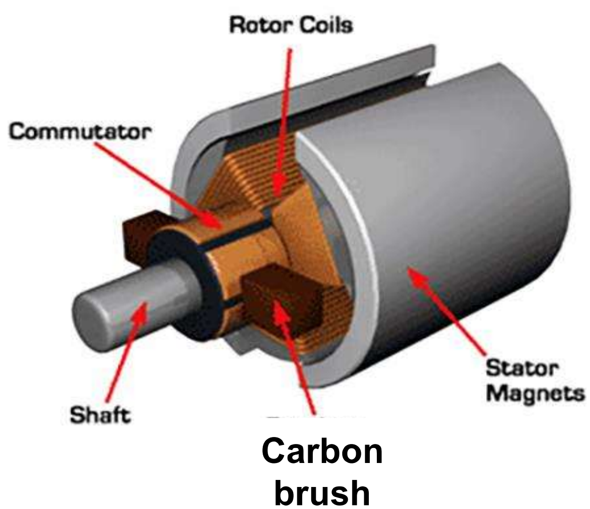
Unlike turbine helicopters, electric power requires no warm up, on instantly. Great for UAM, emergency rescue, police and special operations.

Different Types of Motors

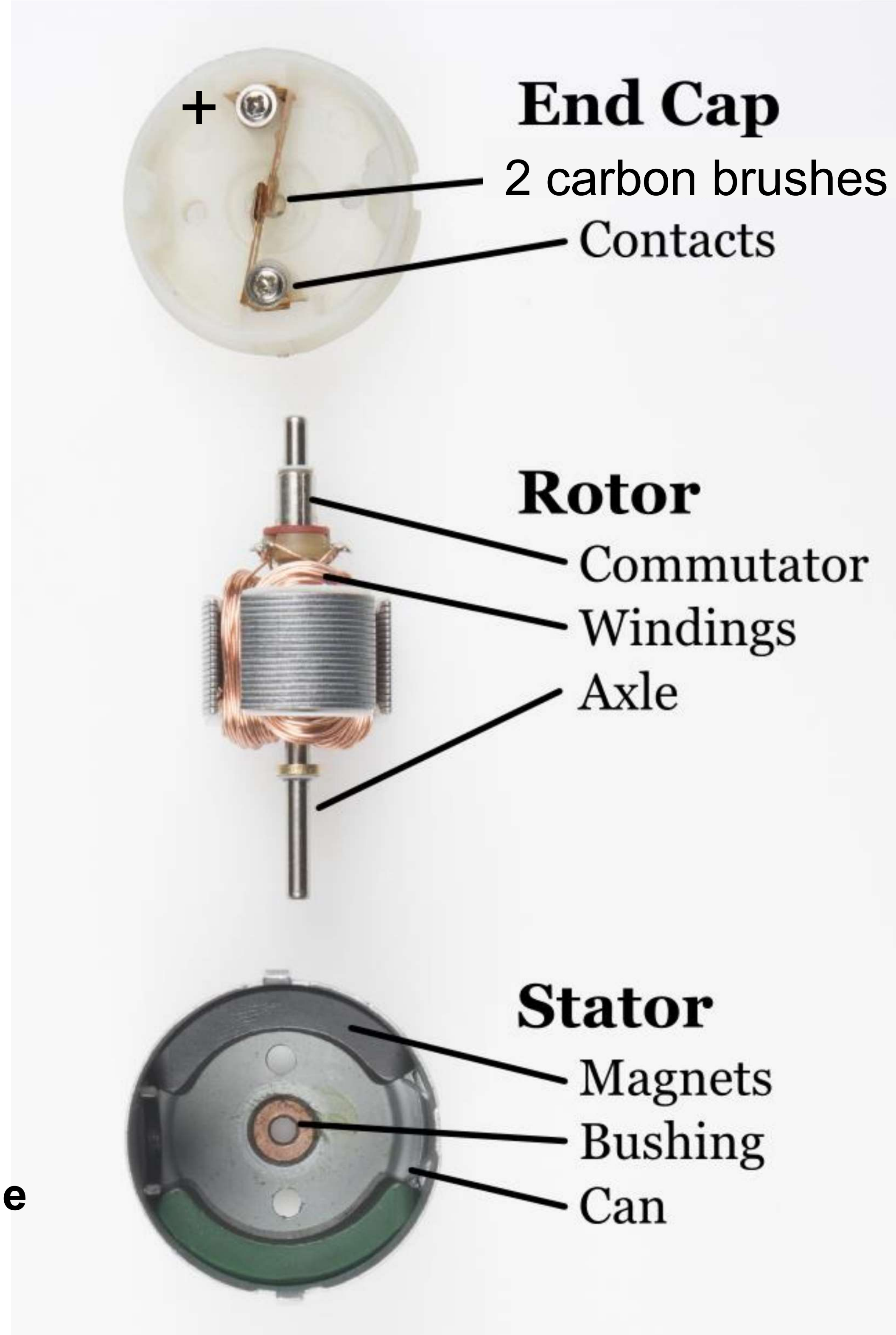
1. DC Brushed Motors (19th century)
2. DC Brushless Motors (1960s)
3. AC Brushless Motors
4. Direct Drive
5. Linear Motors
6. Servo Motors
7. Stepper Motors

1. DC Brushed Motors





- Use DC voltage. Simple 2 wires
- Controls rpm by voltage
- Reverse direction by reverse voltage
- Carbon brushes wear with usage



Disadvantages of DC Brush Motors

- Friction of the brushes sliding along the rotating commutator segments causes power losses

- Soft brush material wears down creating dust Difficult to replace brushes for sealed or maintenance-free applications.

- Electrical resistance of the sliding brush contact causes a voltage drop which consumes energy.

- Repeated abrupt switching of the current through the inductance of the windings causes sparks at the commutator contacts, which is a fire hazard in explosive atmospheres and a source of electronic noise.

2. DC Brushless Motors

Made possible by the development of solid state electronics in the 1960s.

Also known as Electronically Commutated Motor (ECM or EC motor) and synchronous DC motors, are synchronous motors powered by direct current (DC) electricity via an inverter or switching power supply which produces electricity in the form of alternating current (AC) to drive each phase of the motor via a closed loop controller. The controller provides pulses of current to the motor windings that control the speed and torque of the motor. This control system replaces the commutator (brushes) used in many conventional electric motors.

The construction of a brushless motor system is typically similar to a Permanent Magnet Synchronous Motor (PMSM), but can also be a switched reluctance motor, or an induction (asynchronous) motor.

DC Brushless Motors

In-runner type

The spinning rotor with the magnet is at the center.

The armature (stator and wire winding) is stationary on the circumference.

Outrunner type

The spinning rotor is the outer casing with magnet.

The armature (stator and wire winding) is stationary at the center.

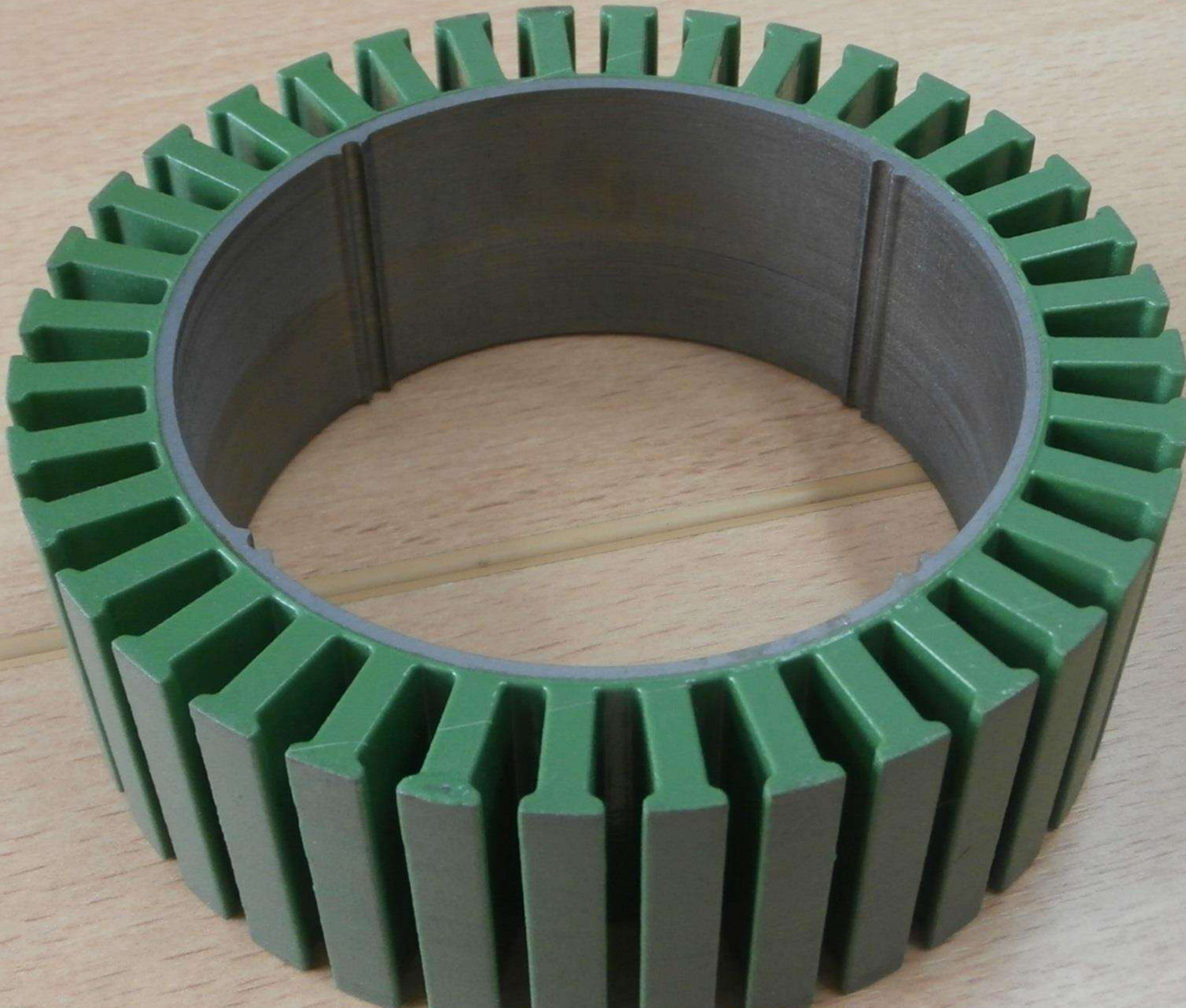
Brushless outrunner motor

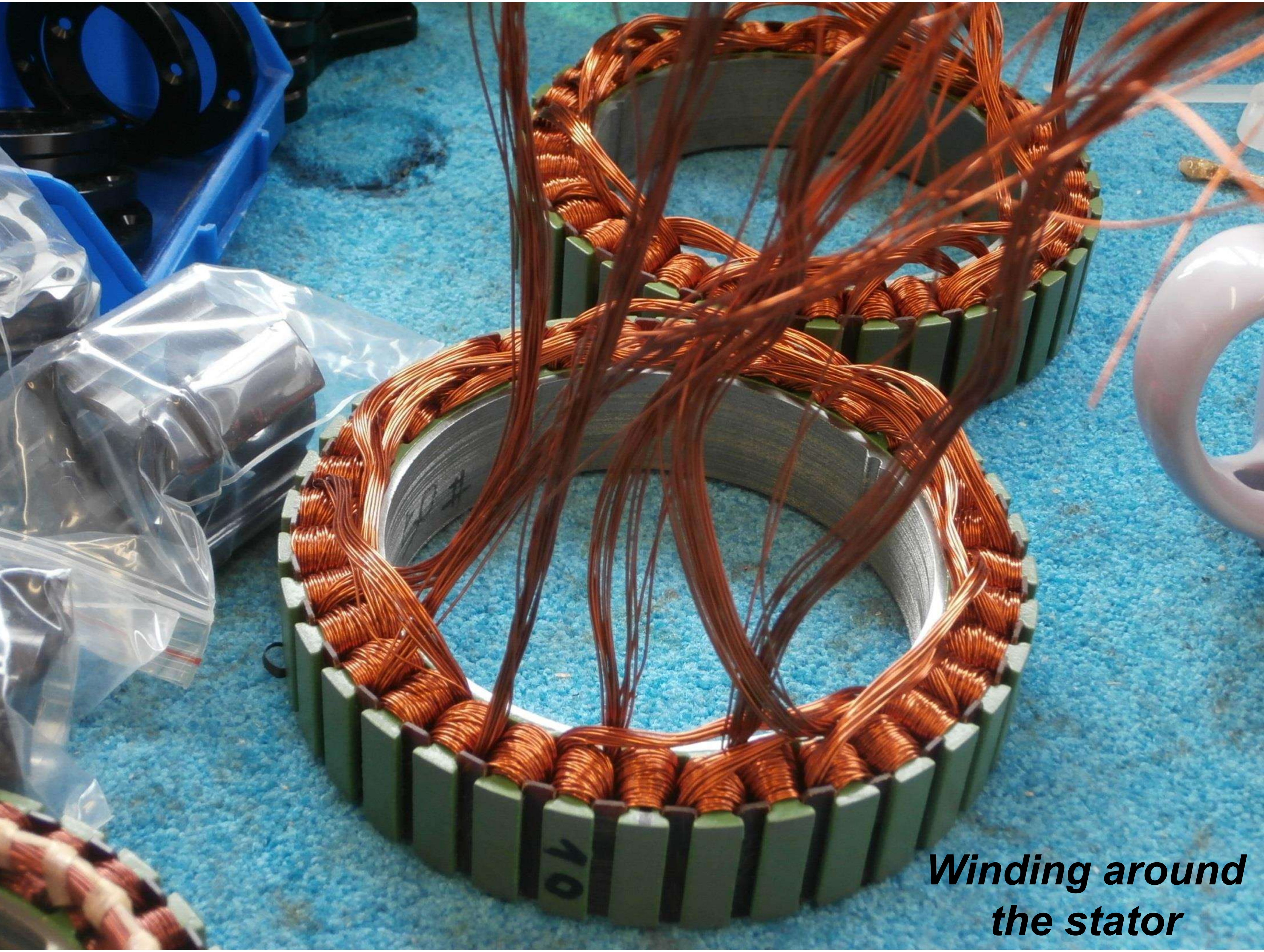
Inside of DC Brushless, 3-Phase, Radial, Out-runner Electric Motors

Electric Motor Buzz Words

- **Stator**
- **Winding**
- **Rotor**
- **Magnetic poles**
- **Brushless and brushed**
- **Kv (rpm/volt)**
- **Timing**
- **Idle current and impedence**

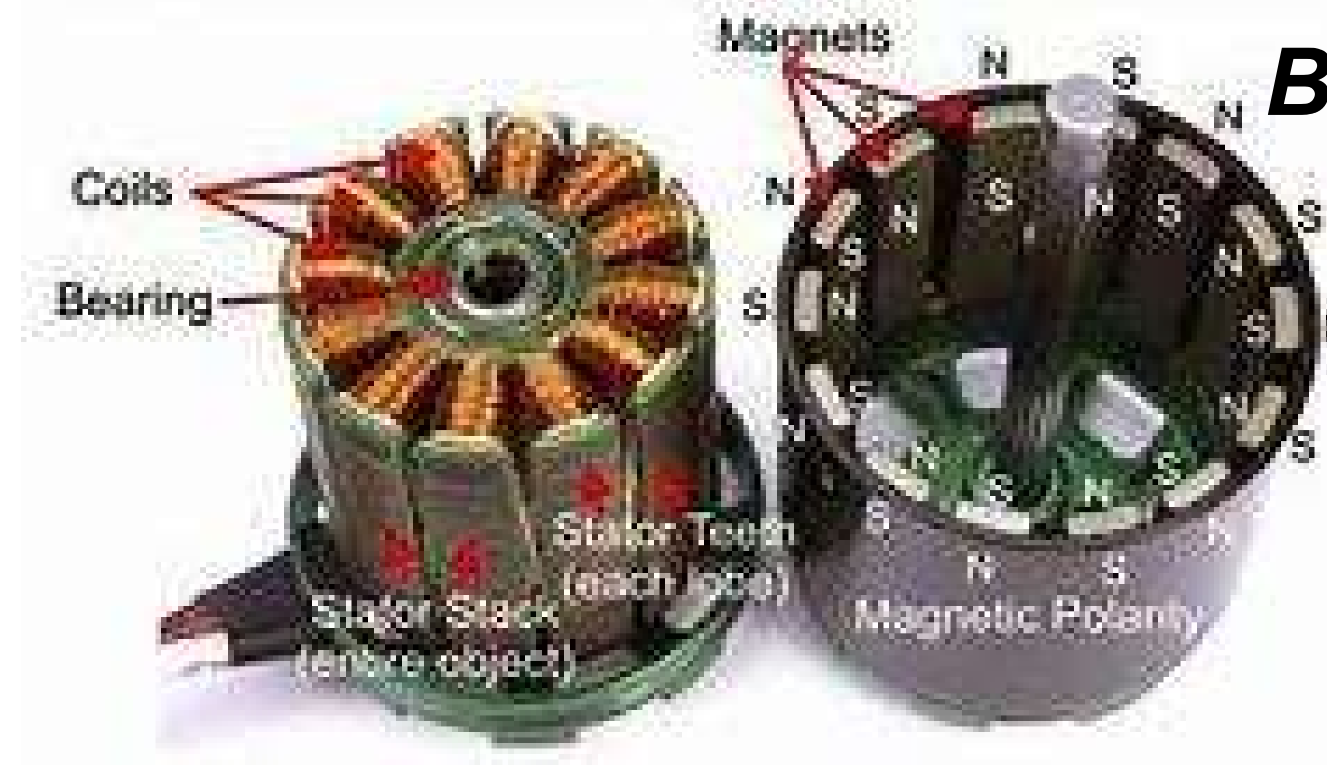
Stator is Made From Iron



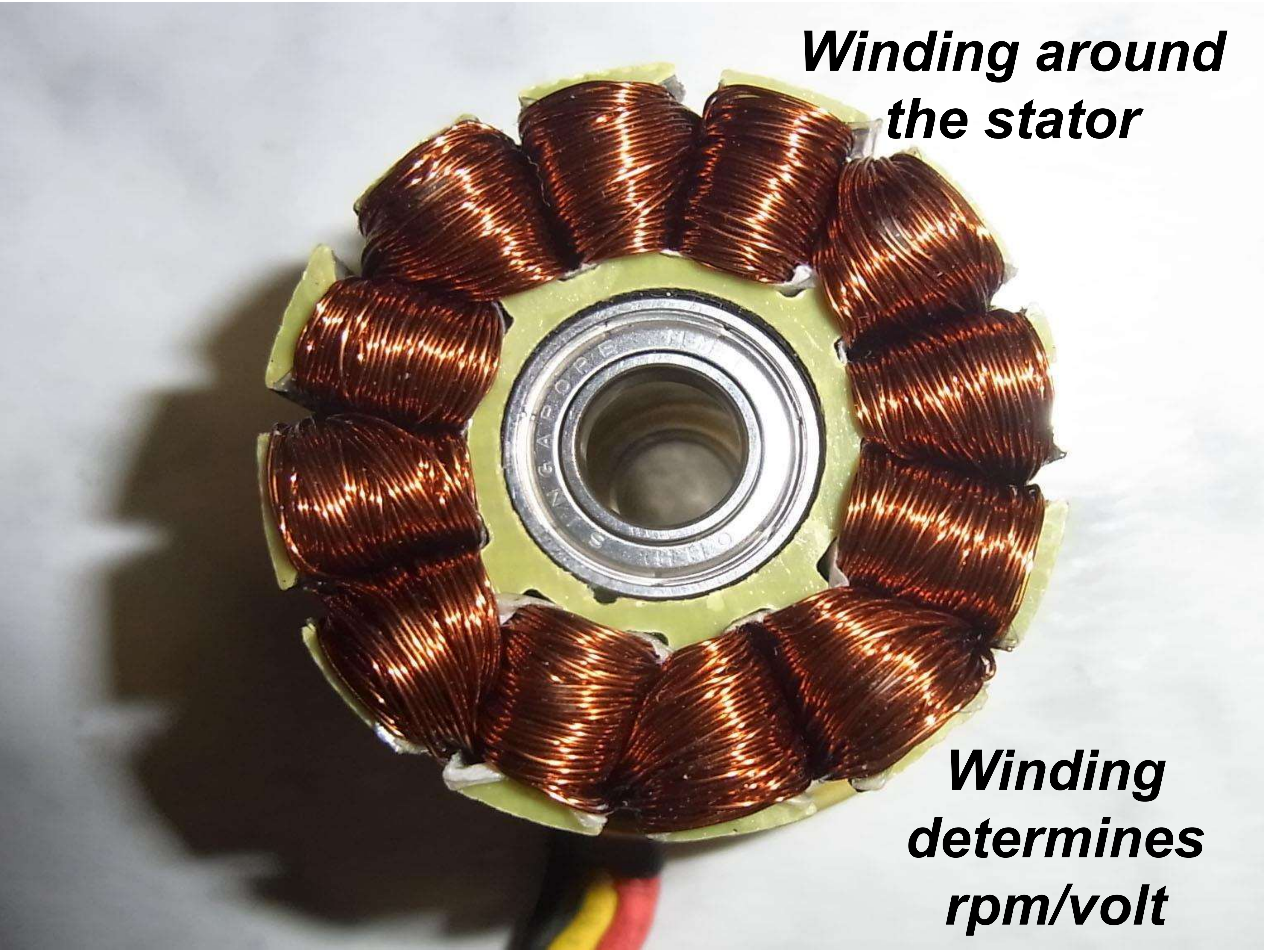


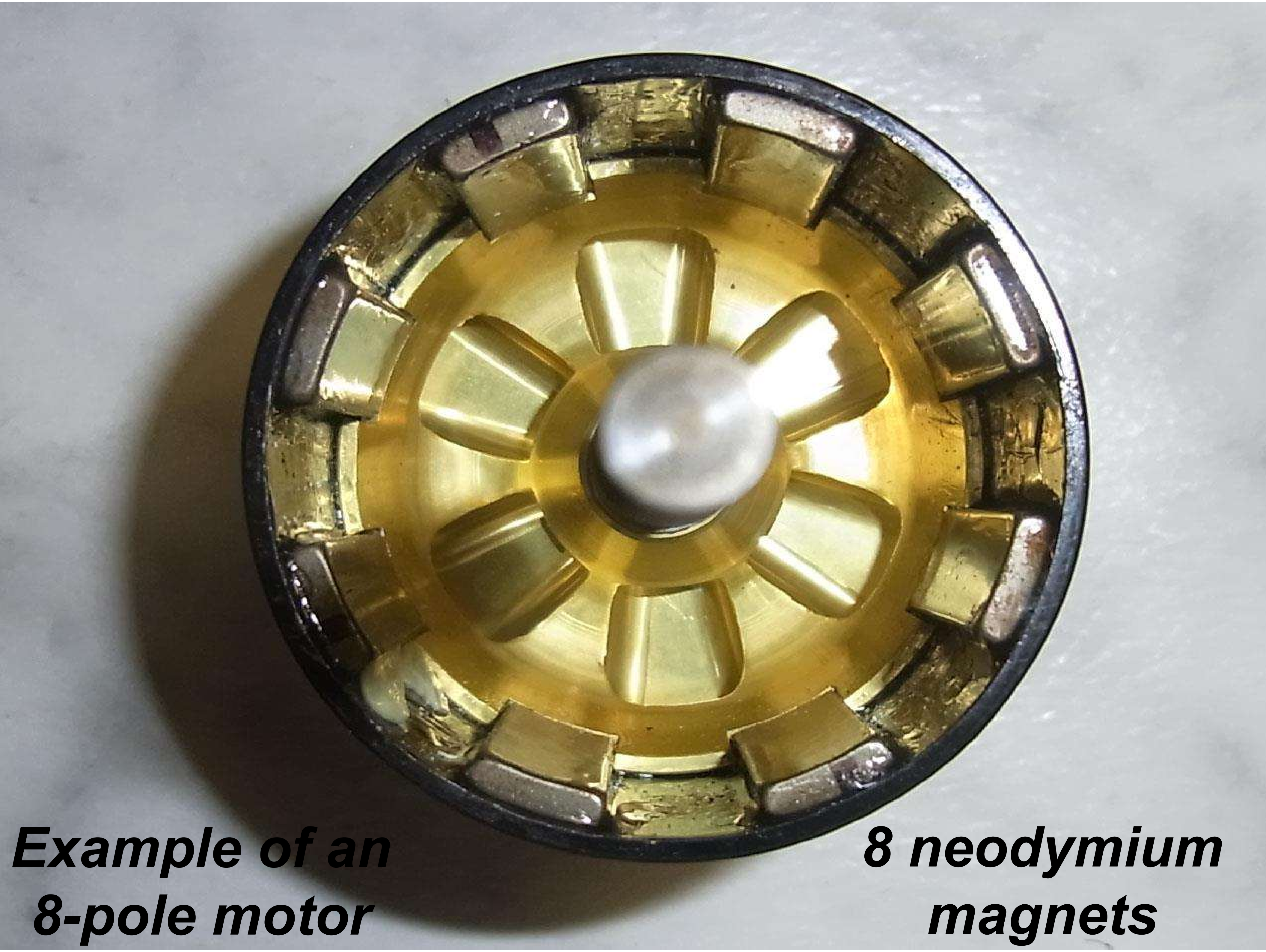
Winding around the stator


Different Sizes

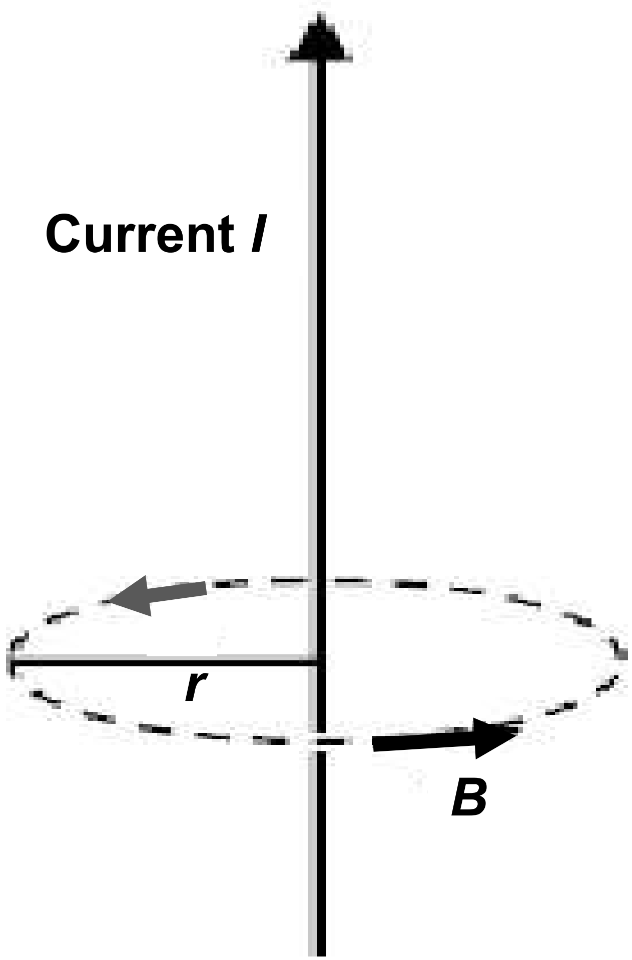


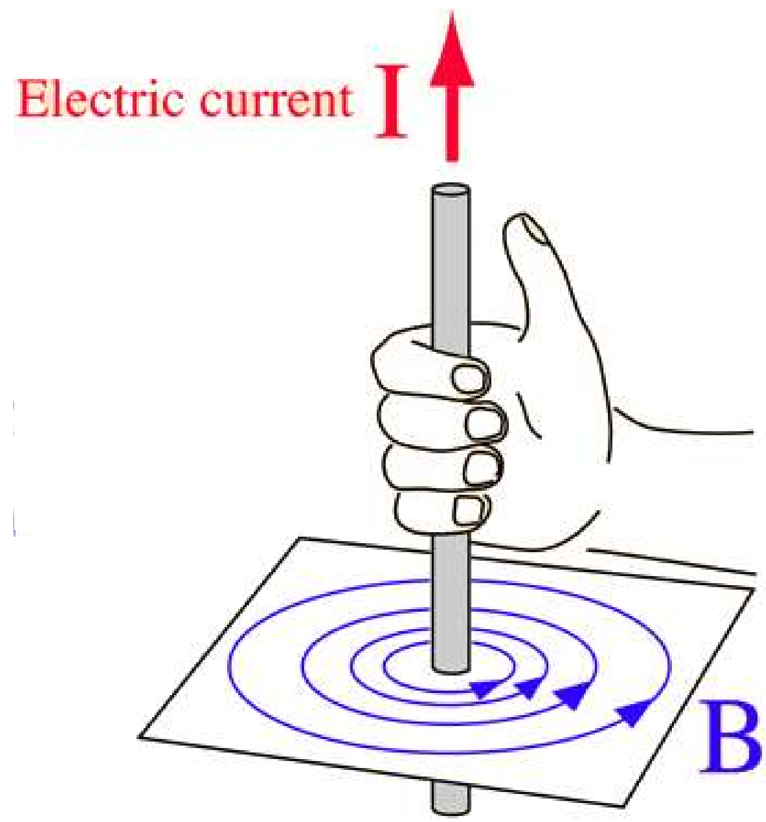
Brushless 3-phase motor components


Winding around the stator
Winding determines rpm/volt


Example of an 8-pole motor
8 neodymium magnets

Ampere's Law - Current flow through a wire will Induce a magnetic field *B* at distance *r*

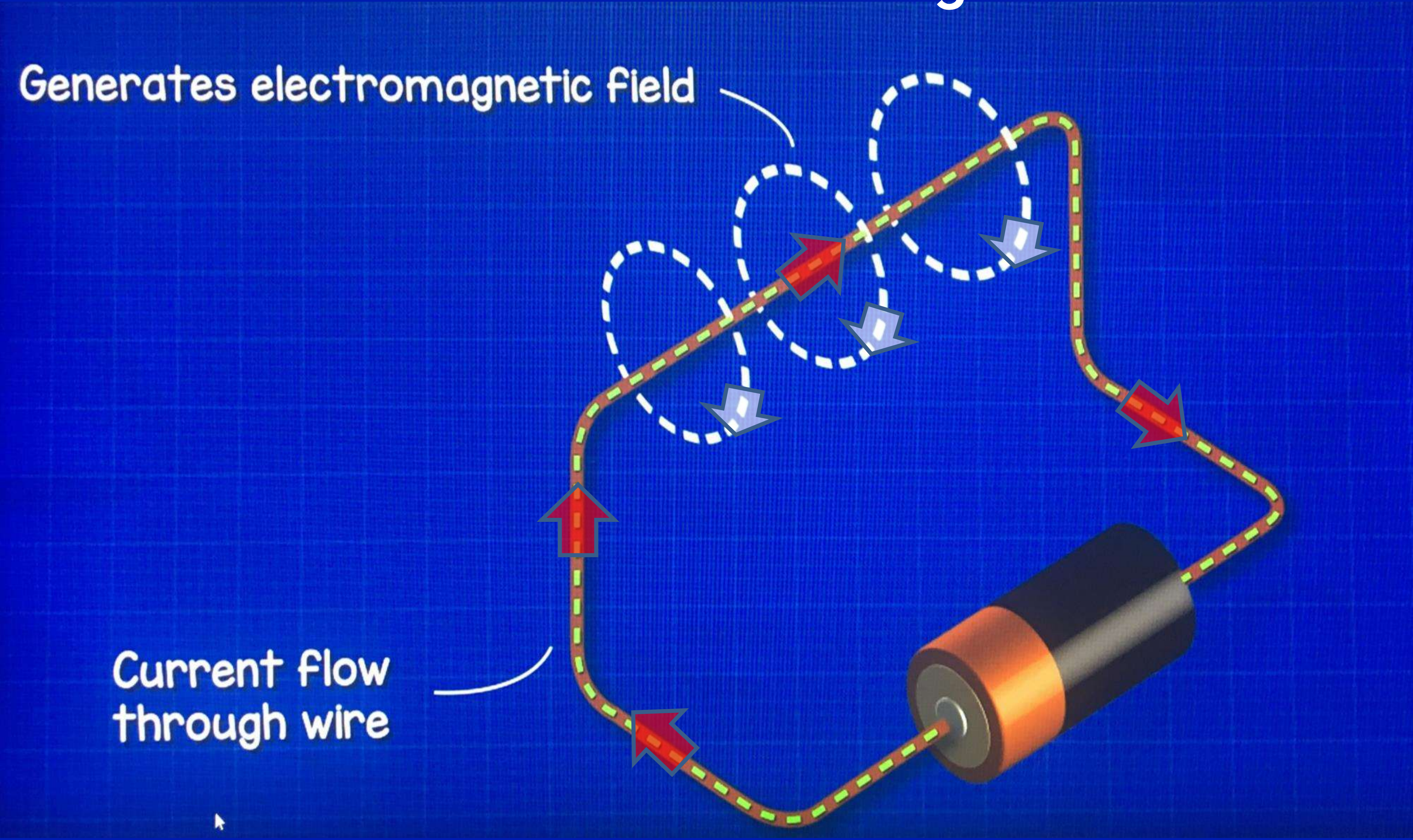




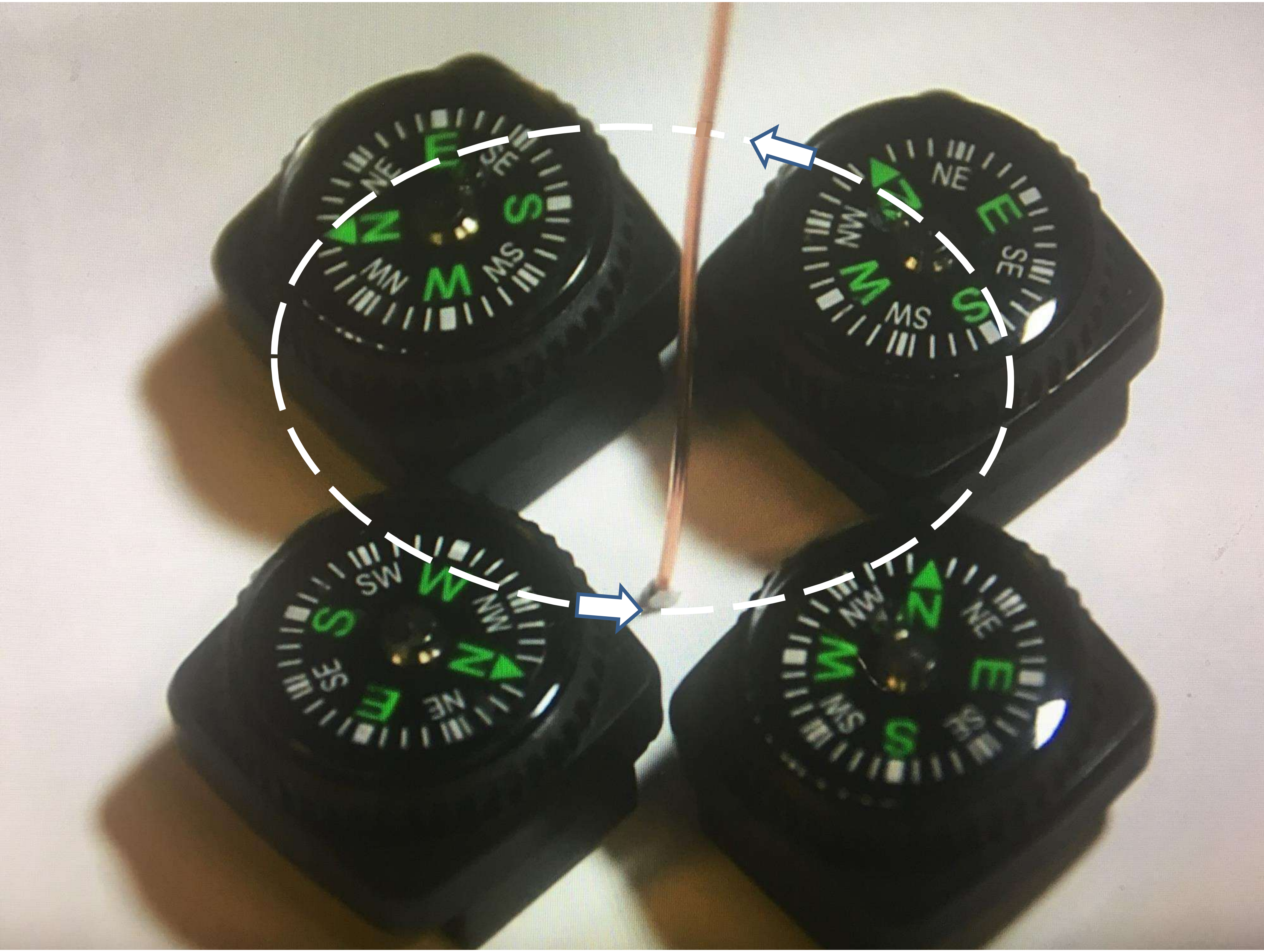
The direction of the magnetic field lines obeys the Biot-Savart Law, right hand rule

Explains Ampere's Law https://www.youtube.com/watch?v=S4uNHue5aNM

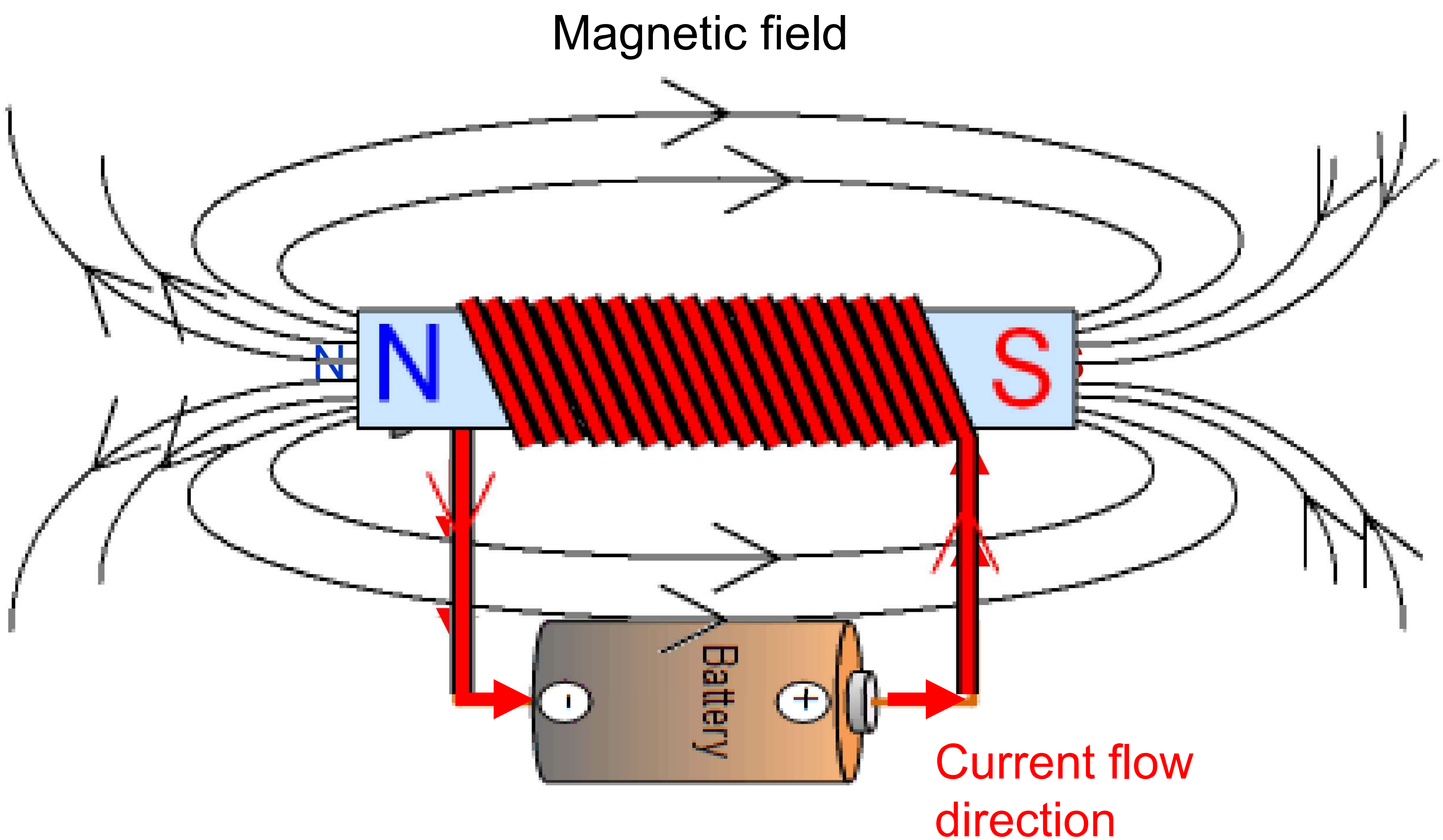
Current Flow Will Induce a Magnetic Field



Source: https://www.youtube.com/watch?v=59HBoIXzX_c



Coiling the Wires Will Produce a Magnetic Flux Through the Center of the Coil and Make it an Electro Magnet



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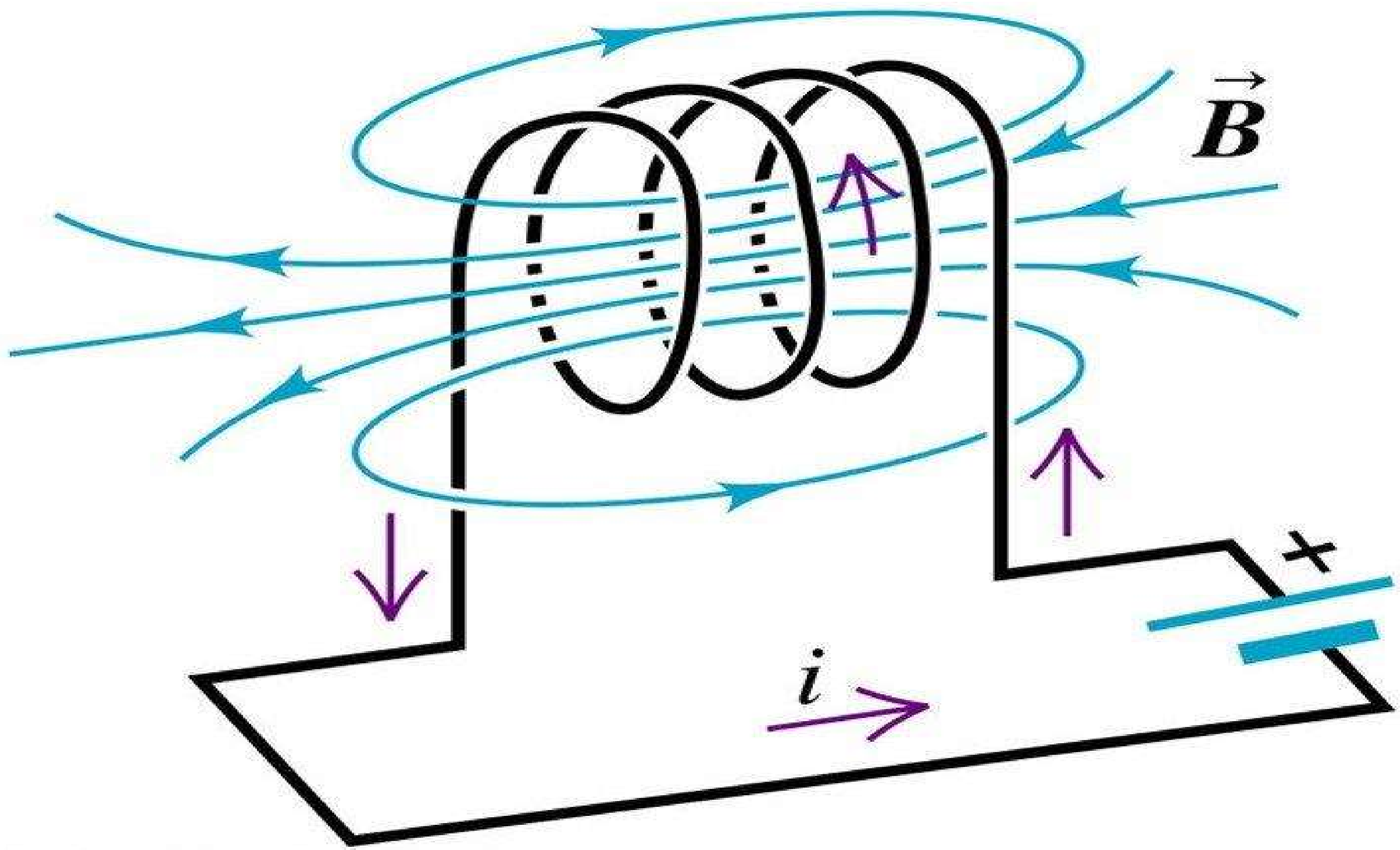
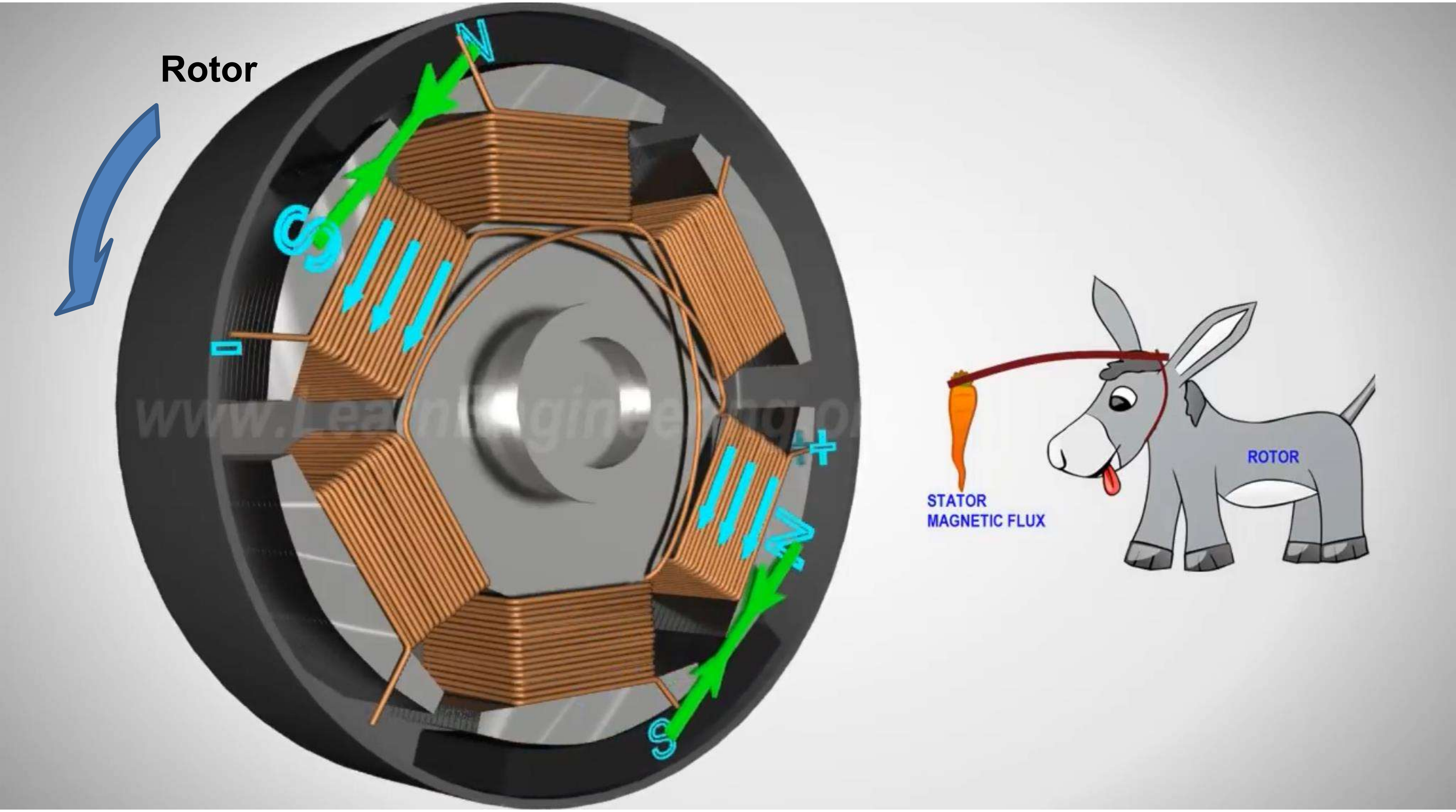
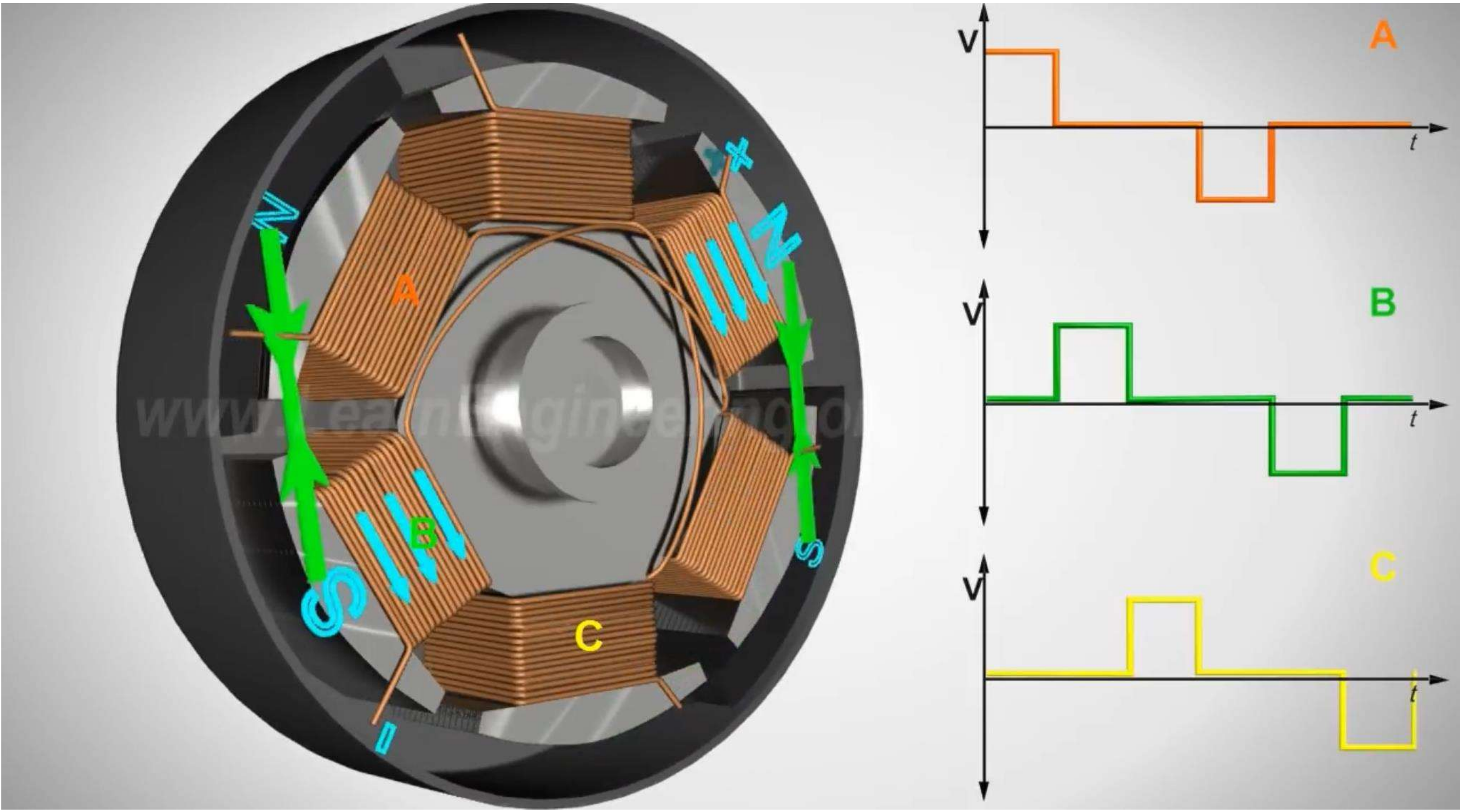


3 Phase DC Brushless Motors



Source: LearnEngineering.com

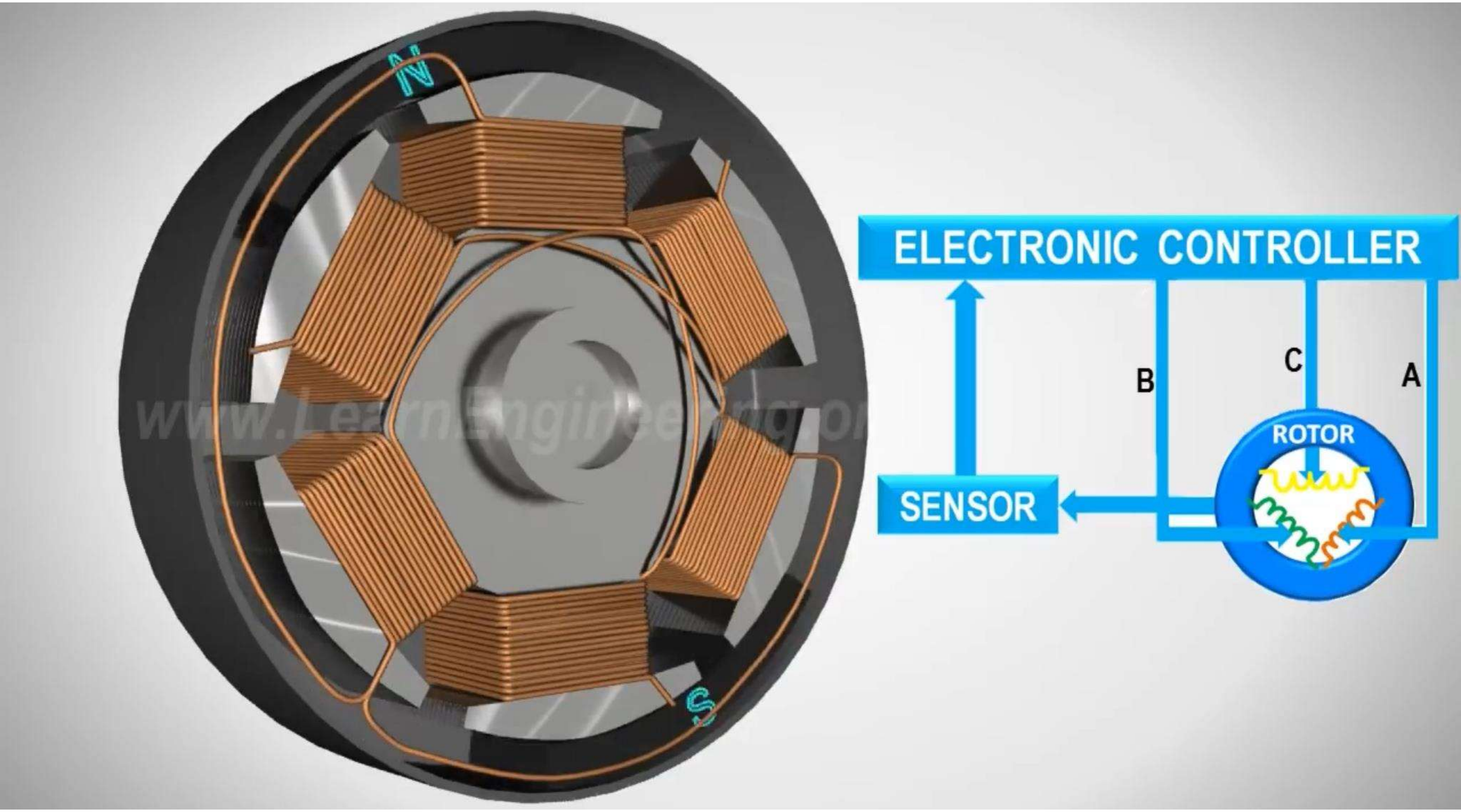
3 Phase DC Brushless Motors



Once the battery voltage is fixed, the frequency of the 3 phases controls the rpm, the current determines the power (P=V×I)

Source: LearnEngineering.com

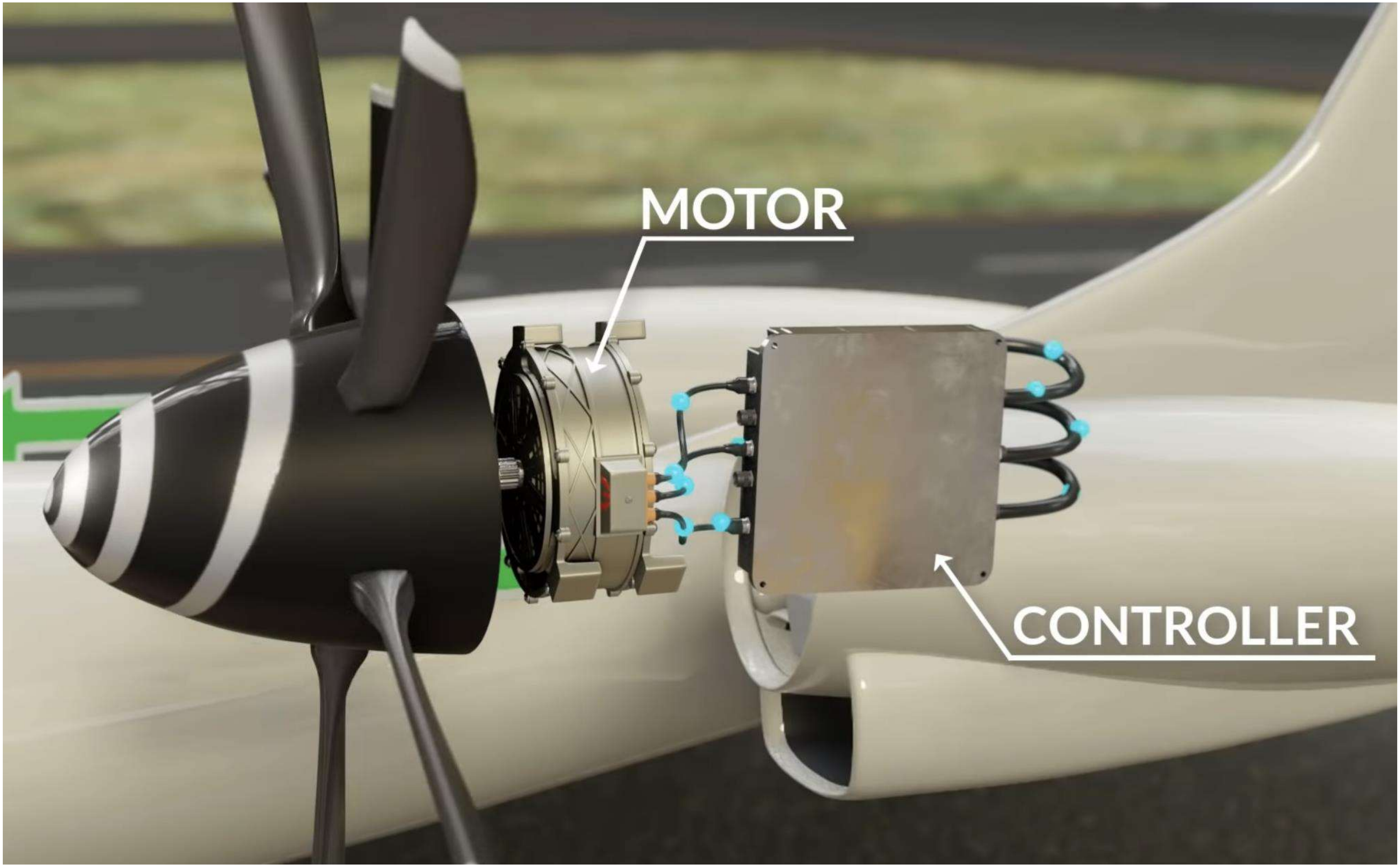
3 Phase DC Brushless Motors



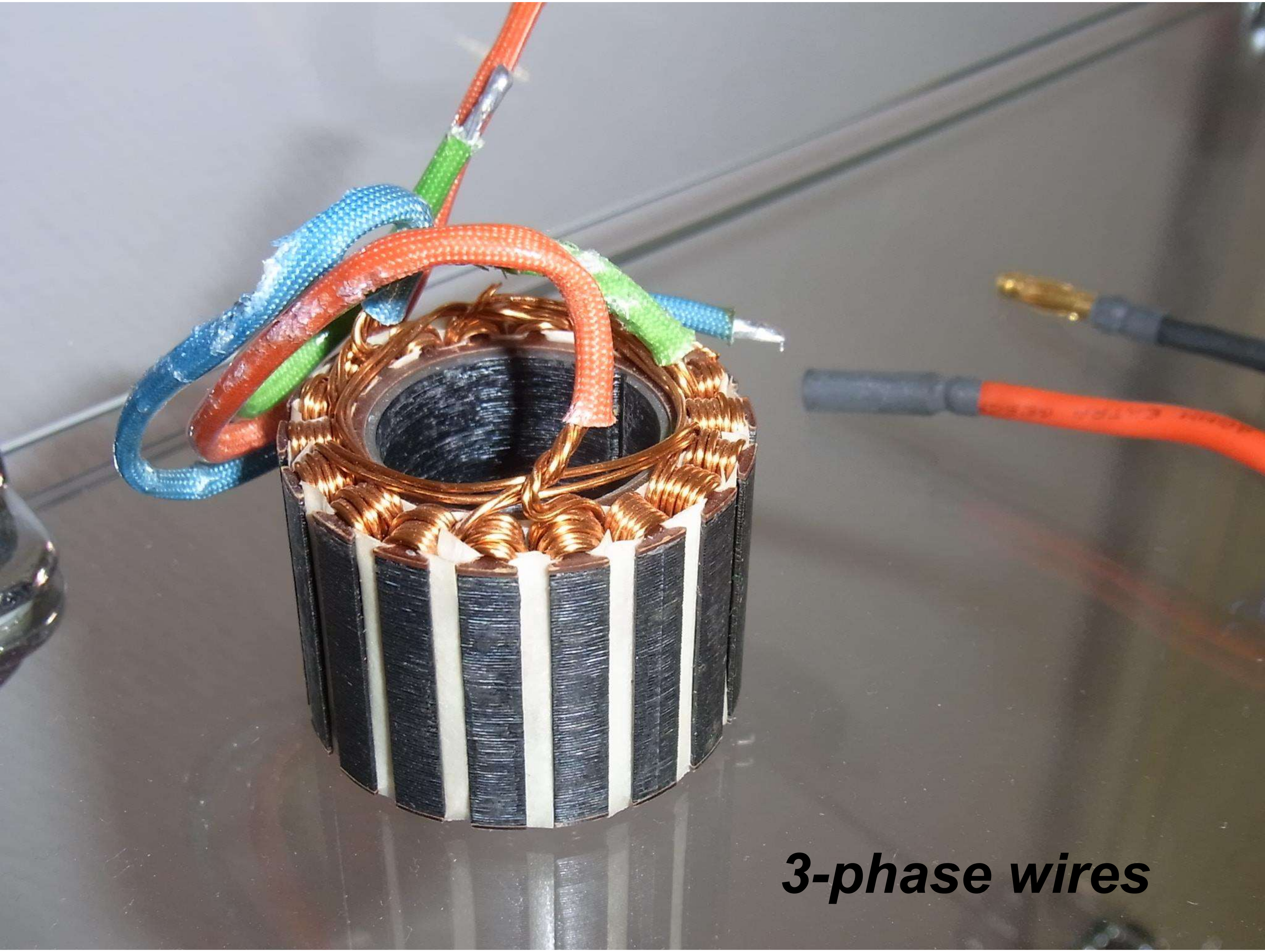
Source: LearnEngineering.com

This explains how Tesla permanent magnet motor works: https://www.youtube.com/watch?v=esUb7Zy5Oio

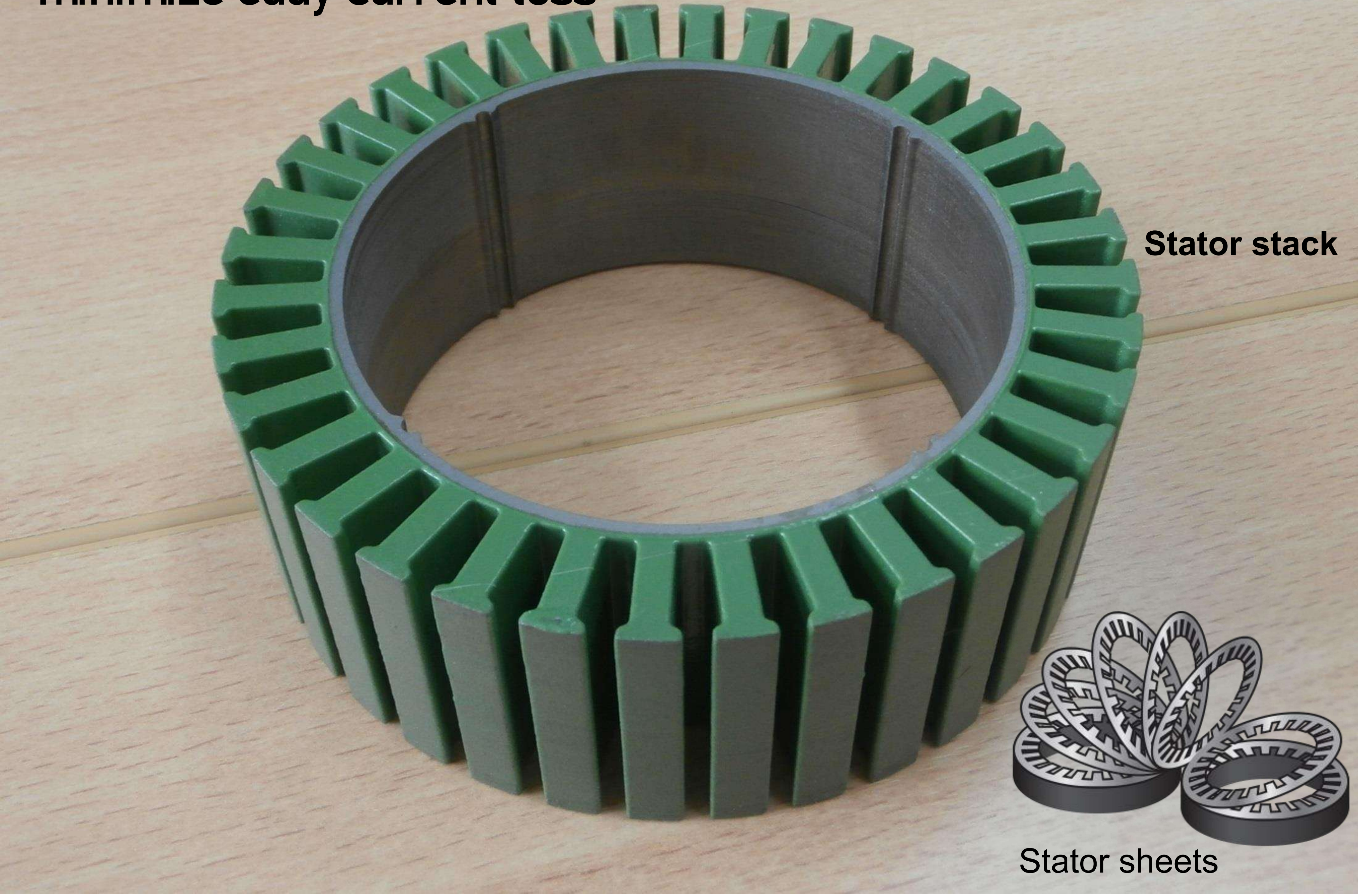
3 Phase DC Brushless Motors



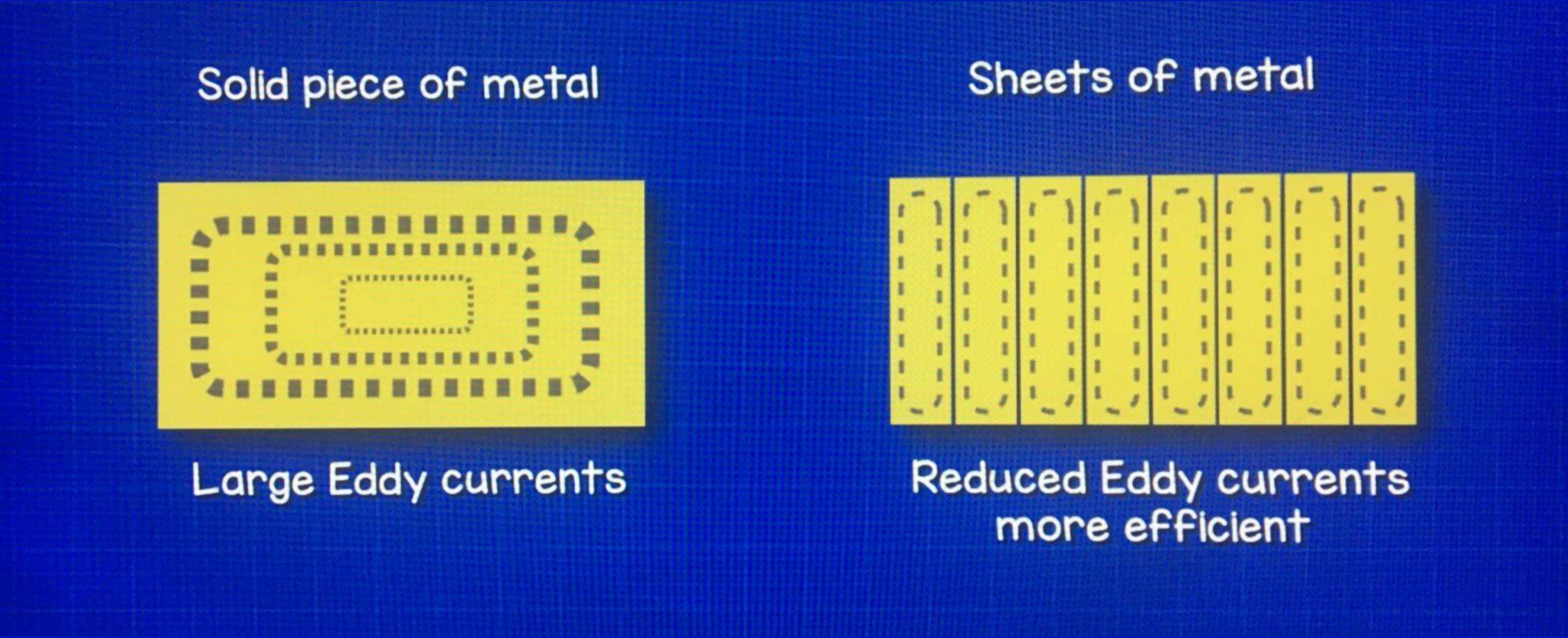
Source: LearnEngineering.com

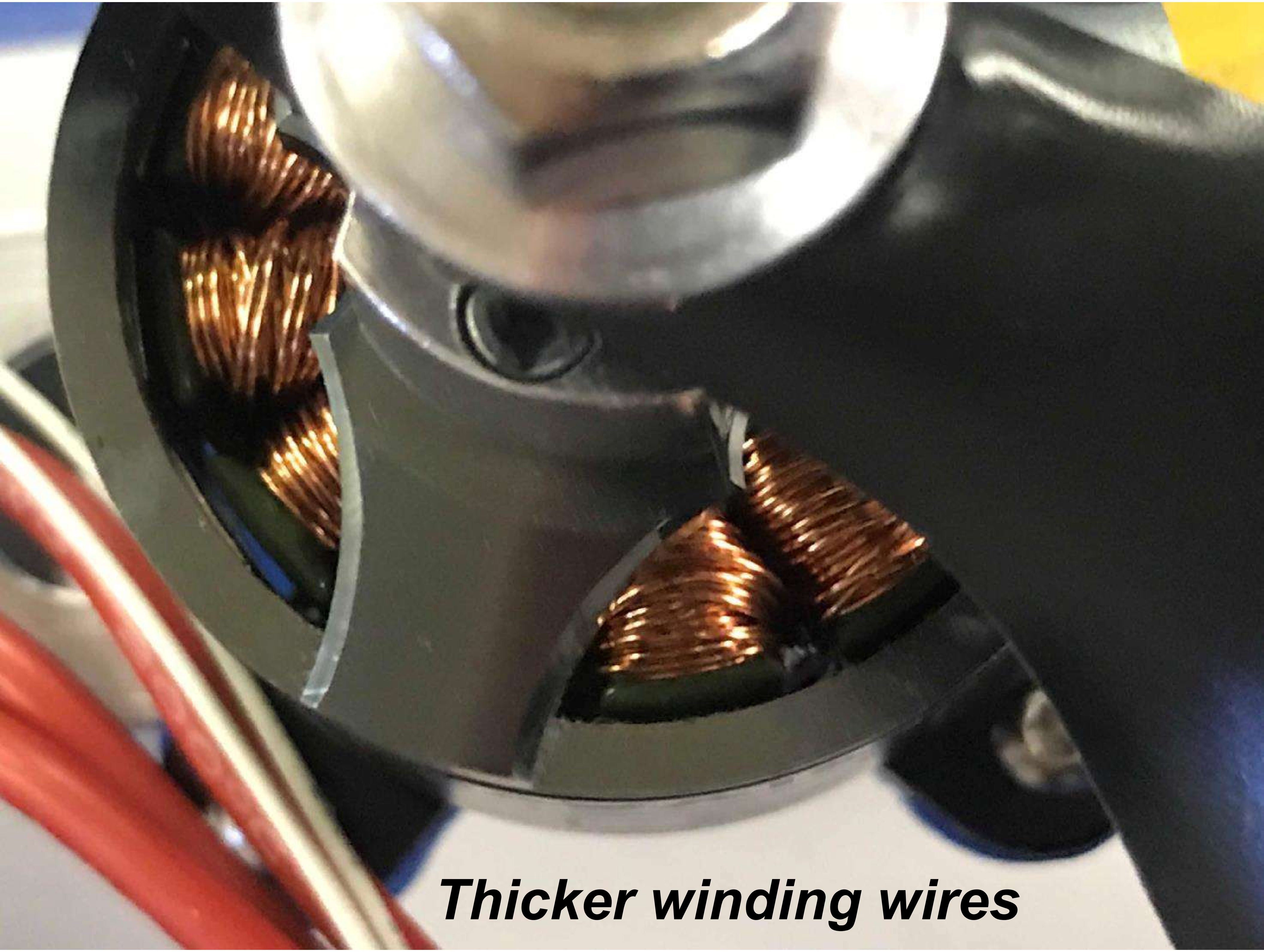

3-phase wires

A Stator is made of many thin layers laminated together to minimize eddy current loss



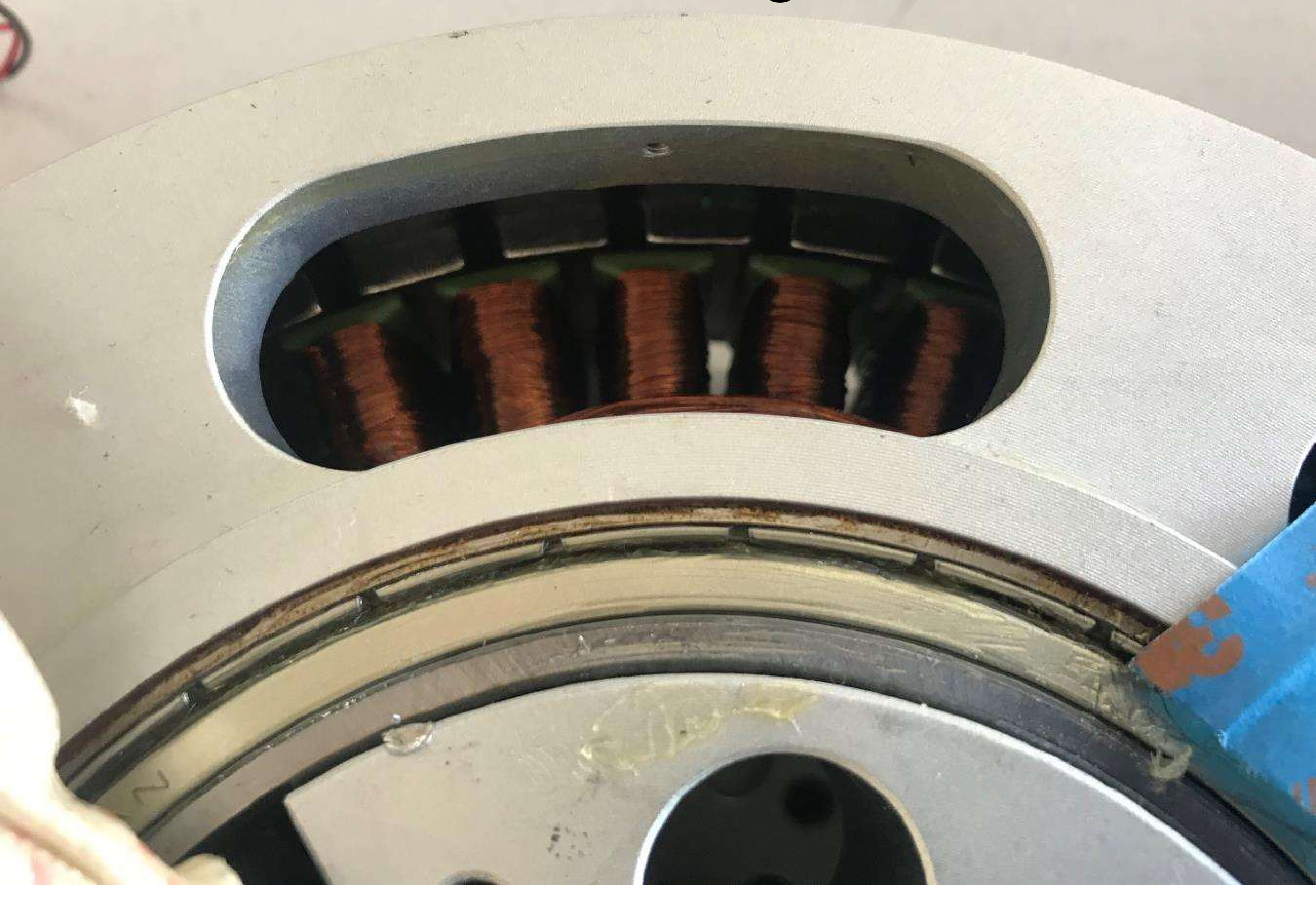
Eddy Current

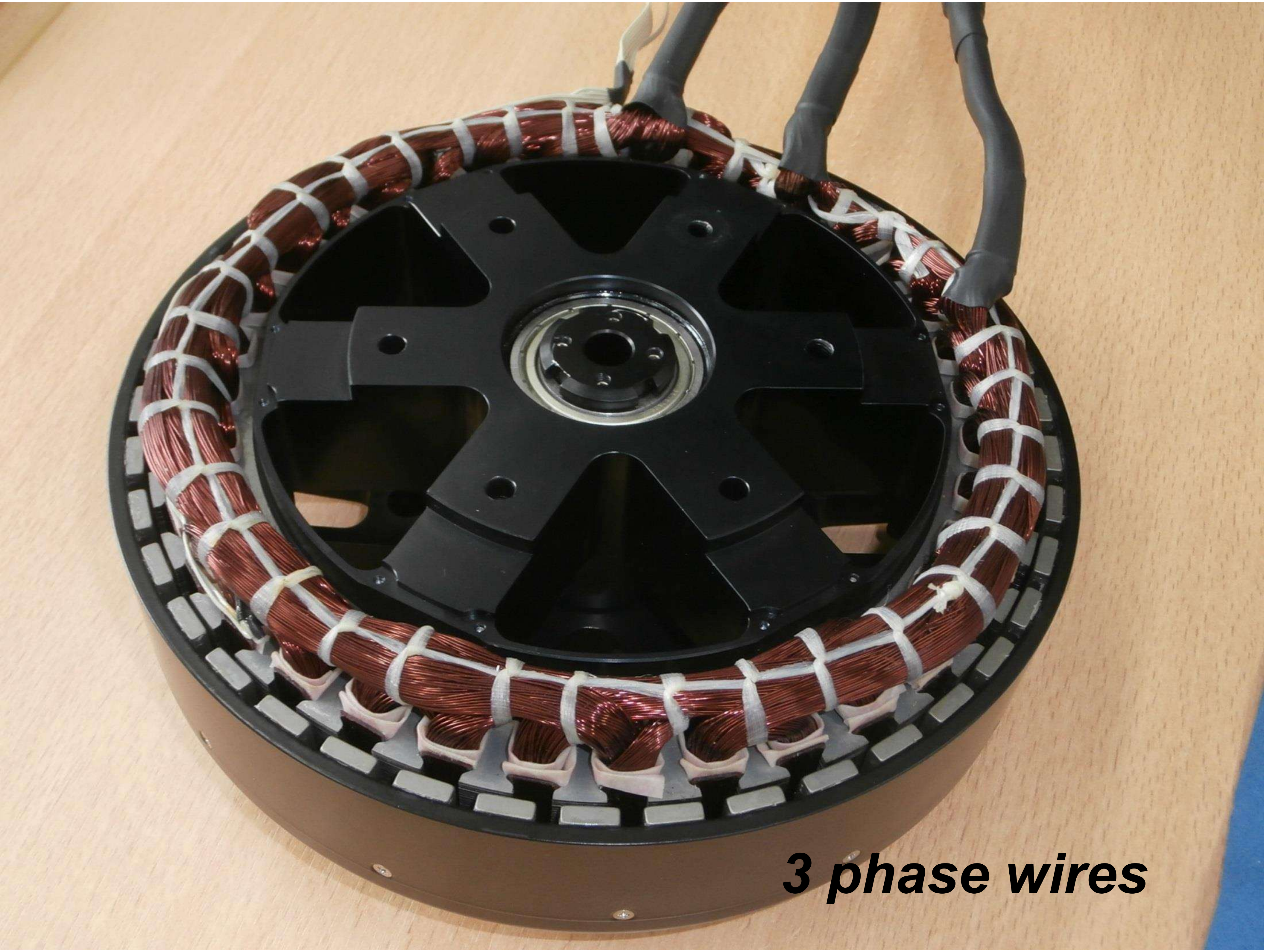




Thicker winding wires

Thinner winding wires

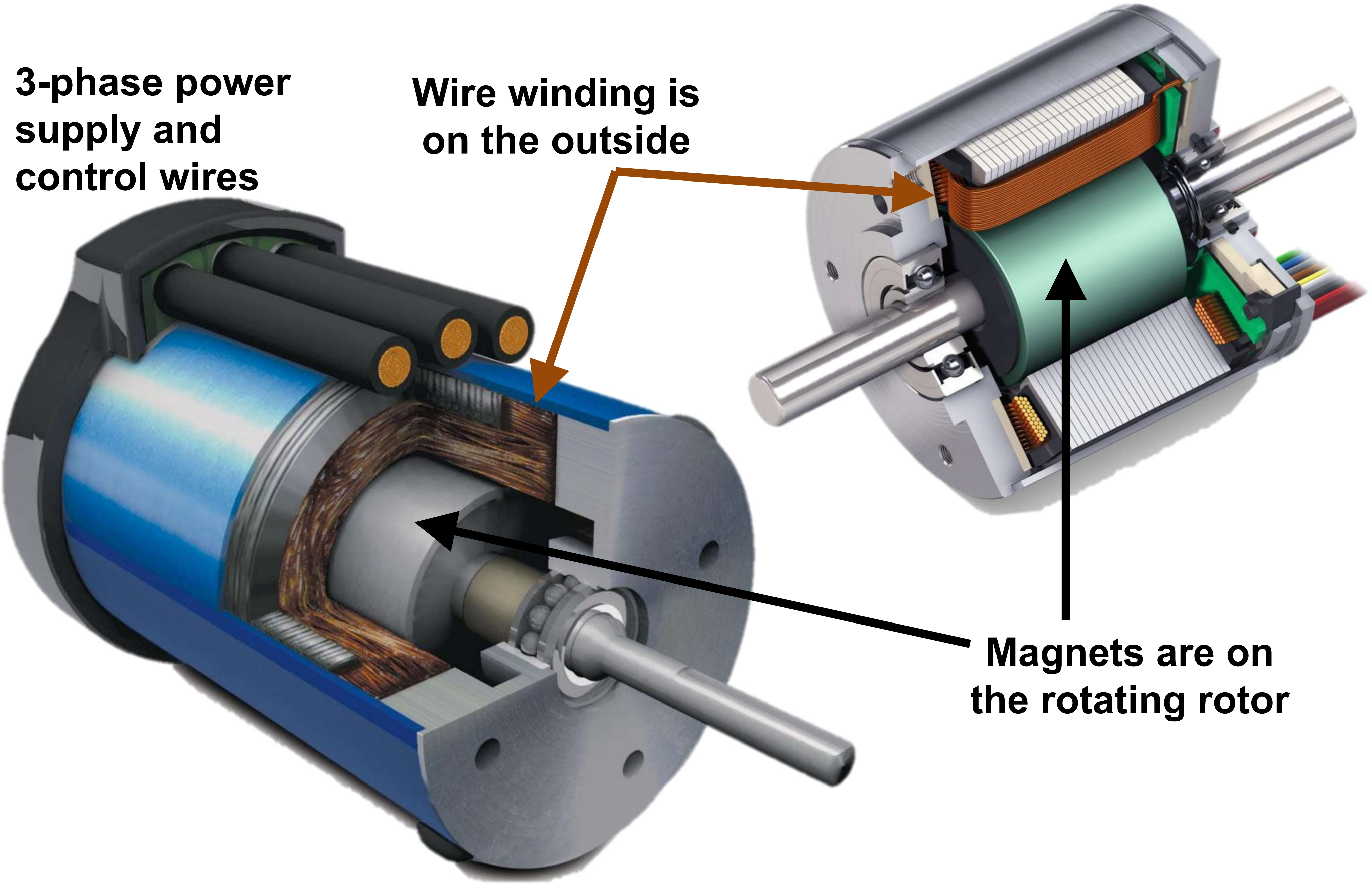



3 phase wires

Bell housing with magnets

Finished motor

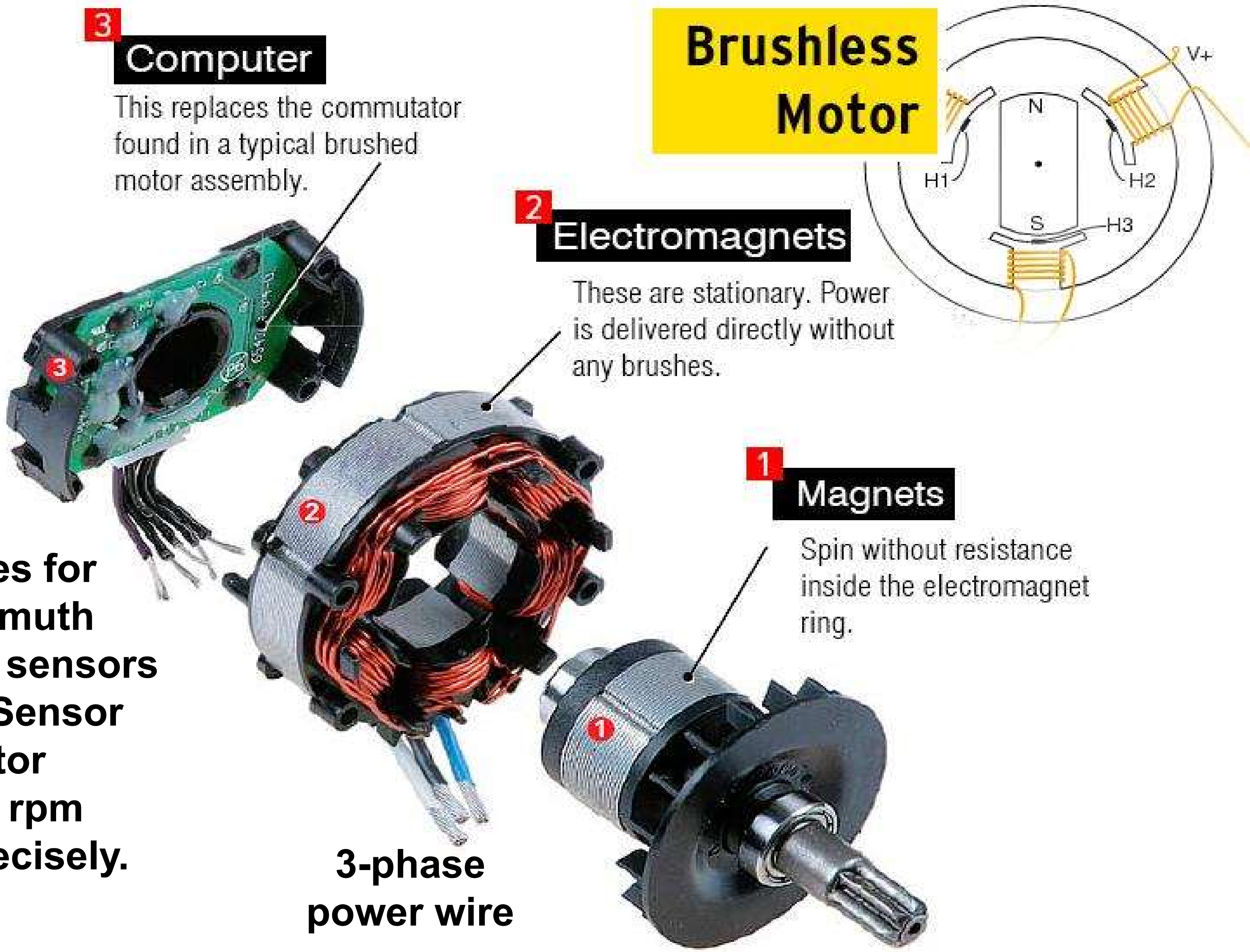
DC Brushless 3-Phase In-runner Motors




Burned out winding on
an in-runner motor

Motor Burned in a 200º C Fire Incident, Neodymium Magnet Became De-magnetized

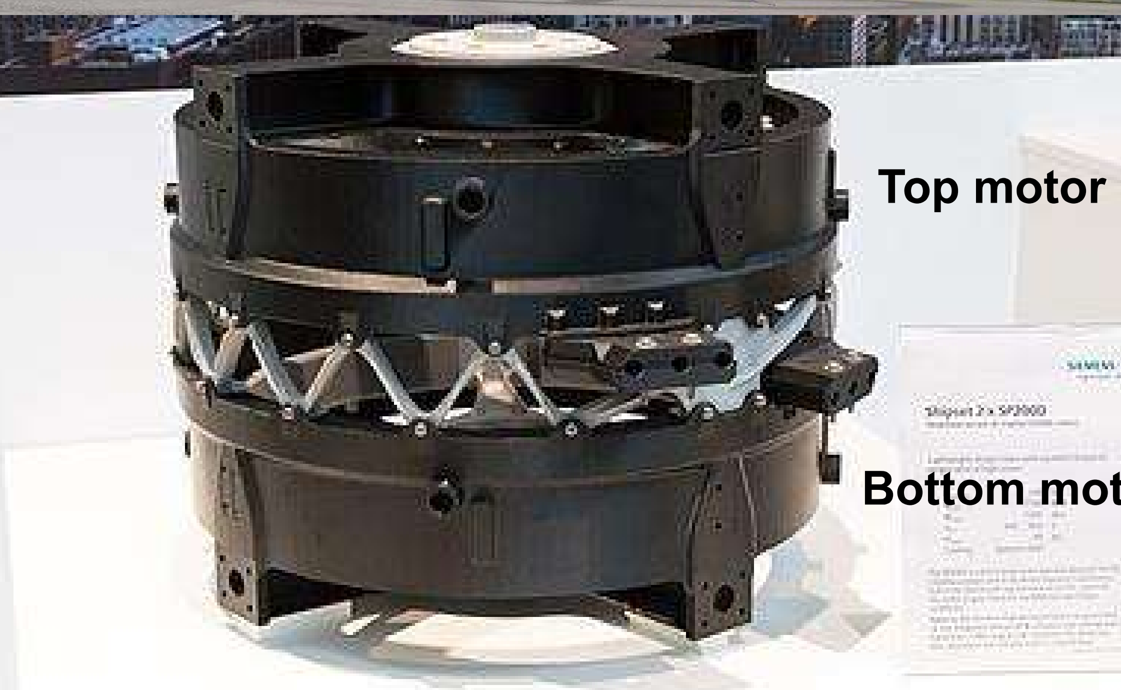
Sensor Type 3-Phase Brushless In-runner Motor

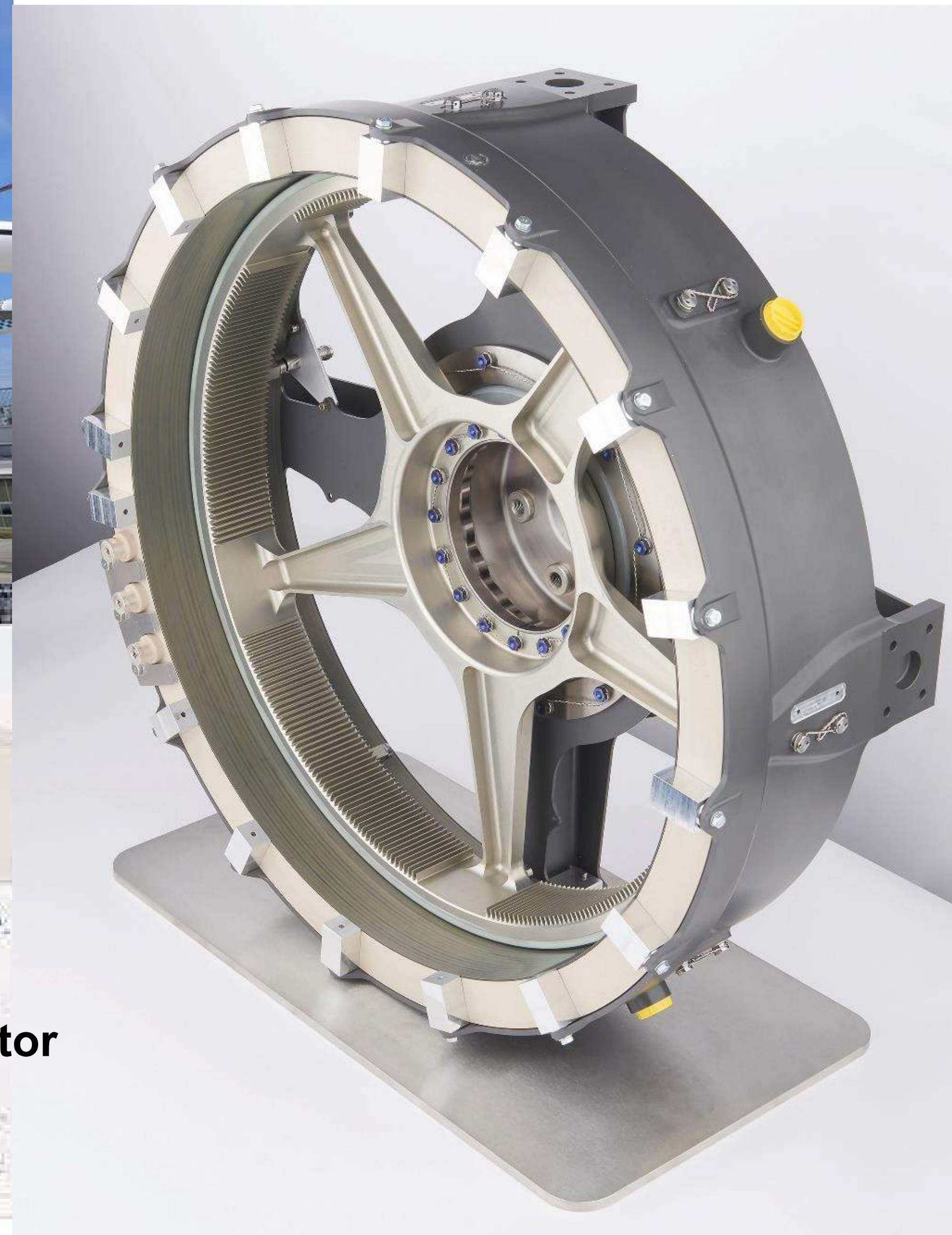


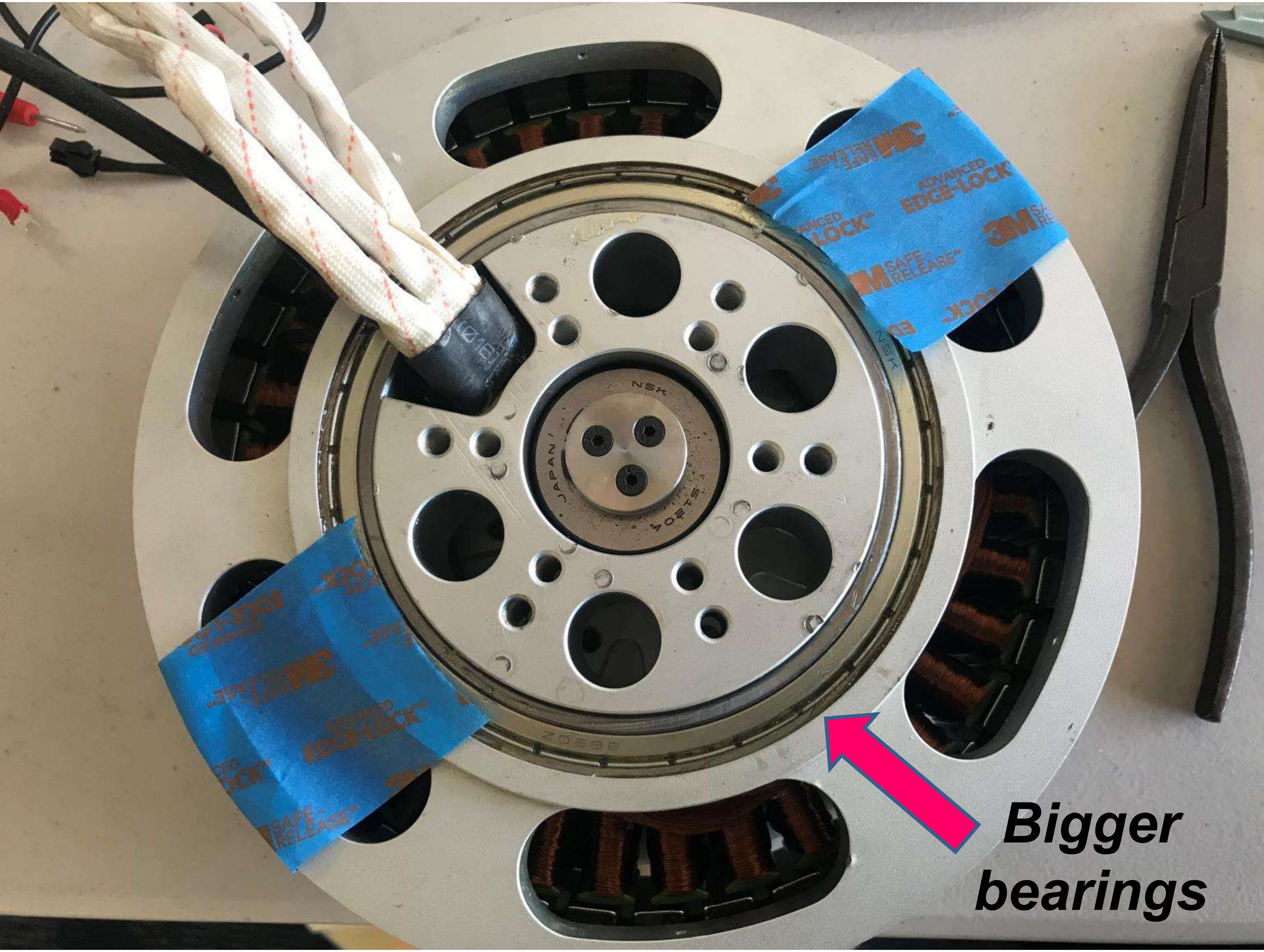
Five wires for rotor azimuth position sensors signal. Sensor type motor controls rpm more precisely.

3-phase power wire

Siemens' Radial Motor on CityAirbus

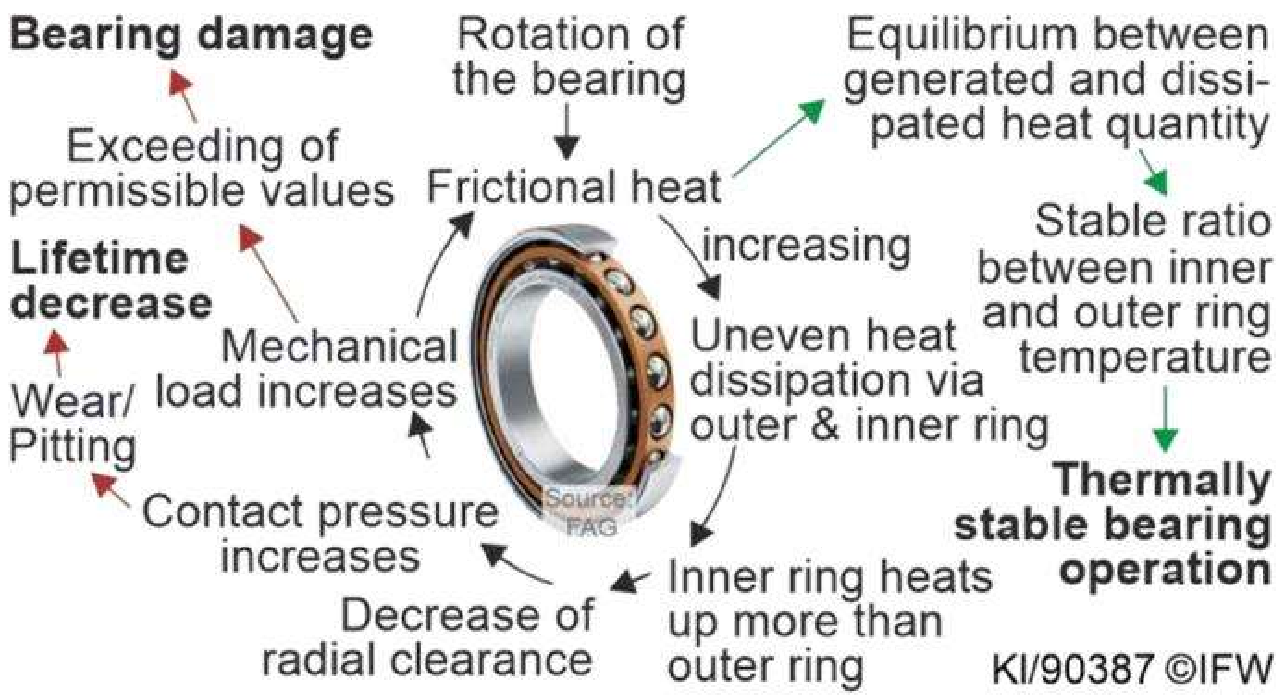





Bigger
bearings

Motor / Rotorshaft Bearings

Motor bearings can experience high loads and heat, especially at thousands of RPM or when rotor is mounted directly to motor shaft. Use radial bearings to take side loads and thrust bearings to handle pushing/pulling on the shaft. Example, Tesla Model S' induction motor uses SKF ceramic bearings to handle heat and prevent expansion



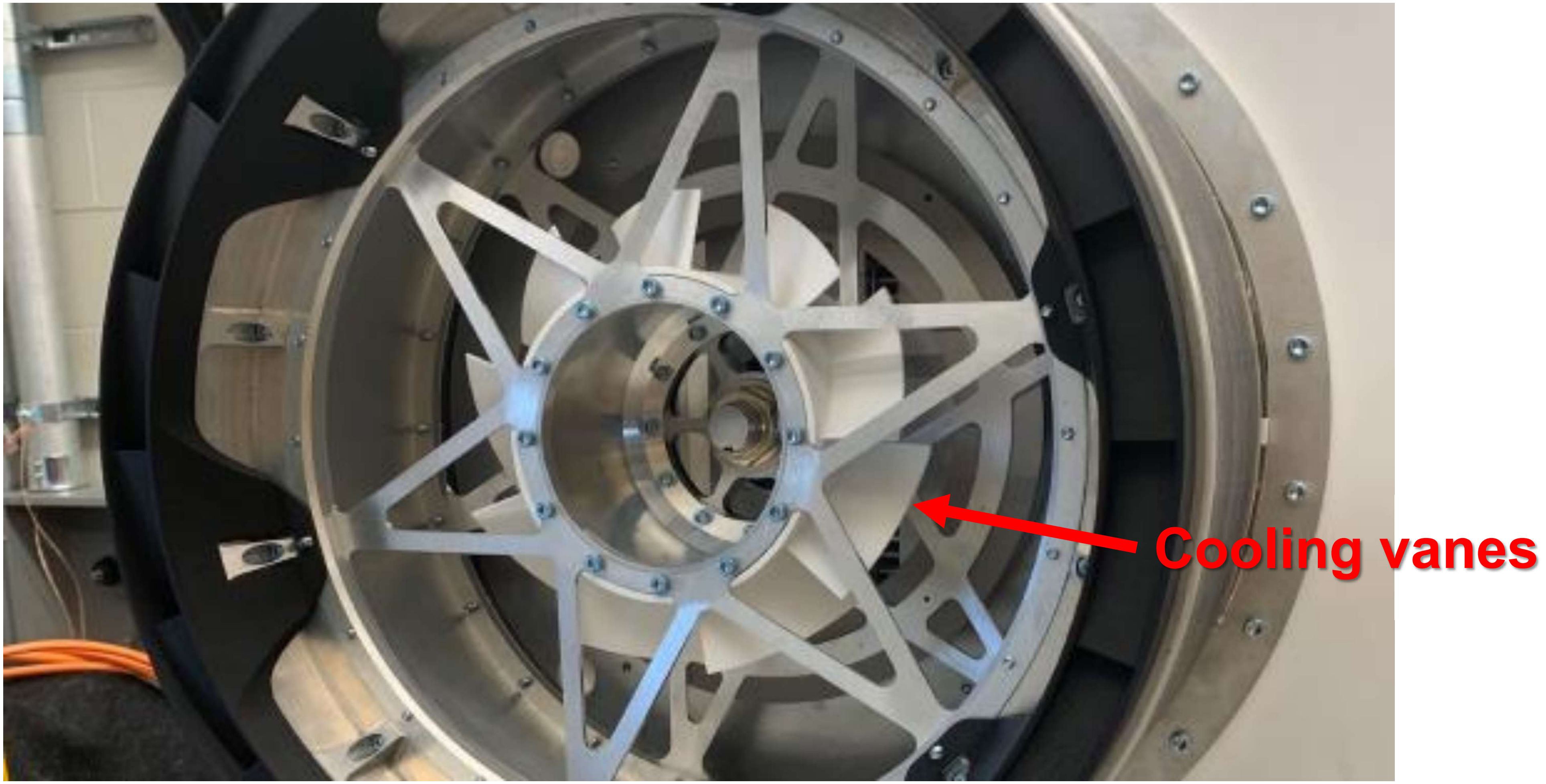
Source: https://link.springer.com/article/10.1007/s00170-020-06069-0

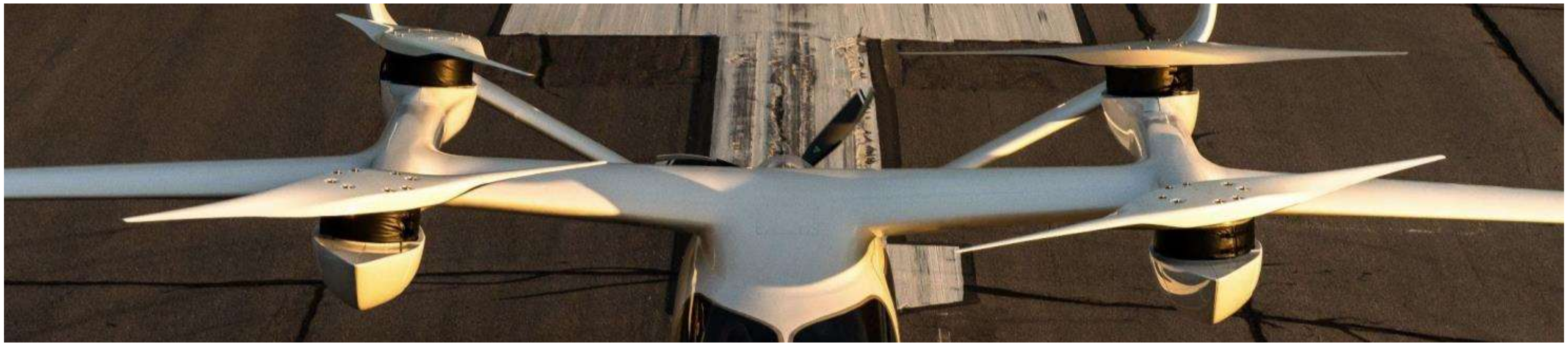
Source: https://insideevs.com/news/322358/tesla-model-s-makes-use-of-skf-ceramic-motor-bearings-video/

Air Cool vs Liquid Cool

MAGicALL air cool motors on Airbus Vahana and on Boeing PAV demonstrators

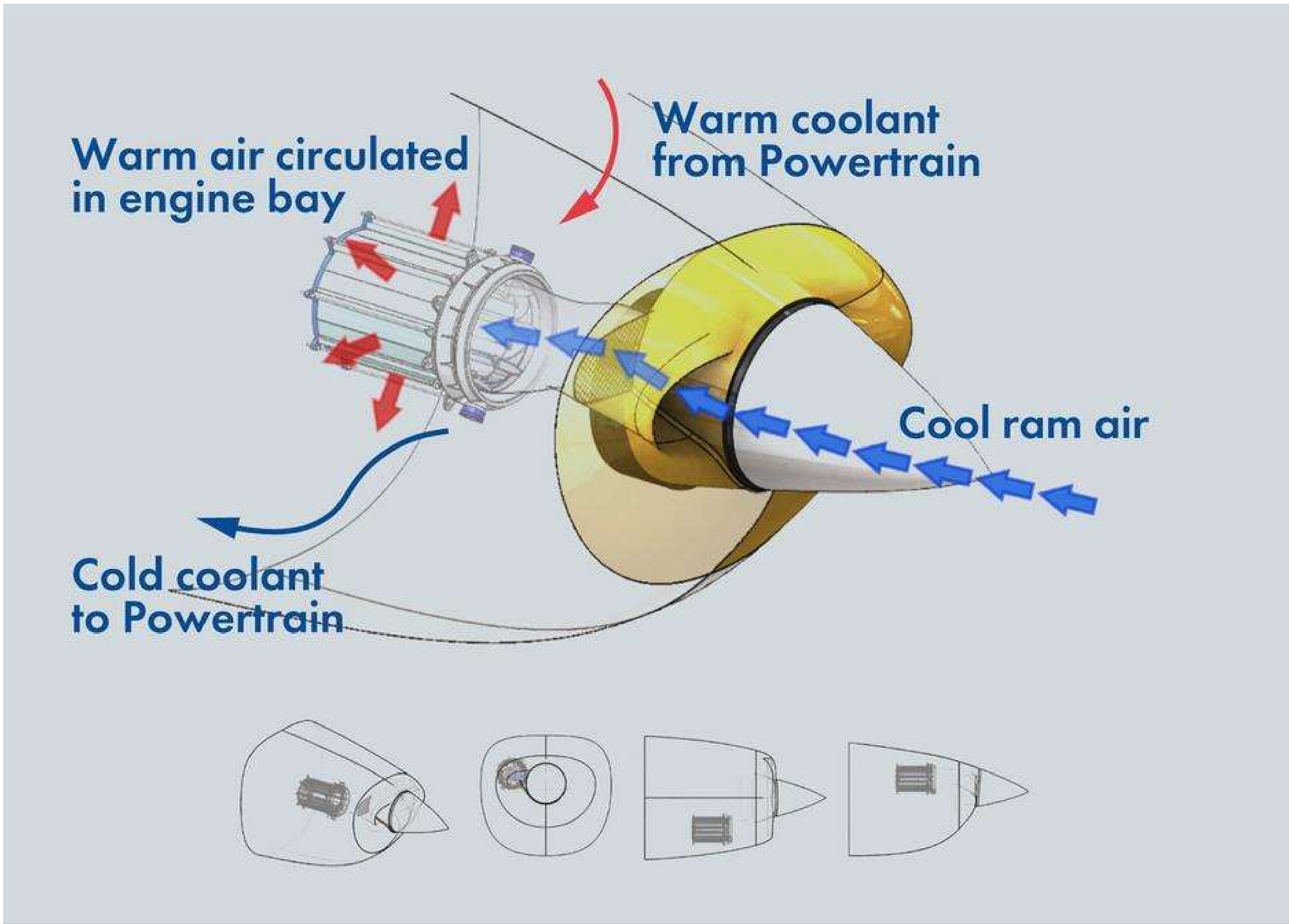
Air Cooled Motor on Beta Technologies Alia





Example: a Circular Radiator Design

Ampaire aircraft company in California commissioned Reactengine in UK to design this compact annual shaped radiator for cooling the coolant



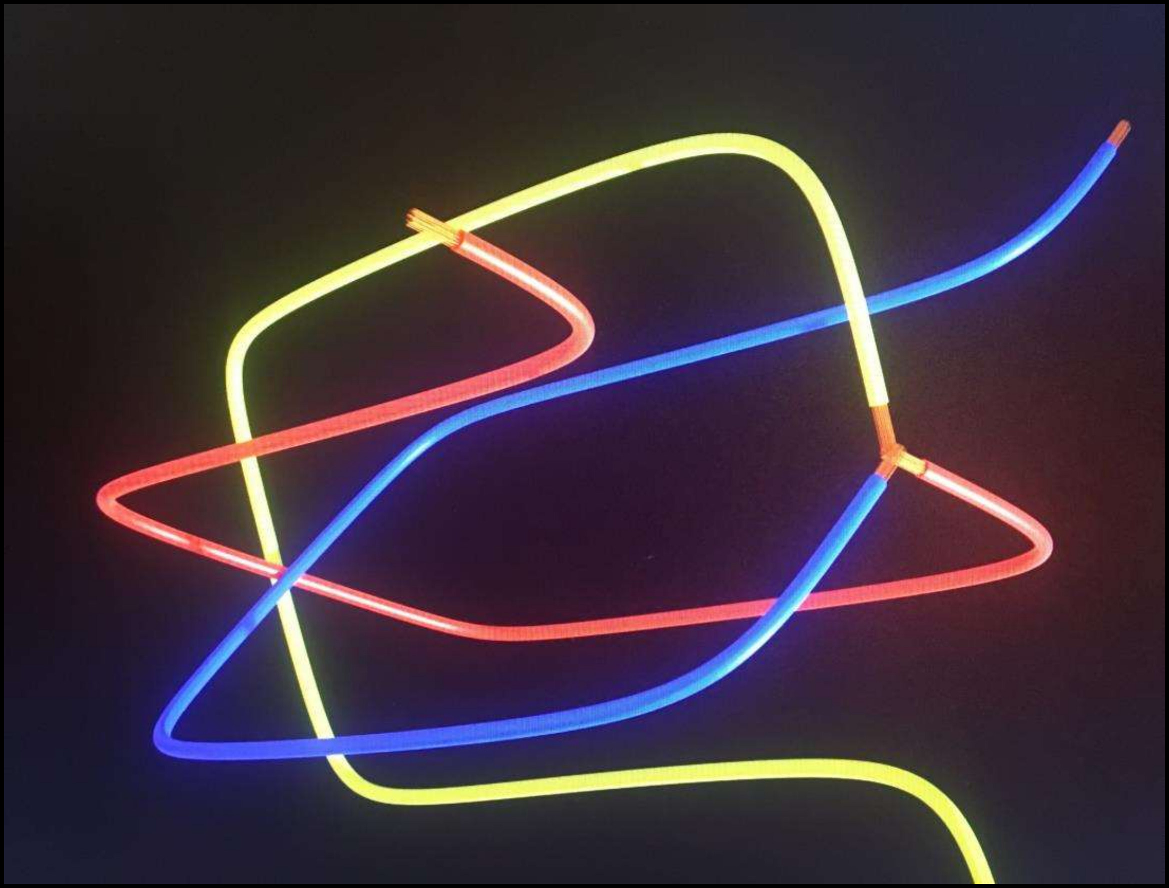
Source: www.reactionengines.co.uk/technology/our-work/advanced-radiator-hybrid-electric-aircraft

3. AC Brushless Induction Motors

The AC induction motor was invented by Nikola Tesla (1856-1943). Three-phase AC induction motors are the most frequently encountered in most industries. They are simple, rugged, easy to maintain and are less expensive than DC motors of equal power and speed ratings. Induction motors inside can get very hot and requires cooling by a fan and fins.

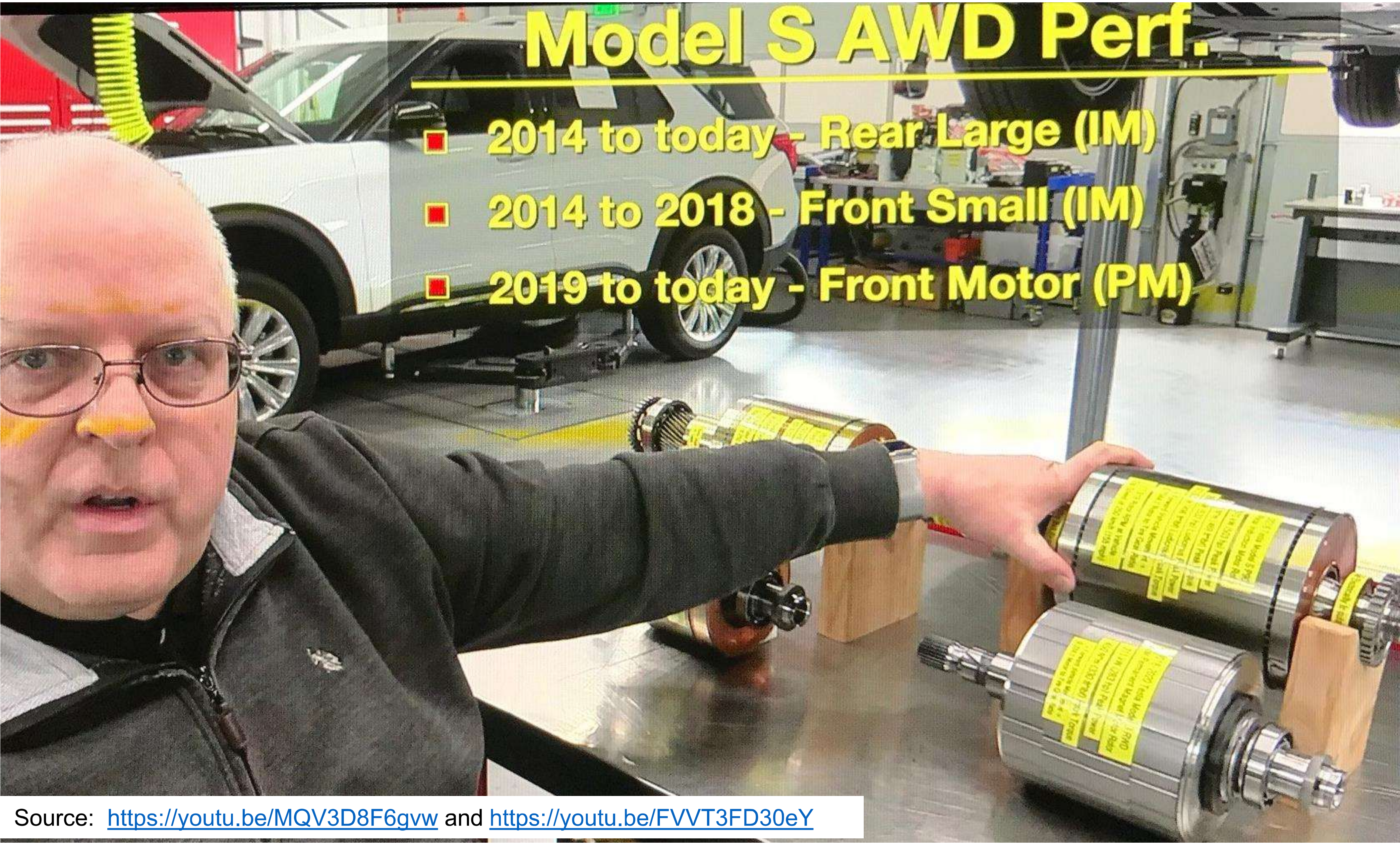
Electric cars, like Tesla Model S, use 3-phase AC induction motors. They are self starting. They do not require permanent magnets.

3Phase AC Induction Motors are most popular and they have 3 sets of windings



Source: https://www.youtube.com/watch?v=AQqyGNOP_3o

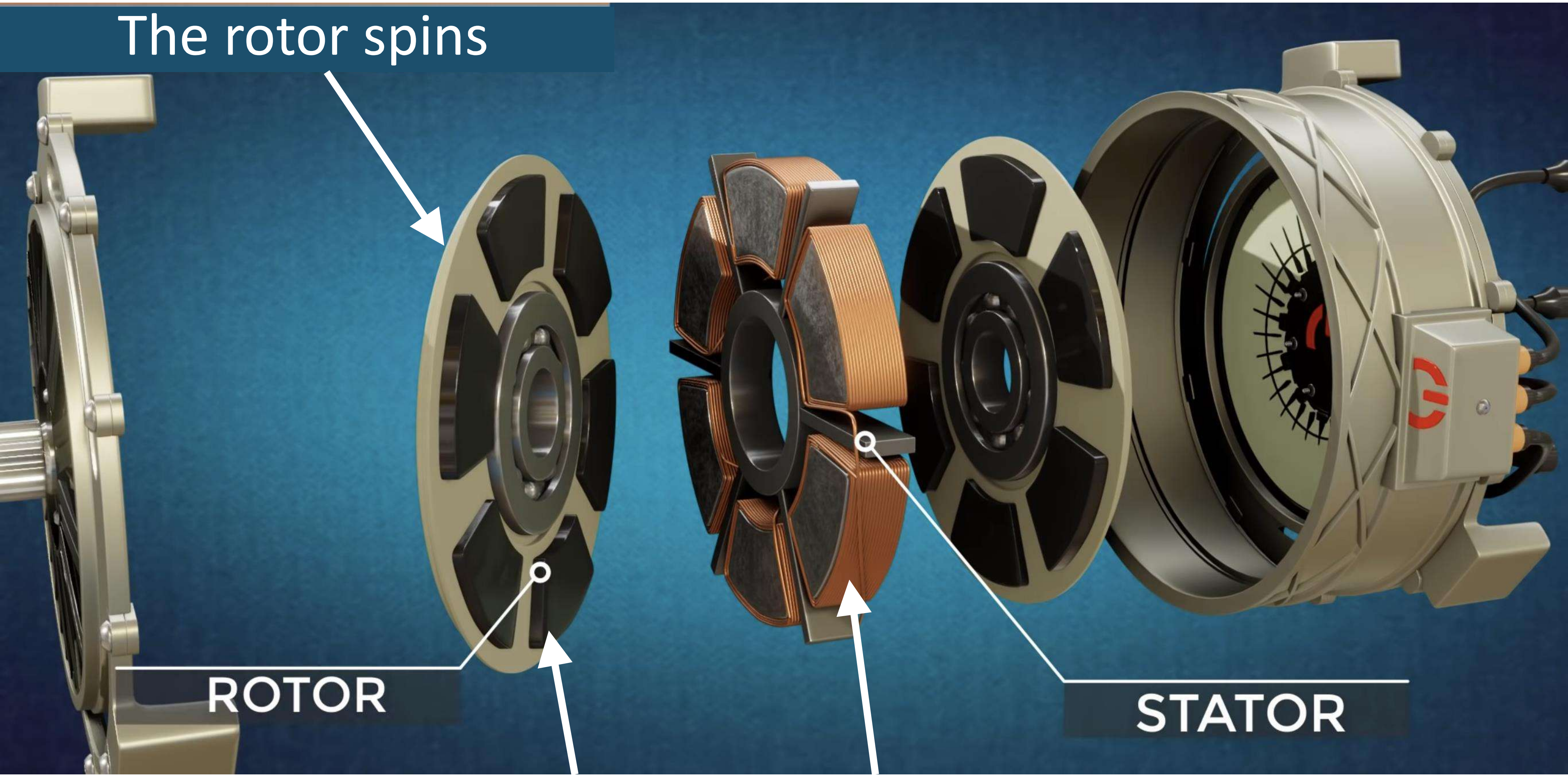
Tesla Uses Induction Motors (IM) and Permanent Magnet (IM) Motors



Source: https://youtu.be/MQV3D8F6gvw and https://youtu.be/FVVT3FD30eY

Axial Flux Motor

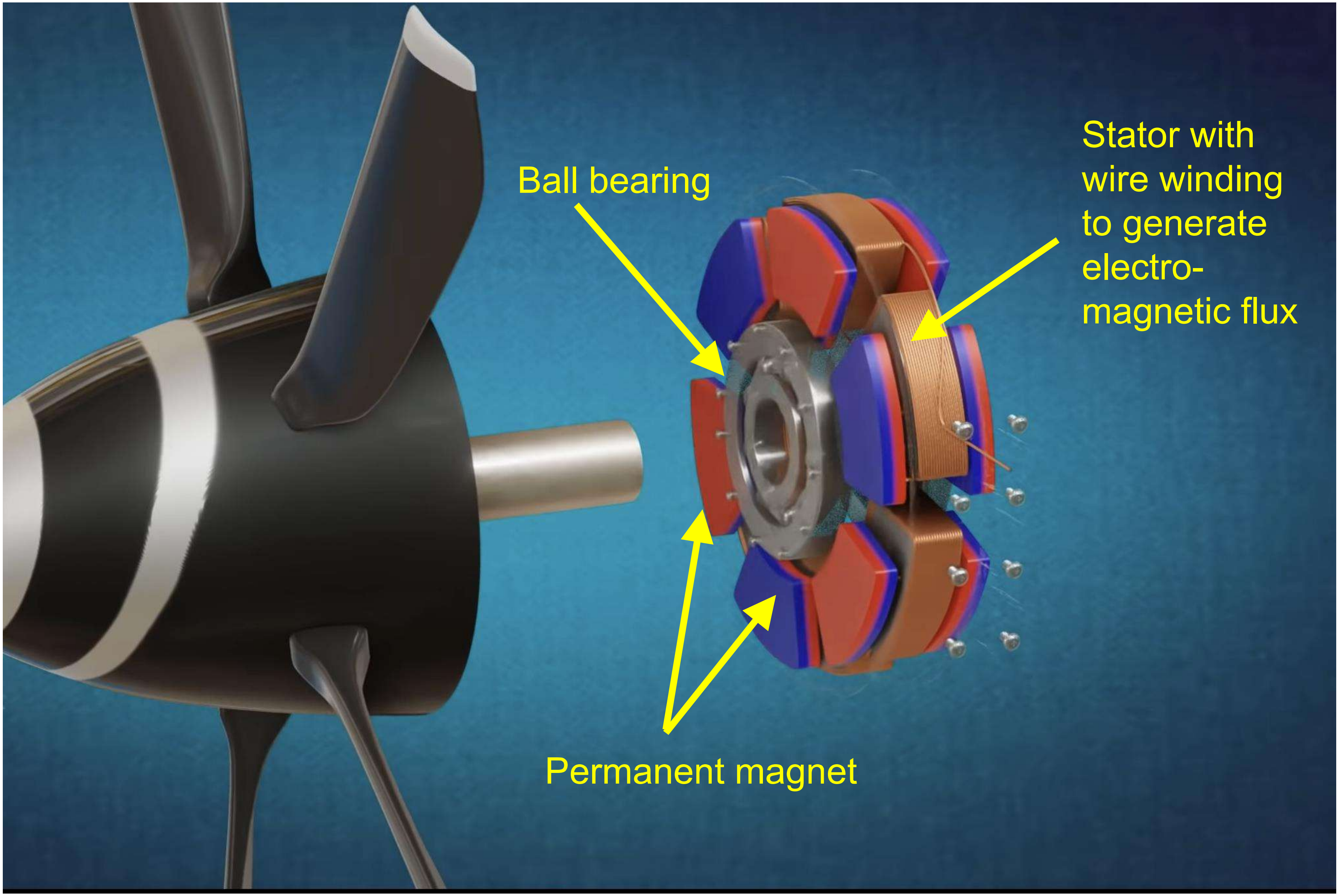
Inside of an Axial Flux Motor



Permanent magnet Copper wire winding

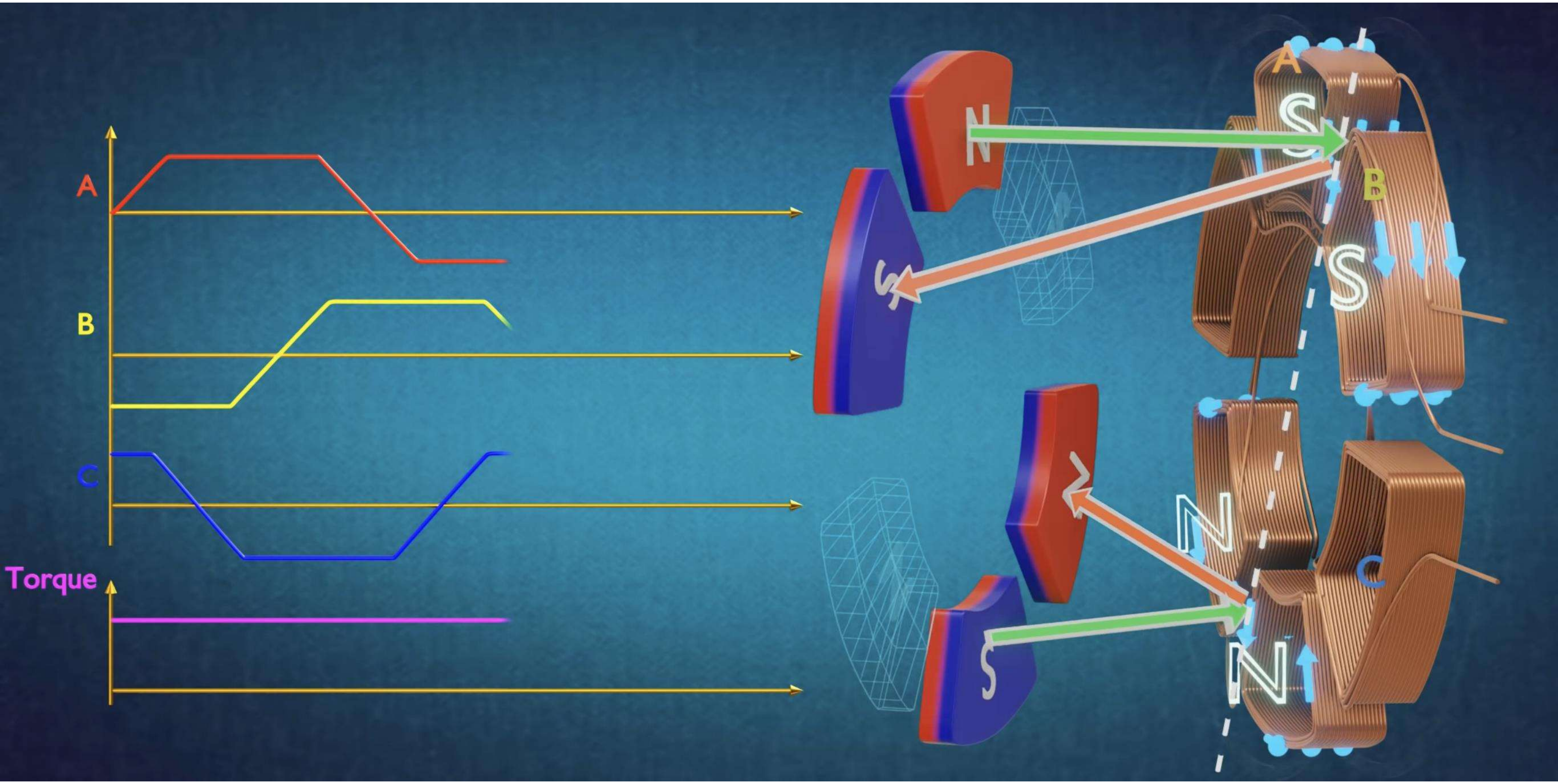
Source: The Dawn of an Advanced Transportation Mode

A Direct Drive with Axial Flux Motor



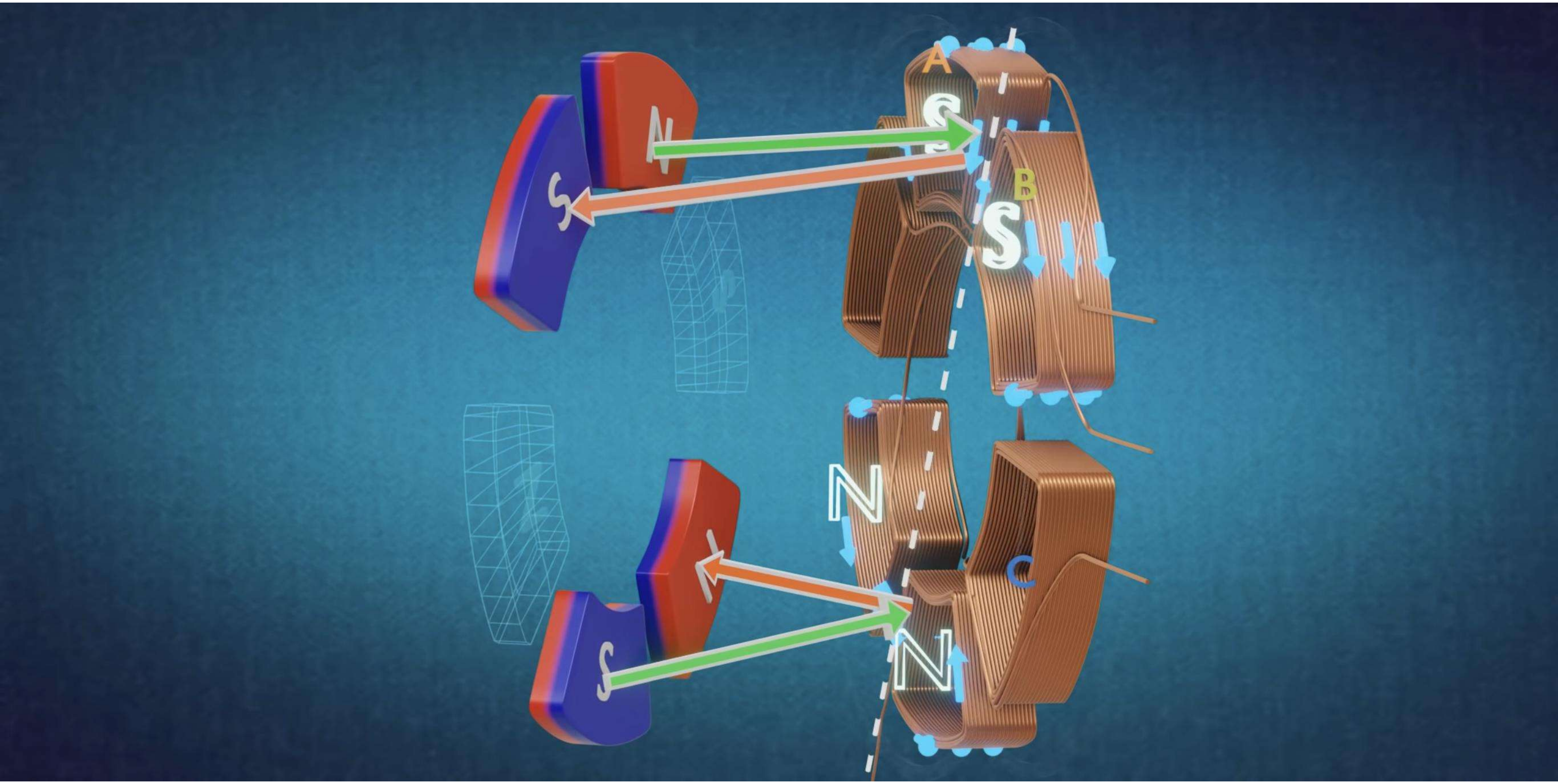
Source: The Dawn of an Advanced Transportation Mode

Axial Flux Motor Controls RPM by the 3 Phases



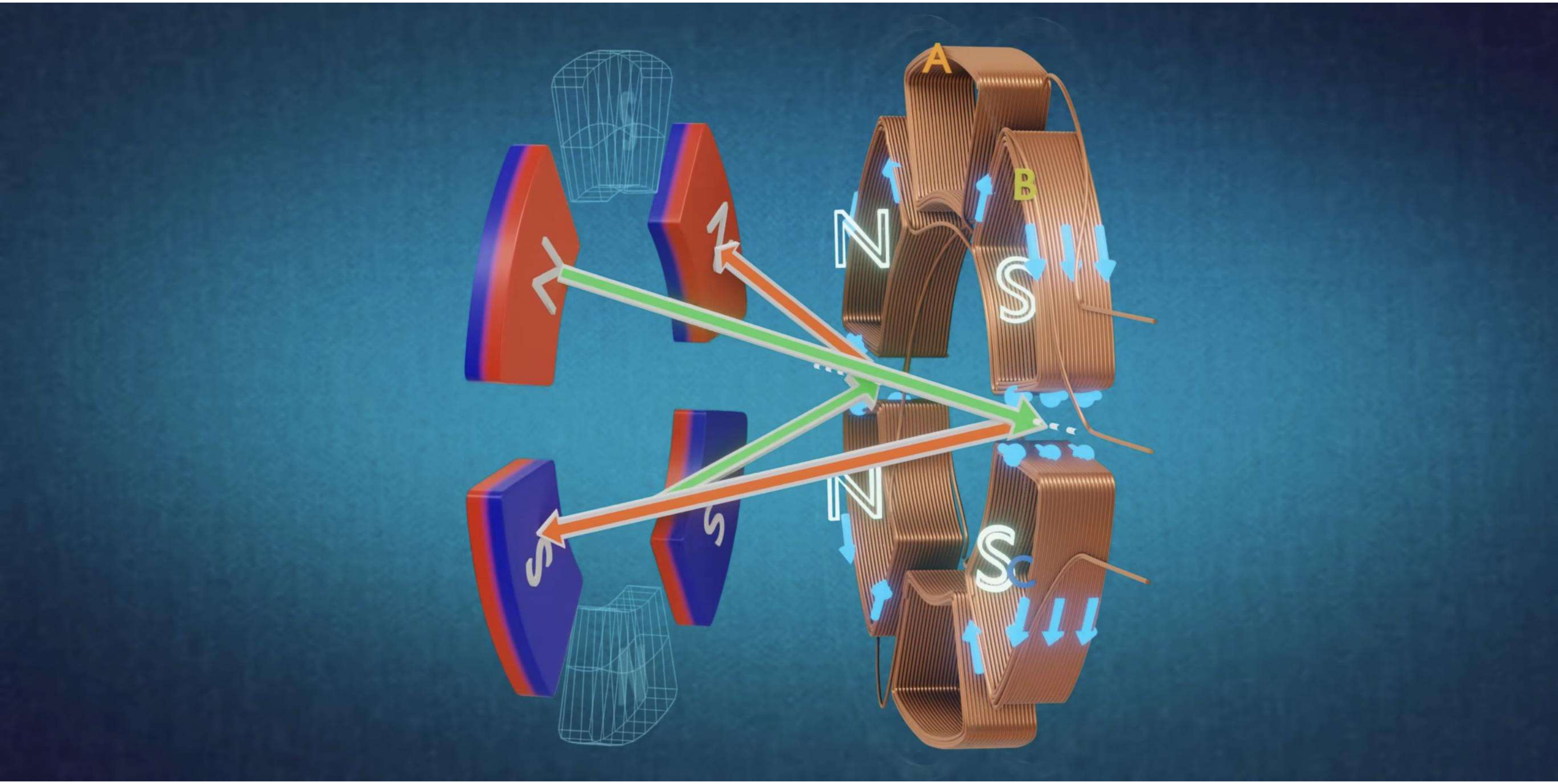
Source: The Dawn of an Advanced Transportation Mode

Axial Flux Motor



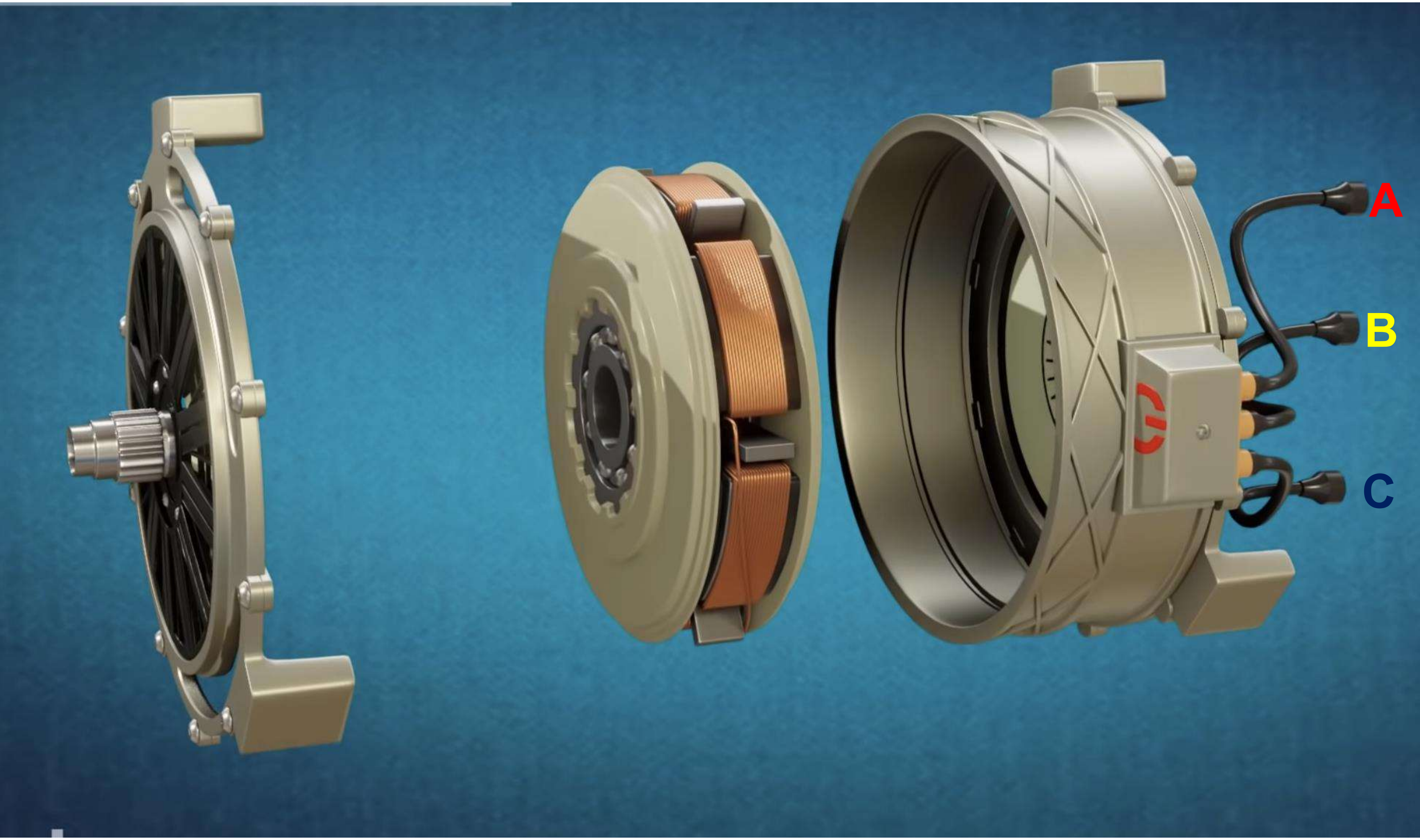
Source: The Dawn of an Advanced Transportation Mode

Axial Flux Motor



Source: The Dawn of an Advanced Transportation Mode

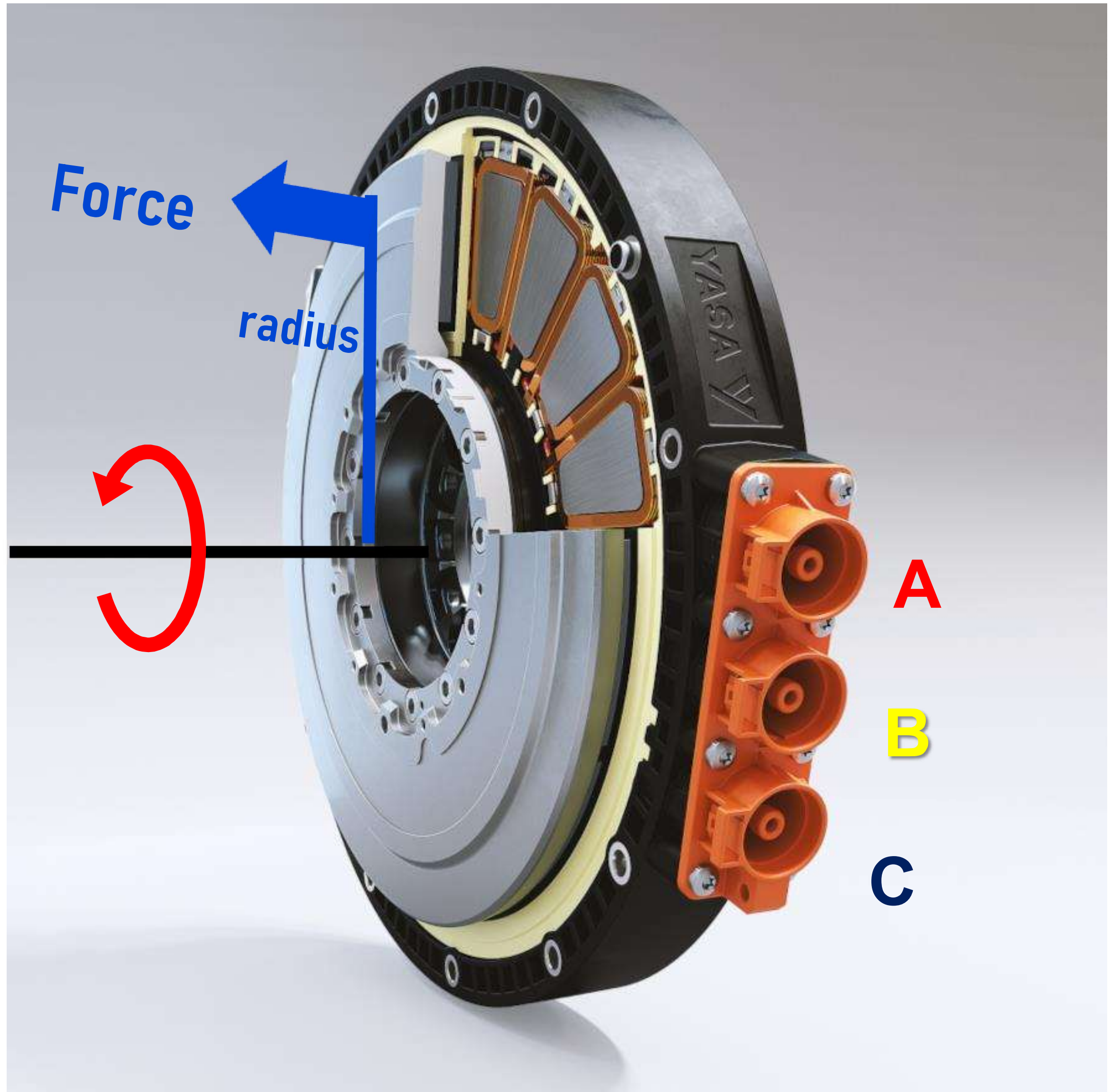
Finished Axial Flux Motor



Source: The Dawn of an Advanced Transportation Mode

Advantages of Axial Flux Motor is More Torque at Lower RPM

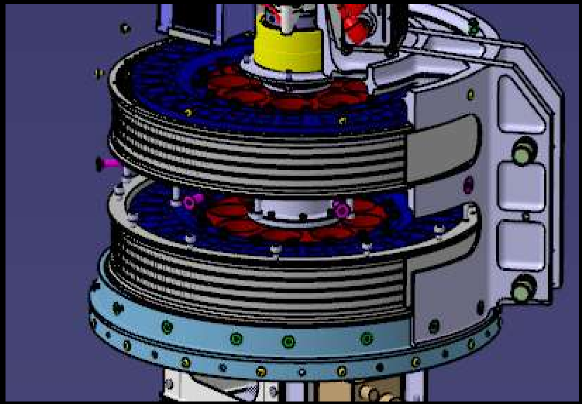
Torque = r x F



Three Methods to Increase Redundancy

1. **Many motors/rotors**

2. **Stack multiple motors on one rotor shaft**



3. **Multiple windings inside each motor**

On a stacked motor, how do we achieve the 30% overpower mentioned earlier?

Example: Voltage is fixed at 800 volts, electric motor kv is fixed at 2, so it will want to spin at 1600 rpm. Motor will pull current to spin at that rpm. Power= v x i , if one motor failed, the blade pitch remains the same, the second motor will pull more current. The second motor will start to heat up, it could take a couple minutes before motor temperature reach 180°C.

That's why motors and inverters have a continuous rating and a peak rating for current.

Electric Motors Have Another Advantage

With an internal combustion engine, if the air/fuel mixture is not changed, but suddenly there is a loading change (example, suddenly reducing propeller's pitch angle), the engine will overspeed because the air/fuel mixing has not changed. While an electric motor will automatically draw less current when external load is reduced.

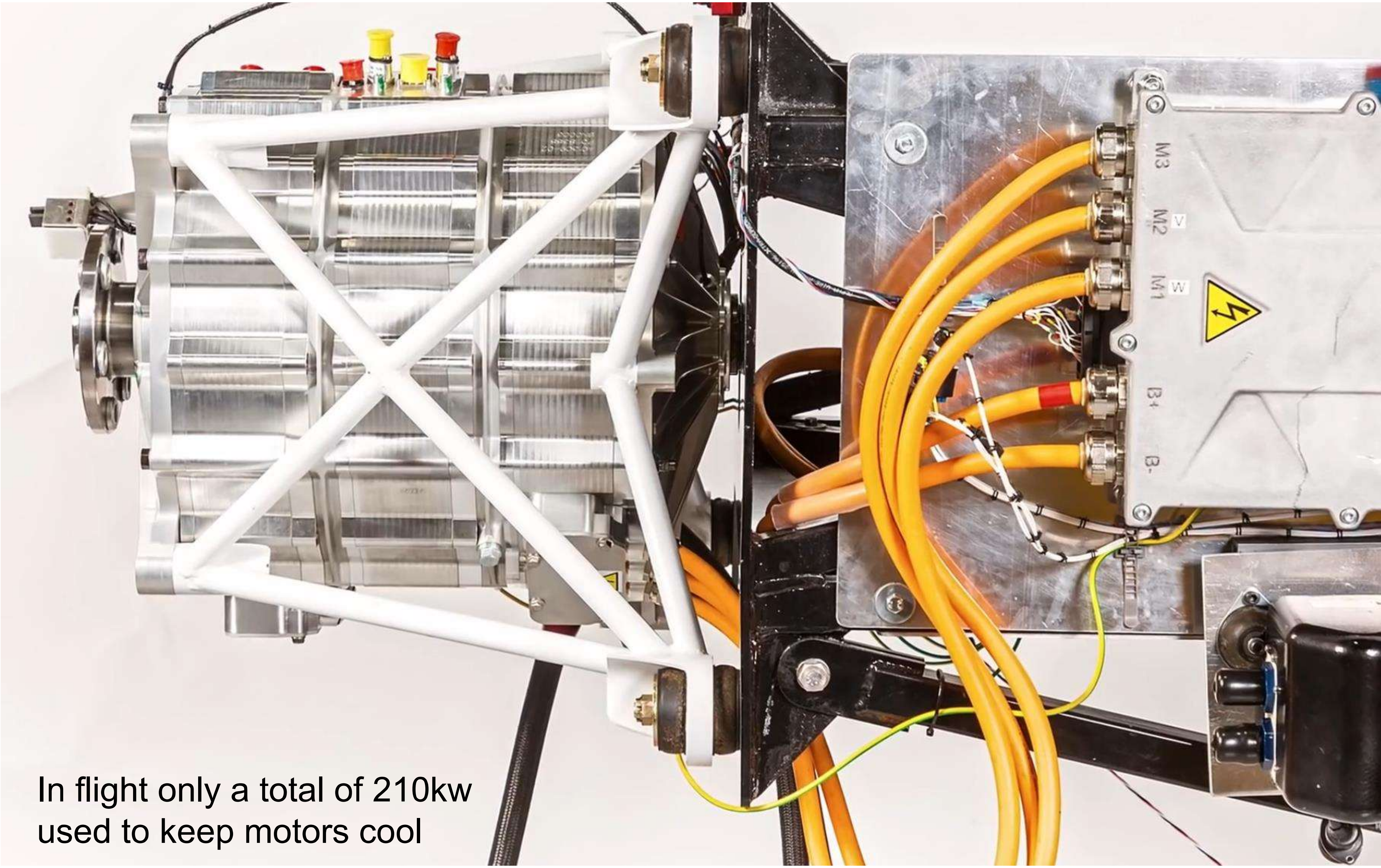
RR Spirit of Innovation Clocks 387 MPH

January 2022

RR Spirit of Innovation

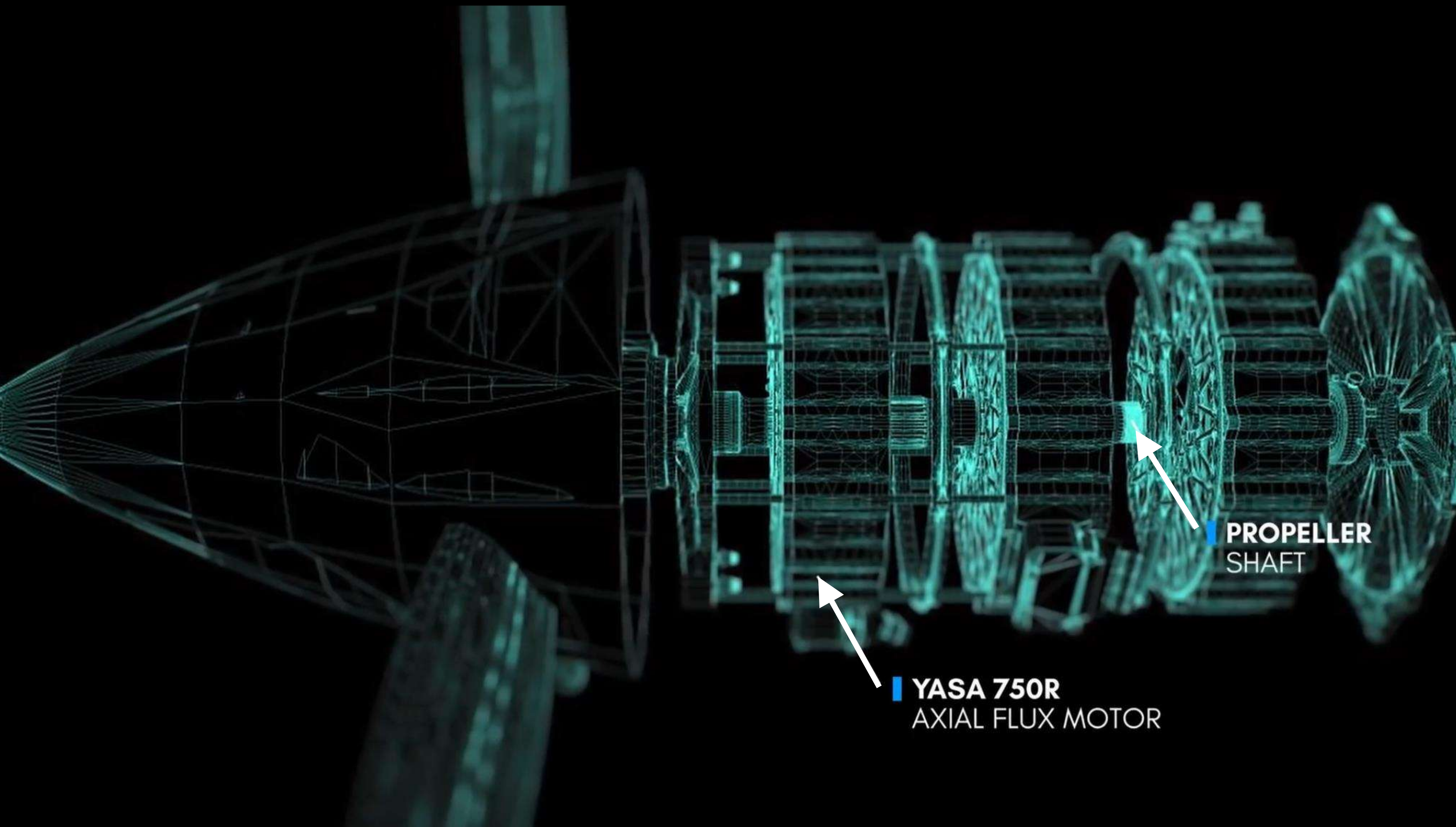
Source: The world's fastest electric airplane
https://youtu.be/GsXGJ1O3ccQ

3 x 250kw Axial Flux Motors on One Shaft

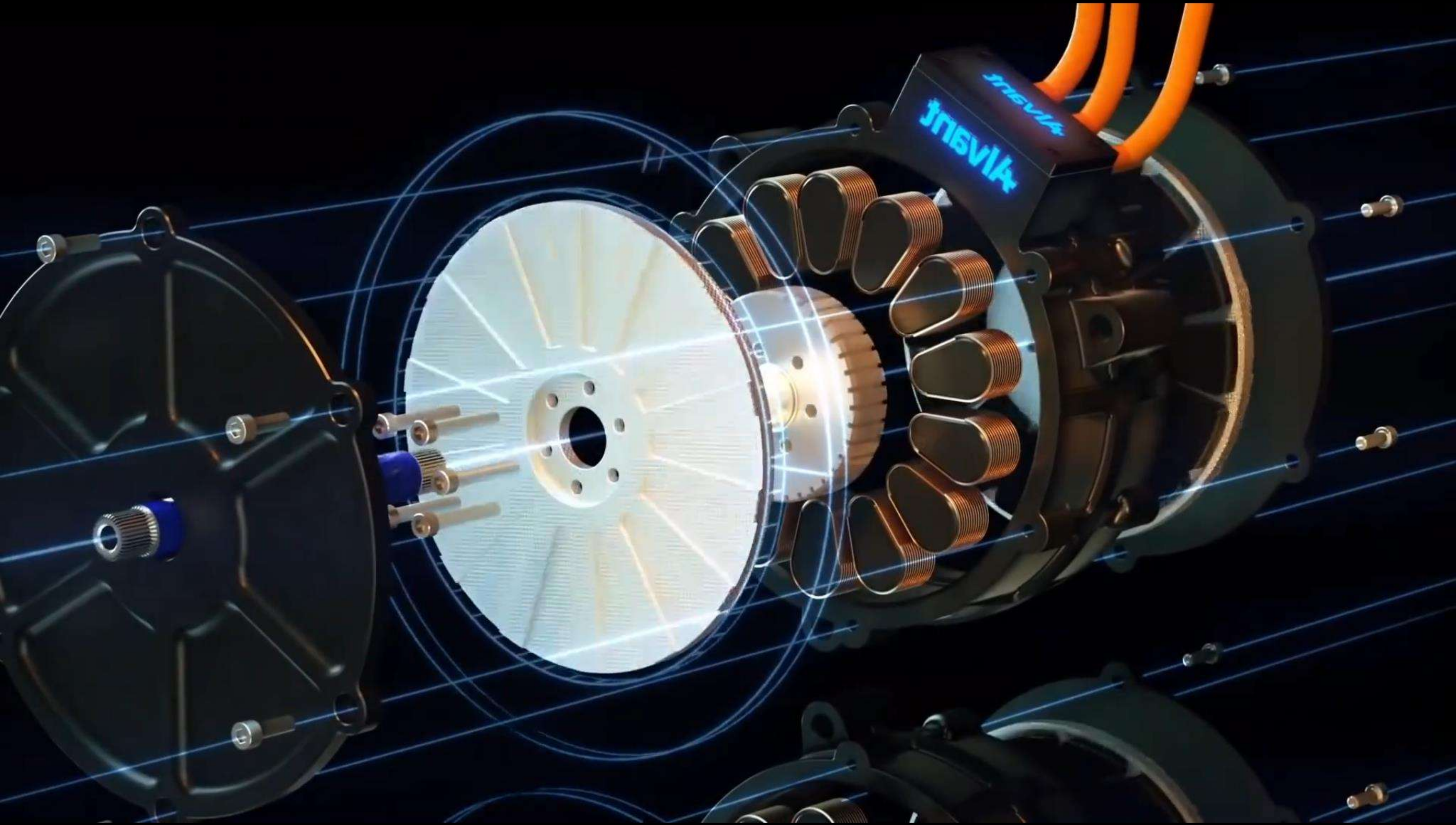


In flight only a total of 210kw
used to keep motors cool

Three Motors on One Shaft

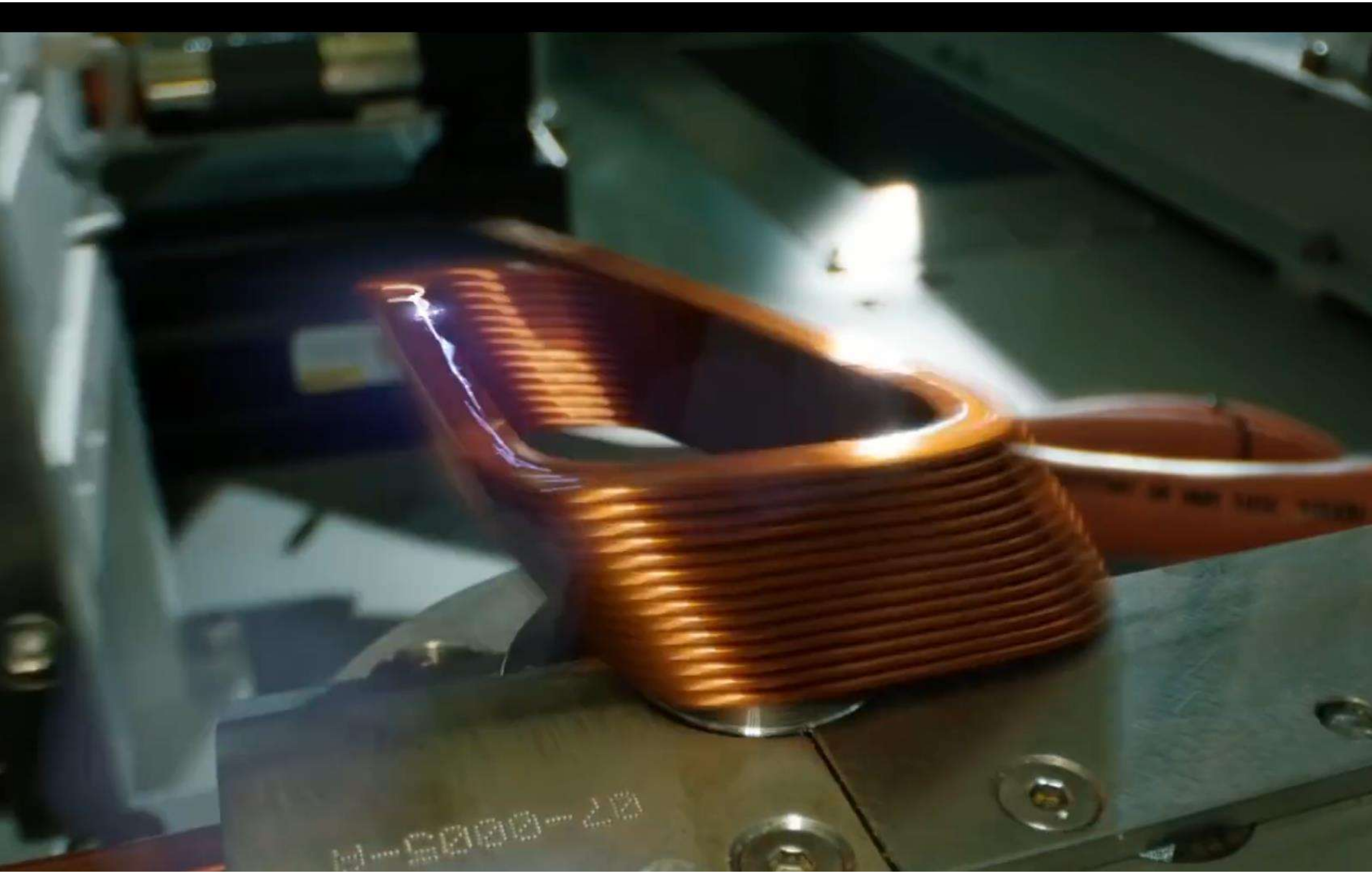


Inside Axial Flux Motors

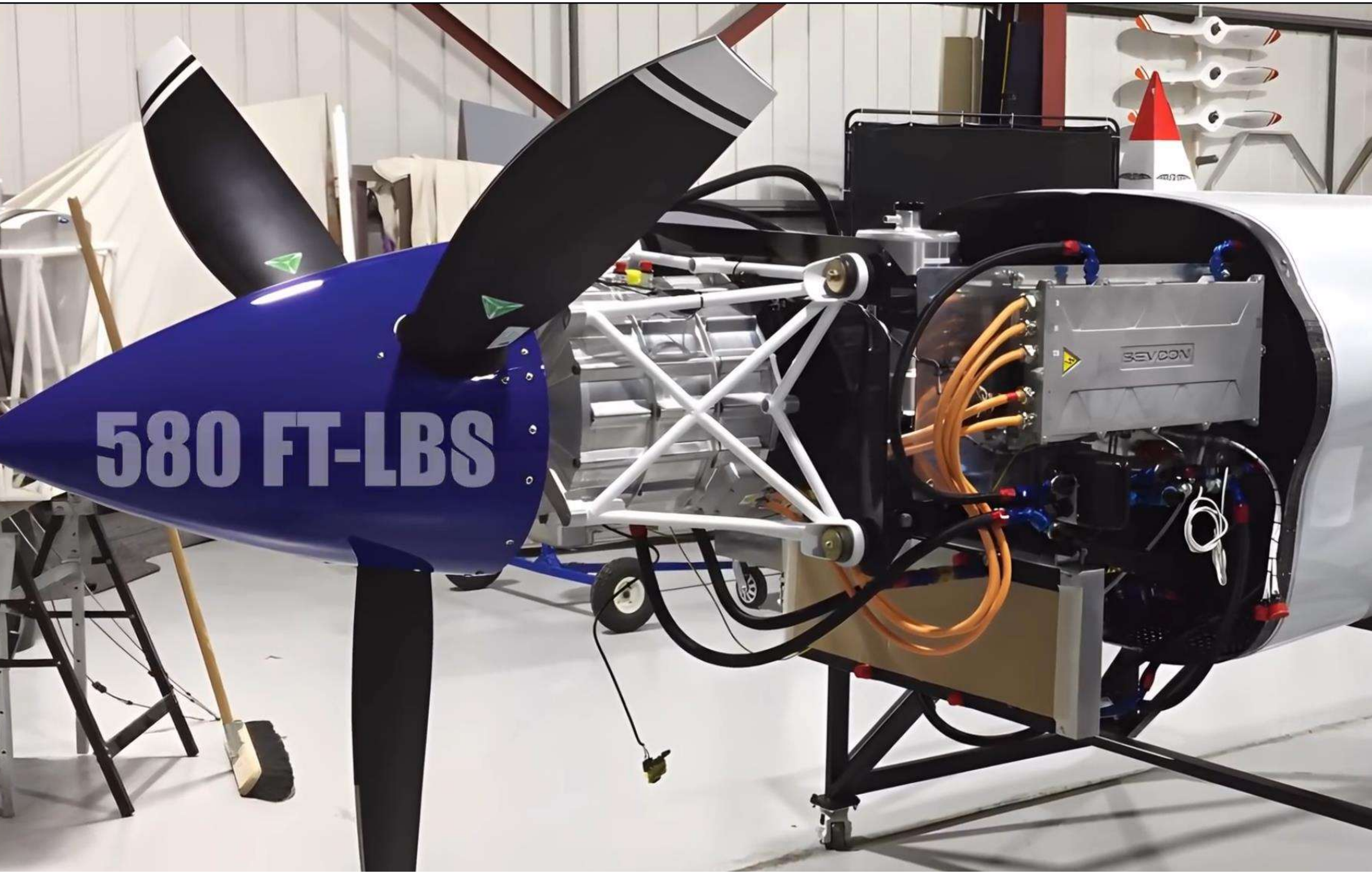


Source: The world's fastest electric airplane
https://youtu.be/GsXGJ1O3ccQ

Wires in Winding Used in Automotive are Flat

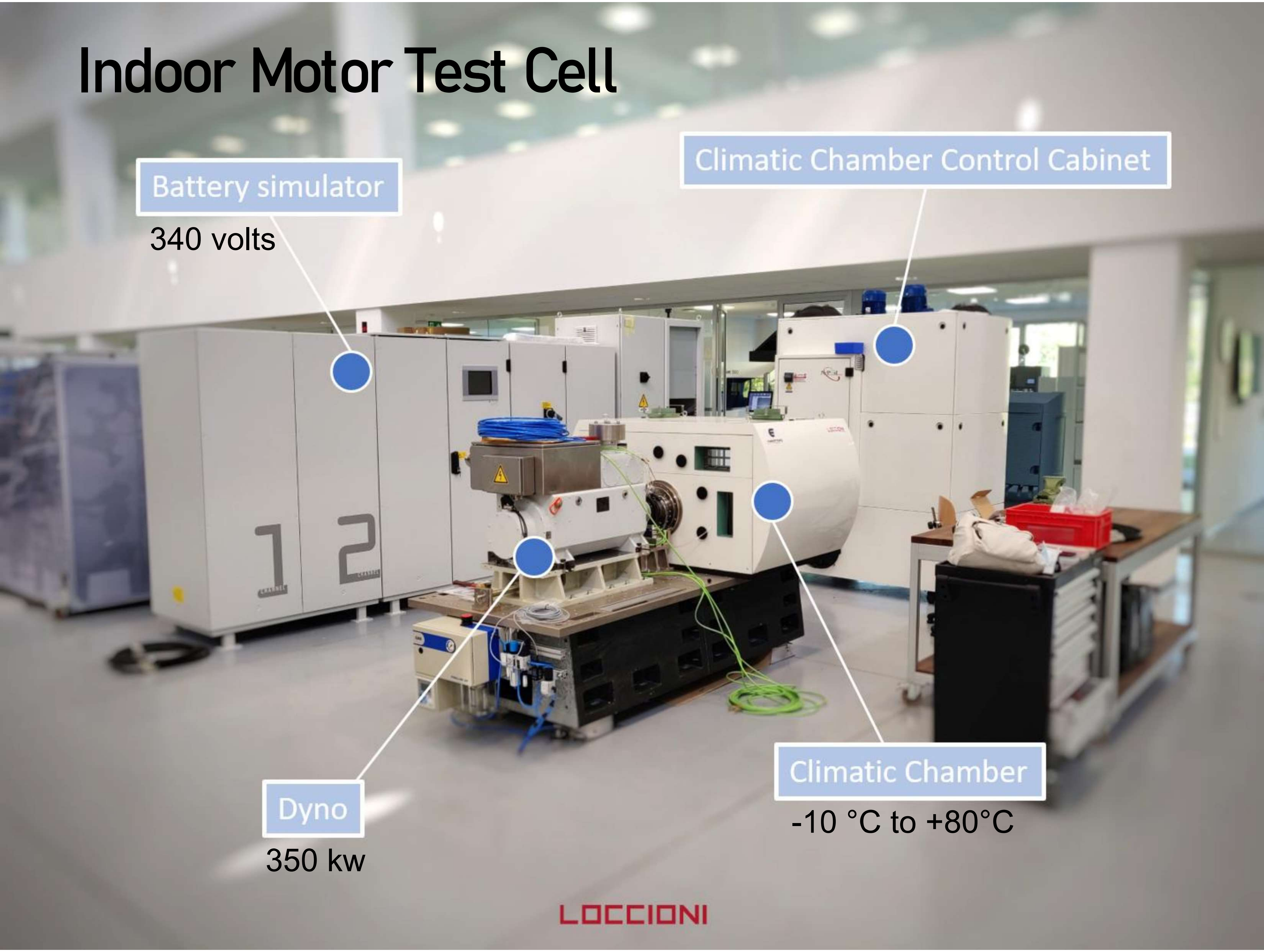


Each Motor Develops 580 ft-lbs of Torque



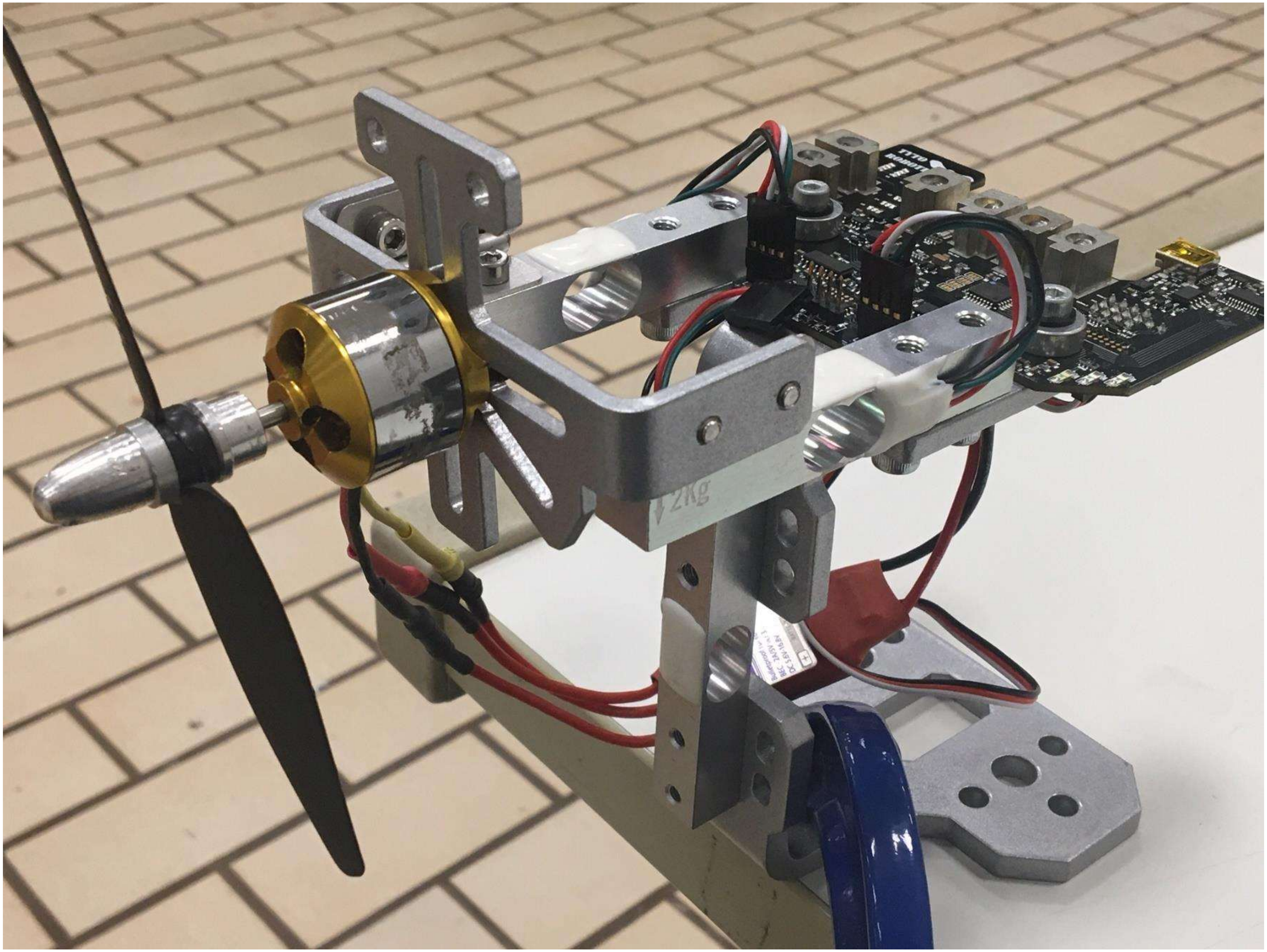
Motor Testing

Indoor Motor Test Cell



A Megawatt Power Test Grid

Small Scale Motor Test Stand



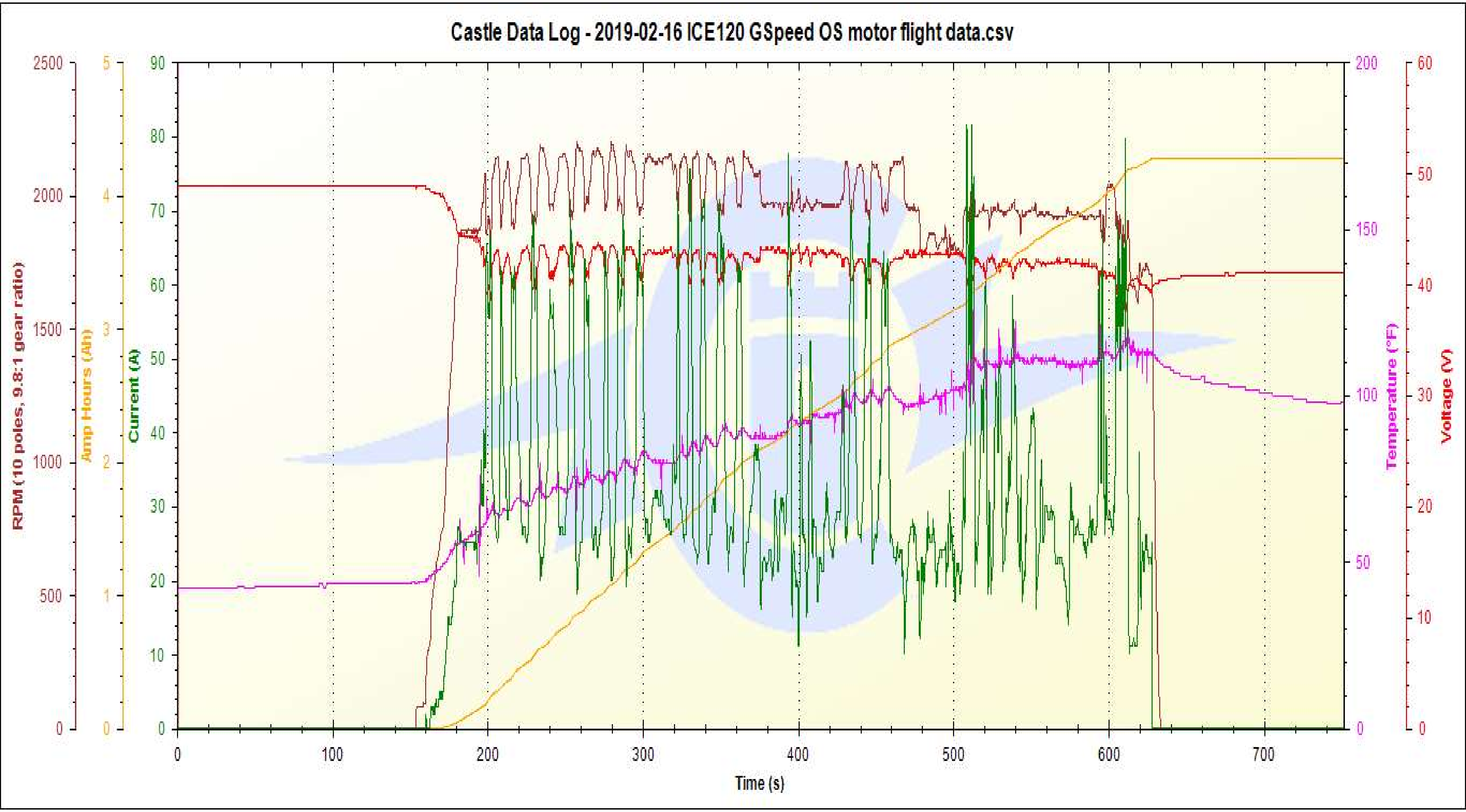
RCBenchmark.com makes small test stands and software

Always Record and Monitor Motor Conditions in Realtime or Datalog

- **Temperature of motor and controller**
- **Temperature of coolant**
- **Voltage**
- **Current**
- **RPM**
- **Command from the flight computer to the motor controller**
- **Command received and output at the motor controller (check for noise)**


Can Collect Power Data on Model Flight Test
700 SAB HELI DIVISION
diameter: 1.6 meter
rpm: 2000
weight: 5.6 kg
optional payload: 5 kg

Data Log Result for Model Tested on Previous Slide



Model Rotor Test Stand

Outside wind tunnel

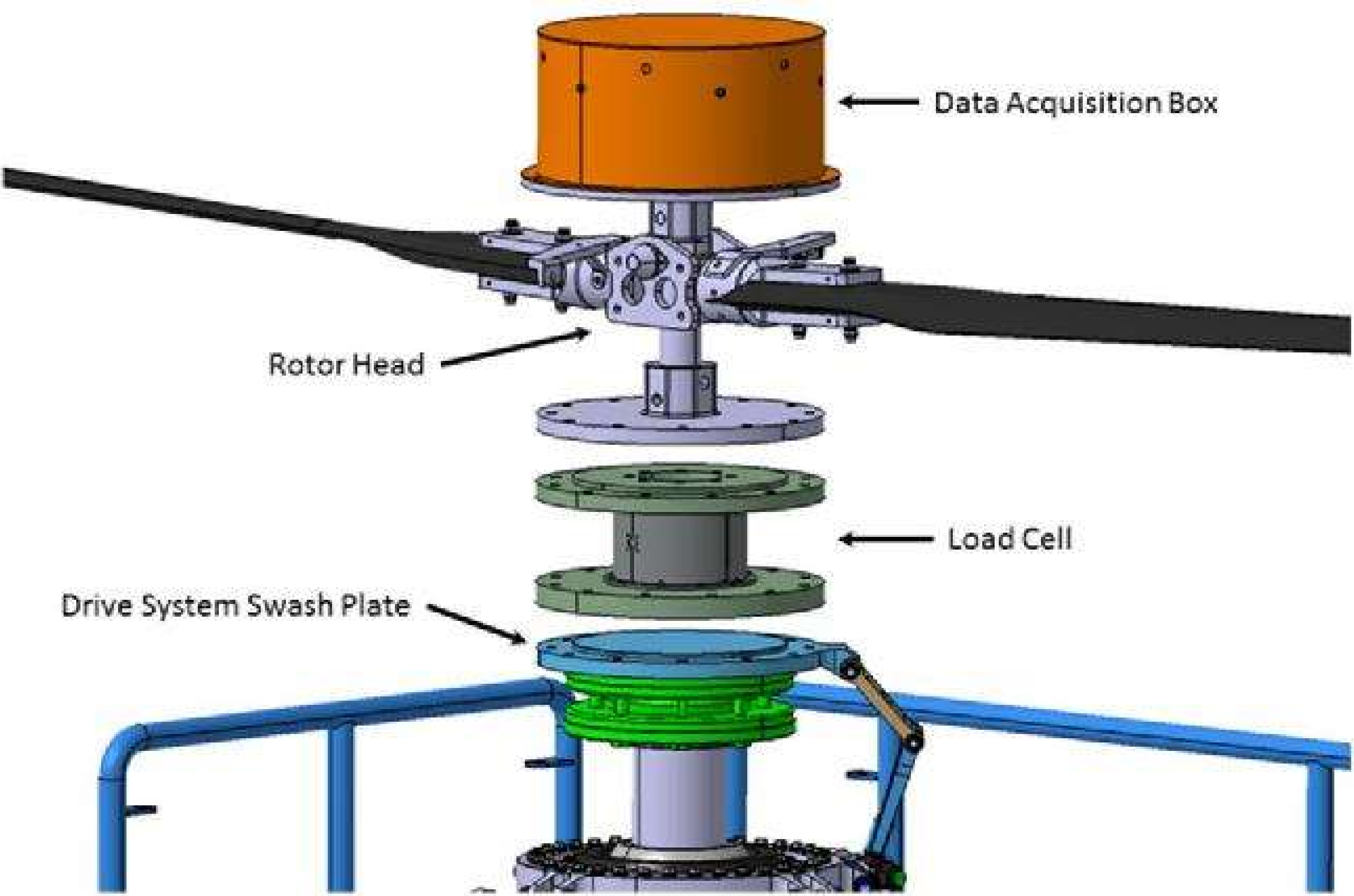
Inside wind tunnel

Indoor Motor/Rotor Test Stand

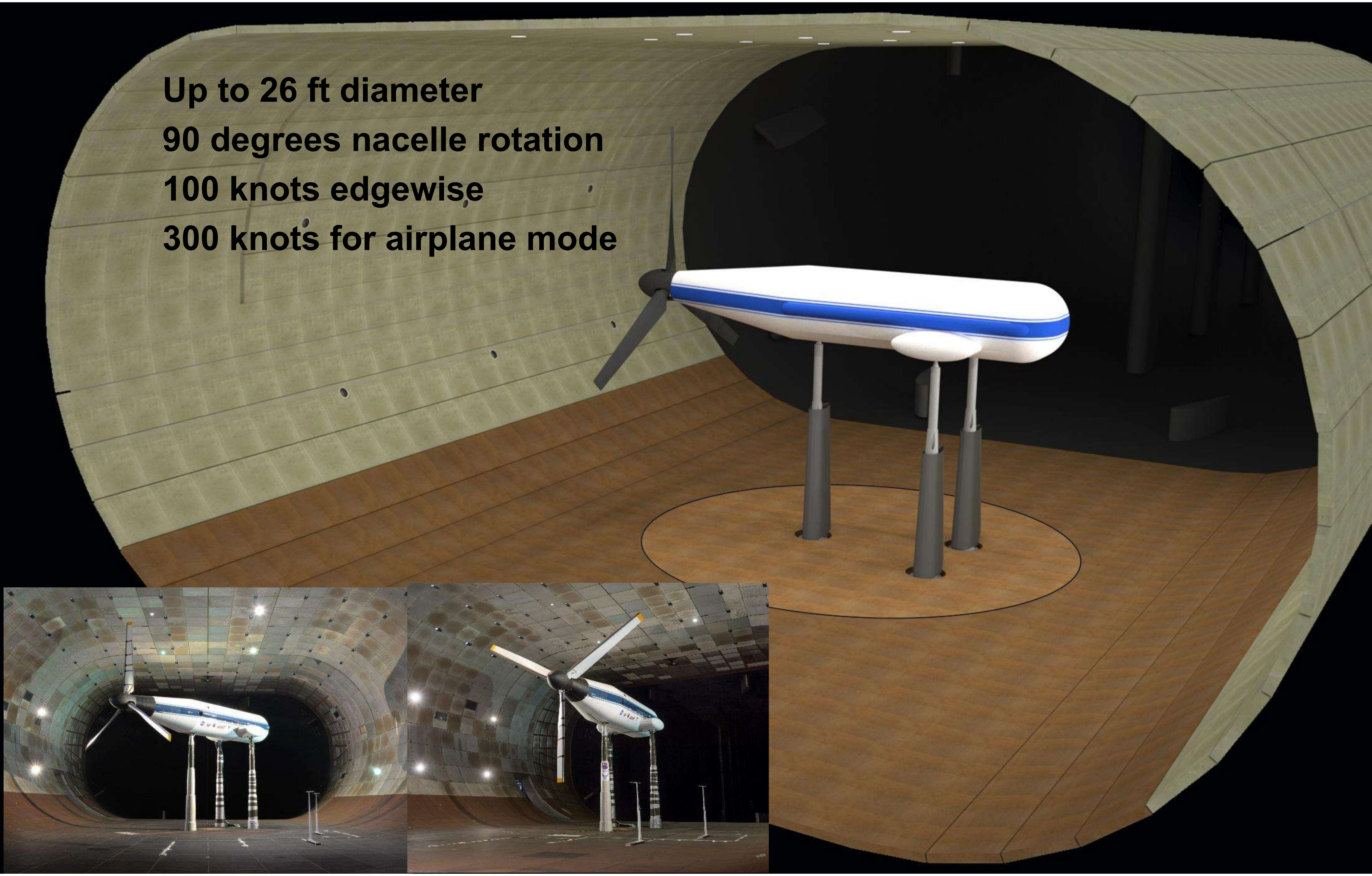
Then Test on Actual Aircraft

Full-Scale Whirl Tower

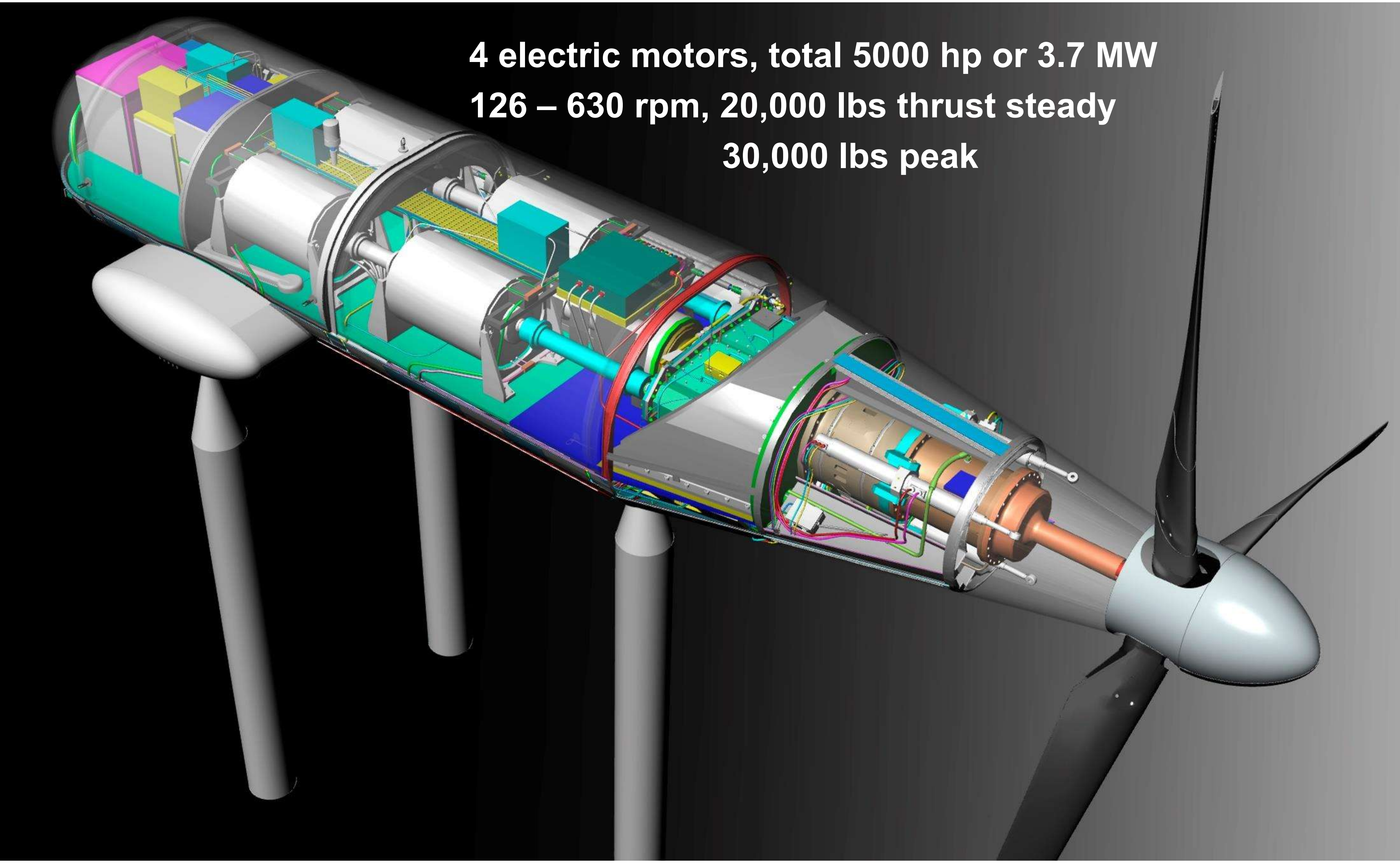
Collecting Rotor Data



NASA Tiltrotor Test Rig (TTR) at NASA 40’ x 80’ Wind Tunnel at Ames Research Center



NASA Tiltrotor Test Rig (TTR)



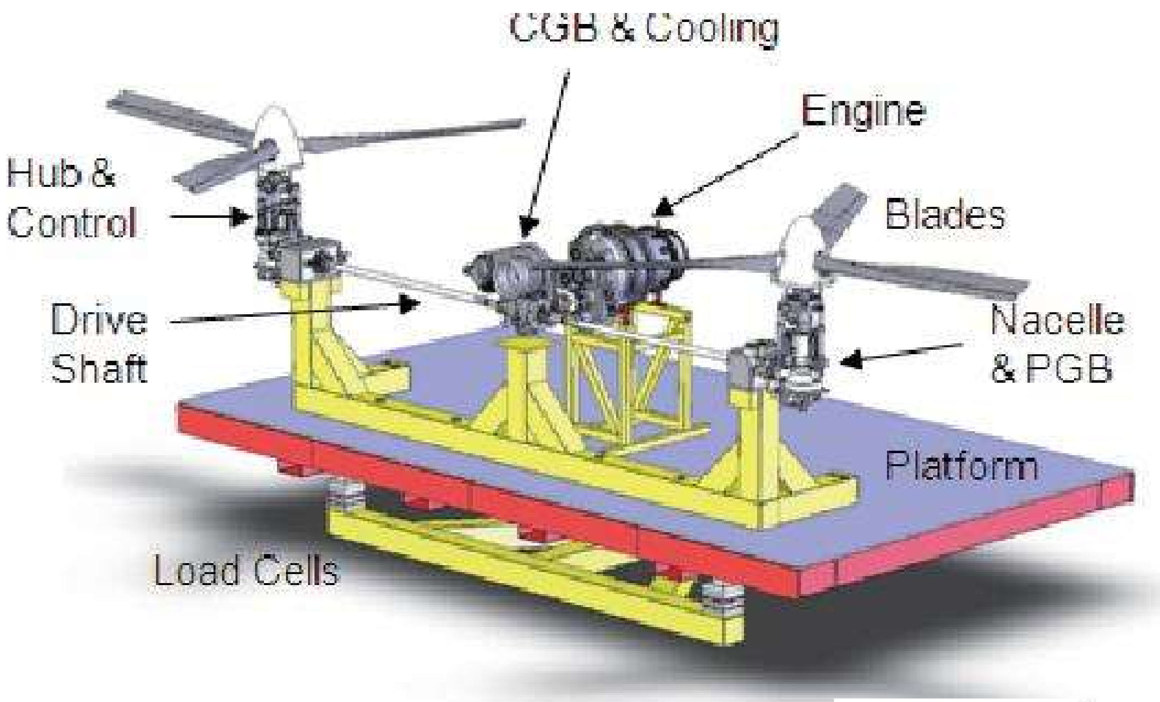
NASA Tiltrotor Test Rig (TTR)

Iron Bird for Testing Electric Powertrain Only

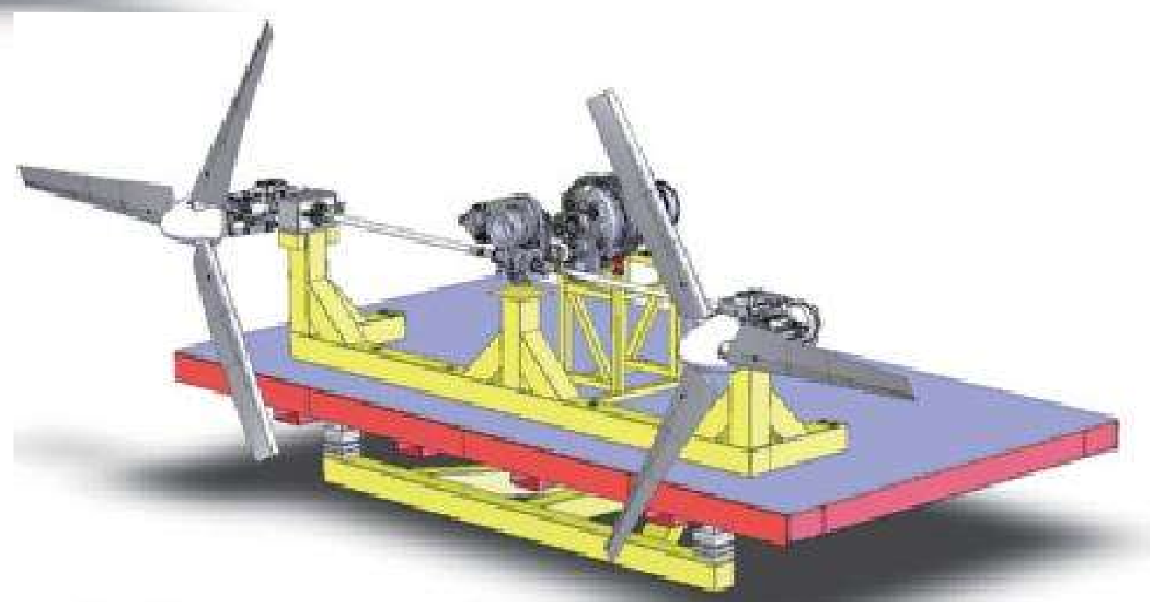
Roll Royce Electric Airplane

Iron Bird for Testing Complete Drivetrain

Iron Bird for Testing Complete Drivetrain



(a) Helicopter mode

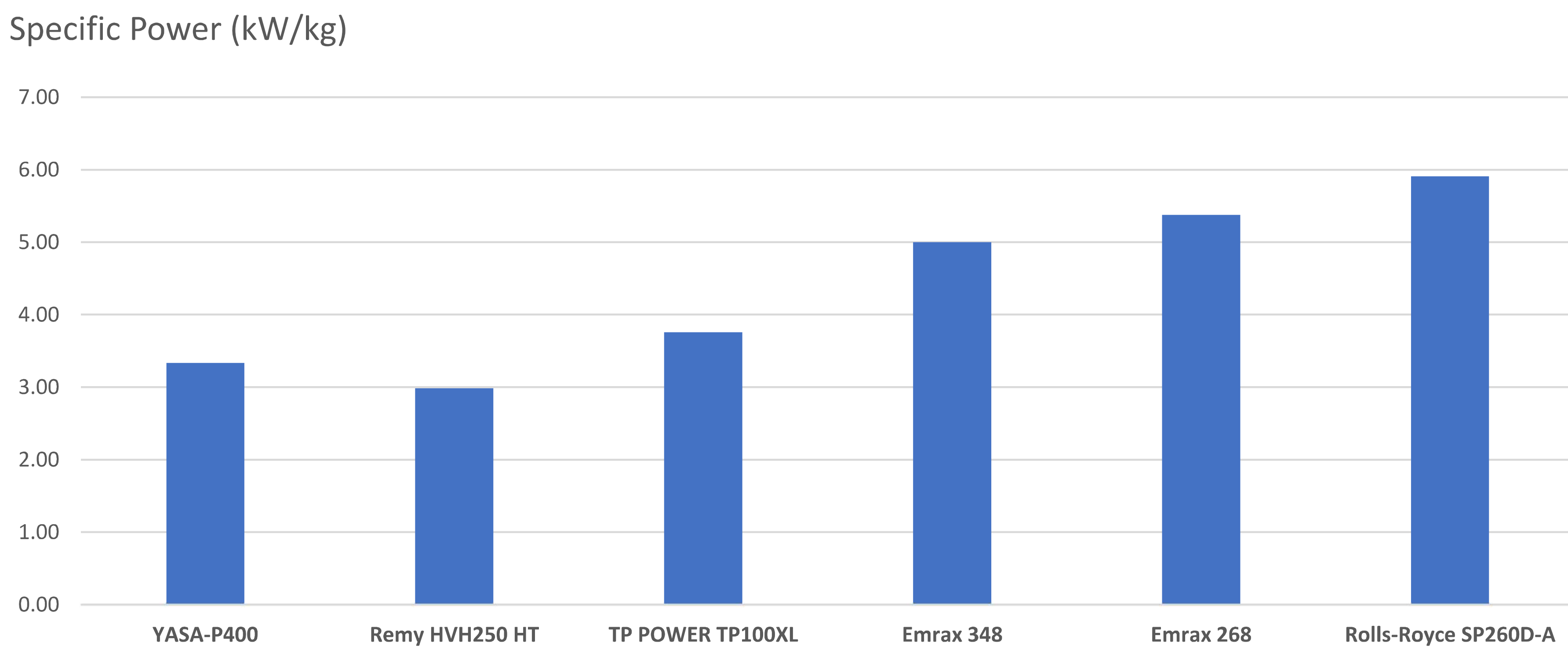


(b) Airplane mode

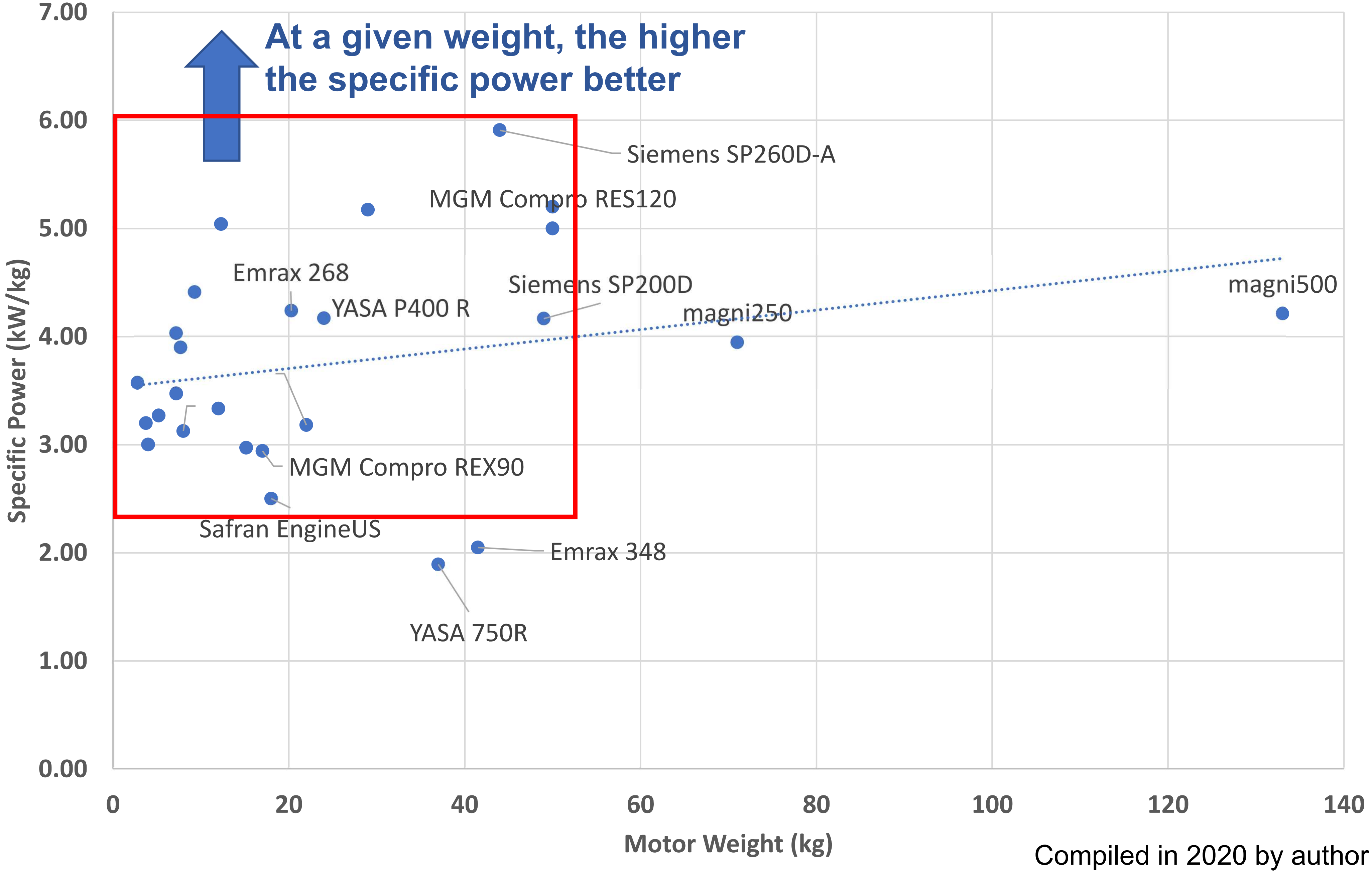
Electric Motor Trade Study with Design Tips for eVTOL Aircraft

(All data are estimated or obtained from public domain, do not assume they are all accurate)

Specific Power for Electric Motors

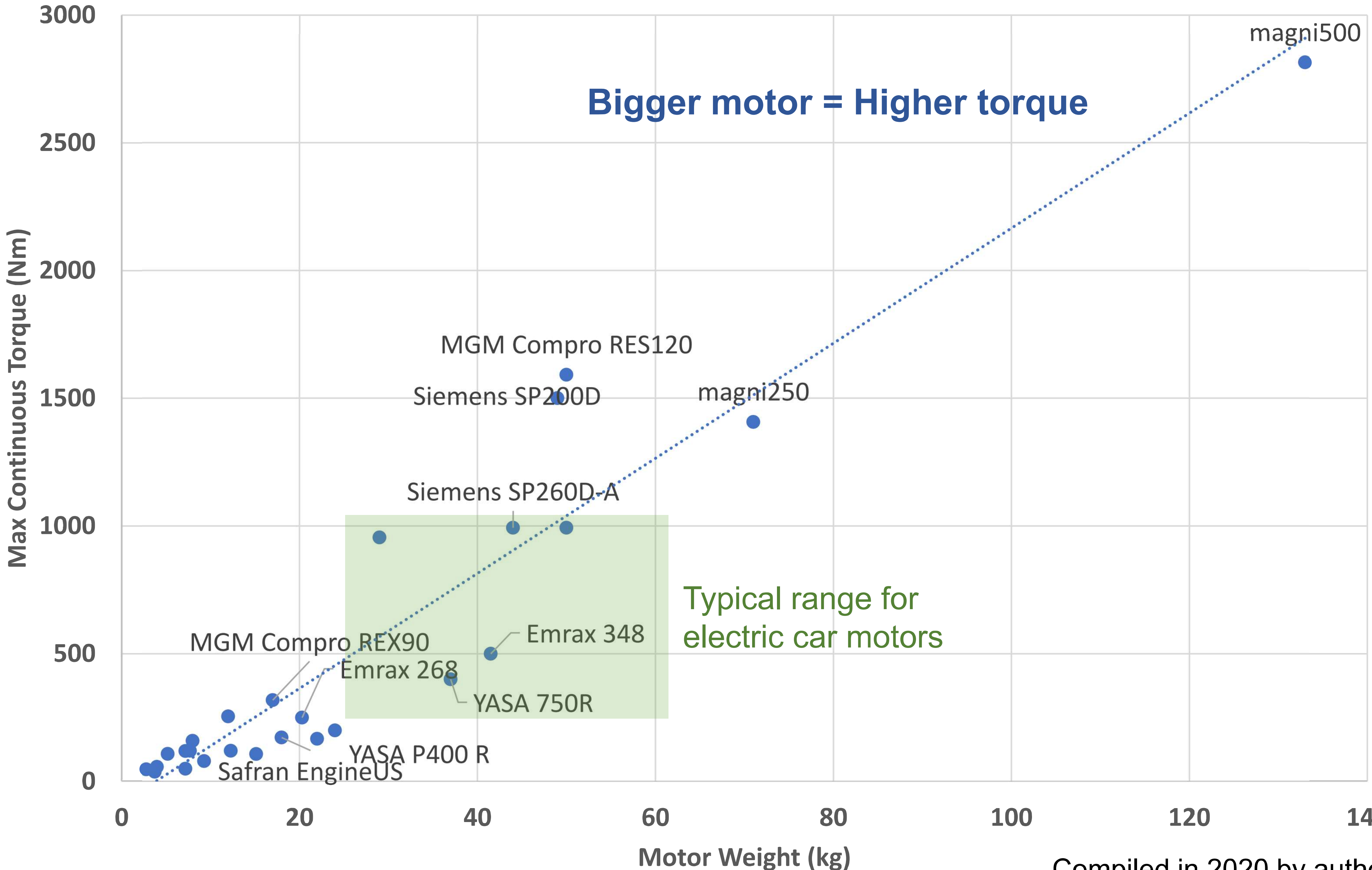


Continuous Specific Power vs Motor Weight



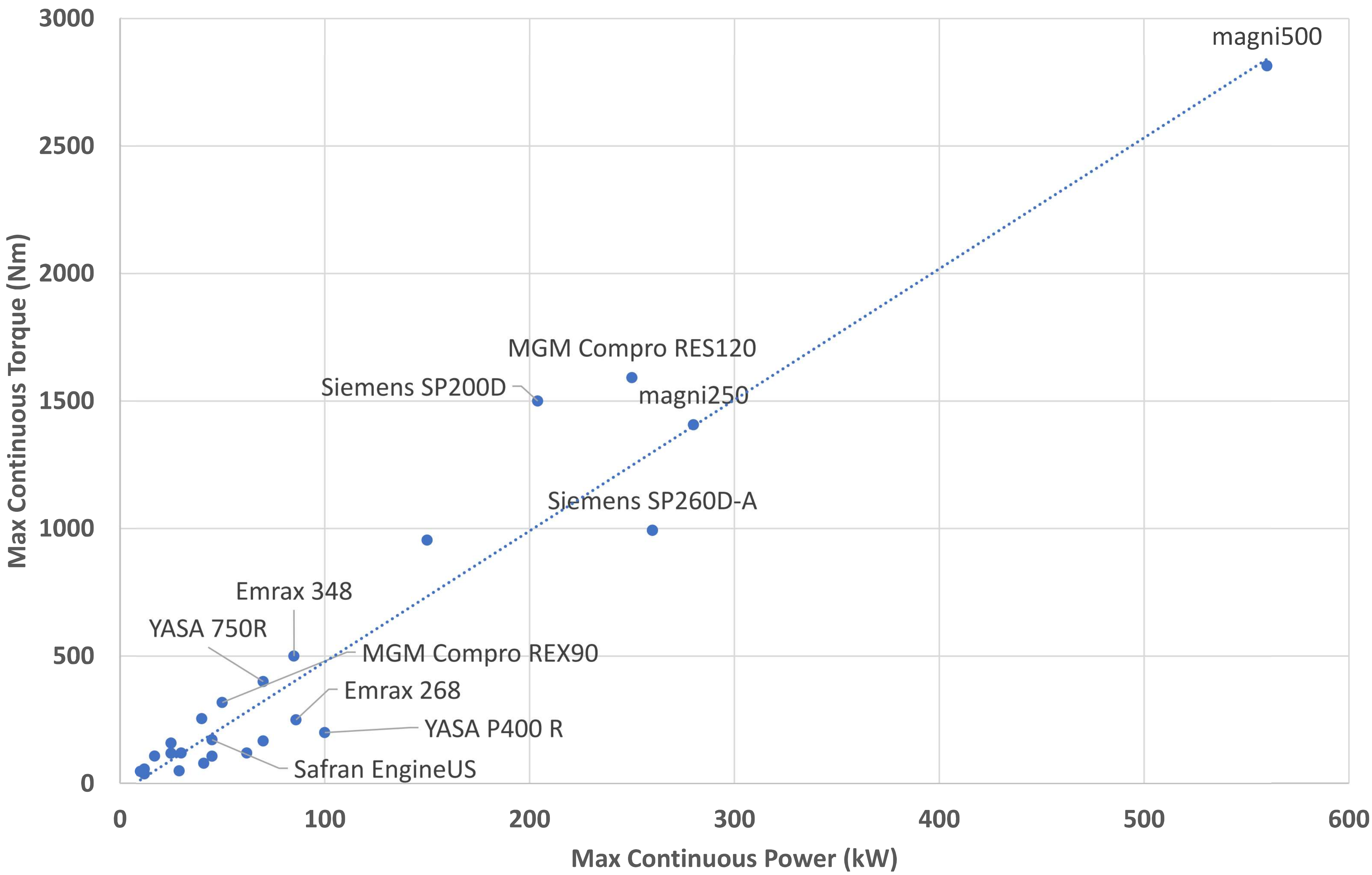
Compiled in 2020 by author

Max Continuous Torque vs Motor Weight

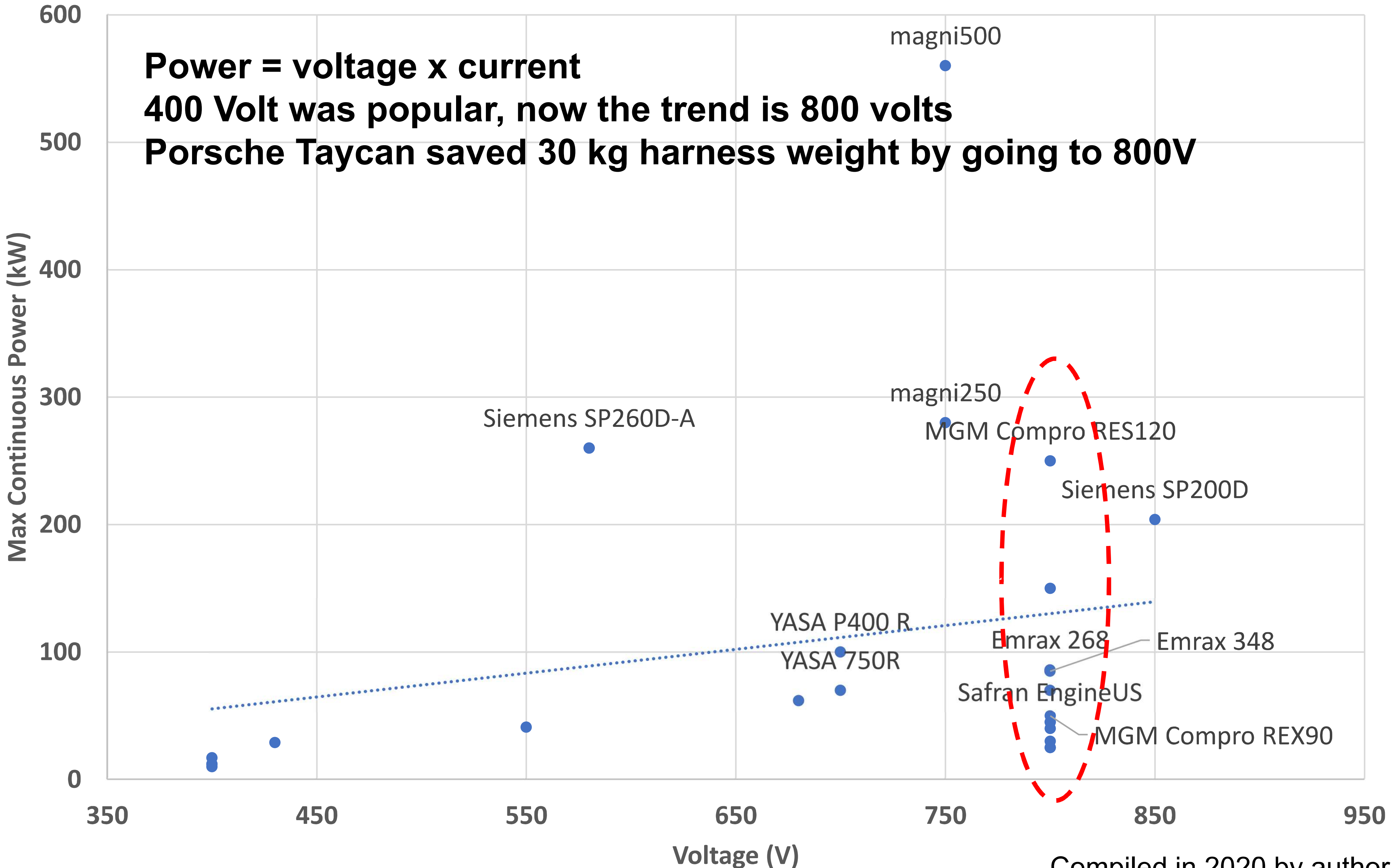


Compiled in 2020 by author

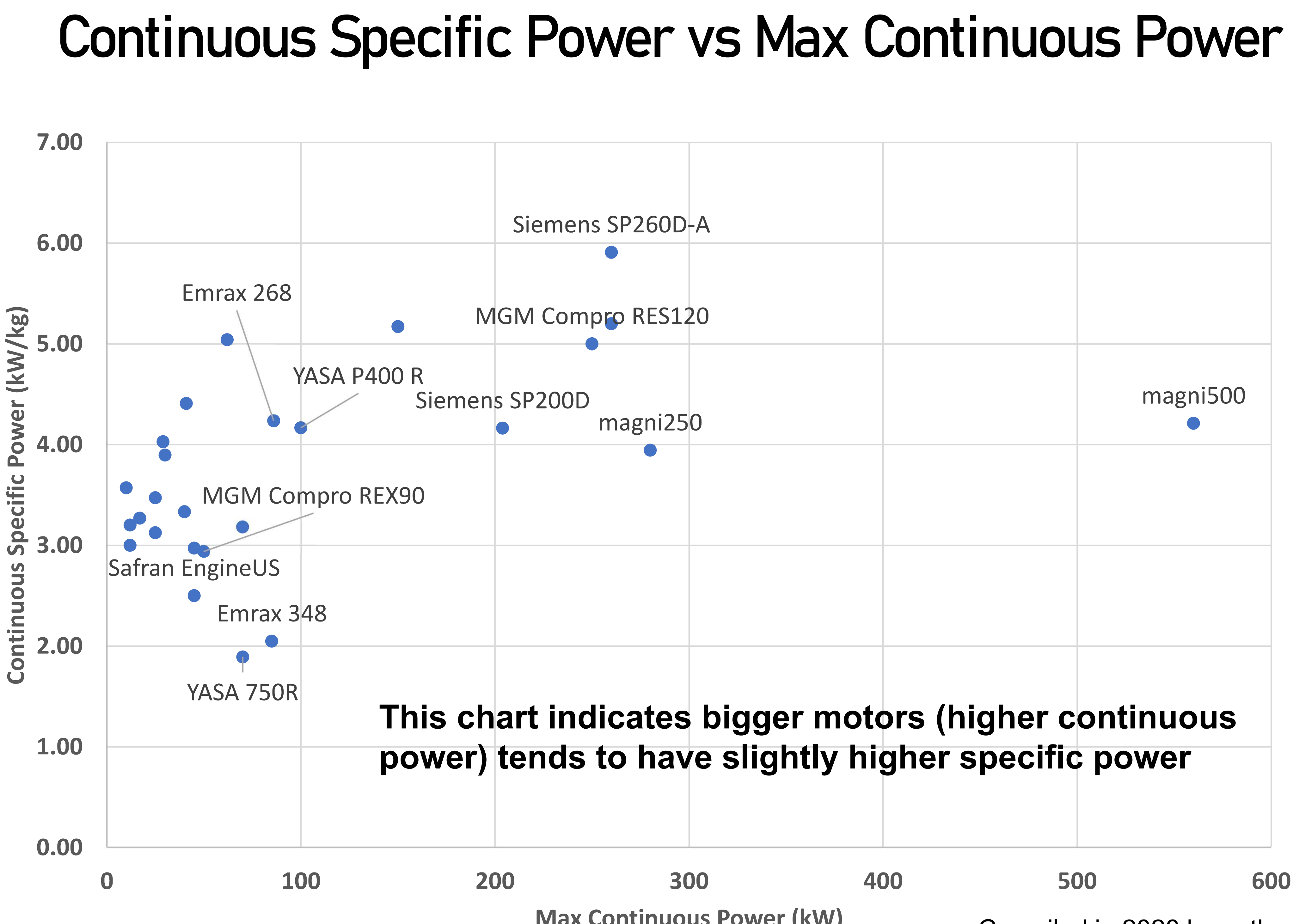
Max Continuous Torque vs Max Continuous Power



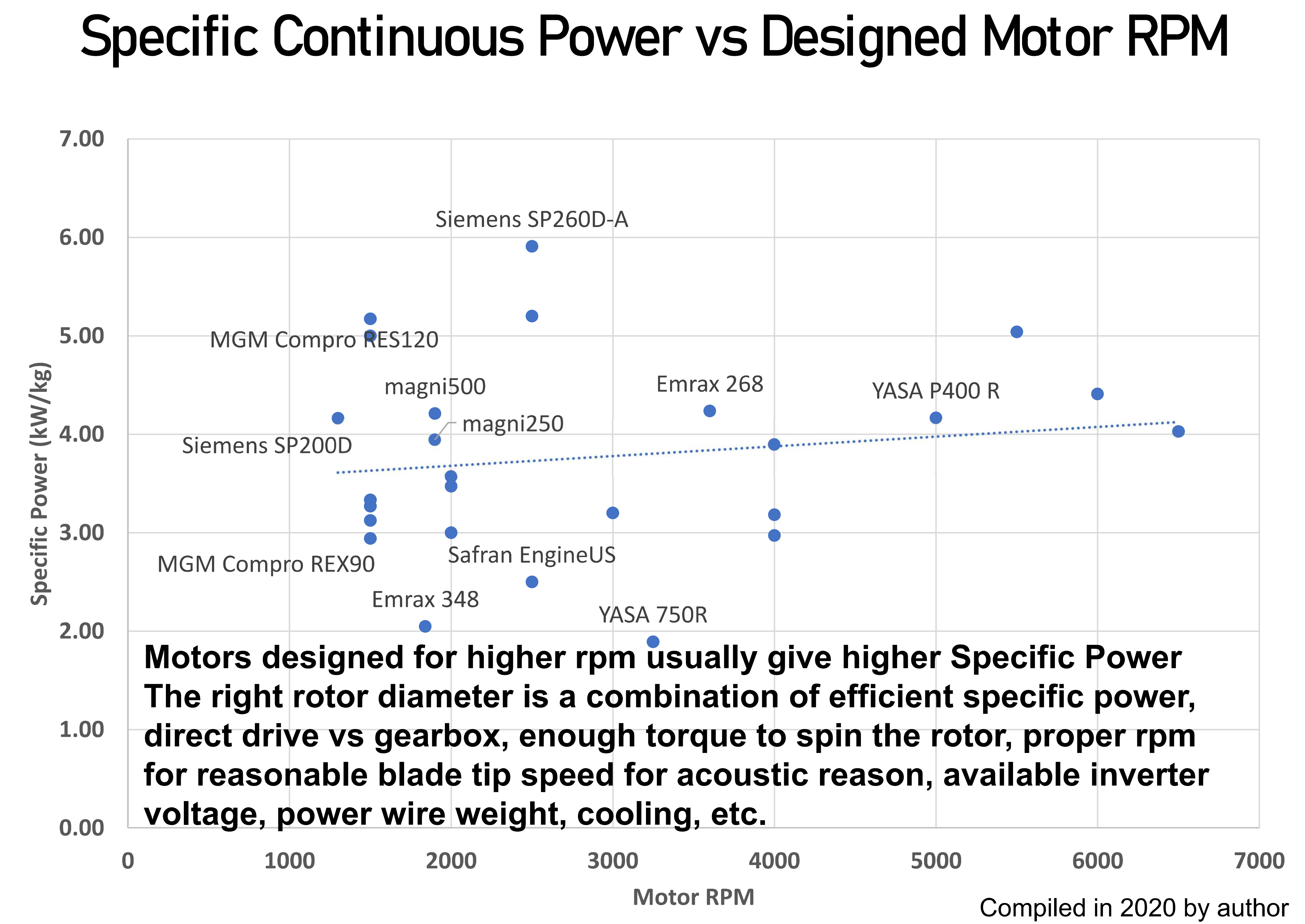
Max Continuous Power vs Voltage



Compiled in 2020 by author

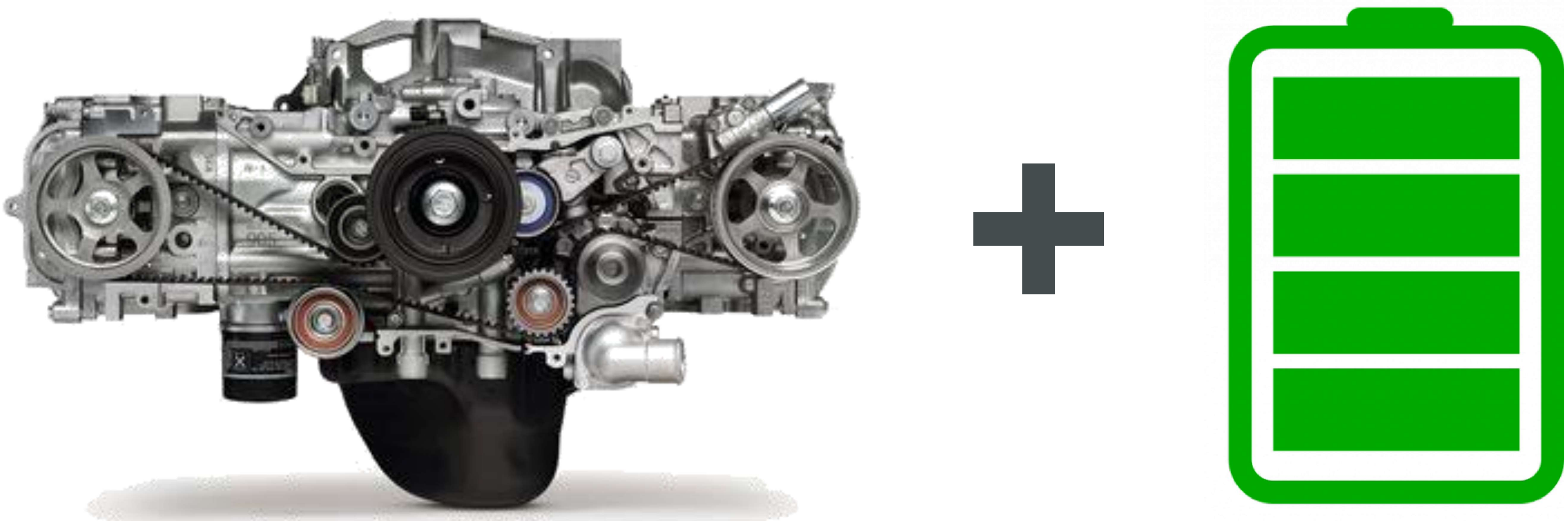


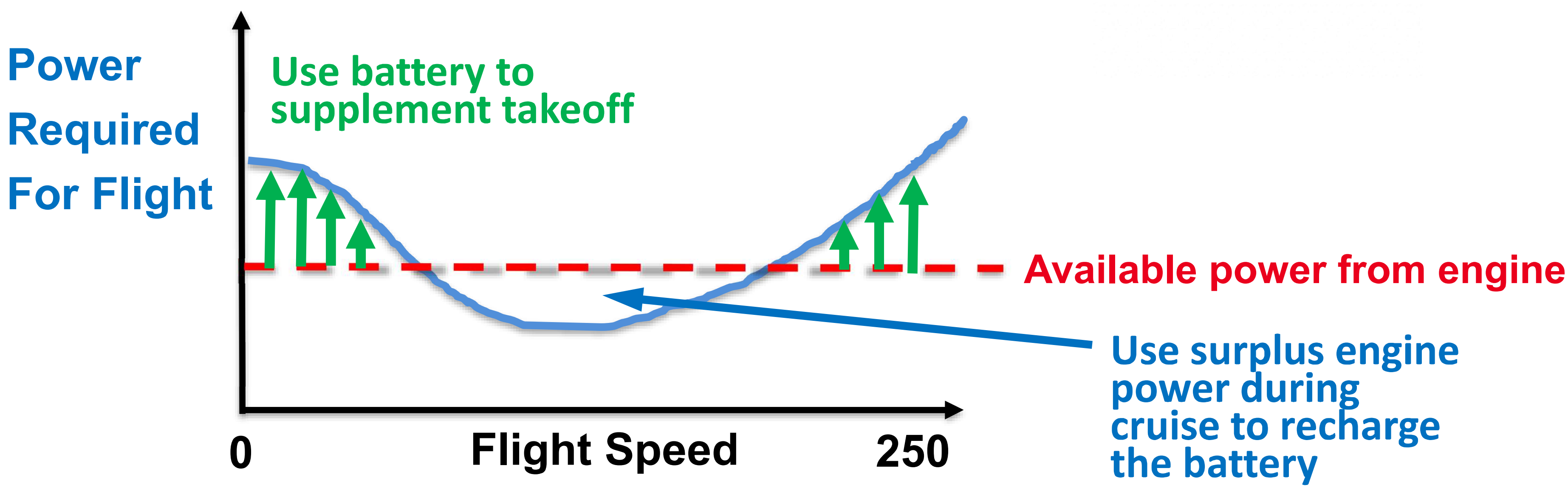
Compiled in 2020 by author


Specific Continuous Power vs Designed Motor RPM
Specific Power (kW/kg)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
1000
2000
3000
4000
5000
6000
7000
Motor RPM
Siemens SP260D-A
MGM Compro RES120
magni500
magni250
Siemens SP200D
Emrax 268
YASA P400 R
MGM Compro REX90
Safran EngineUS
Emrax 348
YASA 750R
Motors designed for higher rpm usually give higher Specific Power
The right rotor diameter is a combination of efficient specific power, direct drive vs gearbox, enough torque to spin the rotor, proper rpm for reasonable blade tip speed for acoustic reason, available inverter voltage, power wire weight, cooling, etc.
Compiled in 2020 by author

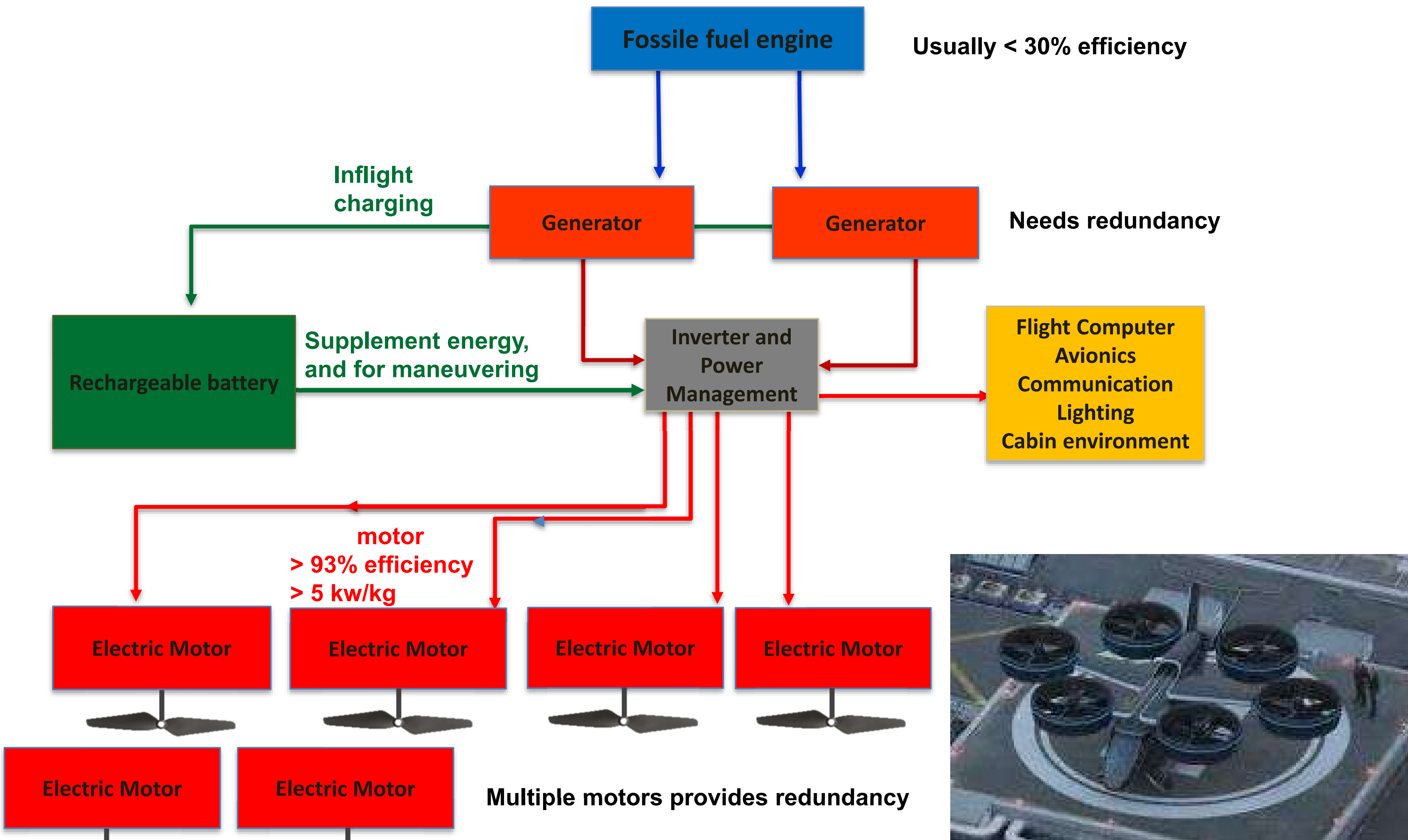
Pure Electric vs Hybrid

Using Hybrid Design to Increase Endurance or Payload



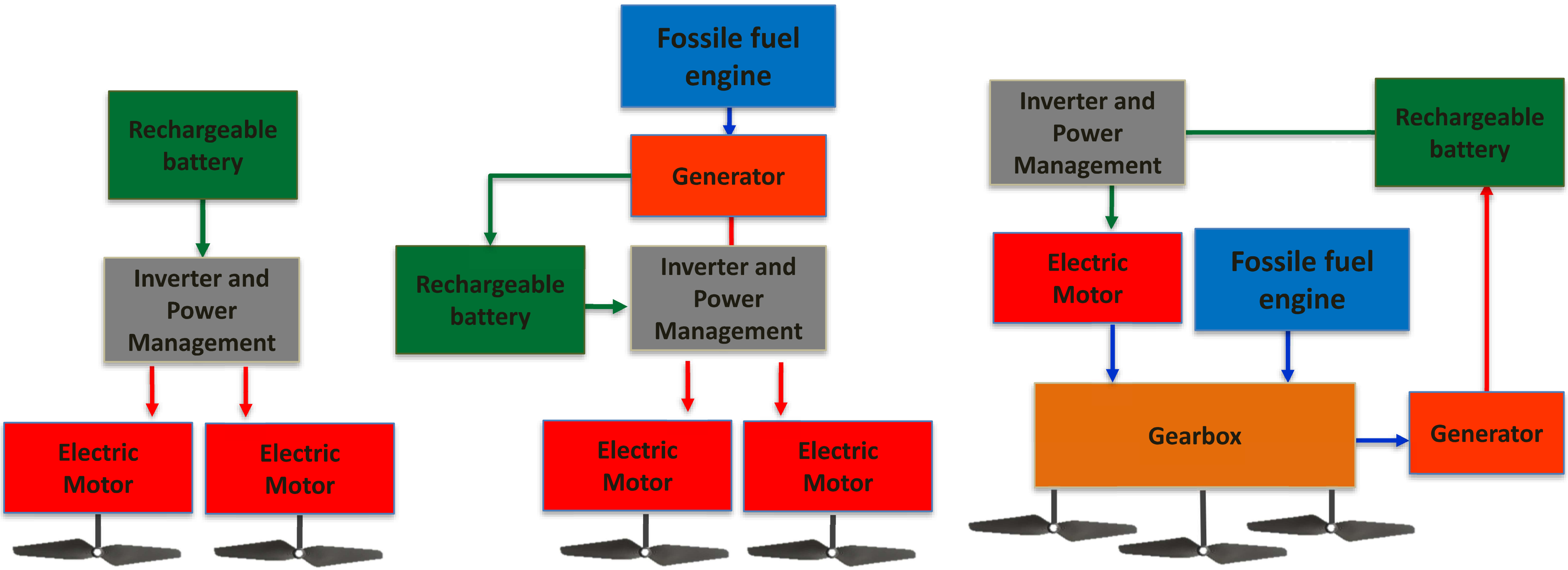


Generic eVTOL Hybrid-Electric Schematic



Example, a hexrotor copter

All-electric vs Serial vs Parallel Hybrid-Electric



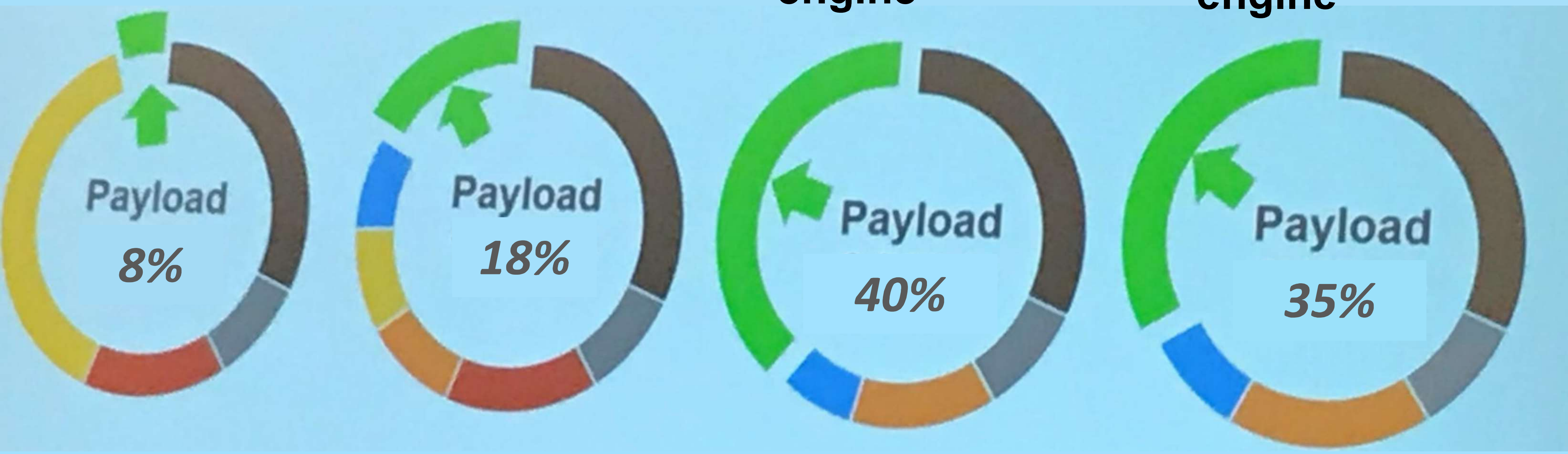
All-electric suitable for:
- <30 min flight (200 Wh/kg pack level)
- <60 min flight (400 Wh/kg pack level)
- Small to medium size aircraft
- Small payload percentage

Serial hybrid suitable for:
- <2 hours flight
- Medium size aircraft
- Reasonable payload

Parallel hybrid suitable for:
- Long endurance
- Medium to large aircraft
- Larger payload

Assume the MTGW are Identical, below results from Honeywell shows all-electric VTOL has the lowest percentage useful payload

All electric | **Hybrid-electric** | **Single turbine engine** | **Twin turbine engine**



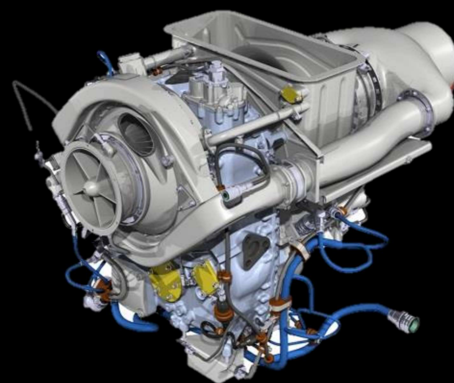
- Payload
- Structure
- Equipment
- Electric propulsion
- Mechanical propulsion
- Battery
- Fuel

From data presented by Honeywell at 2019 VFS Arizona eVTOL Conference

Fossil fuel Engine vs. Electric Power

12,500 Wh/kg

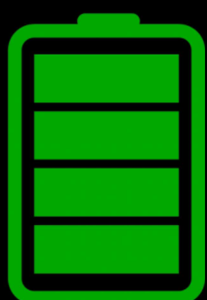
+



25% thermal efficient

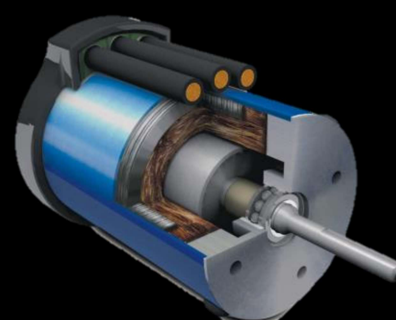
= 4000 Wh/kg

A hybrid could be in between, or improve battery's specific energy



200 Wh/kg

+

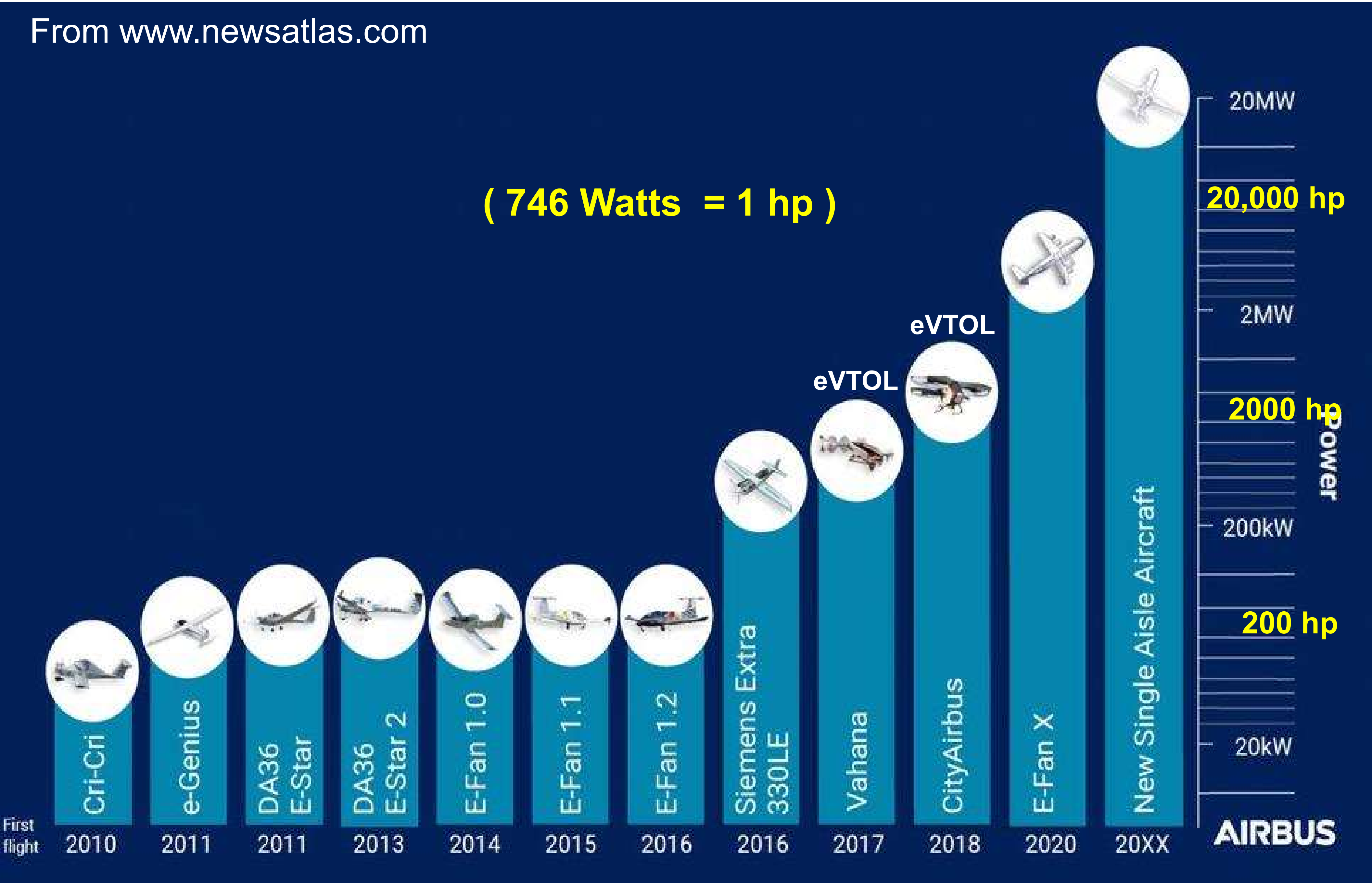


95% efficient

= 190 Wh/kg

How Big Can Electric Get?

Airbus Roadmap for Electric Flight



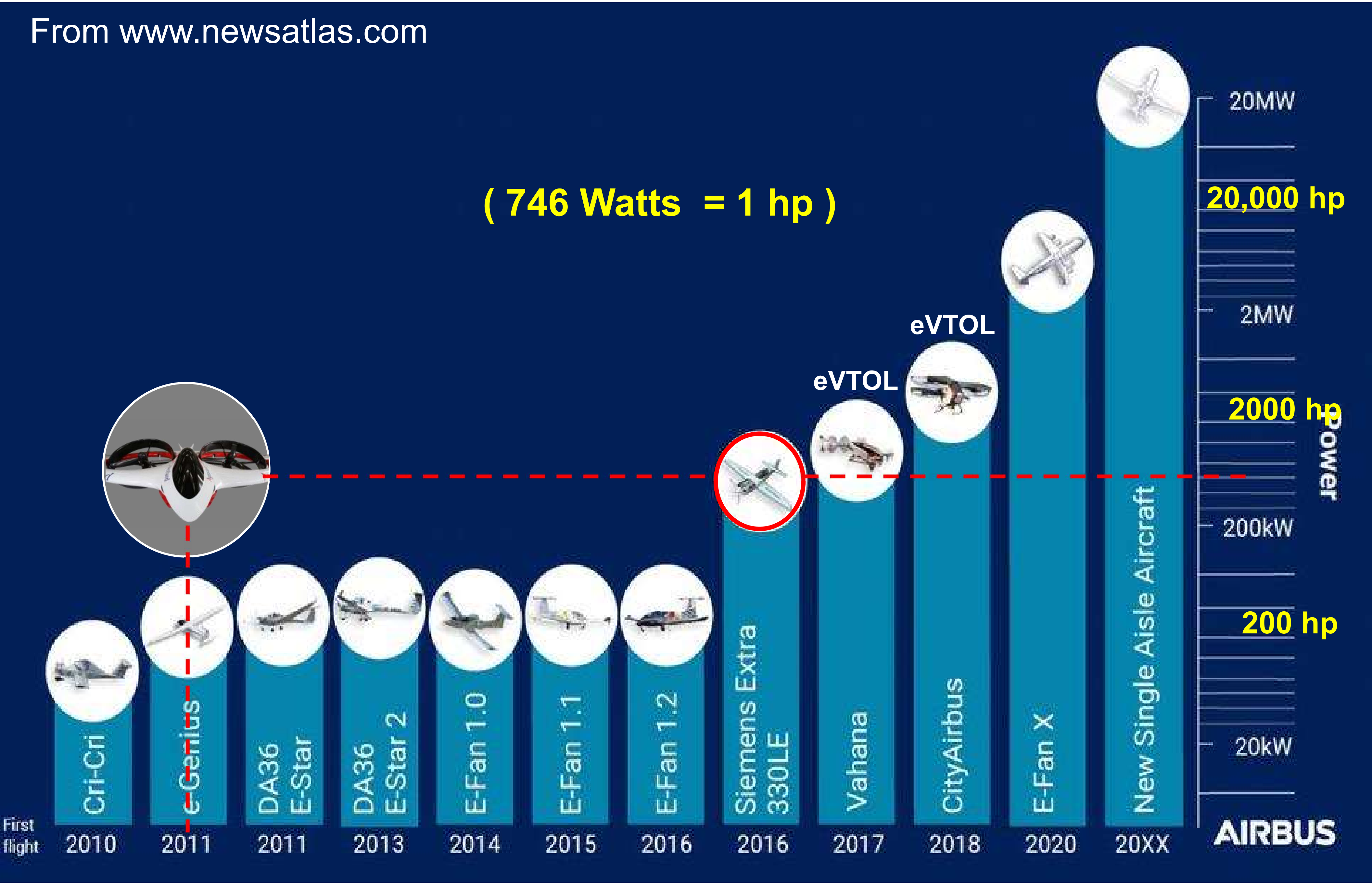
2010 “Cri Cri” MTOW 175 kg, 30 min at 60 kts, 2x25 hp

2015 “E-Fan” 2x40 hp, 240v, 1 hour Endurance

Original Engine Powered Walter Extra 300

2016 "Extra 330LE" 260 kw (348 hp), 50 kg motor
Top speed 337.5 km/h, 20 min cruise at 1000 kg

Airbus Roadmap for Electric Flight



Both have 260 kw total

Both are 1000 kg MTGW

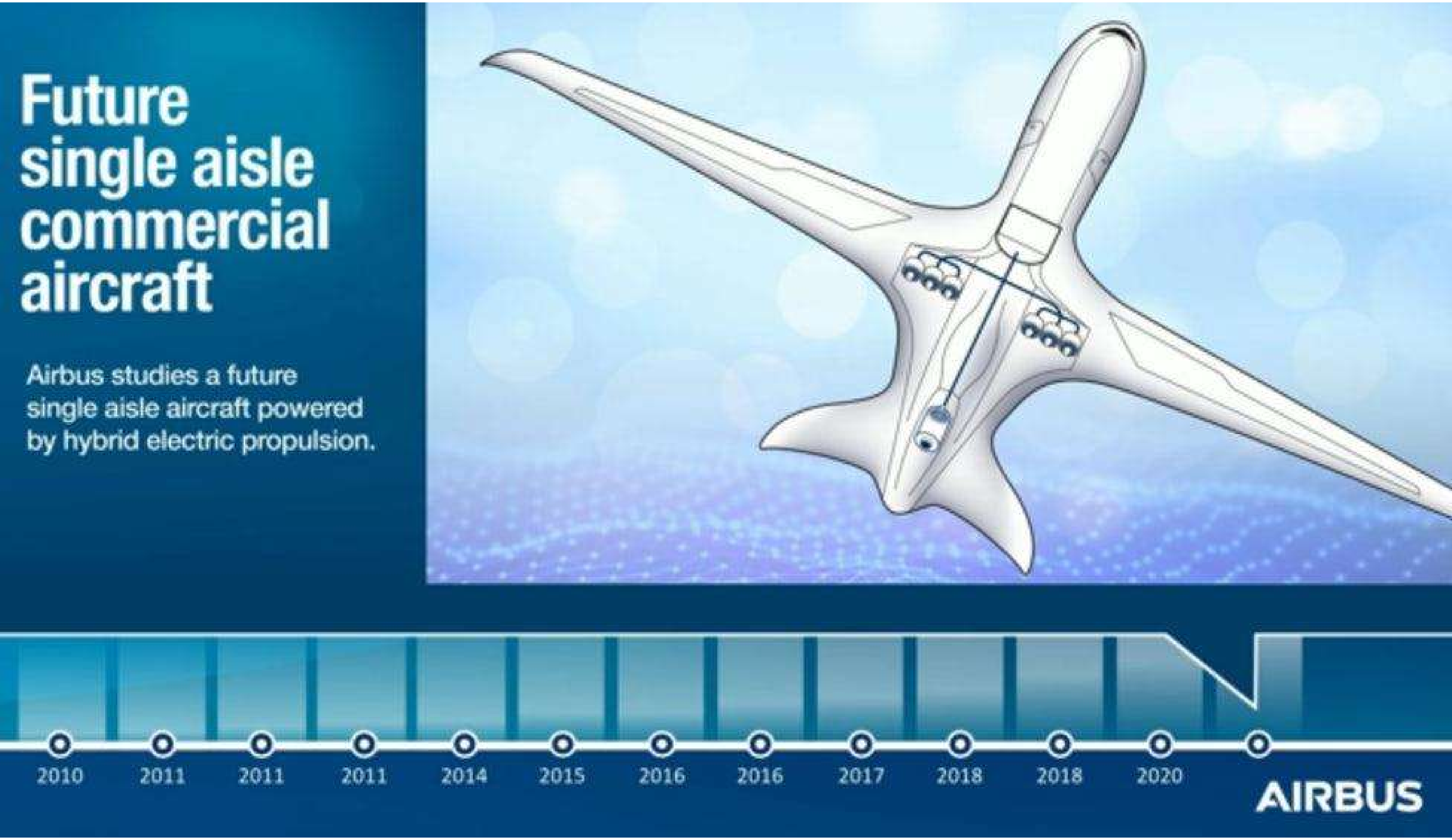
CTOL gives 20 min

versus

VTOL gives 10 min

20 megawatts (26,700 hp)

From www.newsatlas.com



3. Electric Motors and Hybrids

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For students to use in the 2022 eVTOL Design Short Course at SNU,
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