Design of a Magnetic Gear for NASA's Vertical Lift Quadrotor Reference Vehicle

Thomas Tallerico
Zachary Cameron
Justin Scheidler

NASA Glenn Research Center
Materials and Structures Division
Rotating and Drive Systems Branch

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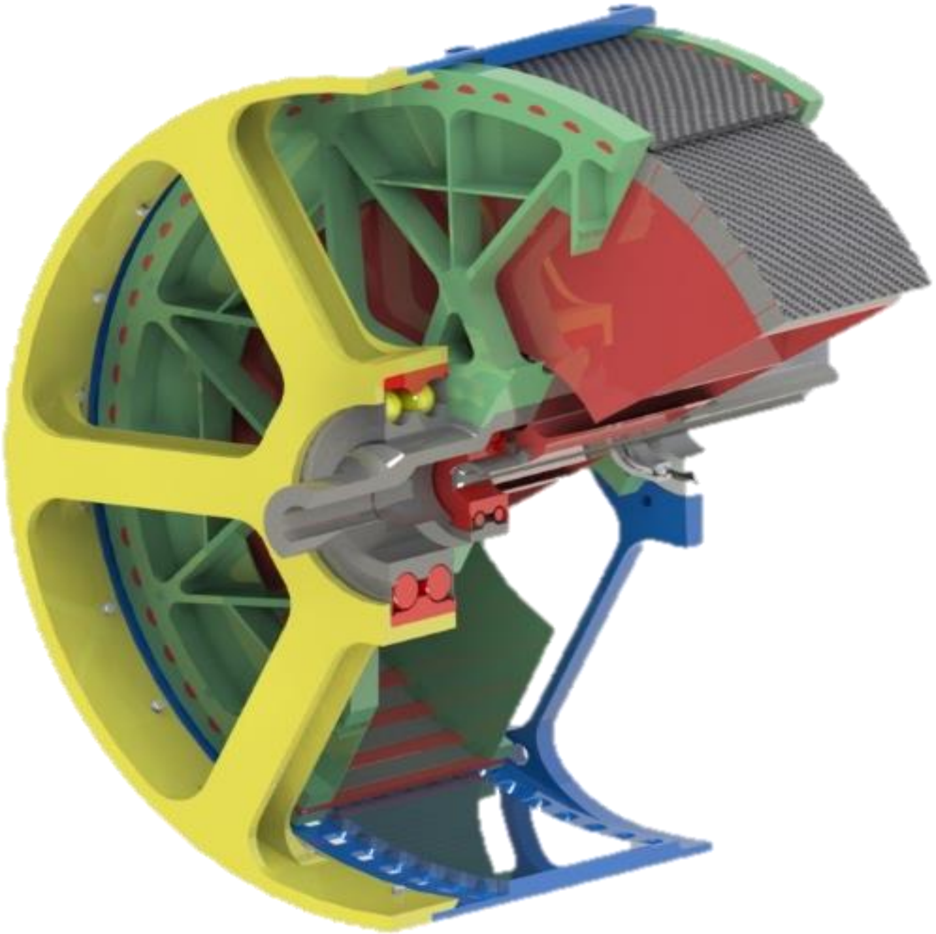
Outline

- Background and Motivation
- Concentric Magnetic Gears
- Enabling Design Principles
- Preliminary Design
  - Design Code
- Final Design
  - Efficiency
  - Thermal
  - Structural
- Conclusions

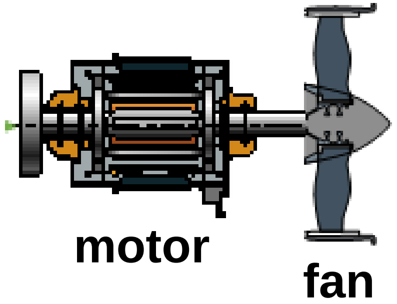


PT-4

Background & Motivation

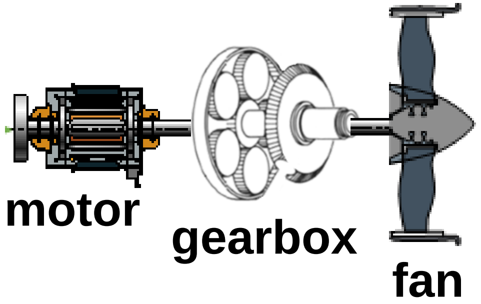
- NASA set goals for aircraft efficiency, emissions, reliability, and noise
- Parallel large & small aircraft development
  - Economic benefit of alternative propulsion
- Electrified aircraft propulsion is a key enabler
- Most concepts use direct drive
- Geared drives are almost always mass optimal

Direct drive



+ Simpler
− Non-optimal motor and/or fan

Geared drive



+ Optimized motor & fan
+ Enables cross shafting
− More complex
− Potentially less reliable

Background & Motivation

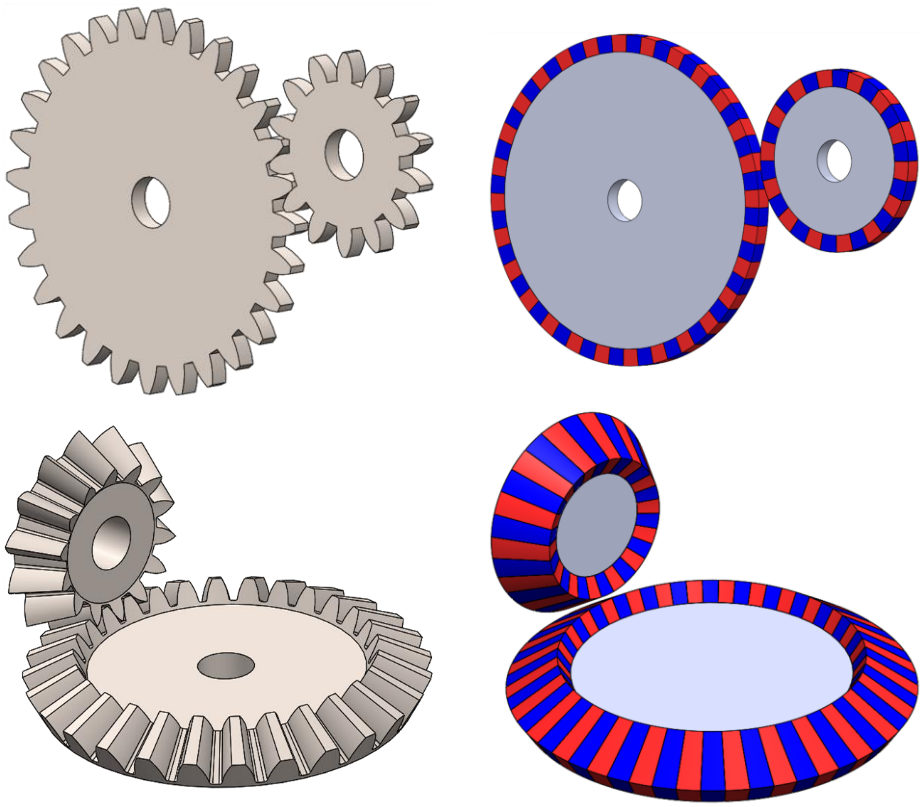
Mechanical gearing

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

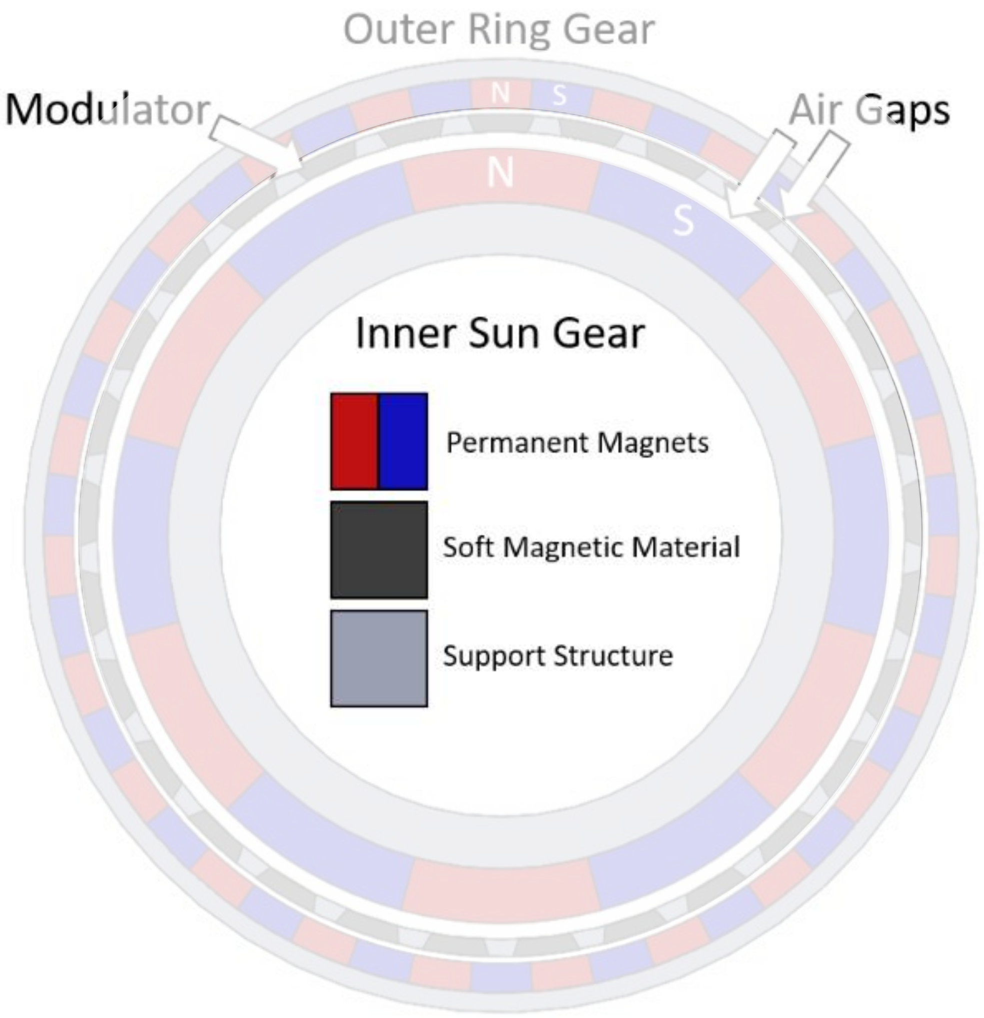
Pros

- \+ 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

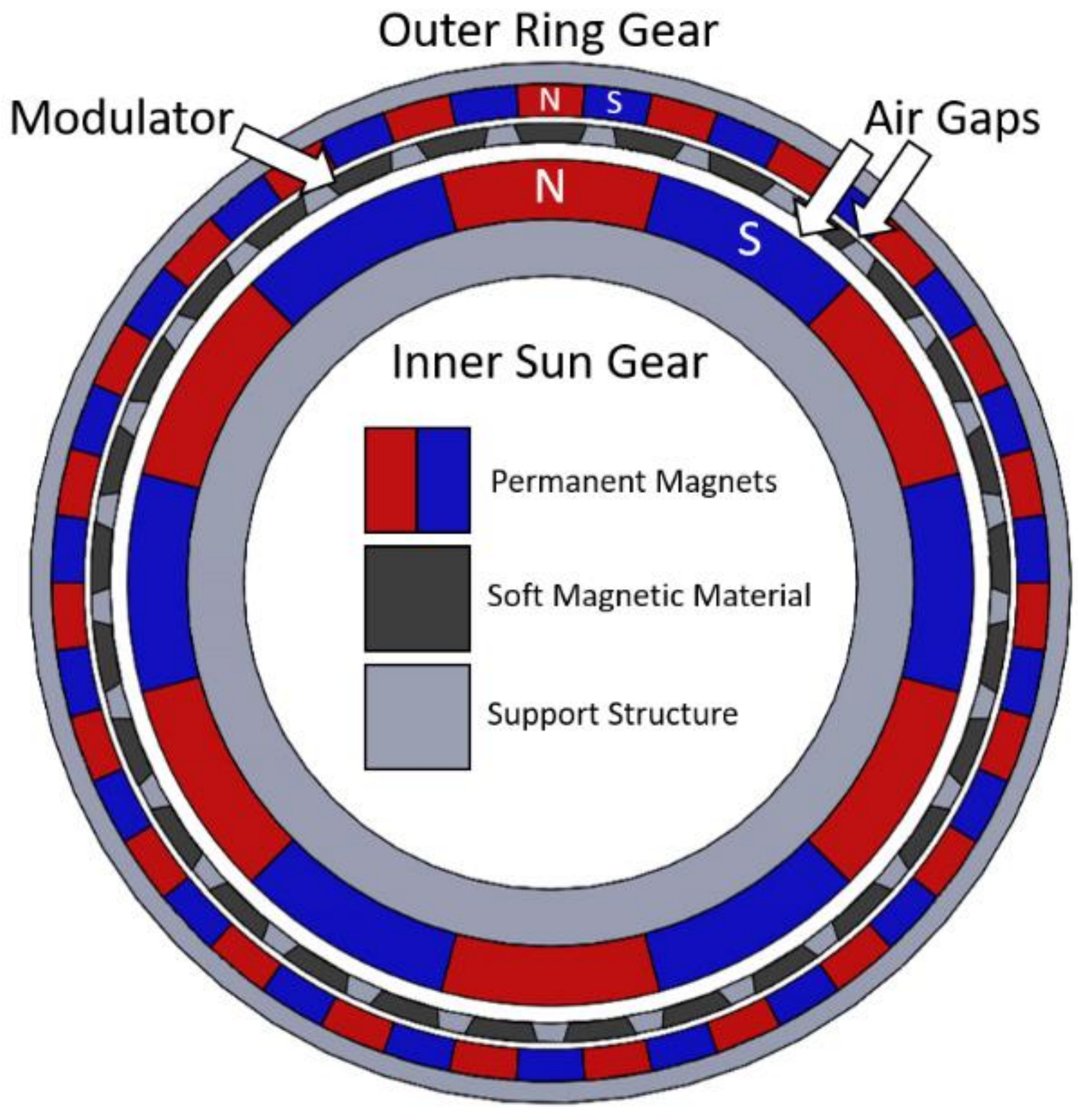
Concentric Magnetic Gears



- Rule of thumb:

  Magnetic fields with matching spatial harmonic order can couple to transmit torque
- Ring and Sun gear have different pole counts
  - Produce different spatial harmonic
- Modulator “modulates” the flux of each rotor so that that have matching spatial harmonic order in the airgaps

Concentric Magnetic Gears



$$\cos(\theta) * \cos(\alpha) = \frac{1}{2}(\cos(\theta + \alpha) + \cos(\theta - \alpha))$$

$$B_{rs} = F * \cos(\boldsymbol{PS} * (\theta + \alpha))$$

Number of Sun Gear Pole Pairs

$$u = u_{avg} + u_m * \cos(\boldsymbol{Q} * (\theta + \beta))$$

Number of Pole Pieces

$$B_{rs} * u_m = u_{avg} * F * \cos(PS * (\theta + \alpha)) + \frac{F * u}{2}\cos\left((\boldsymbol{Q} + \boldsymbol{PS})\theta + PS * \alpha + Q * \beta\right) + \frac{F * u}{2}\cos\left((\boldsymbol{Q} - \boldsymbol{PS})\theta - PS * \alpha + Q * \beta\right))$$

$$\boldsymbol{PR = Q \pm PS} \quad or \quad \boldsymbol{Q = PR \pm PS}$$

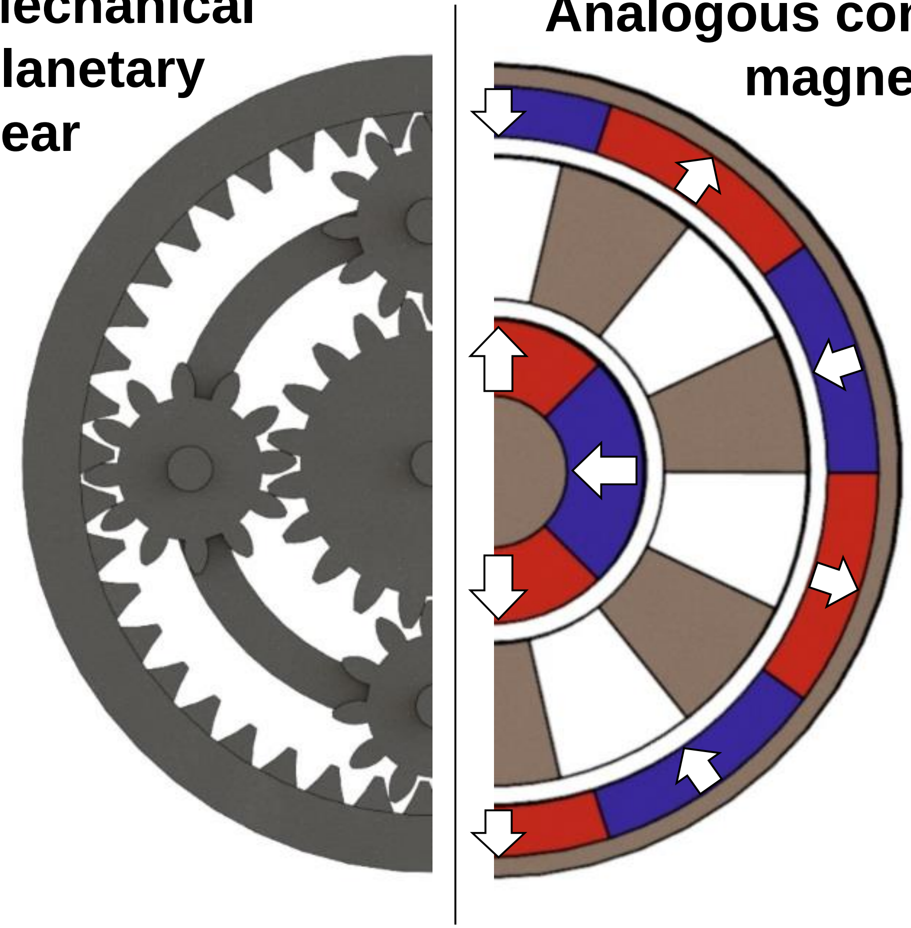
Number of Ring Gear Pole Pairs

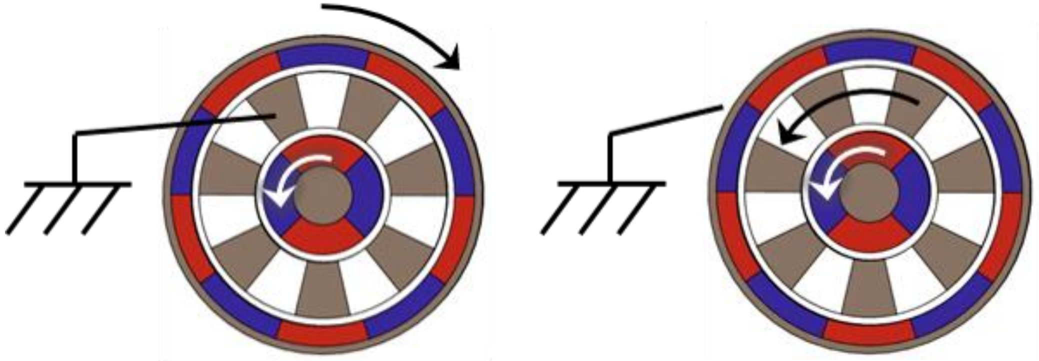
Concentric Magnetic Gears

Gear Ratio

Mechanical planetary gear

Analogous concentric magnetic gear





Output	Q Selection	Gear Ratio
Ring Gear	PR-PS	$\frac{PR}{PS}$
	PR+PS	
Modulator	PR-PS	$\frac{Q}{PS} = \frac{PR}{PS} - 1$
	PR+PS	$\boldsymbol{\frac{Q}{PS} = \frac{PR}{PS} + 1}$

Background & Motivation

Phase I
2017

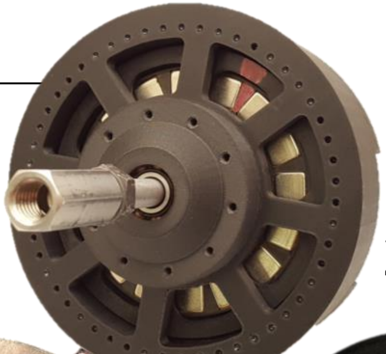
- How do they work? (PT-1)
- Can they be lightweight? (PT-2)

Phase II
2018-2019

- Can they be efficient? (PT-3)
- Can they be efficient and light weight? (PT-4)

Phase III
2019-2020

- How to pair them with motors?
- Can they be reliable?

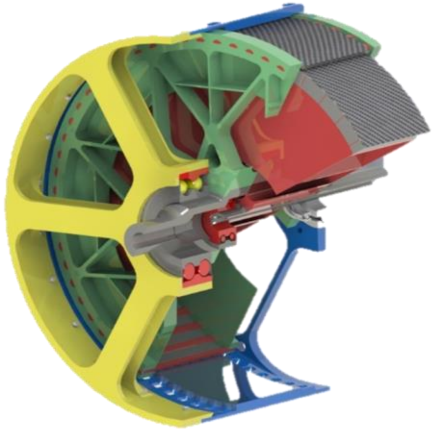


PT-1
20 Nm/kg

PT-2
45 Nm/kg

PT-3 >98%
Efficient

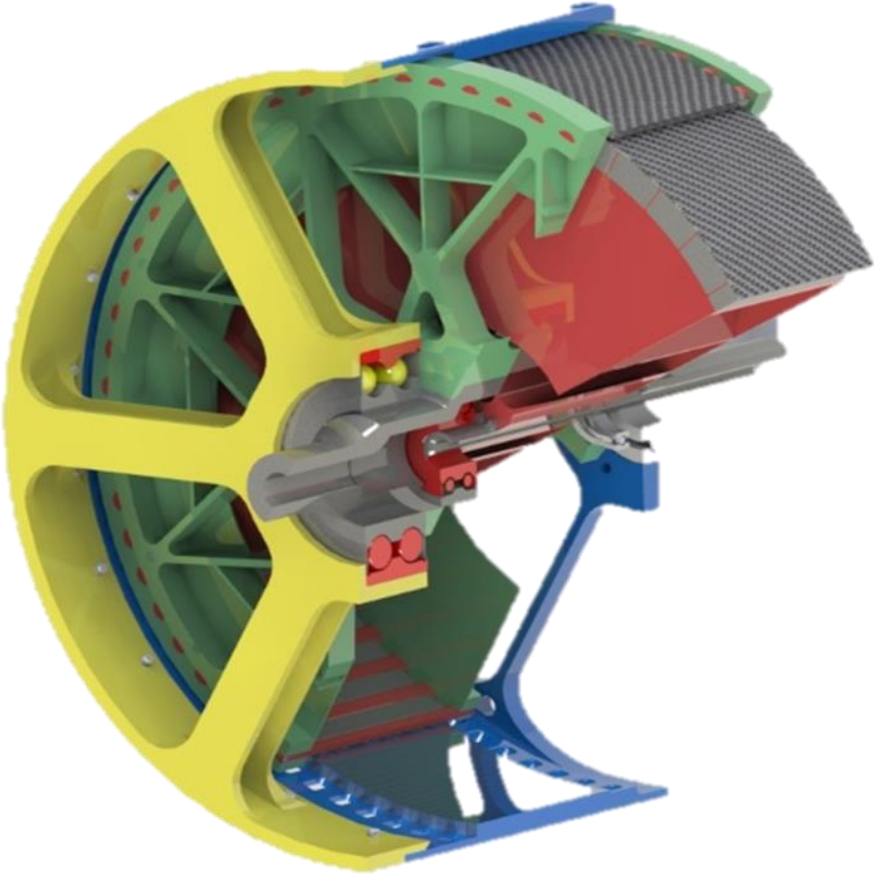
PT-4



Enabling Design Principles

Lightweight and Efficient Magnetic Gears

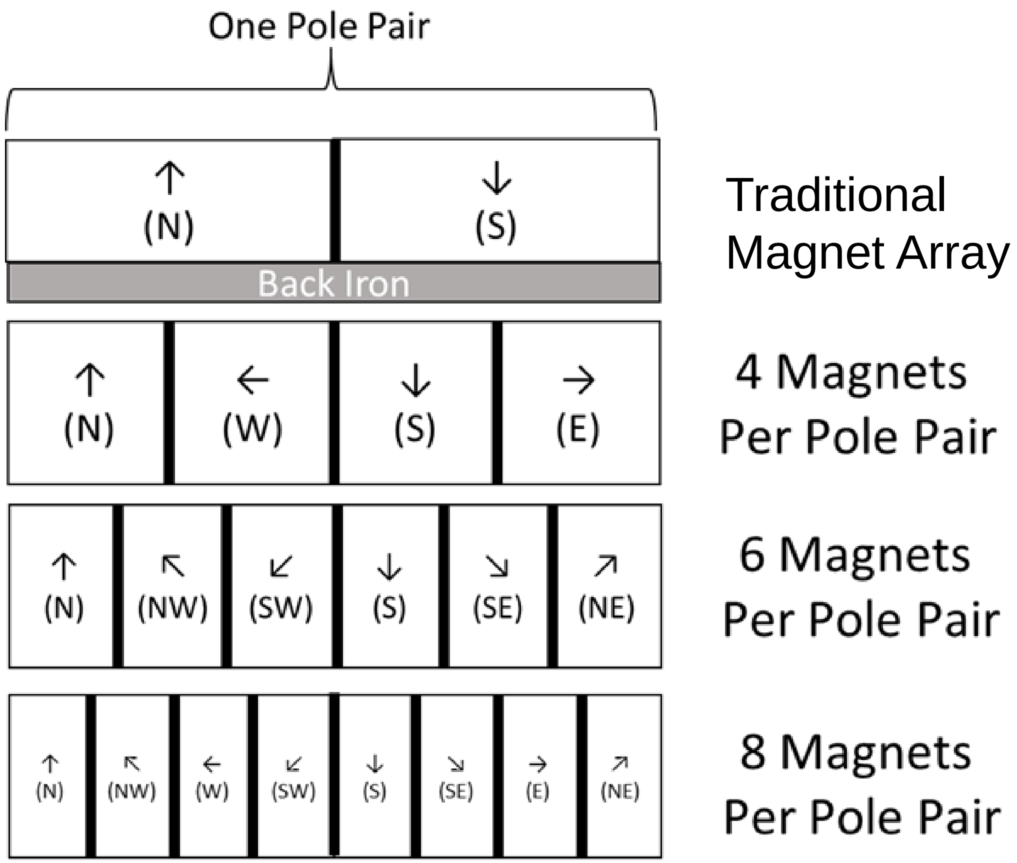
1. Halbach Arrays
2. Magnet Laminations
3. Minimize Modulator Thickness
4. Minimize Airgaps



Enabling Design Principles

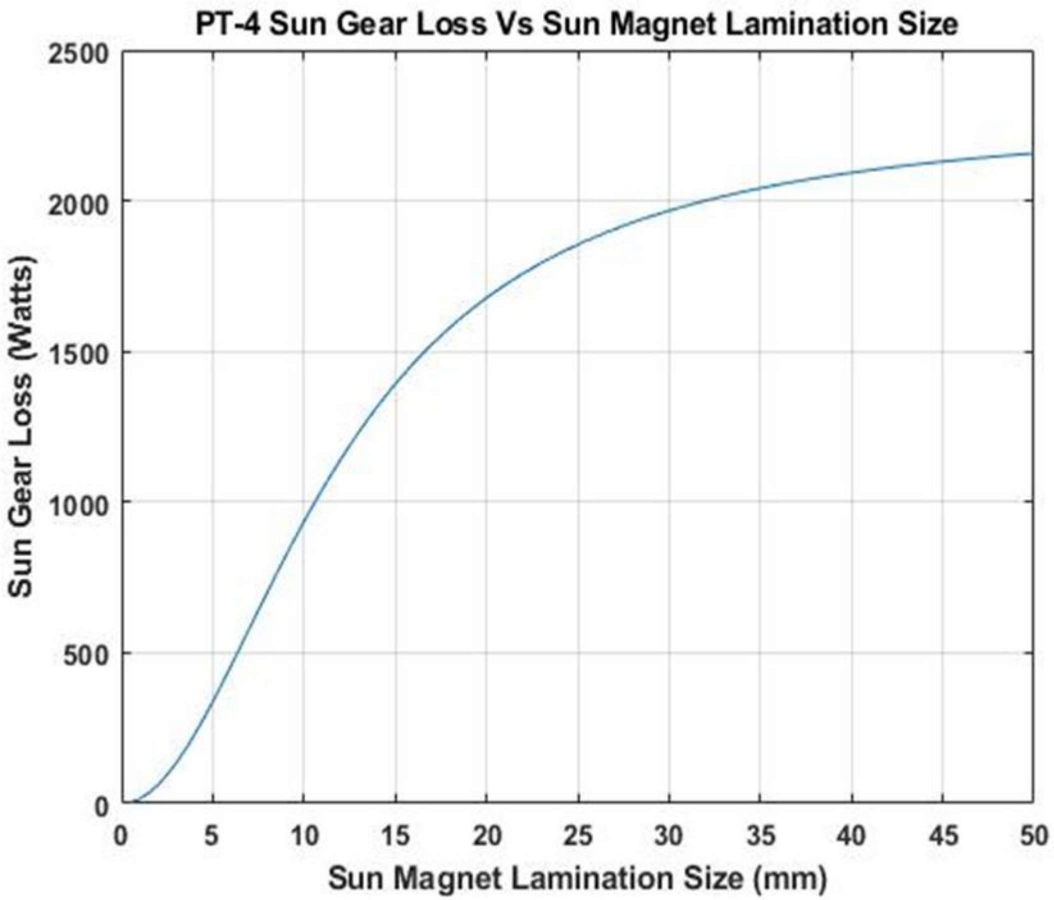
Halbach Arrays

- Eliminate need for back iron
- Increase magnet per pole count:
  - Improves Array specific flux
  - Suppresses Eddy Current Loss
  - Magnet fill percentage loss



Magnet Laminations

- Suppress magnet eddy current loss
- Can enable >99% efficiency
- Magnet Fill percentage
- To enable high efficiency
  - High magnets per pole
  - Small magnet laminations



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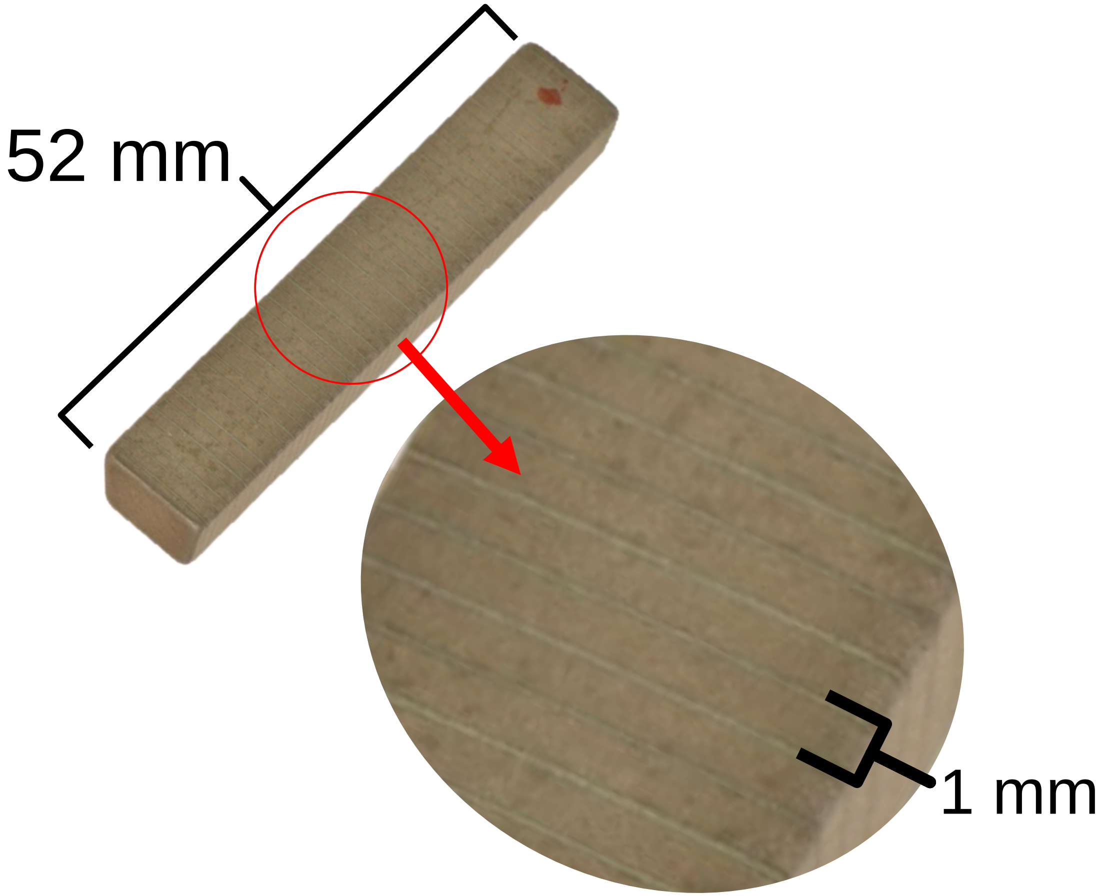
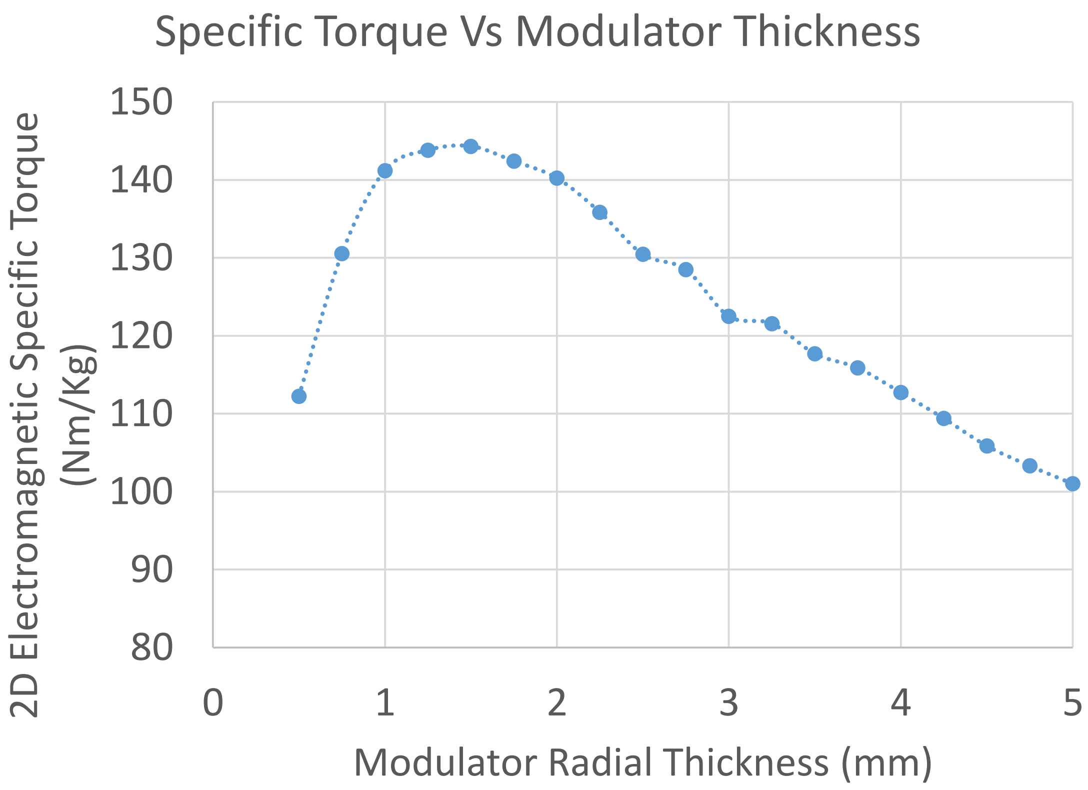


Enabling Design Principles

Minimize Modulator Thickness

- Electromagnetically:
  - There is an optimum Modulator Thickness
  - Typically ~1.5 mm
- Mechanical structure limits thickness
  - Sandwiched between airgaps
- PT-2: 2.6 mm thickness
- PT-4: 2 mm thickness



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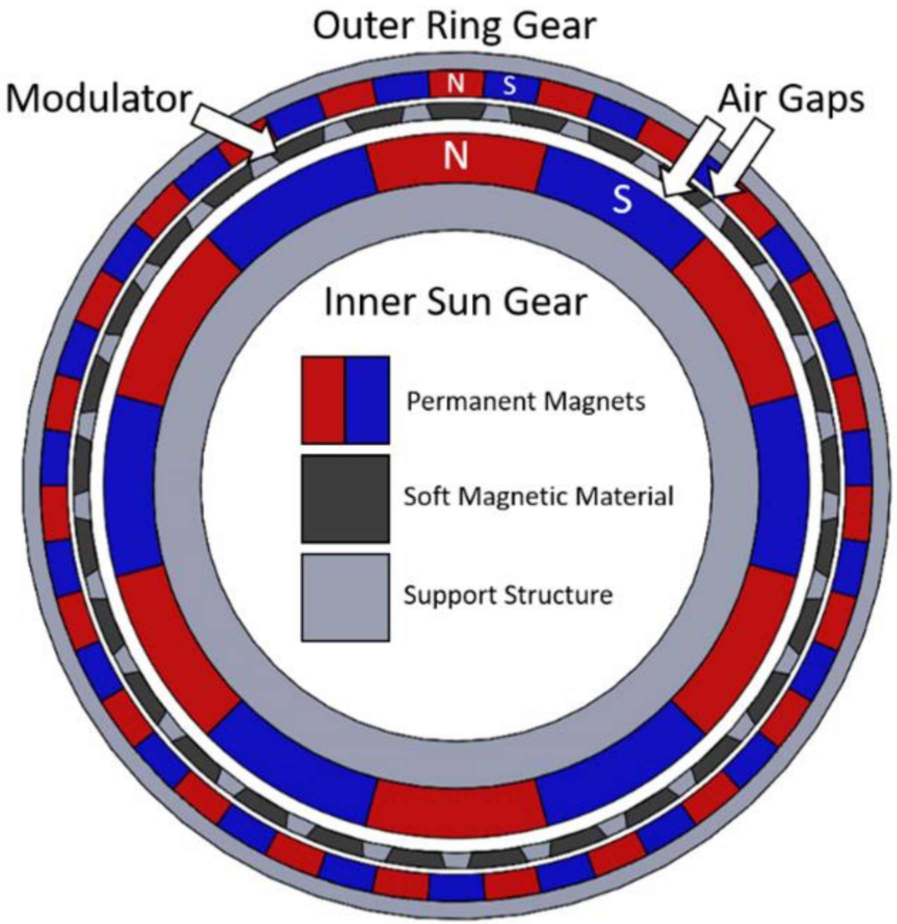
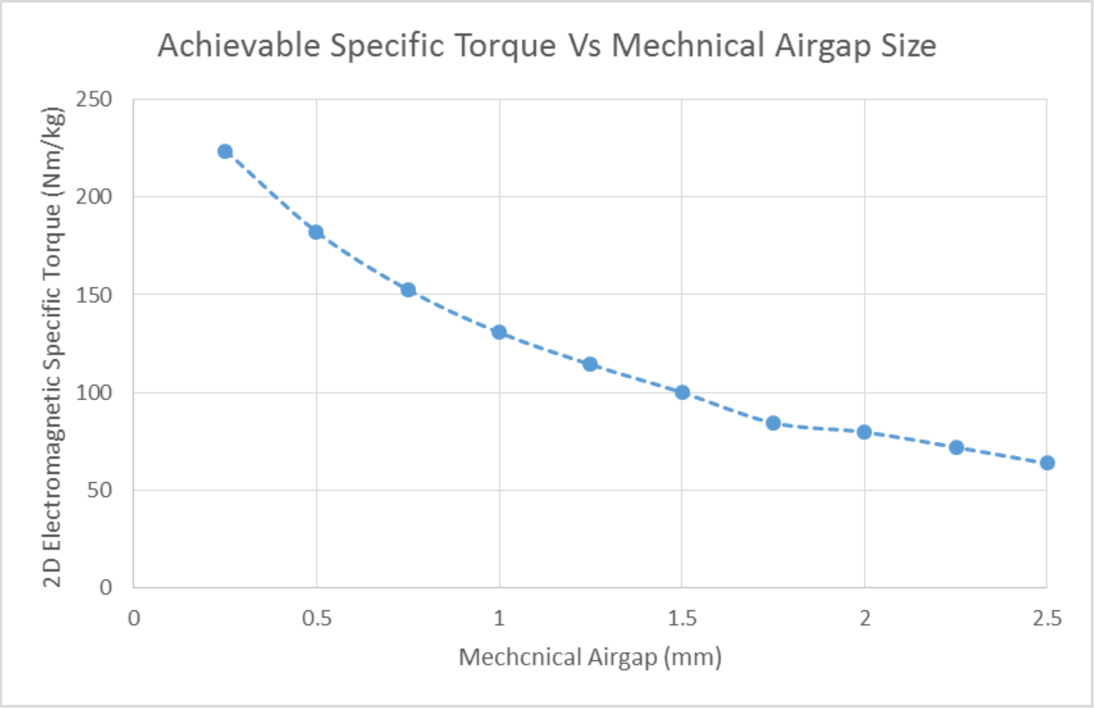


Air Gap Thickness

- Potential to double magnetic gear specific torque
- Smaller airgaps reduces optimal modulator thickness
- Development area to improve magnetic gears:
  - Modulator structure that enables smaller airgaps and smaller modulators



Preliminary Design

PT – 4 Design

- Quadrotor Referance Vehicle
  - NASA’s RVLT Project
  - Single Passenger Air Taxi
  - 4 Rotors
    - 680 RPM (low noise)
    - 16.1 kilowatts
    - ~8000 RPM motor

NASA’s Vertical Lift Quadrotor Referance Vehicle

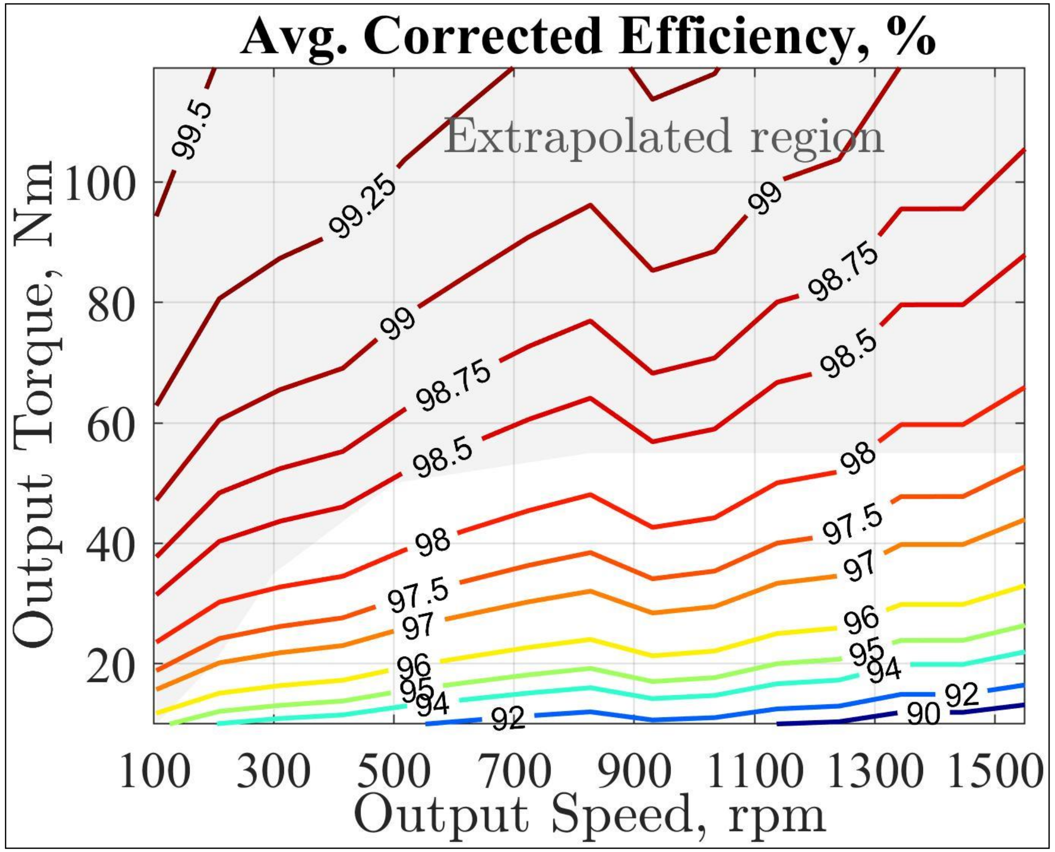
Preliminary Design

	Requirement	Value
Performance Targets	**Target Total Gear Mass**	4.5 kg
	Target Gear Efficiency	>97%
Nominal Operating Point	**Gear Ratio**	~12:1
	Output Torque	226 Nm
	Output Speed	680 RPM
Quadrotor Load Estimates	**Required Bearing Life (99% Reliability)**	10,000 Hours
	Thrust Load	1400 N
	Propeller Mass	10.5 Kg
	Propeller Hub Moment (Worst Case)	1203 Nm
	Propeller Hub Moment (Nominal Case)	604 Nm
	Nominal Propeller Hub Drag	100 N
	Max Turning Acceleration	2 G's
	Nominal Yaw Rate	0.25 rad/s
	Nominal Pitch Rate	0.25 rad/s

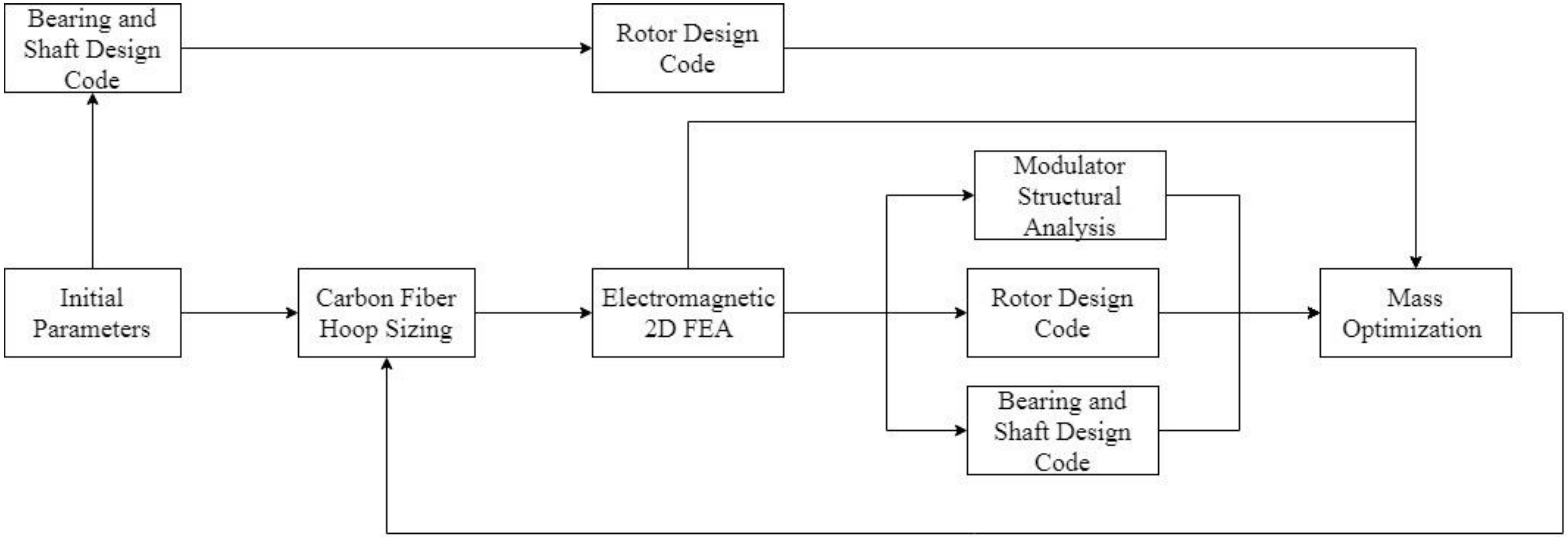
Preliminary Design

- Preliminary Studies
  - > 97% possible with magnet laminations
    - Validated by PT-3 testing
  - Thermal closed
  - Mass was the question mark
- Electromagnetic and Structural Design Code Developed
  1. Total Gear Mass Effects
  2. Modulator Structure
  3. Sun magnet retaining hoop

Results of PT-3 Dynamic Testing

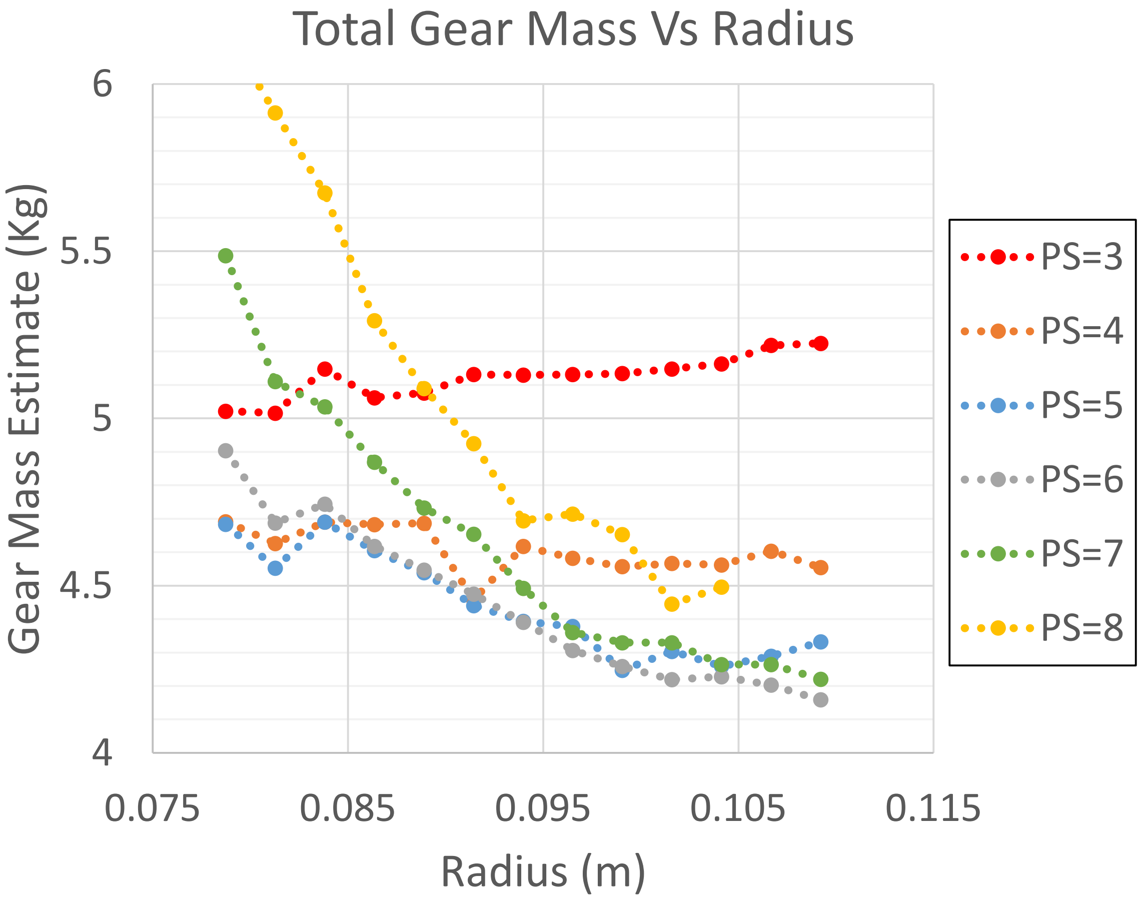


Design Code Architecture



Design Code Results

- Assumed 80C Operating Temp
- N52M Neodymium Magnets
  - Highest Grade with 80C operating T
- $Fe_{49}Co_{49}V_2$ Modulator
- Parametric sweeps of radius and PS
- Designs under 4.5 Kg
  - 5-7 Sun Gear Pole Pairs (PS)
  - >.09 m radius



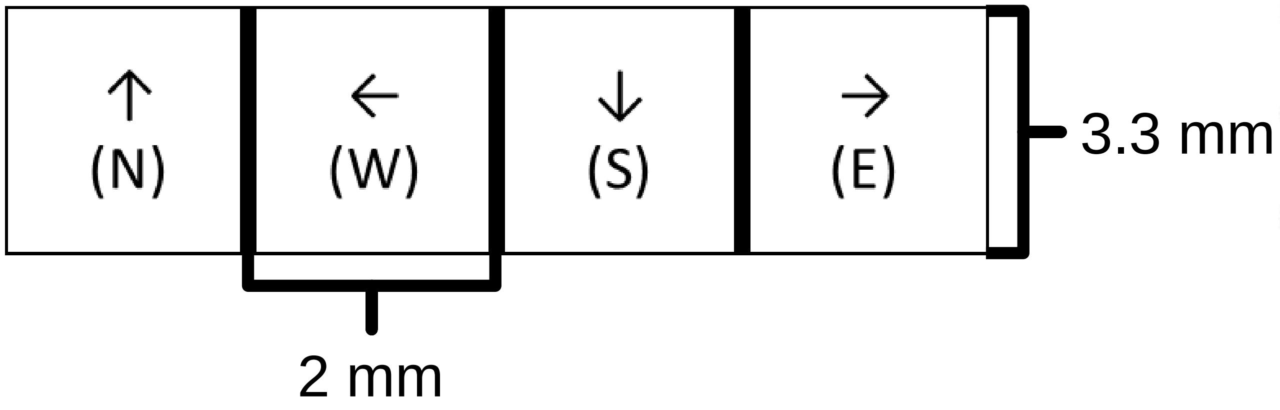
Final Design

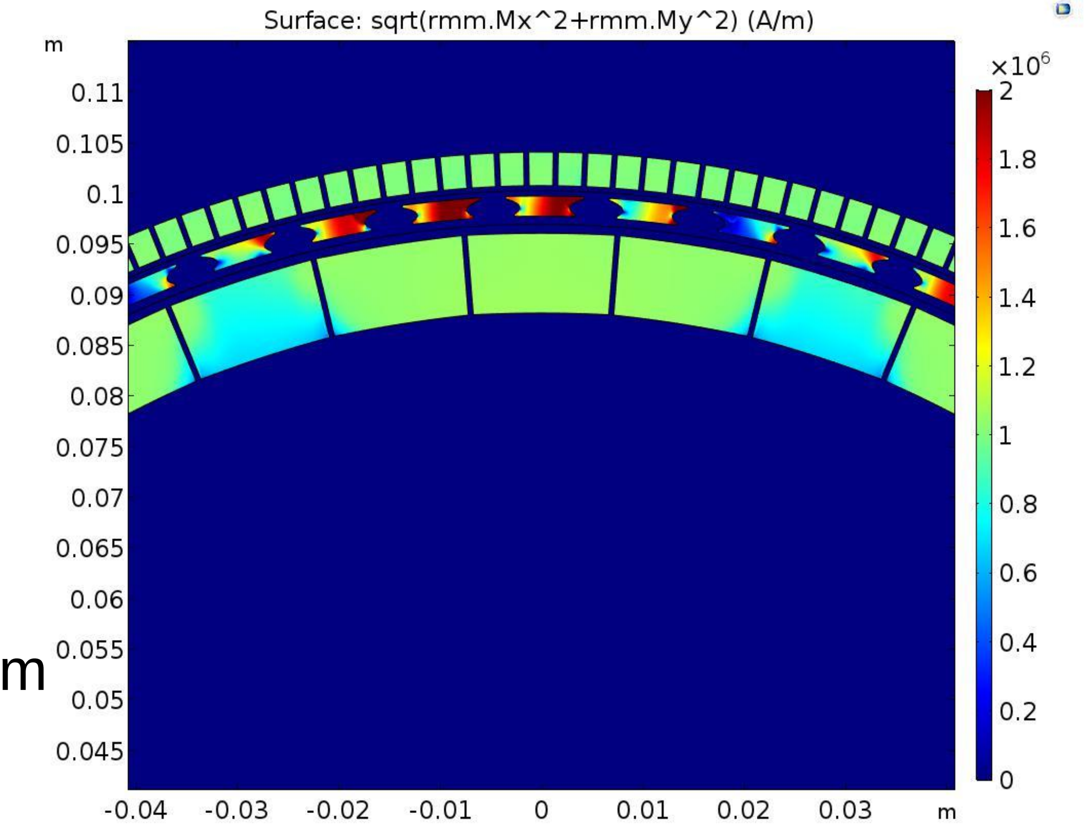
Selected Electromagnetic Design

	PT-4 Electromagnetic Design Parameters	
Limits electrical frequency	**Sun Pole Pairs**	5
	Magnetic OR (mm)	104.1
Reasonable Modulator Thickness Good Ring Magnet Thickness	**Axial Length (mm)**	52
	Sun Magnet Thickness (mm)	7.878
	Modulator Thickness (mm)	2
	Ring Magnet Thickness (mm)	3.302
Eliminates Symmetry To reduce torque ripple	**Modulator Pole Pieces**	61
	Ring Pole Pairs	56
Re-optimized Pole Piece Geometry	**Inner Pole Piece Span Angle**	4
	Mid Pole Piece Span Angle	2.3
	Outer Modulator Span Angle	5.44
	Pole Piece Fillet Radius (mm)	0.127
	Magnetic Mass (kg)	2.705

Demagnetization of Ring Gear Magnet

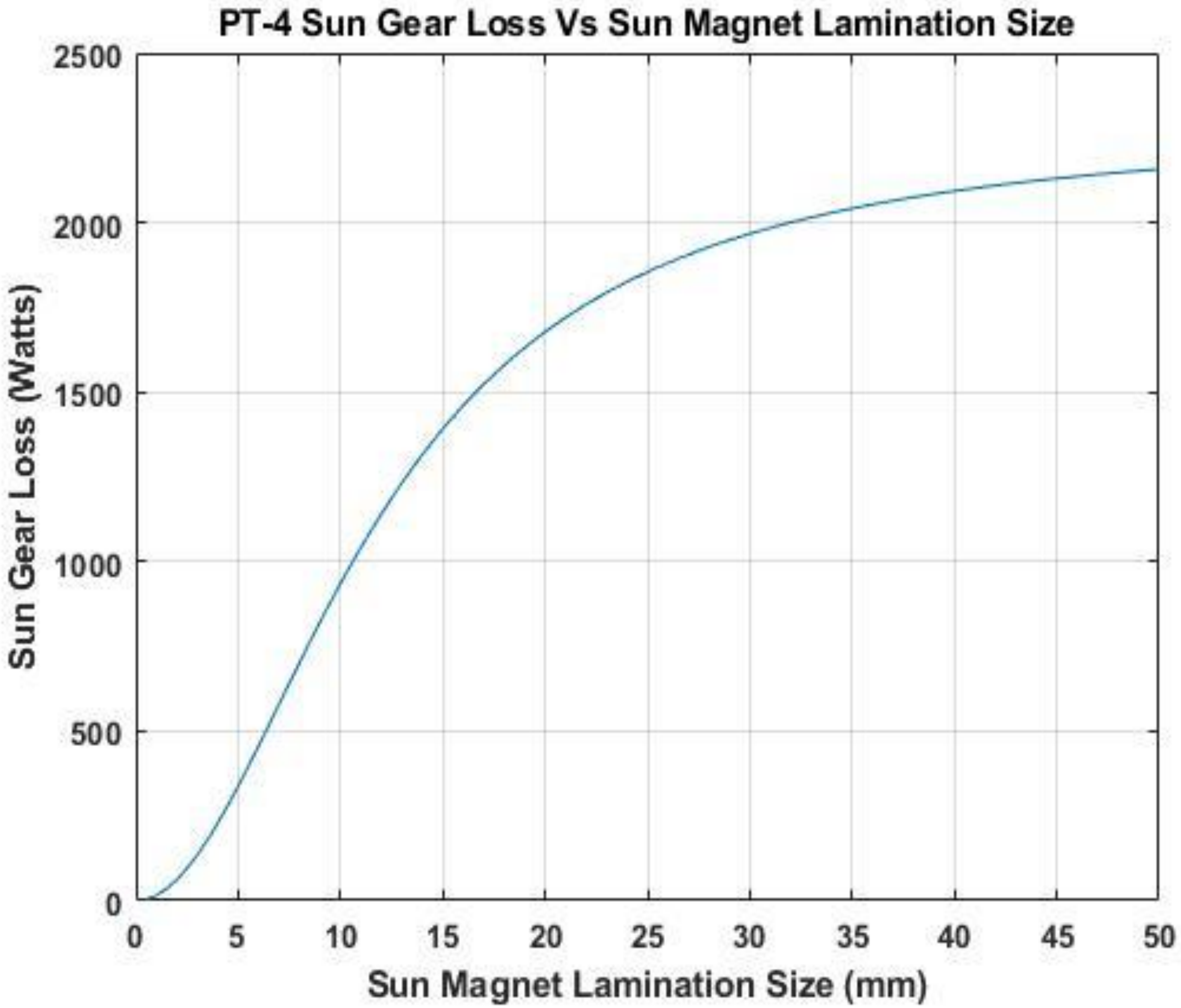
- Ring gear uses 4-magnet Halbach Array
- 3.3 mm Ring Magnet Thickness
    - Prevents N-S Demagnetization
- 2 mm Ring Magnet Width
    - Allows E-W Demagnetization
- Fixed with Material Change
    - N48SH Ring Magnets





Effect of Lamination Size on PT-4 Efficiency

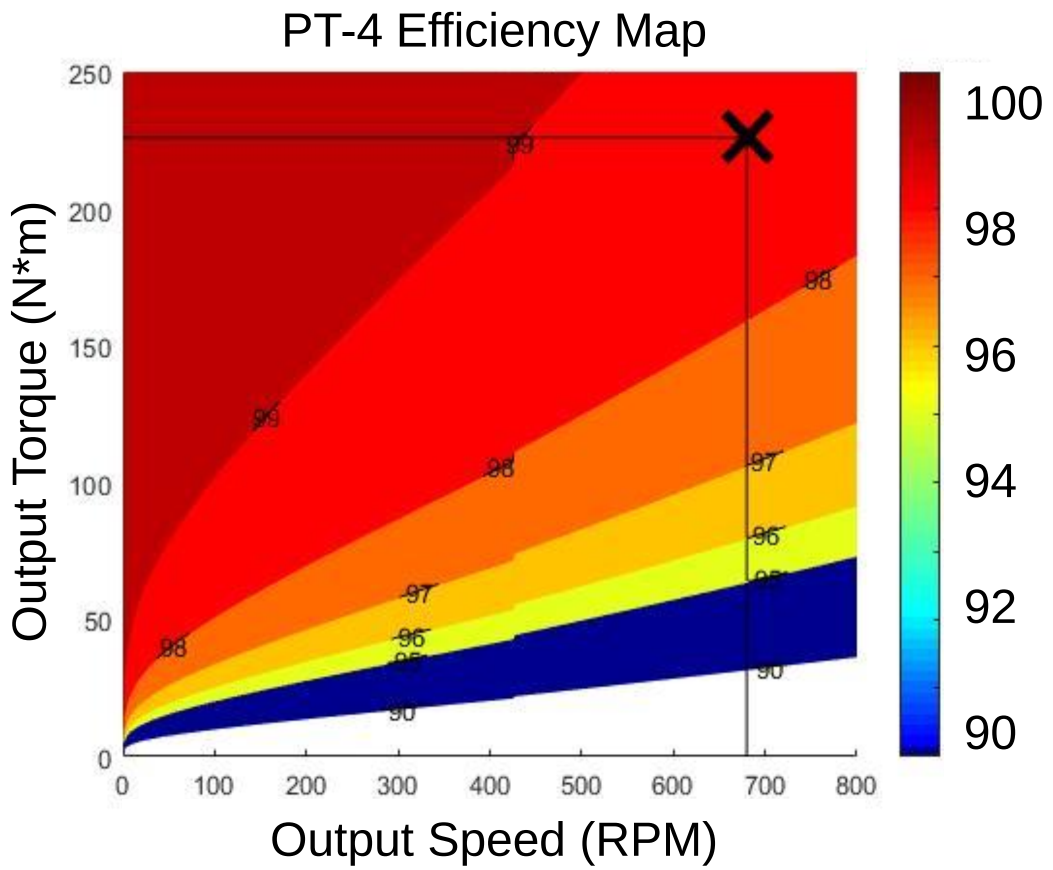
- $P_c = \frac{1}{16}\frac{V}{\rho}\ \frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt$
- Ring Magnet Width ~ 2 mm
  - $P_c \sim w^2$
- Sun Magnet Width ~12 mm
  - $P_c \sim l^2$
- For PT-4 selected
  - 2 mm Sun Laminations
  - No Ring Laminations



Efficiency Analysis

- Included Analytical Predictions of Bearing and Windage Losses
- At 20 C ~ 98.5 %
- At 80 C ~ 99%

Temperature (℃)	Maximum 2D Output Torque (Nm)
20	370
80	303
100	270

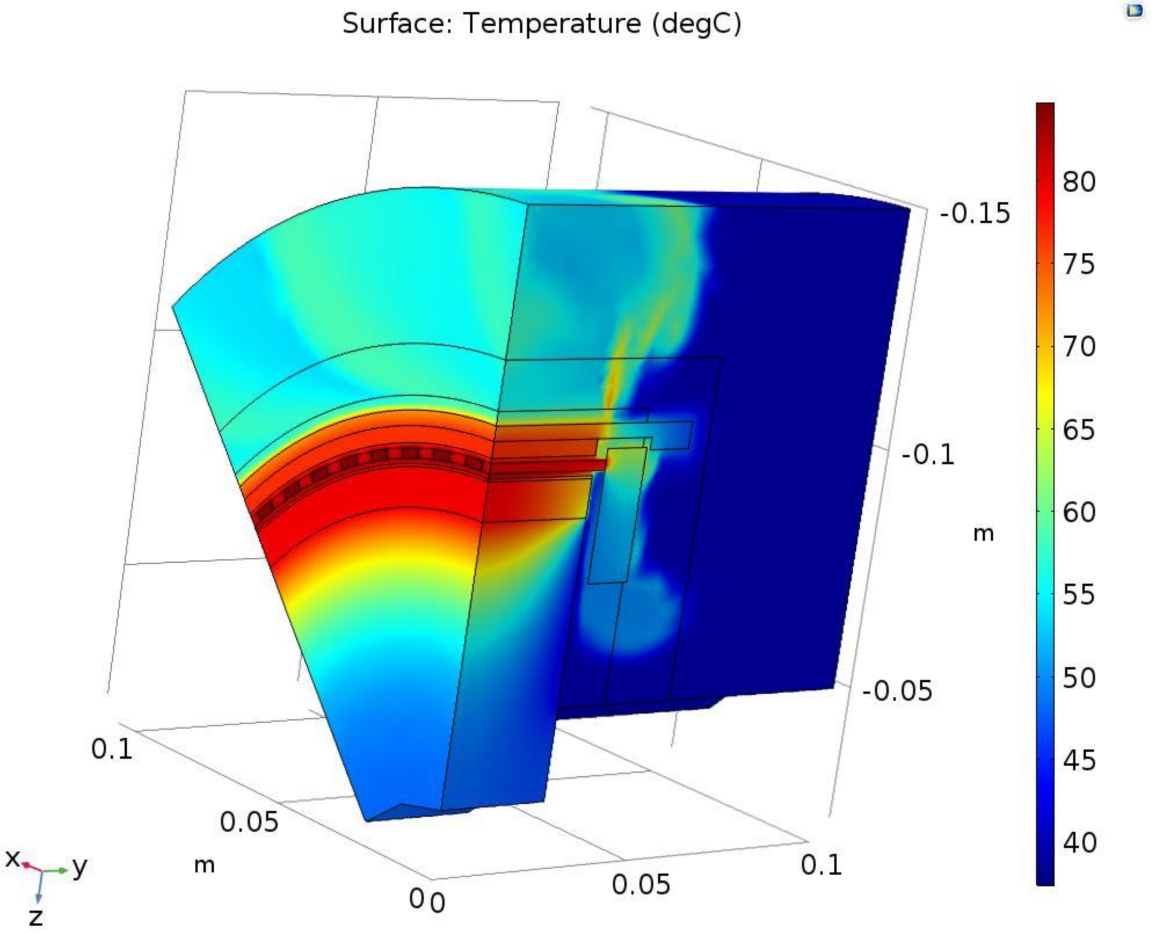


Magnetic Gear Efficiency Improves as Temperature Increases, but Torque Capacity is Lost

Thermal Analysis

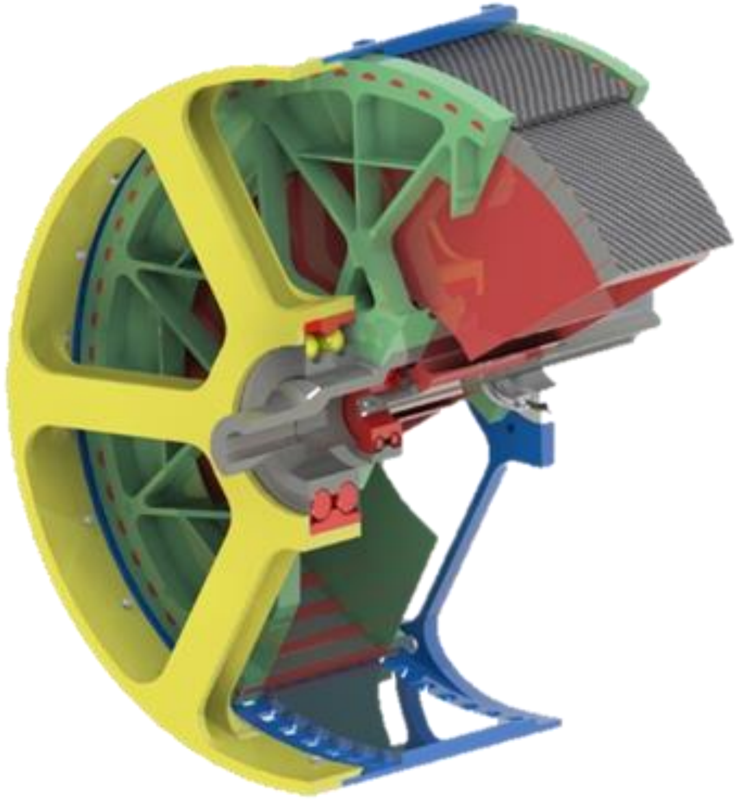
- Centripetally Pumped Cooling
  - Sun Gear tip speed = 50m/s
  - Self cooled
- Assumed 40C Ambient

Magnetic Component	Max Temperature (°C)
Sun Gear Magnets	80
Pole Pieces	85
Ring Gear Magnets	77



Final Mechanical Design

- Final Mass= 4.6 Kg
- 8% higher than Design Code Prediction
  - Shaft Mass
  - Ring Gear Structure
- Carbon Hoop added to Modulator
  - Deflection neglected in code



Conclusions

- PT-4 Final Design
  - 49 Nm/kg at Nominal Operating Condition
    - Expected to be higher at 20C
  - >98.5% Efficiency
- Design Code Developed
  - Creates preliminary design in < 1 Day
  - Under predicted mass by ~8%
    - Some improvements needed

Future Work

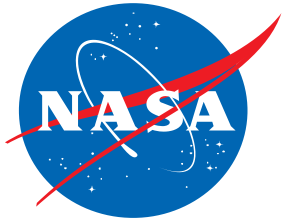
- Build and Test PT-4
- PT-5
  - Designed for X-57
  - Risk Reduction For PT-4
  - >97% efficiency without magnet laminations
- Update design code
- Magnetically geared motors
  - How best to share magnetic and structural components between a motor and a magnetic gear?

Acknowledgements

- NASA Revolutionary Vertical Lift Technology (RVLT) Project
- NASA Internal Research & Development (IRAD) Project
- Glenn Research Center Composites Group
  - Sandi Miller
  - Paula Heimann

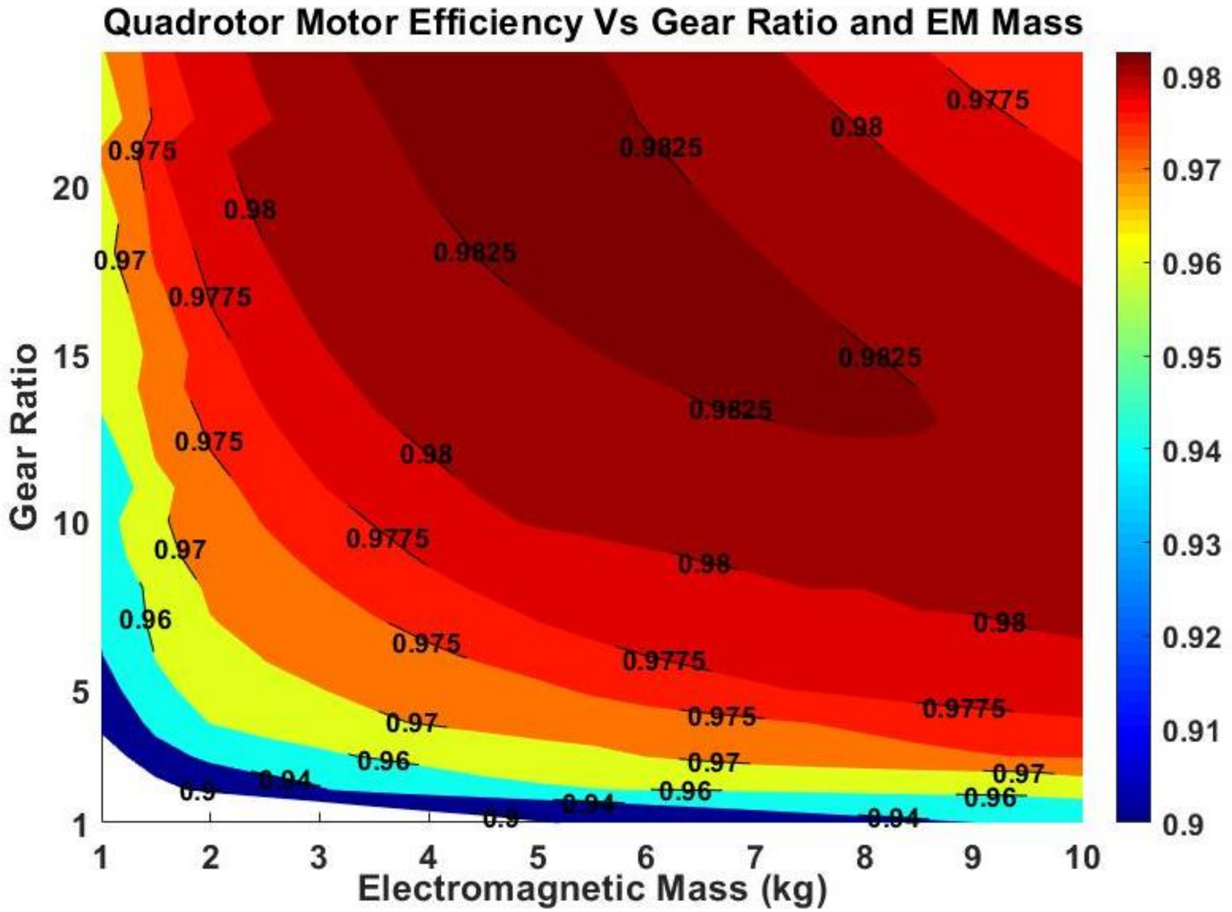
QUESTIONS ?


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


NASA

Effect of Gearbox on Motor for Quadrotor

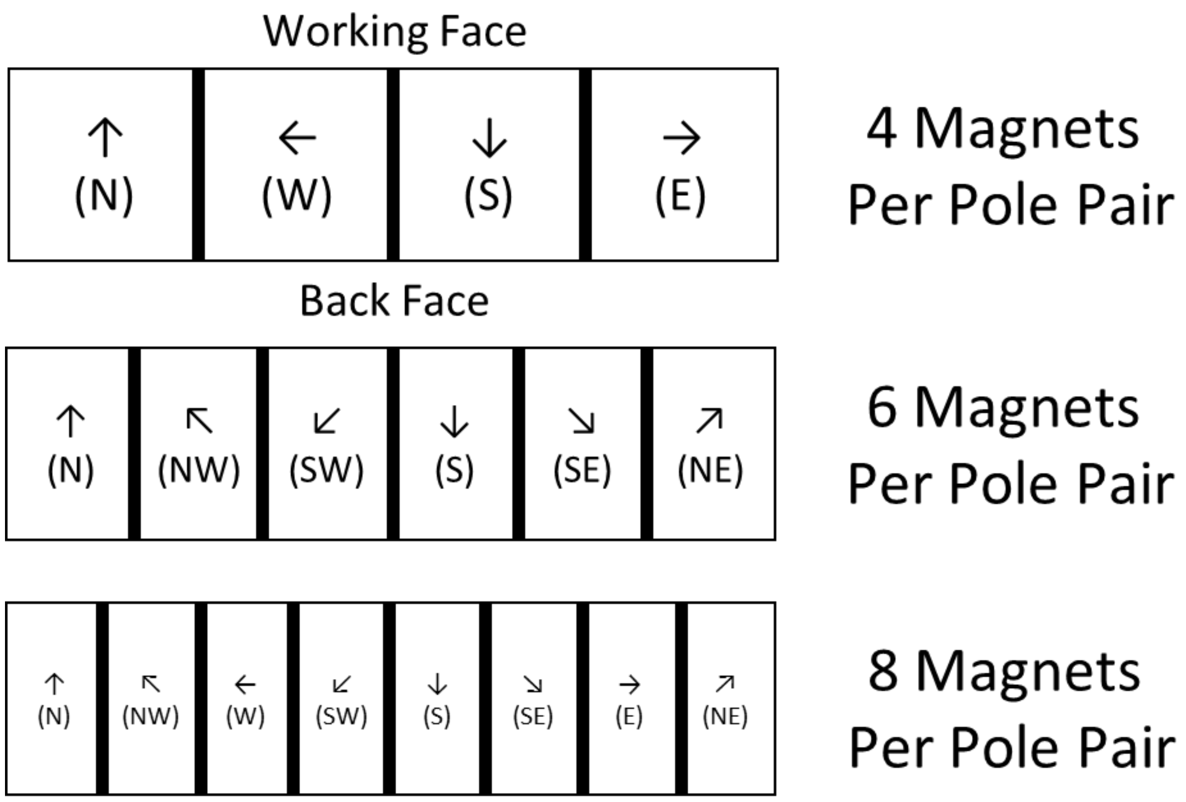
- Fan Speed = 680 RPM
- Shaft Power = 16,100 Watts
- Analytical Equations for:
    - Torque
    - Copper Loss
    - Iron Loss
    - Windage Loss
- Losses under predicted
- No Thermal Considerations



Halbach Arrays

- Improve Specific Torque
  - Don’t need back Iron
  - Higher Specific Flux than traditional array
- Improve efficiency
  - Lower Harmonic Distortion
  - More Magnets per pole
    - $P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt$
    - $w \ll l$
    - $P_c \sim w^2$

One Pole Pair



Arrows denote magnetization direction*

Enabling Design Principles

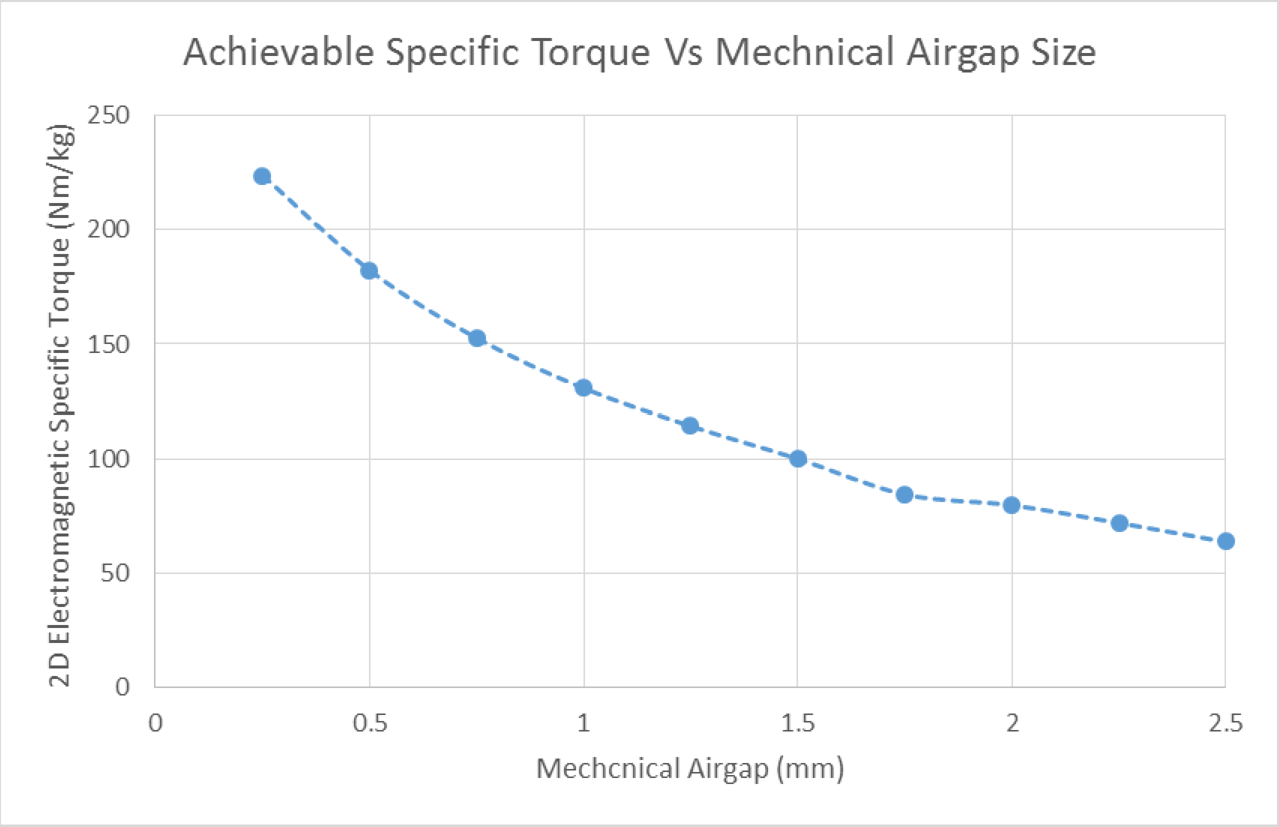
Minimize Modulator Thickness

- Electromagnetically there is a specific torque optimum modulator thickness
- That thickness is typically less than what can be achieved mechanically.
    - Subjected to high magnetic forces
        - Gear’s output torque
        - Radial force
    - Modulator is sandwiched by airgaps
    - Pole pieces do not provide structure
        - Point of failure in PT-2 and PT-3

Enabling Design Principles

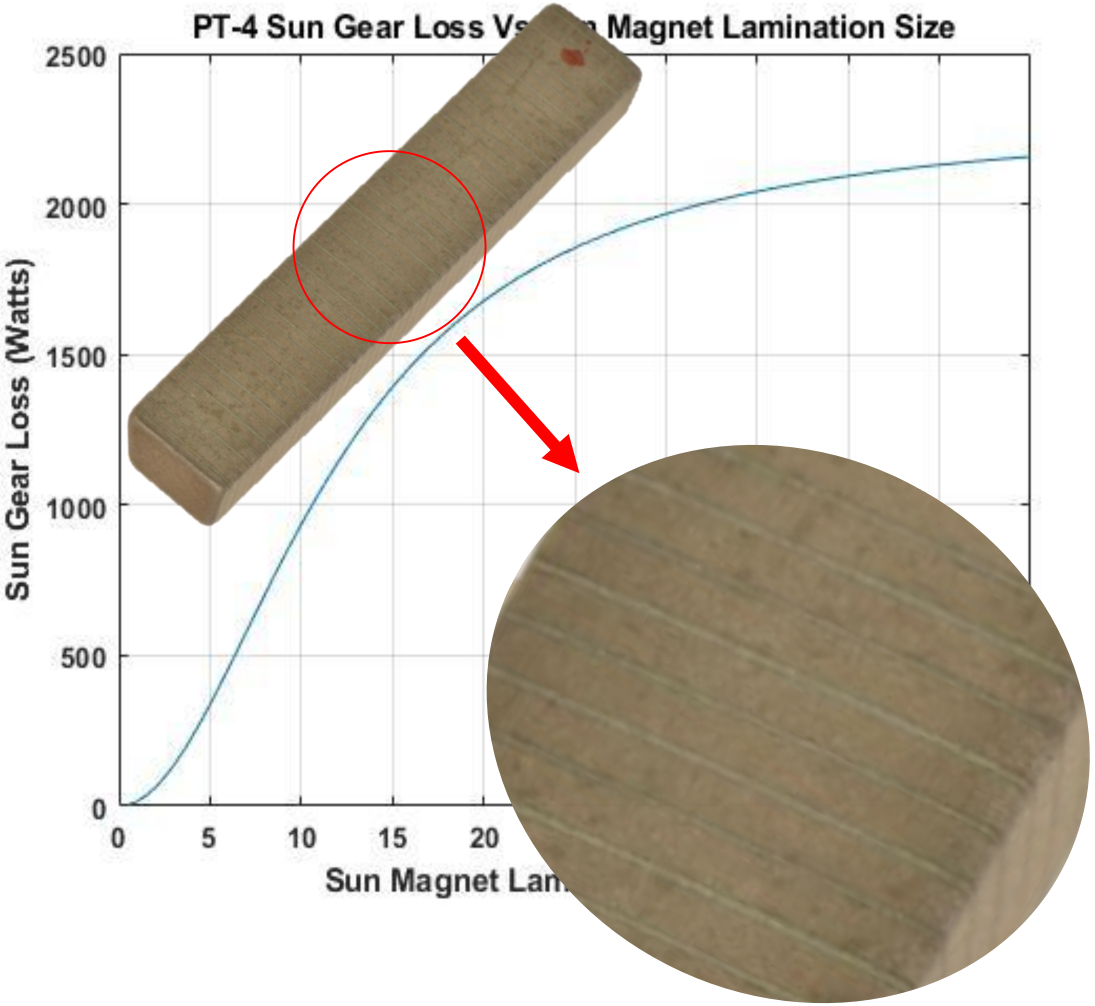
Minimizing Airgap

- Less Reluctance Between Rotors
  - Lowers optimum modulator thickness
- Less Pole to Pole Leakage
  - Increases optimum rotor pole counts
  - Lower reluctance between poles
  - Lowers optimum modulator thickness
- Reduces Efficiency
  - More unmodulated flux crosses airgaps



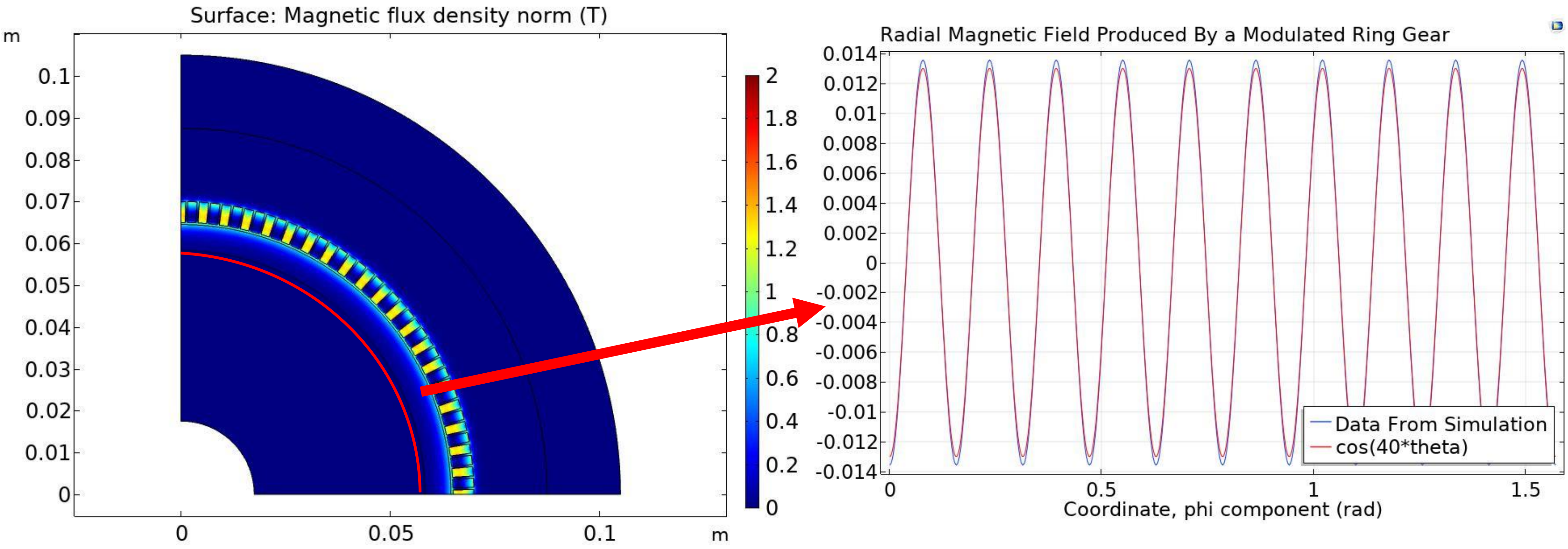
Magnet Laminations

- Enables >99% Efficiency
  - $P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt$
  - $l \ll w$
  - $P_c \sim l^2$
- Magnet Fill Percentage Decreases
  - Lowers Torque
- PT-3
  - 1mm Laminations
  - >98% Efficiency
  - ~80% magnet fill



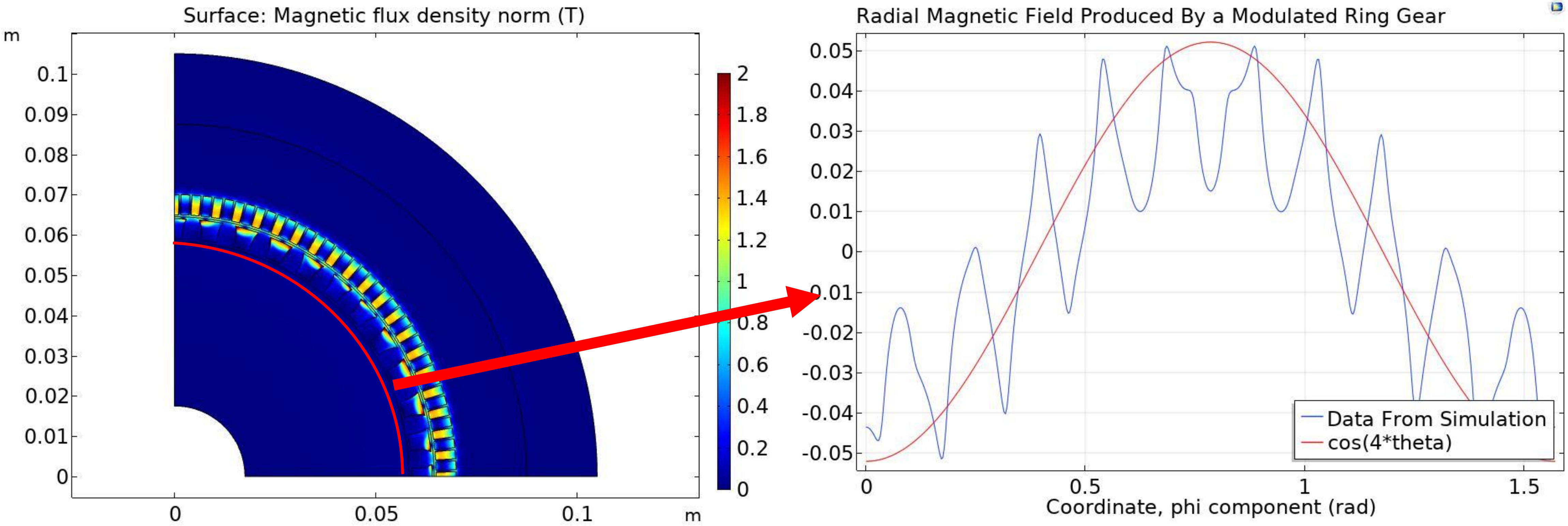
Concentric Magnetic Gears

Flux Modulation Example:
10 Pole Pair Ring Gear Only



Concentric Magnetic Gears

Flux Modulation Example:
Add 11 Pole Piece Modulator



$$PS = Q - PR = 11 - 10 = 1$$