Dynamic Testing of a High-Specific-Torque Concentric Magnetic Gear

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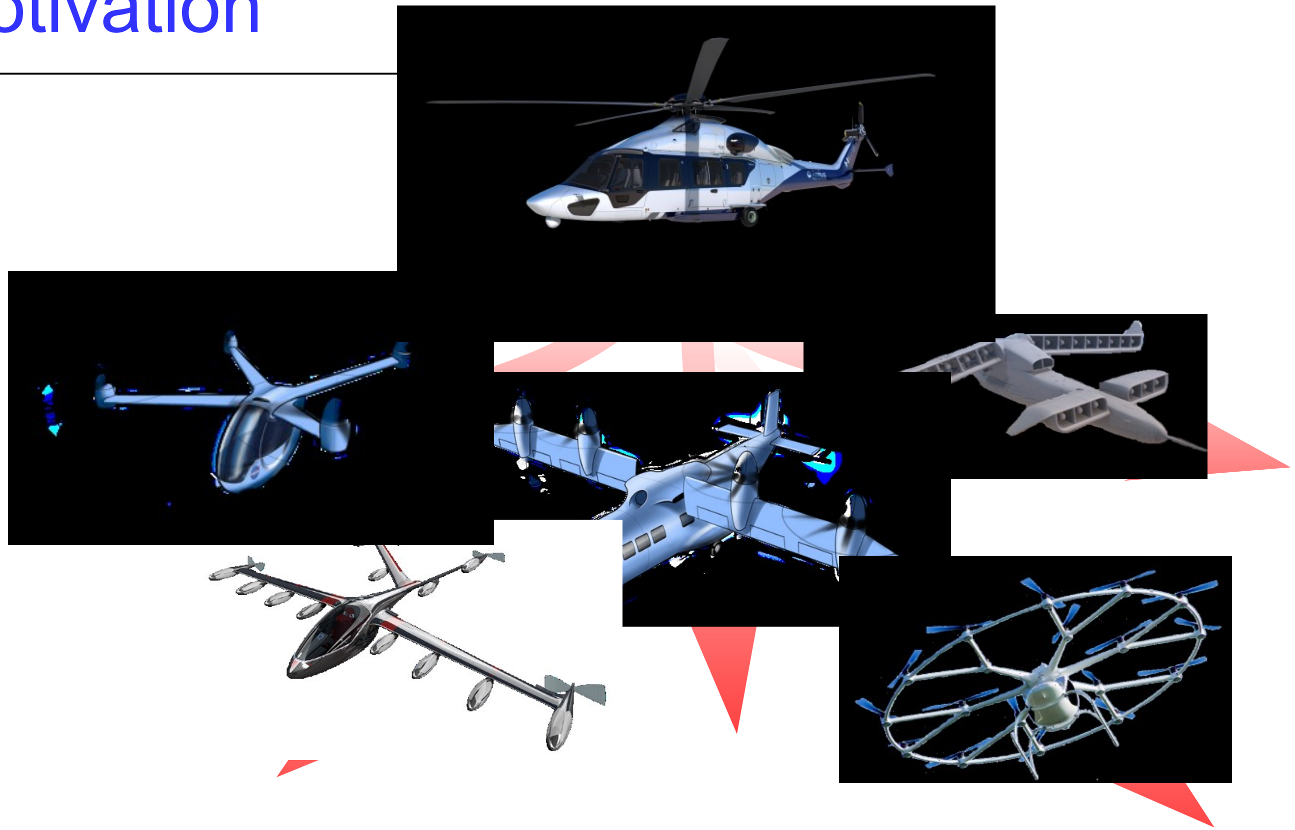
Outline

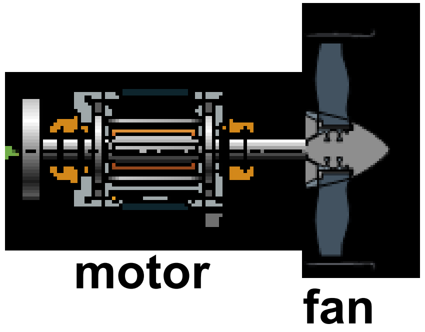
- Motivation
- Summary of NASA's prior work
- New test rig – E-Drives Rig
  - Overview
  - Uncertainty analysis
- Measurements
- Conclusions
- Future work

Motivation



- Growth of short haul market & emergence of urban air mobility market
  - Enabled by electrified propulsion systems
  - Prevalence of smaller (lower torque) propulsors
- Most concepts use direct drive
- Geared drives are almost always mass optimal

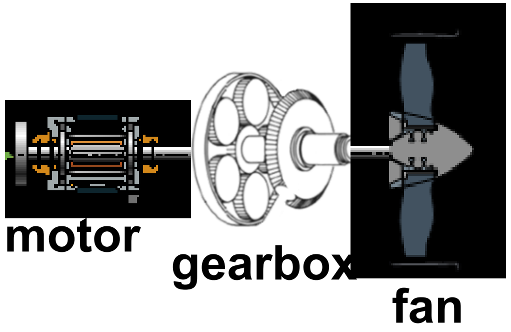
Direct drive



\+ Simpler

− Non-optimal motor and/or fan

Geared drive



\+ Optimized motor & fan

− More complex

− Potentially less reliable

Motivation

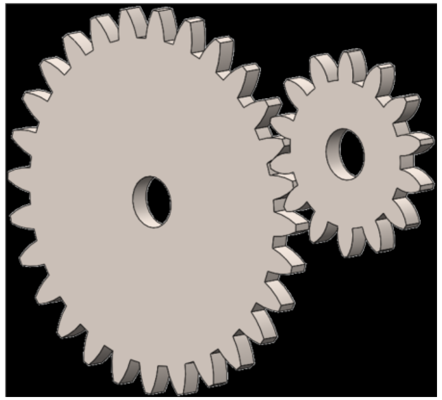
Mechanical gearing

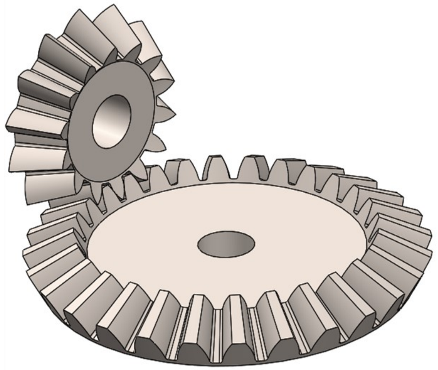
Pros

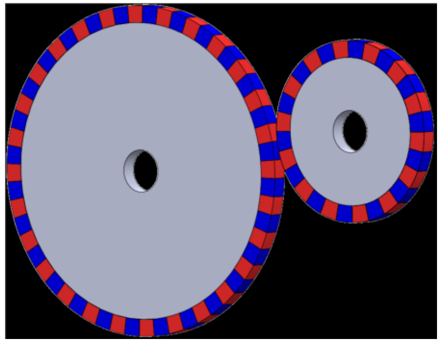
+ High / very high torque/mass (**specific torque**)
+ High / very high efficiency
+ Mature technology

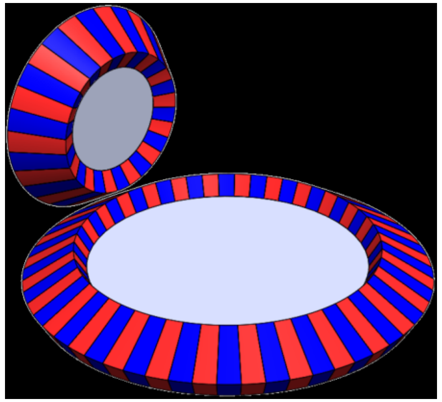
Cons

− Contact-related wear & failure
  − Requires lubrication system(s)
  − Routine & costly maintenance
− Strong tonal vibration & cabin noise









Magnetic gearing

Pros

+ Non-contact
  + No lubrication
  + Low maintenance
+ Easily integrated in electric machines
+ Potentially low vibration

Cons

− Unknown limits on specific torque & efficiency
− Magnet temperature limit
− Individual magnet interaction weaker than 1 gear tooth pair

Concentric Magnetic Gears

Analogous mechanical gear (planetary)

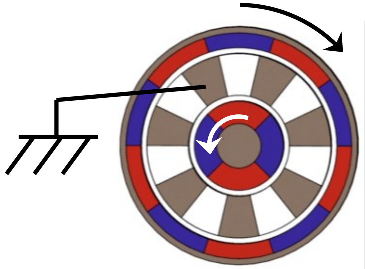
Concentric magnetic gear

Outer magnet array
(“ring gear”)

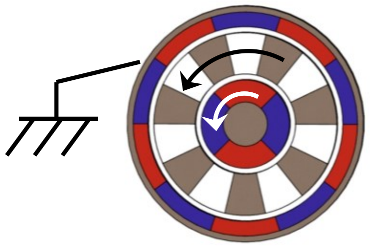
Modulator
(“planet gears”)

Inner magnet array
(“sun gear”)

Gear ratio (GR)



$$GR = \frac{N_{\mathrm{ring}}}{N_{\mathrm{sun}}}$$



$$GR = 1 + \frac{N_{\mathrm{ring}}}{N_{\mathrm{sun}}}$$

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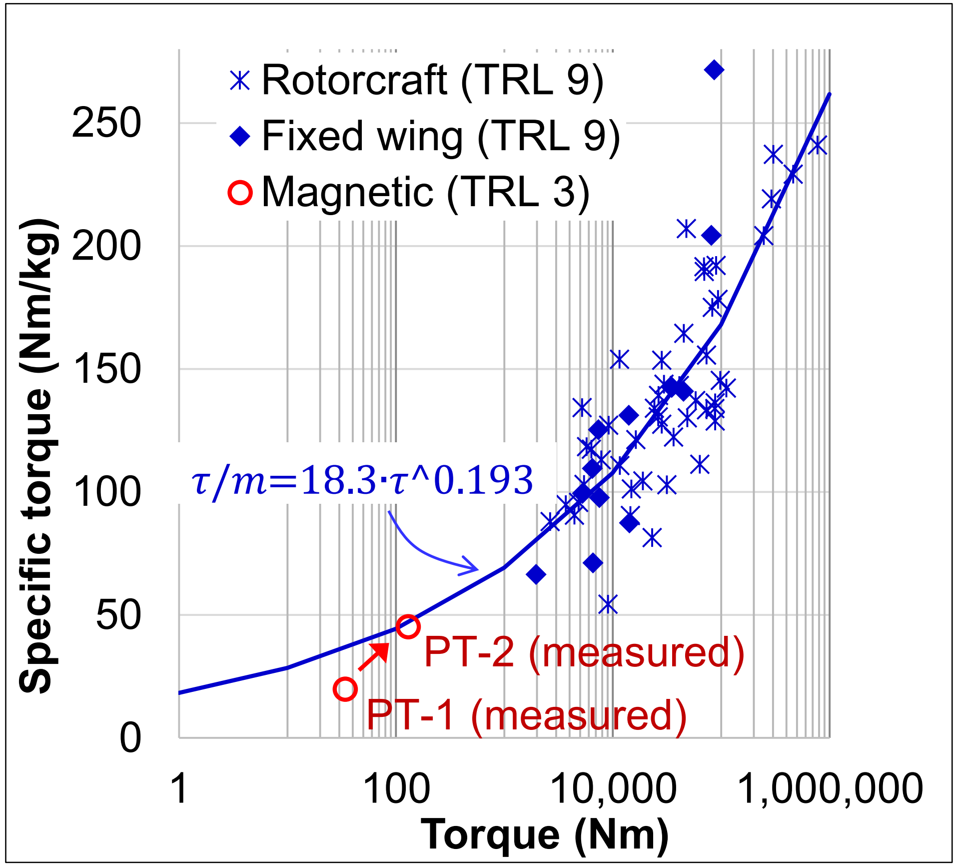
NASA's prior work

- **Key conclusions from NASA's Phase 1 study** (understand & improve specific torque)
  - Magnetic performance limited by mechanical features & minimum gap size
  - Concentric magnetic gears are viable, at least for lower torque applications

5.6" (141 mm) diameter

6.1" (154 mm) diameter

Performance compared to aircraft transmissions



Technology needs:	High precision, dynamic data	Feasibility of aerospace-grade efficiency

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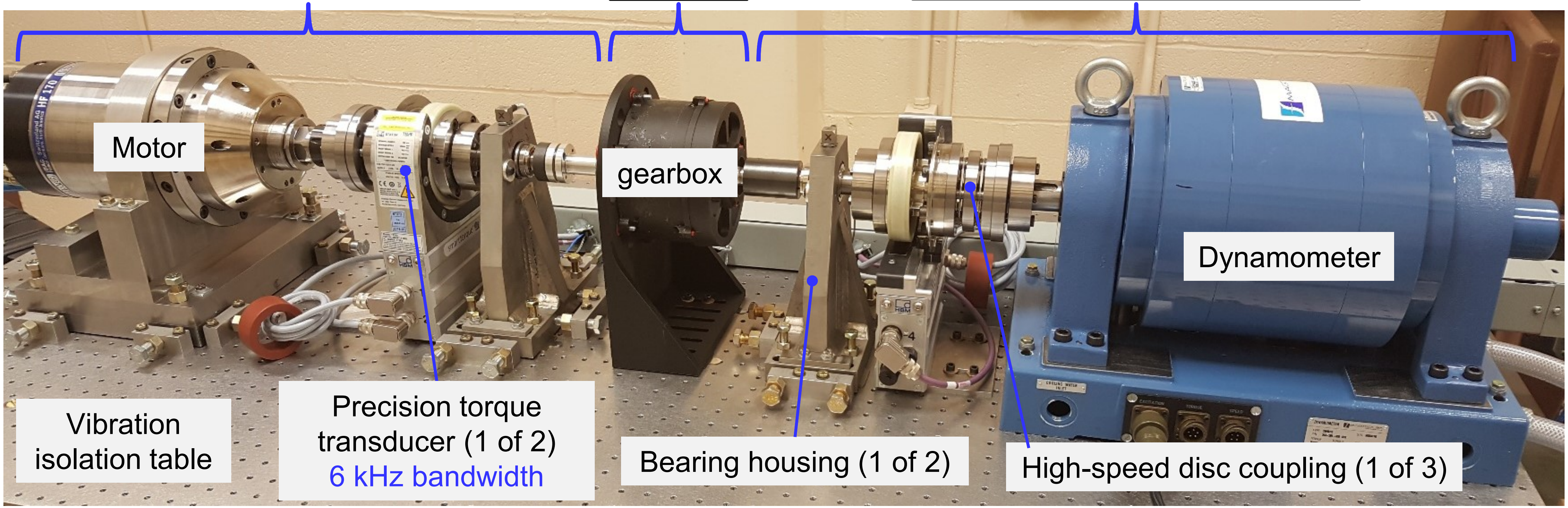
E-Drives Rig – Overview

Input (controlled speed)		
30 kW 40 hp	- 22,000 rpm -	12 Nm 8.9 ft-lb

Test Article

Output (controlled torque)		
30 kW 40 hp	- 15,000 rpm -	100 Nm 73.7 ft-lb

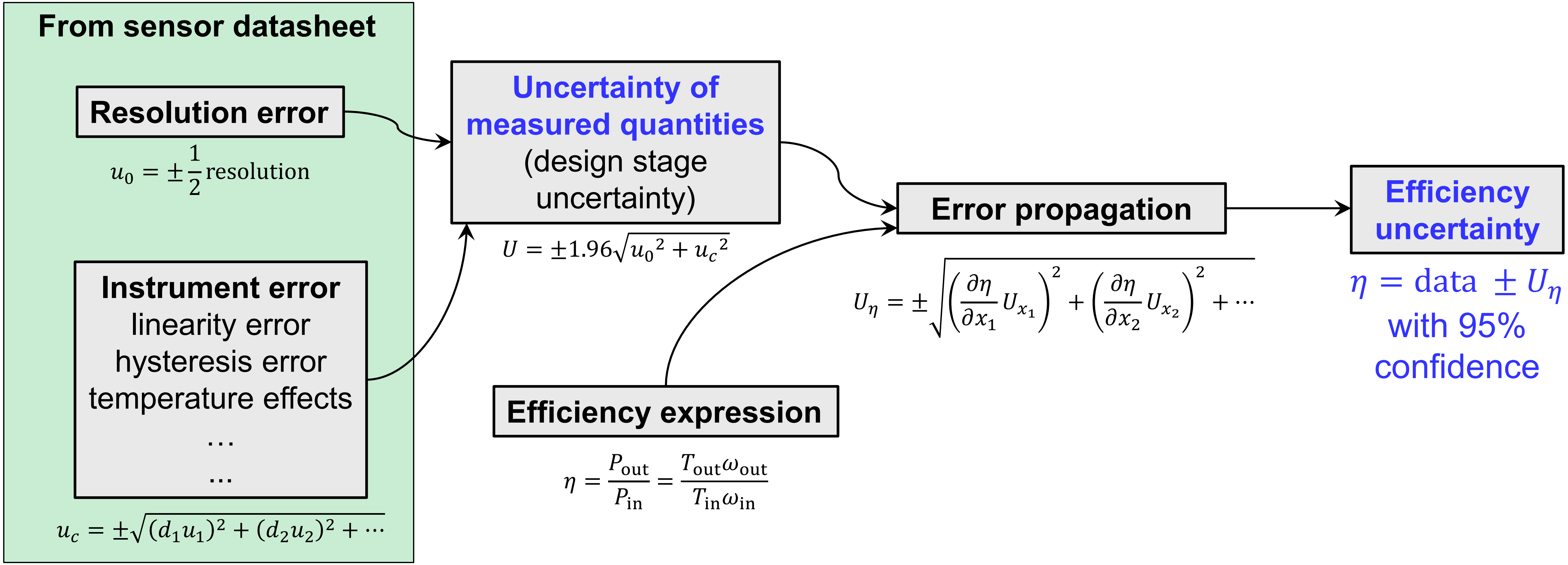


Measurements: torque (in/out), speed (in/out), power (in/out), vibration, temperature

Note: noted specifications are for continuous operation

E-Drives Rig – Uncertainty Analysis

- Formal uncertainty analysis conducted [1,2]



1. Figliola, R. and Beasley, D., Theory and design for mechanical measurements, John Wiley & Sons, Inc., Hoboken, NJ, fourth edition, 2015.
2. HBM, "Webinar: the calculation of the measurement uncertainty for torque applications," Available online [https://www.hbm.com/en/3941/the-calculation-of-themeasurement-uncertainty-for-torque-applications/], 2019.

E-Drives Rig – Uncertainty Analysis

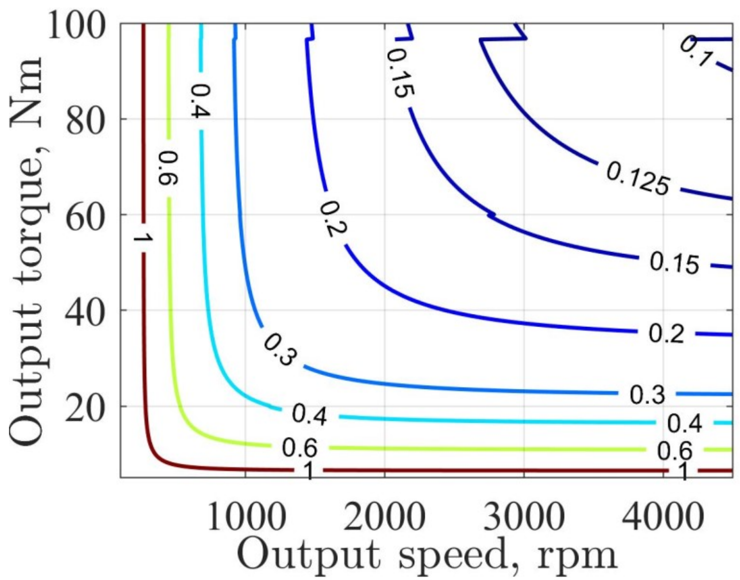
- Torque uncertainty depends on torque & temperature
- Efficiency uncertainty depends on input speed, output torque, & gear ratio
- At a 95% confidence level, can often measure…

Torque to better than ±0.03%

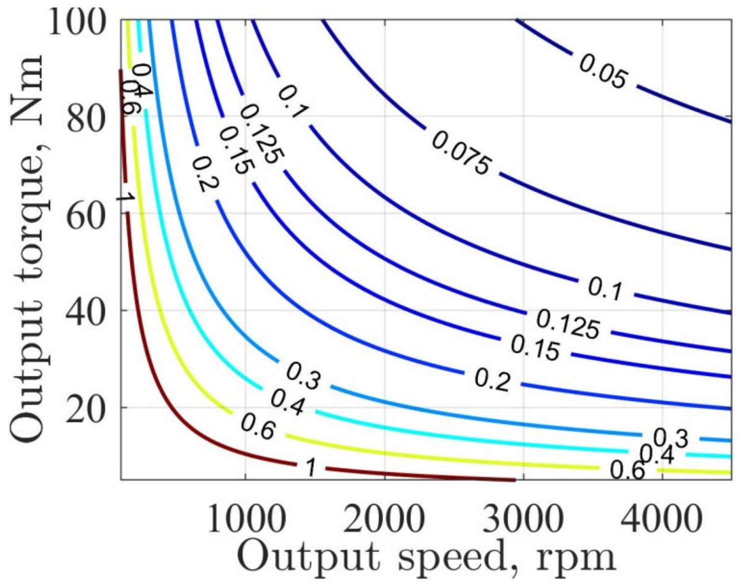
Power to better than ±0.2%

Efficiency to better than ±0.3%

From measured torques & speeds



From measured powers



Efficiency uncertainty (%)

(for gear ratio 4.83 : 1, torque transducer 10 C above its calibration temperature)

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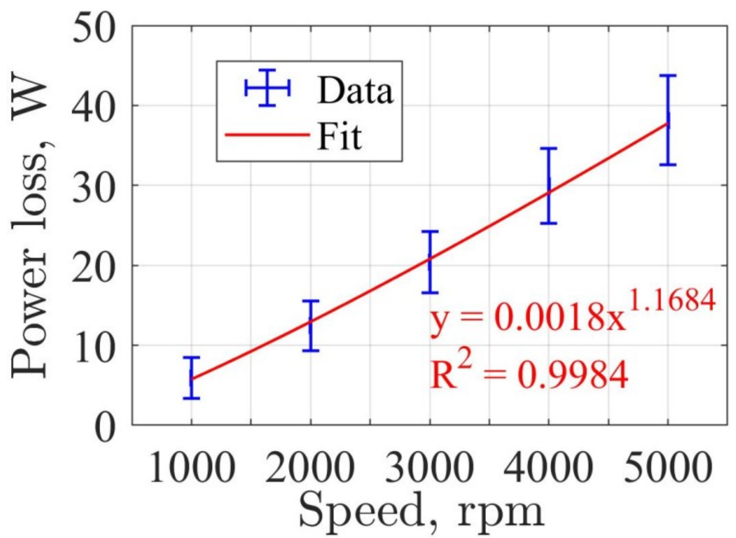
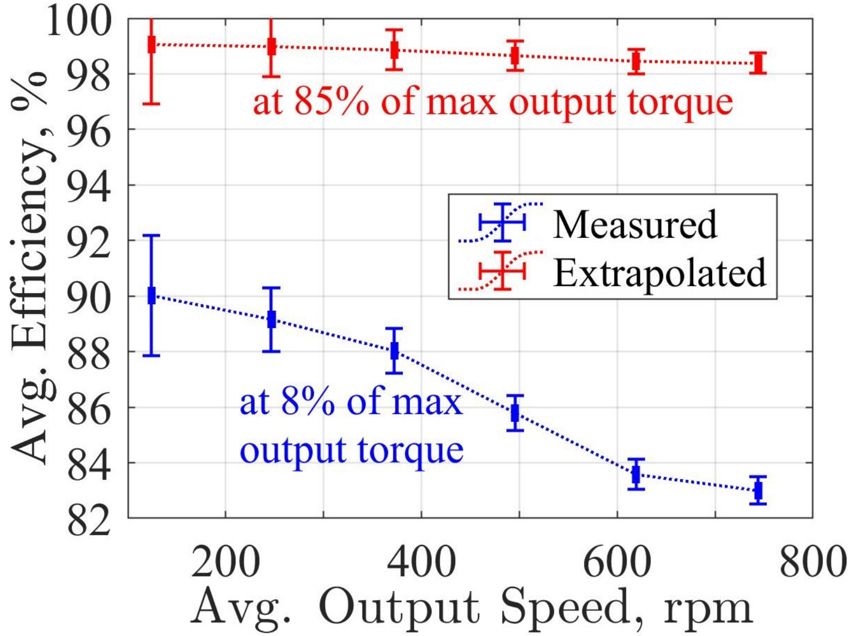
Measurements – PT-2 (High Specific Torque)

Tare loss correction

- E-Drives Rig's bearing housings and some couplings are located between the torque transducers
- Tare loss vs. speed measured when prototype replaced by straight shaft



Measured PT-2 efficiency



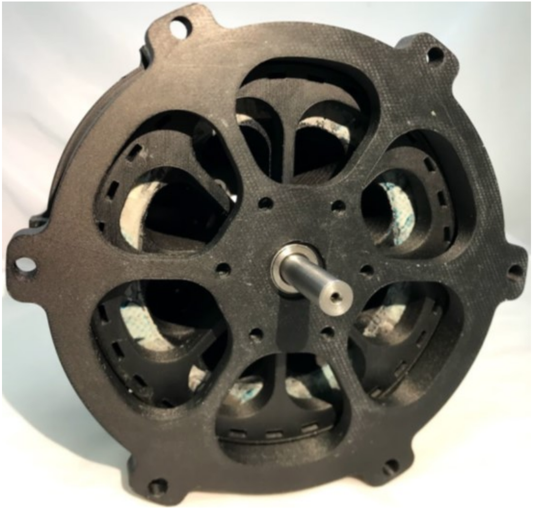
Average corrected efficiency
with 95% confidence error bars

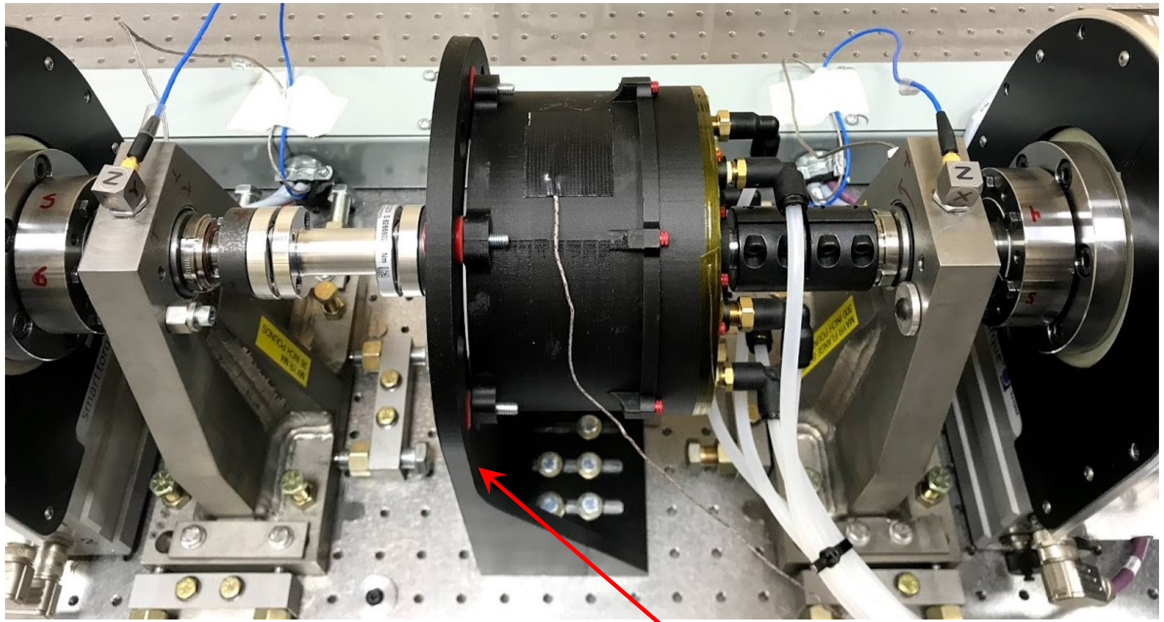
Efficiency extrapolated by assuming energy loss is independent of torque

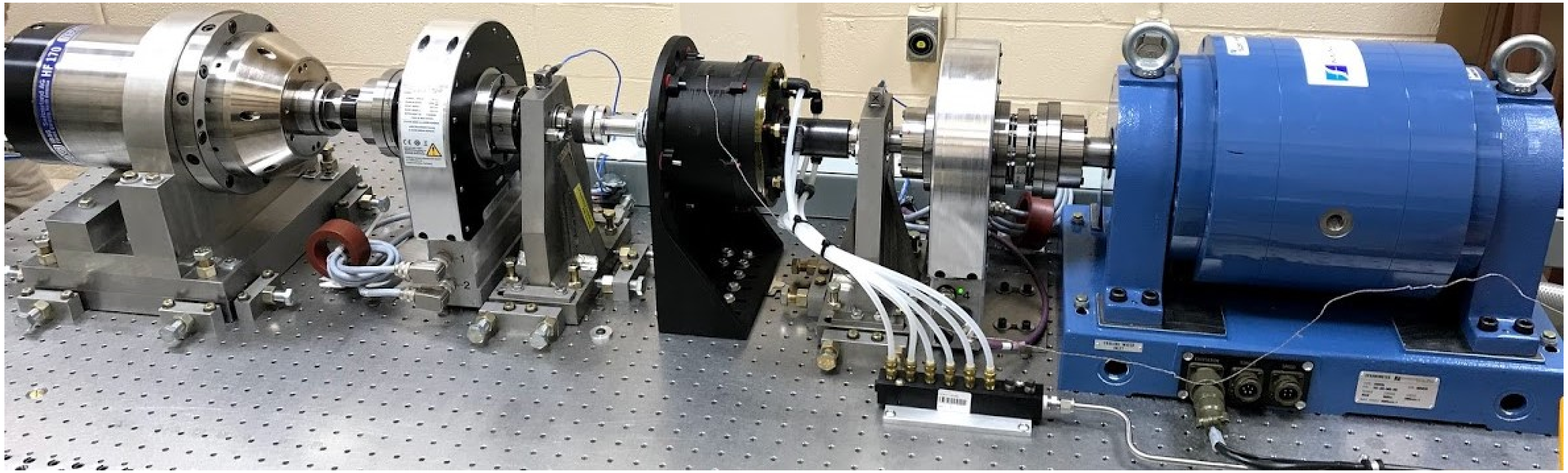
Measurements – PT-3 (High Efficiency)

Output side
(high torque)

Input side
(low torque)

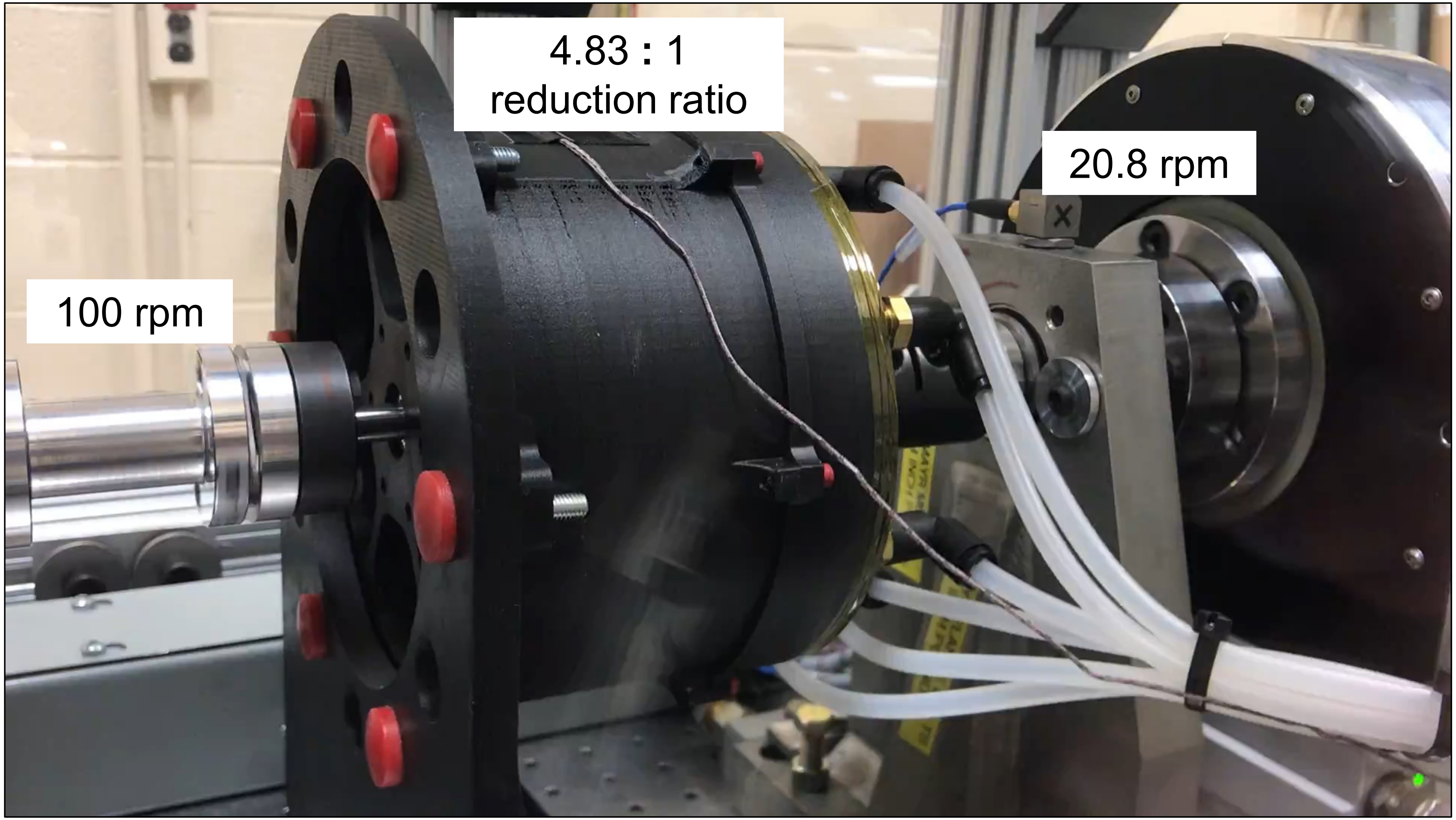






Torque reaction structure (does not constrain radial or axial position)

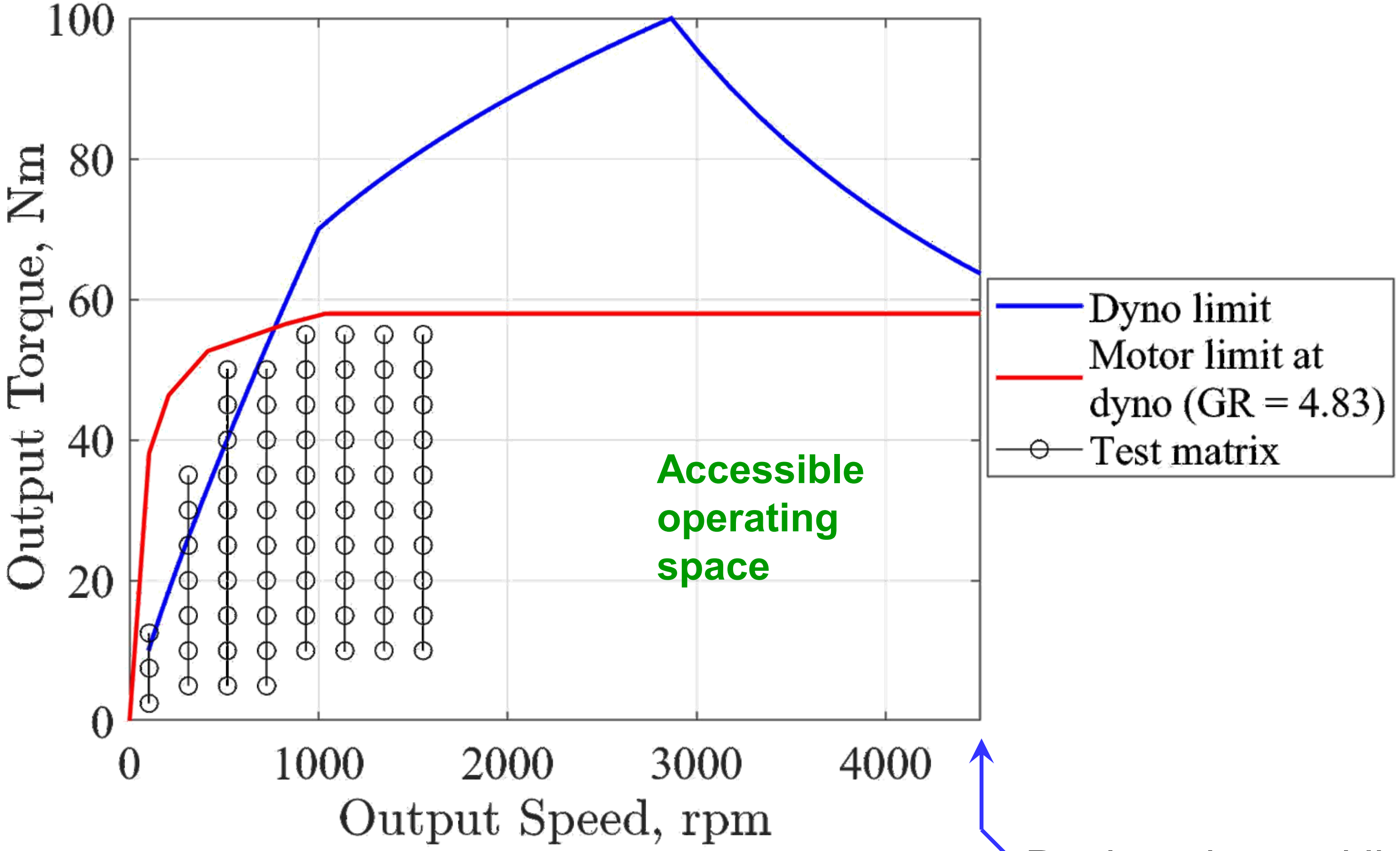
Measurements – PT-3 (High Efficiency)



Measurements – PT-3 (High Efficiency)

Test matrix overlaid on test rig's operating space

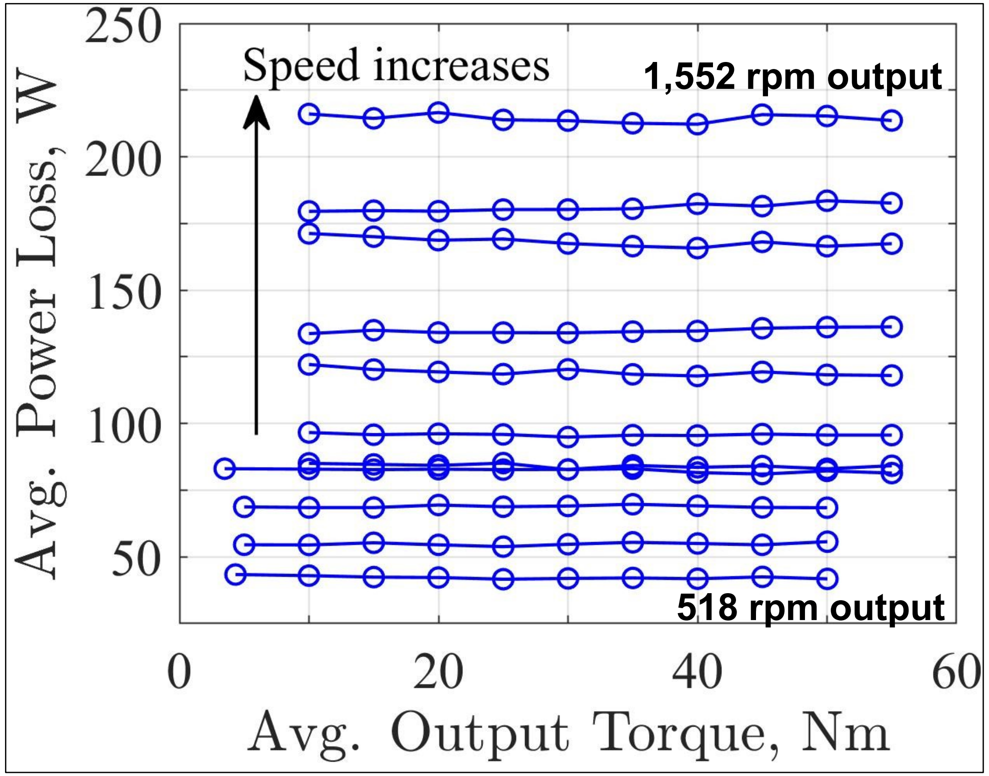
Measured torque limit of PT-3 (~115 Nm)

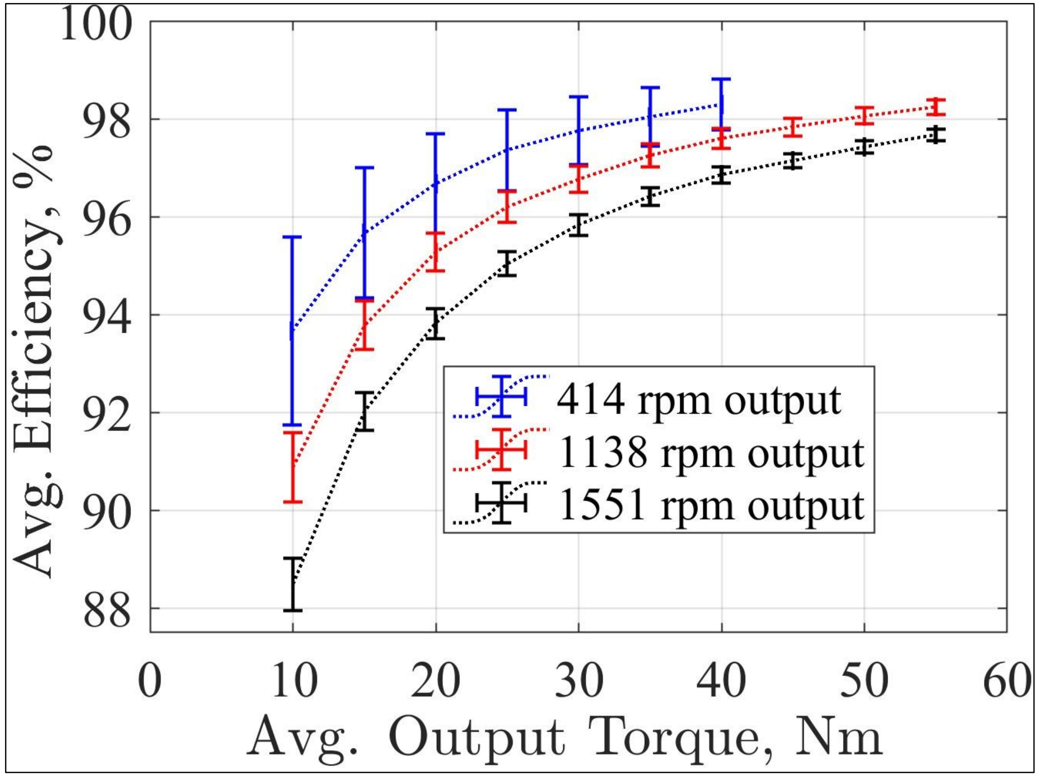


Designed speed limit of PT-3

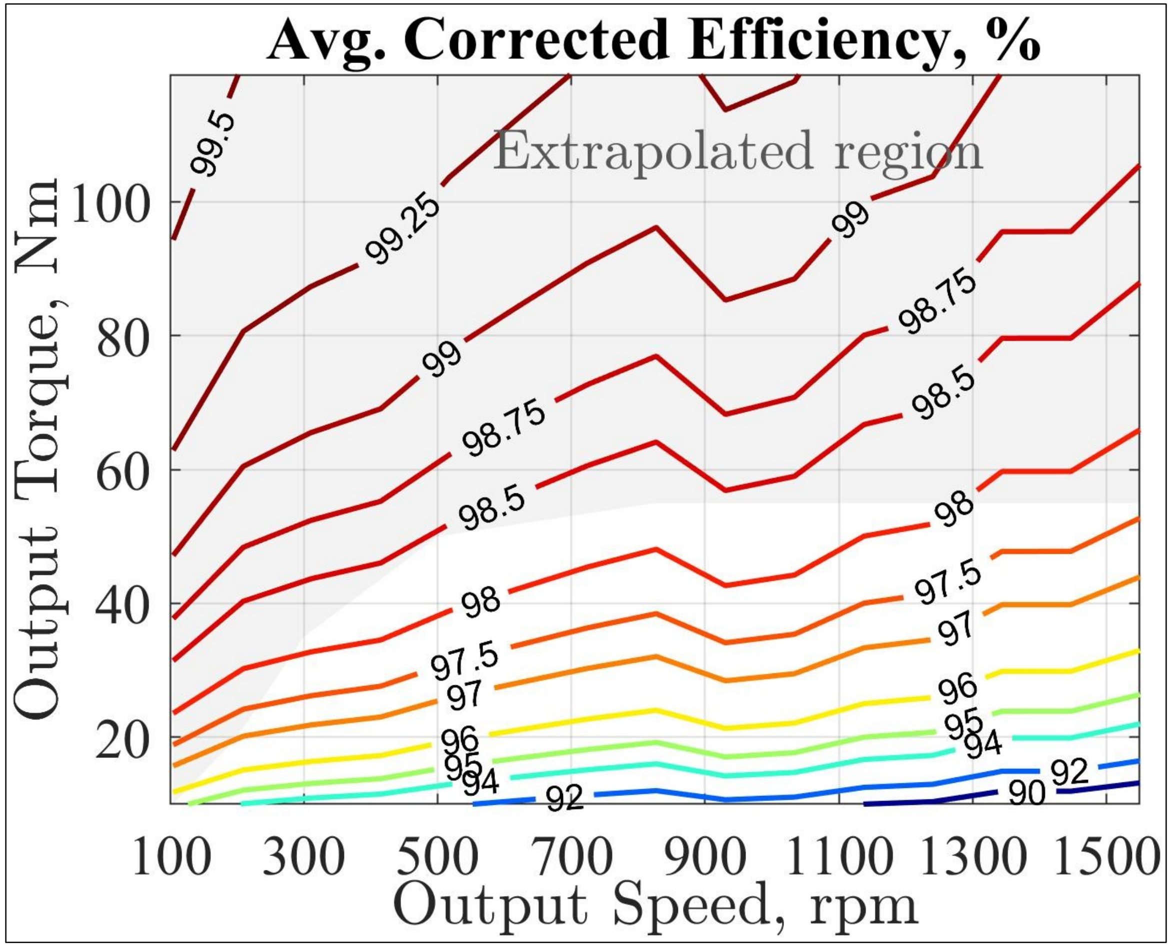
Measurements – PT-3 (High Efficiency)

- Power loss is independent of torque
  - Important for efficiency modeling
  - Allows accurate extrapolation of data to higher torques
- Efficiency uncertainty is sufficiently small to distinguish different trends and speeds





Measurements – PT-3 (High Efficiency)



- Efficiency over 98.3% measured, extrapolated efficiency exceeds 99.5% at low speeds
- Over 99% efficiency should be achieved up to about 1,300 rpm output speed

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Conclusions

Key conclusions from NASA's Phase 2 study (feasibility of high efficiency)

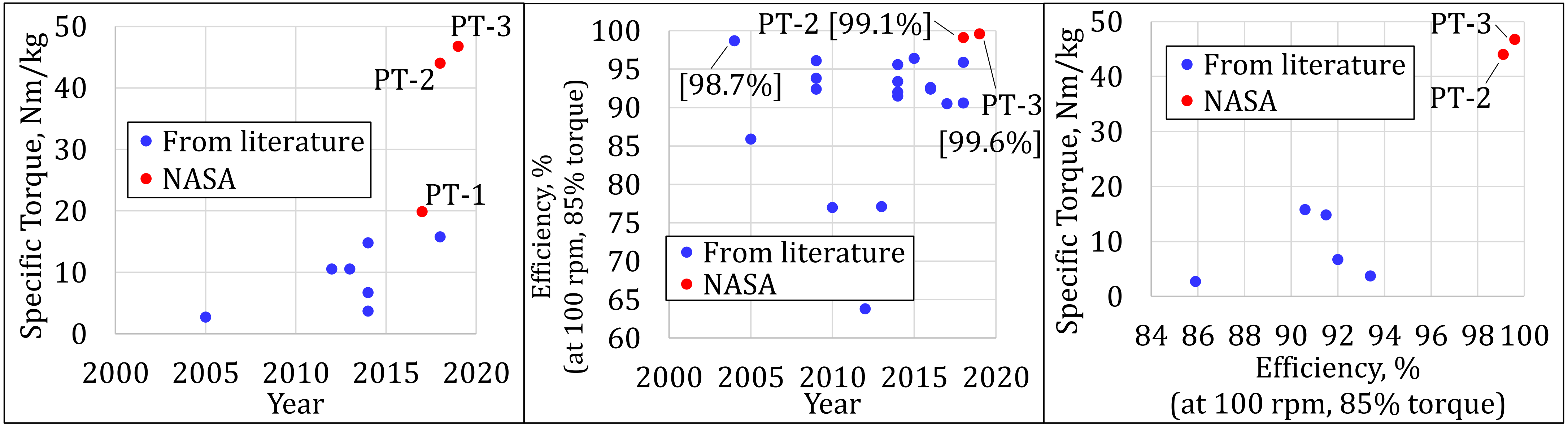
- E-Drives Rig
  - Measurements can be used to confidently calculate efficiencies up to 99.7% for most tests
  - Limited ability to evaluate low speed performance – need higher torque capacity
- Laminated permanent magnets may be required to meet efficiency targets
- Energy loss in magnetic gears is independent of torque
  - Loss & efficiency data can be accurately extrapolated to higher torques
- PT-3 can achieve > 99% efficiency up to output speeds of about 1,300 rpm

Laminated magnet

Magnetic gears can *simultaneously* achieve the high efficiency and high specific torque required for aerospace applications.

Conclusions – State of the Art Advancement

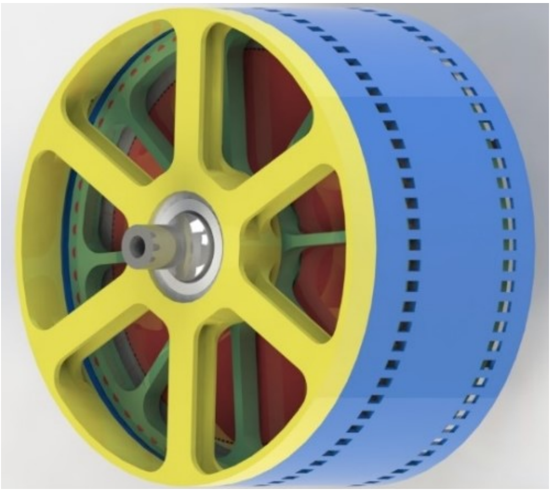
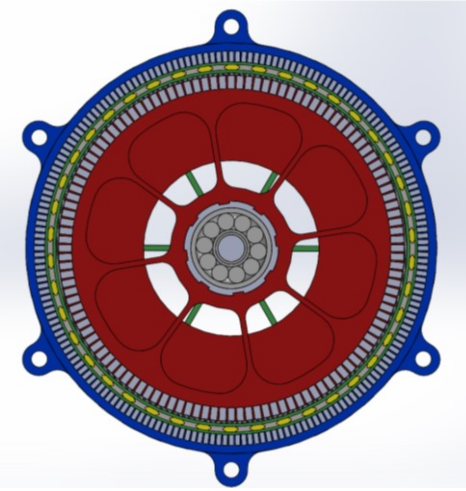
Technology		Specific torque, Nm/kg	Efficiency, %	
			Low output speed (100 rpm)	"High" output speed (900 rpm)
Target: Aerospace gearing		50 – 150	≥ 99.5	98.5 – 99.5
Baseline: SOA magnetic gears		≤ 17	≤ 98.7	87.5
NASA	Prototype 1 (PT-1)	20	–	–
	Prototype 2 (PT-2)	44	99.1	< 98
	Prototype 3 (PT-3)	47 (est.)	99.6	99.2
	Design 4 (PT-4)	49	99.6	99.0



Historical view of NASA's advancement

Future Work

- Can high efficiency be achieved without laminated magnets?
- Can a magnetic gear be passively air cooled?

Prototype	PT-4	X-57
		
Application	RVLT Quad Rotor	X-57 High lift Propellers
Laminations	Only 1.5 mm Sun Magnet Laminations	No Lamination, high magnet per pole count
Cooling Method	Centripetally Pumped Flow	Centripetally Pumped Flow
Gear Ratio	12.1 : 1	4.2 : 1
Specific Torque	49 Nm/kg	~30 Nm/kg
Efficiency	99% at operating speed	97.9% at operating speed

Acknowledgements

- NASA Revolutionary Vertical Lift Technology (RVLT) Project
- NASA Internal Research & Development Project
- Vivake Asnani – NASA Glenn Research Center

References

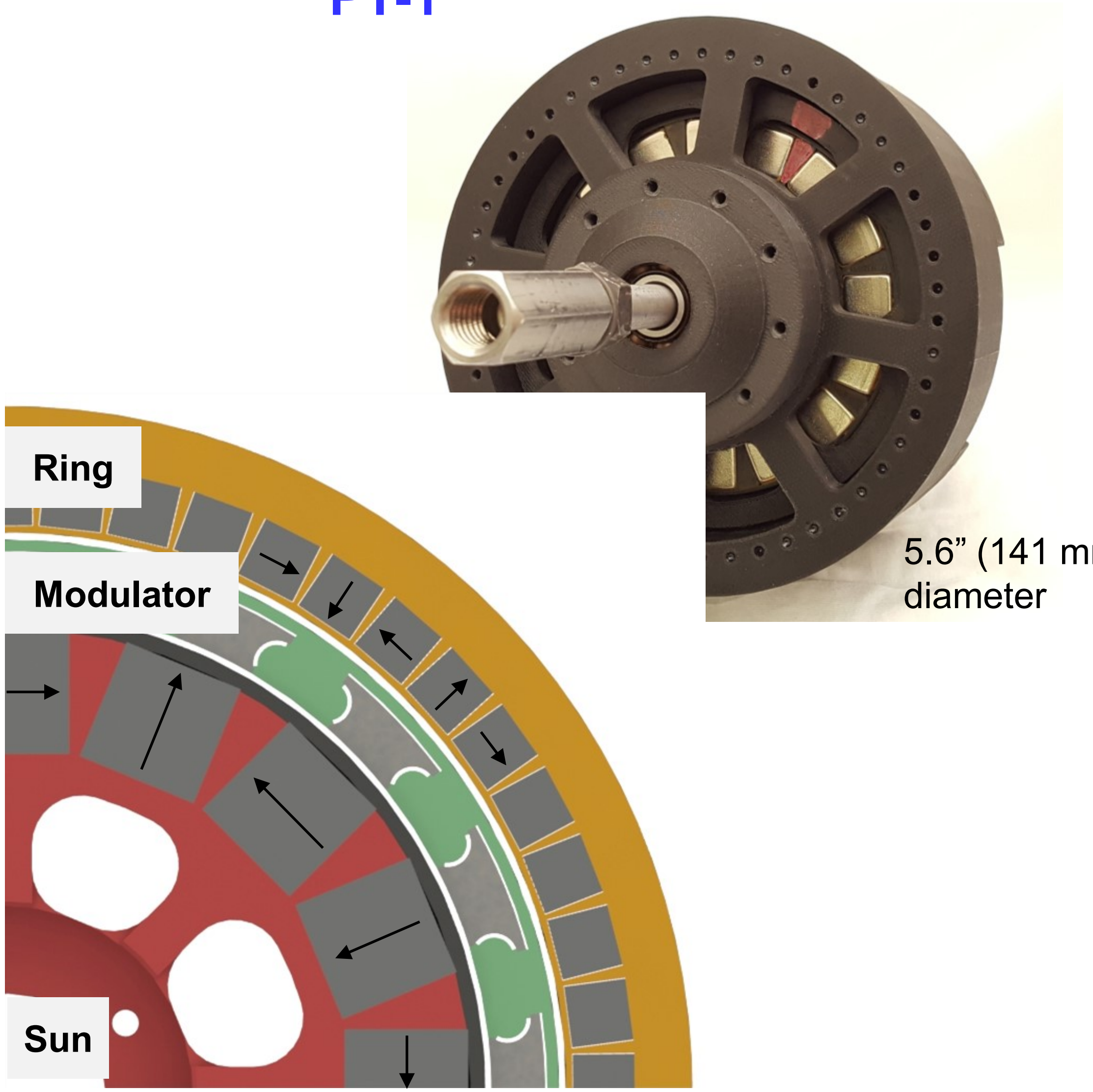
THANK YOU


Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
NASA
Glenn Research Center
FOR THE BENEFIT OF ALL

NASA

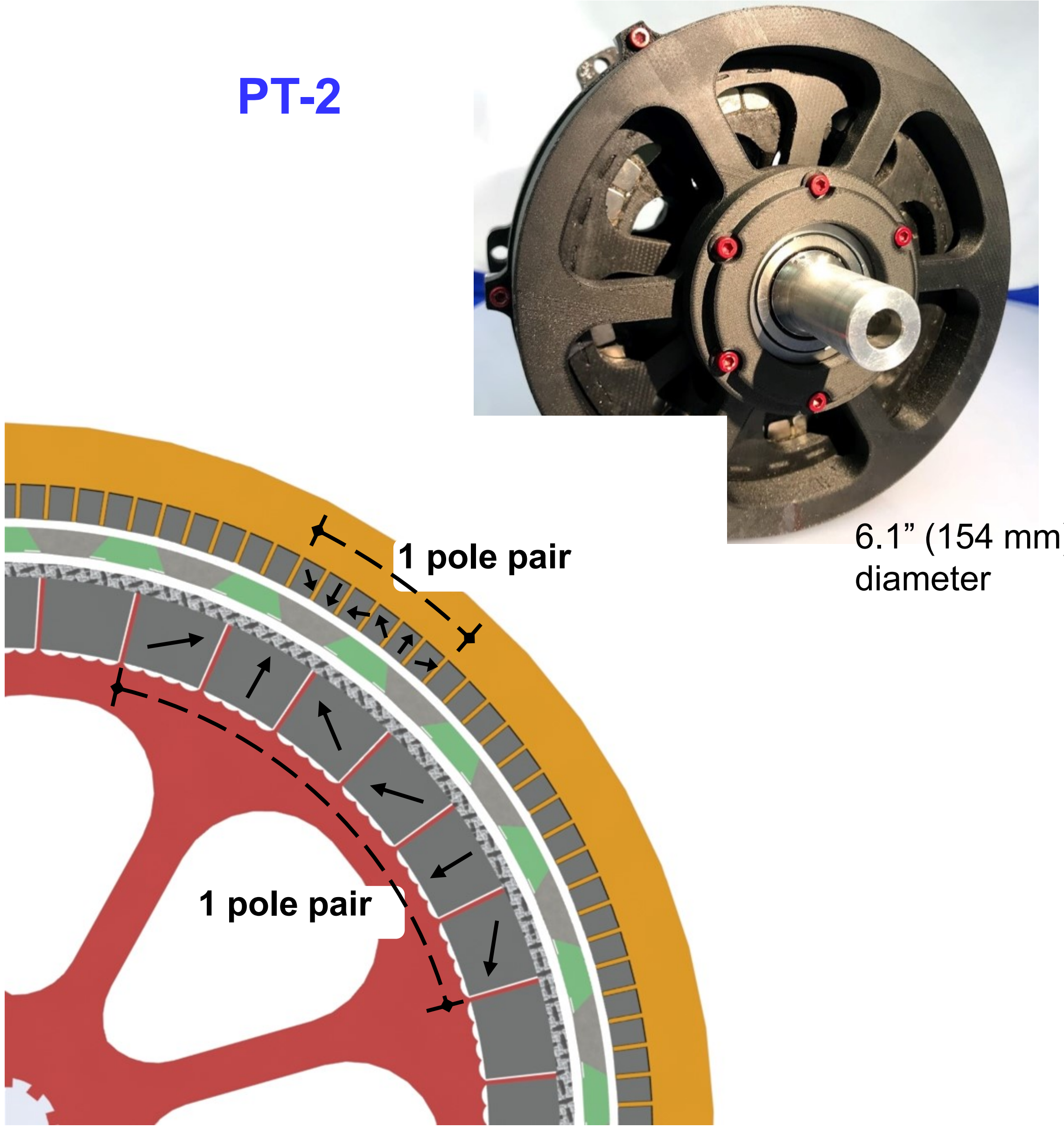
NASA's prior work

PT-1



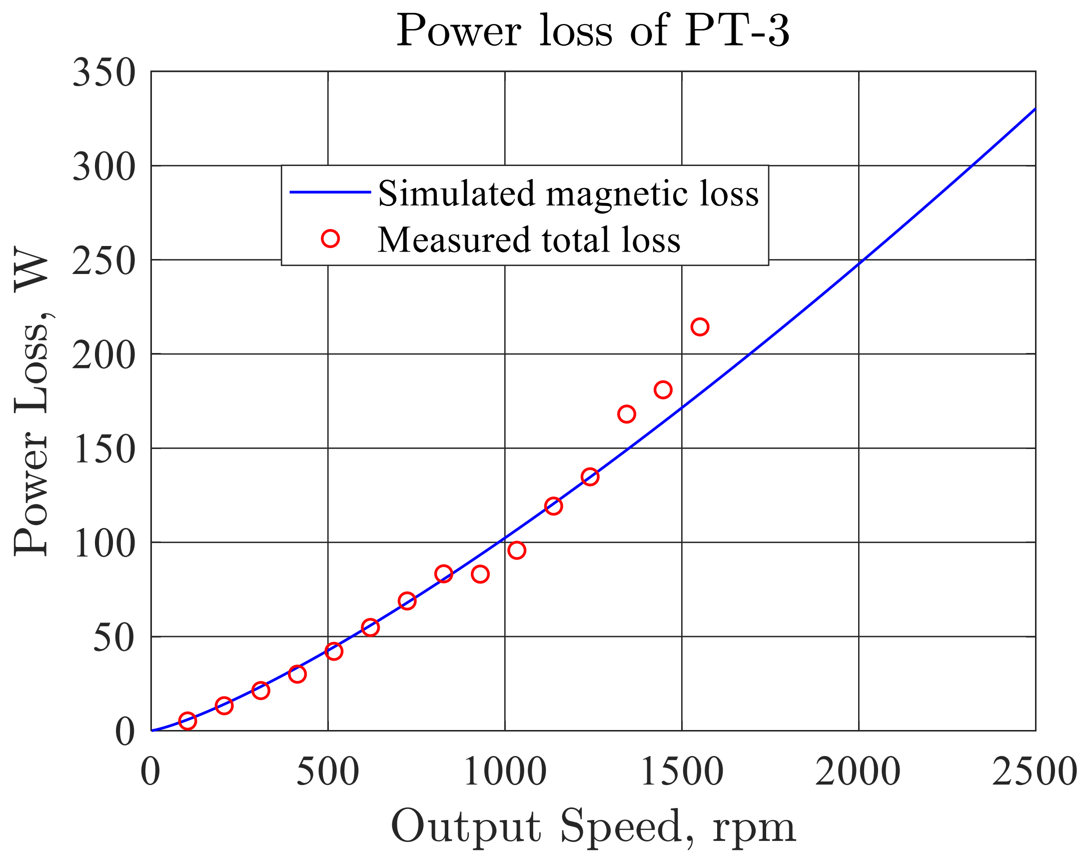
5.6" (141 mm) diameter

PT-2



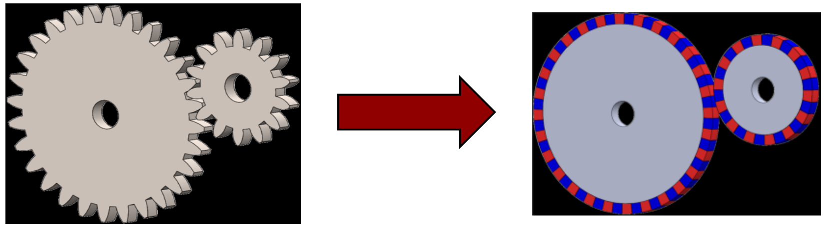
6.1" (154 mm) diameter

Measurements – PT-3 (High Efficiency)

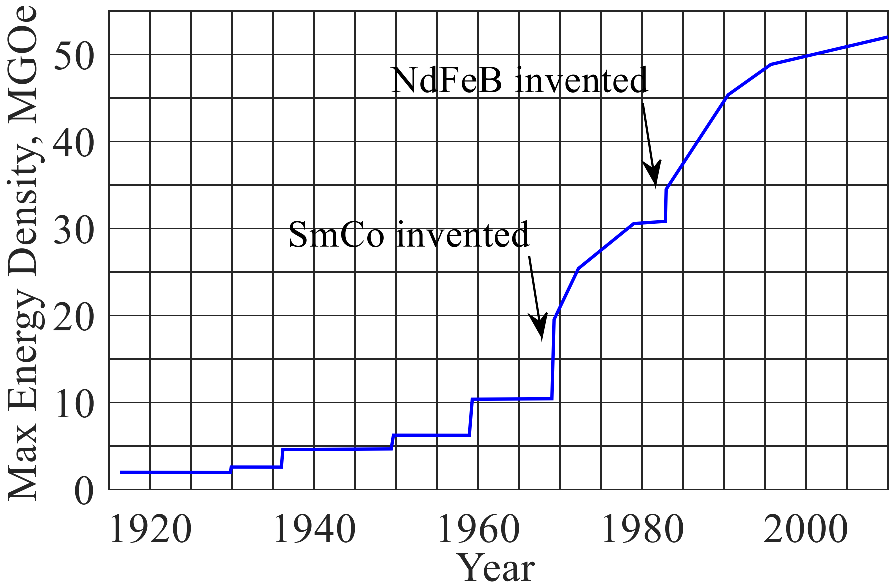


Magnetic gearing

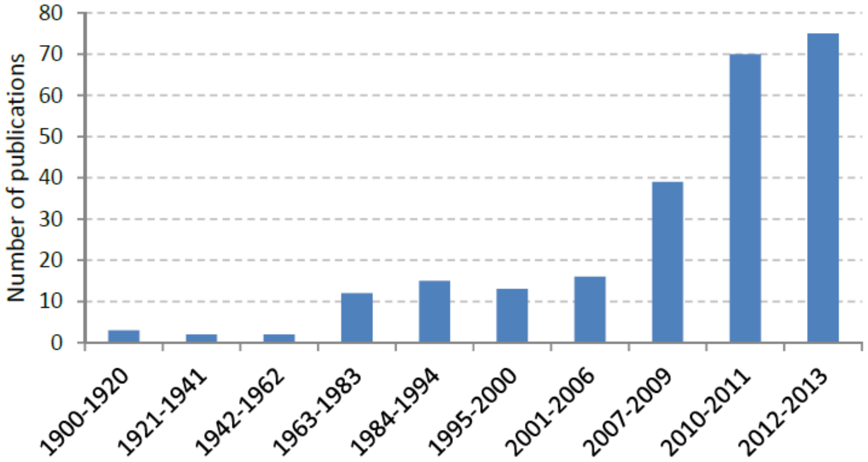
- Direct replacement concepts
  - Magnet energy density was low
  - Designs did not utilize all magnets



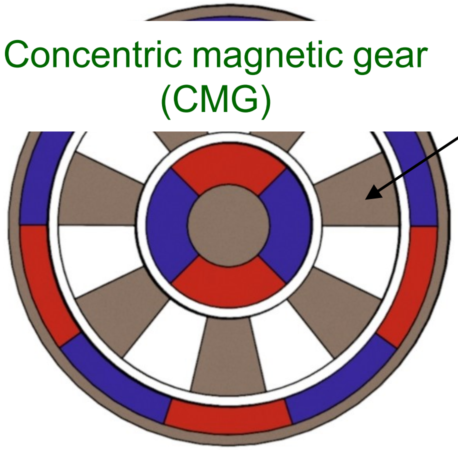
- Magnets have improved dramatically [Ref. 1]



- Material improvements led to increased R&D [Ref. 2]



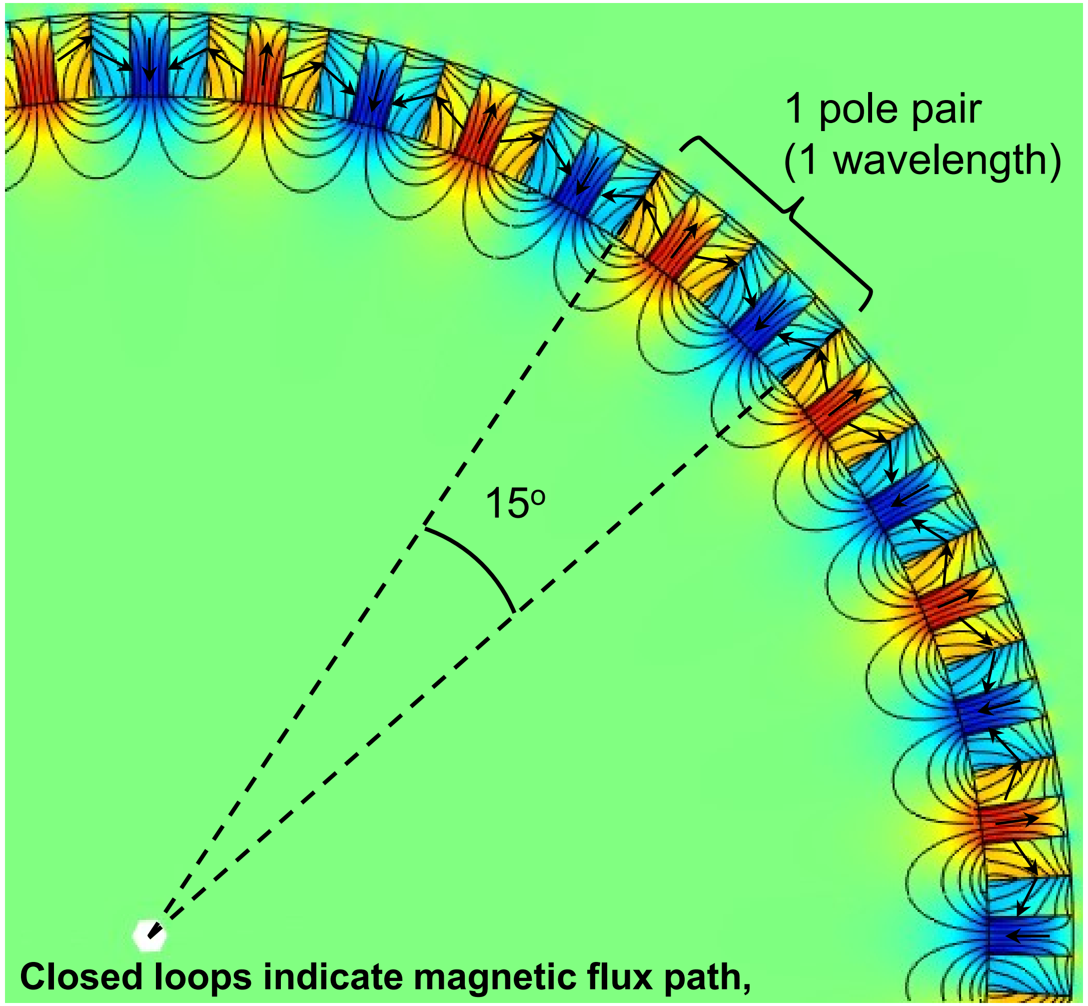
- In 2001, a practical design was created.



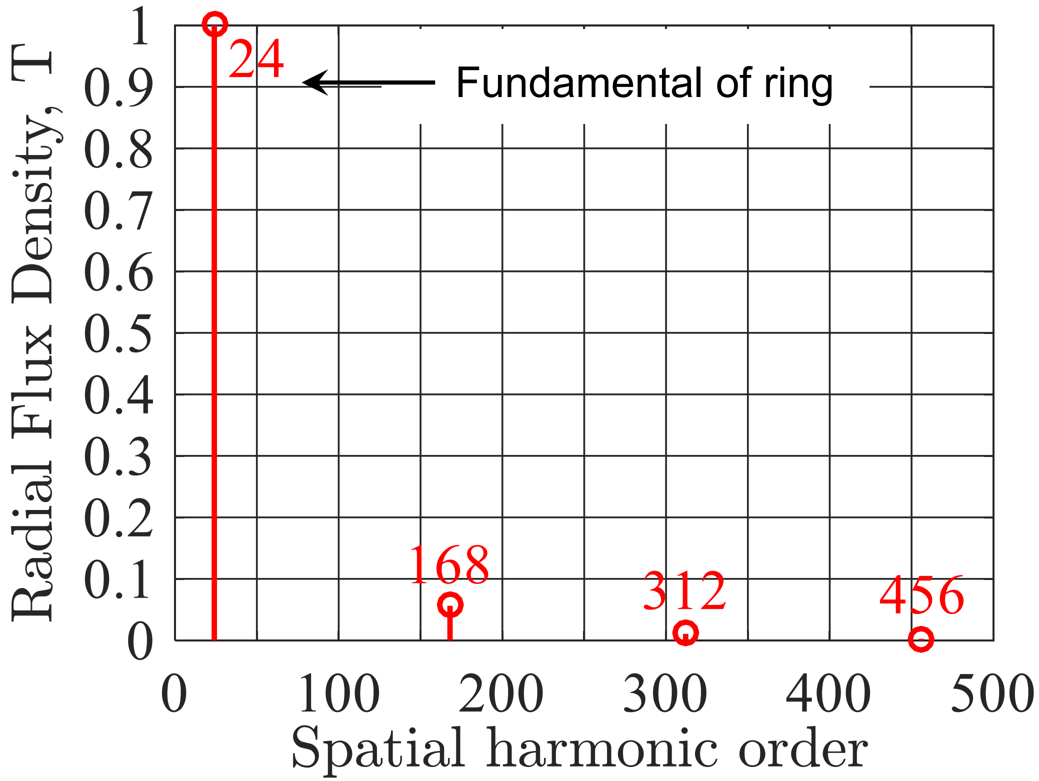
- Iron "*pole pieces*" are used to engage all magnets of the inner and outer rotors.
- Many prototypes developed for ground applications

Principles of Operation

- **Example:** 4:1 gear ratio, 24 pole pairs in ring (15° wavelength), 6 magnets per pair



Closed loops indicate magnetic flux path, color indicates radial component of flux



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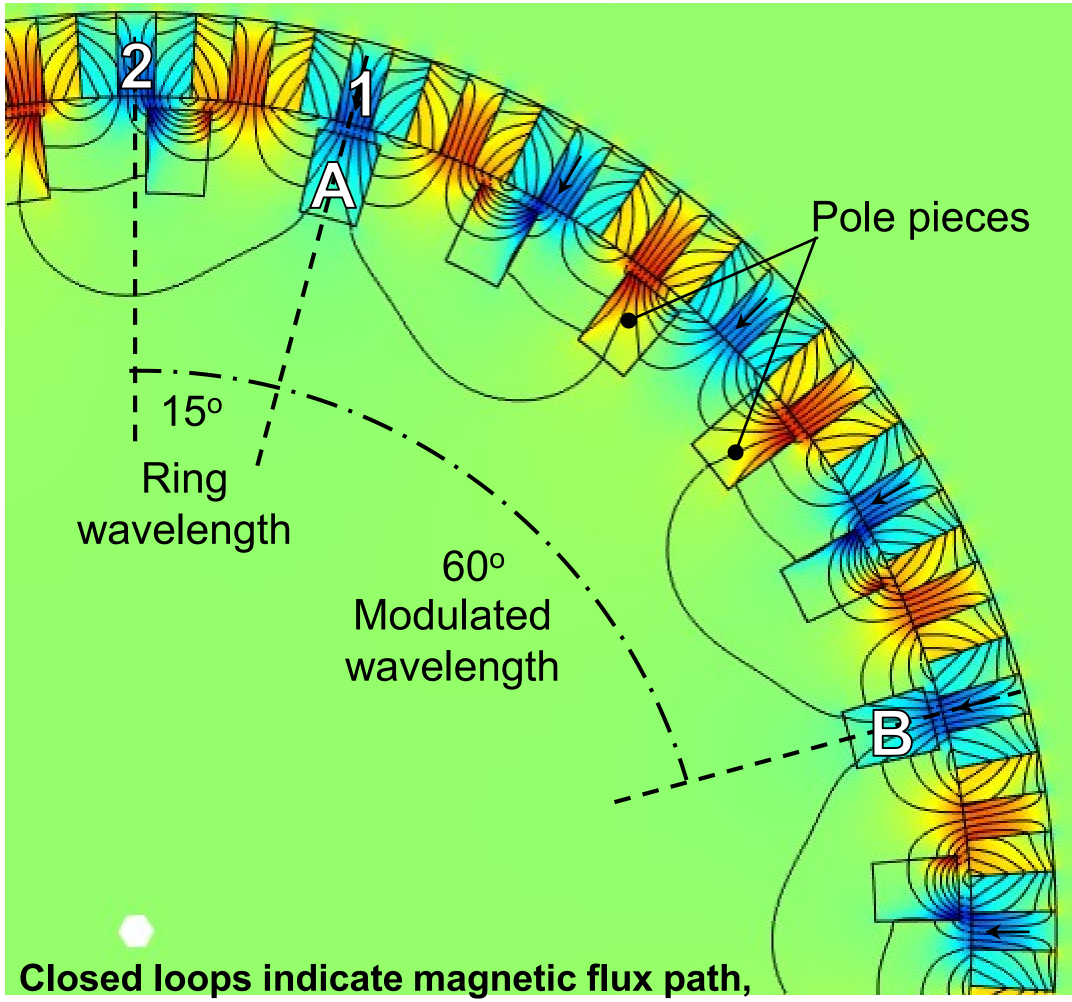

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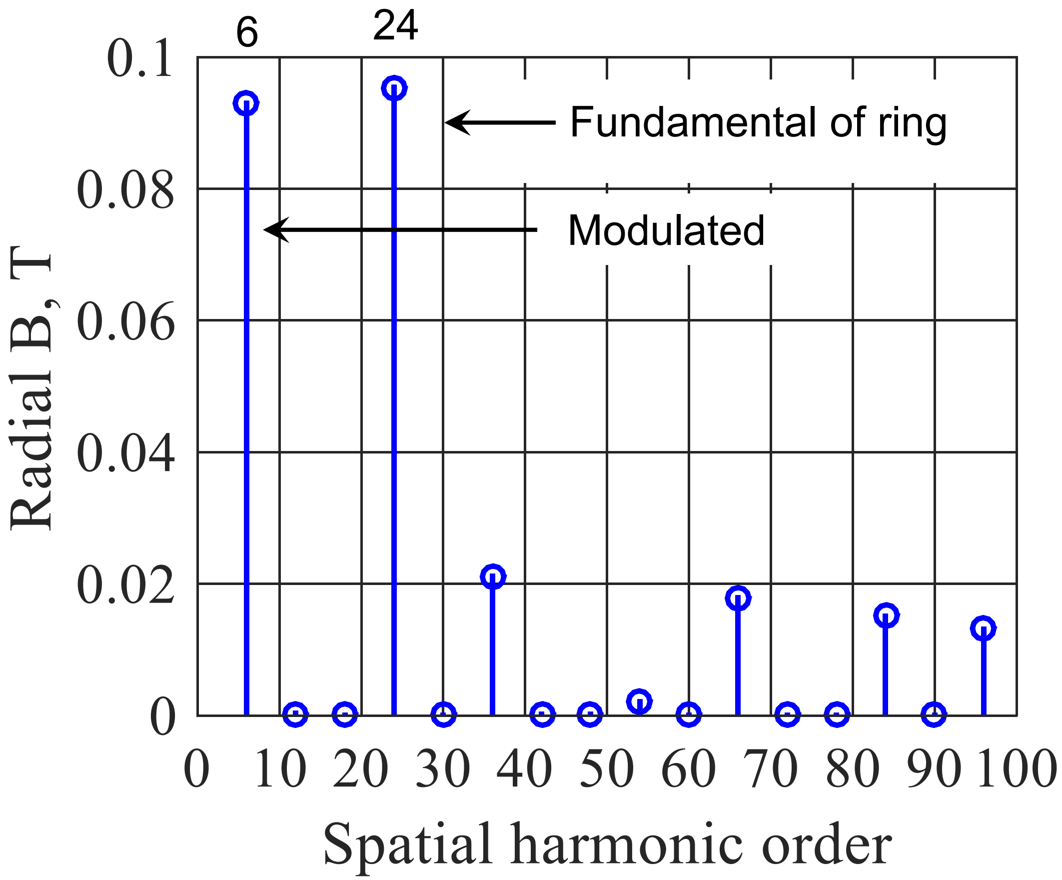
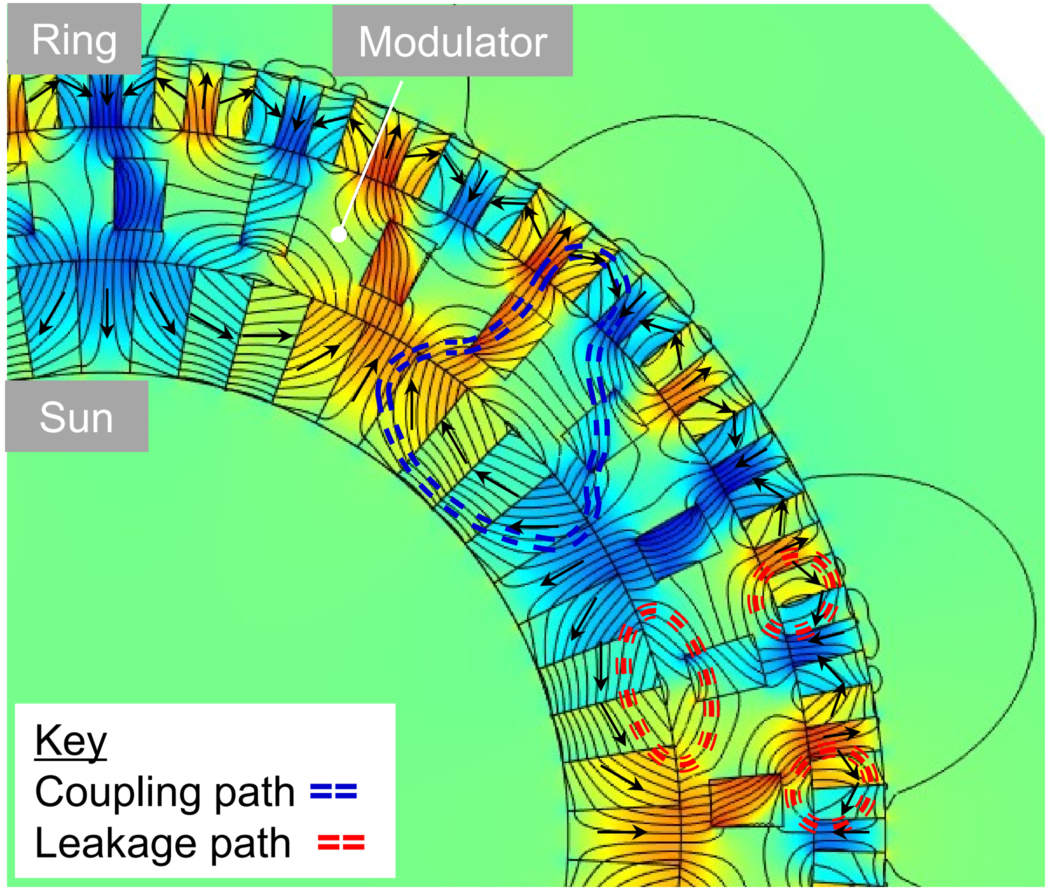
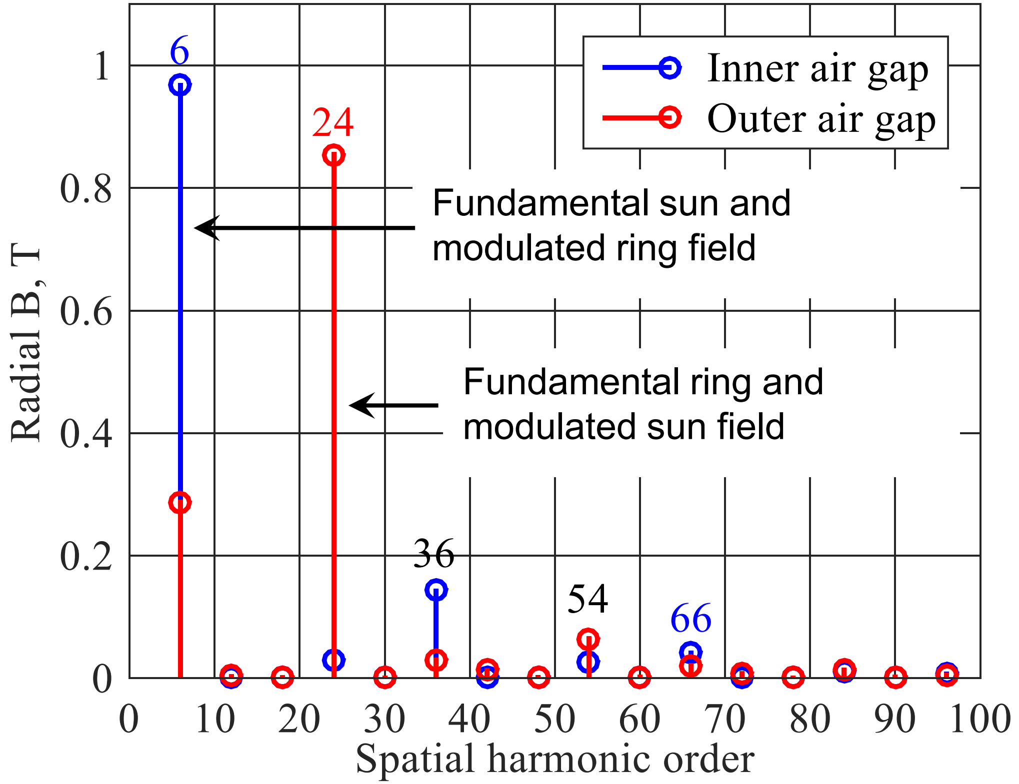
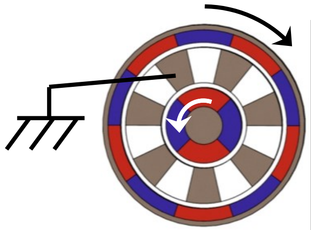


$$N_{\text{modulator}} = N_{\text{ring}} + N_{\text{sun}}$$

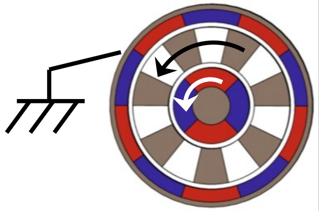
Principles of Operation







$$GR = \frac{N_{ring}}{N_{sun}}$$

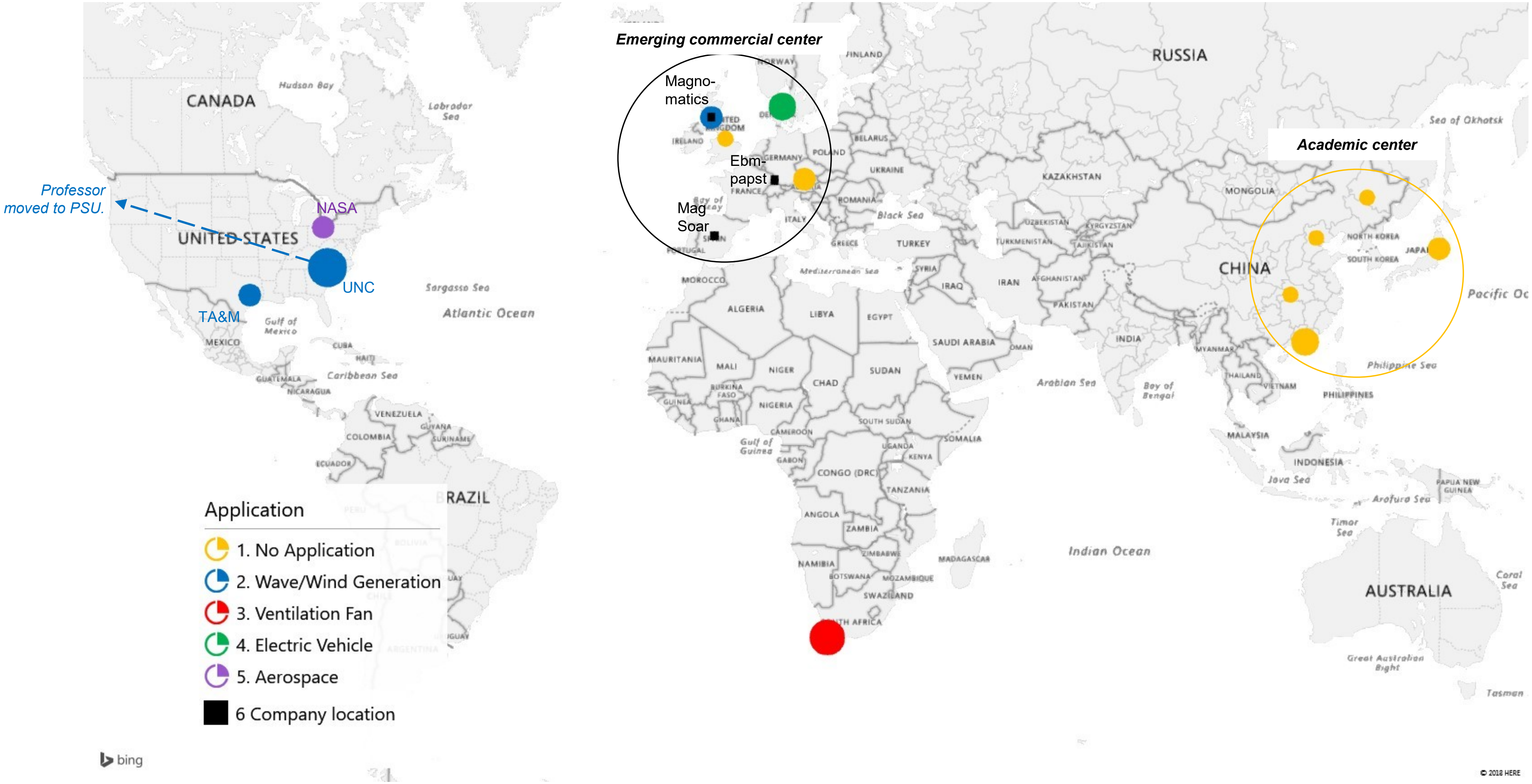


$$GR = 1 + \frac{N_{ring}}{N_{sun}}$$

- Key design variables
  - # of magnetic pole pairs ("teeth")
  - # magnets
  - Radial thickness of components & air gaps

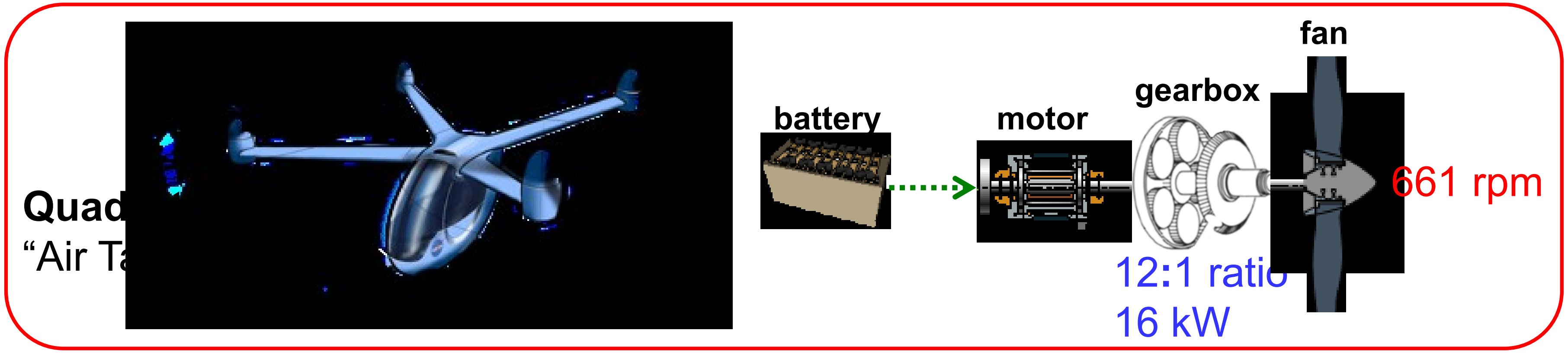
Prototypes by location

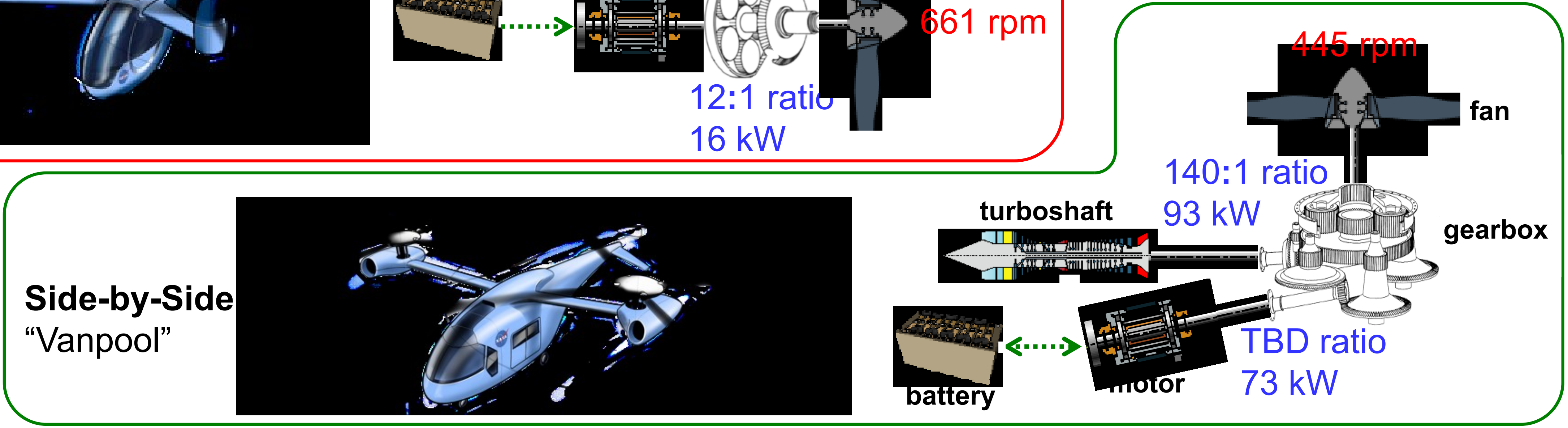
Marker size = Number of prototypes built

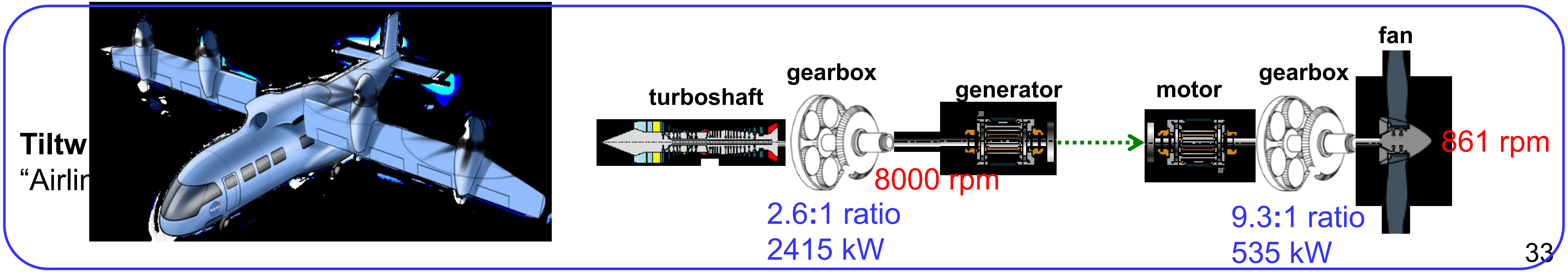


Future Work

- Target NASA's eVTOL reference aircraft [2]



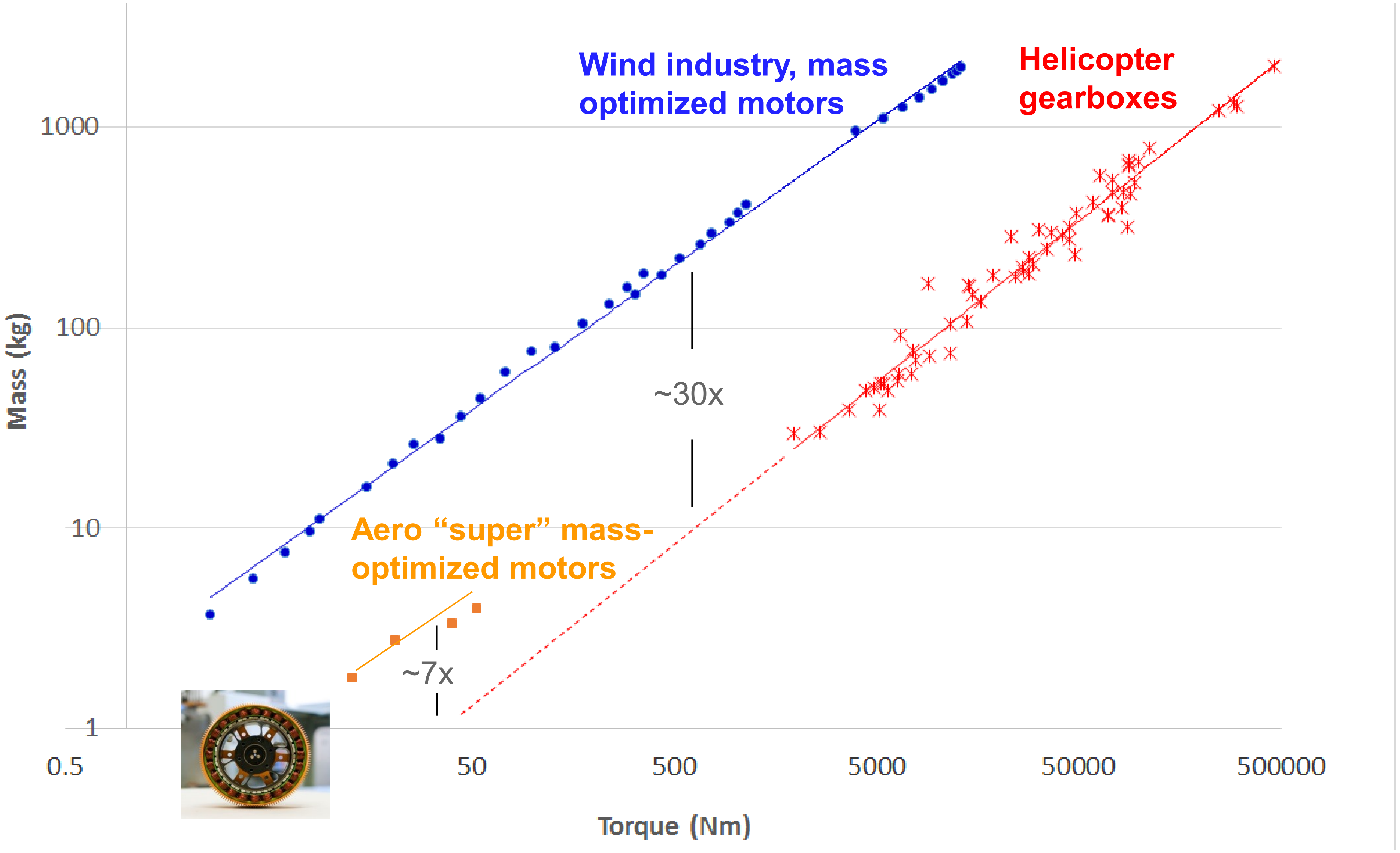




Future Work

	Quad	Side-by-side	Tiltwing
Propulsion configuration:	Electric 4 rotors 4 EM	Par. Hybrid 2 rotors 2 TS, 1 EM	Turbo elec. 4 rotors 4 EM
Gear stage	EM-rotor	TS-rotor	EM-rotor
Ratio	12.1	Up to 140	9.3
Load (kW)	15.9	92.6	535
(rpm)	661	445	861
(Nm)	229	1987	5928
Gear stage	N/A	EM-rotor GB	Genset
Ratio		TBD	2.6
Load (kW)		73.2	2415
(rpm)		445	8000
(Nm)		1,569	2,883

Magnetically-Geared Motors



Magnetically-Geared Motors