# Electromagnetic Efficiency and Mass of Magnetic Gears for Electrified Aircraft

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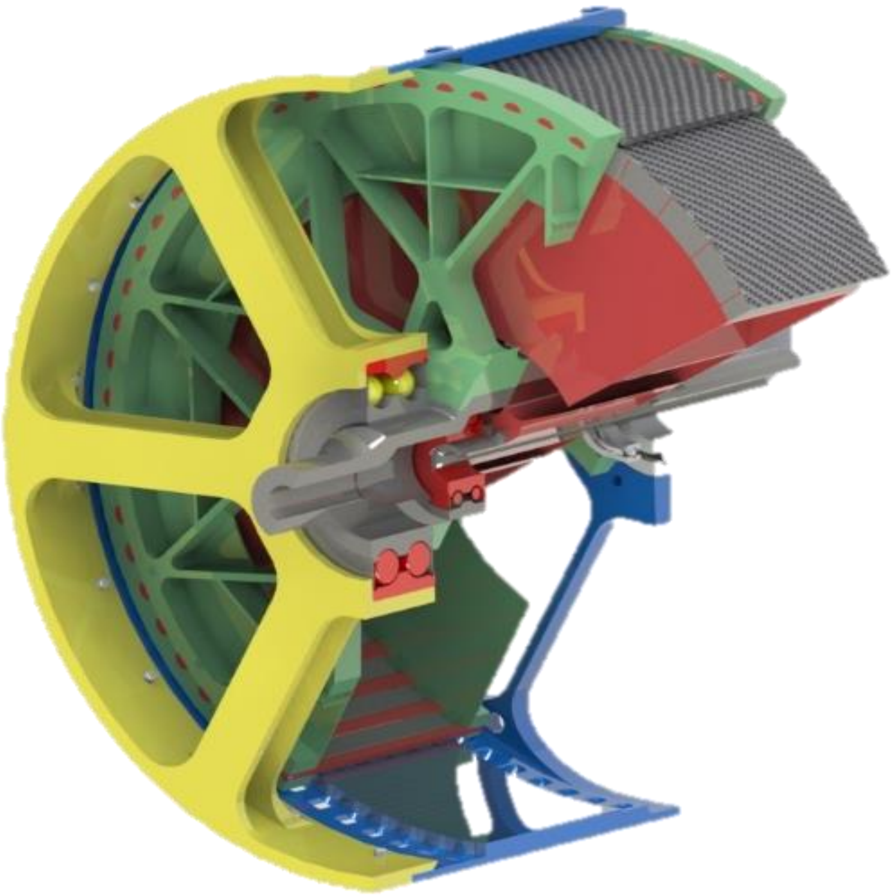
# Presentation Outline

- Background and Motivation
- Study Methodology
- Mass and Efficiency Trends:
  - Magnets per pole pair
  - Sun Gear Pole Pairs
  - Gear Ratio
  - Radius
- Summary



# Background & Motivation

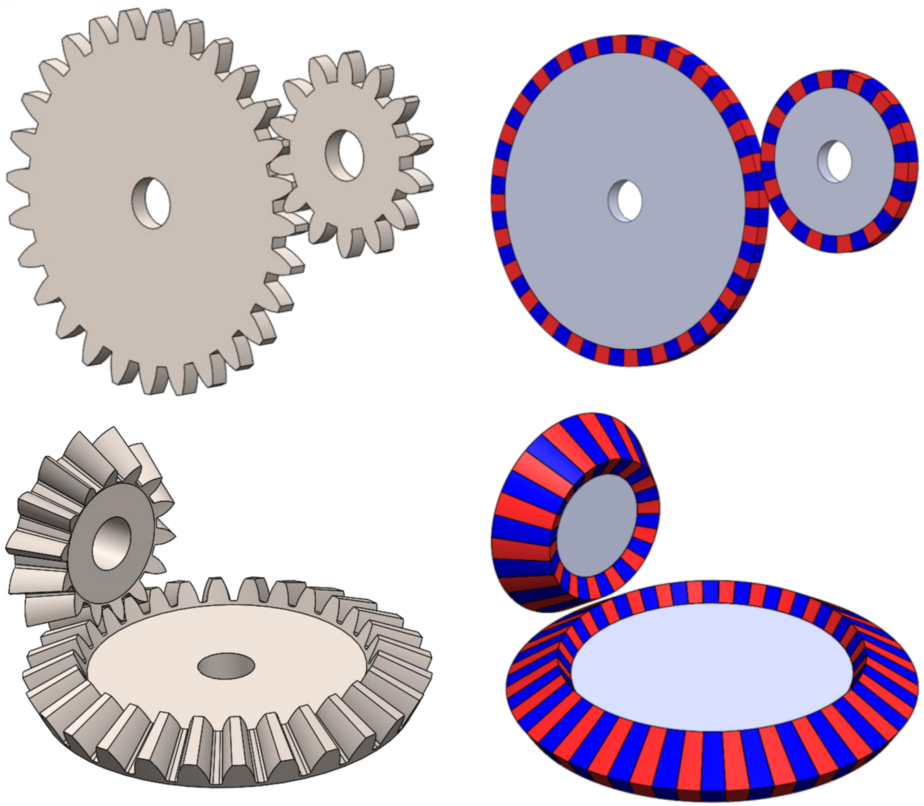
## Mechanical gearing

**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

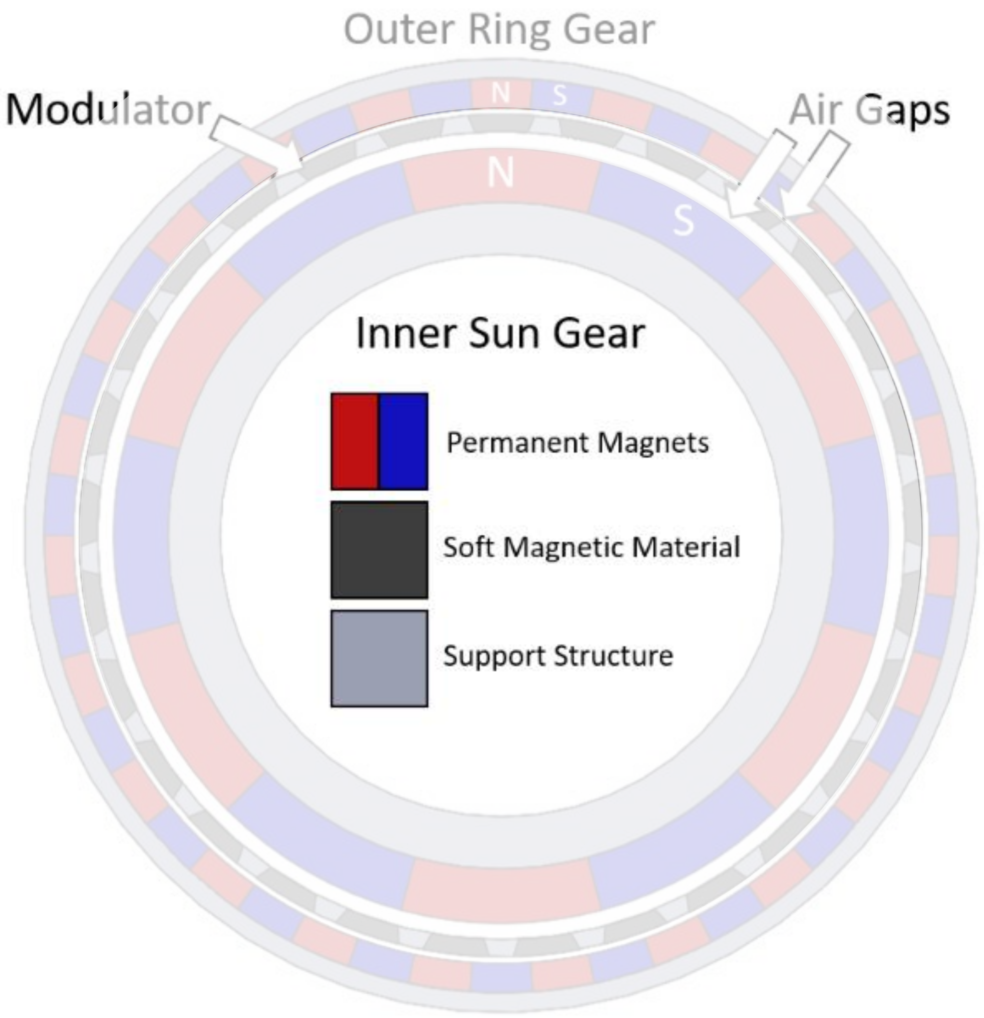
**Pros**

+ 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:

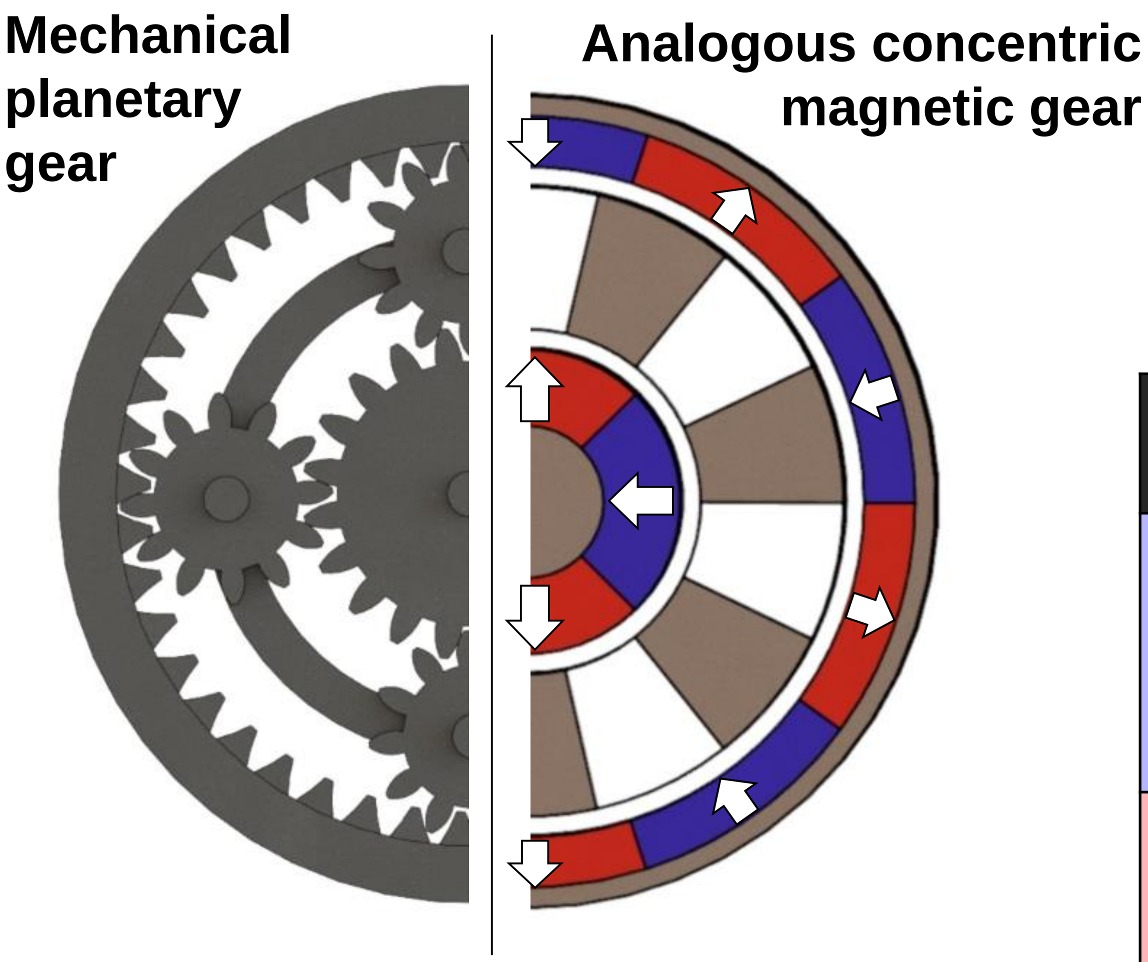
  Magnetic fields with matching spatial harmonic order can couple to transmit torque

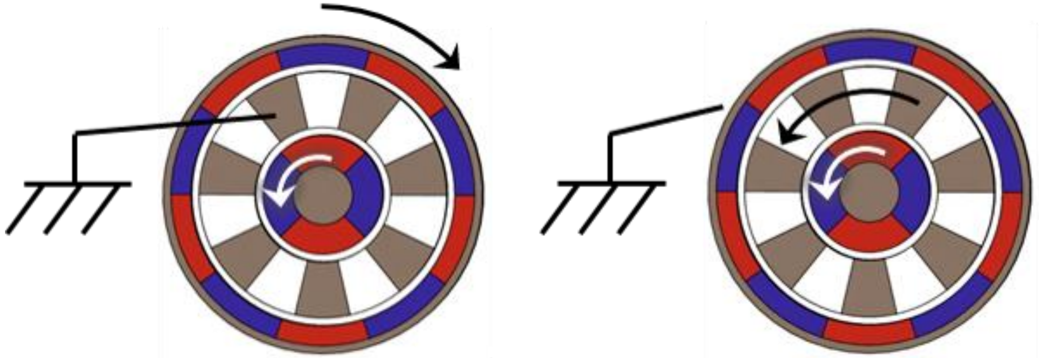
- Modulator “modulates” the flux of each rotor so that that have matching spatial harmonic order in the airgaps

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

$$Q = PR \pm PS$$

# Gear Ratio

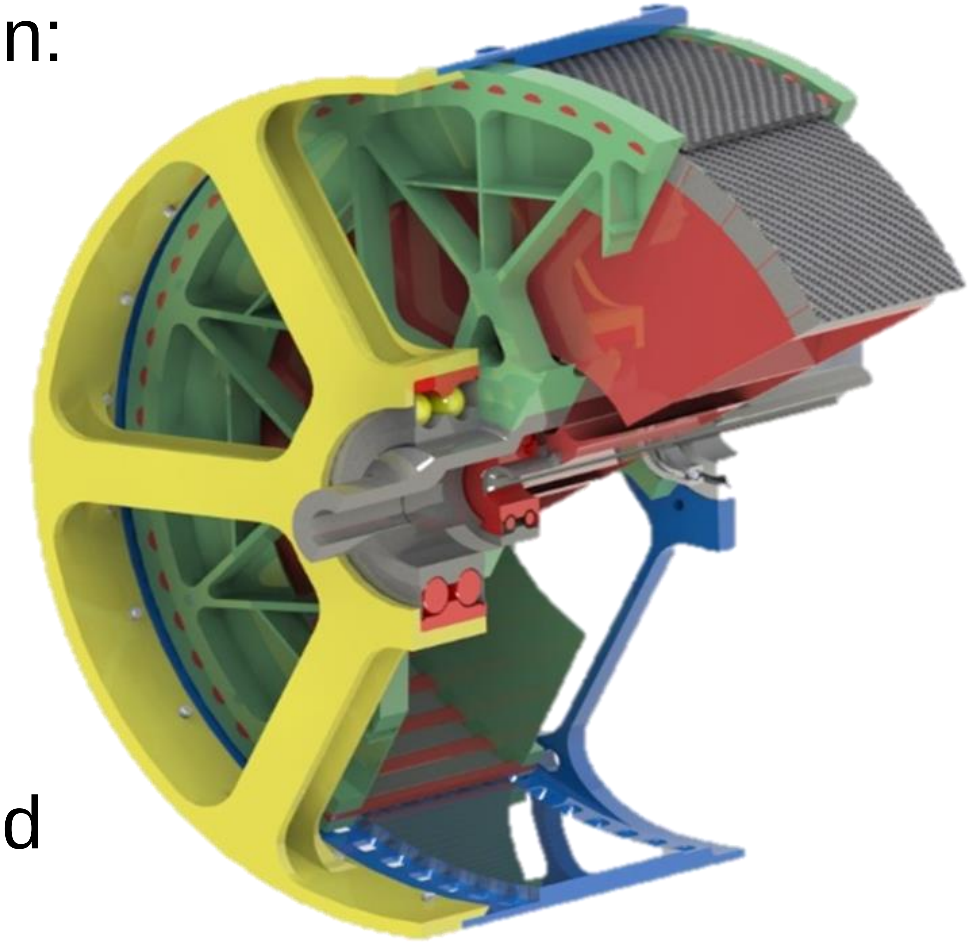


| Output | Q Selection | Gear Ratio |
|---|---|---|
| Ring Gear | PR-PS | $\frac{PR}{PS}$ |
| | PR+PS | |
| Modulator | PR-PS | $\frac{Q}{PS} = \frac{PR}{PS} - 1$ |
| | **PR+PS** | $\boldsymbol{\frac{Q}{PS} = \frac{PR}{PS} + 1}$ |

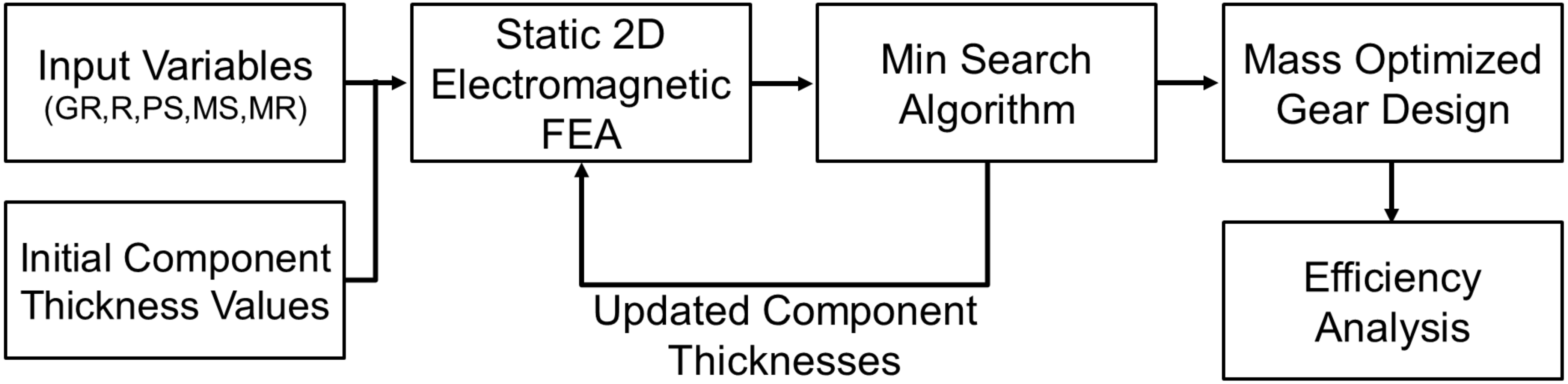
# Motivation for This Study

- Effects of higher level variable selection:
  - Number of magnets per ring gear pole pair (**MR**)
  - Number of magnets per sun gear pole pair (**MS**)
  - Gear Ratio (**GR**)
  - Sun gear Pole Pairs (**PS**)
  - Radius (**R**)
- Previous work focused on Volume and low speed (100 rpm)



# Study Methodology

- PT-4 design code
  - Only electromagnetics
  - Produce electromagnetic (EM) mass optimized designs
- Efficiency analysis on select Designs
- PT-2 used as validation point



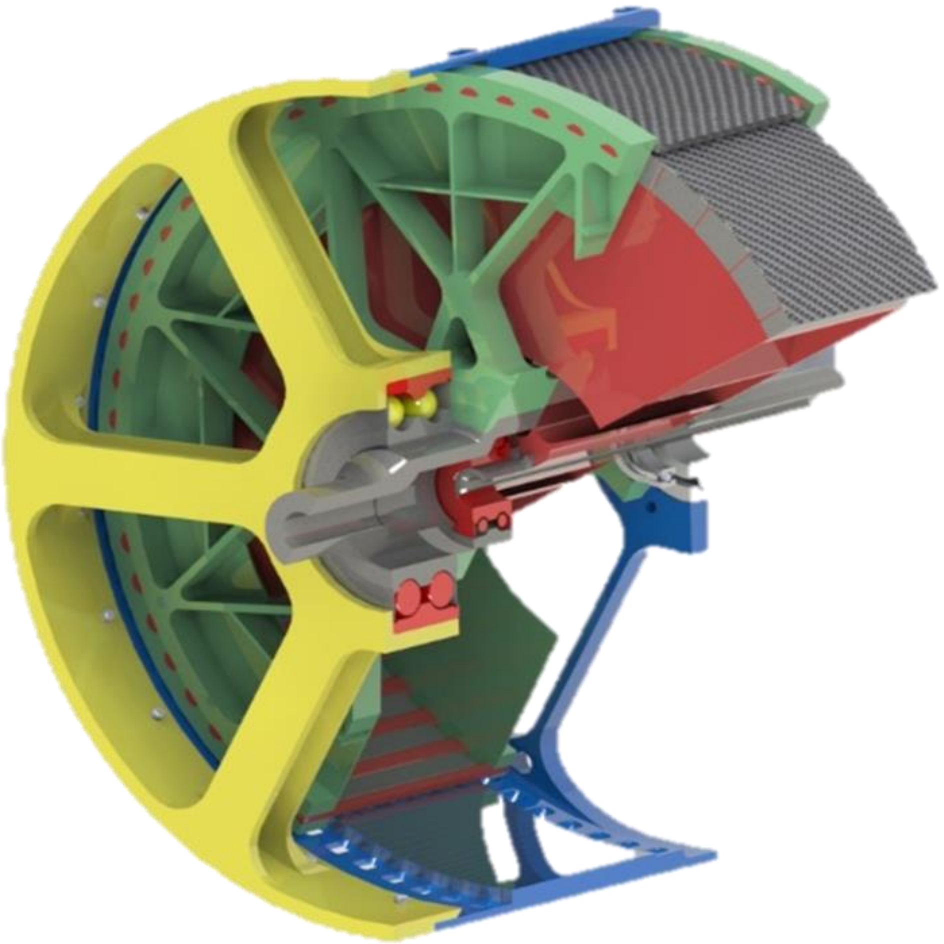
# Fixed Study Variables

- Based on PT-2
- 65% 2D to 3D torque reduction
- ~50 kW output power
- Gap Between Magnets
  - Tolerances/Mechanical
- High-speed Sun Magnet Retaining Hoop
  - Sets Sun-Mod Magnetic Gap

| Variable | Metric |
|---|---|
| Outer Diameter | 140 mm |
| 2D Output Torque | 185 Nm |
| 3D Output Torque | 120 Nm |
| Output Speed | 4000 RPM |
| Mechanical Airgap Thickness | 1 mm |
| Min Sun Magnet Thickness | 5 mm |
| Min Pole Piece Thickness | 2.5 mm |
| Min Ring Magnet Thickness | 3 mm |
| Inter-Magnet Wall Thickness | 0.5 mm |
| Inner Pole Piece Span Angle (rad) | 1.2*π/PR |
| Mid Pole Piece Span Angle (rad) | 1.2*π/PR |
| Outer Pole Piece Span Angle (rad) | 0.6*π/PR |
| Magnetic Material | Neodymium N52 |
| Electrical Steel | $Fe_{49}Co_{49}V_2$ |
| Allowable Stress in Carbon Fiber | 600 MPa |

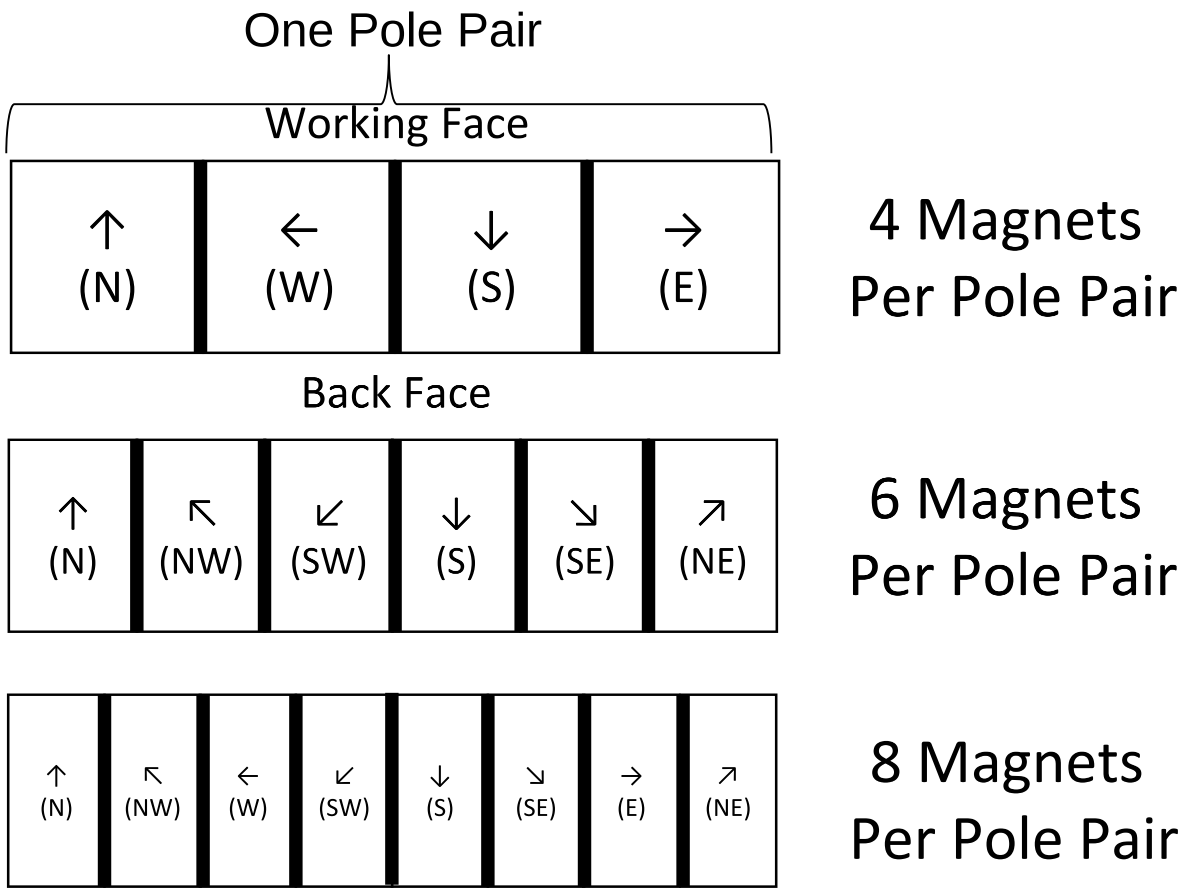
# Specific Torque Definition

- 2D EM Specific Torque
  - Traditional metric for magnetic gears
  - =185/(EM Mass)
- EM Specific Power
  - 50 kw
  - 1 Nm/kg @ 4000 rpm  = .27 kw/kg
  - 130 Nm/kg = 35 kw/kg
  - Typical PM Motor = 5-16 kw/kg



# Magnets Per Pole Pair in Halbach Arrays (MS & MR)

- MS and MR are magnets per sun and ring pole pair
- Increasing Magnets per pole pair:
  - Improves array specific flux
  - Improves harmonic distortion
  - Reduce eddy current loss
- It also decreases magnetic fill percentage
  - 0.5 mm wall assumption




Arrows denote magnetization direction*

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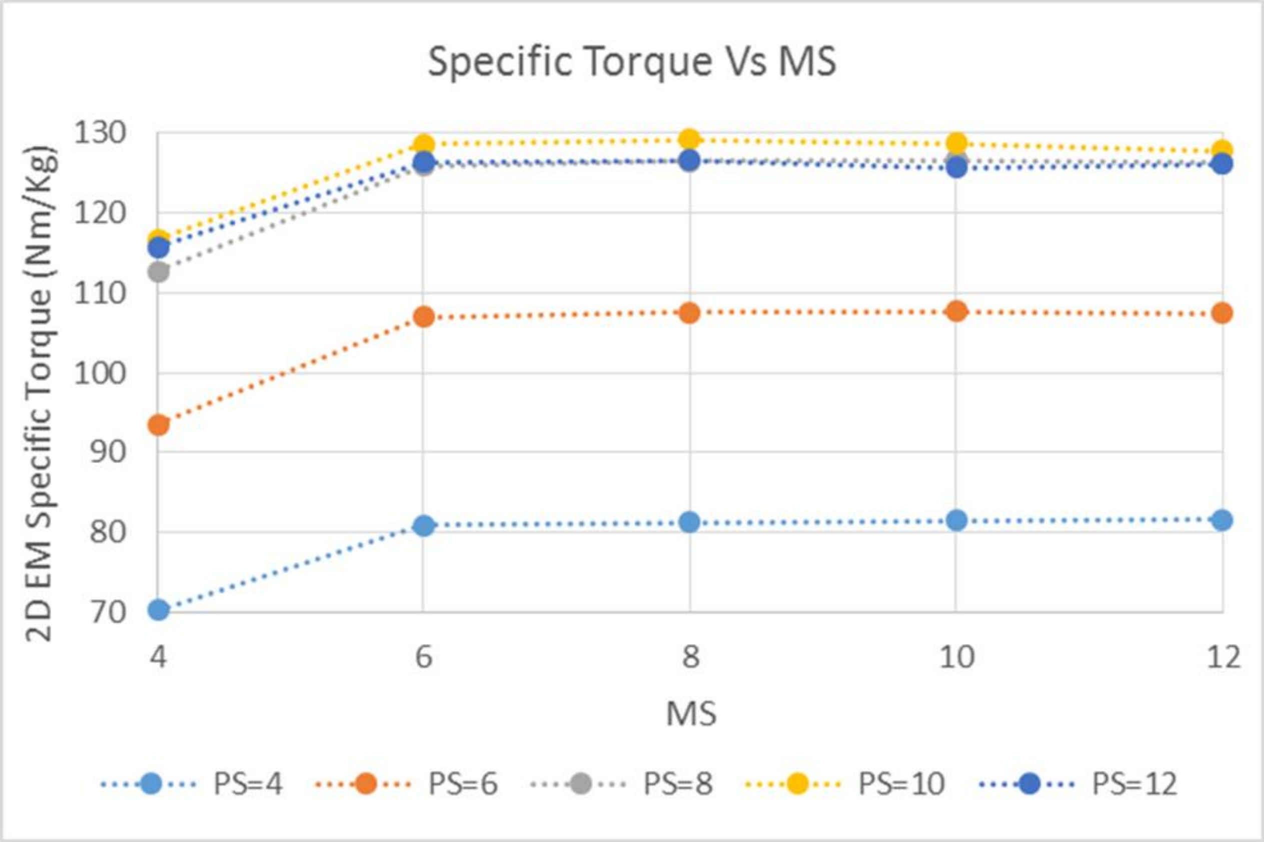

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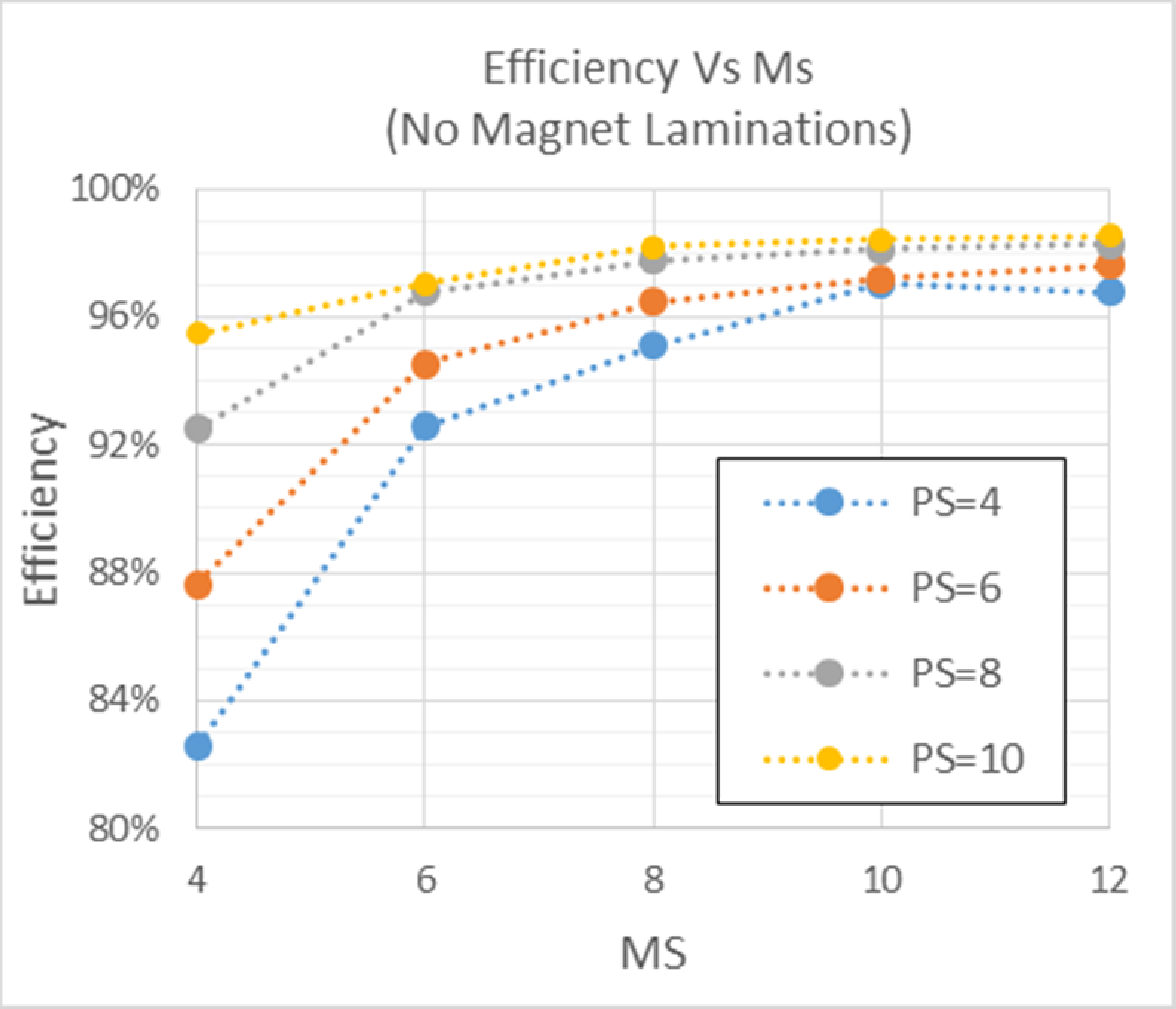
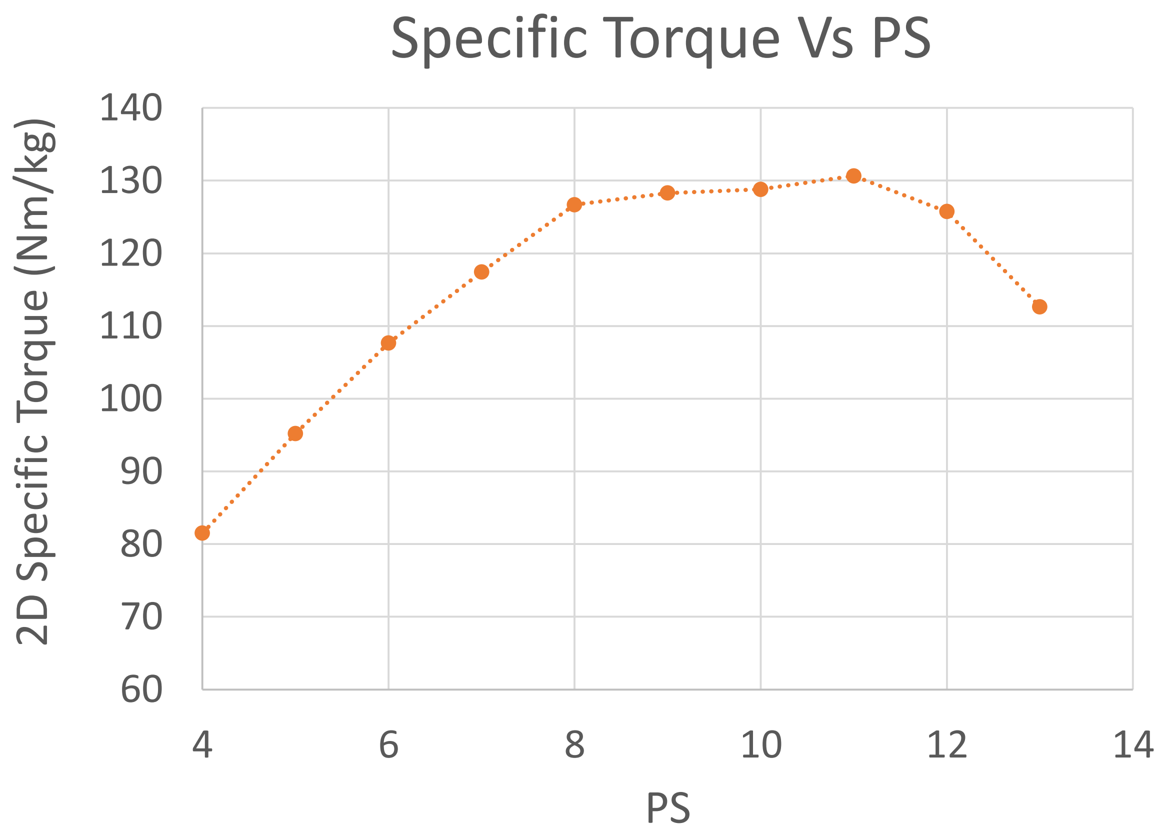


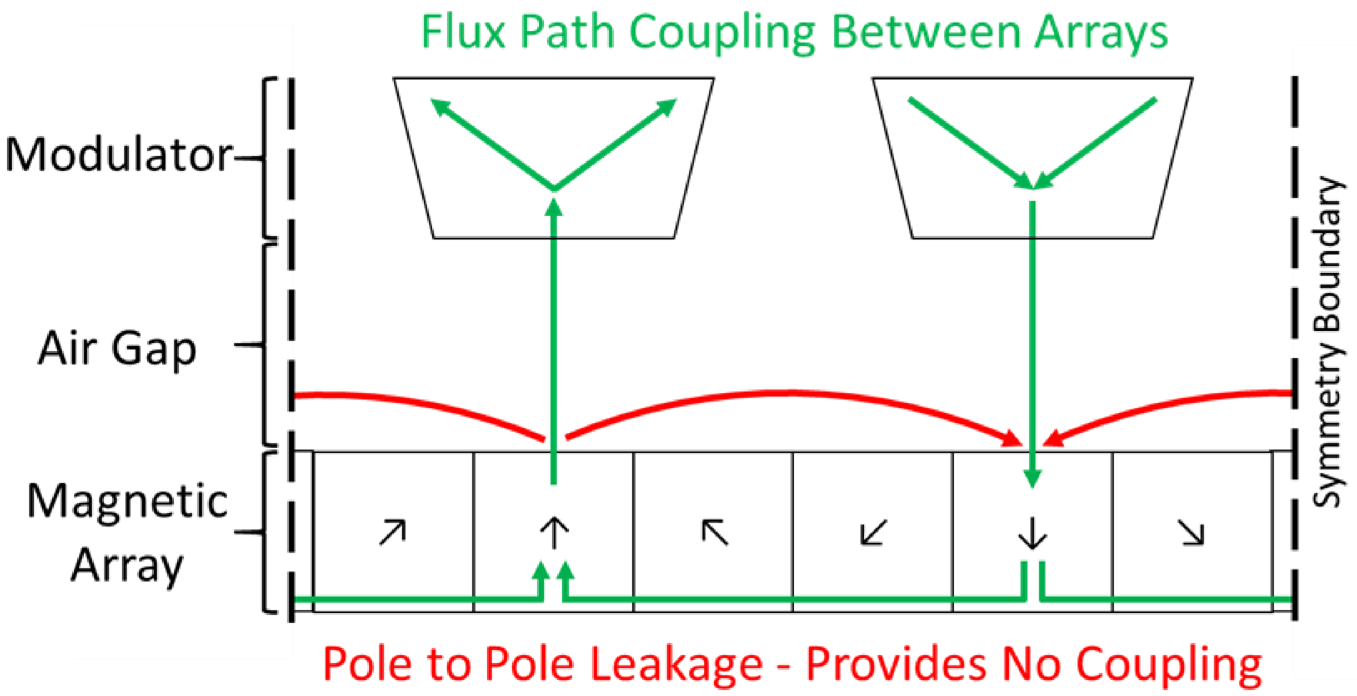
# Effect of Sun Gear Pole Pairs On Specific Torque

- Fixed Variables:
  - OD=140 mm
  - Gear Ratio = 4
  - MS=10, MR=6
- As PS Increases:
  1. Modulator Thickness decrease
     » Lower Reluctance Between Poles
  2. Specific Flux of Arrays increase
  3. Pole-to-Pole Ring Gear Leakage



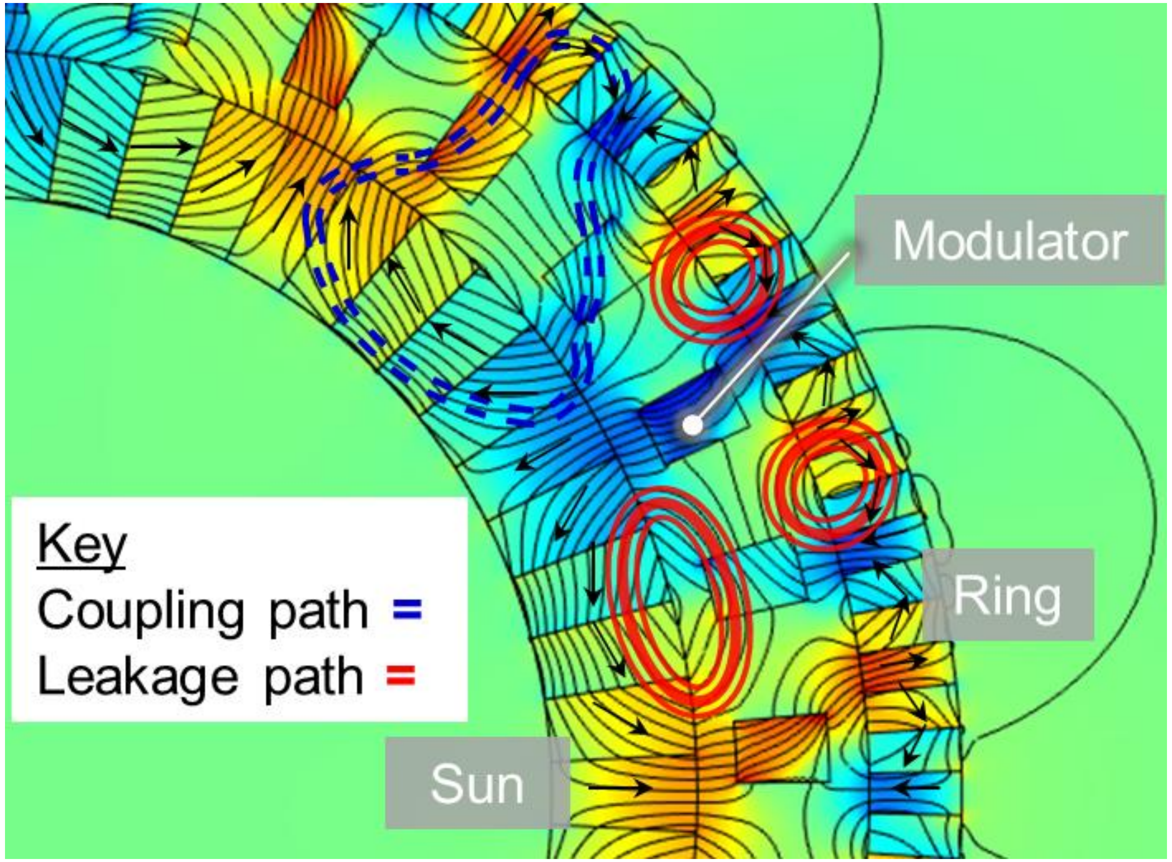
# Pole-to-Pole Leakage Explanation

- Flux that couples between magnetic arrays provides torque
- Flux that leaks through air gap, providing no torque
- Percent of flux that leaks governed by relative reluctance
  - $R_{couple} \sim airgap$
  - $R_{leak} \sim length_{pole-to-pole}$



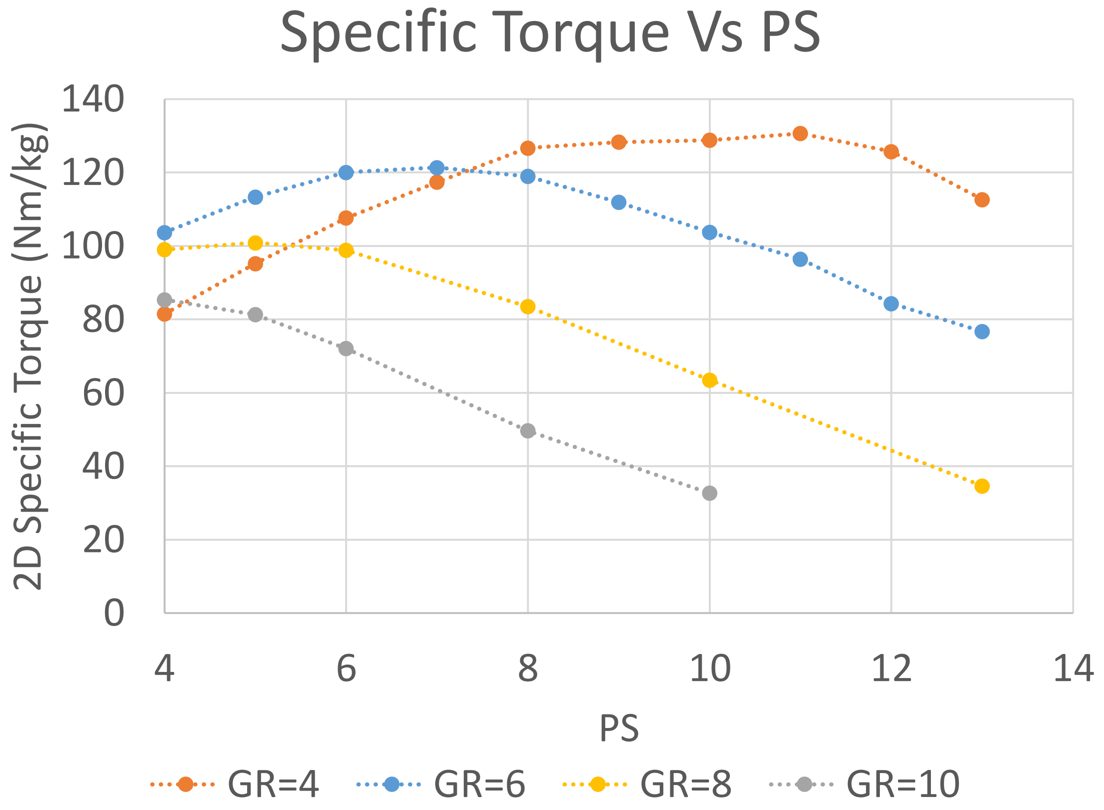
# Pole-to-Pole Leakage Explanation

- PR=Q−PS=(GR−1)∗PS
  - PR>PS
  - Pole-to-Pole length Smaller
- Higher percent of ring gear flux leaks than sun gear
  - Why sun gear magnets are typically thicker
- PR limits optimum PS
  - Optimum PS set by where ring gear leakage is significant



# Effect of Sun Gear Pole Pairs (PS) on Specific Torque

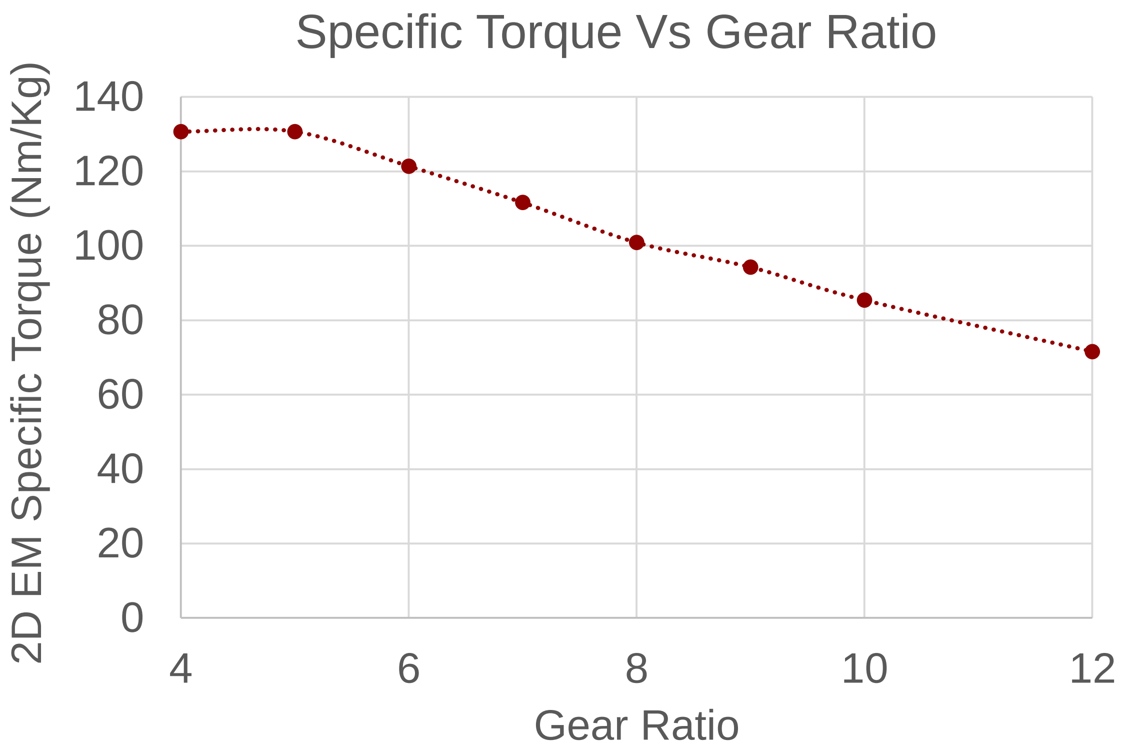
| Gear Ratio | PS Optimum | PR Optimum |
|---|---|---|
| 4 | 11 | 33 |
| 5 | 8 | 32 |
| 6 | 7 | 35 |
| 7 | 6 | 36 |
| 8 | 5 | 35 |
| 10 | 4 | 36 |




At an OD of 140mm
Optimum PR value = 32-36

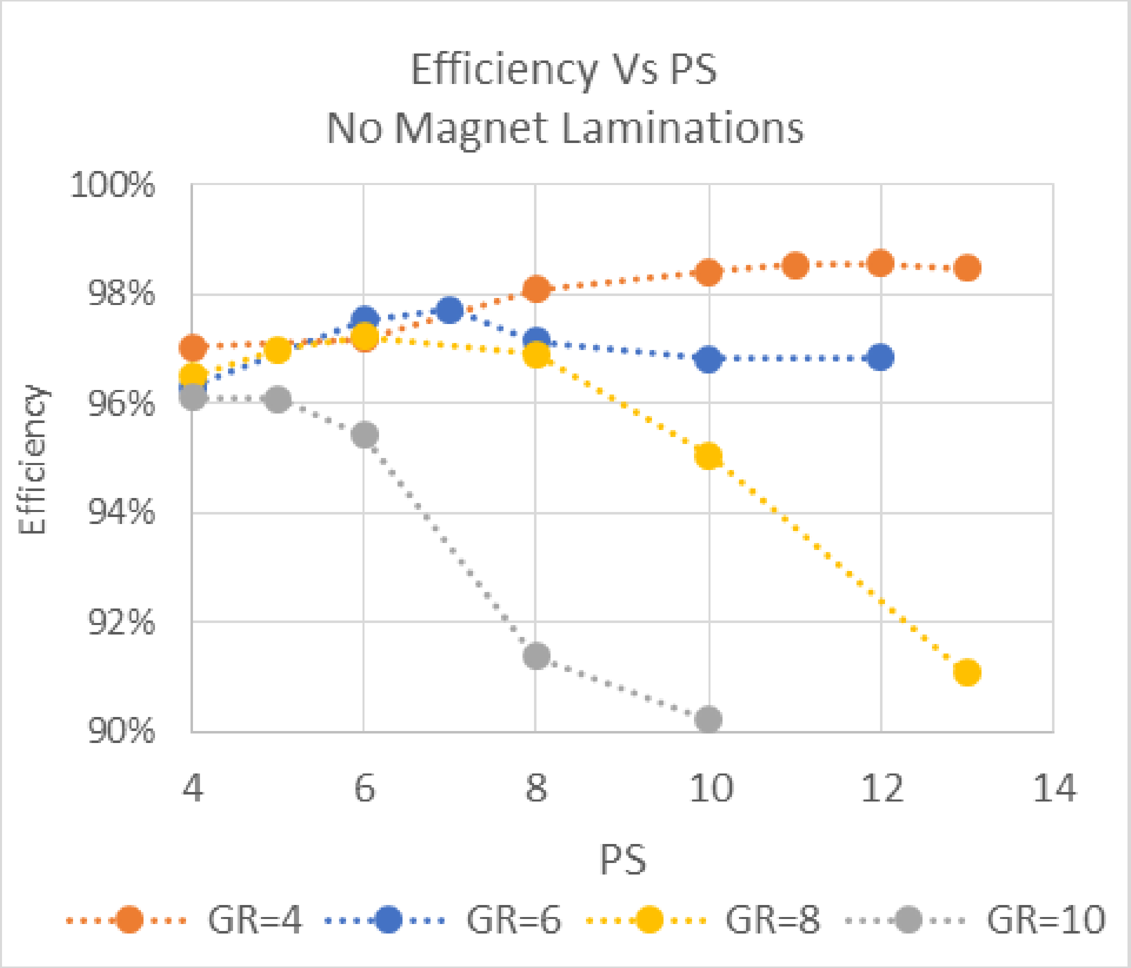
# Effect of Gear Ratio (GR) on Specific Torque

- Output speed = 4000 RPM
- Input speed = 4000*GR
  - At GR=10 Input Speed=40,000
- Leads to large sun gear retaining hoop
  - Large sun gear magnetic airgap
- Secondary Effect:
  - Lower Sun Gear Pole Count



# Effect of PS and GR on Efficiency Without Magnet Laminations

- Without Laminations Sun Gear Losses Dominate
- Sun gear losses go with the size of the sun gear magnets
  - $P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T (\frac{dB}{dt})^2\, dt$
- Overall Efficiency goes with mass



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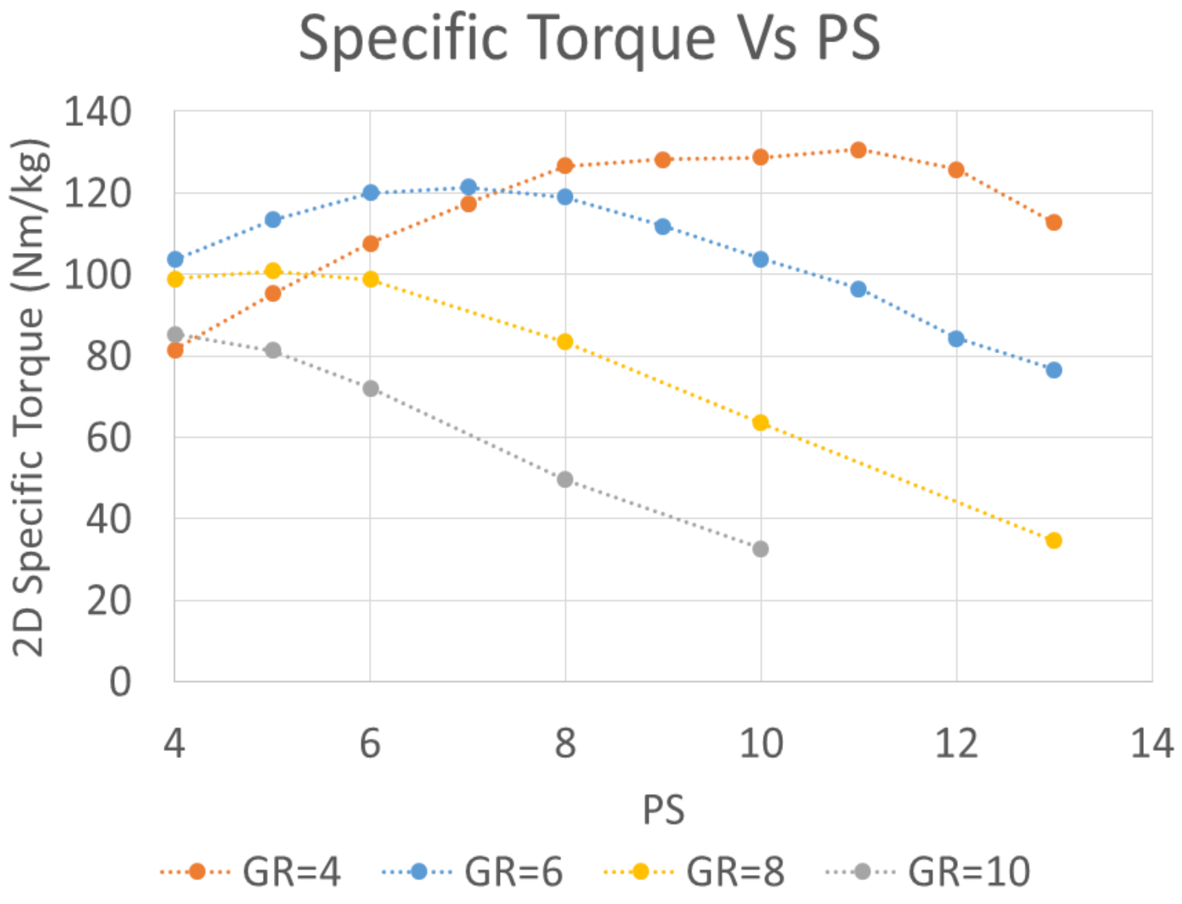
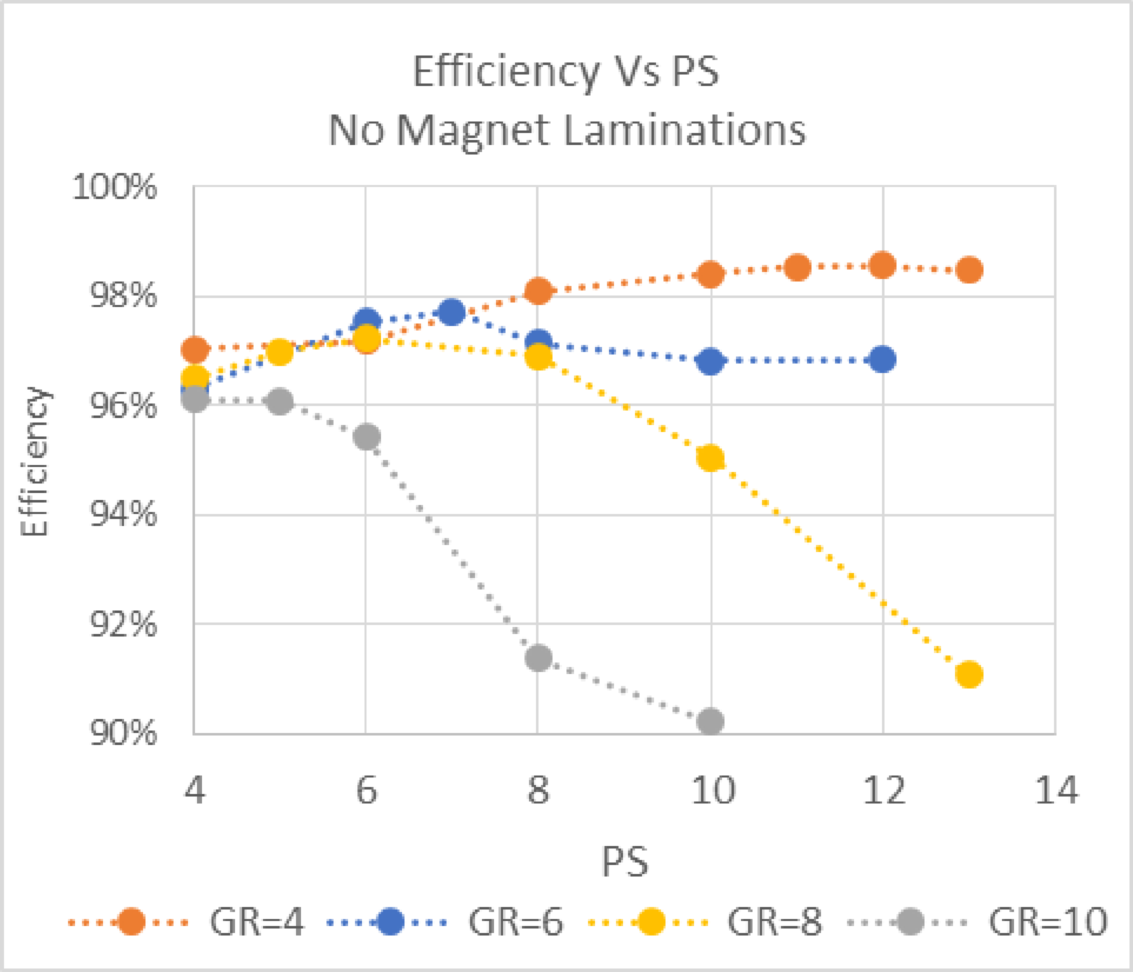
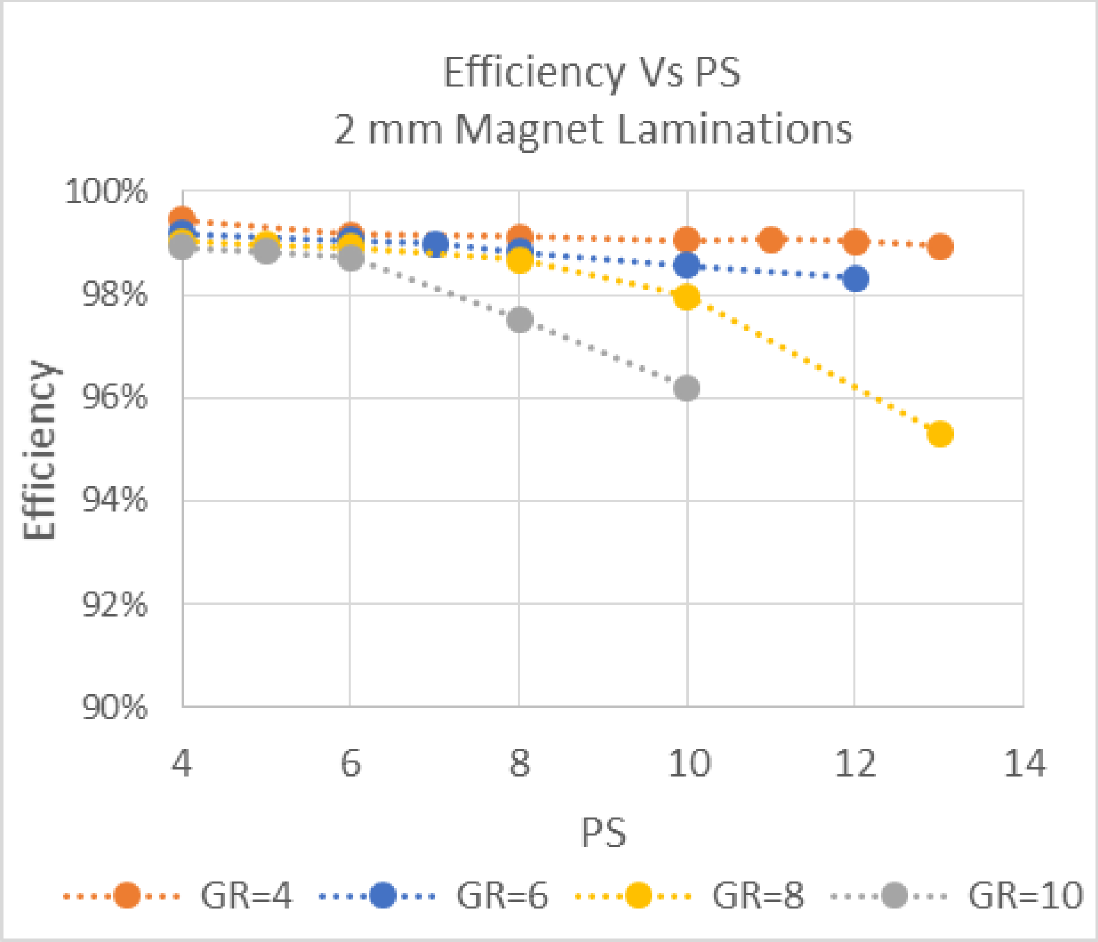


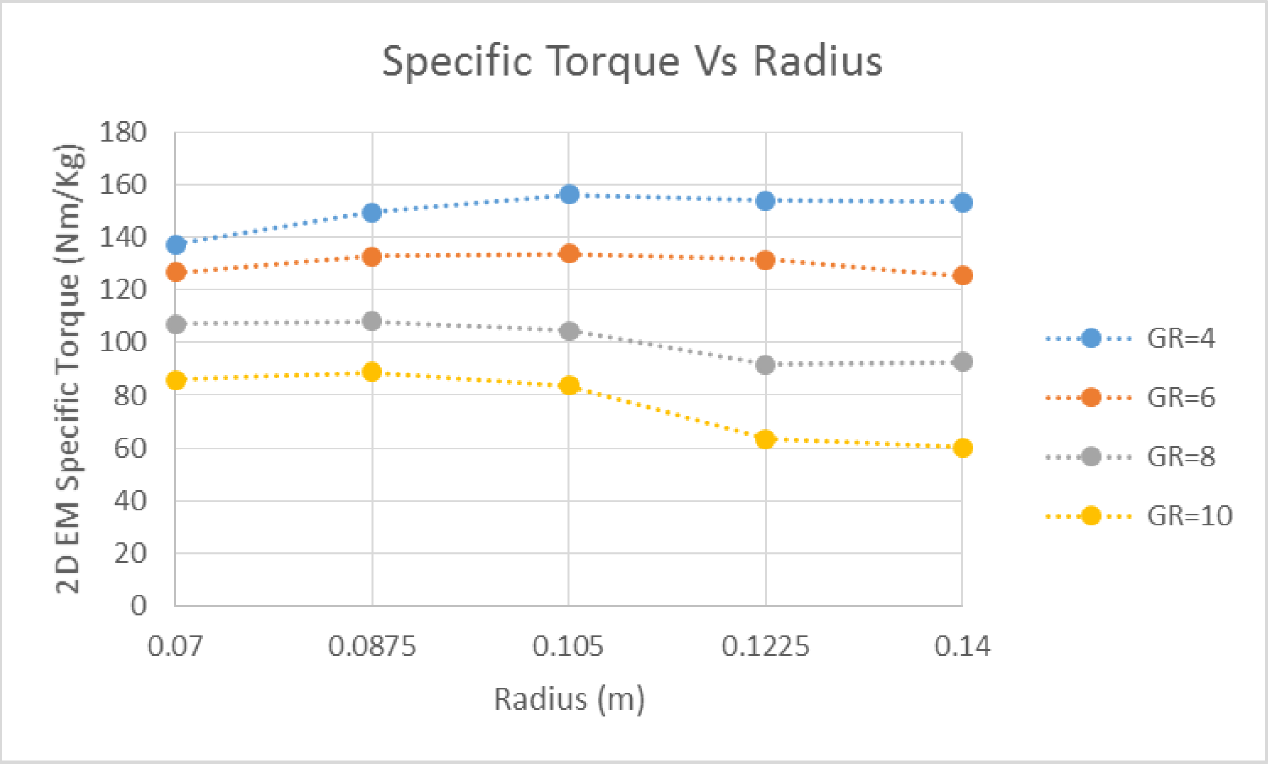
# Effect of PS and Gear Ratio on Efficiency With 2mm Laminations

- Magnet Losses reduced with laminations
- Modulator Losses are dominant
- Efficiency goes with electrical frequency of the sun and ring gears on the modulator



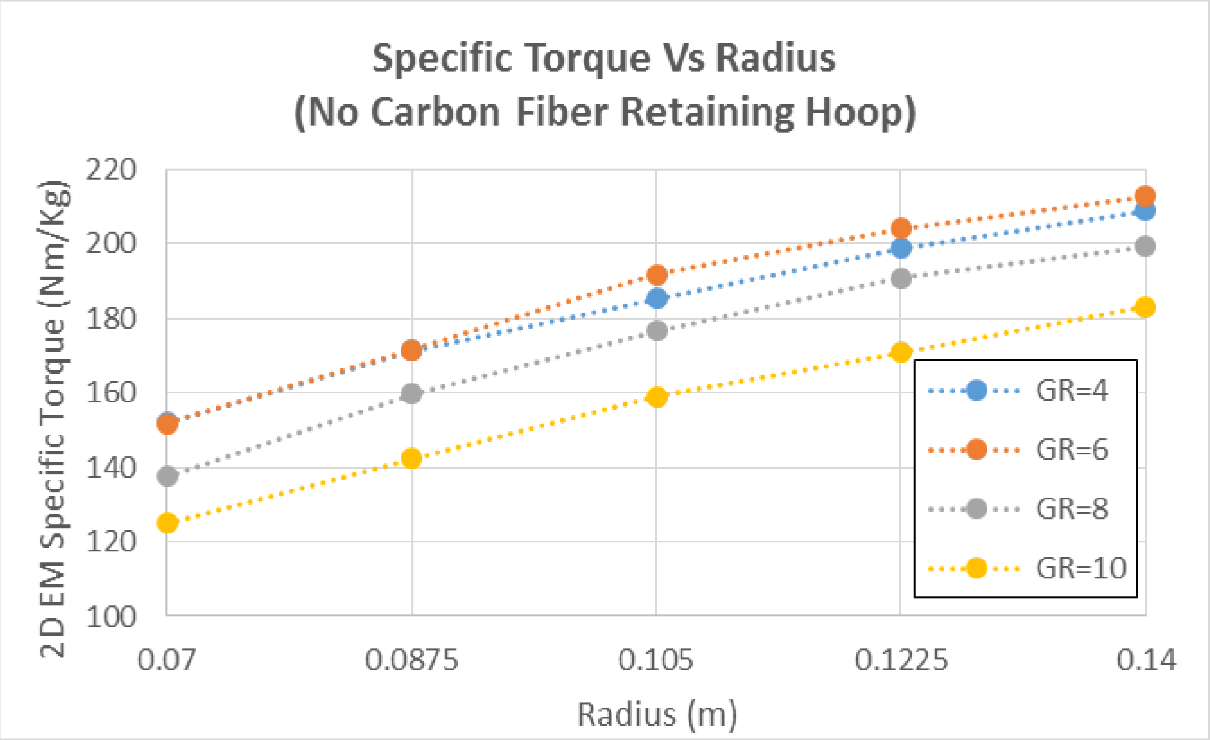
# Radius Effects on Specific Torque

- Fixed Variables
  - MS=10
  - MR=6
- Airgap=(.0047*OD + .27)[mm]
- Swept PS, GR, and Radius
  - Select optimum PS
- 4000 RPM Output Speed
  - leads to large sun magnet retaining hoop



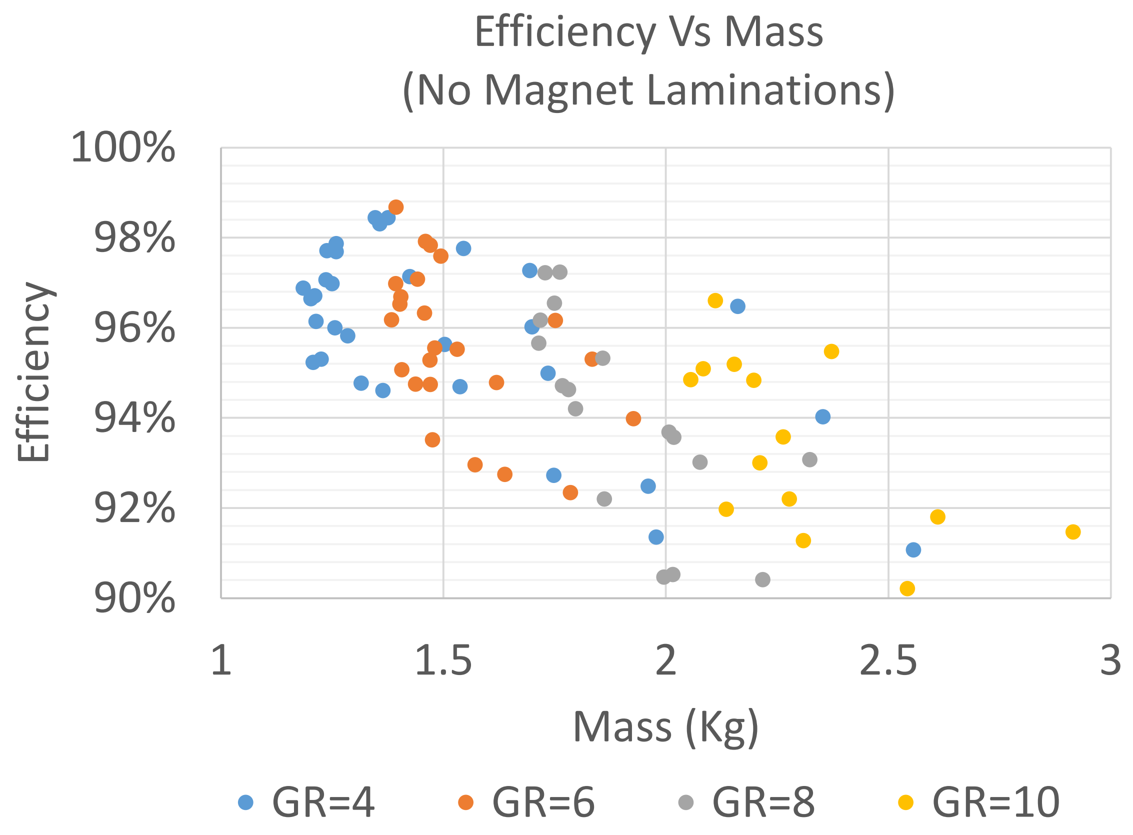
# Radius Effects on Specific torque

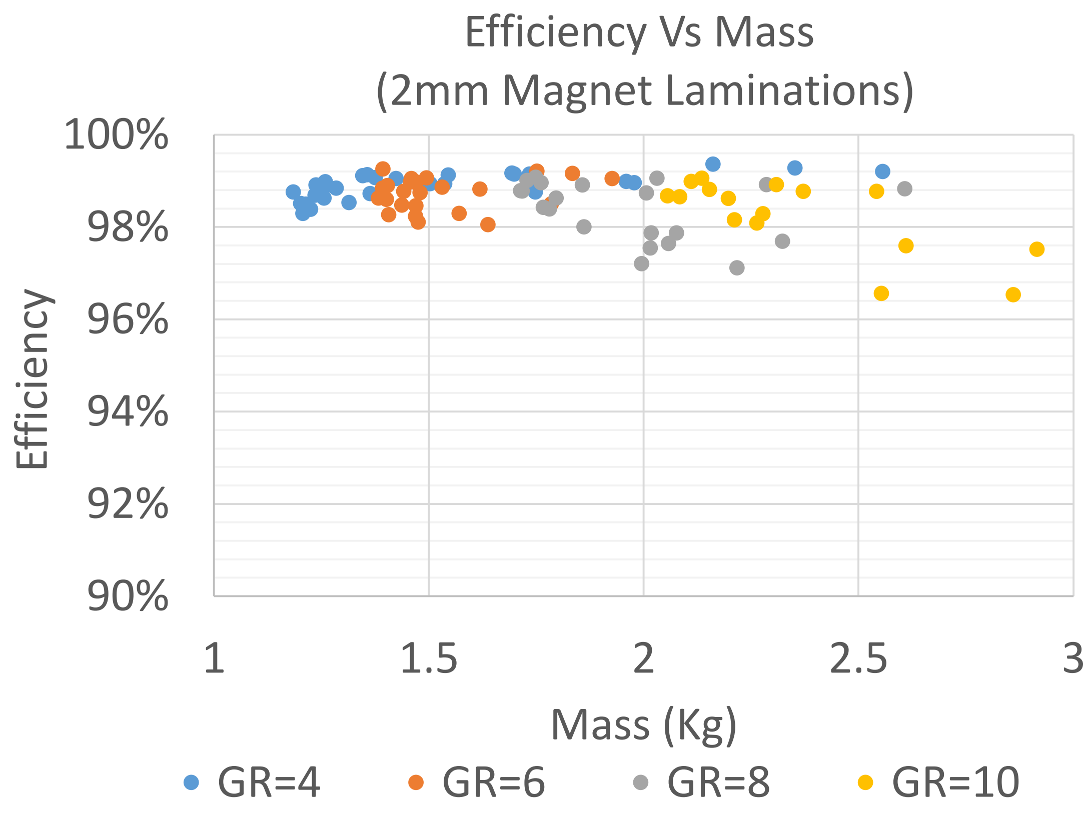
- Rerun with Output Speed = 0
  - No Carbon Fiber Hoop
- Specific Torque increased significantly
- Gear Ratio Effect Reduced
- Specific torque increase linear if constant airgap



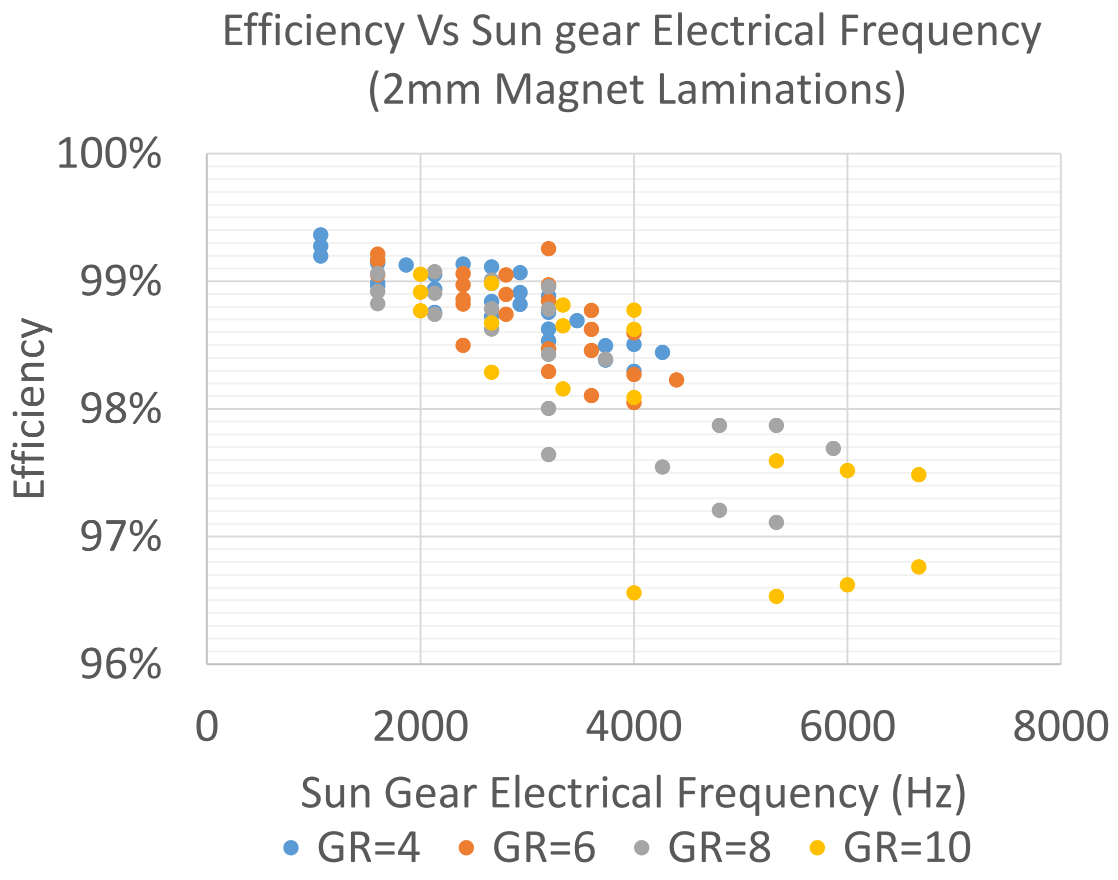
# Mass and Efficiency Trends

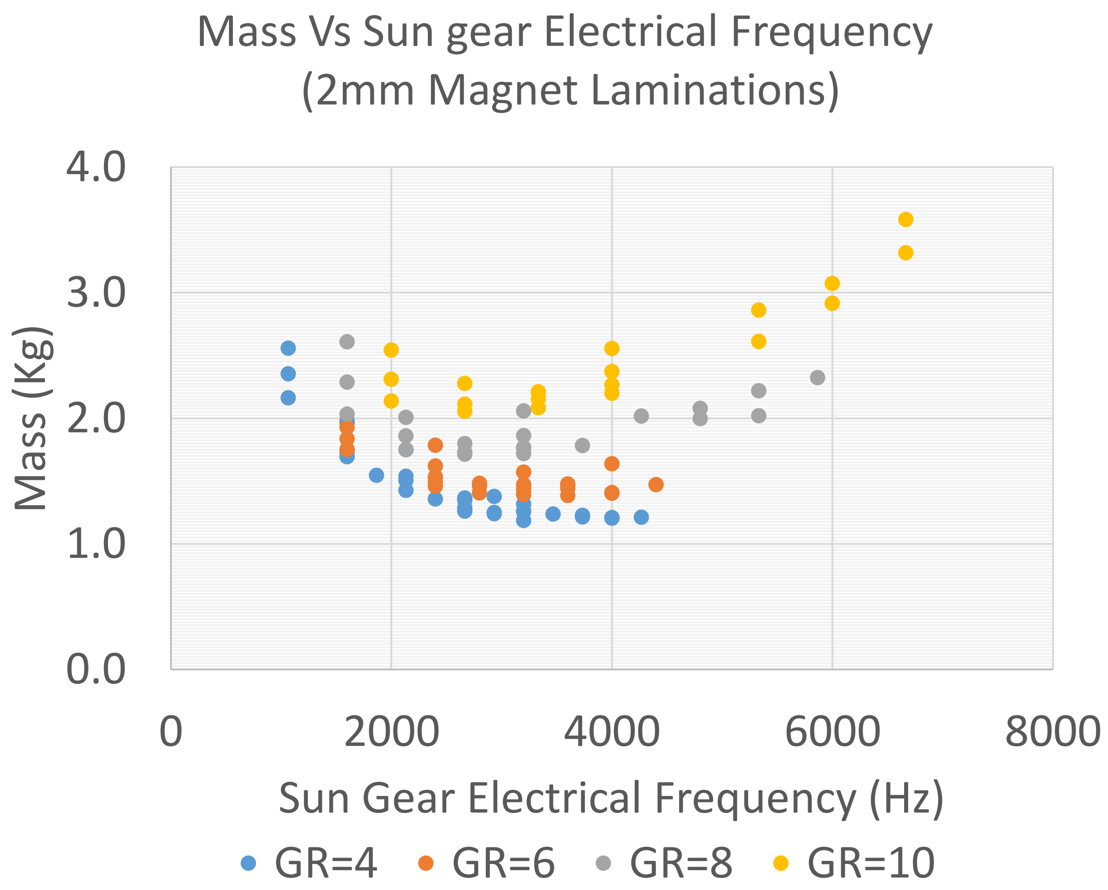
## Efficiency Vs Mass



# Efficiency and Mass Vs Sun Gear Electrical Frequency



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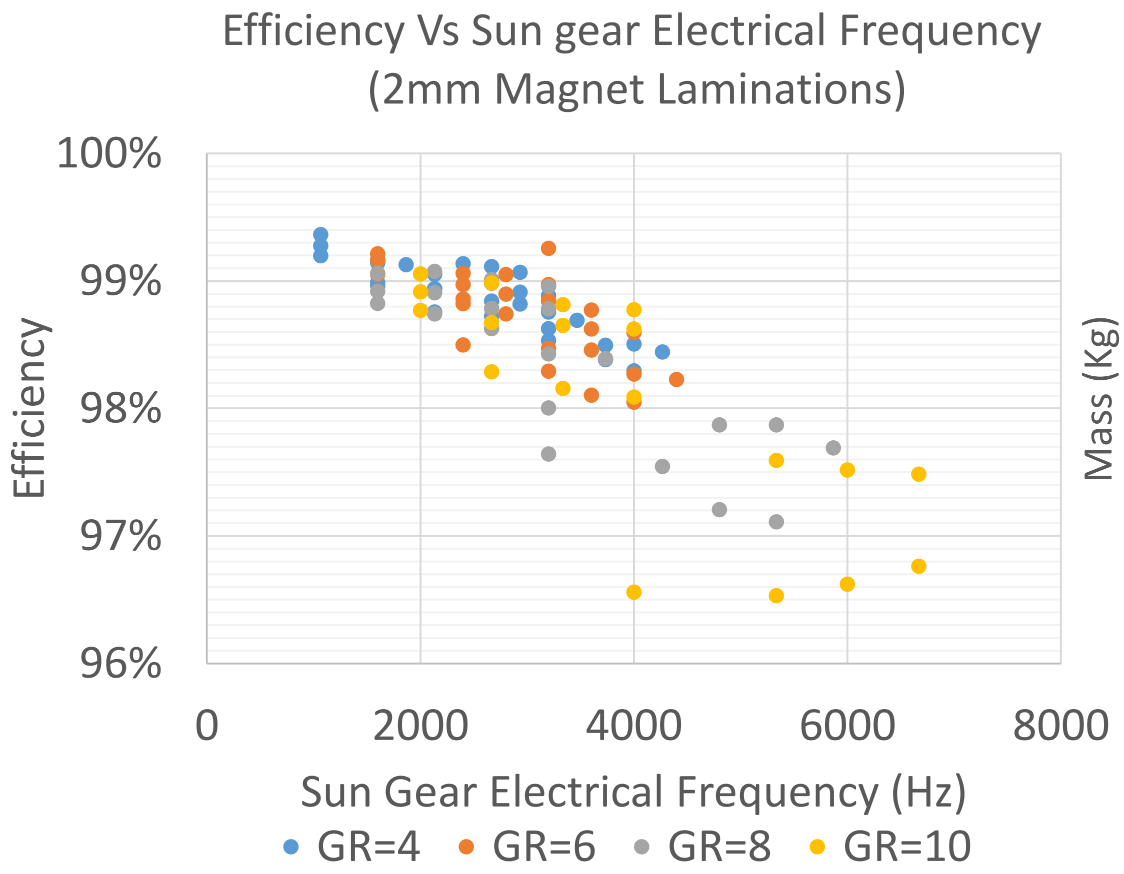


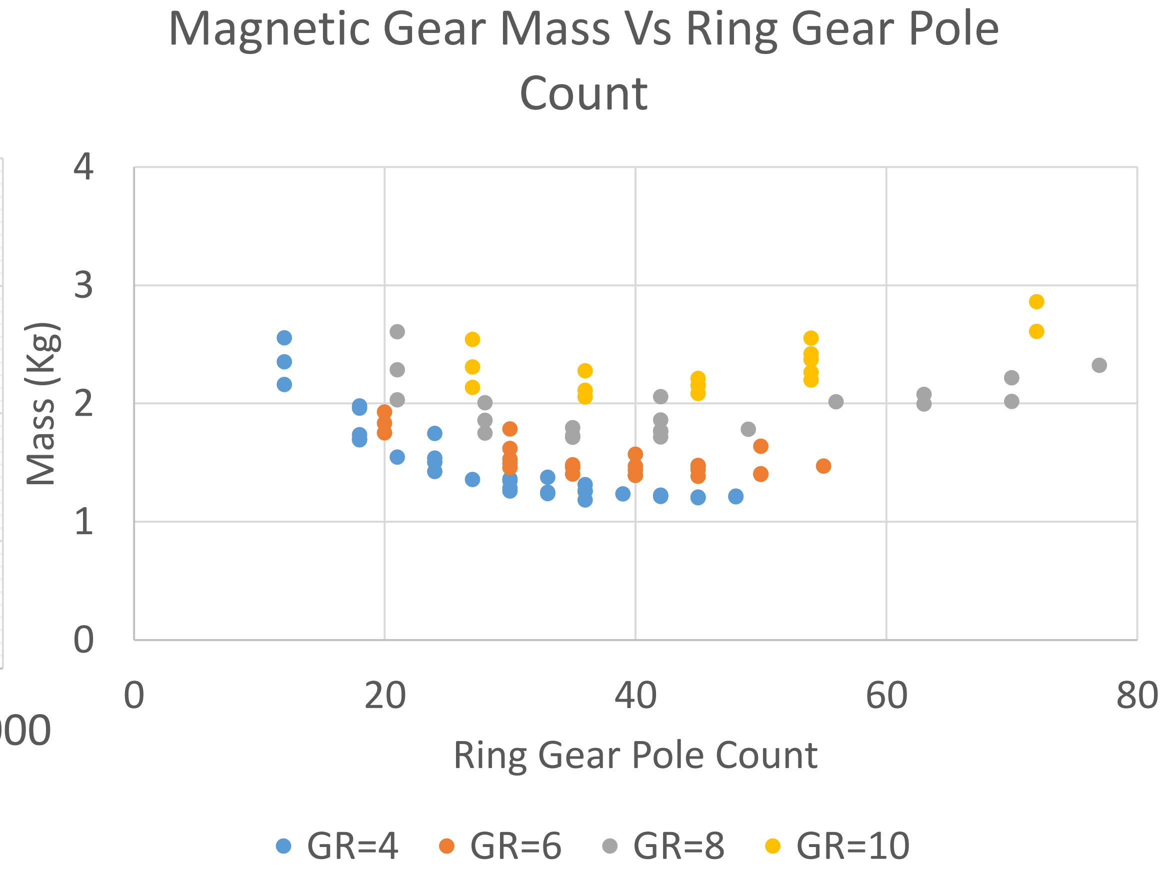

# Summary

- Magnets per pole pair in a Halbach array
  - Increase Specific torque
    - Unless significant magnet fill percentage loss
    - Diminishing marginal returns past a value of 6
  - Increase Efficiency
- At a given Gear Ratio and Radius, there is an optimum Sun Gear Pole Pair Count
  - Set by ring gear pole count (pole-to-pole distance)
- Without laminations sun gear losses dominate
  - Efficiency goes with mass

# Summary

- With magnet laminations modulator losses dominate
  - Efficiency goes with electrical Frequency
  - >99% electromagnetic Efficiency can be achieved
- Sun gear speed significantly affects achievable specific torque
  - Sets sun gear to modulator airgap size
  - Can cause significant specific torque decay with gear ratio
  - Can limit specific torque increases with radius
- Specific torque scales linearly with radius if magnetic gaps constant

# Future work

- Similar study on component thickness
- Fold this work into design code
  - Create a more complete design code
- Optimized magnetically geared drivelines

# Acknowledgements


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

# QUESTIONS ?


Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
FOR THE BENEFIT OF ALL
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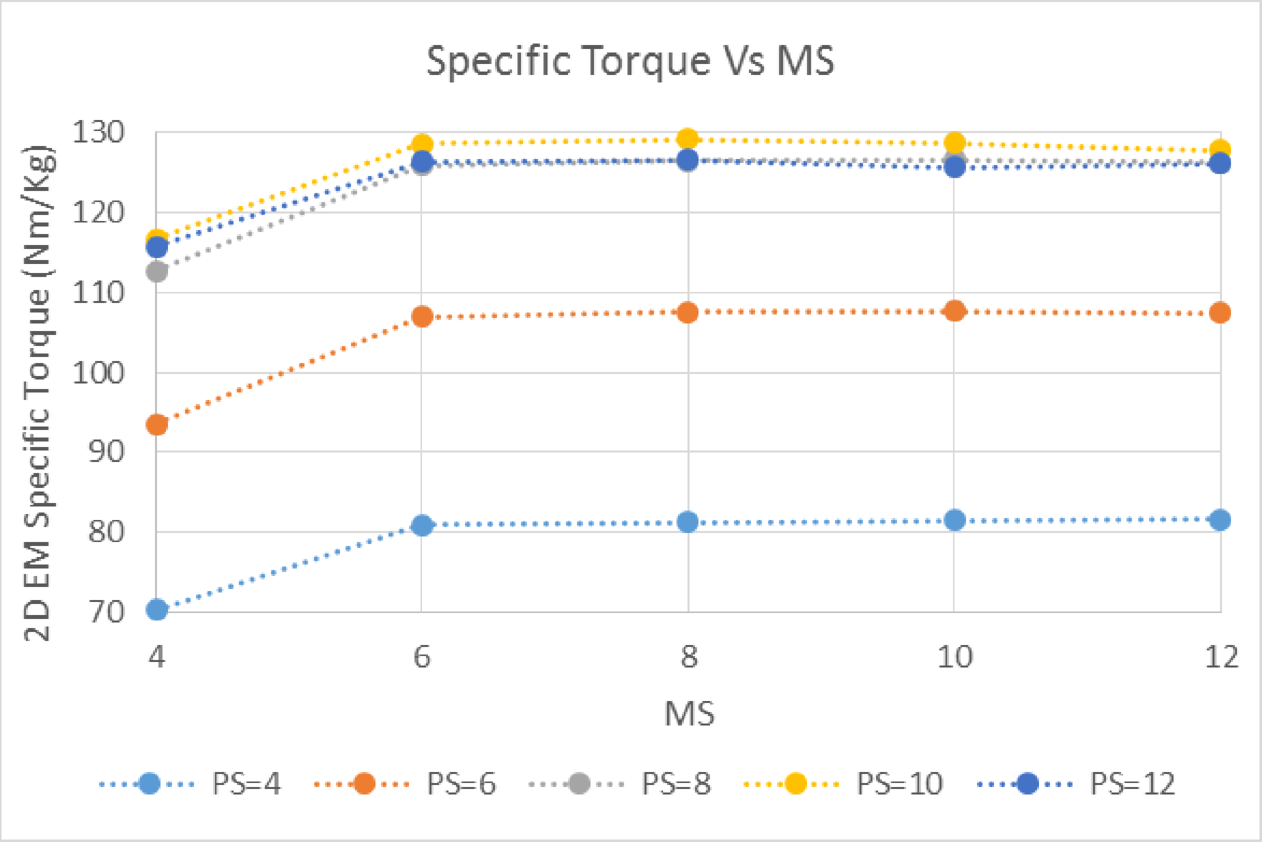
# Specific Torque Effects of MS

- Fixed Variables
  - GR=4
  - OD=140 mm
  - MR=6
- Specific Flux of Halbach Arrays
  - Diminishing marginal returns
- 0.5 mm wall leads to loss of fill at high Total sun magnets (TSM)
  - $TSM = PS * MS$



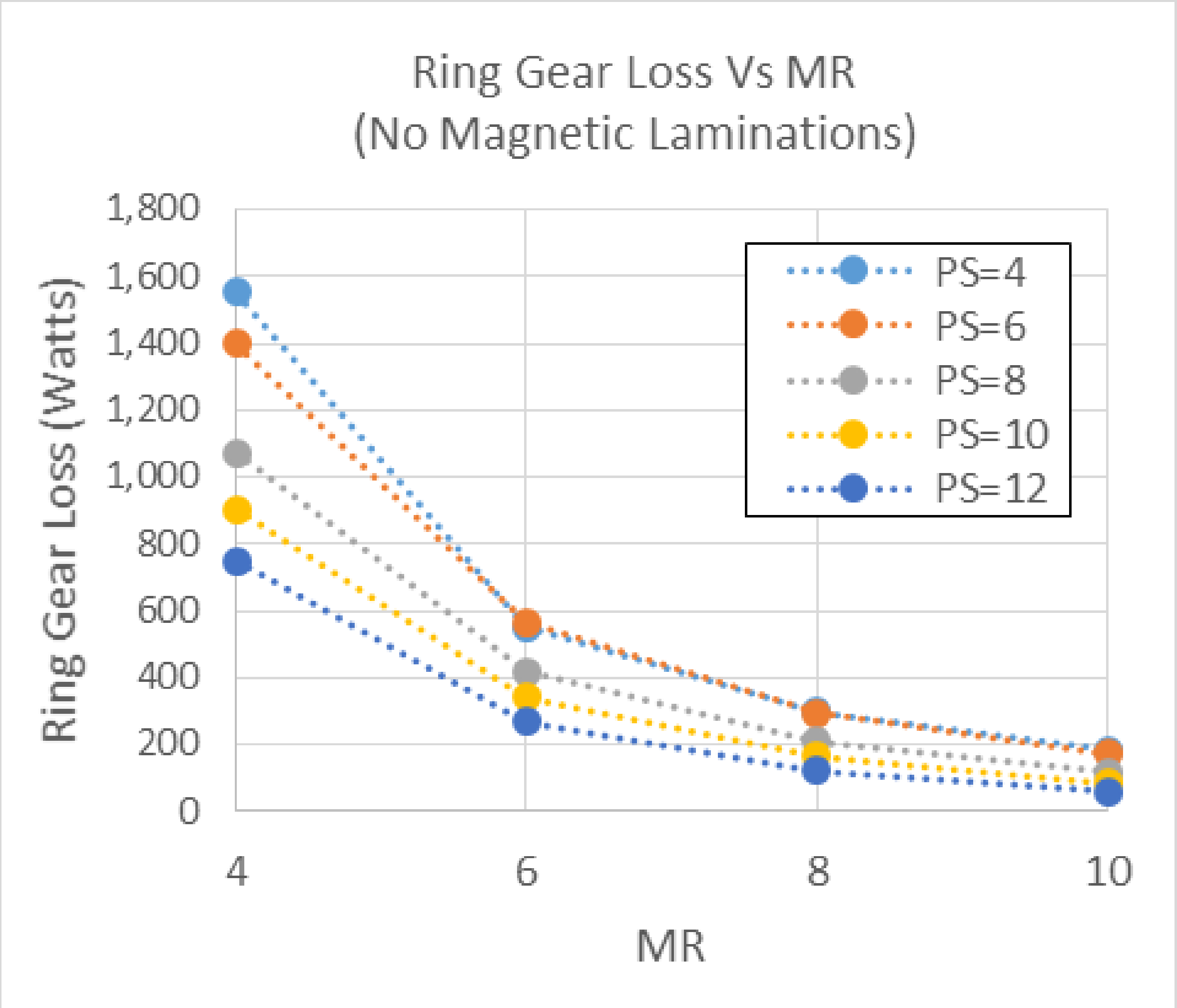
# Specific Torque Effects of MR

- Loss of Fill more prominent:
  - $TRM = PR * MR$
    $= (GR - 1) * PS * MR$
- At low PS Halbach Array Specific Flux increase dominate
- At high PS loss of fill dominate
  - 0.5 mm wall
- Different gear ratio
- Different radius

- Loss of Fill more prominent:
  - $TRM = PR * MR$
    $= (GR - 1) * PS * MR$
- At low PS Halbach Array Specific Flux increase dominate
- At high PS loss of fill dominate
  - 0.5 mm wall
- Different gear ratio
- Different radius

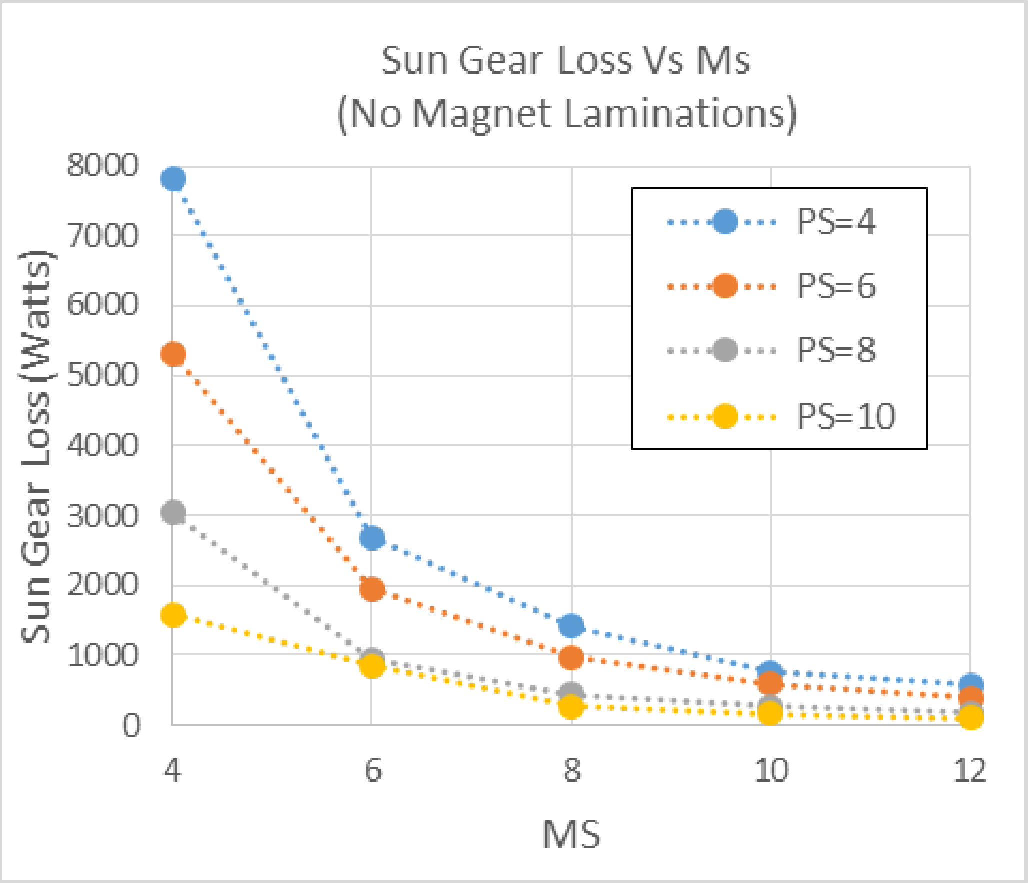
# Effect of Increase Magnet Count on Losses

- *Eddy Current Power Loss in a magnet:*
  - $P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T (\frac{dB}{dt})^2\, dt$
- $w \ll l$ :
  - $P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{l^2}\frac{1}{T}\int_0^T (\frac{dB}{dt})^2\, dt$
  - $P_c \sim w^2$
- Higher PS = lower losses
  - $TRM = PR * MR = (GR - 1) * PS * MR$



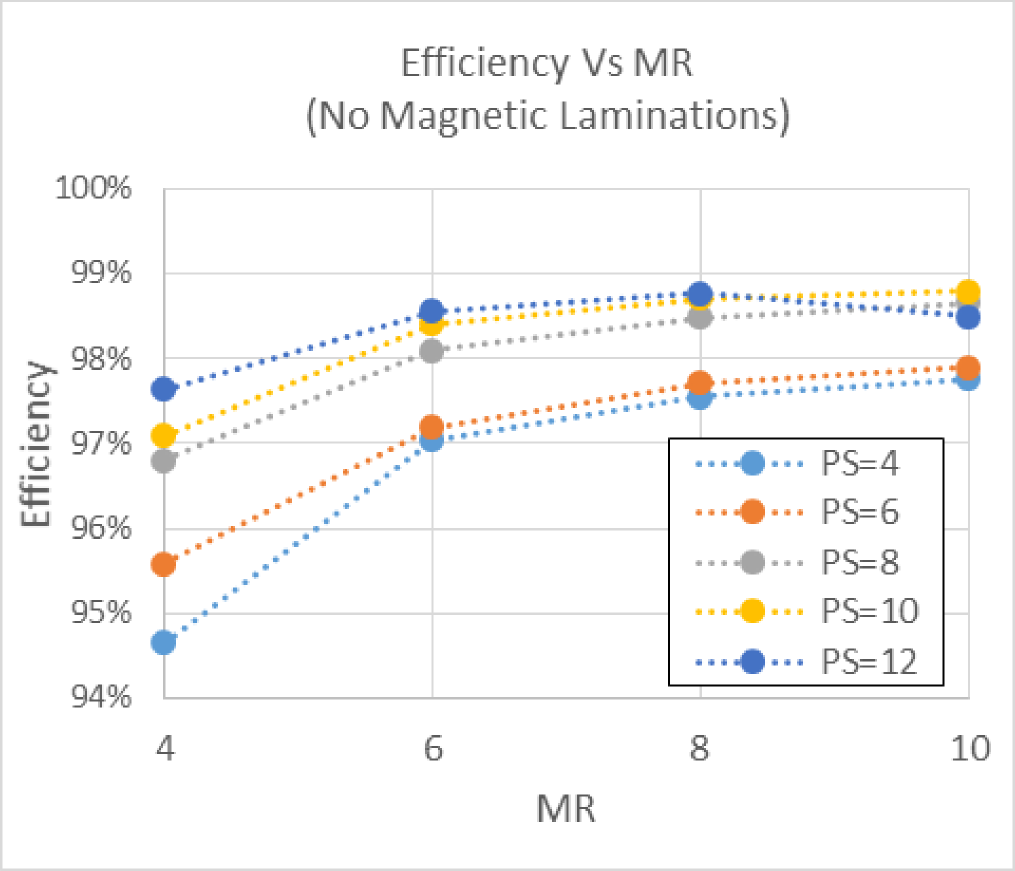
# Effect of Magnets Per Pole On Sun Gear Losses

- Similar to MR
  - $w < l$ not $w \ll l$
- Losses higher in sun gear
  - Larger width
  - Overall Larger Volume
  - Frequency of Ring Flux on Sun
- Higher PS decreases losses
  - $TSM = PS * MS$

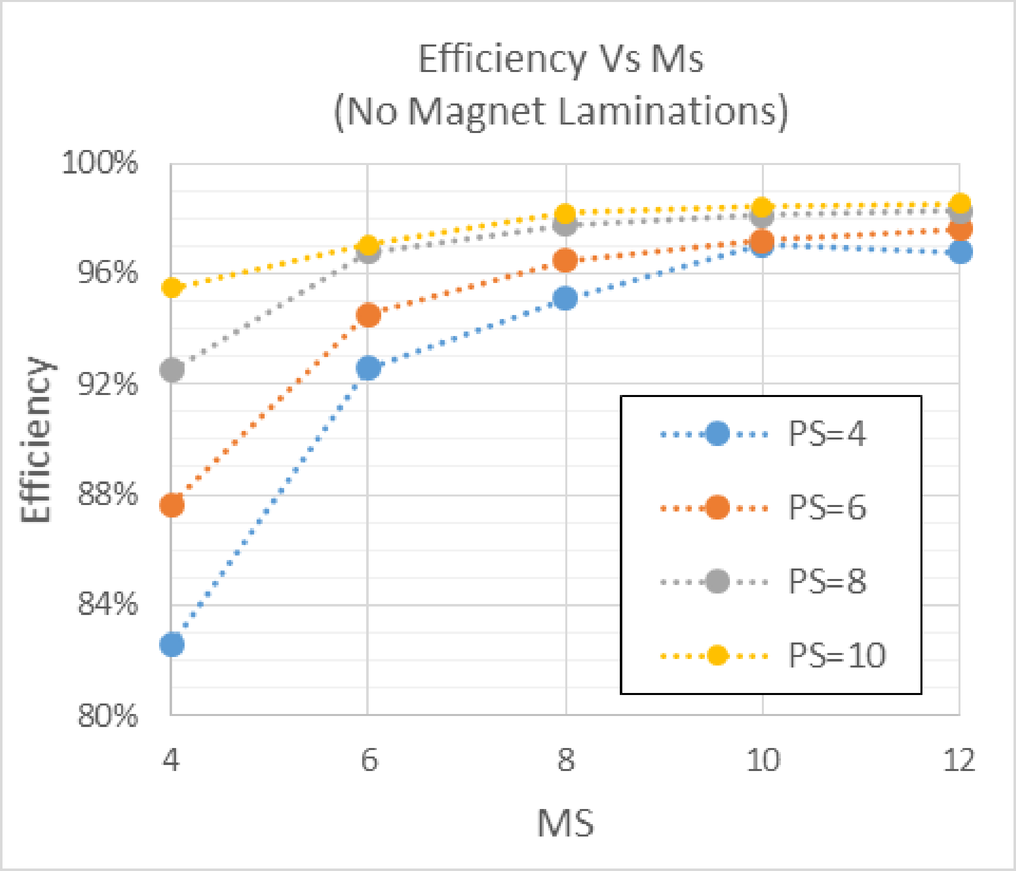


# Efficiency Effects of Magnets Per Pole Pair

## MR Effect at MS of 10

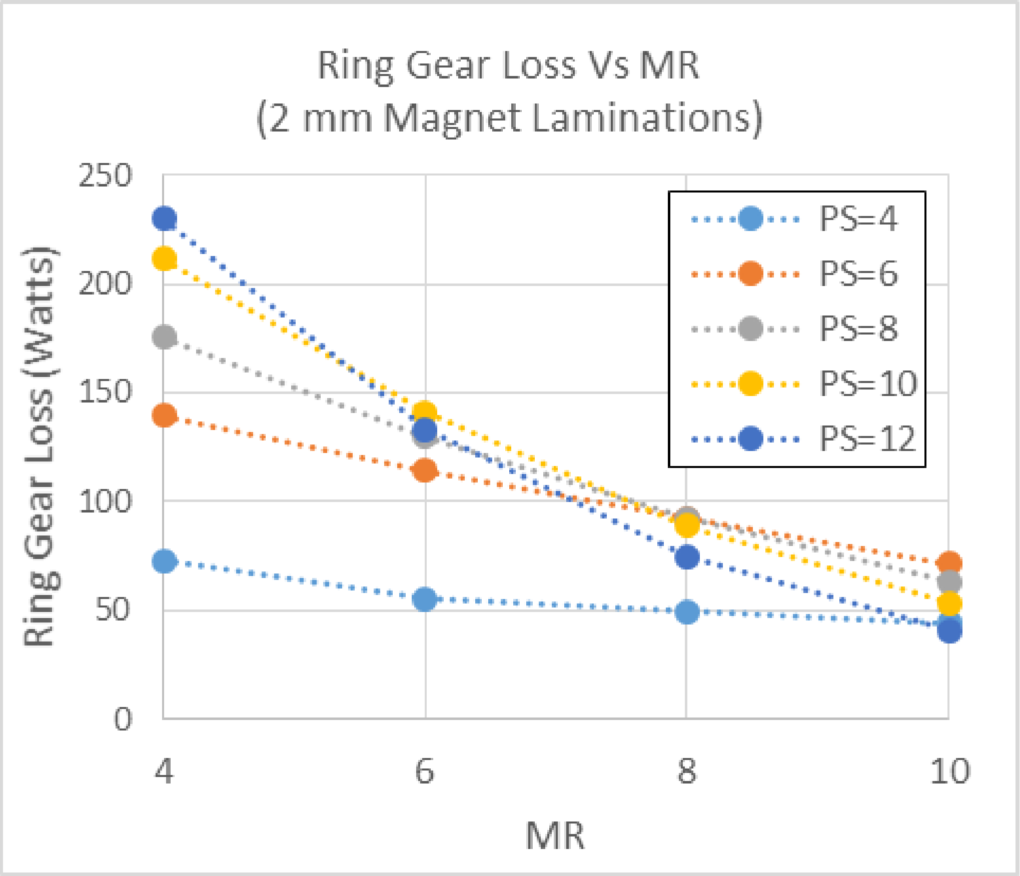



## MS Effect at MR of 6



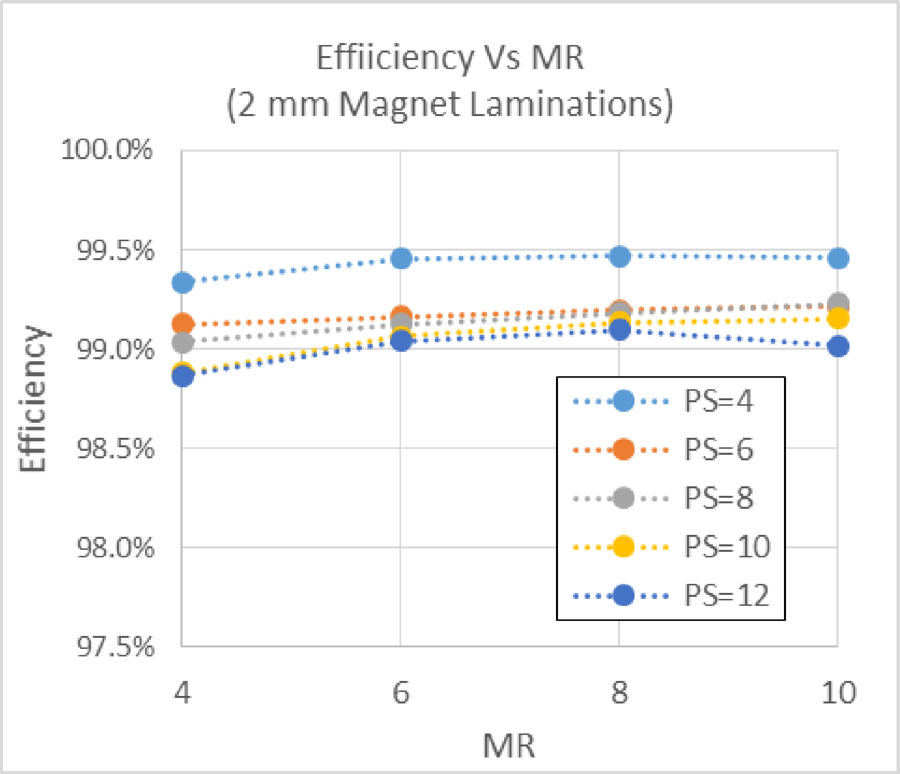
# Magnet Losses with 2 mm Laminations

- $P_c = \frac{1}{16}\frac{V}{\rho}\frac{w^2 l^2}{w^2+l^2}\frac{1}{T}\int_0^T (\frac{dB}{dt})^2\,dt$
- $l = .002\ m$
  - *Losses lower*
  - $w > l$
- Increase PS Increase Losses



# Efficiency Effects of Magnets Per Pole Pair with 2 mm magnet laminations

## MR Effect at MS of 10




## MS Effect at MR of 6