Magnetic Gears and Their Structural Limitations

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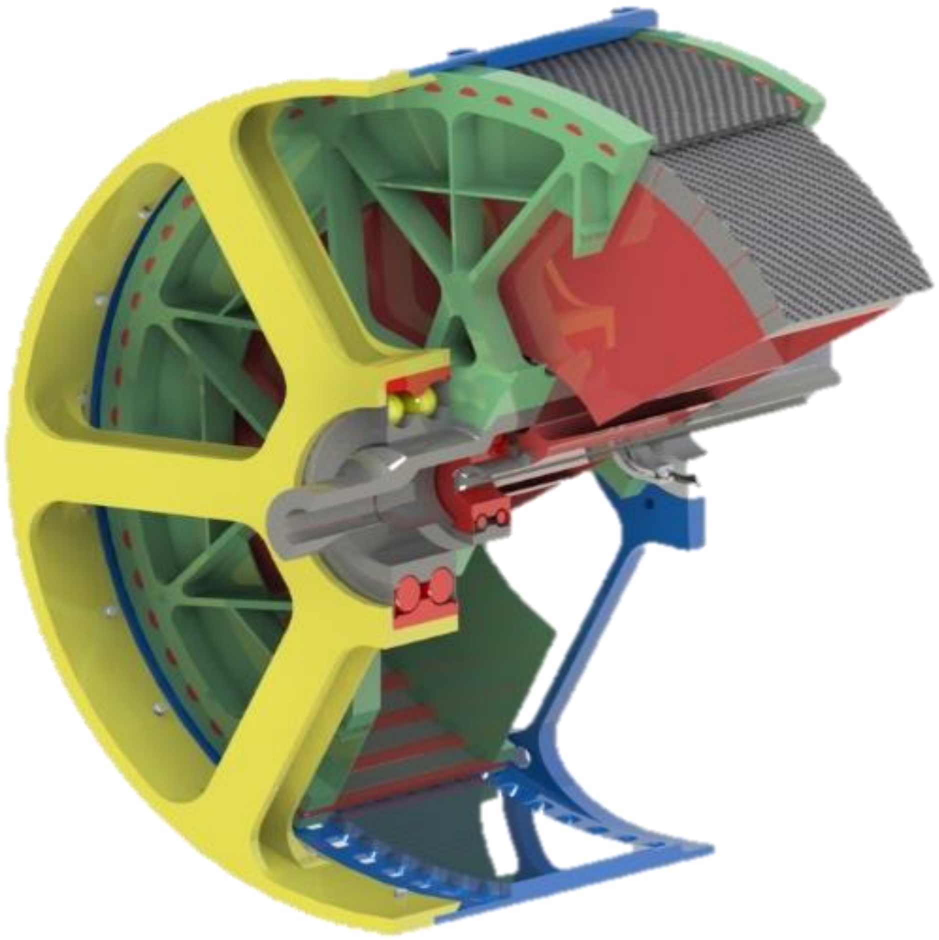
SLAMS 2019
September 9-13, 2019
Armstrong Flight Center

Outline

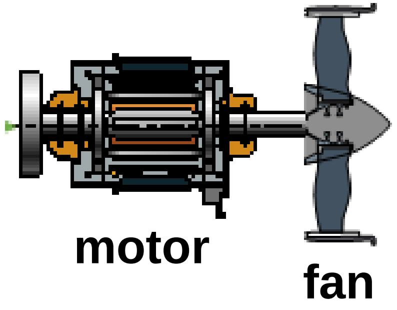
- Background and Motivation
- Concentric Magnetic Gears
- Enabling Design Principles
  - Efficiency
  - Lightweight
- Modulator Structure
- Conclusions



Background & Motivation

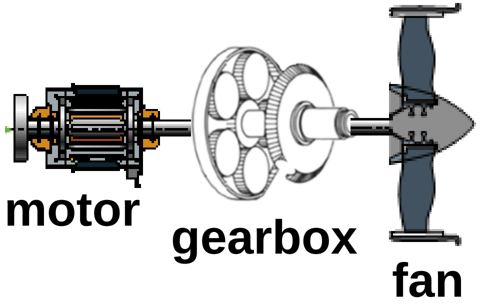
- NASA set goals for aircraft efficiency, emissions, reliability, and noise
- Parallel large & small aircraft development
  - Economic benefit of alternative propulsion
- Electrified aircraft propulsion is a key enabler
- Most concepts use direct drive
- Geared drives are almost always mass optimal

Direct drive



\+ Simpler
− Non-optimal motor and/or fan

Geared drive



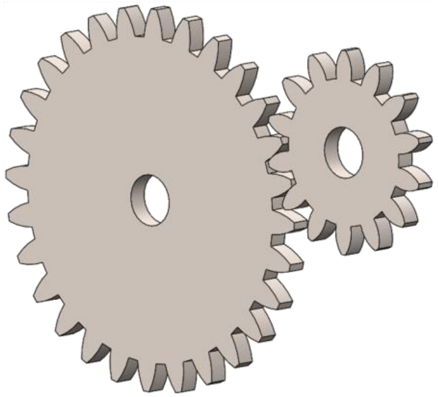
\+ Optimized motor & fan
\+ Enables cross shafting
− More complex
− Potentially less reliable

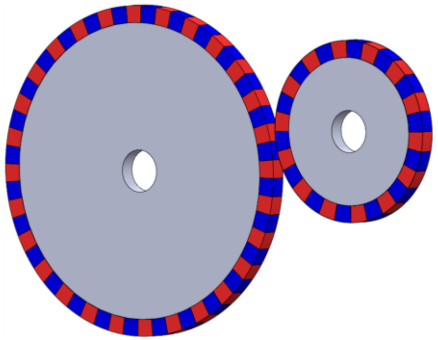
Background & Motivation

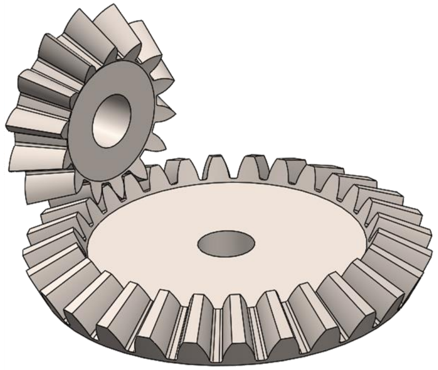
Mechanical gearing

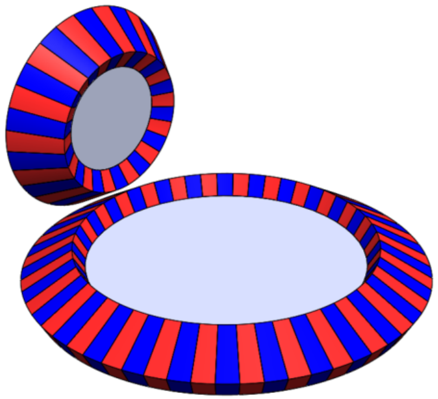
Pros

- \+ 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

Background & Motivation

Phase I
2017

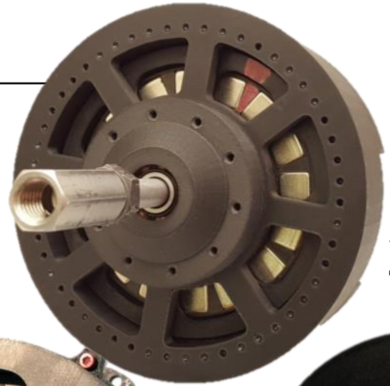
- How do they work? (PT-1)
- Can they be lightweight? (PT-2)

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?

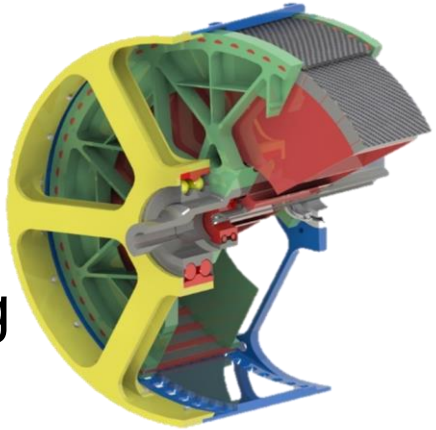


PT-1
20 Nm/kg

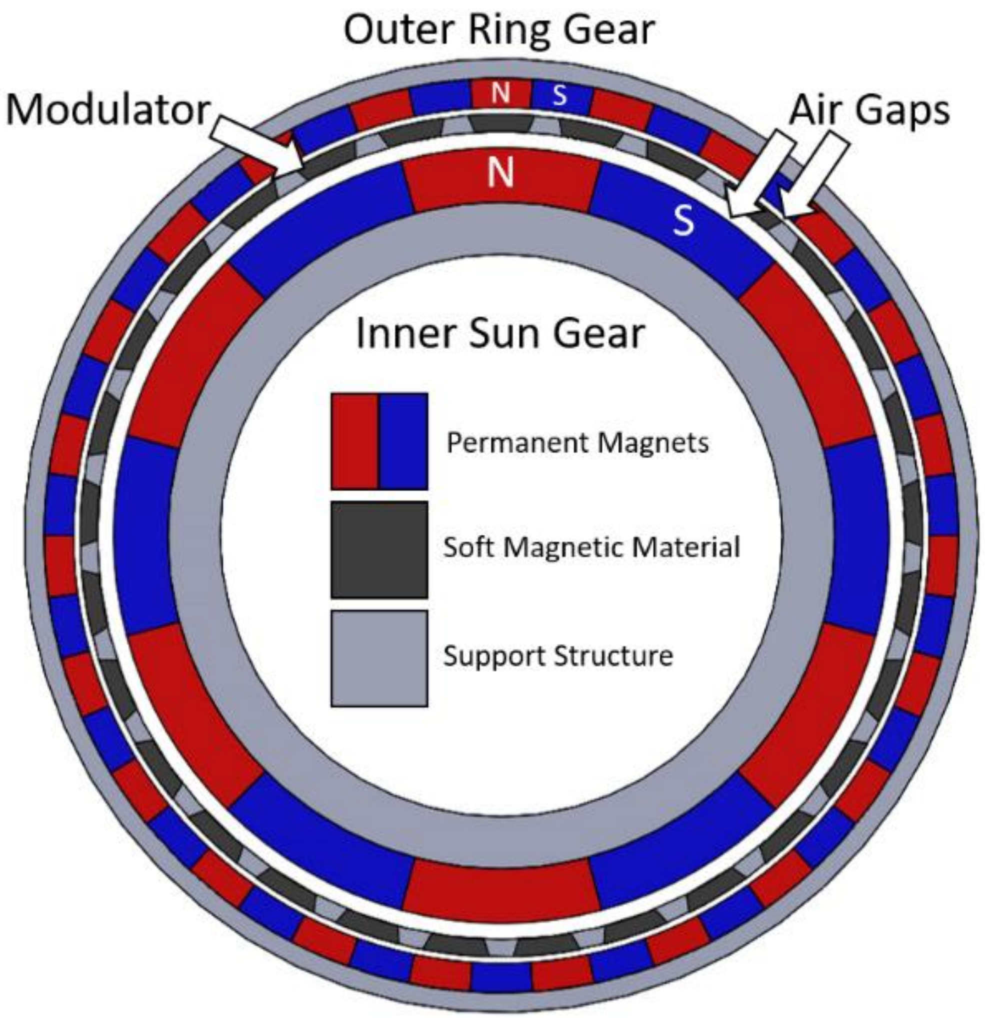
PT-2
45 Nm/kg

PT-3 >98%
Efficient

PT-4
>98.5%
>55 Nm/kg



Concentric Magnetic Gears

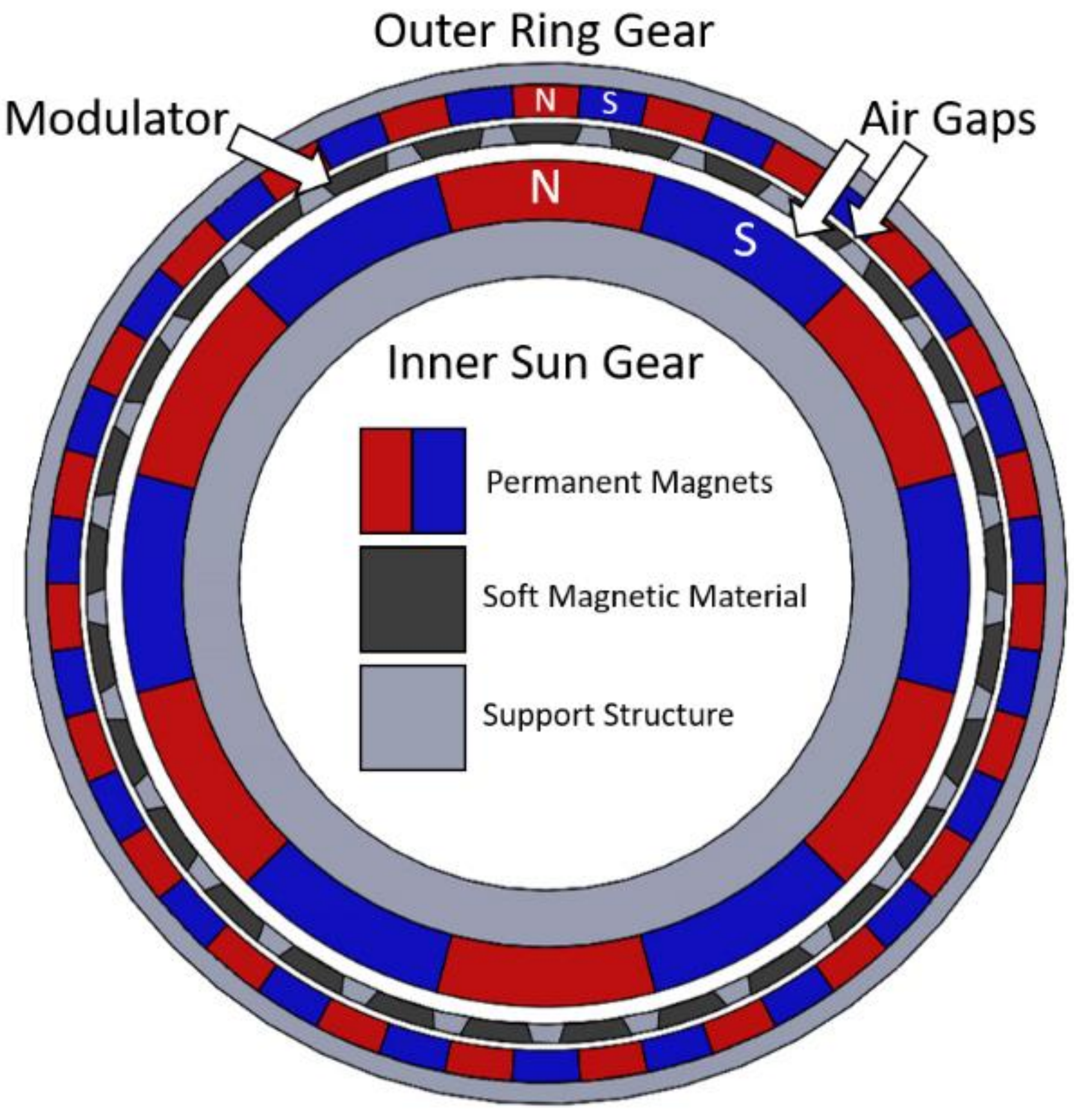


- Rule of thumb:

  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

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

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

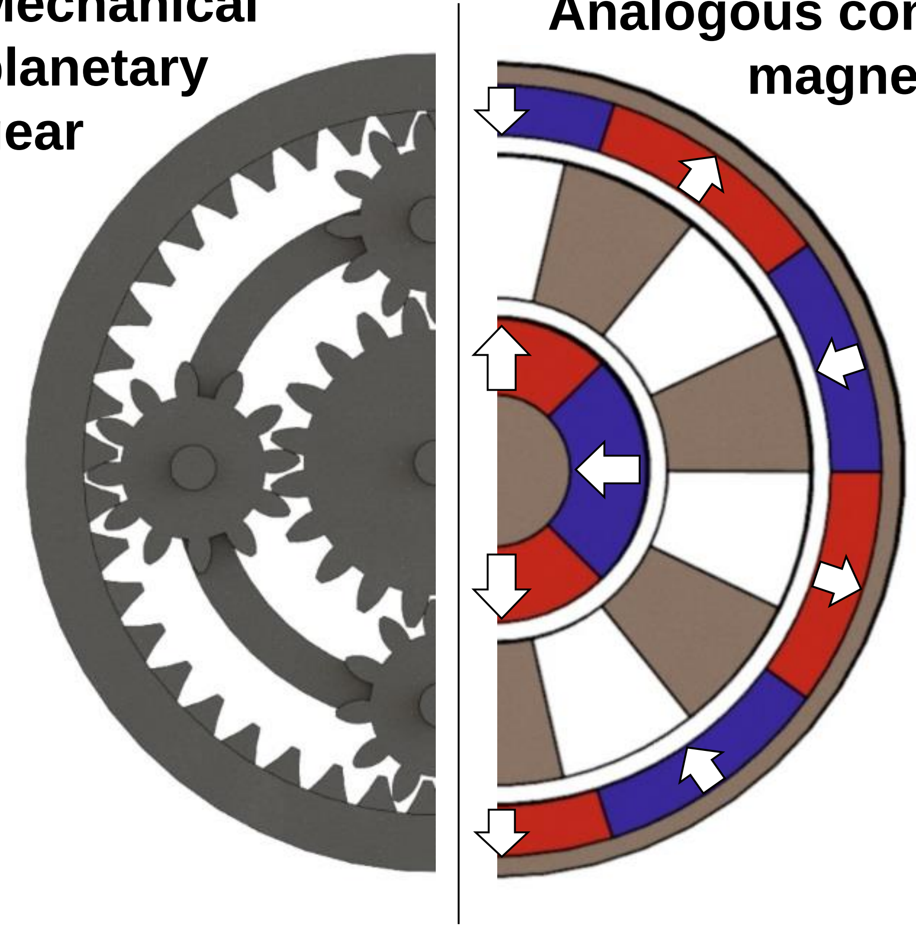
Number of Ring Gear Pole Pairs

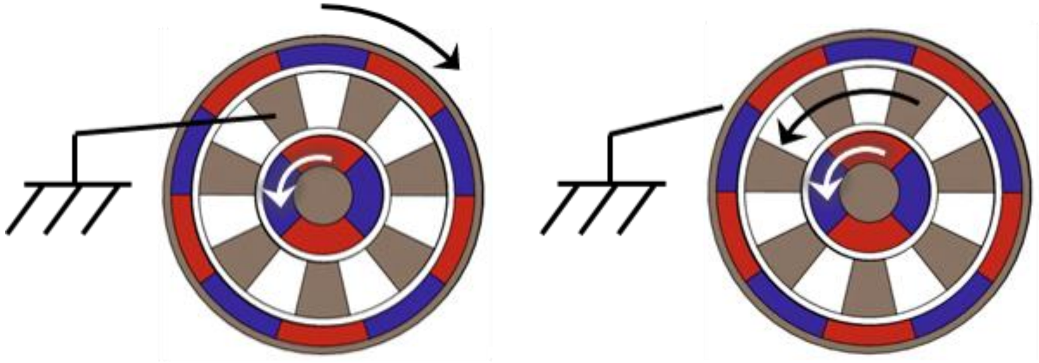
Concentric Magnetic Gears

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	$\boldsymbol{\frac{Q}{PS} = \frac{PR}{PS} + 1}$

Efficient Magnetic Gears

- Main loss source = eddy currents
- Time varying magnetic fields produce electrical fields:

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

- Electrical fields drive currents:

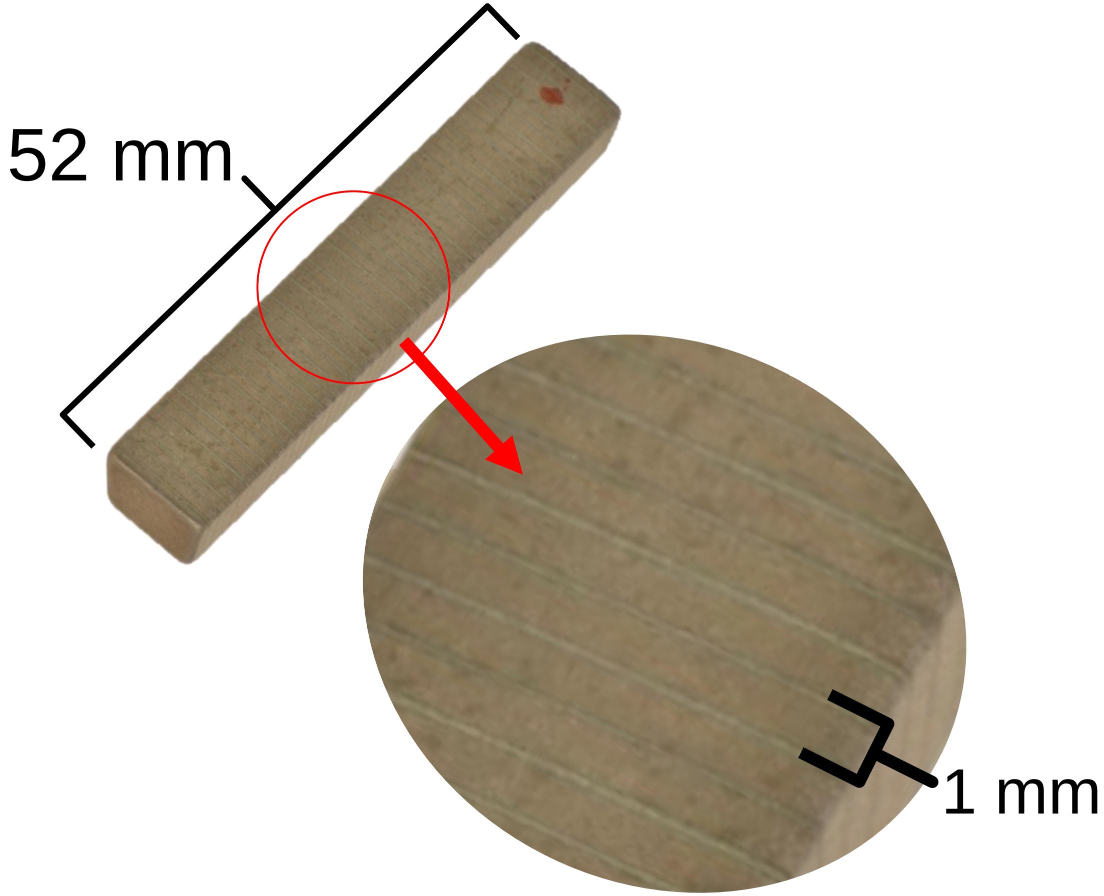
$$I = \frac{V}{R}$$

- Currents produce heat:

$$Q = RI^2 = \frac{V^2}{R}$$

Minimizing Eddy Currents

1. Use non-conductive (non-metallic) Structures
   - Plastics
   - Composites
   - Ceramics ($$)
2. Laminate Electrical Components
   - Laminated Electrical Steel
   - Laminated Magnets
   - Increases effective (Bulk) resistivity



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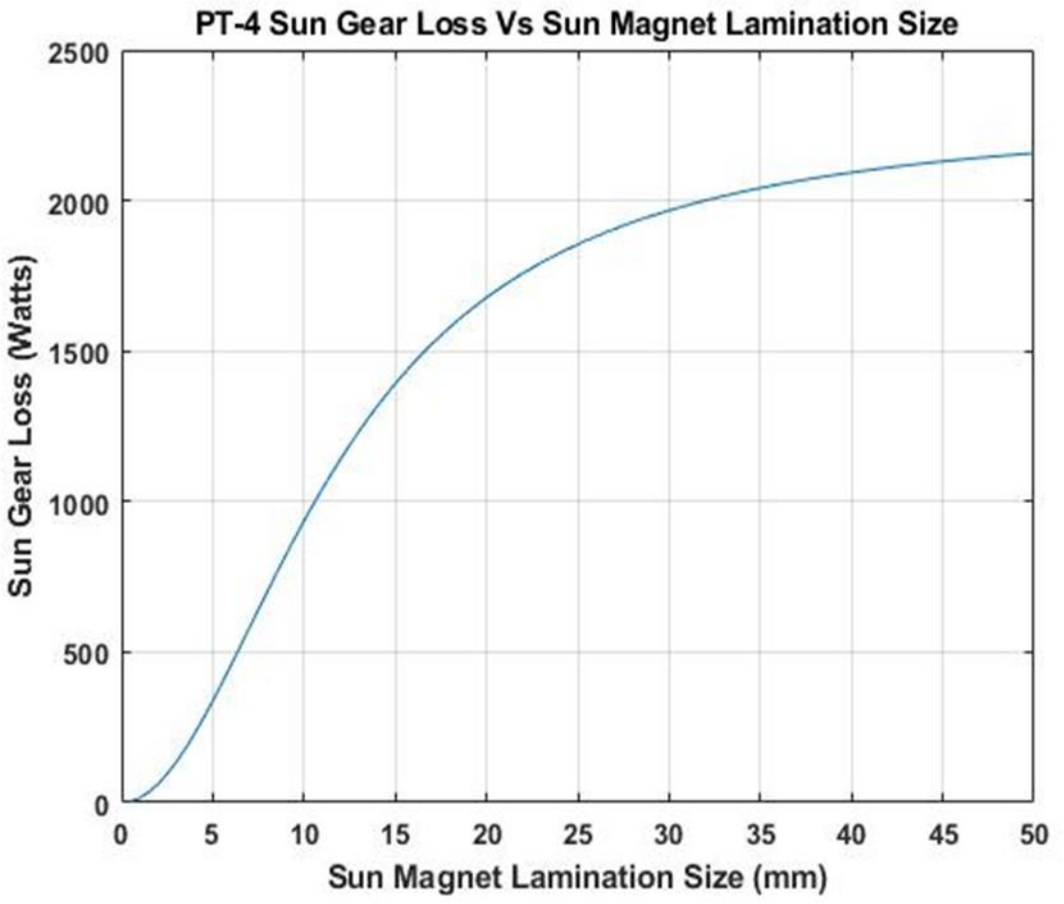
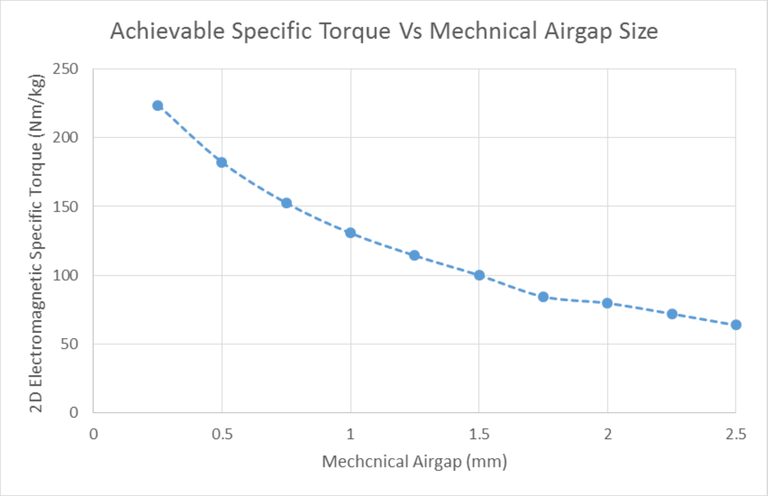
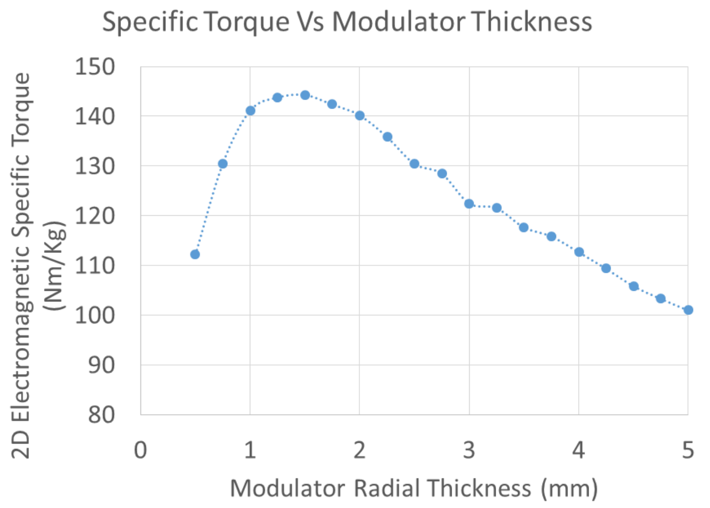


Light Weight Magnetic Gear



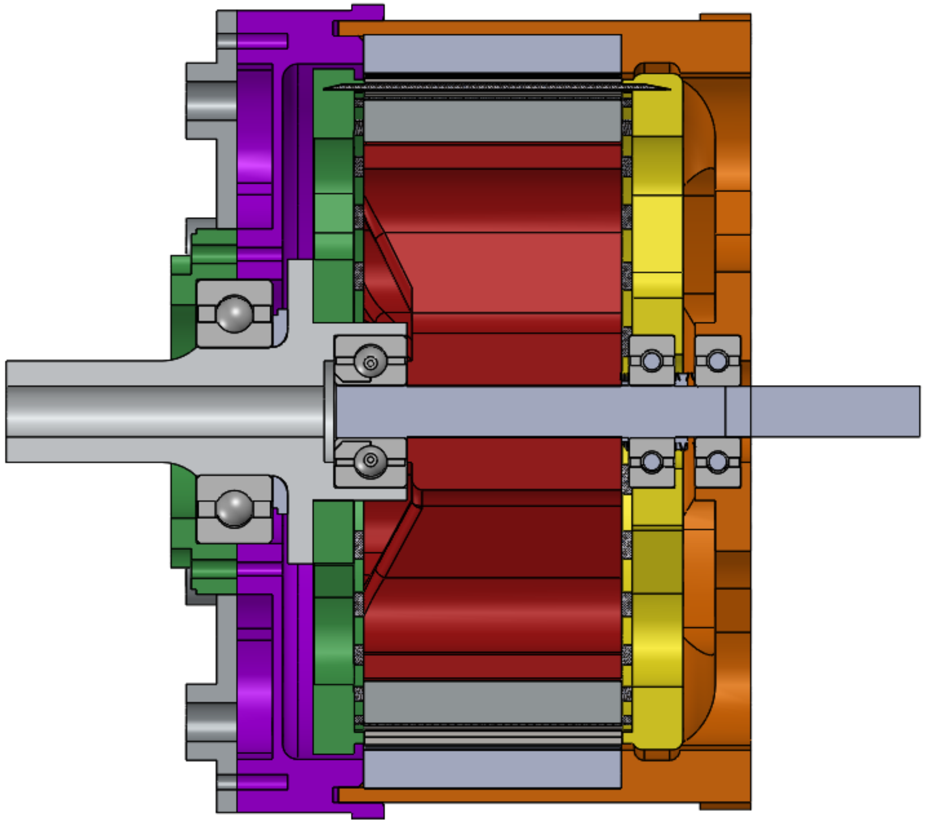
- Small Modulator Thicknesses
  - There is an optimum Modulator Thickness Electromagnetically
  - Typically ~1.5 mm
- Small Airgaps
  - ~100 Nm/Kg improvement per 1 mm airgap reduction
  - Outer Airgap more important

Limit on both = Modulator Structure



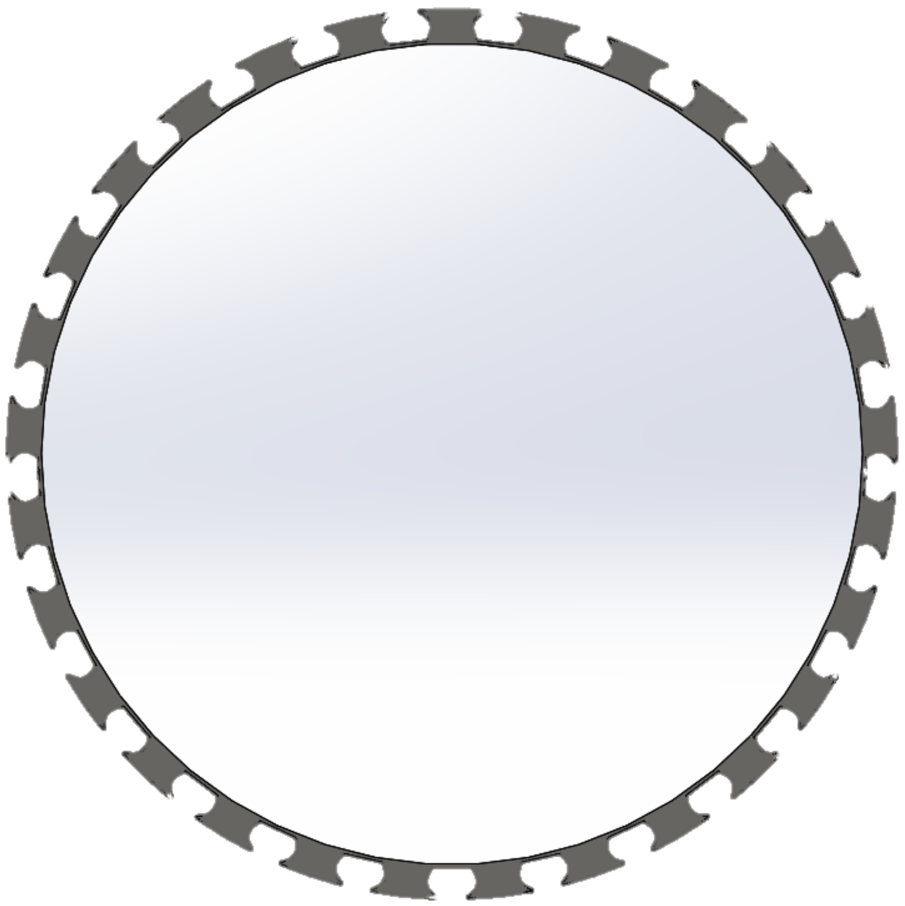
Modulator Structural Problem

- Modulator sees high electromagnetic forces
  - Carries output torque of the gear
  - Radial forces from Magnets
- Modulator “nested” between airgaps
  - Limits Structure
  - Limits Allowable Deformation
- Pole Pieces cannot transmit shear load



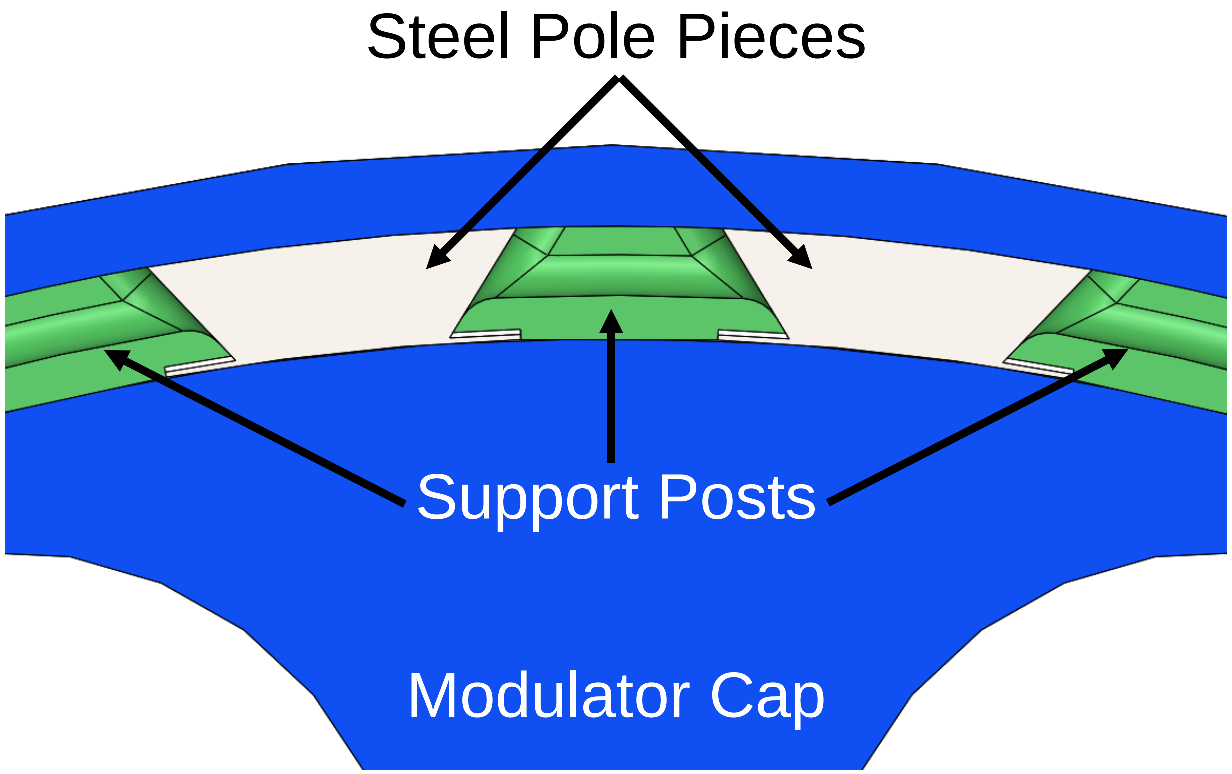
Traditional Solution

- Modulator Bridges
  - Gives modulator hoop strength
  - Results in torque reduction
    - Creates Flux Leakage Path
    - Reduces Modulation



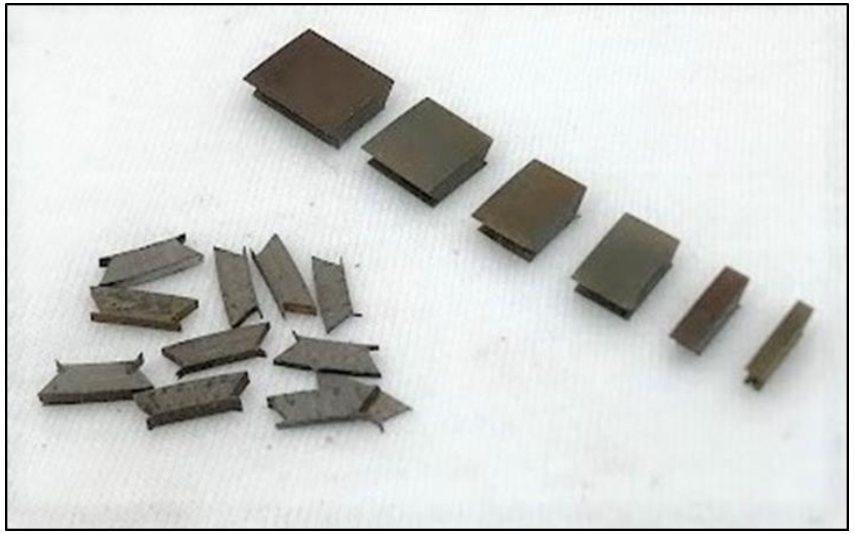
PT-2 and PT-3 Structures

- Laminated Electrical Steel Pole Pieces
- Unidirectional Carbon Fiber Support Posts
- 3D Printed End Caps
  - Nylon + Carbon Fiber Chop
  - Reinforced with continuous fiber



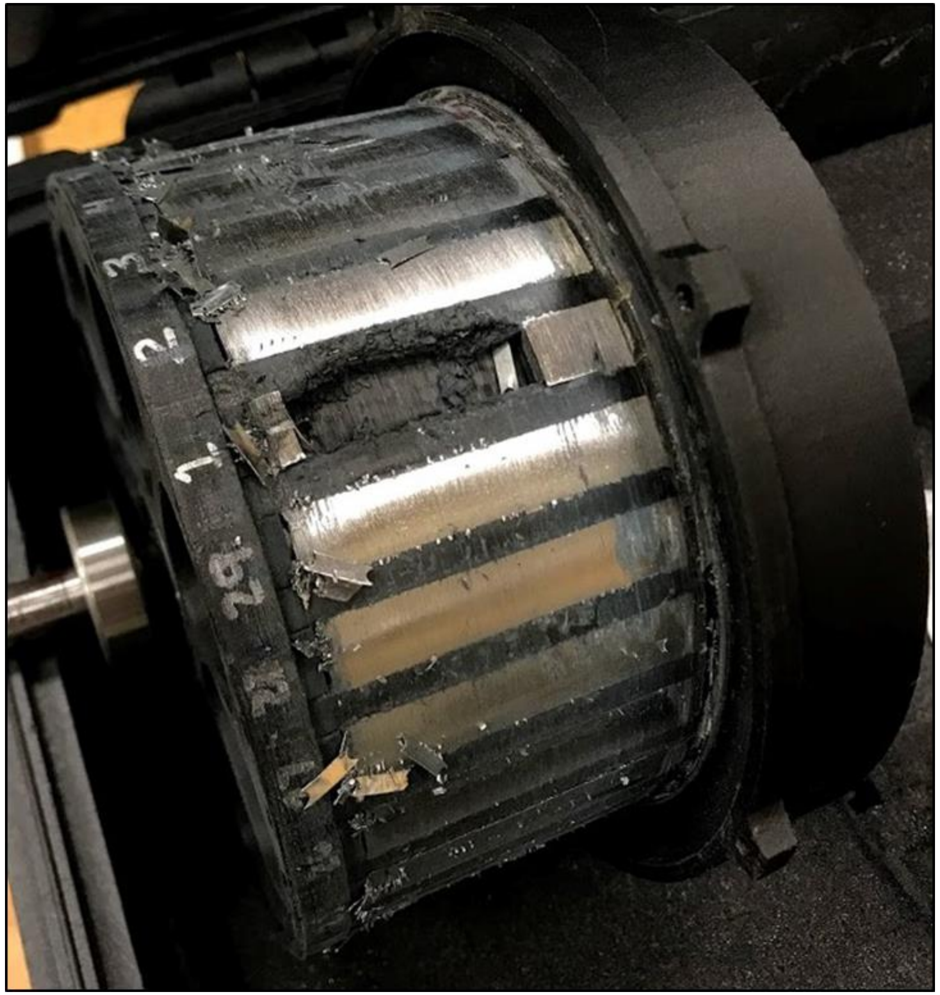
Issue With Our Pole Pieces

- Epoxy bond between layers very weak
  - Resultant from small area
    - Defects that are small in a motor lamstack are large
  - Softens at 60C



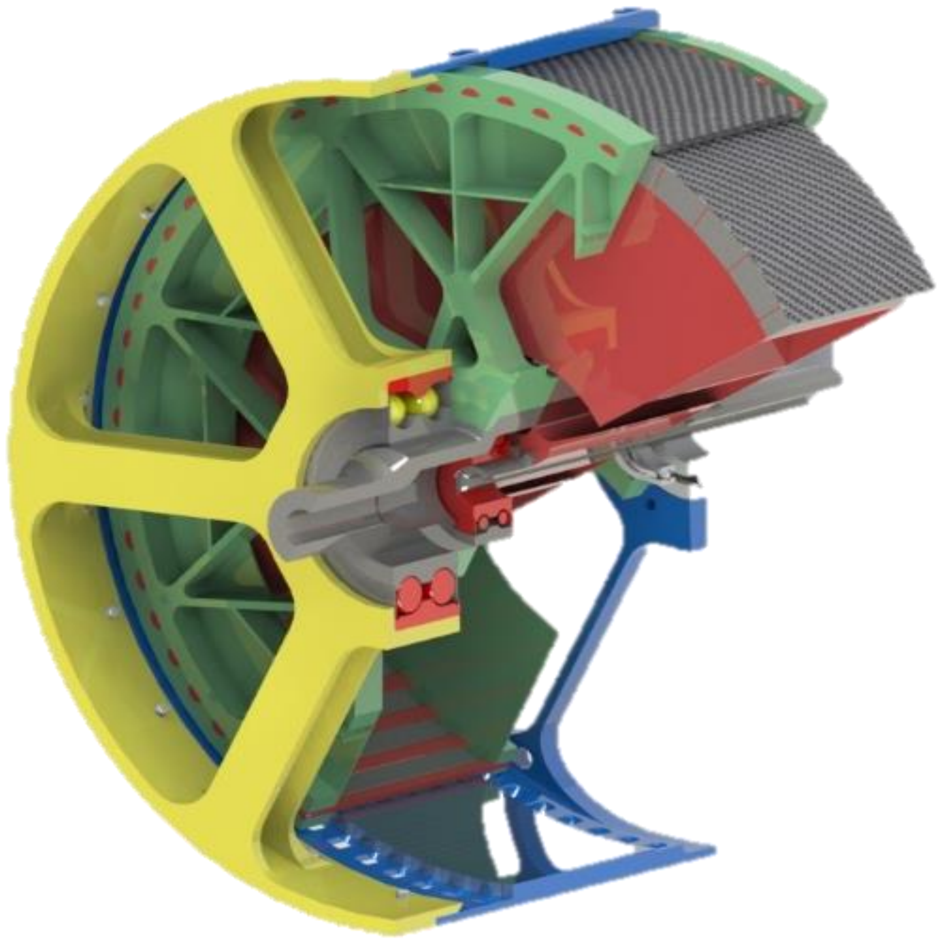
PT-2 and PT-3 Failure

- Both failed at ~ 4000 rpm input
- Both not designed for thermal failure at 60 C
- Theory:
  - Thermal failure of pole piece glue bond
  - Single pole piece cuts into modulator support structure
  - Makes space allows failure to propagate



Current Fixes

1. Add Carbon Fiber Hoop
   - Plan for PT-4
   - Used in PT-3 Rebuild
2. Stack and Bond Internally
3. Caged Modulator Structure
4. Modulator Bridges
   - If Enables Smaller Airgaps



Conclusions

- Magnetic Gears are a potential alternative to mechanical gears for aerospace applications
  - Reliability benefits over mechanical gears
  - Able to achieve 99% efficiency
  - Need to be light weighted further
- Modulator structural improvements are the obvious path to improve magnetic gear specific torque

Future Work

- Build and Test PT-4
- Magnetically geared motors
  - How best to share magnetic and structural components between a motor and a magnetic gear?
- Space Applications
  - Low lubrication requirements
    - Bearings still need lubrication
  - Over load protection
    - Robotic arms

Acknowledgements

- NASA Revolutionary Vertical Lift Technology (RVLT) Project
- NASA Internal Research & Development (IRAD) Project

QUESTIONS ?


Glenn Research Center
Lewis Field
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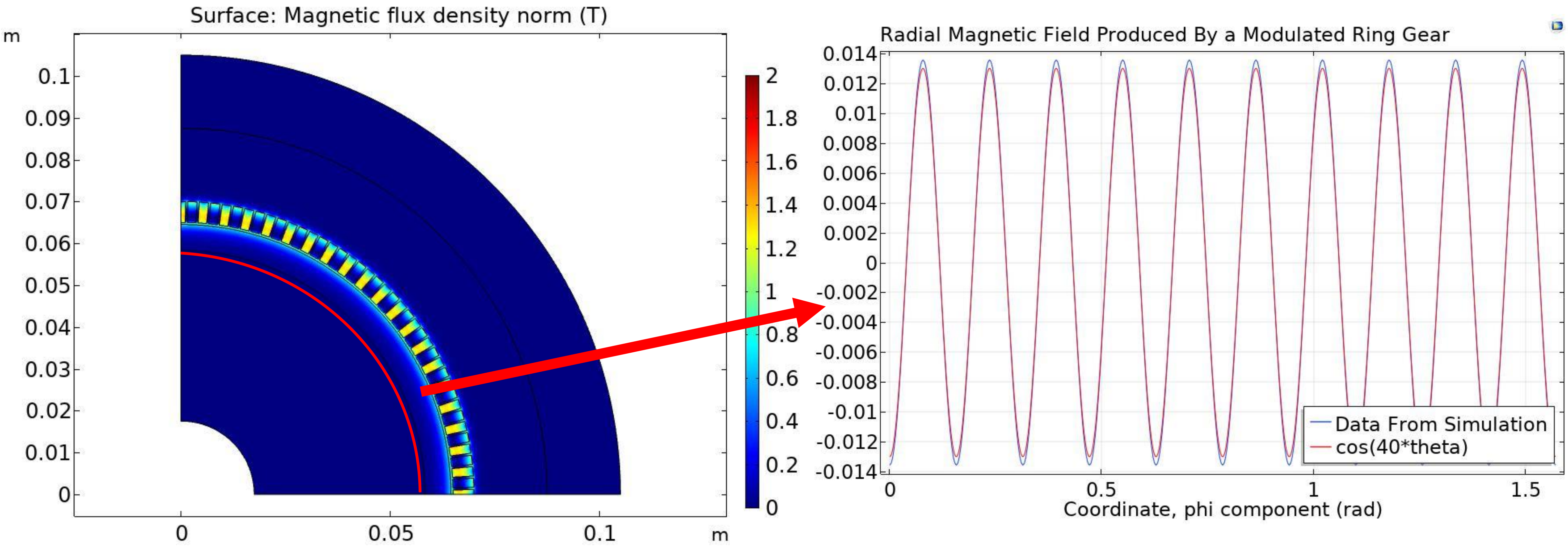
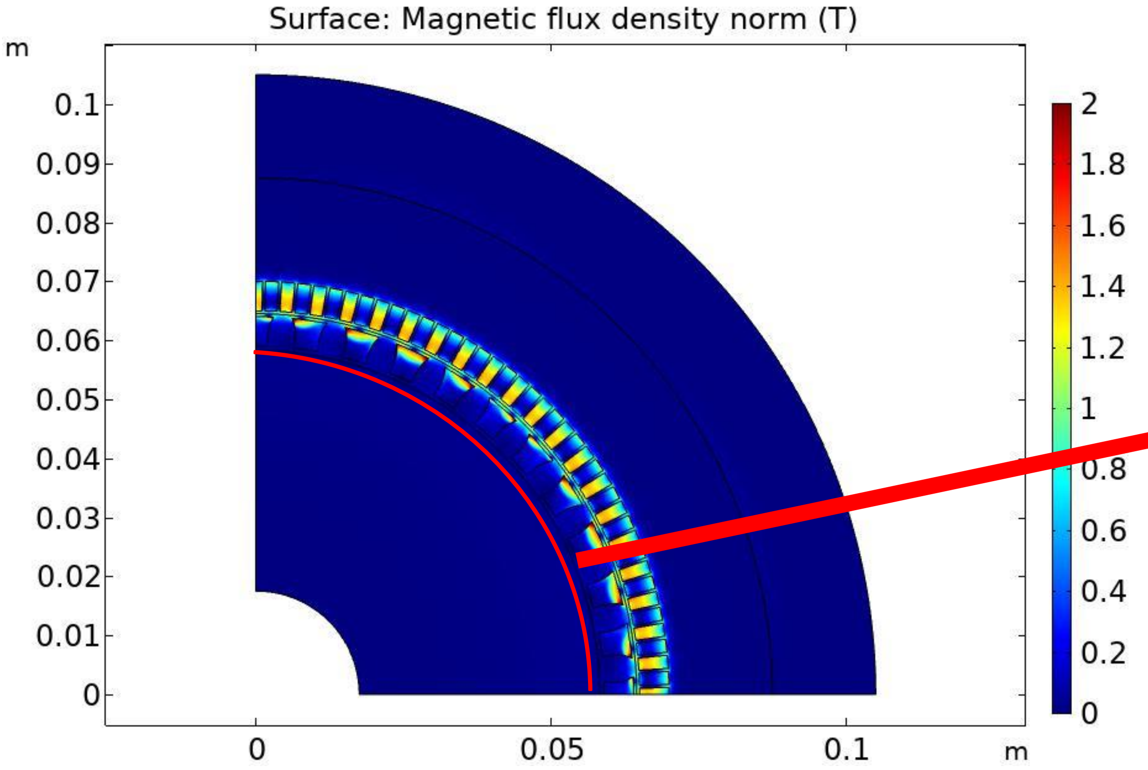
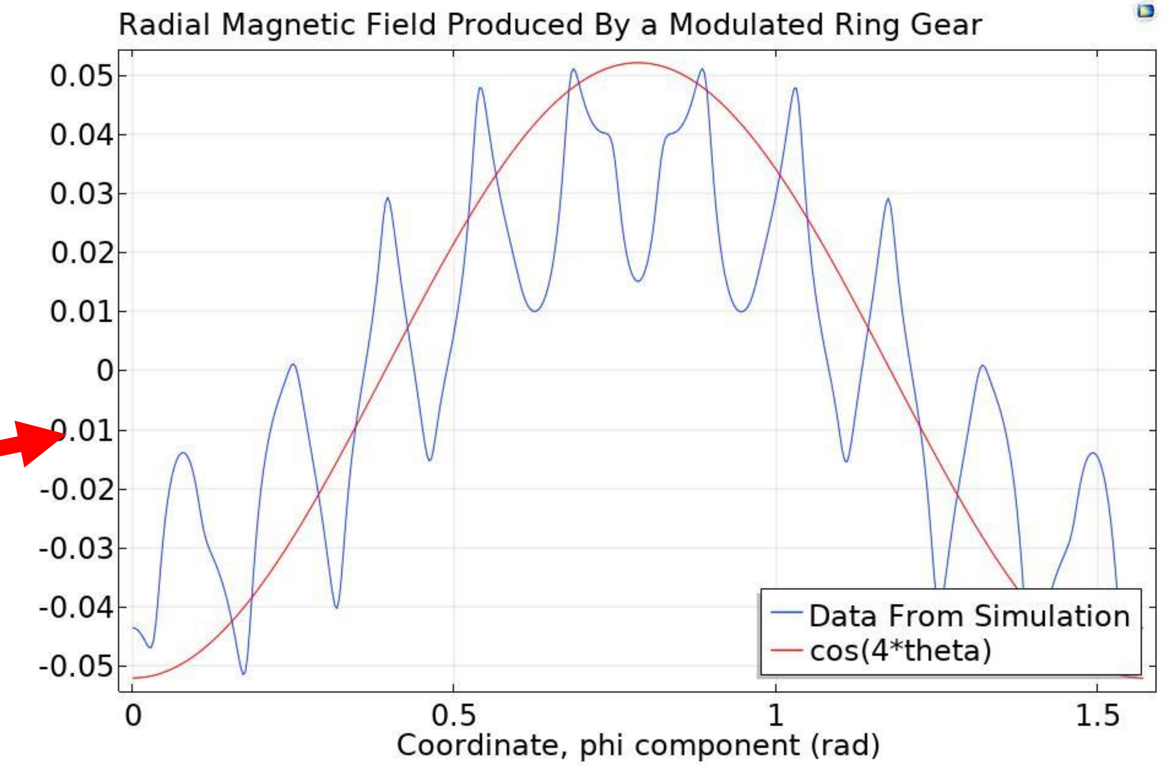
Concentric Magnetic Gears

Flux Modulation Example:
10 Pole Pair Ring Gear Only



Flux Modulation Example:
Add 11 Pole Piece Modulator





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

Efficient Magnetic Gears

- PT-3 >98% Efficient
  - Plastic Structure
  - 1 mm Magnet Laminations
  - 0.15 mm Laminated Iron Cobalt electrical steel Pole Pieces