# A high power density, high efficiency axial flux Halbach array motor/generator

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TECHNOLOGIES

# LaunchPoint Snapshot

- A technology development company
  - Approx. 15 engineers
  - Approx. 5 administrative staff
  - Founded in 1992 by the Paden family
    - Brad Paden – CEO, UCSB Professor, IEEE Fellow
    - Al Paden – 30 years of engineering experience
    - Dave Paden – Mechanical Engineer and machinist
- Primary facility is in Goleta, CA
  - Includes a machine shop, mech. assy, elect. assy, lab space
  - Small offices in Pittsburgh and Phoenix
- Focus is on innovation, technology & business development
  - Idea maturation, prototyping, with a transition to production
  - Minimal production is done in-house

The campus of U.C. Santa Barbara

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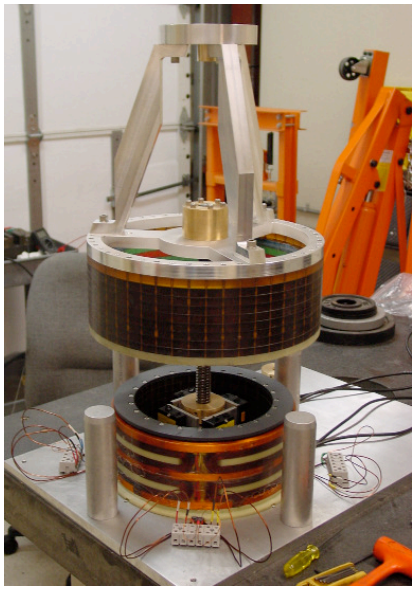
# LaunchPoint's expertise

- New Ventures/Product Development
  - Magnetic bearings
  - Motor, alternator, generator design
  - Energy storage
  - Medical devices
  - Custom prototyping
- Engineering Consulting Services
  - Electromagnetic analysis and design
  - Control system analysis and design
  - Modeling and system optimization
  - Life-critical electronic systems
- Research
  - Funded by federal grants and private investments
  - Intellectual property creation, patents

# More power, less weight

- Why power density of the motor matters:
  - In aircraft, weight can never be minimized enough
  - For power hungry VTOL aircraft, the weight of the motor is critical
    - The best available electric motors can deliver only about 3 kW/kg
    - The best available batteries can deliver 20 kW/kg
    - Turbine engines typically can deliver about 16 kW/kg
- Speeds must be appropriate for propellers and ducted fans
  - Increasing the shaft speed can increase power density, *but*
  - Fan tips must stay below the speed of sound in air
- The goal:

  Design an electric motor to deliver over 8 kW/kg for lift fans

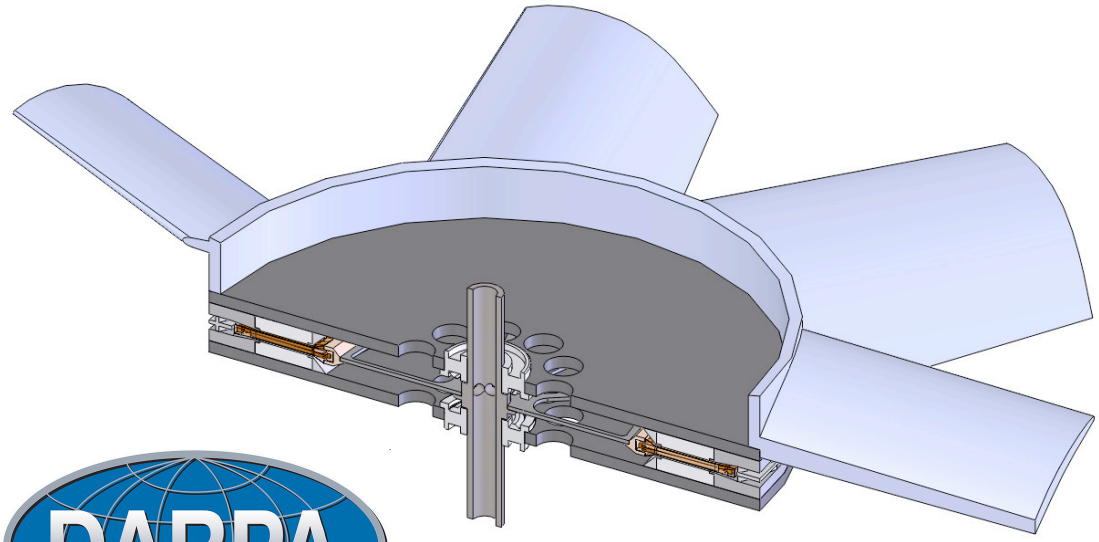
# Some electric motor design options

- Cooling method?
  - Cooling capability frequently limits power density
  - Liquid cooling is more effective, but weighs more than forced air cooling
- Gearbox?
  - A gearbox will generally increase power density at the expense of reliability
- Motor inside fan or fan inside motor?
  - Increasing the surface velocity of the motor improves electro-magnetic performance, *however*
  - Putting the motor on the outside of the fan means that the surface velocity will be near the speed of sound and that drag will be high
  - Stiffness can also be an issue
- Iron core?
  - Iron core motors are well understood and minimize magnet material, *however*
  - Iron has a low stiffness to weight ratio and represents a large portion of the losses in a high power density motor
- Cryogenic?
  - Magnets get stronger and copper gets more conductive at cold temperatures, *however*
  - Keeping the motor cold is difficult, heavy and energy expensive

**There are a lot of permutations with a vast solution space**

# DARPA UAV Motor

- Motor performance:
  - 5 hp/lb or 8.2 kW/kg
  - 7 hp @ 8400 rpm & 95% efficiency
  - 1.4 pounds or 0.64 kg
  - 6” diameter
- Developed under an SBIR Phase I grant
  - Target application is an electric powered, ducted fan UAV
- This performance is unrivaled
  - No other motor has 5 hp/lb at 8400 rpm while maintaining 95% efficiency

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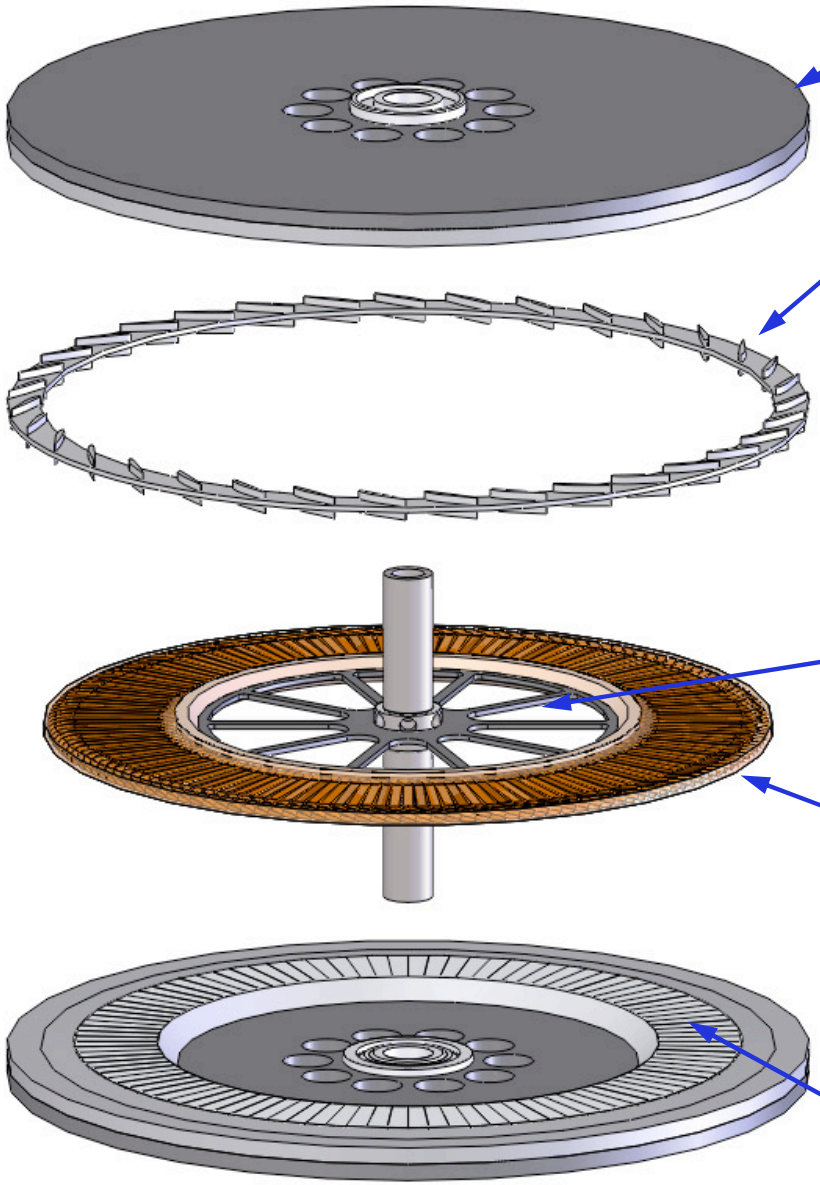
# Attributes of the LaunchPoint motor:

- A brushless permanent magnet motor/generator
- Axial flux configuration (pancake shape)
  - Allows for smaller gaps, higher efficiency than a radial configuration
  - Deflection from centrifugal forces and CTE mismatches are parallel to gap
  - Making parts very flat is easier than making them perfectly round and concentric
- Uses two Halbach arrays
  - Halbach arrays concentrate magnetic field without using iron
  - Optimized pole count to maximize field in gap, typically ~90% of $B_r$
- Highly efficient
  - Halbach arrays generate a field of >1 tesla in the gap
  - Litz wire results in very low copper eddy current losses
  - There is no iron: no hysteresis or iron eddy current losses
- Lightweight
  - Carbon fiber can be used in place of iron for structure
  - The motor is magnet, copper, carbon fiber – each ideal for its purpose

# Motor Components



Carbon fiber backing plate

Impeller ring pulls air over winding for cooling

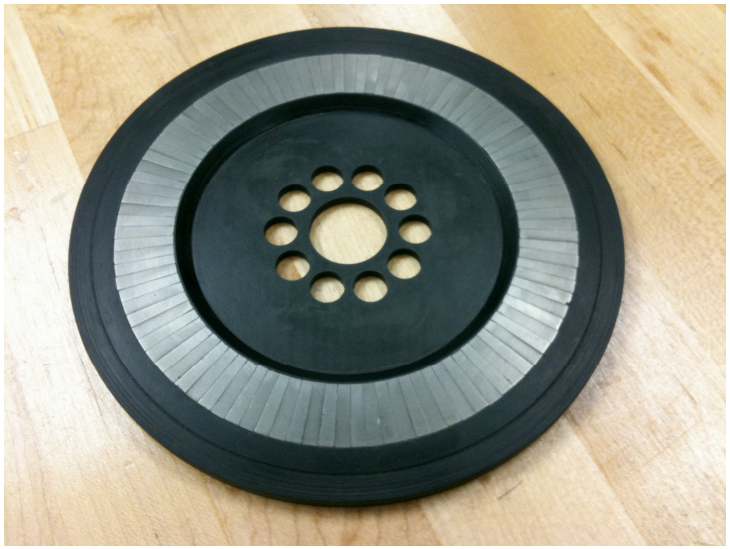
Carbon fiber spokes

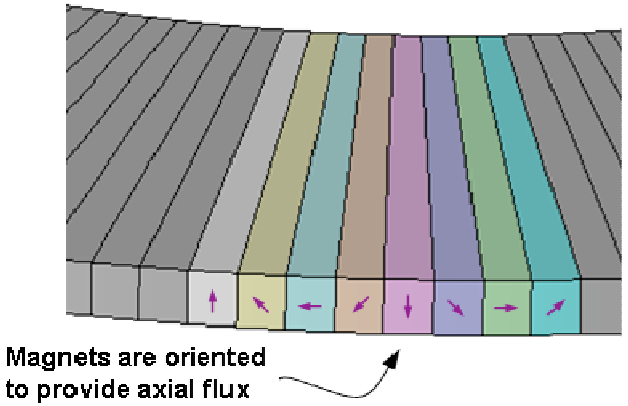
Three phase, litz wire winding

Halbach array

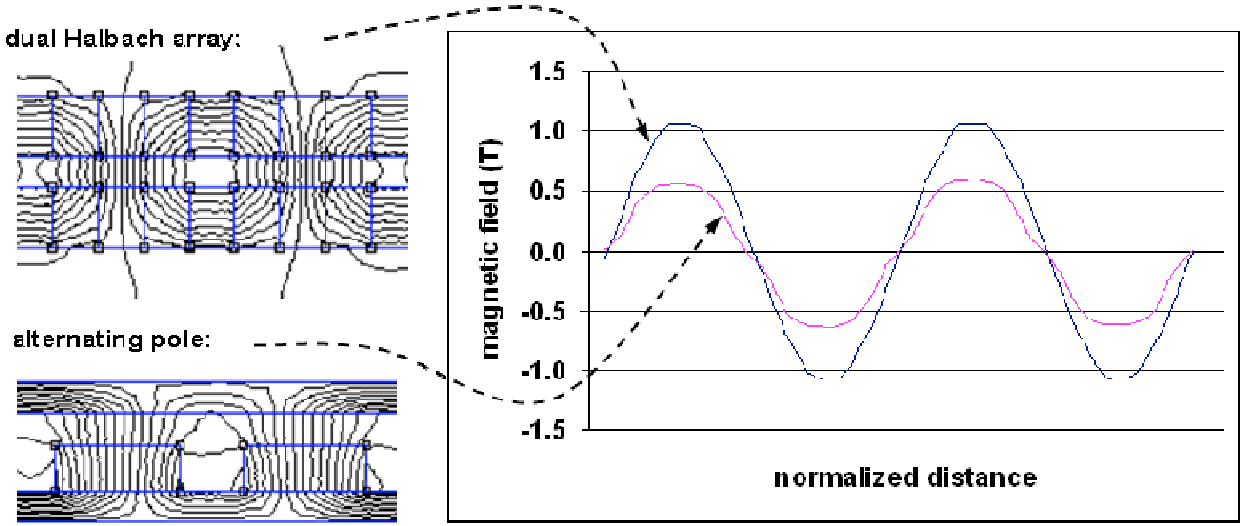
# Halbach arrays are one key enabler

## A Halbach array is an arrangement of magnets:



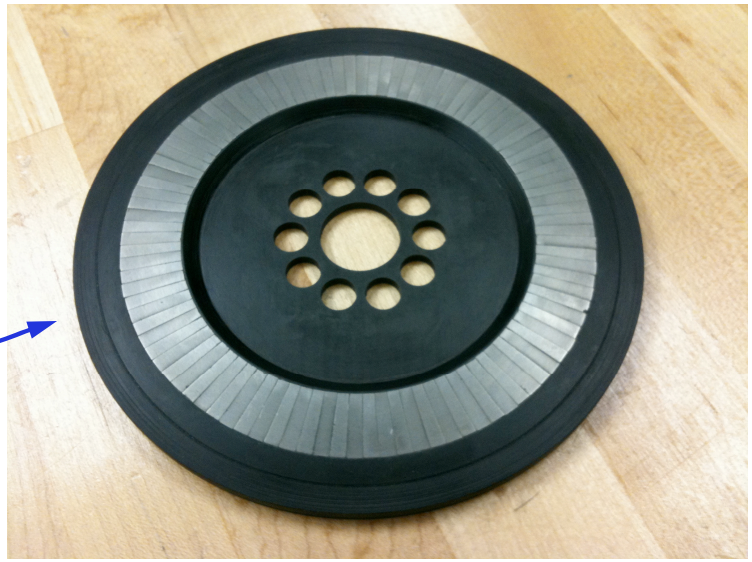


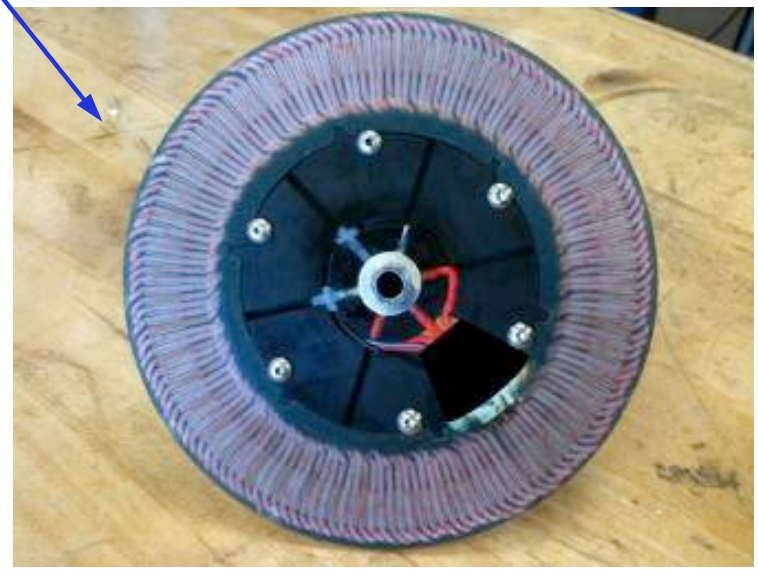

## The dual Halbach array has a much stronger field for a given size and weight:

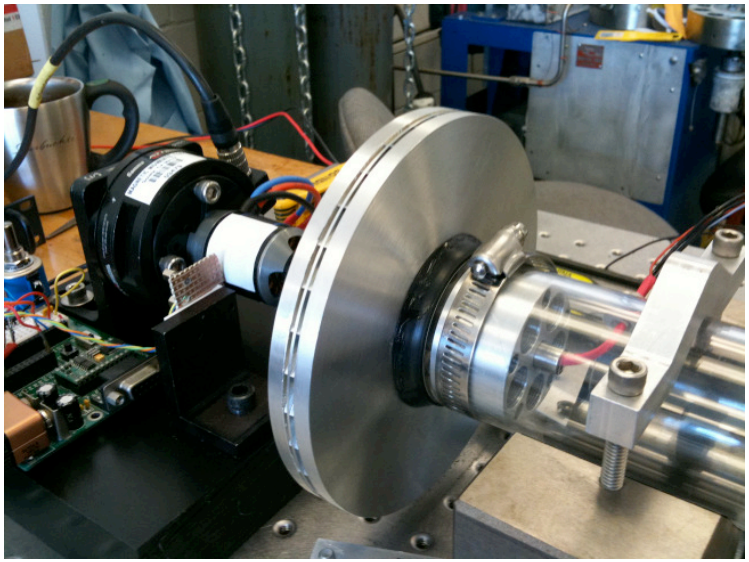


# Hardware validation of models

- Analytical model developed, validated
  - Optimizes thermal, fluid dynamics, electro-magnetic, mass properties
- Halbach array assembly tooling developed
- Winding tooling has been developed
  - Patent application in progress
- Thermal design has been tested and validated

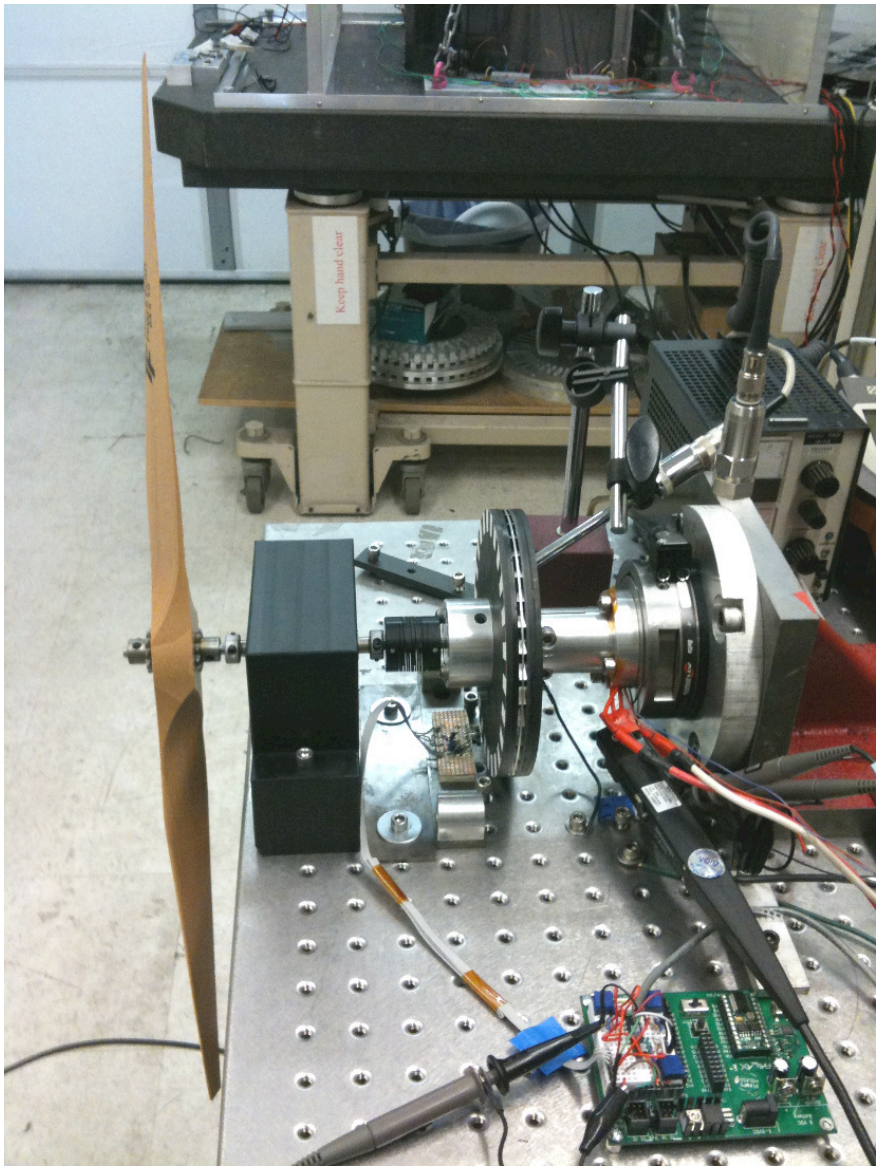






# Validation of models (continued)

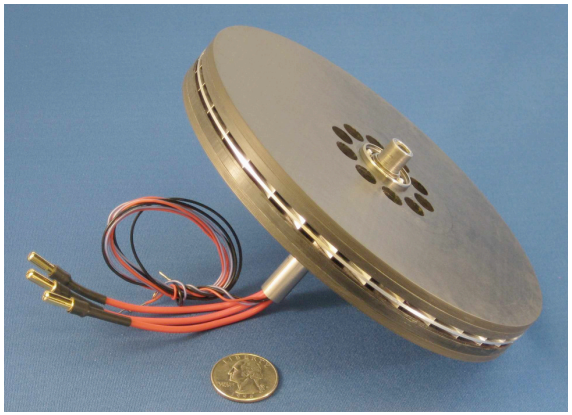
- Back EMF amplitude has been validated
- Terminal resistance has been validated
- No-load spinning losses at 8400 rpm have been validated
- A 20” propeller was spun using an off-the-shelf motor controller
  - 1 hp of shaft power was generated
  - Stator temperature prediction was validated



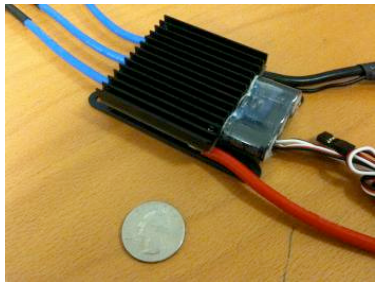
# Next prototype development steps

- Complete trade studies for motor controller
  - Commercial off-the-shelf motor controllers aren't necessarily compatible without special accommodation
  - Need to accommodate extremely low inductance, high PM flux linkage, high excitation frequency
  - Several appropriate power electronic architectures have been demonstrated
    - Need to optimize and pick the best one
- The controller will likely be similar in power density compared to off-the-shelf controllers:

5 kW motor, 0.625 kg



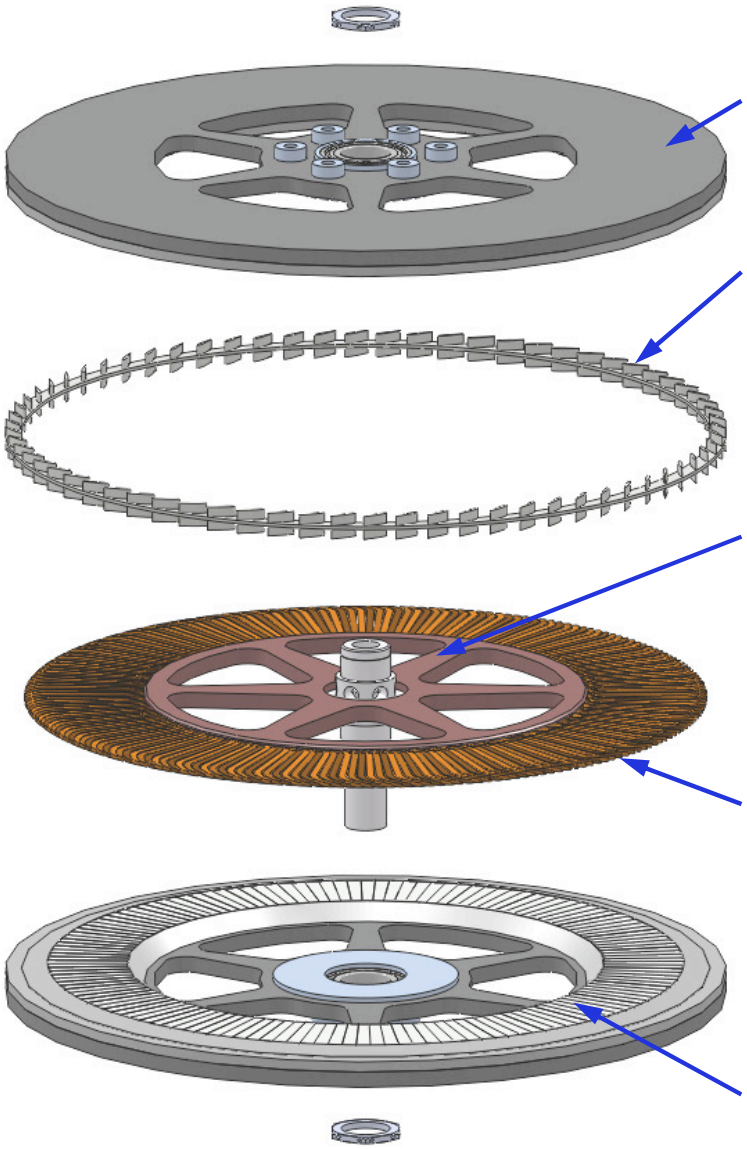
5 kW controller, 0.140 kg



# Other well suited applications

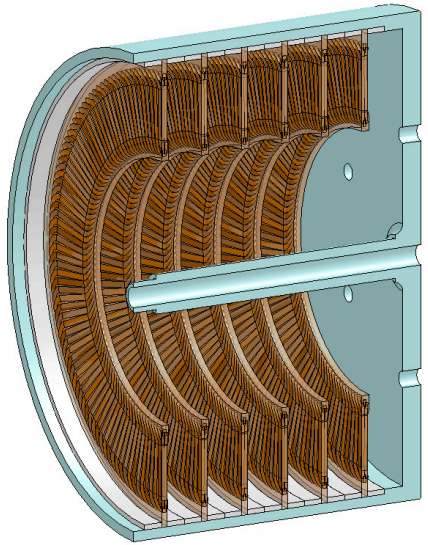
# The design can be scaled up

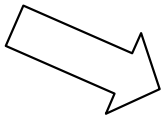
- A larger motor suitable for the DARPA Transformer program:
  - 18” diameter
  - 15 kilograms
  - 97% efficient at 150 hp, 3500 rpm
  - 97% efficient at 100 hp, 2700 rpm
  - Capable of up to 5 hp/lb

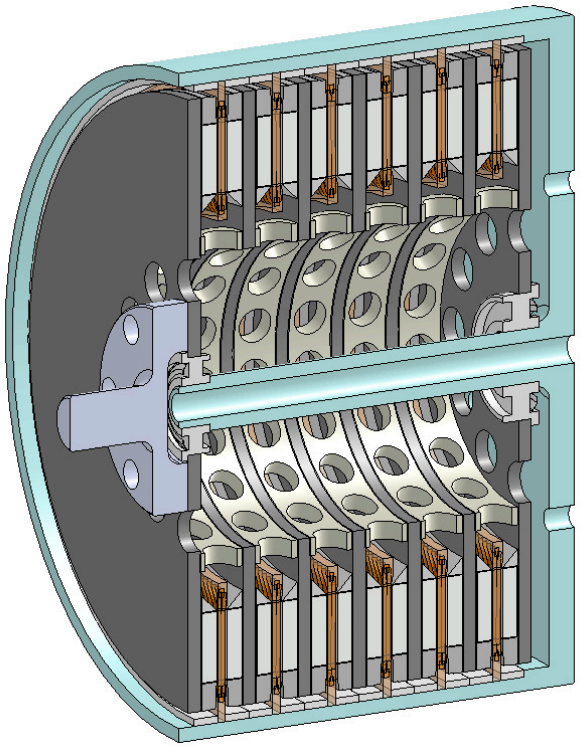


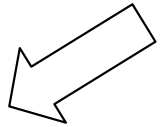
# Motors can be stacked up

Stationary components:

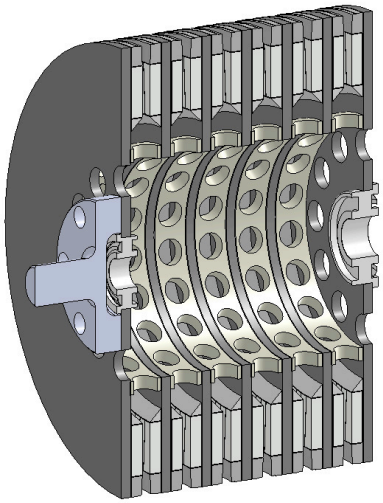






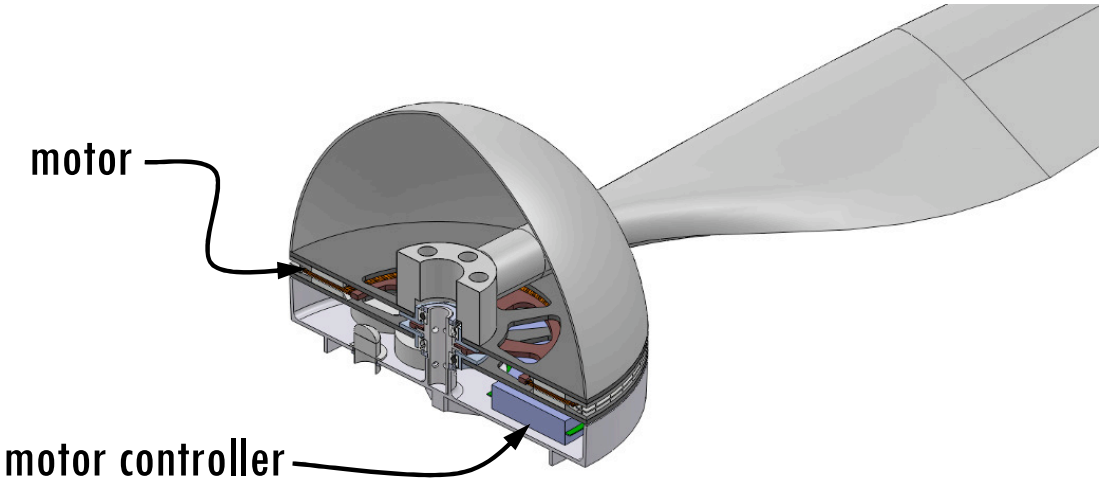


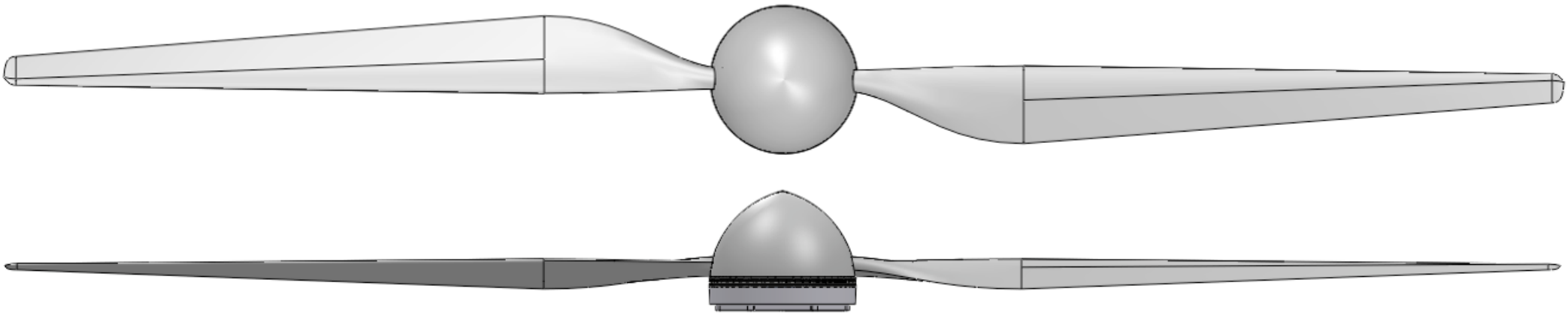
Rotating components:



In this configuration, the stator is held from the outside

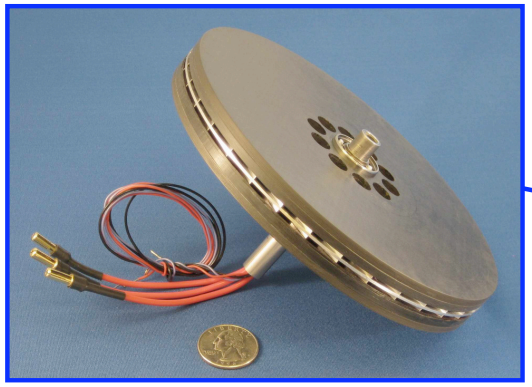
# Driving an aircraft propeller



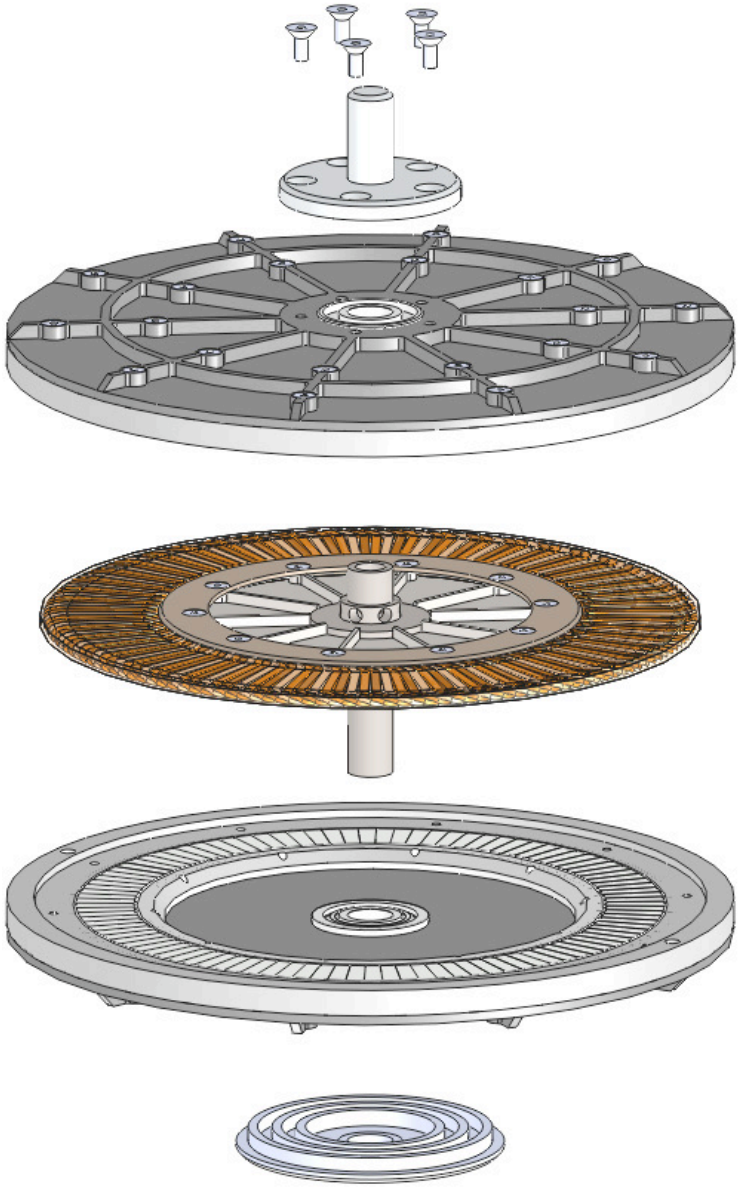
# Landing gear wheel motor/generator

- Motor-in-wheel gives near-silent taxiing
  - Steer-by-wire
- Tire spool-up pre-touchdown
- Regenerative braking
- Motor volume and weight minimization is an enabler



# NASA SBIR configuration

- Ongoing Phase I SBIR
  - Work began mid-March
- Like the DARPA configuration, except:
  - Must operate from 40 K to 403 K
  - Must operate in a vacuum
- May be used in future lunar or Mars rovers, cranes, etc.
- Technology developed will be used to robustify motors for aircraft applications



# Works equally well as a generator

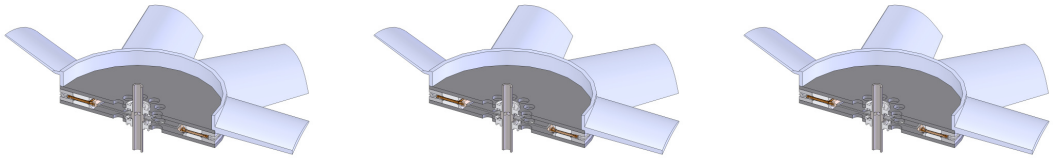
- Can be an integrated starter/generator
- A prime mover with a single generator can drive multiple distributed motors

Prime mover
- Turbine
- Wankel
- Diesel

LaunchPoint generator

Auxiliary power

LaunchPoint motor in lift fans

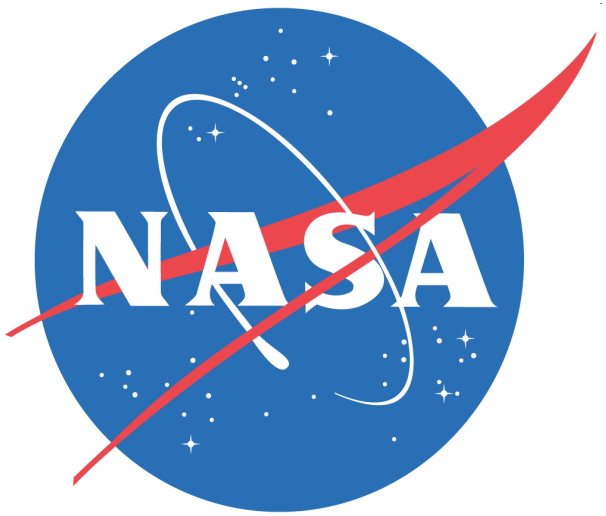


LaunchPoint motor in wheel motors

# Key takeaway message

This technology can provide a significant improvement in power density

# Thanks to DARPA and NASA!


Some of the work that has been presented was funded by DARPA and NASA through the Small Business Innovation Research (SBIR) program

# Call today to discuss your application!

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