ADAMBOTS
Team 245

Review of Motors used for FIRST FRC Robots

Common Motors Used for FIRST FRC Robots

- **Common motors used for FRC Robot applications:**

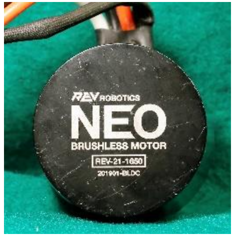
BAG Motor

775 Motor

Mini CIM

Full Size CIM

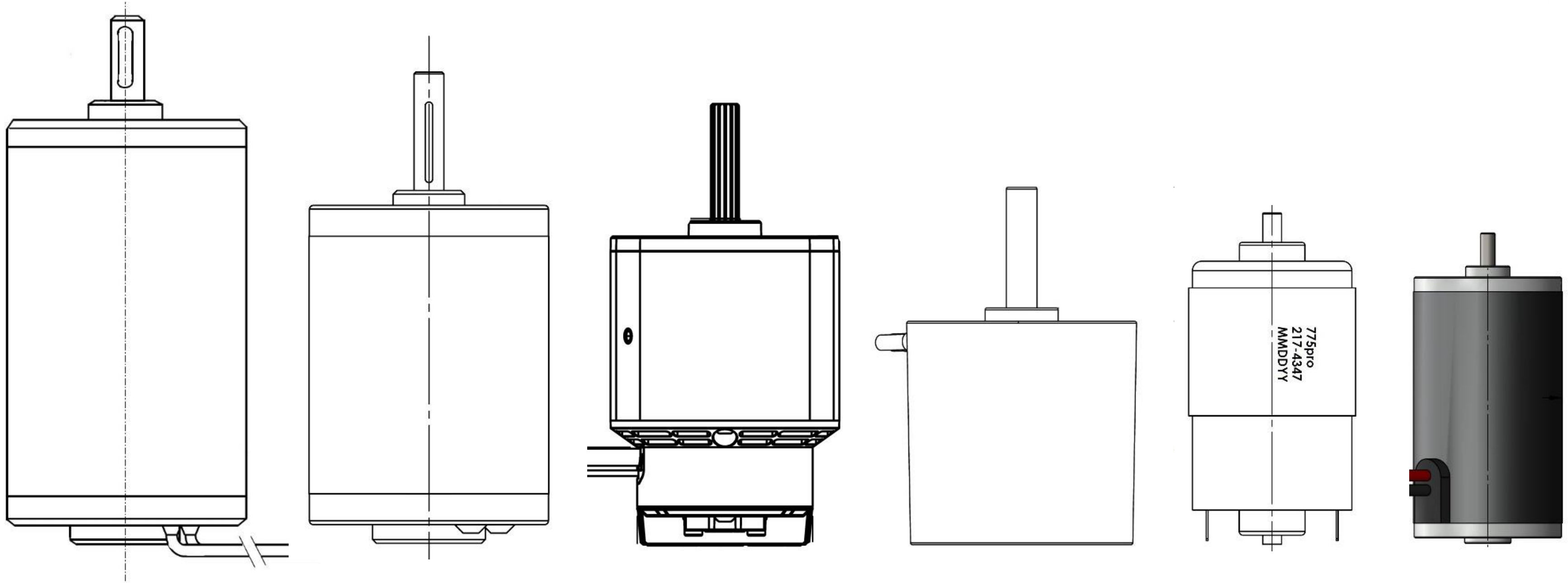
Falcon Brushless



Neo Brushless

Neo 550 Brushless and other motors are not included in this review

Scale Comparison of Motors



Full Size CIM:
5.50“ Long
2.52” Dia
2.8 Lbm

Mini CIM:
4.95“ Long
2.52” Dia
2.16 Lbm

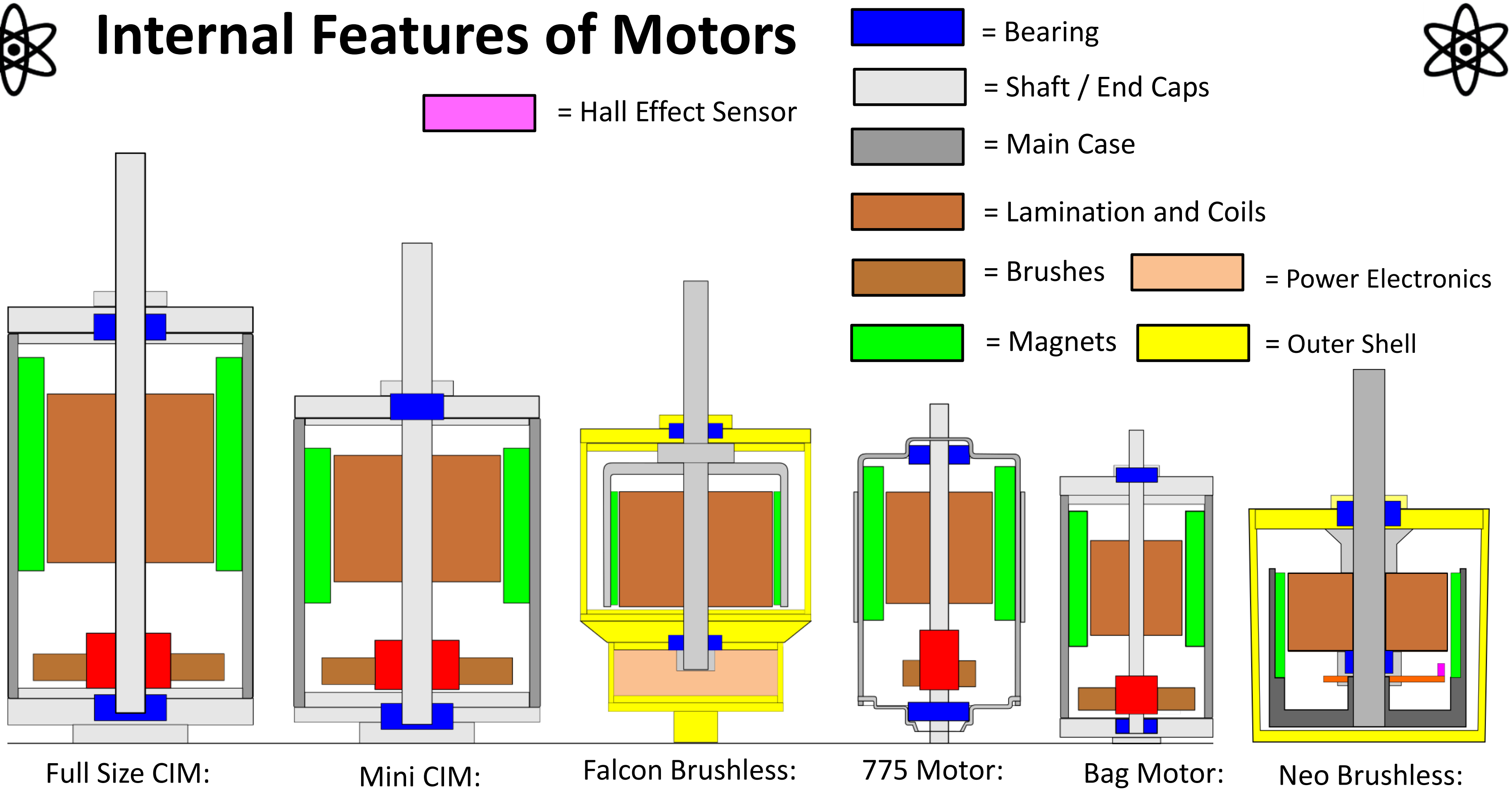
Falcon Brushless:
4.57“ Long
2.36” Dia
1.10 Lbm

NEO Brushless:
3.67“ Long
2.36” Dia
0.94 Lbm

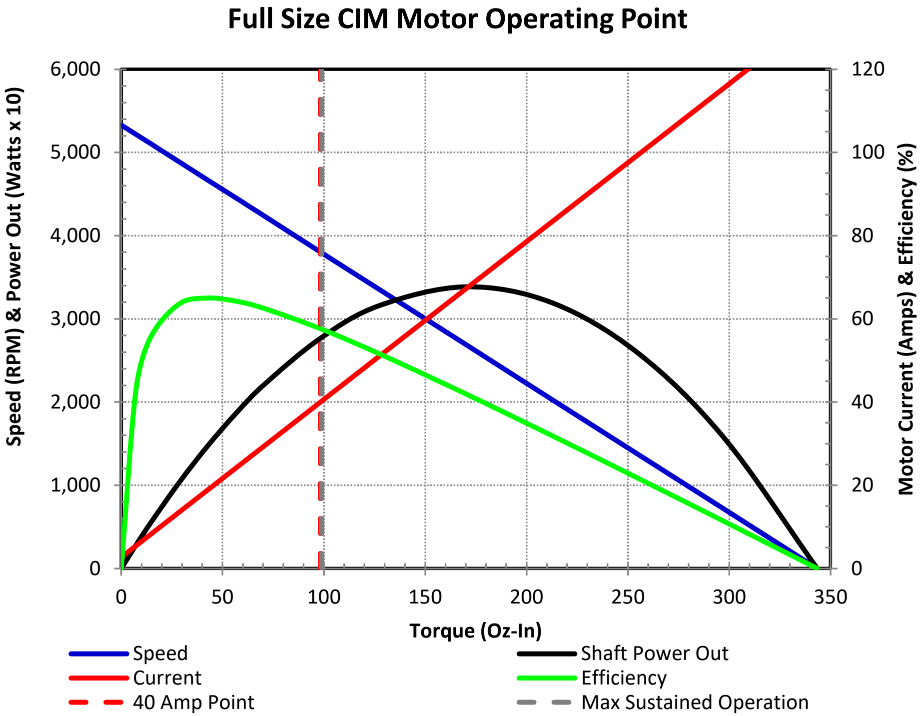
775 Motor:
3.47“ Long
1.74” Dia
0.81 Lbm

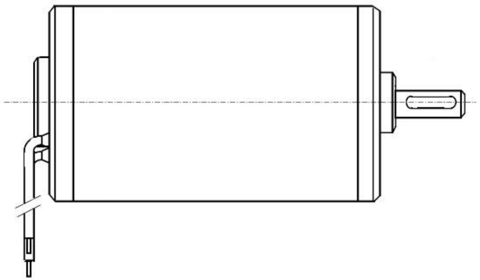
Bag Motor:
3.27“ Long
1.59” Dia
0.71 Lbm

Internal Features of Motors



Performance Summary: Full Size CIM

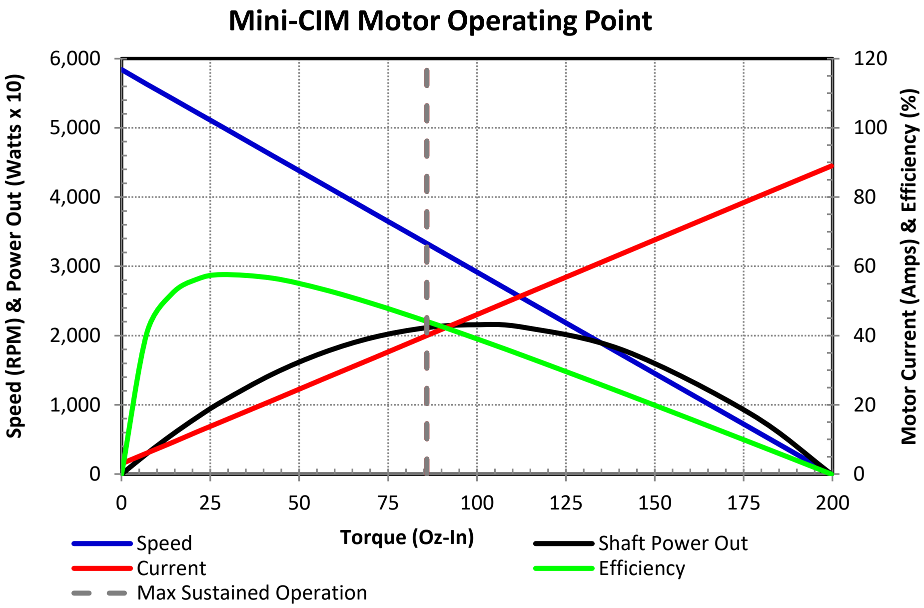


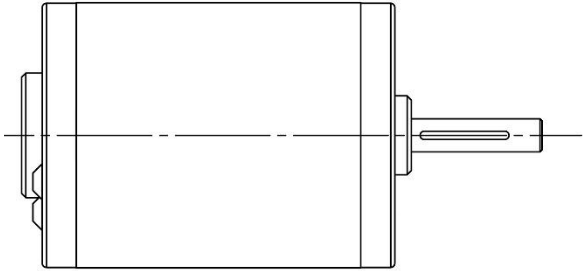


Full Size CIM:
5.50“ Long
2.52” Dia
2.8 Lbm

Full Size CIM					
12.0 Volt Performance	Free Speed (RPM)	5330	Performance at Max Power Output	Torque (Oz-In)	170
	Idle Current (Amp)	2.7		Speed (RPM)	2692
	Stall Torque (Oz-In)	343.4		Current (Amps)	67.2
	Stall Current (Amps)	133		Power Out (Watts)	338
				Efficiency (%)	42.0
Performance at Peak Efficiency	Torque (Oz-In)	42.5	Performance at Max Power Continuous Operation	Torque (Oz-In)	98.3
	Speed (RPM)	4671		Speed (RPM)	3804
	Current Amps)	18.82		Current (Amps)	40
	Power Out (Watts)	146.8		Power Out (Watts)	276.7
	Efficiency (%)	65.0		Efficiency (%)	57.6

Performance Summary: Mini CIM

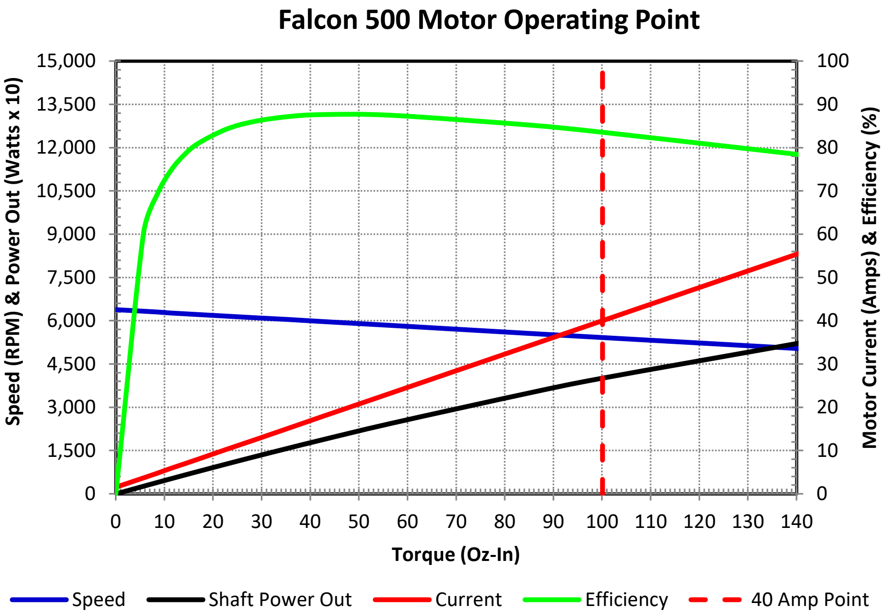


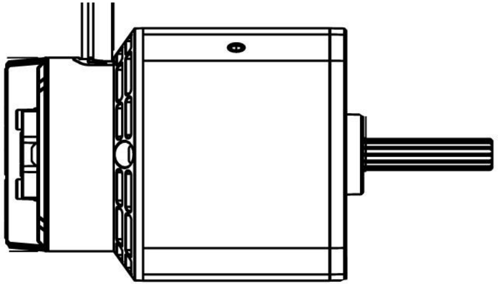


Mini CIM:
4.95“ Long
2.52” Dia
2.16 Lbm

Mini CIM					
12.0 Volt Performance	Free Speed (RPM)	5840	Performance at Max Power Output	Torque (Oz-In)	100.6
	Idle Current (Amp)	3.0		Speed (RPM)	2899
	Stall Torque (Oz-In)	199.7		Current (Amps)	46.3
	Stall Current (Amps)	89		Power Out (Watts)	215.7
				Efficiency (%)	38.8
Performance at Peak Efficiency	Torque (Oz-In)	31.2	Performance at Max Power Continuous Operation	Torque (Oz-In)	85.9
	Speed (RPM)	4929		Speed (RPM)	3328
	Current Amps)	16.42		Current (Amps)	40
	Power Out (Watts)	113.6		Power Out (Watts)	211.5
	Efficiency (%)	57.7		Efficiency (%)	44.1

Performance Summary: Falcon 500

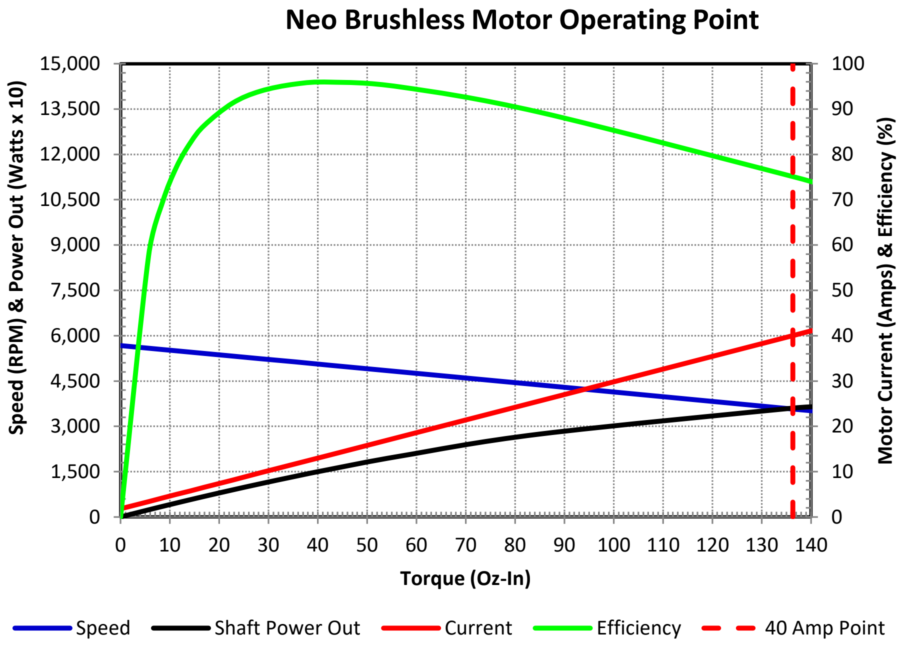


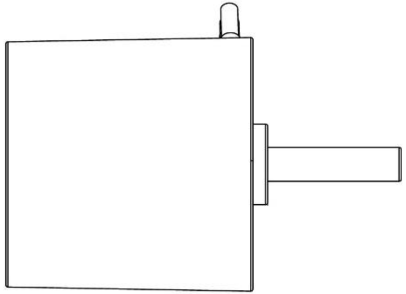


Falcon Brushless:
45.67“ Long
2.36” Dia
1.10 Lbm

Falcon 500 Motor					
12.0 Volt Performance	Free Speed (RPM)	6380	Performance at Max Power Output	Torque (Oz-In)	N/A
	Idle Current (Amp)	1.5		Speed (RPM)	N/A
	Stall Torque (Oz-In)	664		Current (Amps)	N/A
	Stall Current (Amps)	257		Power Out (Watts)	N/A
				Efficiency (%)	N/A
Performance at Peak Efficiency	Torque (Oz-In)	46.7	Performance at Max Power Continuous Operation	Torque (Oz-In)	100.1
	Speed (RPM)	5931		Speed (RPM)	5419
	Current Amps)	19.48		Current (Amps)	40
	Power Out (Watts)	205.1		Power Out (Watts)	401.1
	Efficiency (%)	87.71		Efficiency (%)	83.6

Performance Summary: Neo Brushless

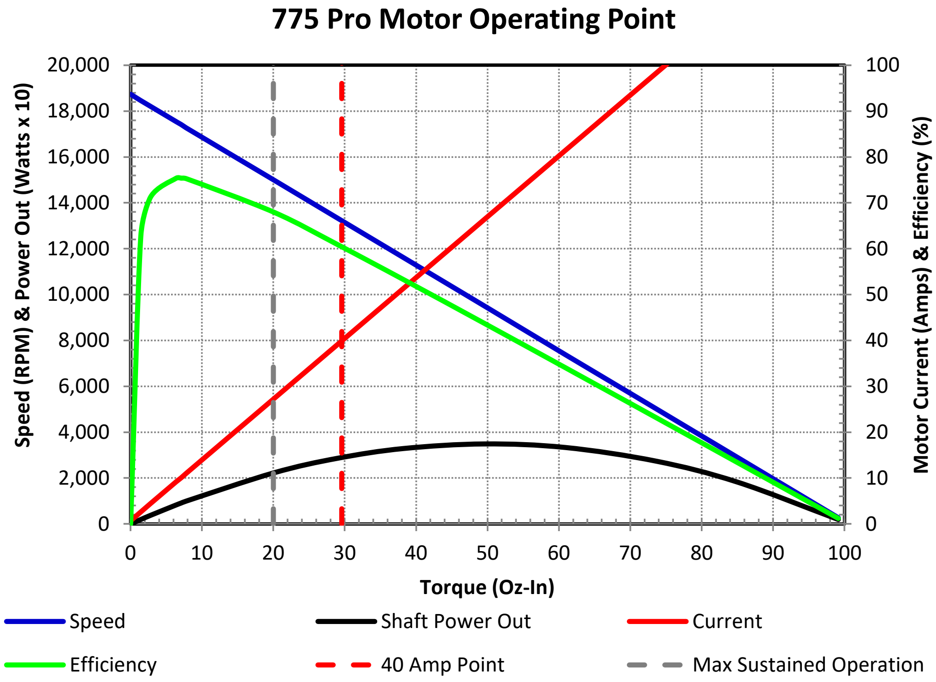


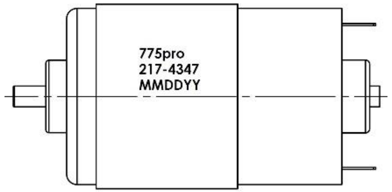


Neo Brushless:
4.57“ Long
2.36” Dia
0.94 Lbm

Neo Brushless Motor					
12.0 Volt Performance	Free Speed (RPM)	5676	Performance at Max Power Output	Torque (Oz-In)	N/A
	Idle Current (Amp)	4.8		Speed (RPM)	N/A
	Stall Torque (Oz-In)	36802		Current (Amps)	N/A
	Stall Current (Amps)	105		Power Out (Watts)	N/A
				Efficiency (%)	N/A
Performance at Peak Efficiency	Torque (Oz-In)	42.5	Performance at Max Power Continuous Operation	Torque (Oz-In)	136.3
	Speed (RPM)	5239		Speed (RPM)	3575
	Current Amps)	11.72		Current (Amps)	40
	Power Out (Watts)	134.4		Power Out (Watts)	360.5
	Efficiency (%)	95.95		Efficiency (%)	73.5

Performance Summary: 775 Motor

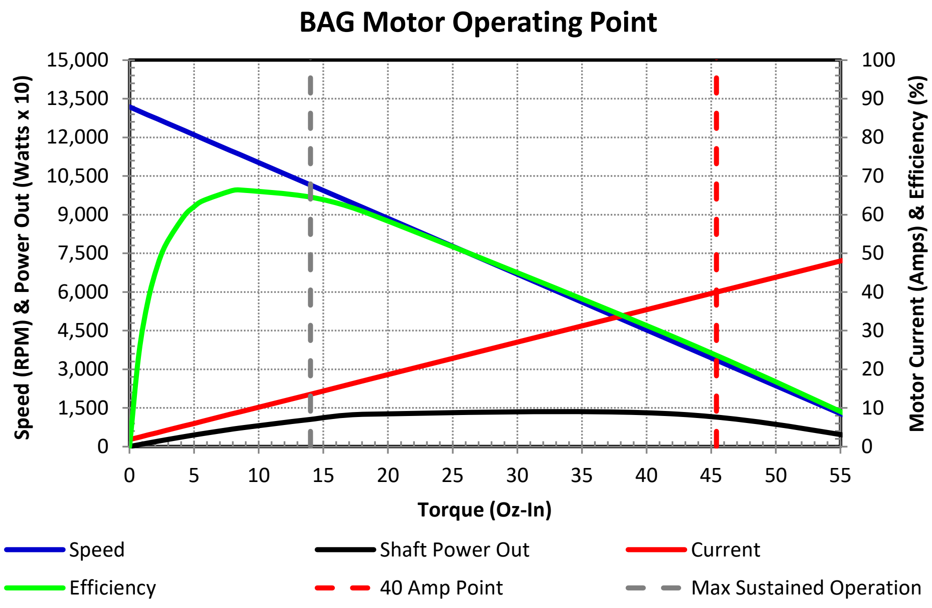


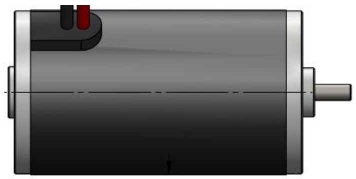


775 Motor:
3.47" Long
1.74" Dia
0.81 Lbm

775 Motor					
12.0 Volt Performance	Free Speed (RPM)	18730	Performance at Max Power Output	Torque (Oz-In)	49.6
	Idle Current (Amp)	0.7		Speed (RPM)	9497
	Stall Torque (Oz-In)	100.6		Current (Amps)	66.41
	Stall Current (Amps)	134		Power Out (Watts)	348.3
				Efficiency (%)	43.7
Performance at Peak Efficiency	Torque (Oz-In)	7.1	Performance at Max Power Continuous Operation	Torque (Oz-In)	20
	Speed (RPM)	17411		Speed (RPM)	14997
	Current Amps)	10.09		Current (Amps)	27.27
	Power Out (Watts)	91.2		Power Out (Watts)	222.3
	Efficiency (%)	75.35		Efficiency (%)	68

Performance Summary: Bag Motor

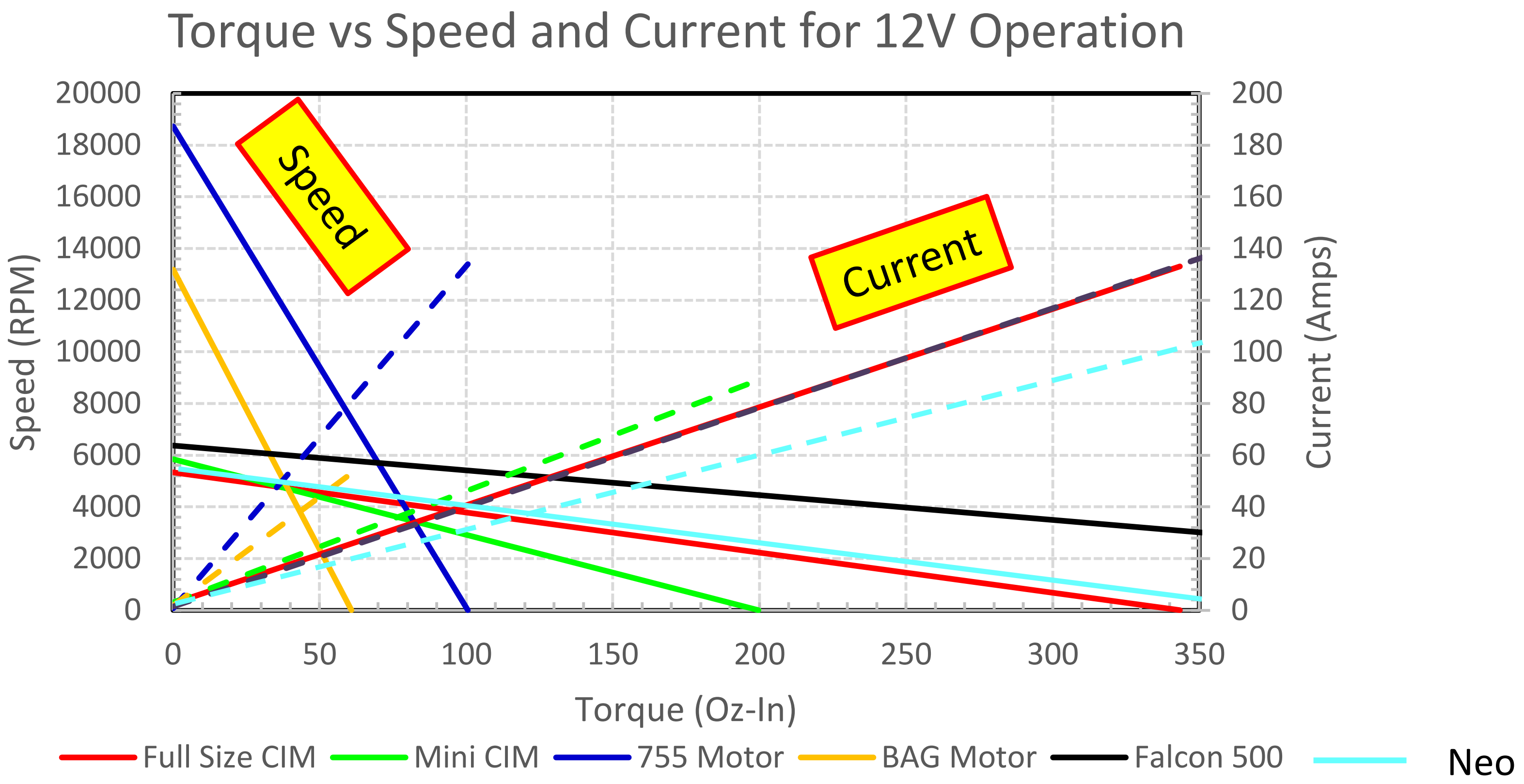




Bag Motor:
3.27“ Long
1.59” Dia
0.71 Lbm

Bag Motor					
12.0 Volt Performance	Free Speed (RPM)	13180	Performance at Max Power Output	Torque (Oz-In)	29.7
	Idle Current (Amp)	1.8		Speed (RPM)	6743
	Stall Torque (Oz-In)	60.9		Current (Amps)	26.8
	Stall Current (Amps)	53		Power Out (Watts)	148.4
				Efficiency (%)	46.1
Performance at Peak Efficiency	Torque (Oz-In)	9.3	Performance at Max Power Continuous Operation	Torque (Oz-In)	14
	Speed (RPM)	11157		Speed (RPM)	10150
	Current Amps)	9.66		Current (Amps)	13.57
	Power Out (Watts)	77.2		Power Out (Watts)	105.1
	Efficiency (%)	66.6		Efficiency (%)	64.6

Motor Performance Comparison



Proper Applications for Different Motor Types

- Neo, Falcon 500 and Full Size CIM motors are best for high torque load, high duty cycle applications
  - Neo & Falcon 500 Brushless motor were designed to be a high efficiency, smaller package size, weight saving drop in replacement for the Full size CIM motor
  - Good applications for these motors are:
    - Chassis drive wheels
    - Wheels for shooters
    - Large arm manipulation
- Mini CIM's can also be used for less demanding similar applications

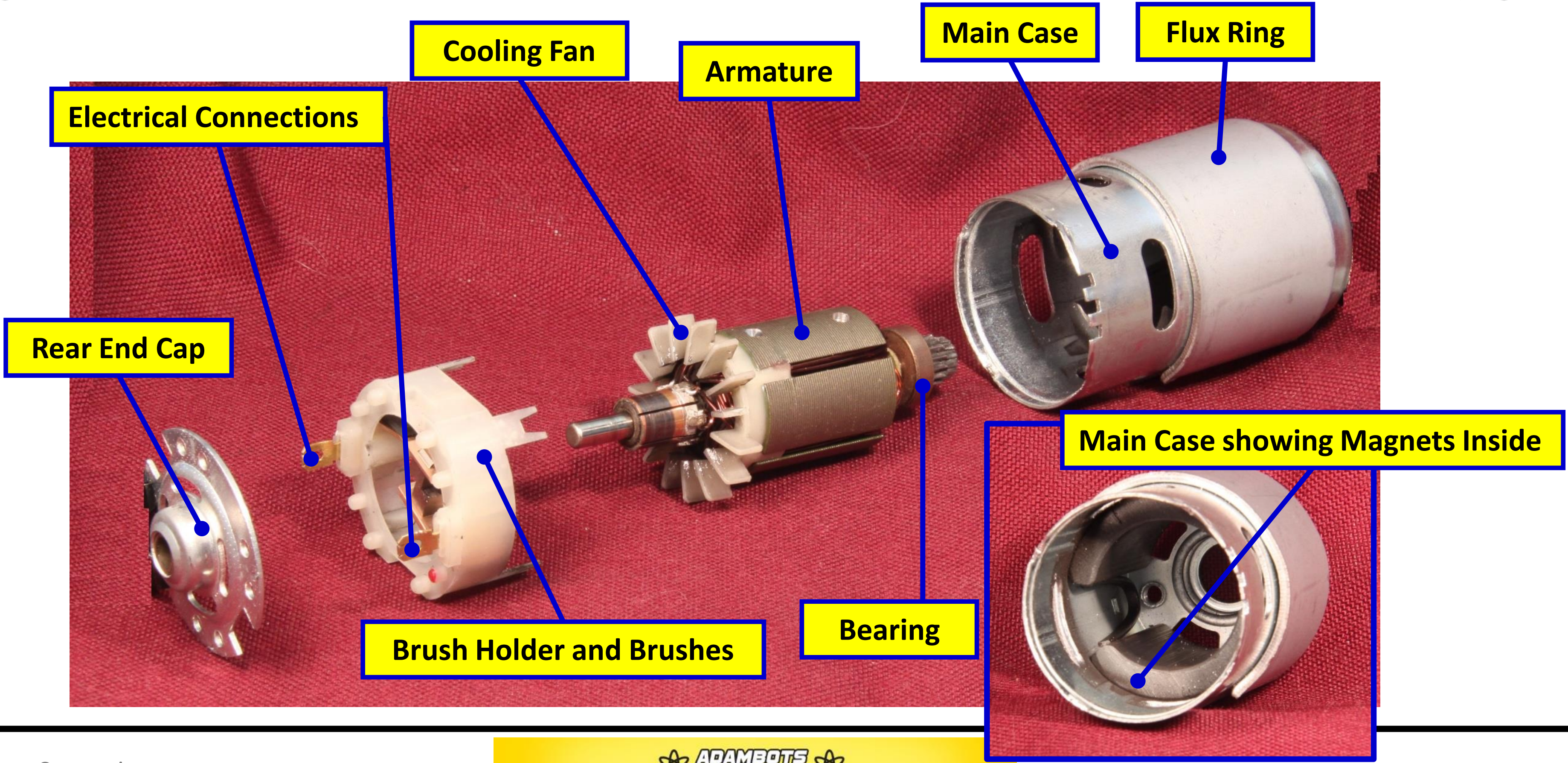
Proper Applications for Different Motor Types

- 775 Motors can be used for intermittent duty cycle applications with higher torque requirements
  - 775 motors require much higher gear reduction ratios for use.
    - Speeds for 775 motors are 2 to 3x higher than CIM motors at similar working power levels
  - Good applications for these motors are:
    - Belt drive systems for game piece manipulation
    - Robot climbing application often using 2x motors driving same output shaft

Proper Applications for Different Motor Types

- **BAG Motors can be used for intermittent duty cycle applications with lower torque requirements**
  - **BAG motors will also require high gear reduction ratios for use.**
    - **Best paired with Versa Planetary gear systems**
  - **Good applications for these motors are:**
    - **Lower torque drives for wheels used to input game pieces**

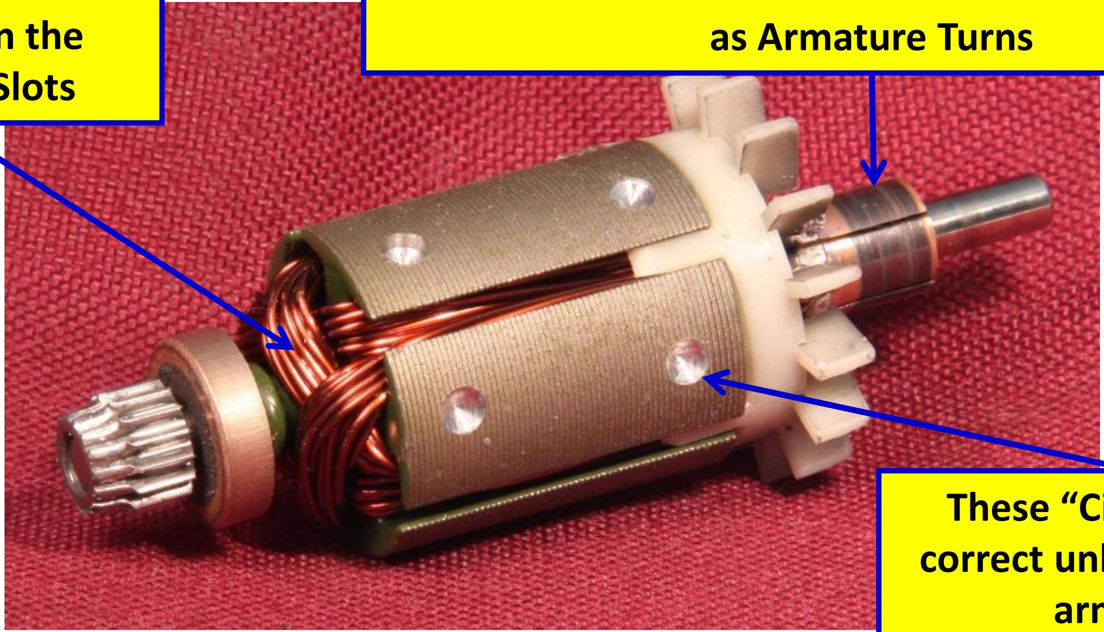
Motor Internal Structure: 775 Brush Motor Example



Motor Internal Structure: 775 Motor Armature

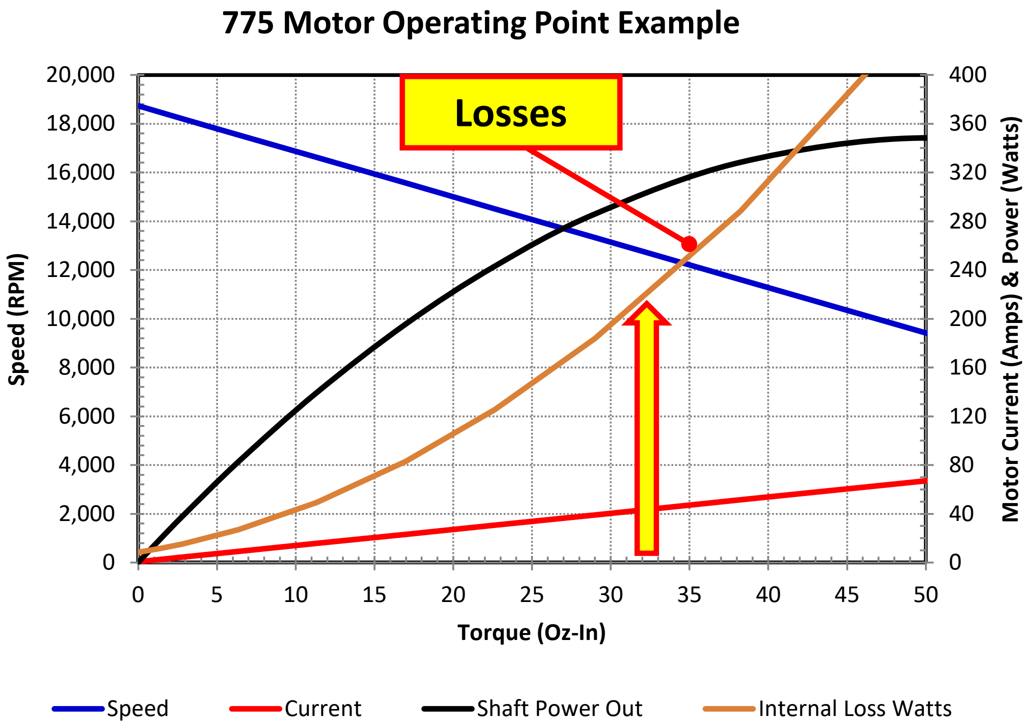
Multiple Individual Coils Within the Armature Slots

Commutator Bars Connected to Each Wend of the Wire Coils Maintain Electrical Connection with the Brushes as Armature Turns



These "Circles" are to correct unbalance of the armature

Losses Within the Motor As Function of Operating Torque

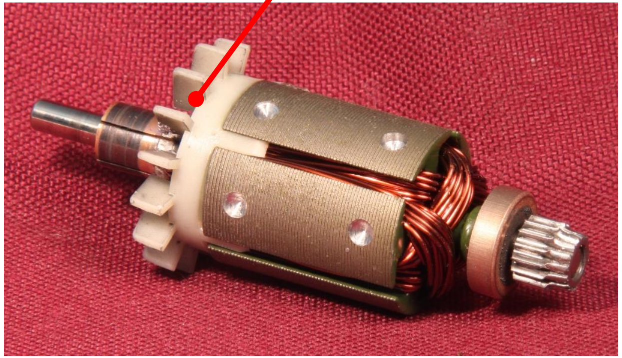


Losses within the motor increase with increasing motor torque and current levels

Majority of losses or temperature gain occur in armature coil wires and the commutator/brush interface

Heat Rejection Paths from Motor Itself

- **Primary cooling method for 775 is cooling airflow drawn through motor by internal cooling fan**
  - **Higher motor speeds increases motor cooling airflow**
  - **Higher speeds also increases heat transfer within motor internal components**
- **Secondary cooling method is conductive heat transfer through motor case, end caps, and shaft**

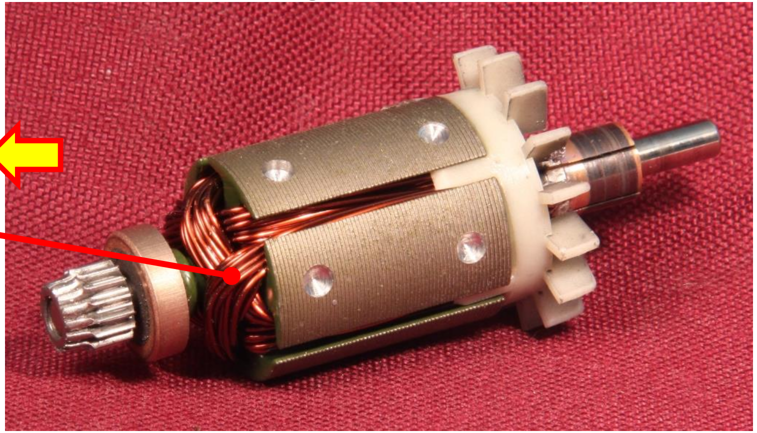


Motor Overheating Failure Mode

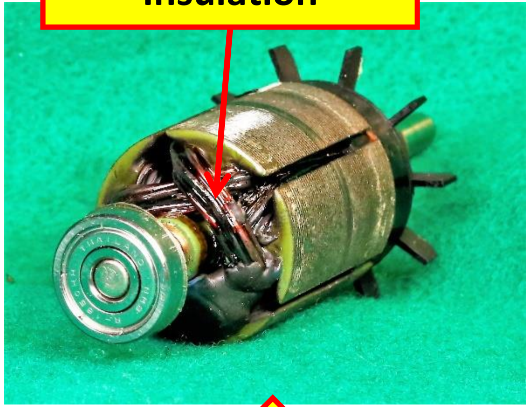
- **Motor temperatures escalate when rate of heat generation within motor exceeds capacity for heat rejection from the motor**
  - **Varnish insulation on magnet wire coils is the initial failure point in the motor**
    - **Wire temperature exceeds temperature rating of varnish insulation causing it to soften and bubble allowing individual wire coils to make contact and short together causing motor to run slower, increase current draw, which further increases wire temperature that leads to progressive failure of entire motor**
    - **Smoke often seen from an overheated motor comes from overheated varnish**
    - **A Smoking motor is not always a Dead Motor. Varnish can smoke for some time before adjacent wire coils begin to short if power is removed before permanent damage**
  - **Any Non-Brushless motor will eventually overheat if subject to stall operation for a long period of time**

Key Failure Mode Related to Operating at Excessive Current/Torque Levels

Temperature within armature exceeds Max rating of varnish insulation coating used on wire coils



Blackened Wire Insulation



Failure of wire insulation results in Electrical shorts between adjacent coils that reduces speed, increases current draw, which further increases temperature that accelerates failure of motor

This temperature related failure releases the “Blue Smoke” often seen when motors fail

This is a motor that has experienced failure due to breakdown of wire insulation

Limits of Motor Operating Torque

- Maximum operating torque or current draw for continuous or intermittent duty cycle is a function of motor design elements and overall sizing
  - Smaller diameter wire in armature coils has a lower maximum current density limit (Amps per Sq-Millimeter) than larger diameter wire
    - Larger diameter wire has higher surface are and can more easily reject heat from resistance related losses
    - Wire used in CIM motors is much larger diameter than BAG and 775 motors
  - Larger diameter motors also have larger external surface area that increases capability to reject heat
  - 775 Motor can achieve higher operating power levels due to internal cooling fan that is not present in larger, similar power motors

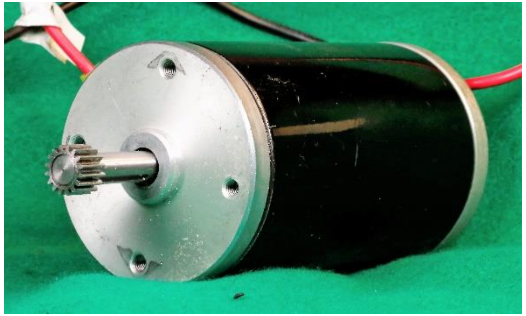
Operating Current Levels for FIRST Motors

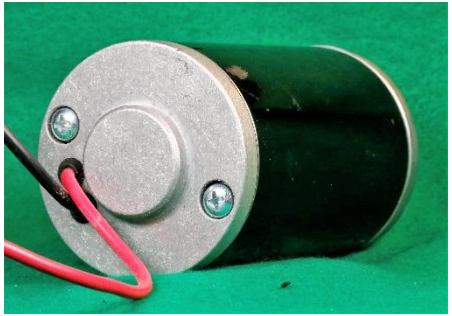
- Full Size CIM, Neo, and Falcon 500 motors can run for full 2 ½ minute match time at 40 Amp Current without suffering damage from internal heating
  - Motors will get "Warm", and may loose some performance, but will generally not suffer permanent damage
    - Motor performance does decrease with higher motor temperature. This is why FIRST allows 6 Minutes for motors to cool down between matches during the finals

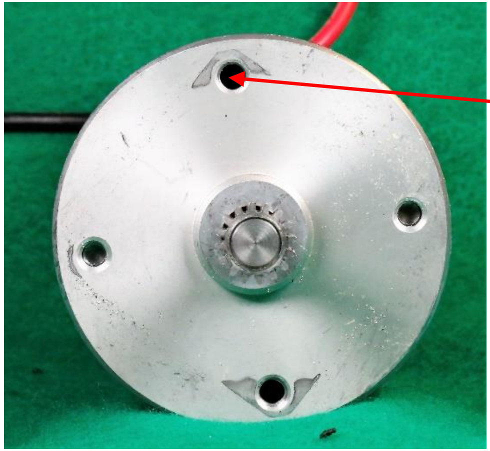
Operating Current Levels for FIRST Motors

- 775 and Mini-CIM Motors can run intermittently at 40 Amp levels without suffering damage during 2 ½ minute match time
  - Short term 10 Second climb once per match is a good application for 40 Amp operating point with these motors
    - Design at 40 Amp operating point is not a good practice since this is too close to 40 Amp circuit limit
- Should use a longer term current draw limit of 25 Amps for 775 motors within 2 ½ minute match duration
- BAG Motors should use a 13 Amp limit for longer term current draw limit during a 2 ½ minute match duration

Internal Structure of Full Size CIM Motor



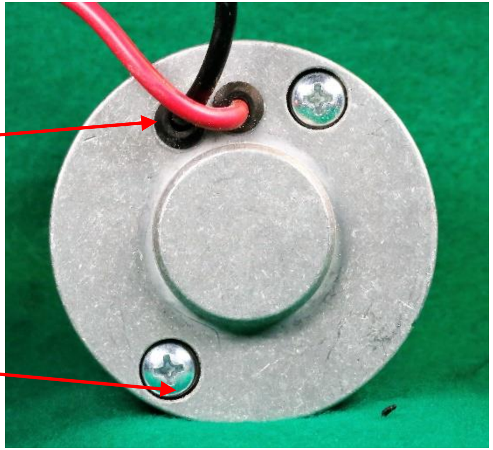




4x Mounting screw locations in front end cap

Rubber grommet sealing motor leads

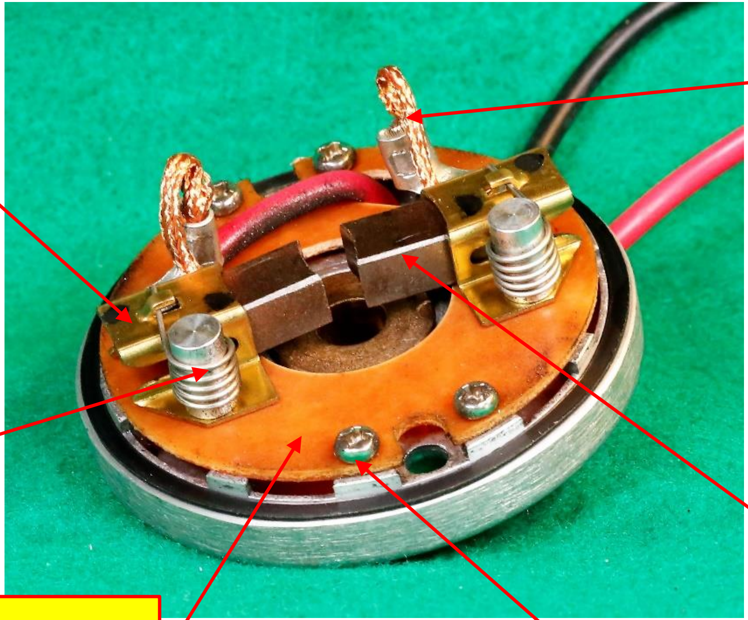
Through Bolts Holding Motor Together



Details of Brush Card of Full Size CIM Motor

Brass Brush box keeps brush in position as brush wears away

Flexible Brush shunt conducts current from leads to brush as brush wears away



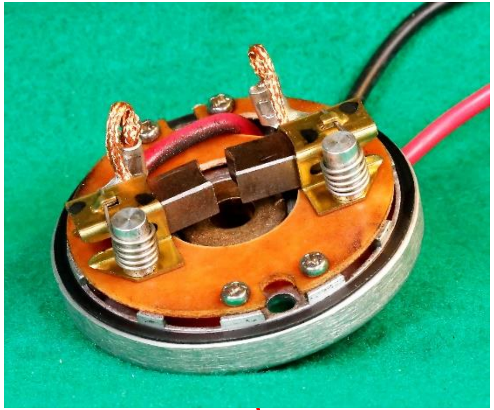
Brush Springs keep brush in contact with commutator as brush face wears away with use

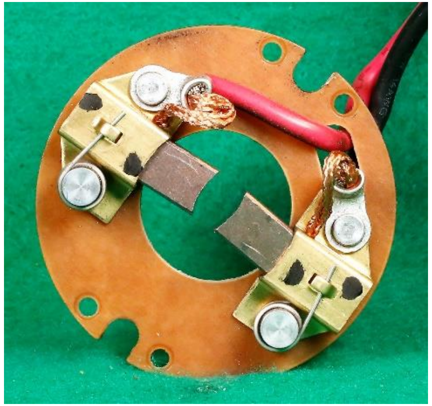
Non-Conductive base plate

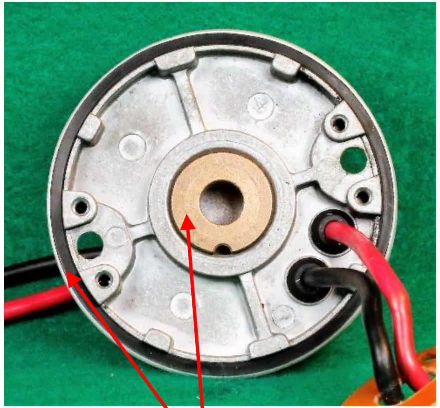
Mounting Screws

Brushes conduct current to commutator bars. These wear away with use

Brush Card and Rear End Cap: Full Size CIM





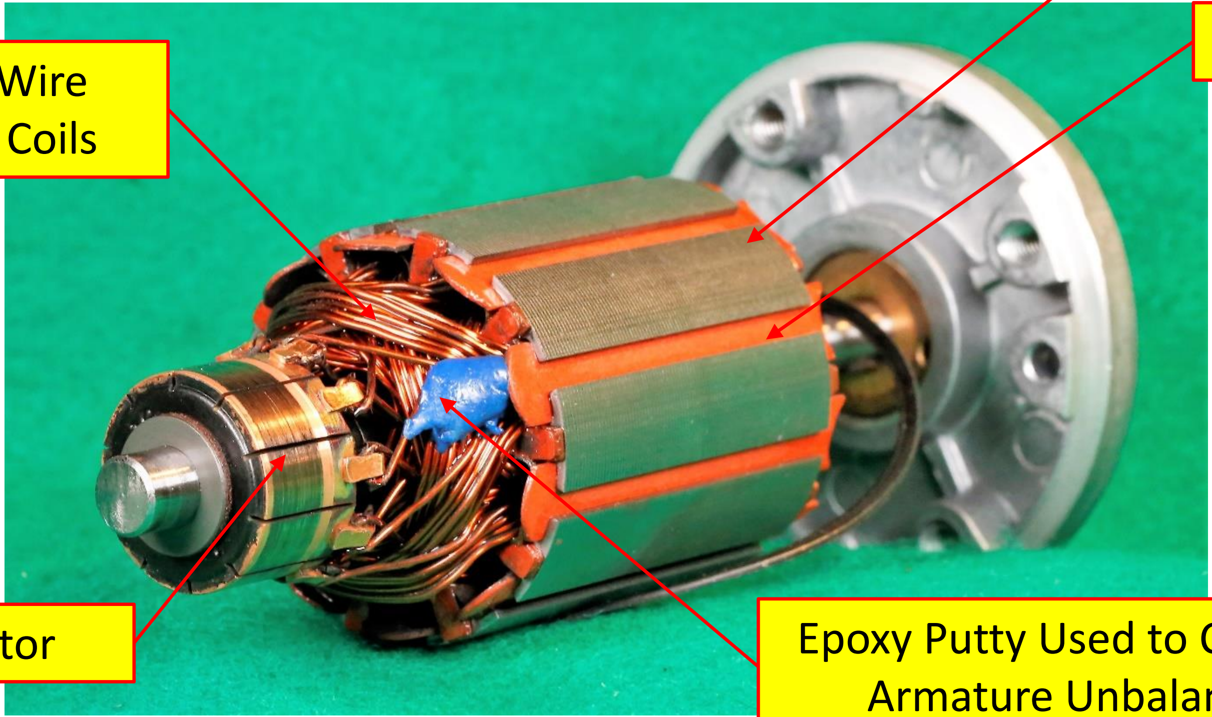


Brush Card fastened to rear end cap by 4x screws

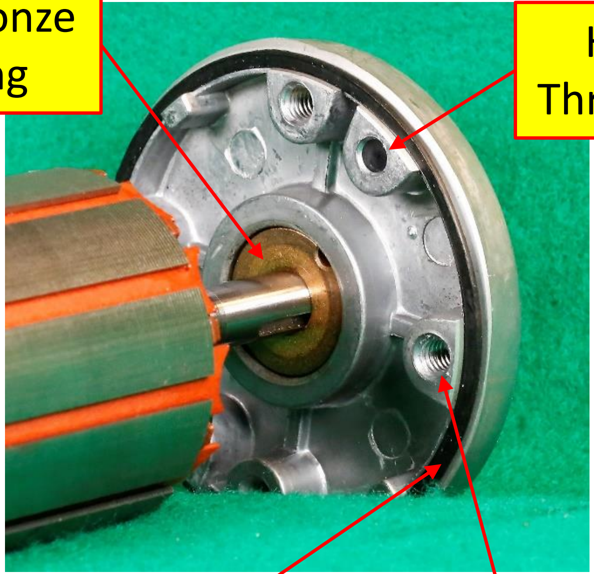
Front & Back of Brush Card

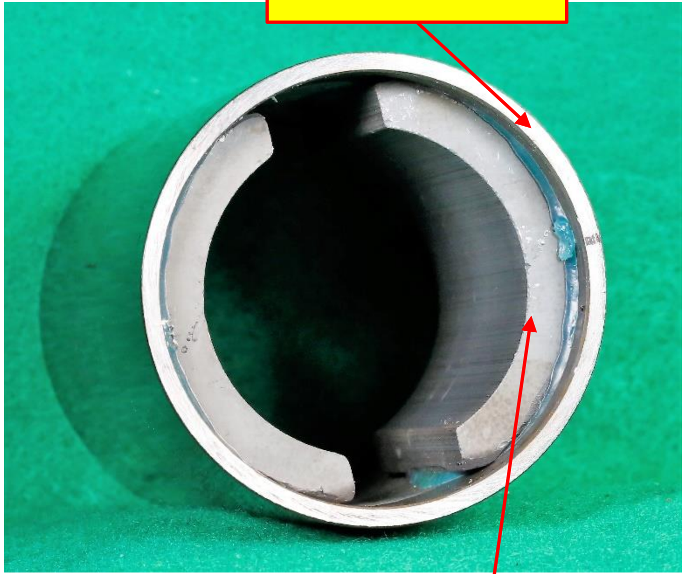
Rear end cap with sintered bronze bushing and rubber sealing ring

Armature Detail: Full Size CIM



Front End cap & Case/Magnet: Full Size CIM



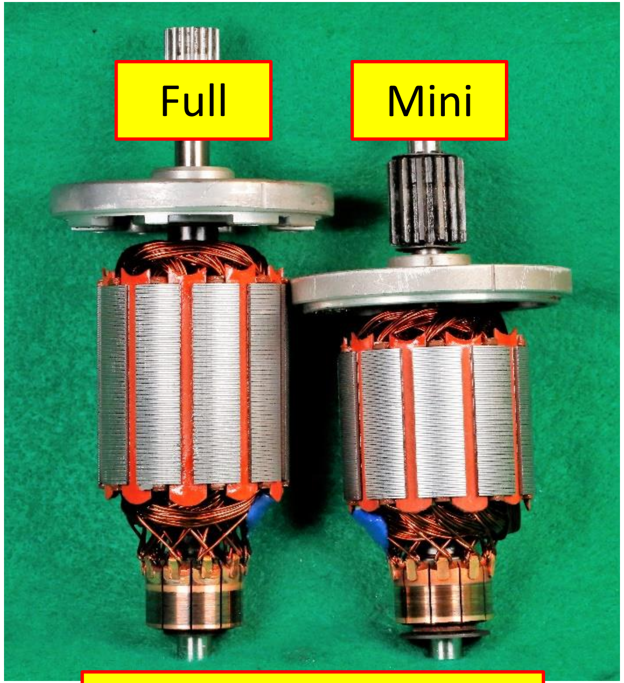


Mini CIM Motor

Mini-CIM is a shorter version of Full Size CIM

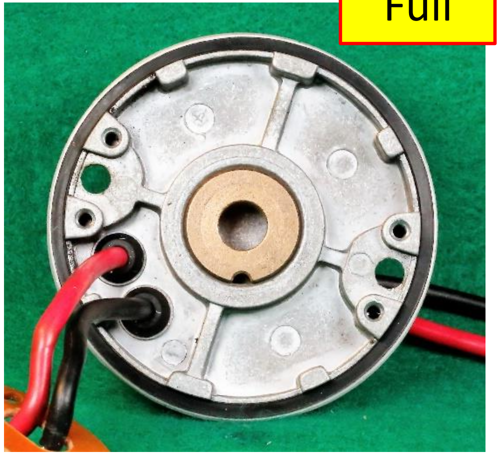
Different End Cap Design

Full   Mini

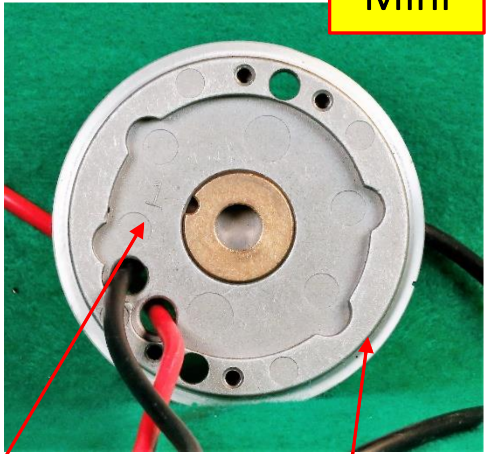


Same Components Just Shorter

Full



Mini



No Structural Ribs

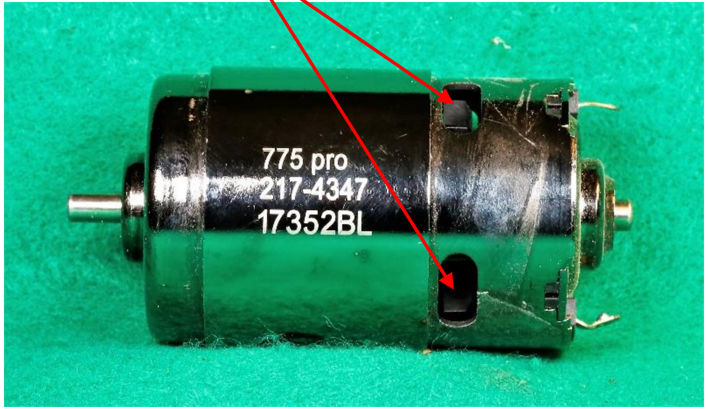
No Rubber Sealing Ring

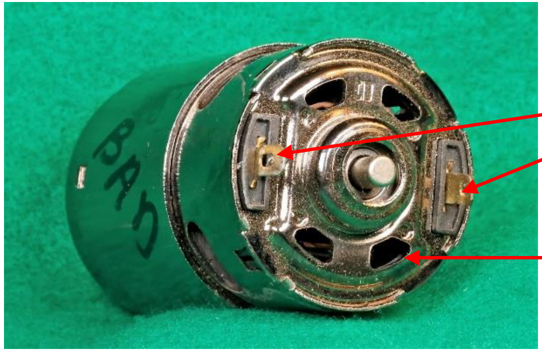
775 Motor

Back

Front

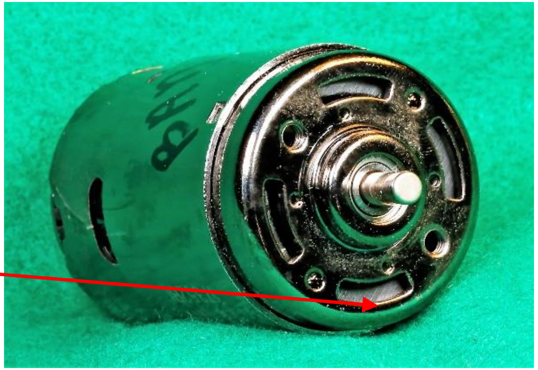
Cooling Airflow Outlet



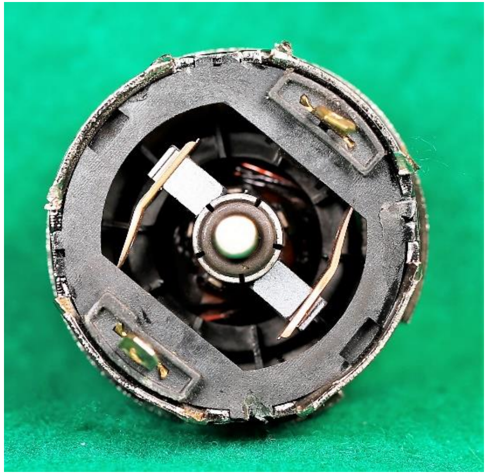


Motor Connectors are very small

Cooling Airflow Inlets on both Front and Back End caps

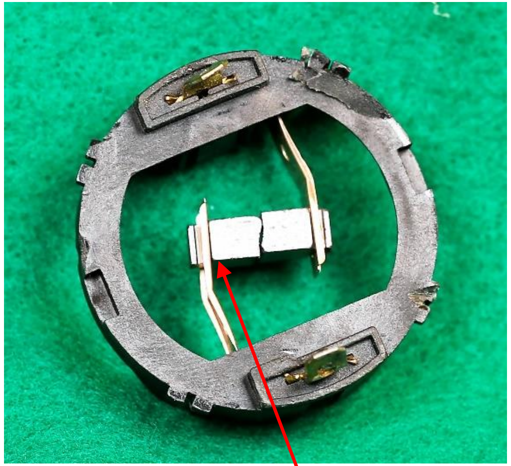


Brush Assembly: 775 Motor



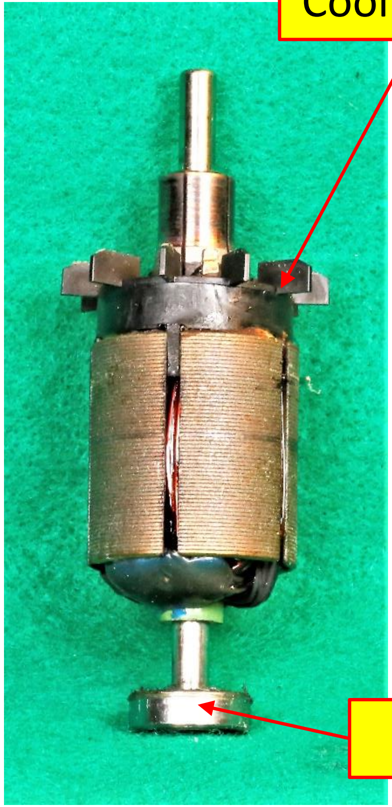
Brushes on Commutator

Connector and cantilever spring are one part



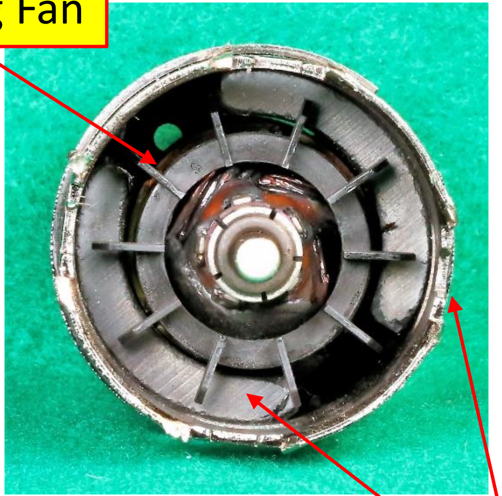
Brushes mounted directly on cantilever Springs

Brush Assembly: 775 Motor



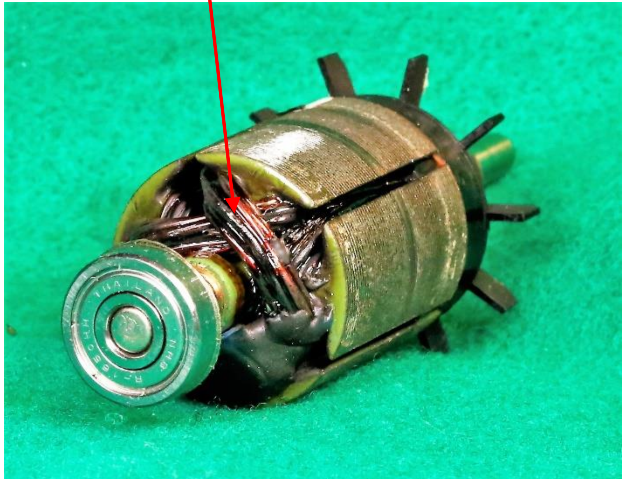
Cooling Fan

Ball Bearing



Case and Magnets

This motor has Burned Armature Windings

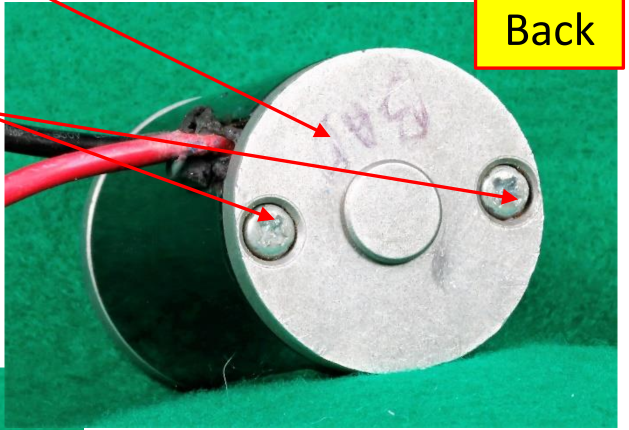


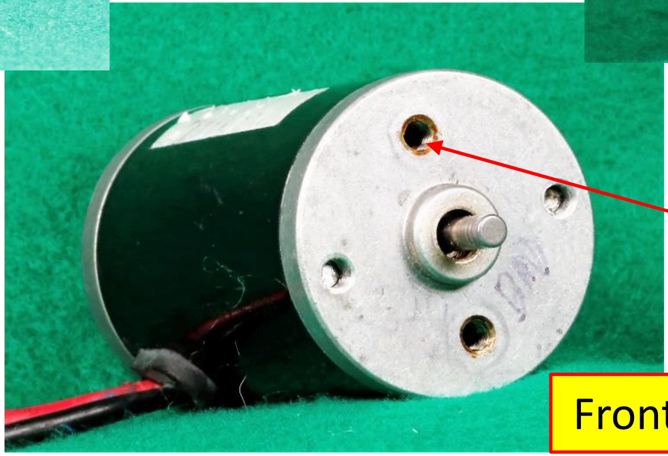
BAG Motor

Case Construction Similar to CIM Motors

Through Bolts

Back



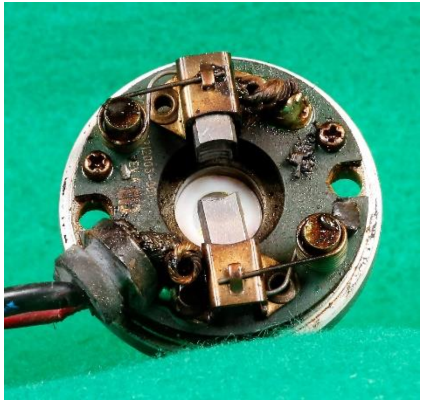


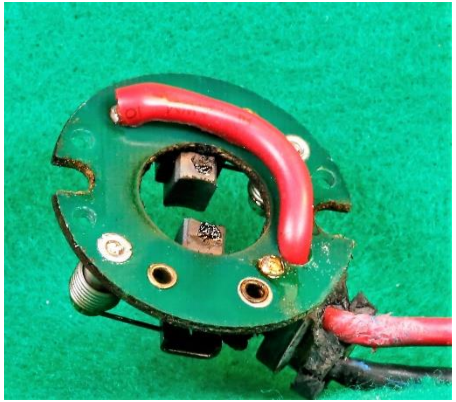
2x Mounting Screw Holes

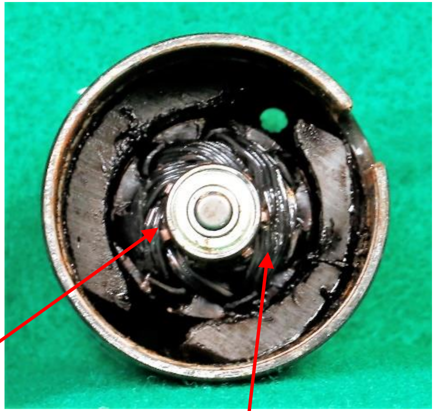
Front

BAG Motor

Photos From a Motor with a Burned Armature







Brush Card Construction
Similar to CIM Motors

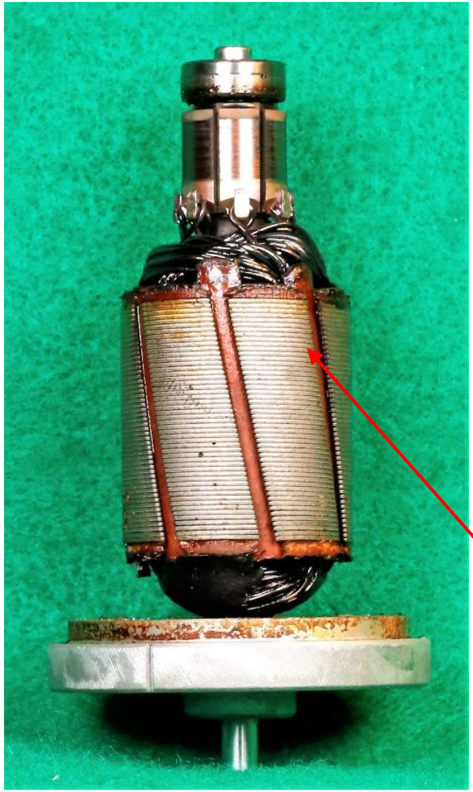
Ball Bearing

Burned Armature
Winding Coils

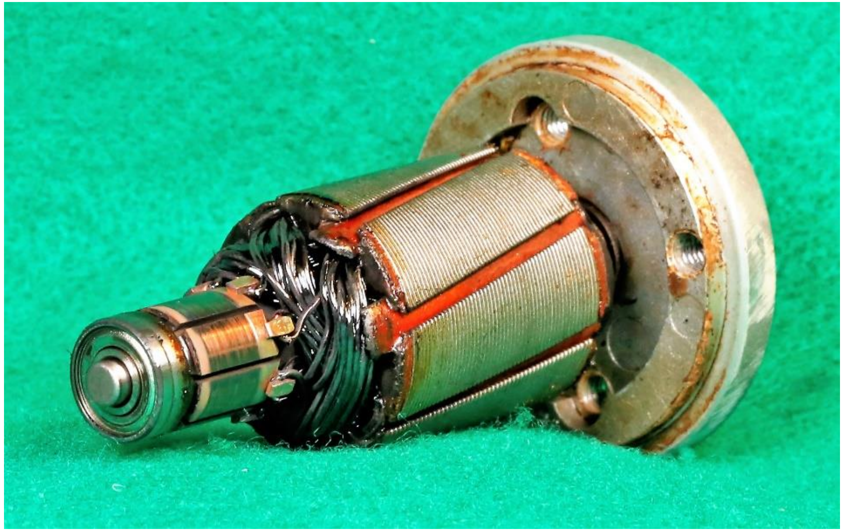
Condensed Residue from
Overheated Winding
Insulation

BAG Motor Armature

Photos From a Motor with a Burned Armature



Armature Construction Similar to CIM Motors

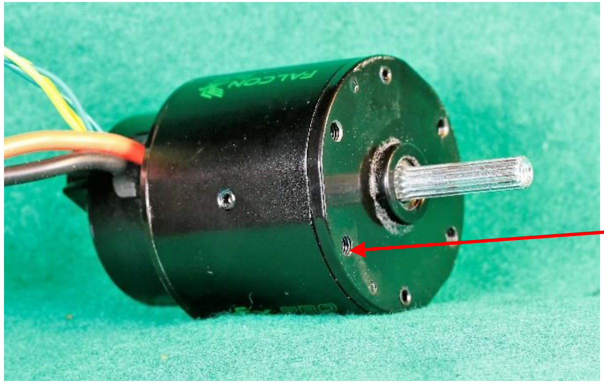


Laminations are Skewed as opposed to Straight as on CIM Motor in effort to reduce Vibration/Noise coming from interaction with magnetic field

Falcon 500 Brushless Motor

Controller is Integrated with Motor

Spline Shaft Unique to Falcon

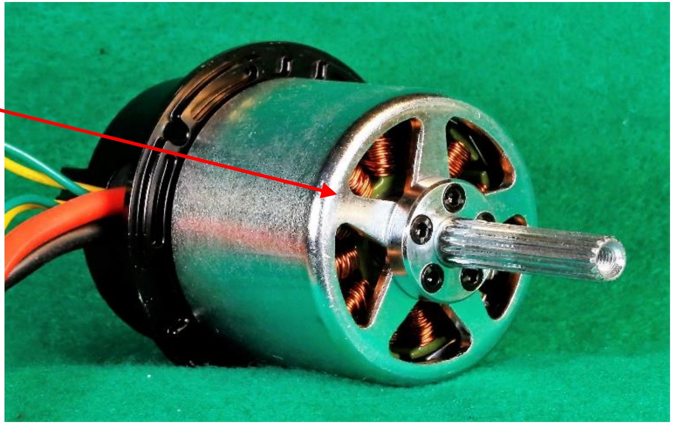


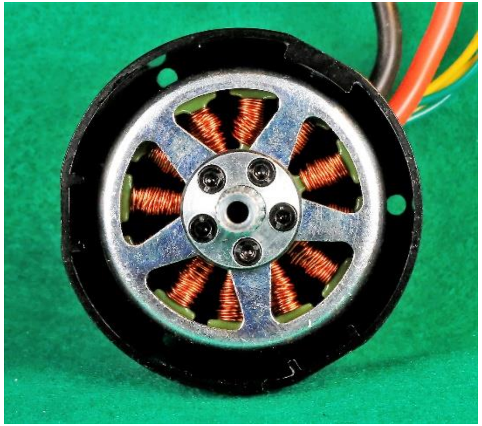
4x Mounting Screw Holes

Falcon 500 Brushless Motor

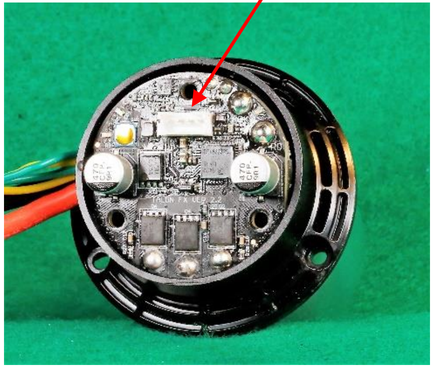
Plastic Cover Removed

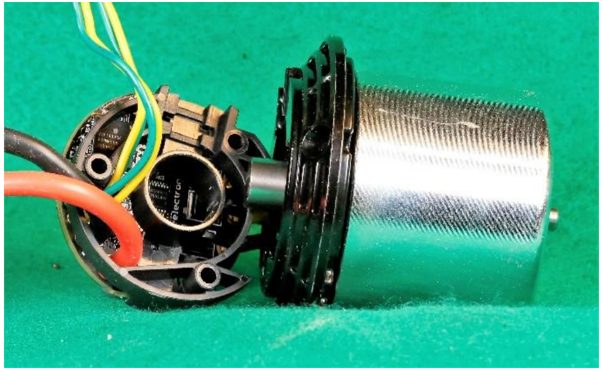
Rotor Cup with Shaft Attached





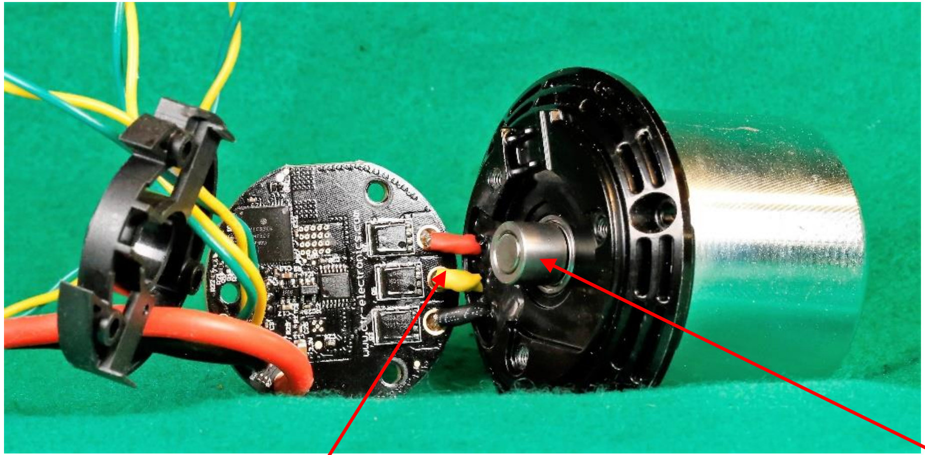
Power Electronics Located Inside Back Cover





Motor has “Inside Out” Architecture. Windings and laminations are fixed and Magnet /Steel rotor rotate around fixed copper windings

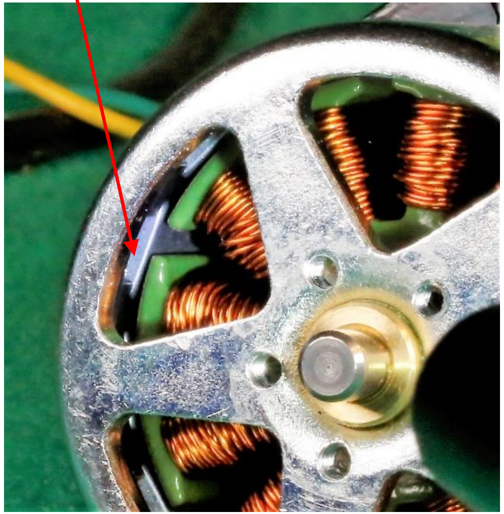
Falcon 500 Brushless Motor



High Energy Product Neodymium Magnets bonded to inside of rotor cup. One reason for higher efficiency and lower weight

Power Leads for 3-Phase Winding from Electronic package to Fixed coils inside stator

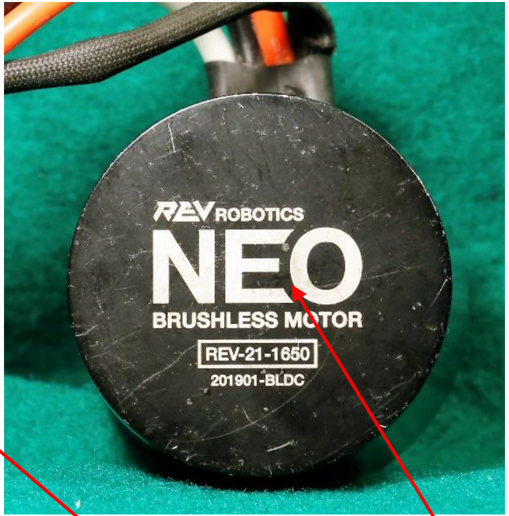
Larger Dia Shaft Sleeve has magnet chip with interacts with Hall Effect Sensor to provide motor speed feedback

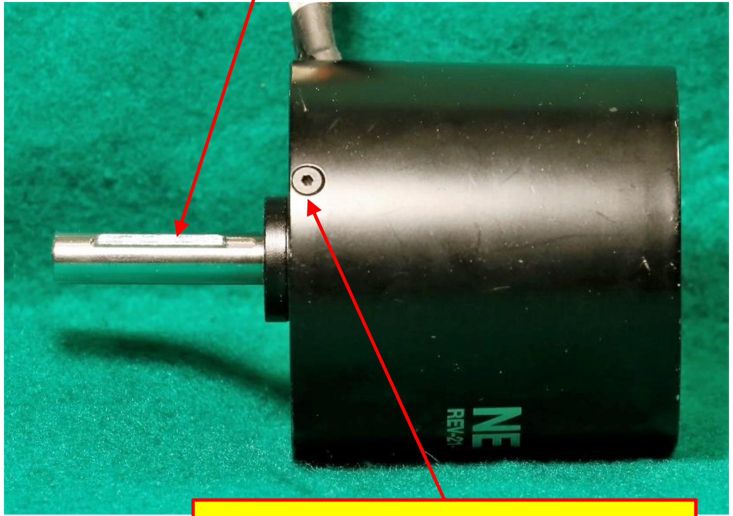


NEO Brushless Motor

Ball Bearing

8 mm Shaft with Keyway





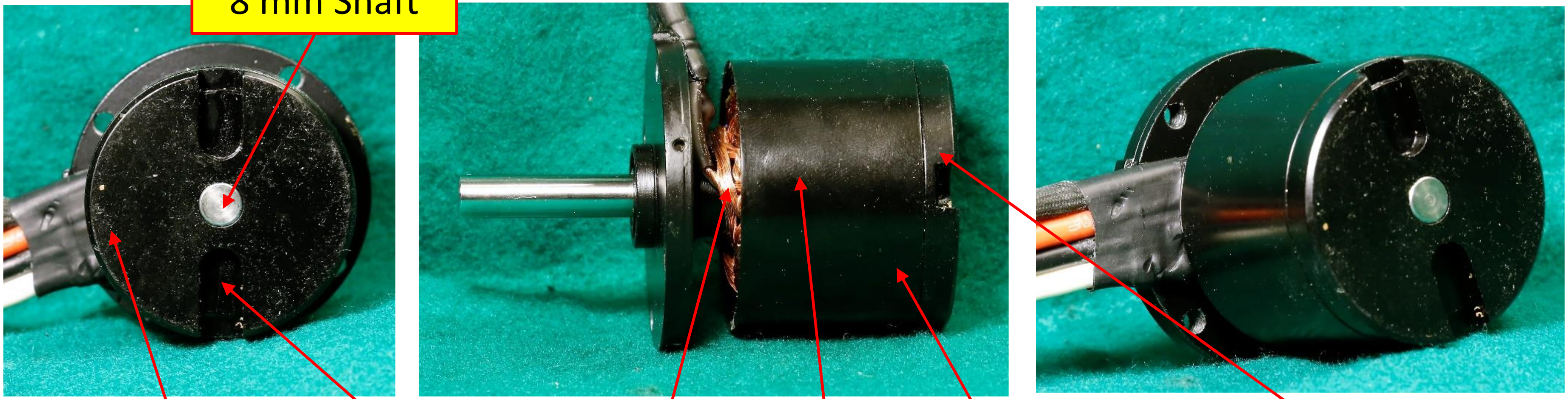
Snap ring provides axial Retention for shaft

Allen screw to attach outer shell to front flange (3x Total)

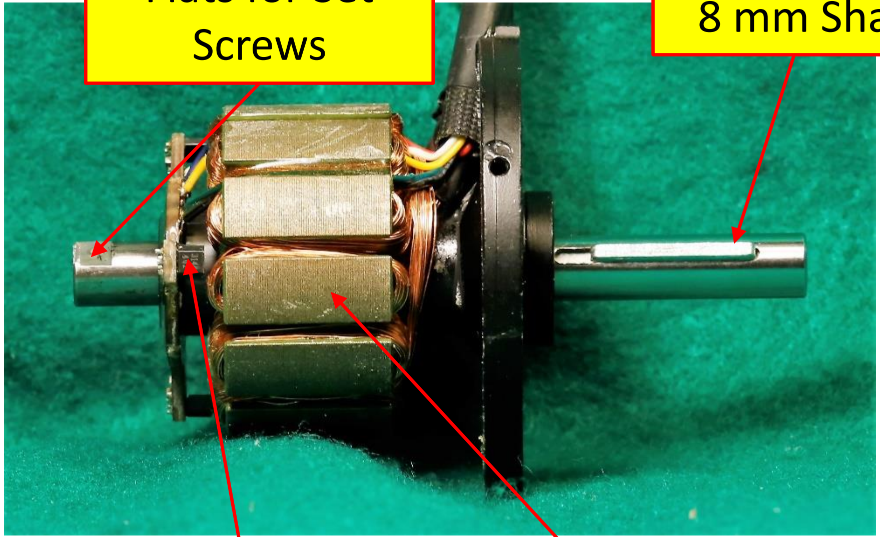
Outer Shell

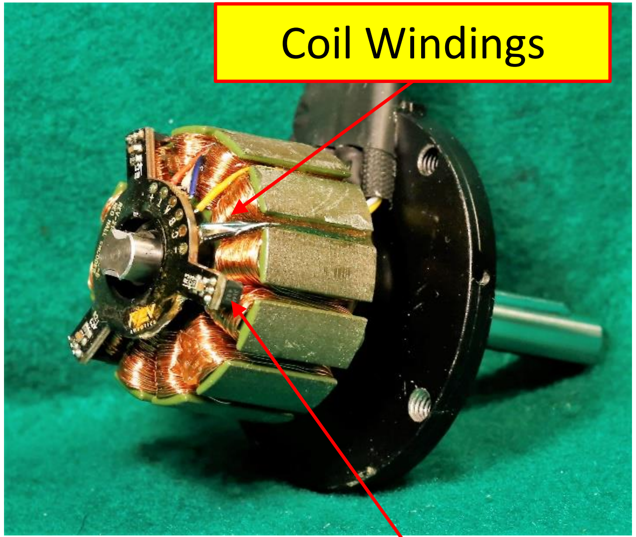
4x 10-32UNF mounting holes (Same as CIM)

NEO Brushless Motor: Outer Shell Removed

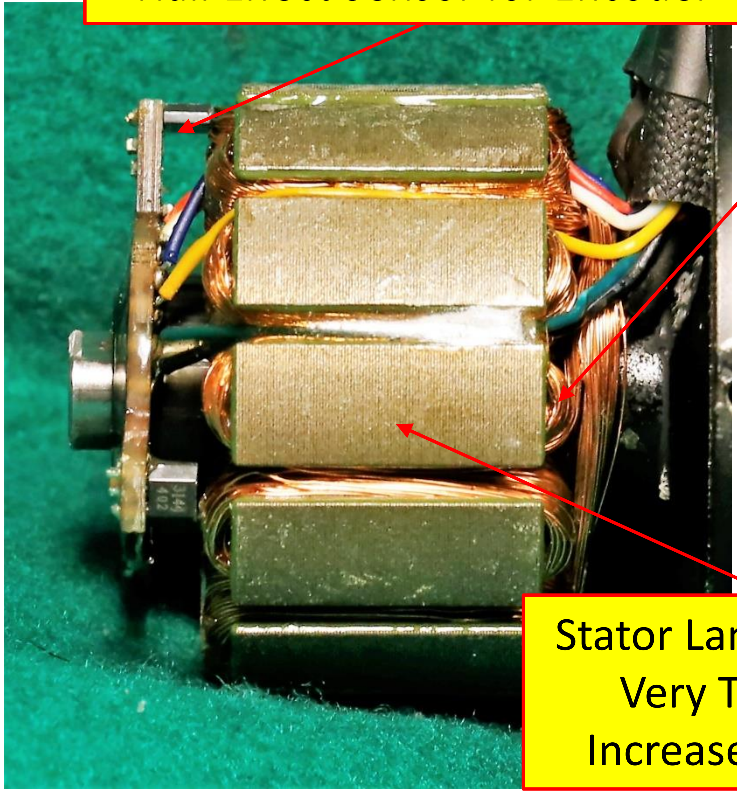


NEO Brushless Motor: Fixed Stator and Coils





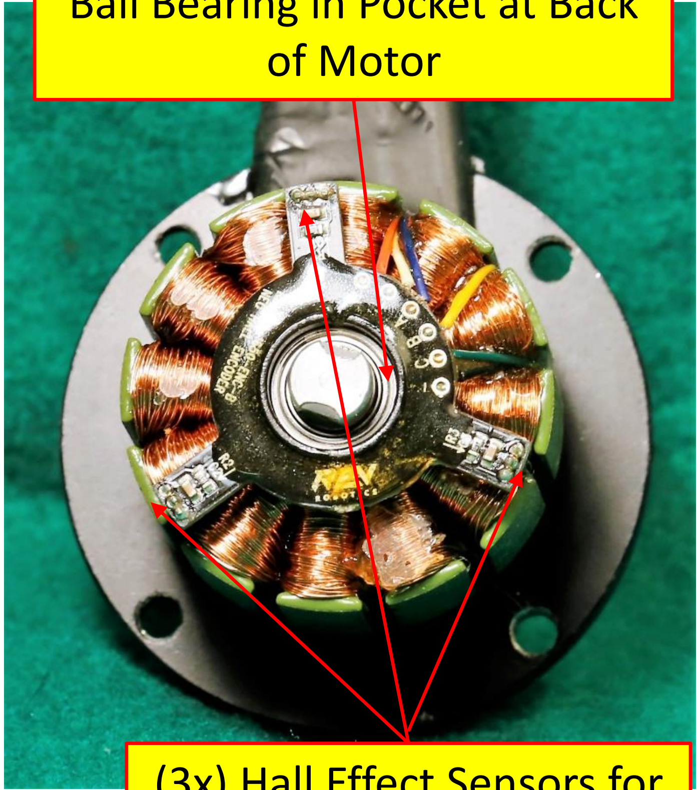
NEO Brushless Motor: Fixed Stator and Coils



Hall Effect Sensor for Encoder

12X Coils, 4 Coils in each Phase

Stator Laminations are Very Thin which Increases Efficiency



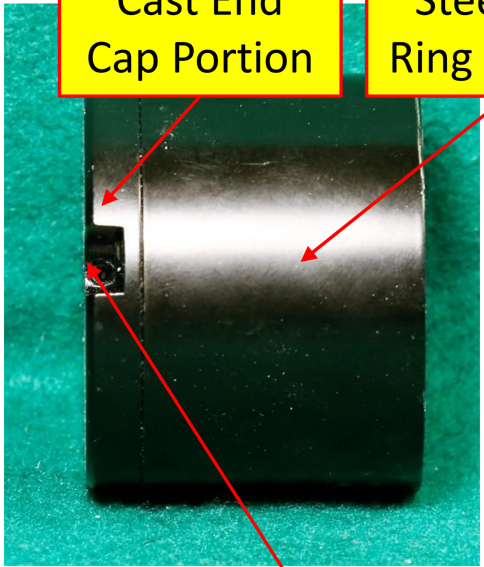
Ball Bearing in Pocket at Back of Motor

(3x) Hall Effect Sensors for Encoder

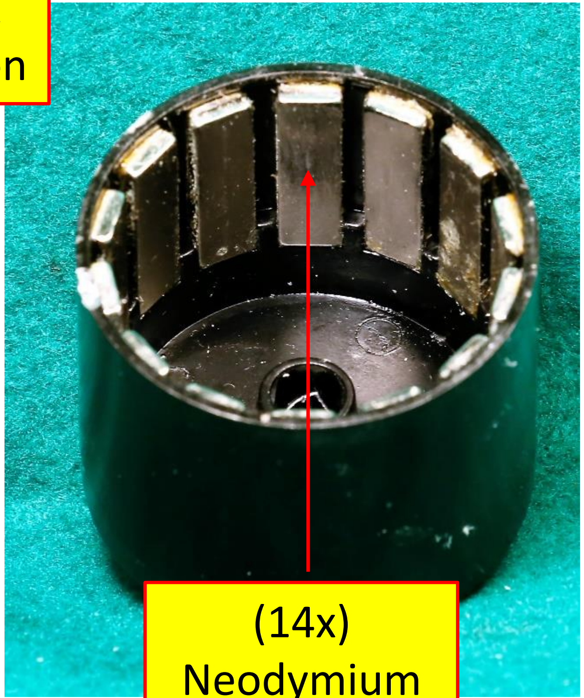
NEO Brushless Motor: Rotor Cup

Cast End Cap Portion

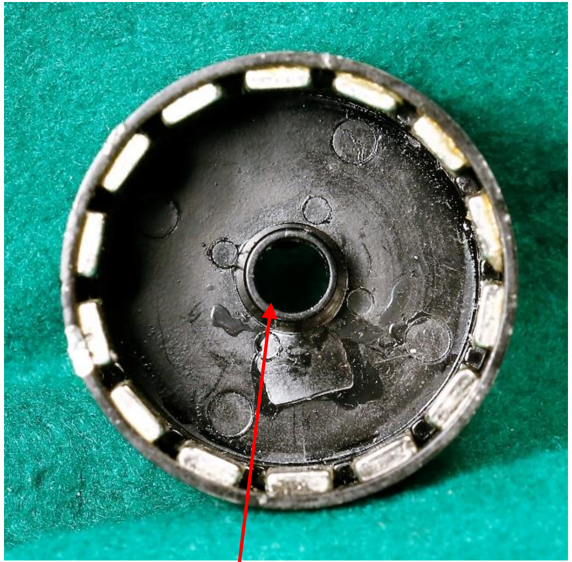
Steel Flux Ring Portion



Set Screw to Hold Shaft at Bottom of Access Channel



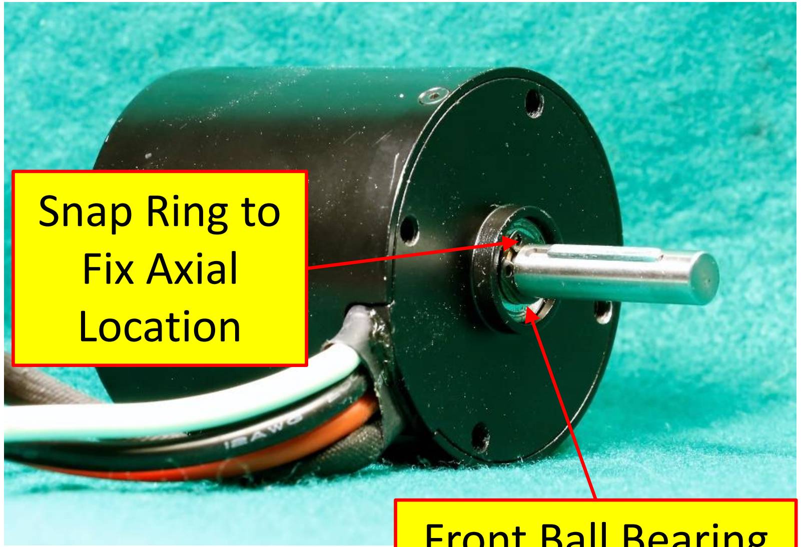
(14x) Neodymium Magnets



Sleeve has tight fit with OD of 8 mm Shaft

NEO Brushless Motor: Shaft and Bearings

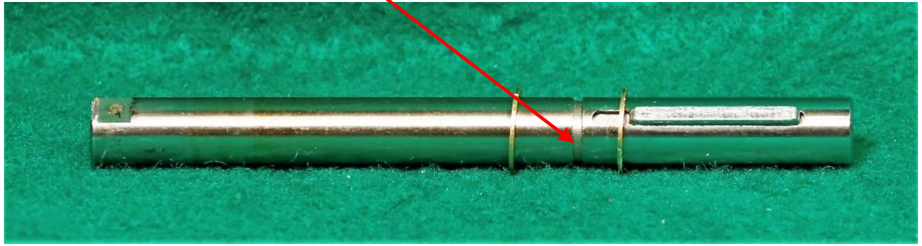
Rear Bearing pressed in place inside center stator core



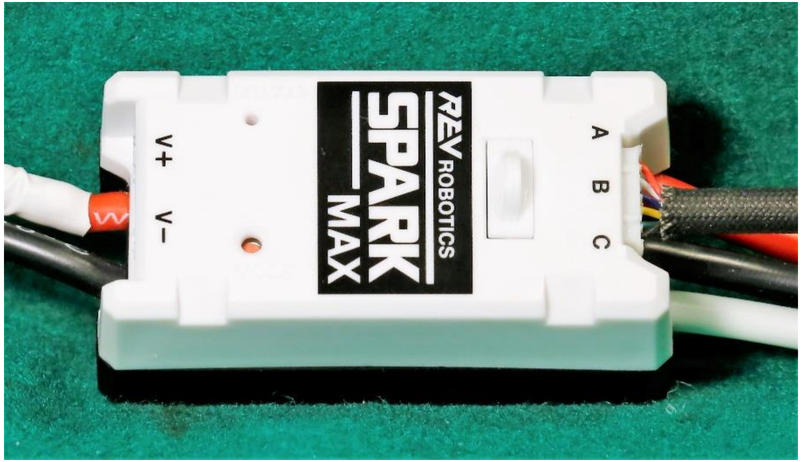
Snap Ring to Fix Axial Location

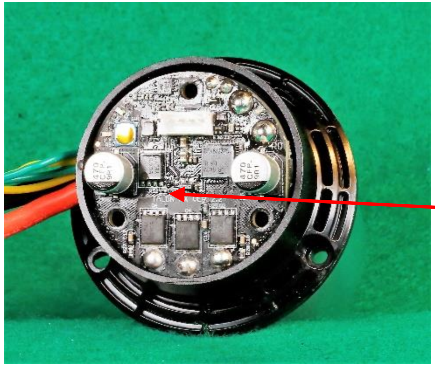
Front Ball Bearing pressed in place in front end cap

Groove in Shaft for Snap Ring



Controller for NEO Brushless Motor





Falcon Motor Controller is Integral to the Motor Itself

Benefits of Brushless Motors

- Significantly higher operating efficiency
  - CIM at 200 Watt power out is 63% Efficient
  - Falcon 500 at 200 Watt power out is 87% Efficient
  - Neo at 200 Watt power out is 95% Efficient
  - Savings of 7+ Amps at same output power level
- Lower Motor only Weight
  - CIM motor = 2.8 Lbm Falcon = 1.1 Lbm NEO + Controller = ~1.2 Lbm
- Additional mass and weight savings
  - Motor controller is integrated inside Falcon 500 brushless motor that saves packaging space on electronics board and provides additional 0.26 Lbm weight savings

Benefits of Brushless Motors (Continued)

- Brushless motor controller offers stall protection
  - Motor will shut down if presented with a stall condition and will not overheat
- Lower rotating inertia provides quicker acceleration compared to CIM motors
- Brushless motor system provides feedback of rotor speed and can maintain exact command speed
  - No need for stand alone encoders
  - CIM Brush DC motor cannot achieve target command speed without external encoder bases sensor PID loop
  - Critical for control of shooter wheel speed to control shot distance

Benefits of Brushless Motors (Continued)

- Can run longer without needing to cool motor due to higher efficiency
- Falcon brushless motors have advantage compared to Neo motors due to integrated power electronics which eliminates need for separate controller on electronics board
- Falcon 500 Motors proven after 2+ FIRST Seasons and have proven to be reliable

Comparison of Climb Performance

- **Motor performance for different motor options to Climb a 150 Lbm robot 36 Inches with cable winding on a 0.75 Inch diameter spool using a 40:1 Speed Reduction Ratio with 12.0 Volts applied to motor terminals with 100% Speed command:**

36" 150 Lbm Climb Performance		
Motor	Current (Amps)	Time to Climb (Seconds)
Full Size CIM	13.3	6.7
Mini CIM	15.1	6.5
Falcon 500	12.3	5.4
NEO	9.7	6.2
2x 775 Motors	19.3 (*)	2.0
(*)	Amps per motor	

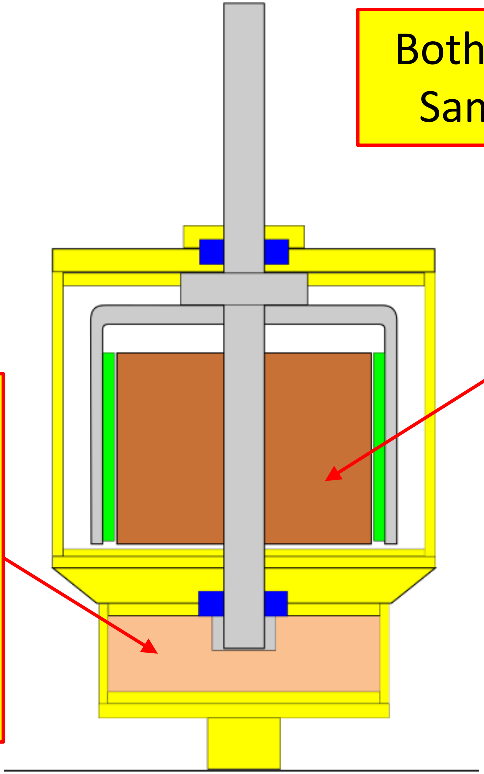
- **NEO would save 3.5 Amps from Full size CIM**
- **NEO Would save 2.6 Amps from Falcon 550**
- **Current draw for all motors would be acceptable for short duration climb event**
- **2x 775 Motor performance would reduce current draw with higher speed reduction ratio**

Comparison of Neo and Falcon Brushless Motors

Both Motors have Same Diameter

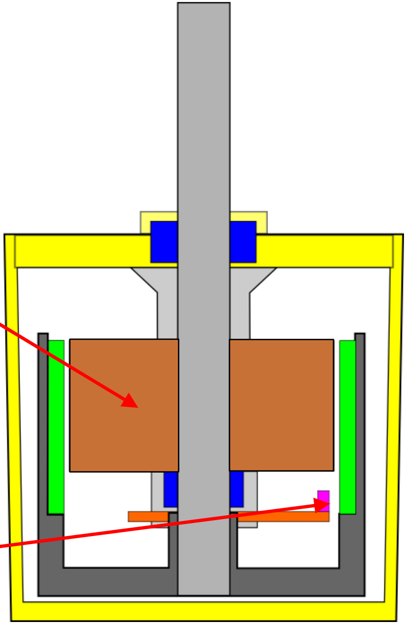
NEO is 0.90” Shorter and is 0.16 Lbm Lighter

Power Electronics are Integrated into Falcon Motor

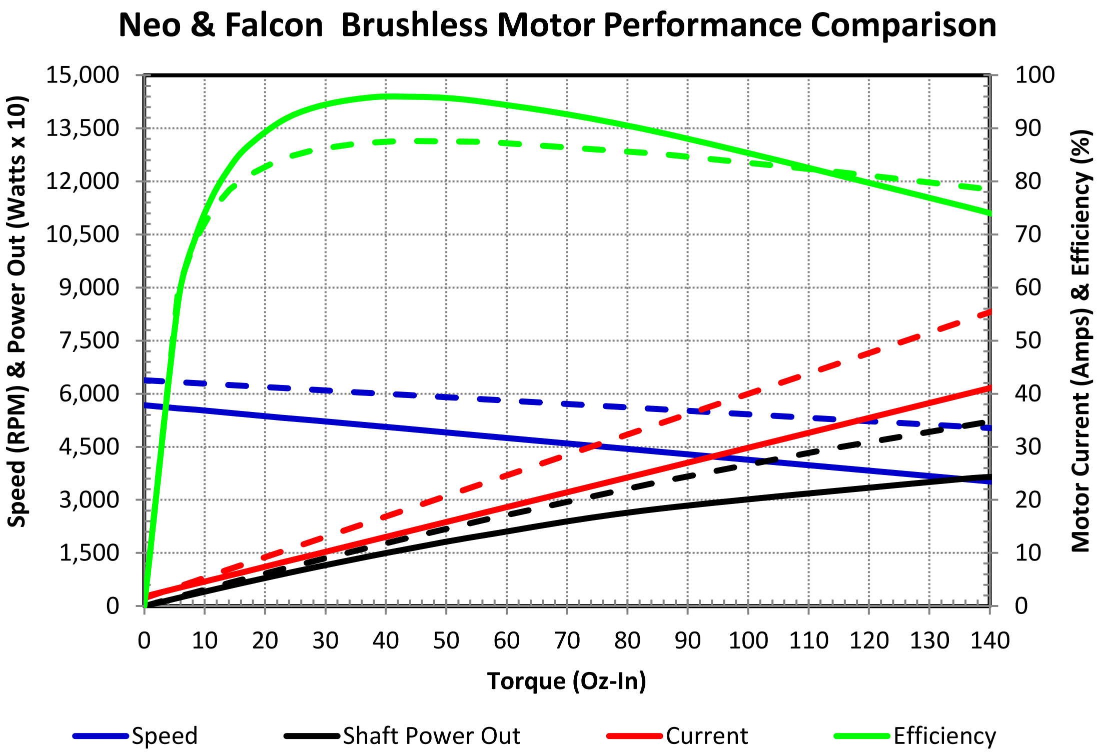


Coil/Lamination Stack of Falcon has Smaller Diameter, but Longer Than Neo

Hall Sensors for Encoder Are Only Electronics inside NEO Motor



Performance Comparison: NEO = Solid Falcon = Dashed



- Falcon has higher speed at same Torque
- NEO has higher operating efficiency
- Falcon has higher power out at same torque levels within operating range by virtue of higher speed
- NEO speed torque curve is much closer to behavior of Full Size CIM and is basically a drop in replacement for a CIM

Weight Comparison

- NEO motor is 0.14 Lbm less than Falcon 500
- However….
  - Falcon 500 motor has power electronics integrated directly into motor itself
  - NEO requires external controller that weighs 0.25 Lbm that makes NEO motor + controller 0.11 Lbm more than Falcon 5000
  - Mass advantage of Falcon 500 is greater when taking wiring into account
    - Falcon: 2x Large Dia Power and 4x Lower Dia signal leads
    - NEO: 3x Large dia Power and 6x Lower Dia signal leads

Packaging Comparison

- NEO Requires a separate motor control on electronics board while Falcon Does not
  - Significant advantage for Falcon 500
- NEO motor body itself is 0.90” smaller than Falcon
  - NEO may have advantage if package space for motor is tight
  - NEO may also be better if mounted on end of articulated arm where lower mass and inertia may be of advantage

Bottom Line: NEO vs Falcon 500

- **Falcon 500 is the preferred motor for FIRST FRC Applications**
  - **Lower overall system weight**
  - **Avoids packaging a dedicated motor controller on electronics board**
  - **Wiring is less complex**
- **NEO is only better when package space for motor is very limited**