Lessons Learned in Fabrication of a High-Specific-Torque Concentric Magnetic Gear

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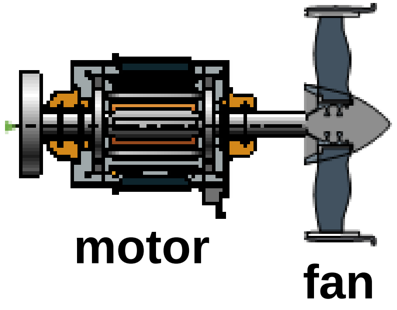
Outline

- Background & Motivation
- Prototype-2 Fabrication
- Prototype-3 Fabrication
- Conclusions
- Future Work

Background & Motivation

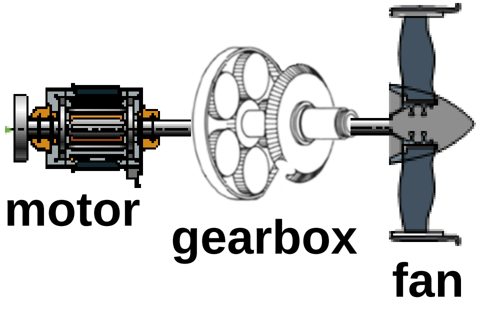
- Growth of short haul market & emergence of urban air mobility market
  - Enabled by electrified propulsion systems
  - Prevalence of smaller (lower torque) propulsors
- Most concepts use direct drive
- Geared drives are almost always mass optimal

Direct drive



+ Simpler
− Non-optimal motor and/or fan

Geared drive



+ Optimized motor & fan
− More complex
− Potentially less reliable

Background & Motivation

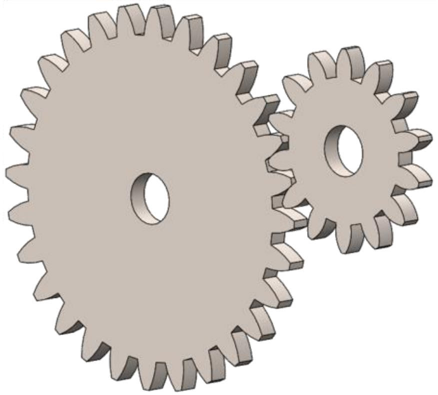
Mechanical gearing

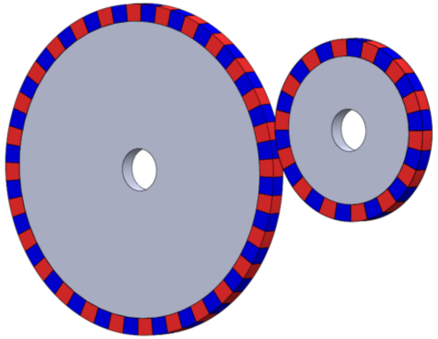
Pros

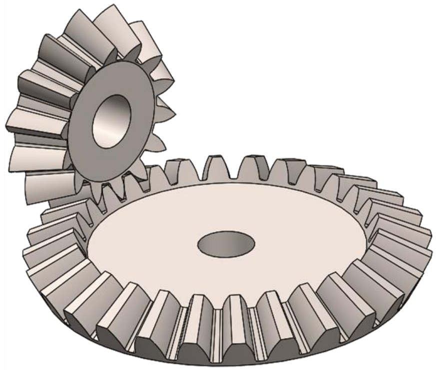
+ High / very high torque/mass (**specific torque**)
+ High / very high efficiency
+ Mature technology

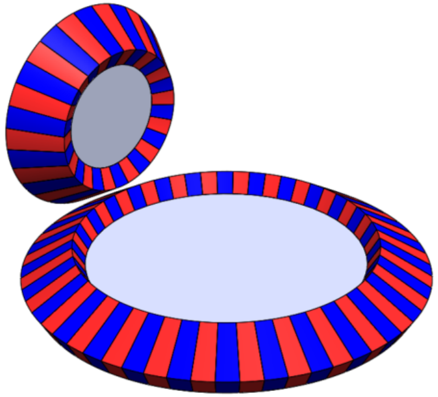
Cons

− 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

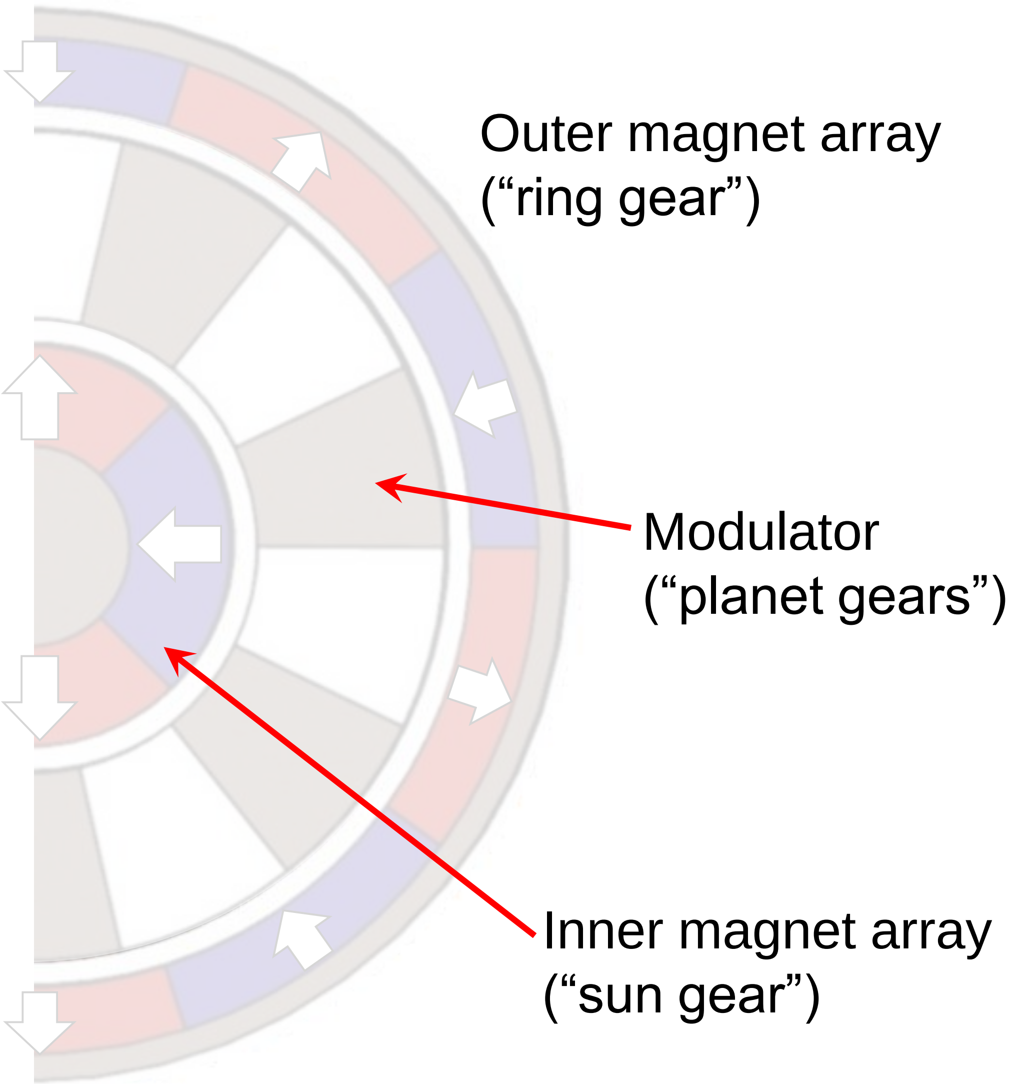
Cons

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

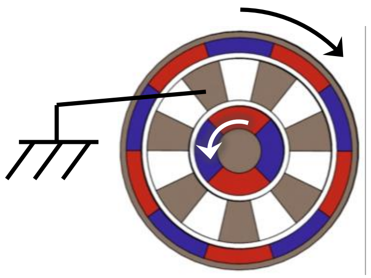
Background & Motivation

Analogous mechanical gear (planetary)

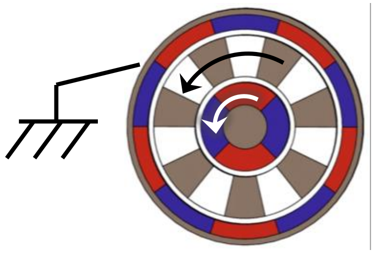
Concentric magnetic gear



Gear ratio (GR)



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



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

Background & Motivation

Phase I
2017

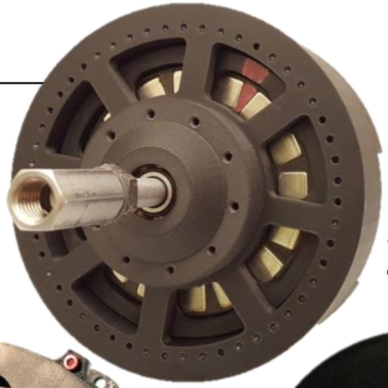
- How do they work?
- Can they be lightweight?

Phase II
2018-2019

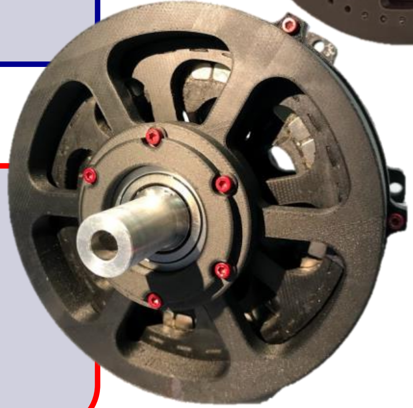
- High specific torque shown
- Can they be efficient?

Phase III
2019-2020

- How do they pair with motors?
- PT-4 designs complete

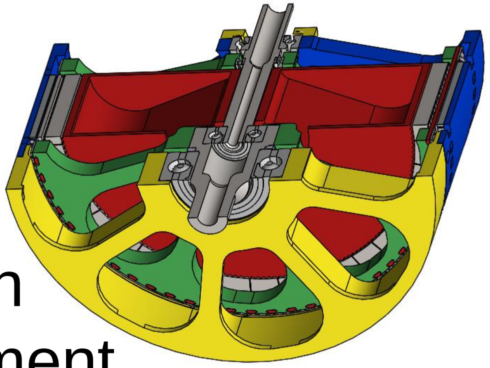


PT-1
20 Nm/kg



PT-2
45 Nm/kg

PT-3 98%
Efficient

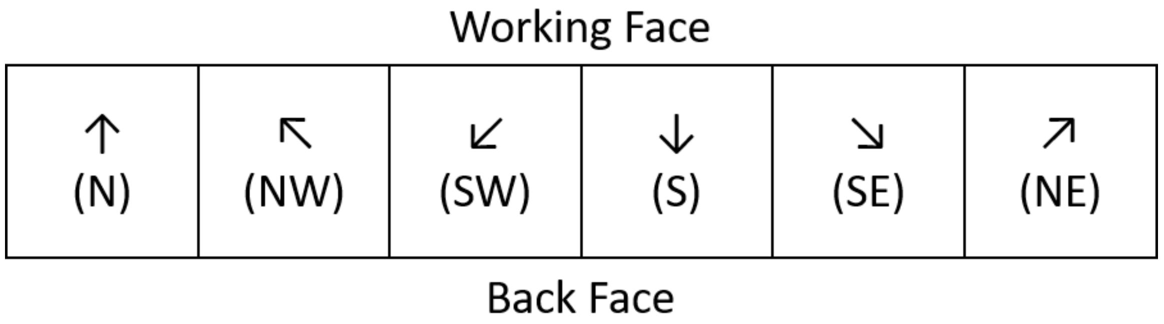


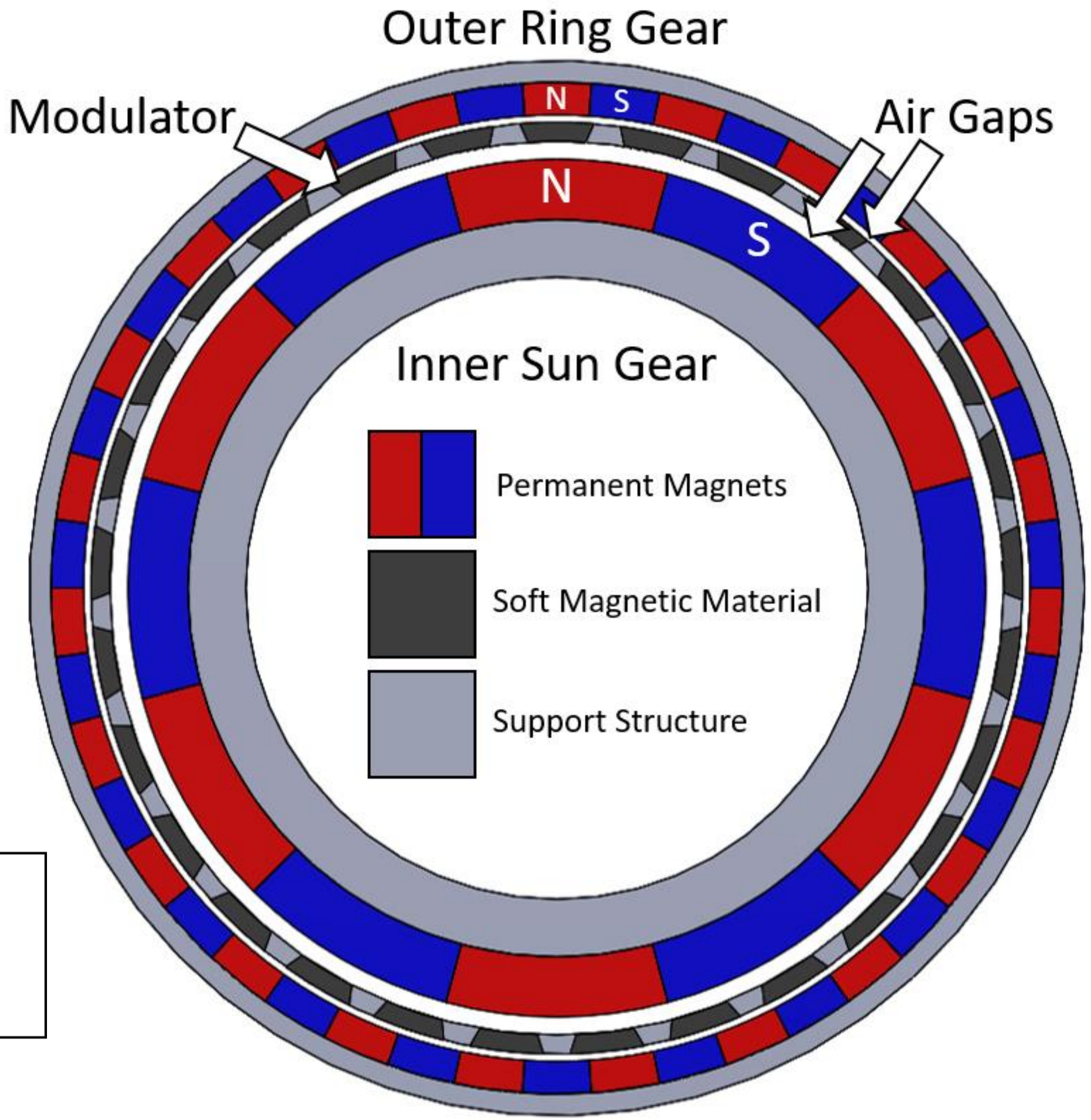
PT-4 in
development

Background & Motivation

What Enables High Performance CMGs

- High Specific Torque
  - Thin air gaps
  - Thin modulator
  - Halbach arrays directing flux
- High Efficiency
  - Sinusoidal flux (clean waveform)
  - Electrically insulative materials
  - Laminated magnetic materials



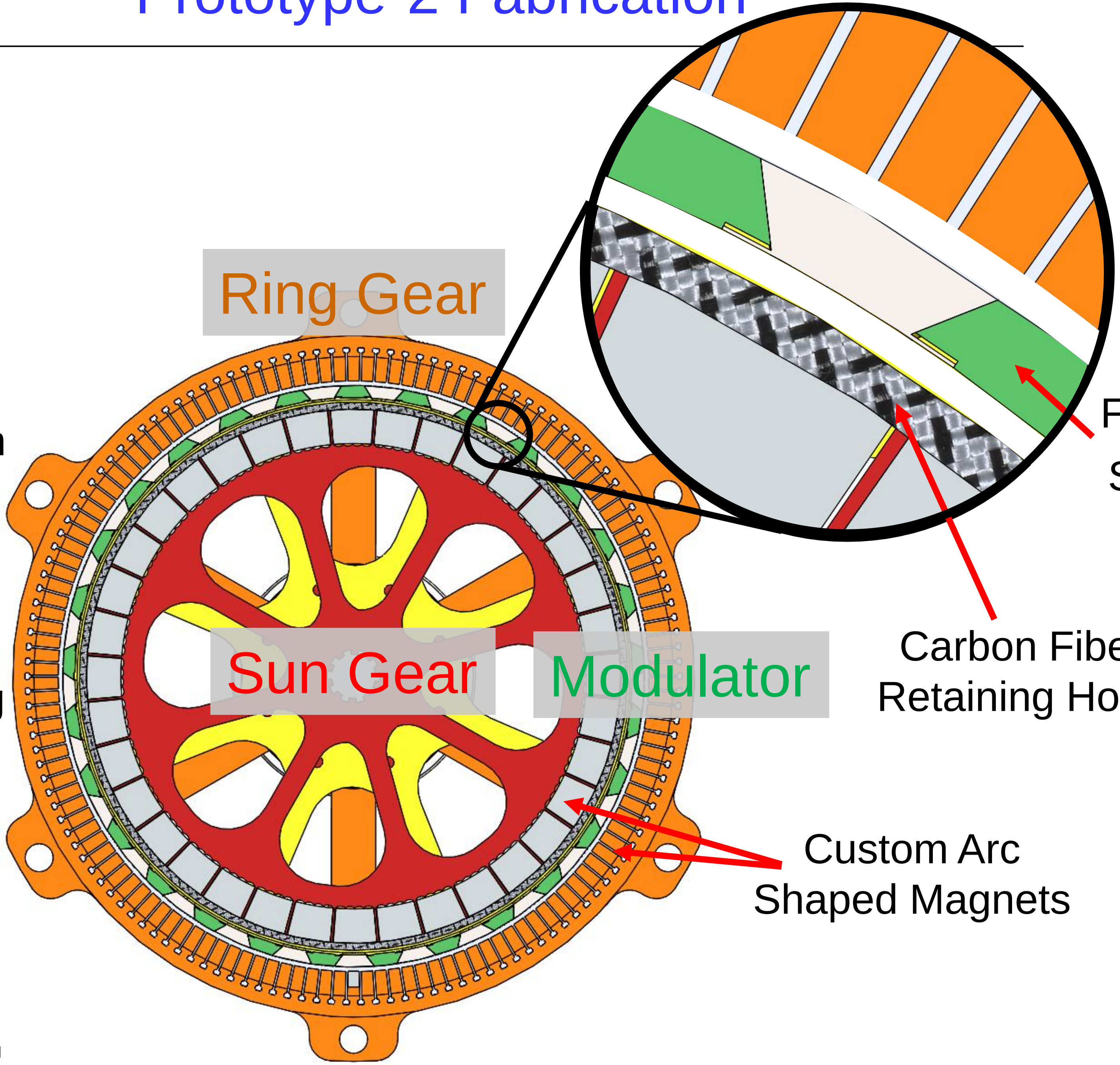


Prototype-2 Fabrication

High Specific Torque Enabling Design

- Thinner modulator
- Retaining wall on sun gear only
- Thin structural feet on modulator
- Custom magnet shapes

Specific Torque = 45 Nm/kg



Prototype-2 Fabrication

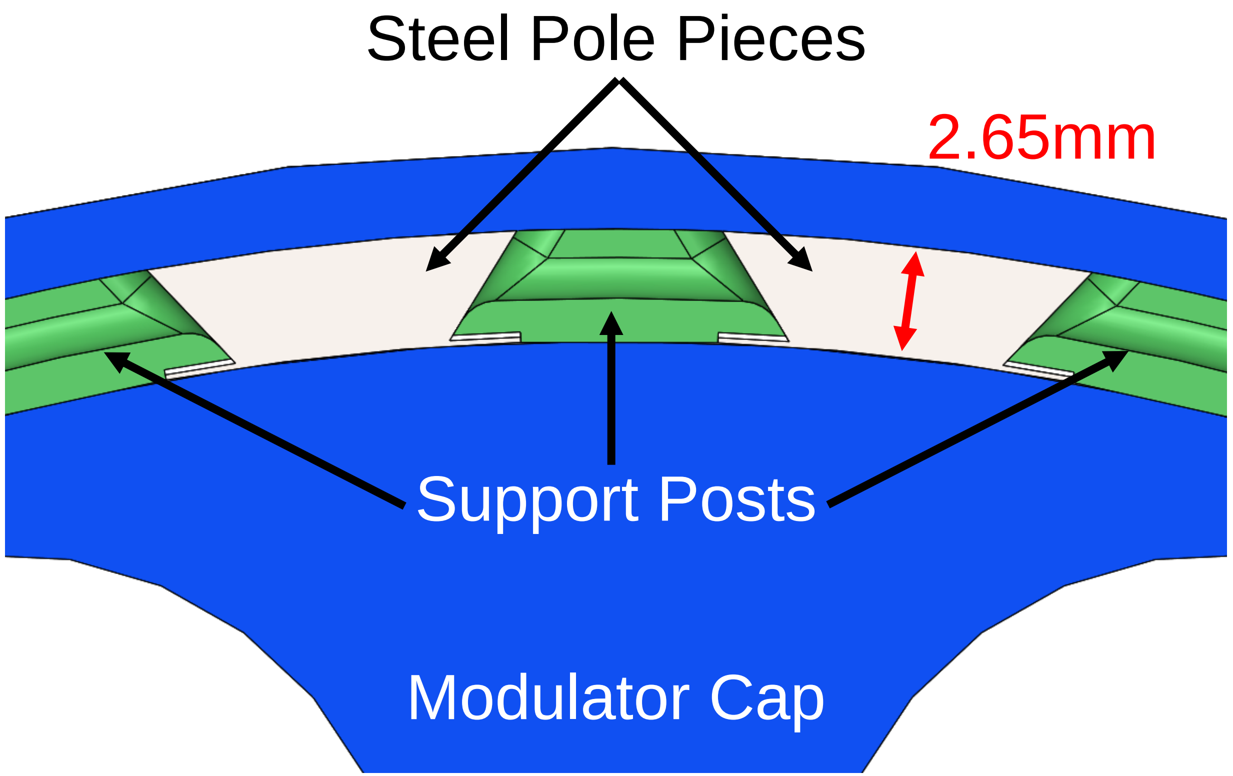
Magnetic Arrays

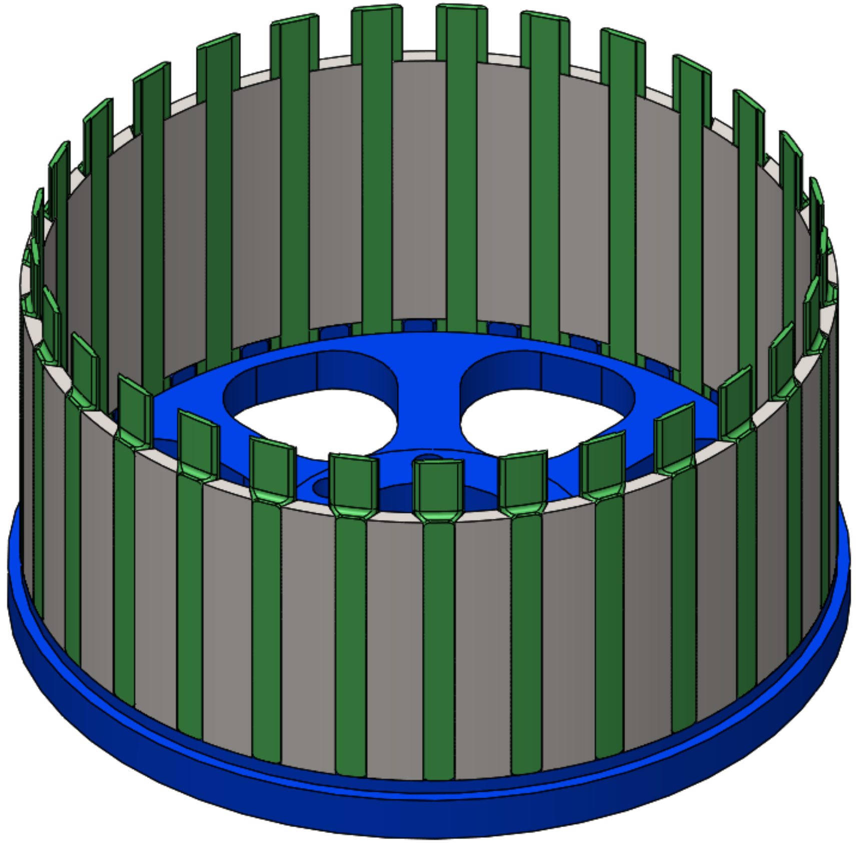
- Six magnets per each Halbach array with N52 grade magnets
- Bodies made of 3D printed carbon fiber reinforced nylon

Prototype-2 Fabrication

Modulator Fabrication

- By far the most difficult and complex part to fabricate (60 total pieces)
- 3D printed carbon fiber reinforced posts press fit into cap
- Pole pieces then inserted with epoxy

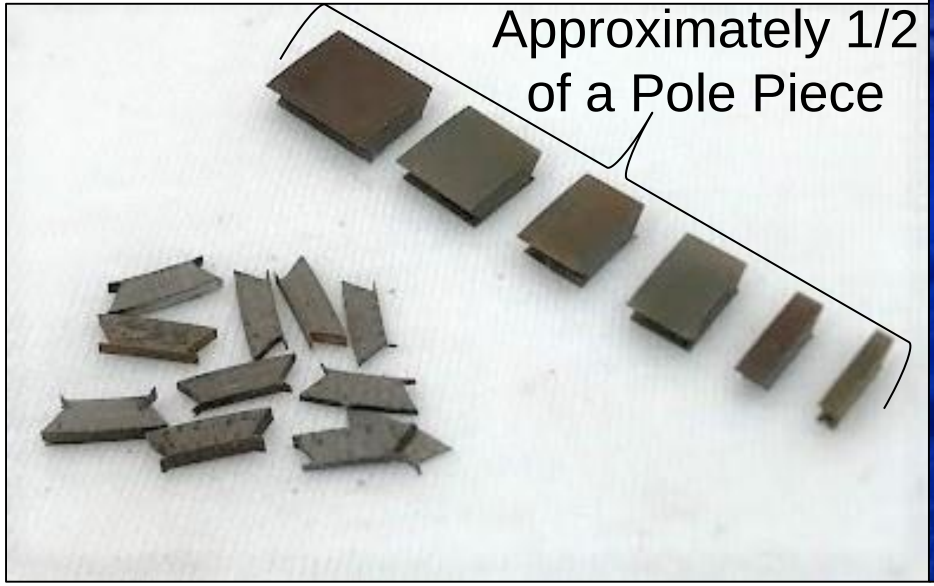


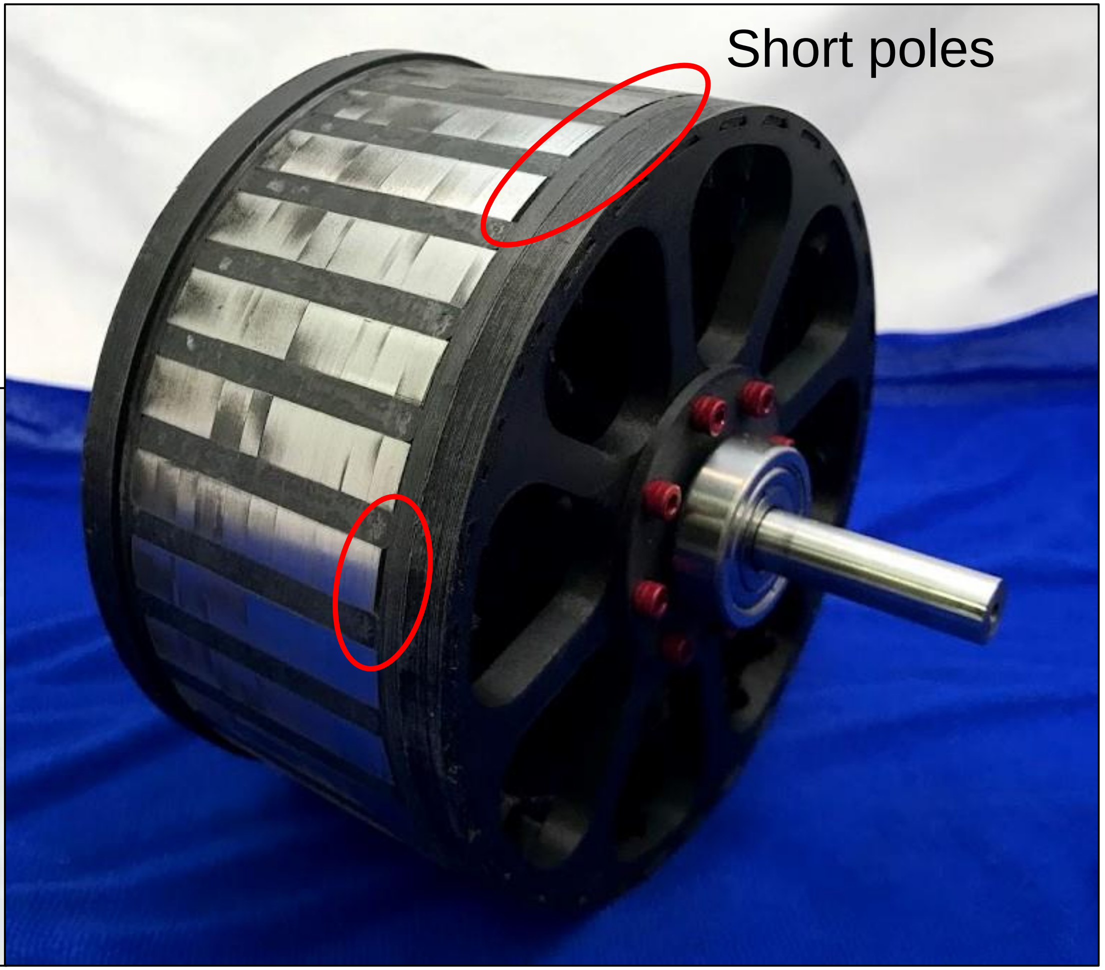


Prototype-2 Fabrication

Modulator Fabrication

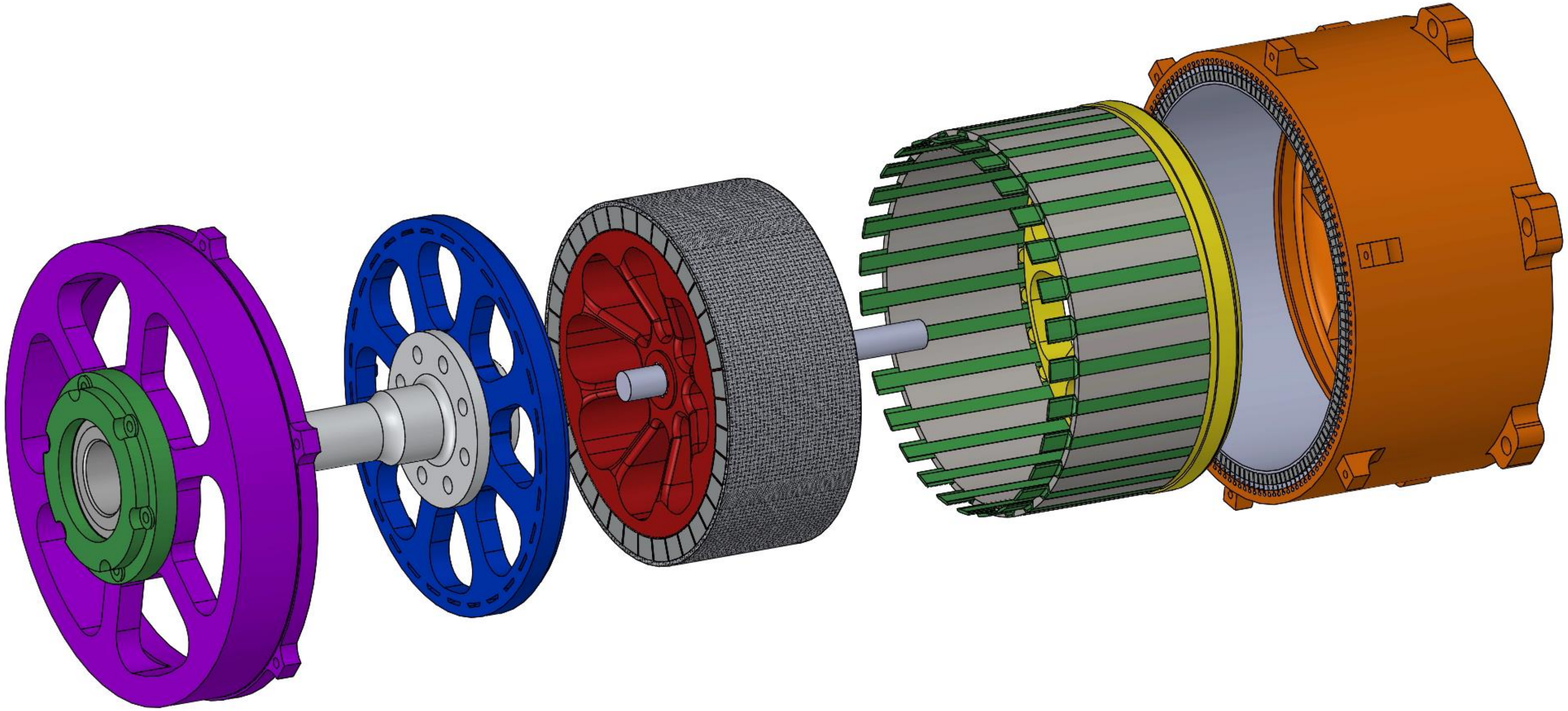
- Wire EDM pole pieces fell apart
- Made assembly very difficult
- Some poles turned out short





Prototype-2 Fabrication

Assembly Process



Prototype-2 Fabrication

Assembly Process

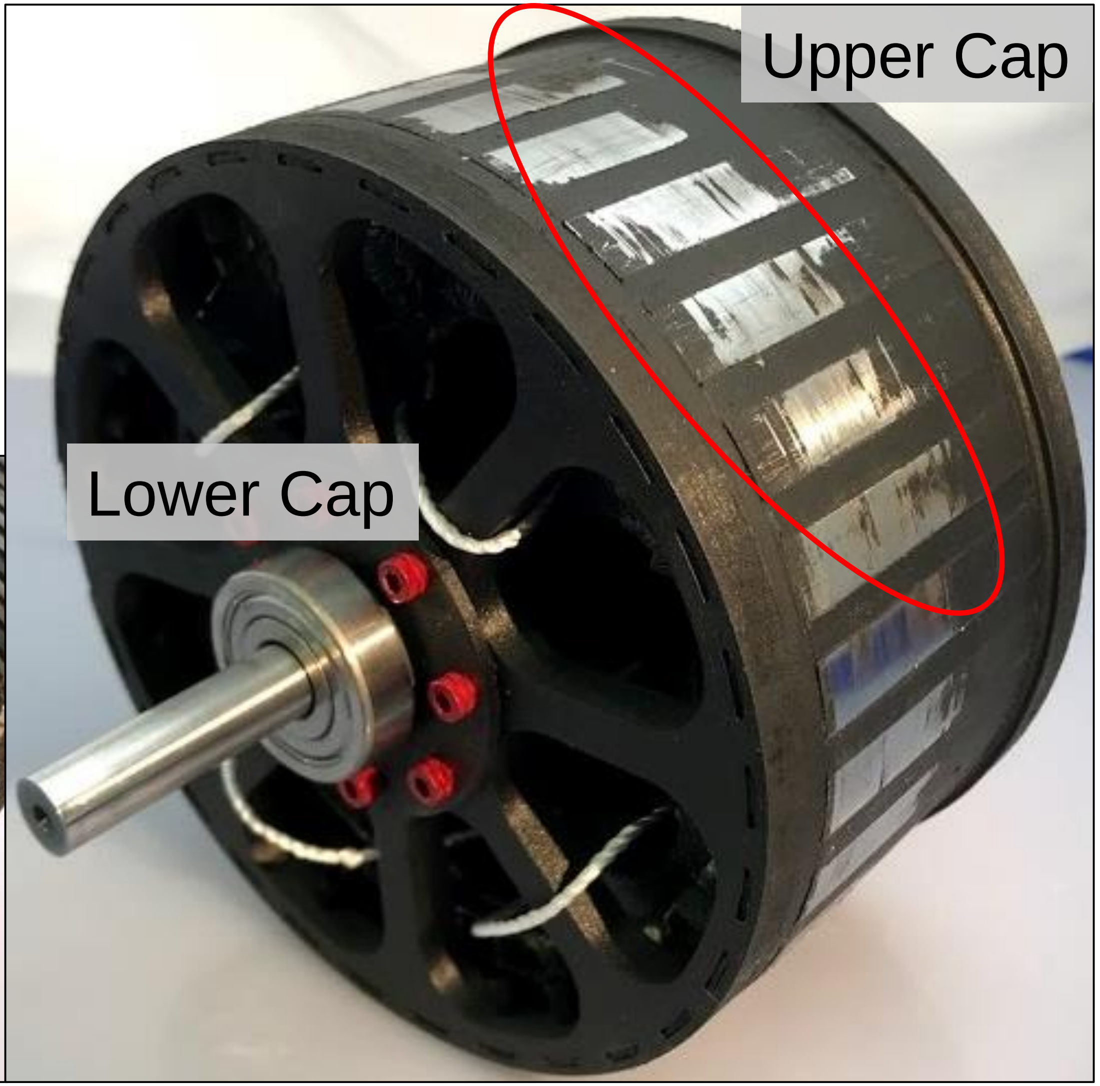

Sun and Modulator Assembly


Entering Ring Gear


Ring Gear Cap Secured

Prototype-2 Fabrication

- North and South Magnets Protruding
- Modulator Deflecting When Loaded
  1. Lower cap not sufficiently stiff
  2. Delaminated pole pieces lack stiffness



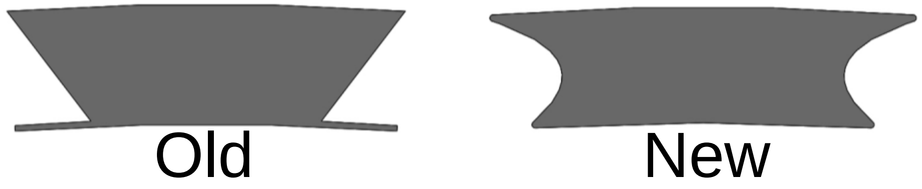
Modulator and Ring Gear Rubbing Visible from Black Marking Compound

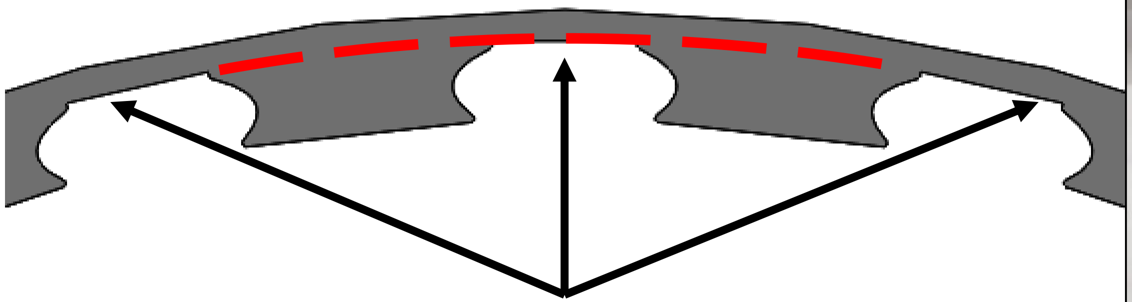
Prototype-2 Fabrication

Modulator Rebuild

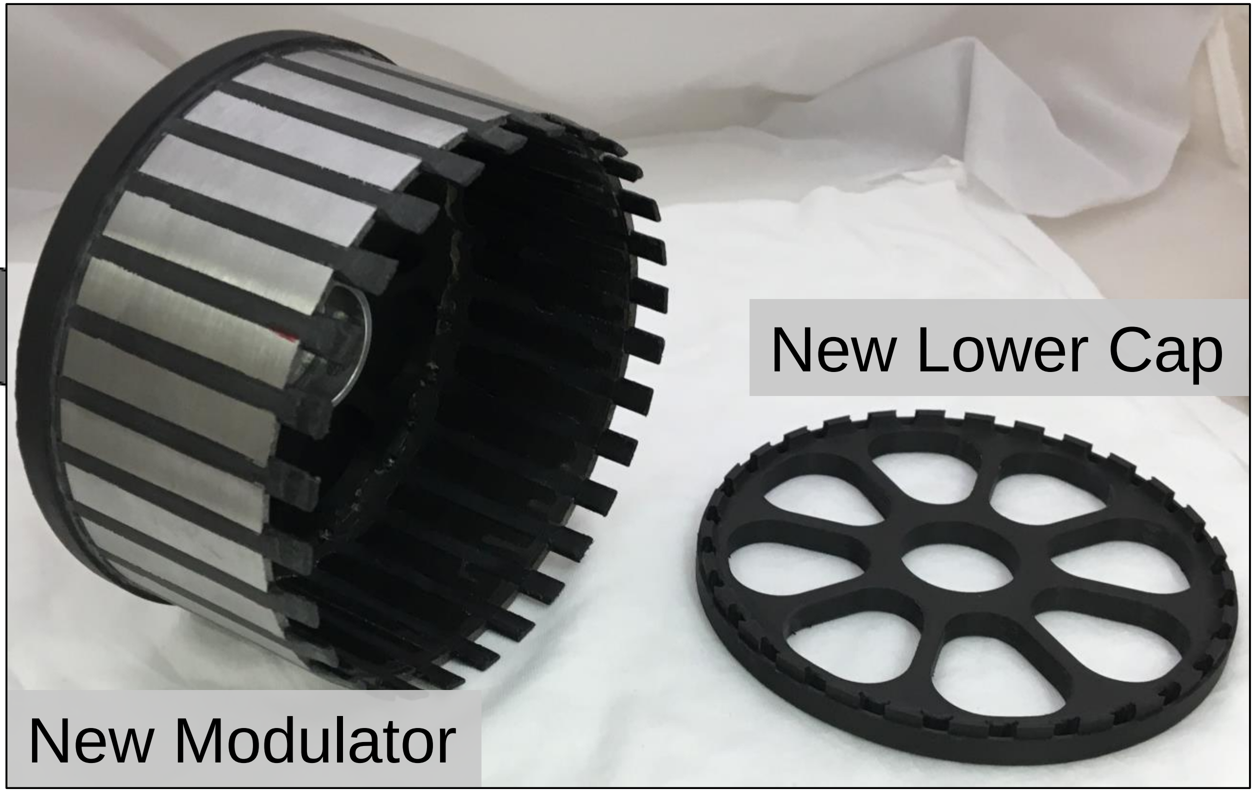
1. Thickened lower cap
2. Modified pole piece geometry
3. Changed pole piece fabrication process

Pole Piece Design Change



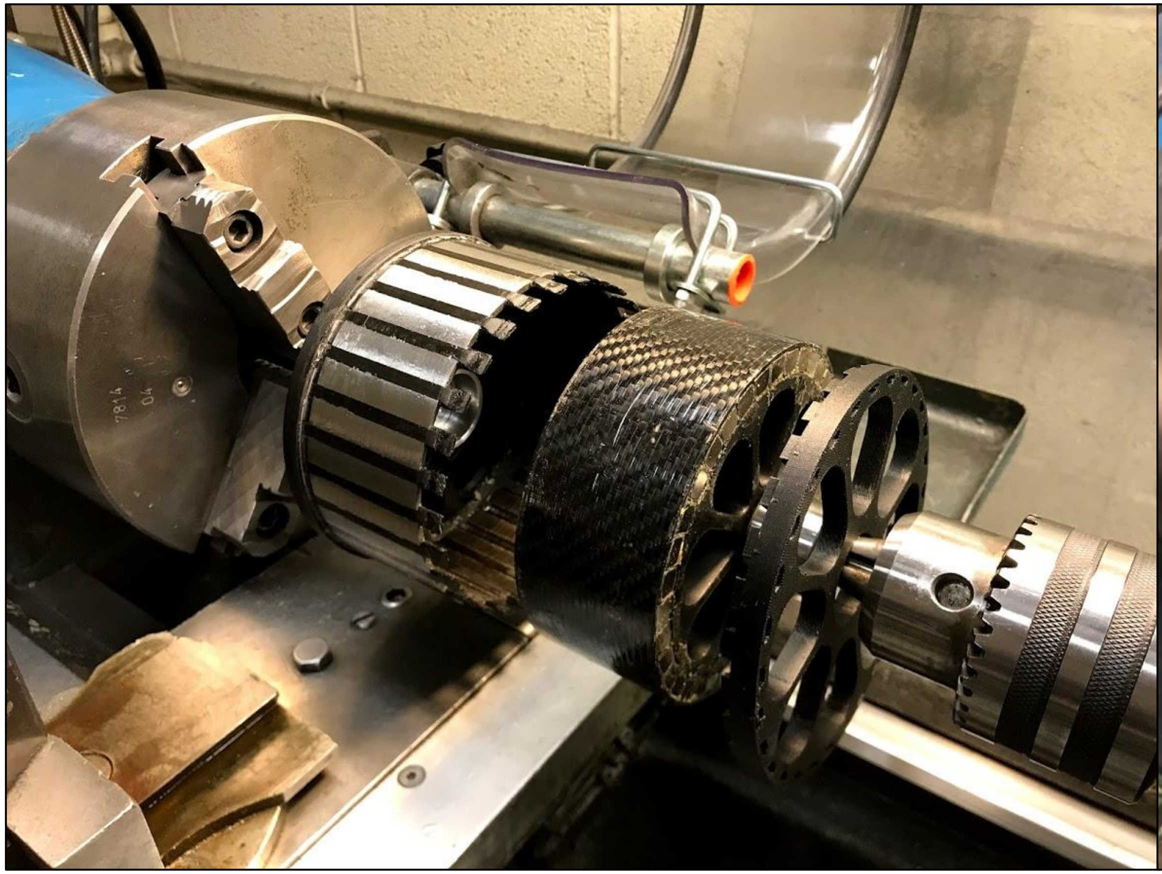


Bounding ring for assembly machined off after adhesive dried

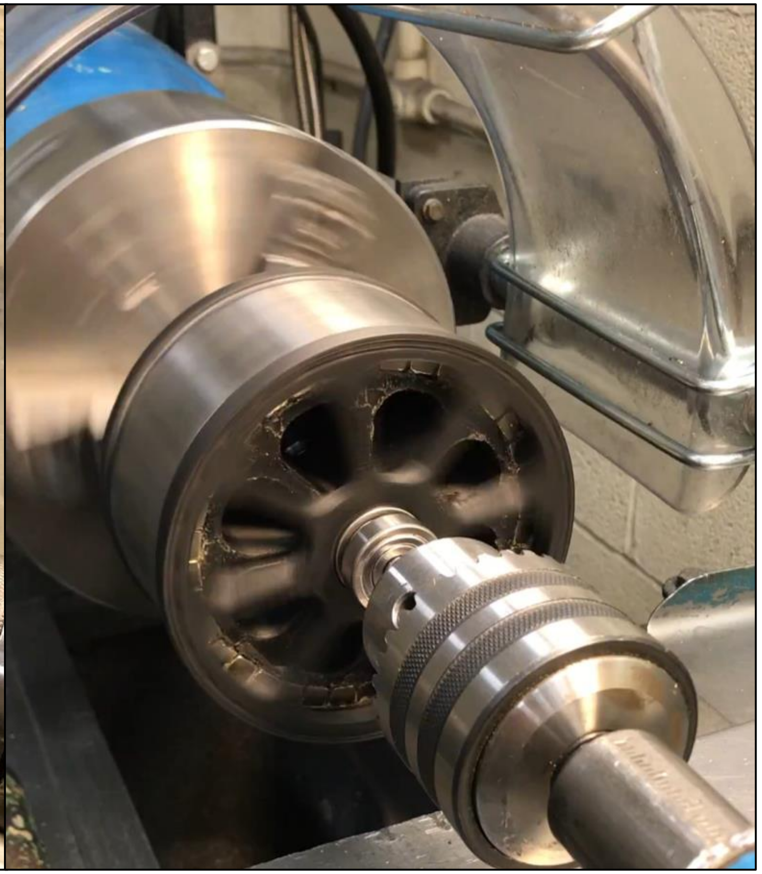


Prototype-2 Fabrication

Reassembly of Prototype 2



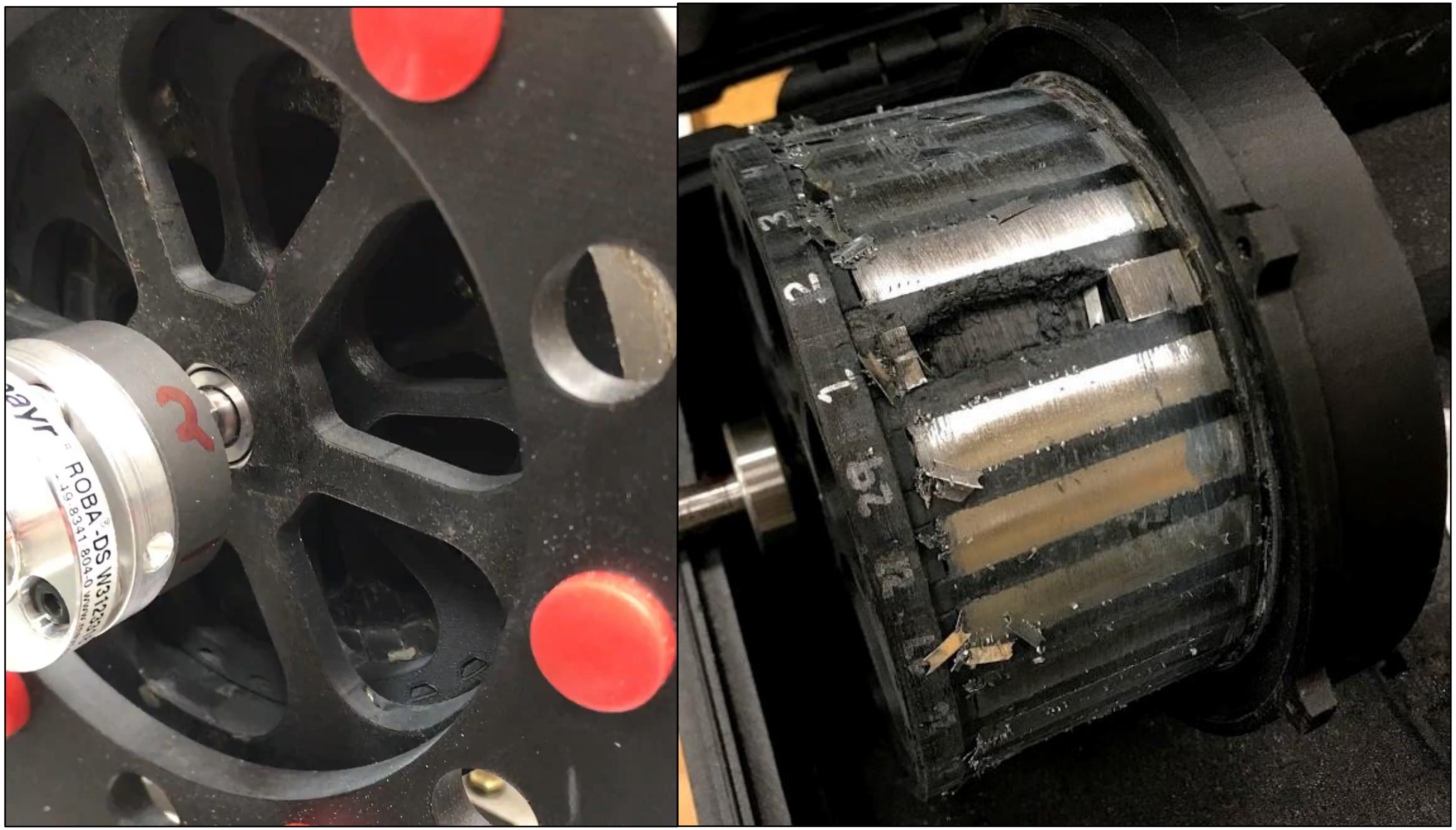
Assembling modulator and sun gear



Rotating

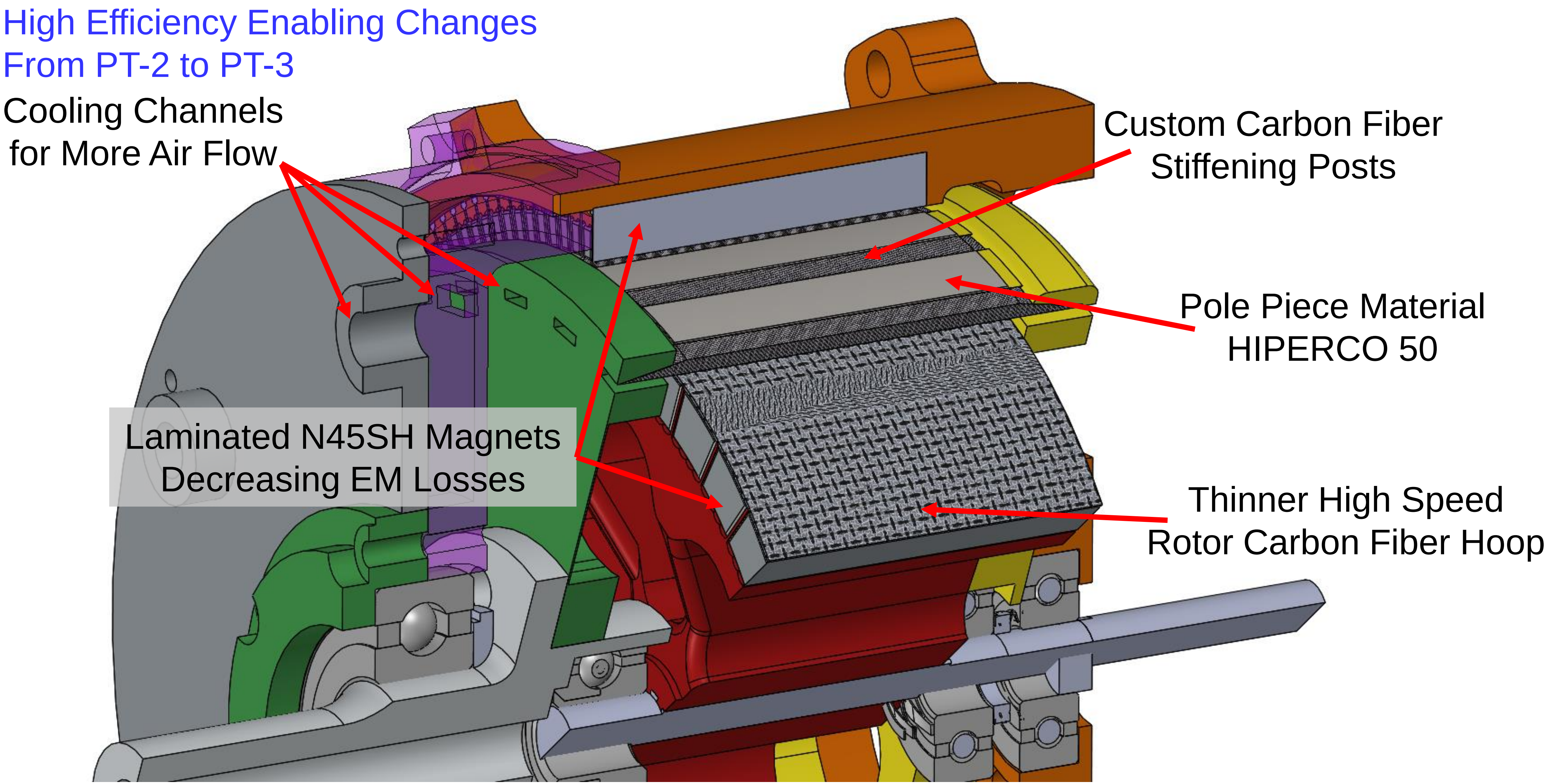
Prototype-2 Fabrication

Prototype 2 Failure



Modulator failure after limited dynamic testing

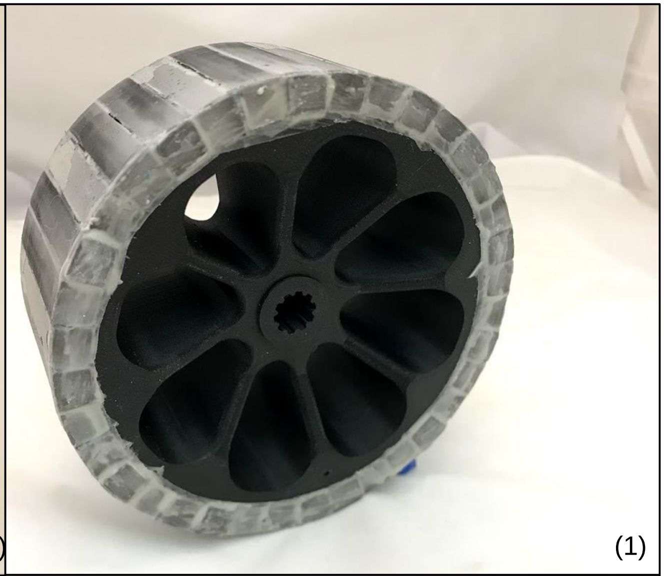
Prototype-3 Fabrication

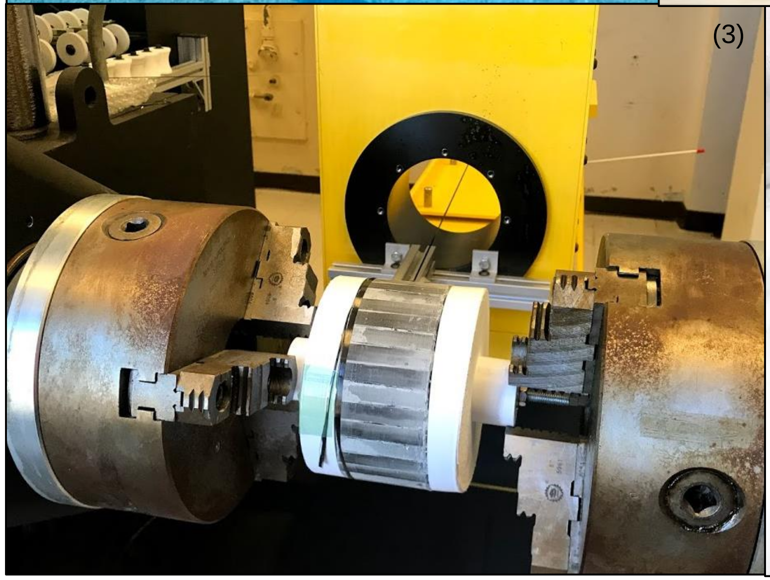


Prototype-3 Fabrication

Sun Fabrication

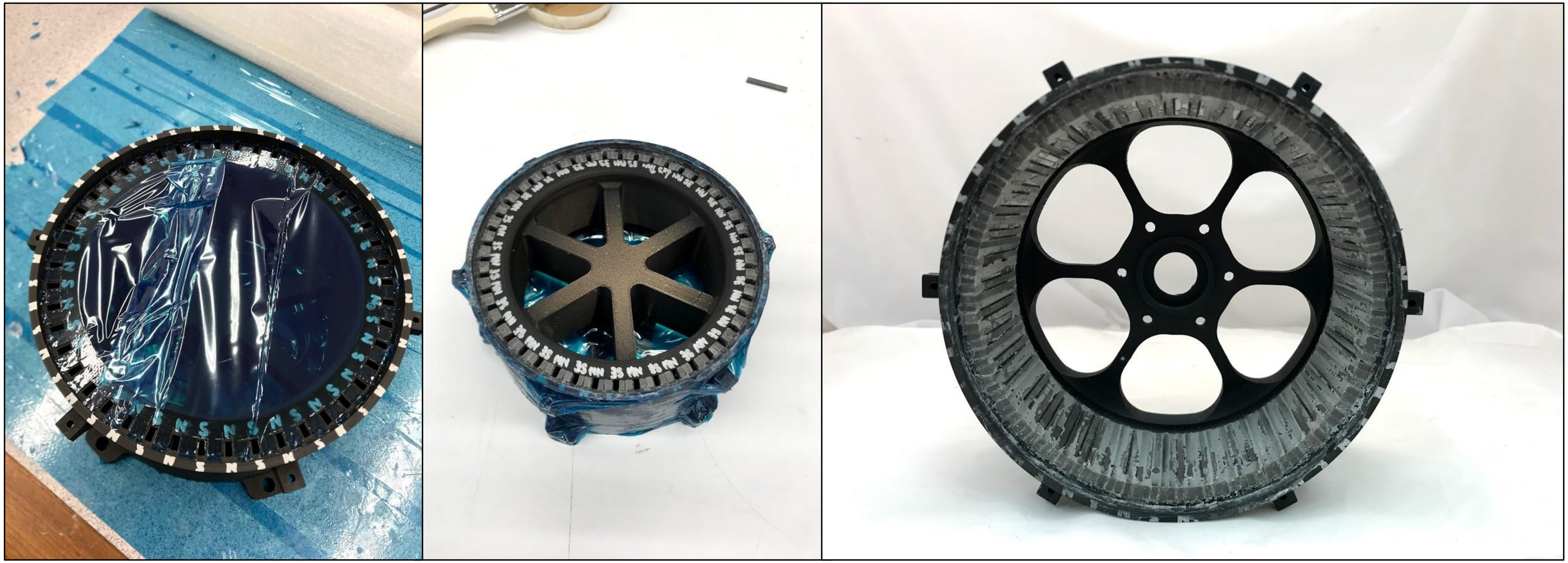
- New Halbach array assembly process used (1)
- Laminated custom arc magnets used (2)
- Custom carbon fiber hoop wound directly to array (3)
- Significantly decreased sun gear-modulator air gap





Prototype-3 Fabrication

Ring Fabrication



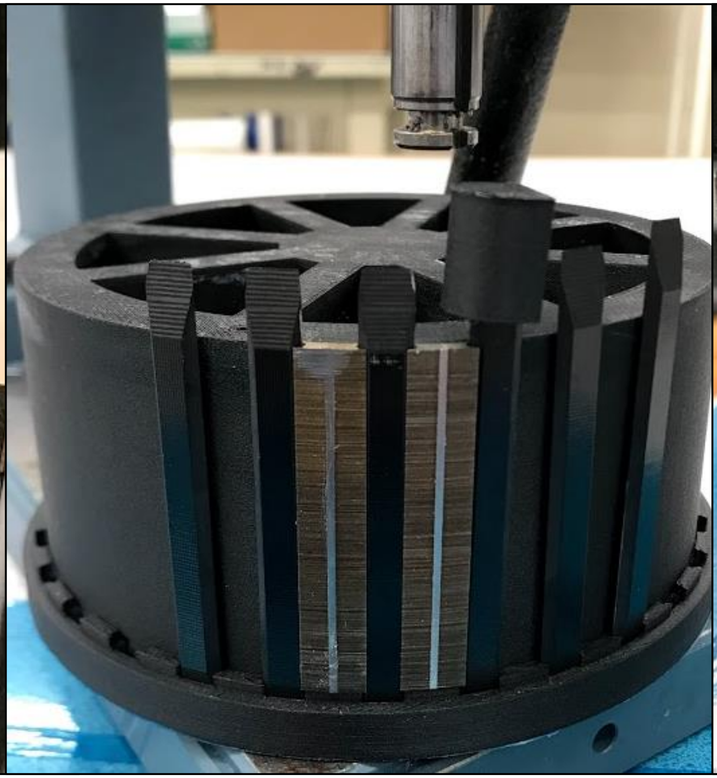
New assembly method, similar to one used on sun gear

End result was Halbach array with no bulging magnets

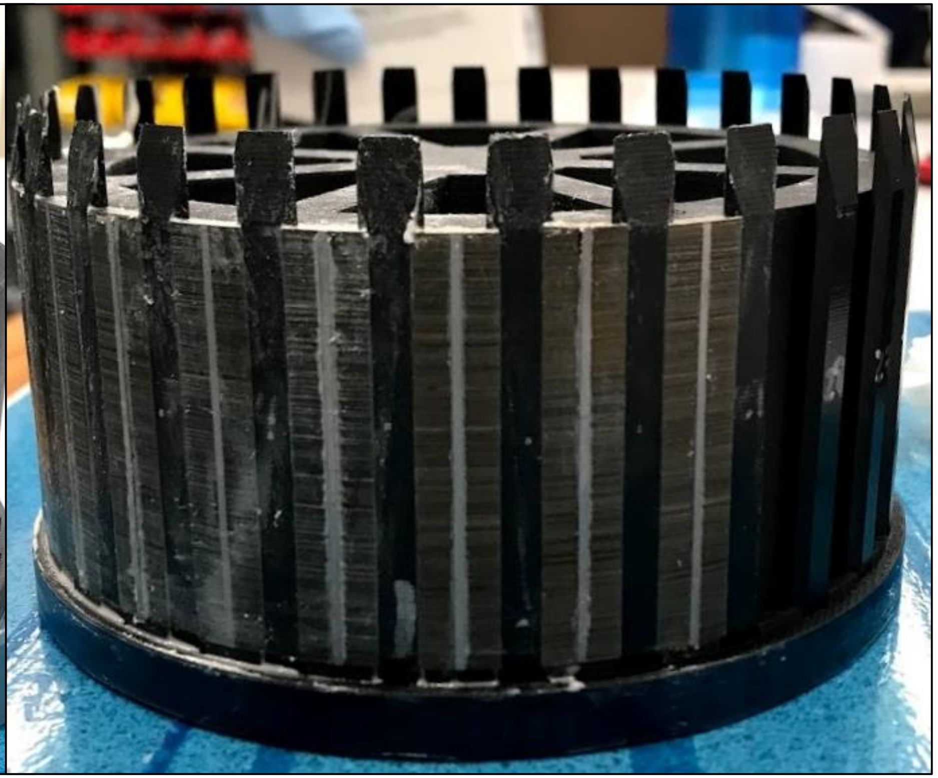
Prototype-3 Fabrication

Modulator Fabrication

Cutting individual pole pieces



Pressing in carbon fiber posts



Inserting pole pieces with epoxy

Prototype-3 Fabrication

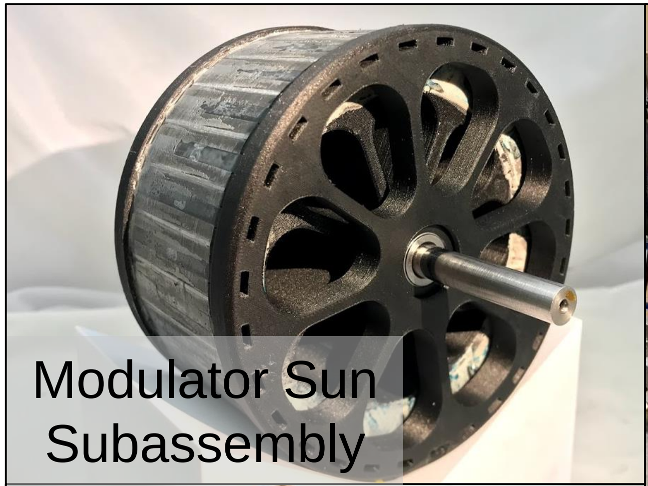
Modulator Fabrication

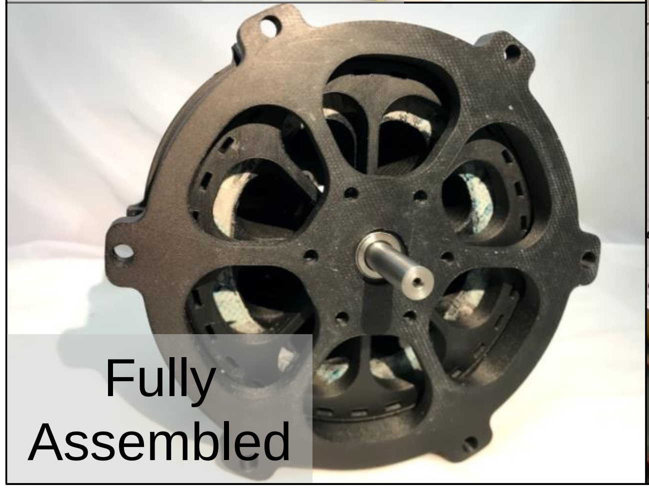
Side view of modulator

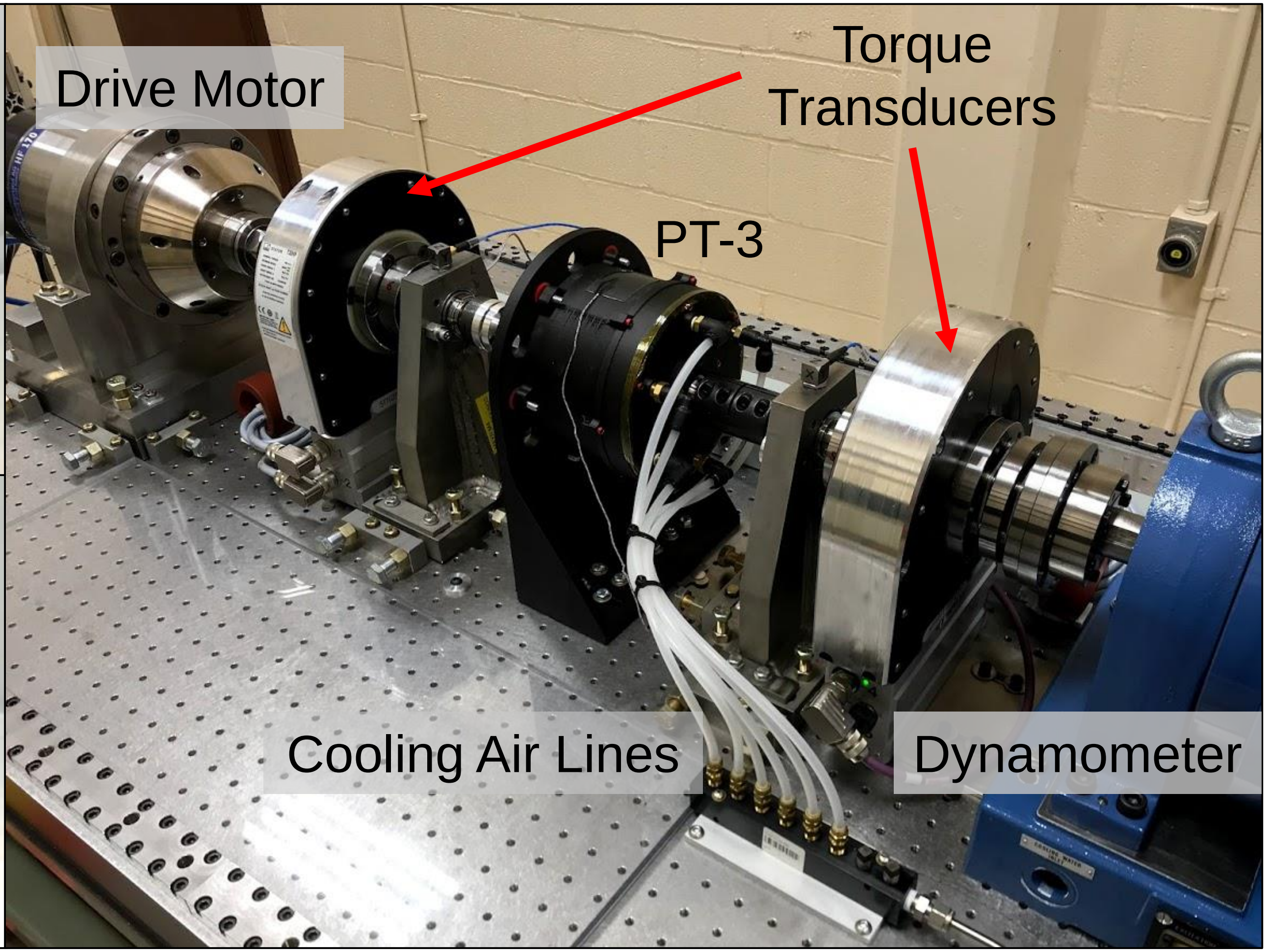
Internal View

Prototype-3 Fabrication

Assembly and Installation in Rig





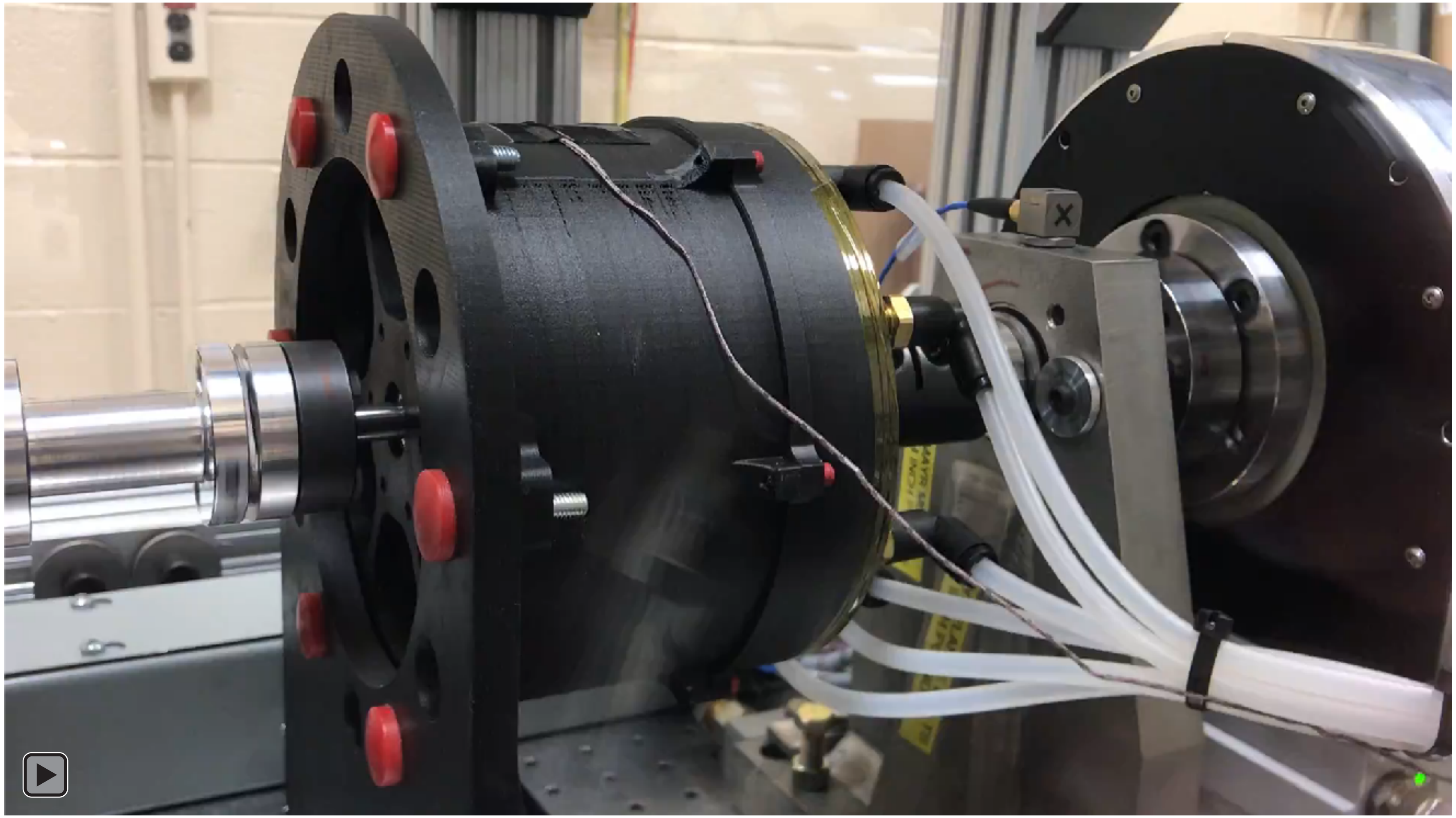


Prototype-3 Fabrication

In Operation

4.83:1
Reduction Ratio

100 RPM



20.8 RPM

Conclusions

- Designed, built, statically tested and dynamically tested 2 prototypes
  - **PT-2** – achieved high specific torque, some manufacturing and stiffness issues
  - **PT-3** – achieved high efficiency, leveraged fabrication lessons from PT-2
- Key conclusions from fabrication in NASA's Phase 2
  - **High Specific Torque is Possible**
    - PT-2 utilized thin air gaps, custom magnets, and thin modulator
  - **High Efficiency is Possible**
    - Enabled by careful material selection & laminations
  - **Modulator is most critical and most difficult structure to fabricate**
    - multiple assembly methods attempted
    - structures must be very stiff and very durable
    - Enables high performance

Future Work

Phase 3 – integrate high efficiency, high specific torque CMGs with electric motors

- **Design**
  - Continued improvement to structural designs
  - Explore topologies combining CMGs and motors
  - Continued development of fabrication methods
- **Innovation**
  - Unconventional solutions for magnet & pole piece containment
  - Electrically-insulating, thermally-conductive structural materials
- **Targeted Applications**
  - eVTOL UAM vehicles electric propulsors
  - Electrified fixed wing aircraft/X-57 high lift propulsors drive systems
  - Space applications where conventional gearing isn't feasible

Acknowledgements

- NASA Revolutionary Vertical Lift Technology (RVLT) Project
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- Vivake Asnani
- Glenn Research Center Composites Group
  - Sandi Miller
  - Paula Heimann

QUESTIONS ?


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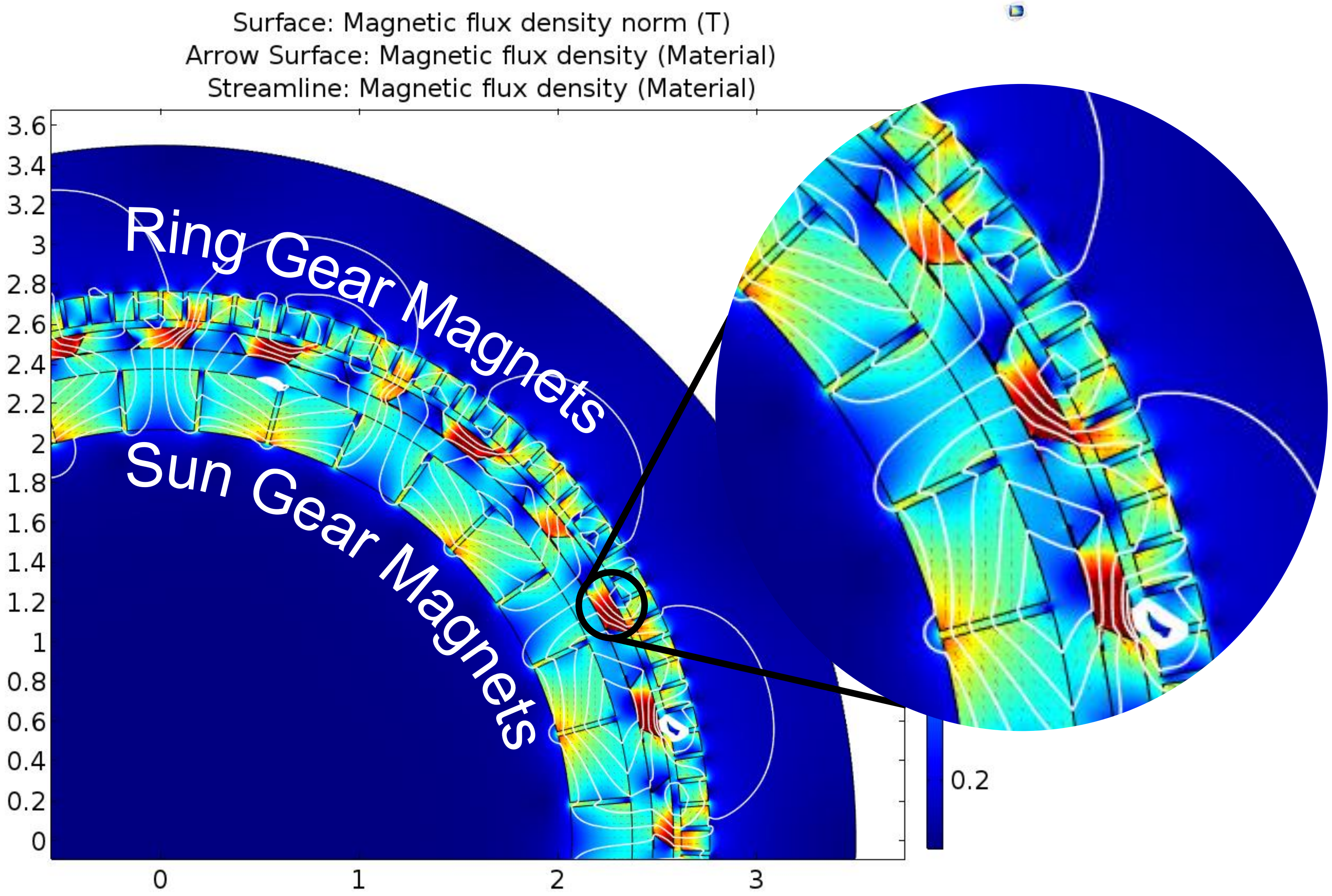
Prototype-2 Fabrication

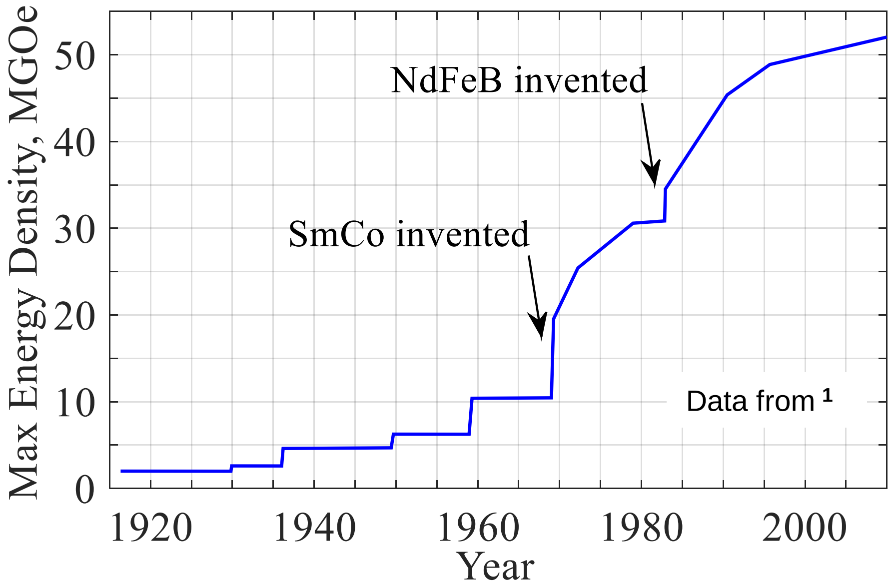
- Magnetic array design

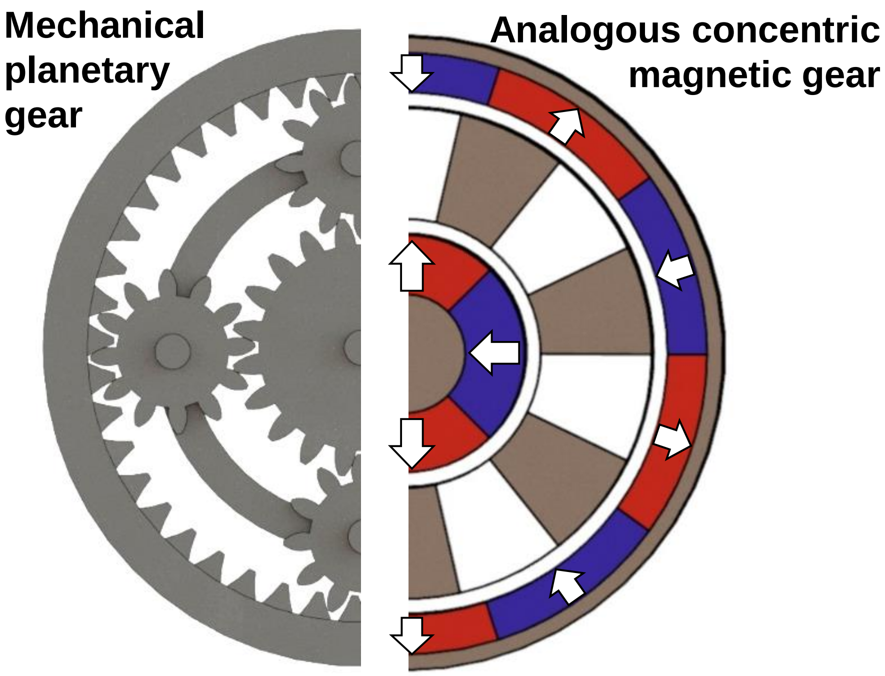


Background & Motivation

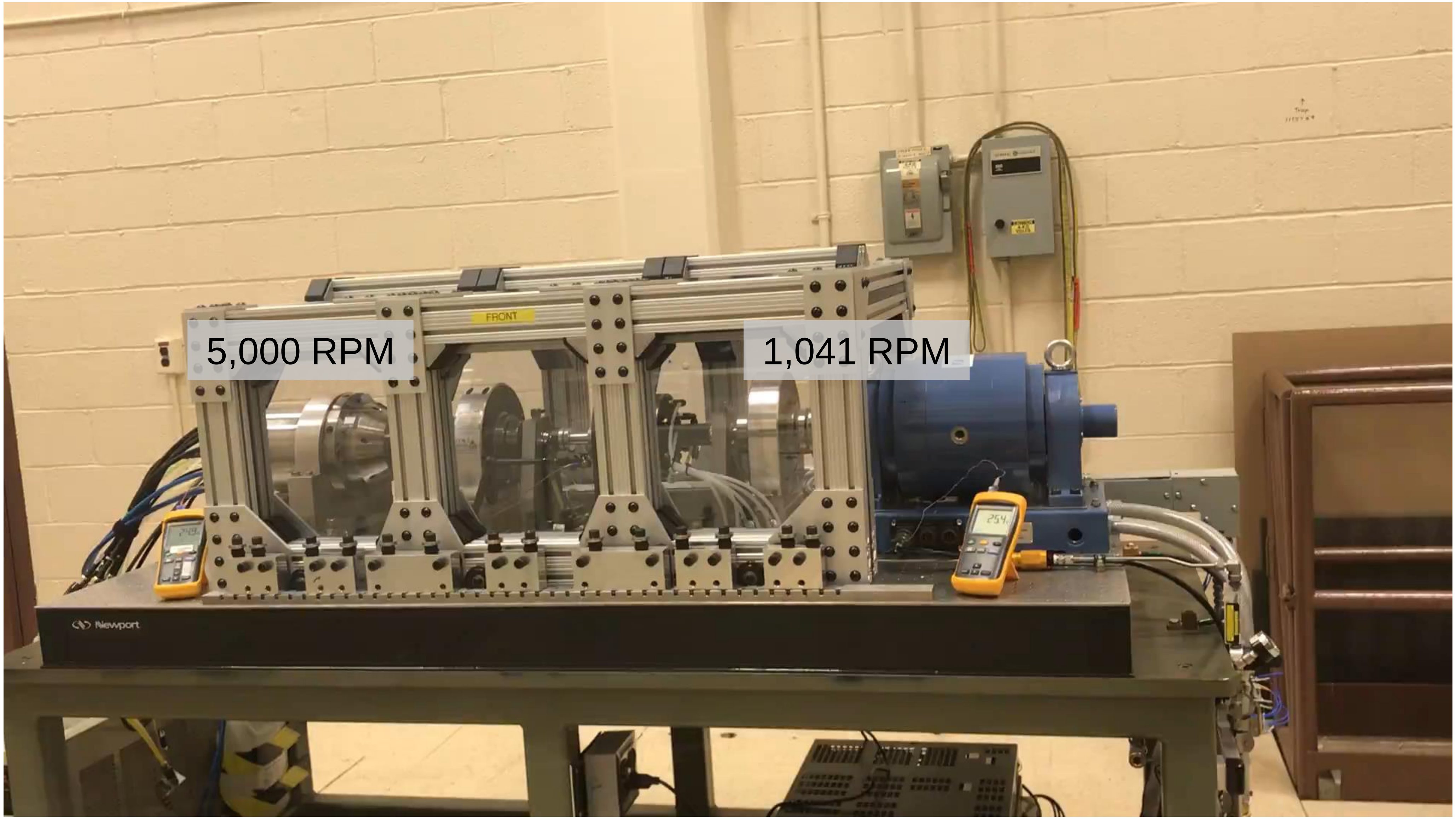
Why Concentric Magnetic Gear (CMG) Was Selected

- Large amount of previous work to base starting point off of
- Concentric input & output is most logical for most concepts
- High specific torque
- Easily integrated in electric machines





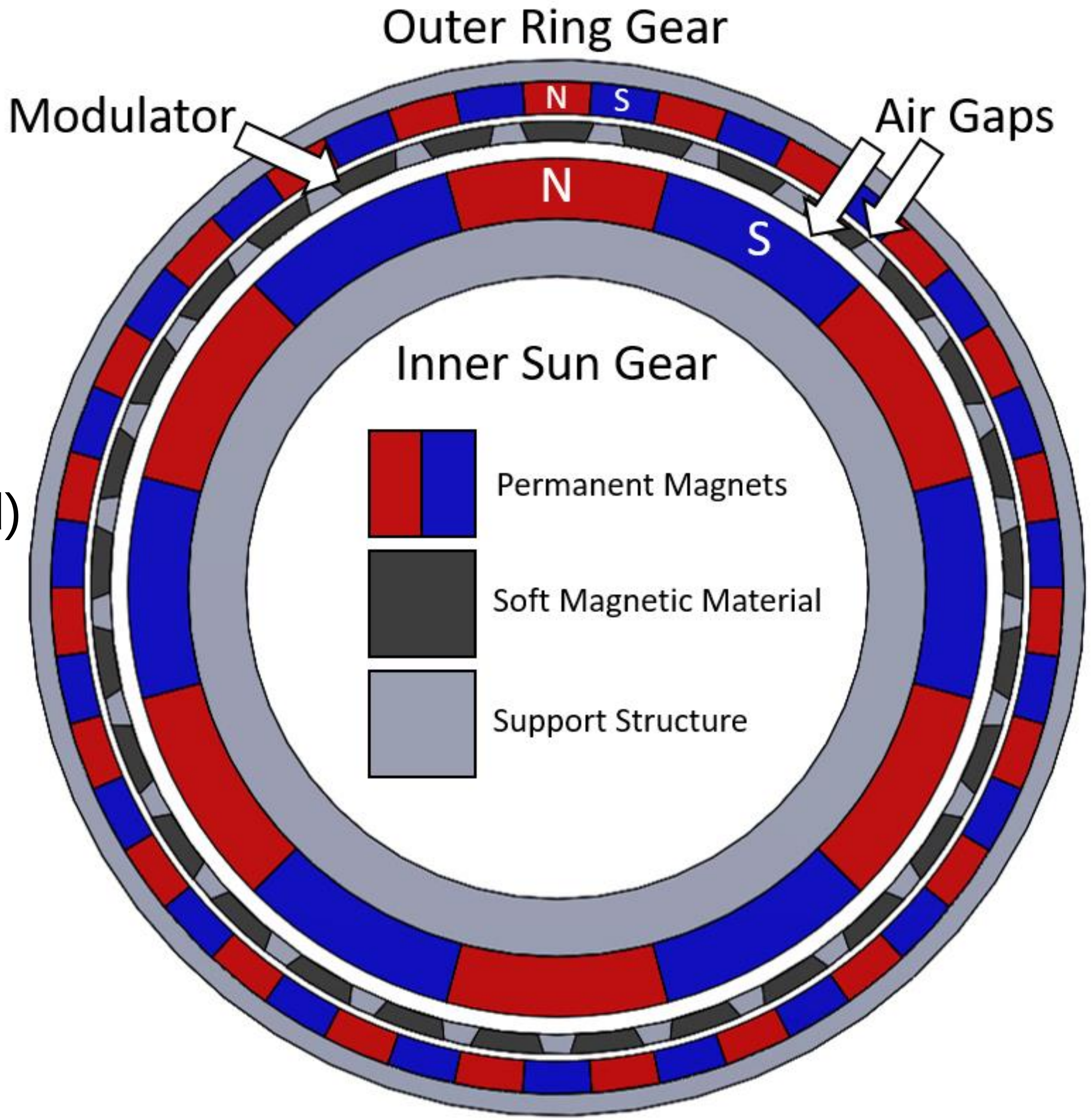
High Speed Operation PT-3



Background & Motivation

What is a Concentric Magnetic Gear (CMG)

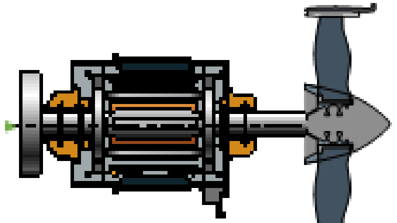
- Three main components
  - Permanent magnet ring gear (fixed)
  - Permanent magnet sun gear (high speed)
  - Modulator (low speed)
- Well established working principles
- Concentric input & output shaft
- Easily integrated with electric machines



Background & Motivation

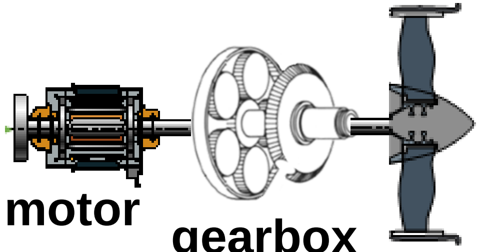
- NASA set goals for aircraft efficiency, emissions, reliability, and noise
- Parallel large & small aircraft development
  - Economic benefit of alternative propulsion
- Electrified aircraft propulsion is a key enabler
- Most concepts use direct drive
- Geared drives are almost always mass optimal

Direct drive



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

Geared drive

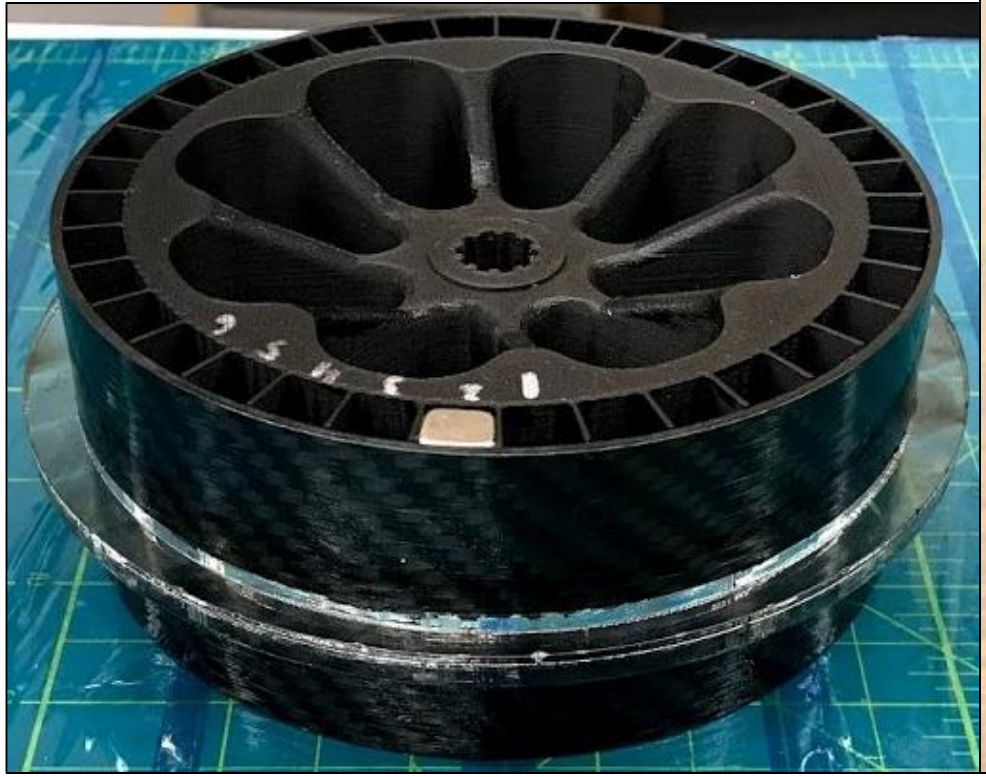


\+ Optimized motor & fan
\+ Enables cross shafting
− More complex
− Potentially less reliable

Prototype-2 Fabrication

Sun Gear Fabrication

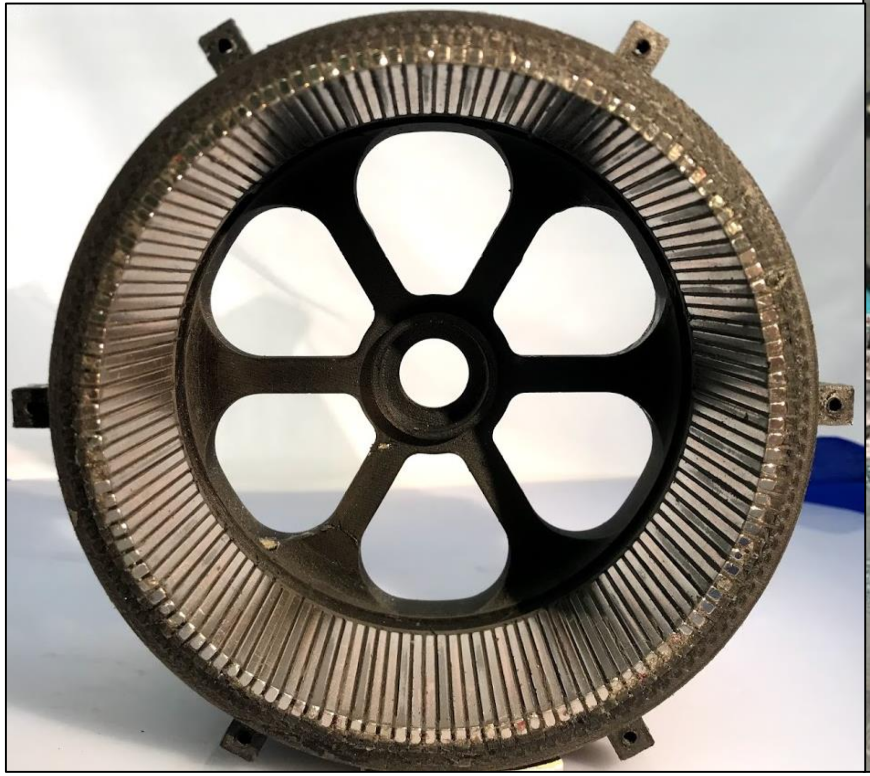
- Magnetic array populated in COTs hoop
- Body made of 3D printed carbon fiber reinforced nylon
- Adhesive allowed to cure before removing acrylic ring

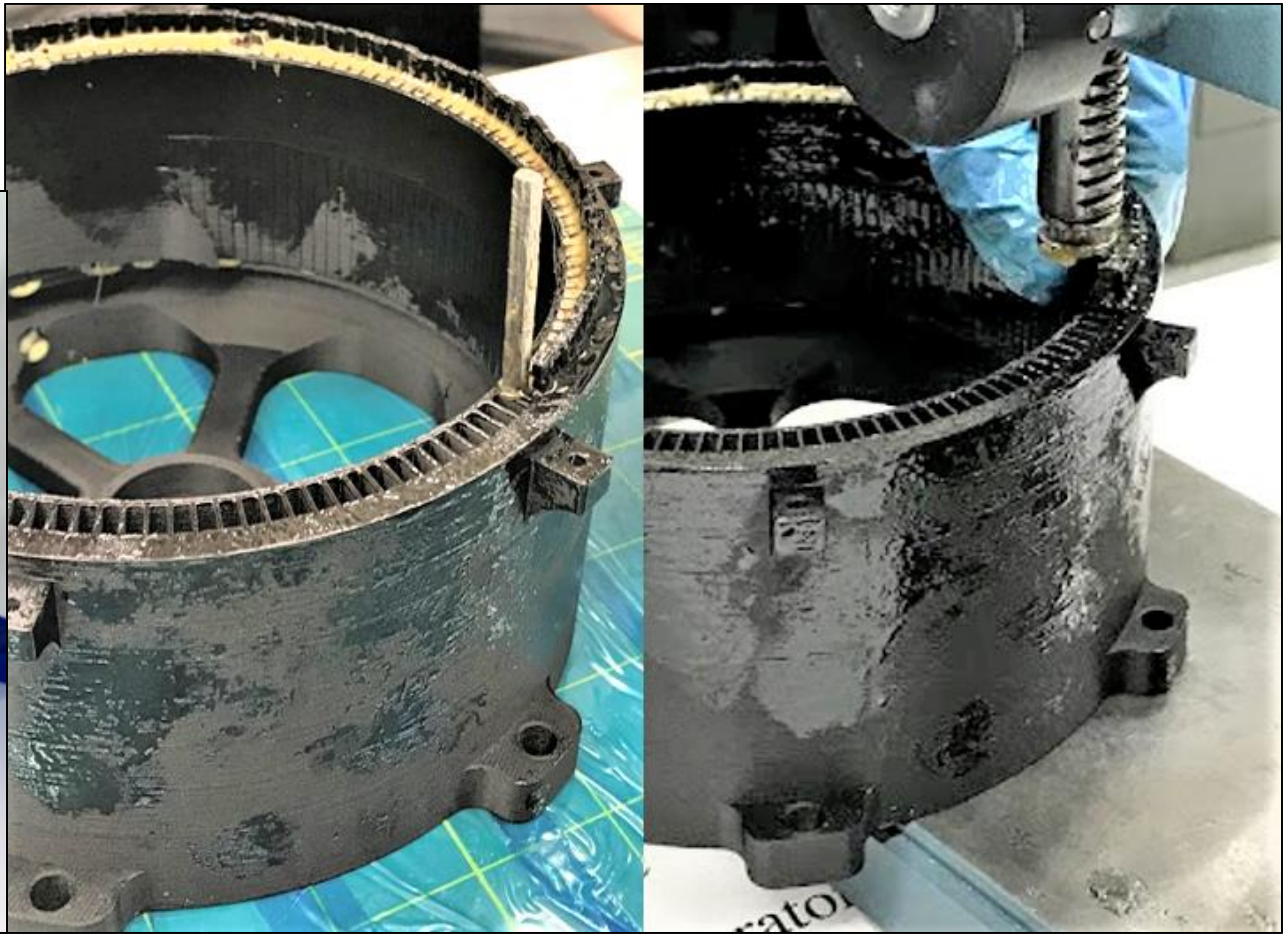


Prototype-2 Fabrication

Ring Fabrication

- Forced into place with locating post
- Temporary inner wall removed when adhesive dried

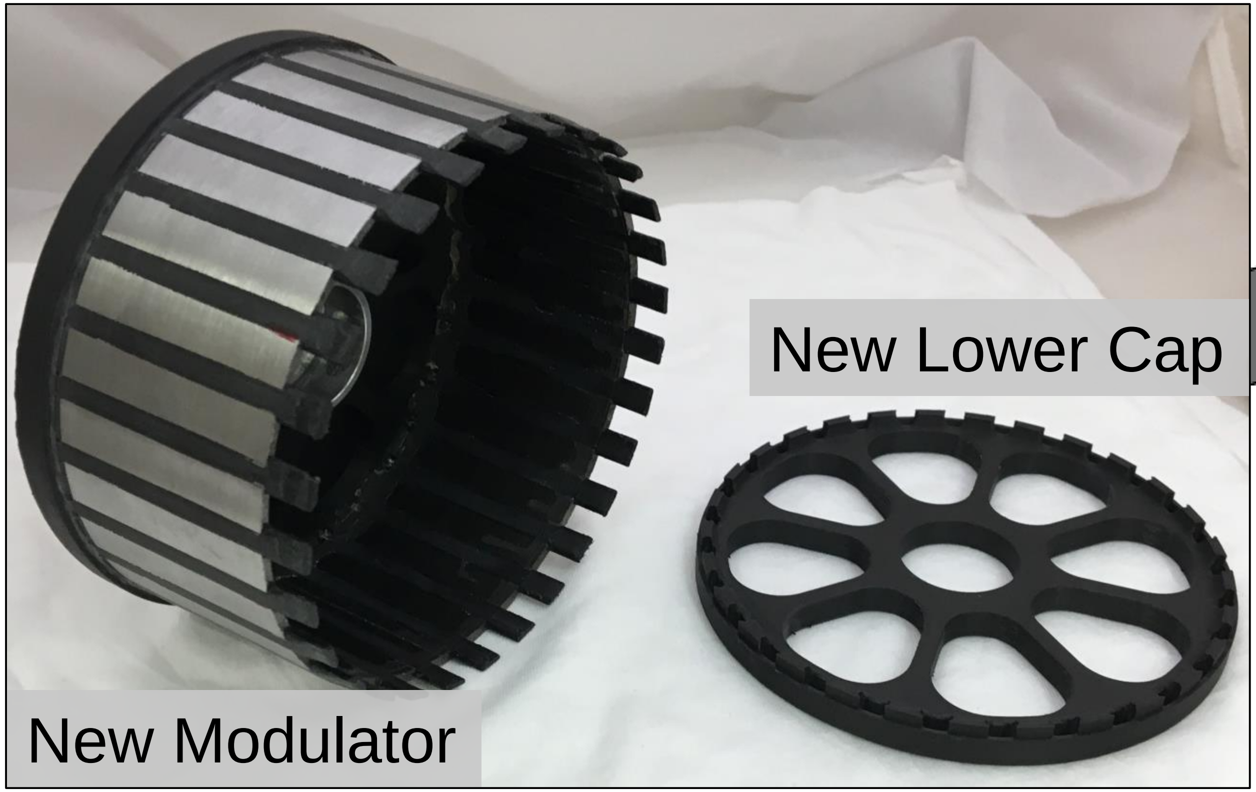




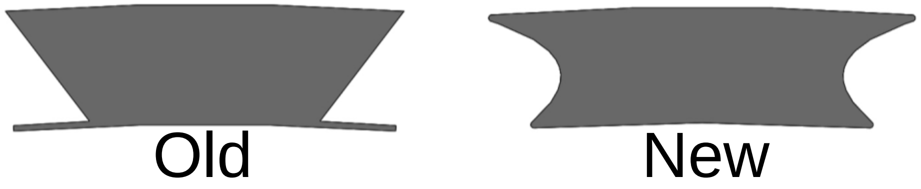
Prototype-2 Fabrication

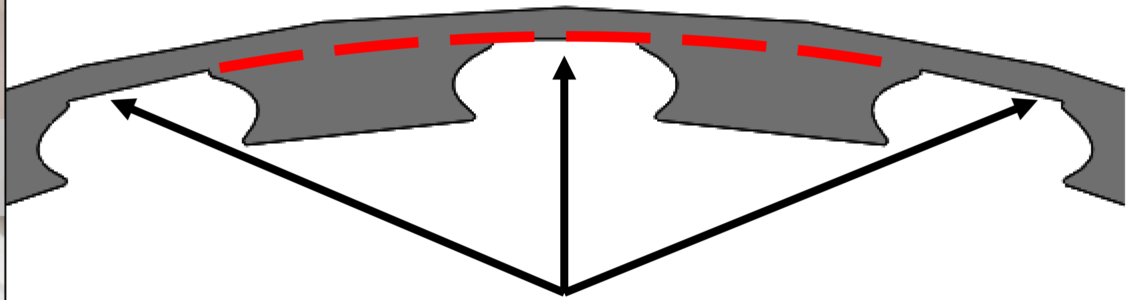
Modulator Rebuild

1. Thickened lower cap
2. Modified pole piece geometry
3. Changed pole piece fabrication process



Pole Piece Design Change





Bounding ring for assembly machined off after adhesive dried

Prototype-2 Fabrication

Prototype 2 Key Takeaways

- Higher specific torque possible
- Halbach array assembly critical to air gaps
- Modulator stiffness critical to durability and high performance
    - Can’t depend on laminated pole pieces for stiffness
    - Structural posts need to be stiffer