Development of Electric Machines that Produce Radial Magnetic Forces to Statically Unload Foil Bearings and Enable Hermetic sCO_2 Turbomachinery

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Our Program

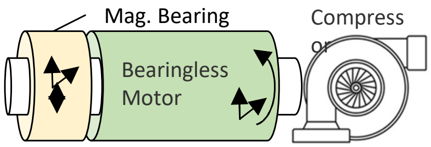
Most recent courses taught

- Design of Rotating Electric Machines
- Introduction to Engineering
- Motion Control Laboratory
- Power Electronic Circuits

Research: *Design and actuation of new electric machine concepts for sustainability*

- Group Members : 6 PhD (3 alumni) **+** 2 MS (14 alumni) **+** 2 post-doc researchers (2 alumni) **+** 6 undergraduate researchers
- 107+ peer-reviewed papers, 11 patents issued/pending

Levitation



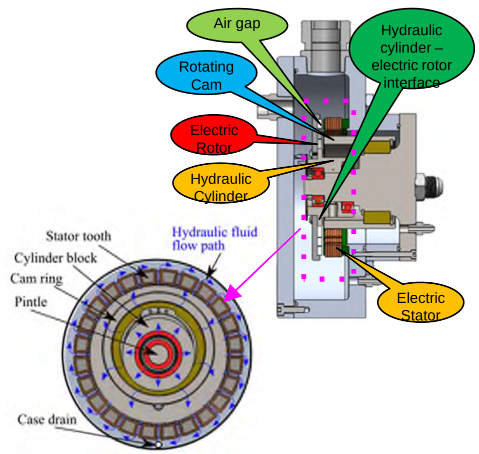
Active Magnetic Bearing

Bearingless PM Motor

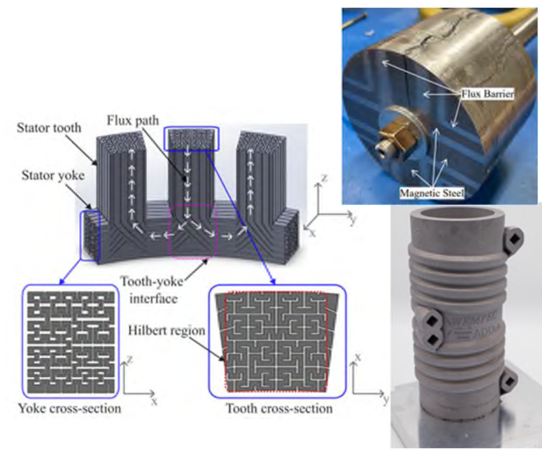
High Speed

Components of 100+ kRPM motor systems

Electro-Hydraulic



Additive Manufacturing



NSF DEVCOM ARMY RESEARCH LABORATORY BETA TRANE TECHNOLOGIES JMAG REVTERRA DELTA CCEFP Sandia National Laboratories

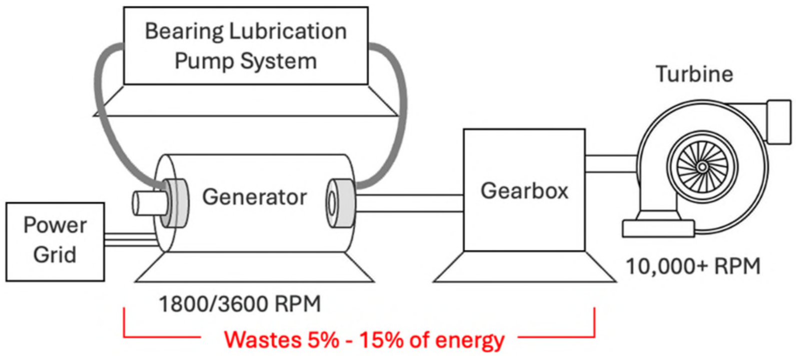
Overview

- Motivation: Bearing Challenges in Hermetic Turbomachinery
- Proposed Foil Bearing Unloader
- Design Space Exploration of a Case Study Machine
- Performance Analysis of Selected Machines from the Design Space

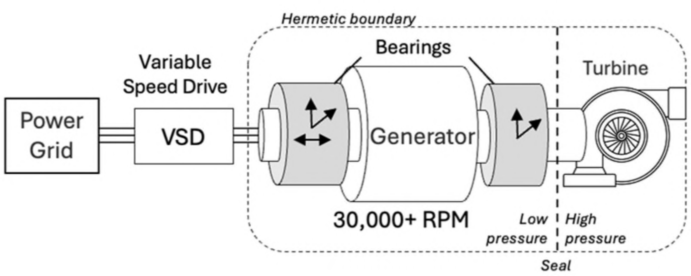
Problem: Closed Brayton Cycles Limited by Bearings

Need for cost-effective bearings that operate in hermetic environment

Conventional high power turbomachine system



Hermetic systems that are limited by bearing technology



- Large size → *compromises the power density advantages of fluids like sCO2*
- High cost → *dry gas seals*
- Maintenance, reliability concerns

- Compact and highly integrated
- Needs oil-free bearings
  - *Gas: foil or externally pressurized*
  - *Maglev*
- Current technology has shortcomings

[1] T. Noguchi, W. Chan, N. Petersen, L Rapp, E L Severson, "Opportunities to Enhance sCO2 Power Cycle Turbomachinery with Bearingless Motor/Generators," *Solar Compass*, 2024.

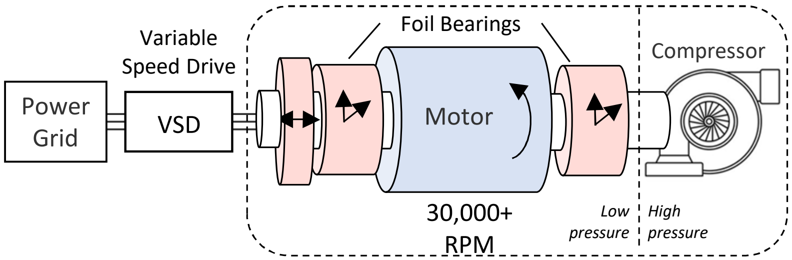
Today's Hermetic Bearing Solutions

Gas Foil

- **Benefits**
  - Completely passive operation
  - No pass-throughs into cavity

Source: Sulzer

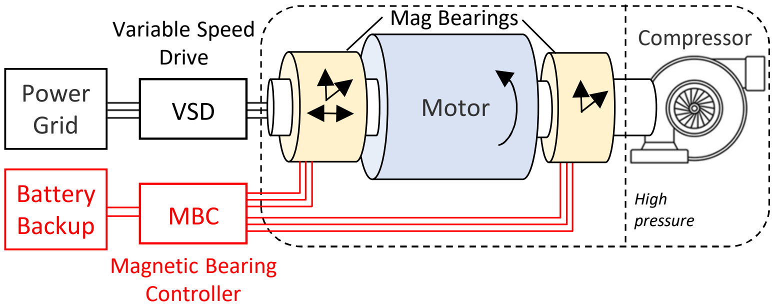
- **Challenges**
  - Wear during start/stop
    - Limits maximum shaft weight / lifetime
    - < 200 kW
  - Reputation for low damping



Active Magnetic

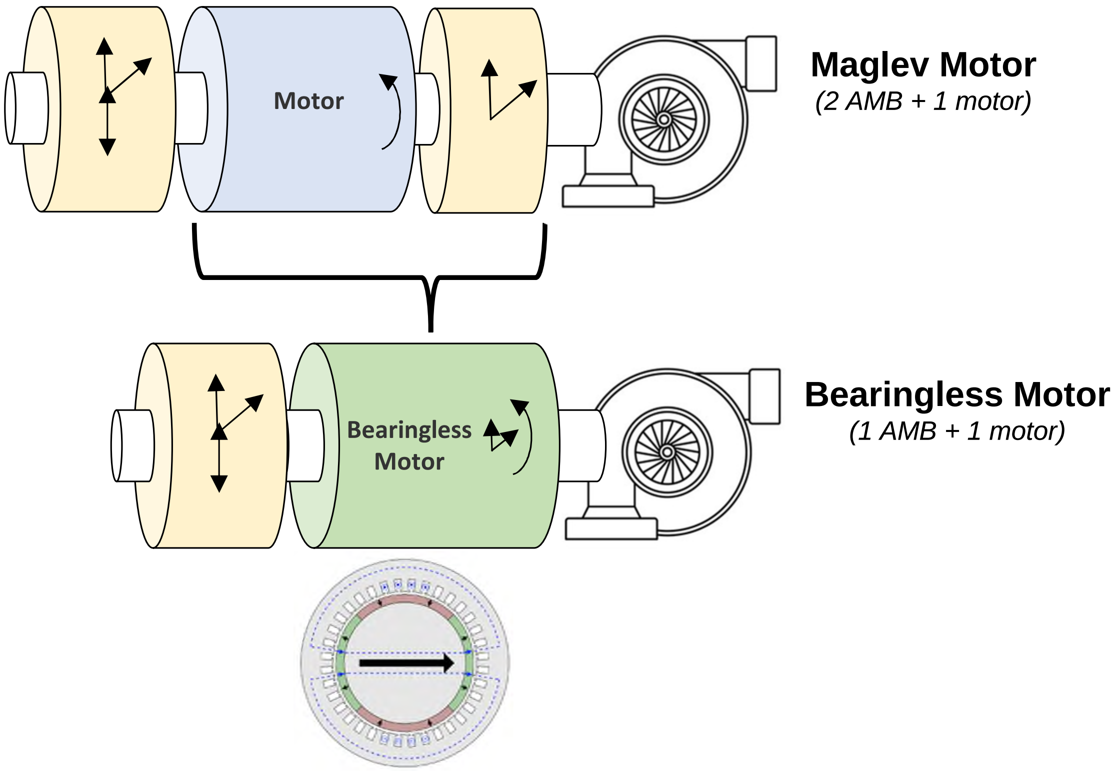
- **Benefits**
  - Works for large shafts
  - Excellent vibration / acoustics
  - System health monitoring

- **Challenges**
  - High cost
  - Increased axial shaft length
  - Large number of passthroughs



New Alternate Technology: “Bearingless” Motor

Motor technology that controls magnetic forces on shaft



Technology:

- Standard motor + new winding
- Standard VFD
- No performance degradation
- Support rotor weight with 5% power reduction

AMB: Active Magnetic Bearing

Status: Example Benchtop Demonstrations in Our Lab

Bearingless PM Machines

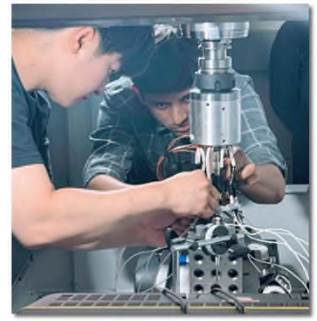
1. 1 kW, 30,000 RPM Motor
2. 10 kW, 160,000 RPM Motor
3. 3.4 kW, 35,000 RPM “Twin” Motor
4. 13 kW, 140,000 RPM “Twin” Motor
5. 50 kW, 80,000 RPM Generator
6. 13 kW, 160,000 RPM Motor + foil bearings

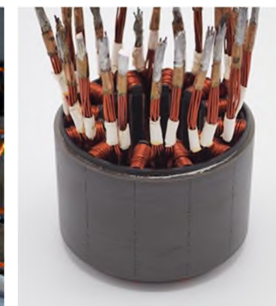
Bearingless Induction Machines

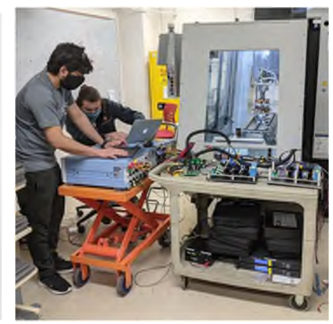
1. 3.6 kW, 30,000 RPM Motor

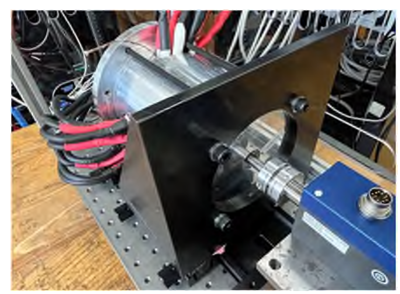
AC Homopolar Machines *(for flywheels)*

1. 1 kW, 3,600 RPM Motor
2. 6 kW, 10,000 RPM Motor/Generator







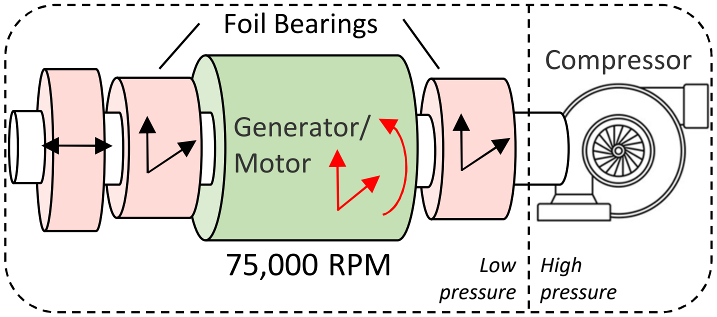


Proposed Foil Bearing Unloader

Using Magnetic Forces to Enhance Foil Bearings

We aim to develop an electric motor that can control radial shaft forces to solve the shaft weight limitations of foil bearings

Bearing Unloading
(Creates torque and unloading force)



	Bearingless Motor	Foil Bearings
Advantages	Active radial force control	Simple, purely passive
Challenges	Missing thrust control Require backup bearings	Friction/wear at start/stop Low damping

Goal of this project

Potential future project

Foil Bearings + Bearingless Motor
Foil as backup bearings Bearingless motor: • **Unload static force** • **Add damping** • **Supercritical operation**

We aim to show that our bearingless motors can reduce foil bearing wear

Research Questions and Paper Contributions

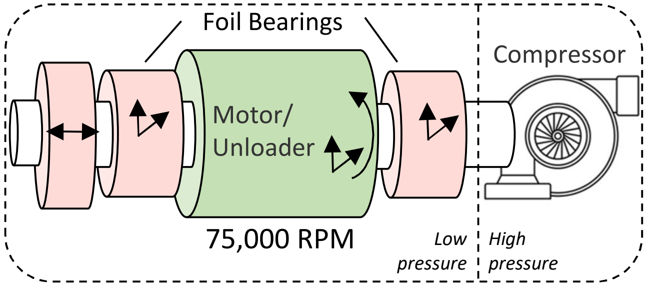
Research questions and technical challenges for applying the unloader concept in hermetic turbomachines:

1. What is the most promising winding configuration to create an electric machine be a foil bearing unloader?
2. Is it possible to add unloading force capability without compromising motor/generator performance at high speed?
3. What are the implementation challenges of applying this concept in sCO_2 environments?

Addressed in our work in ECCE 2025 [2] (questions 1 and 2)

The goal of this paper (question 3)

Electric motor creates radial forces to unload the shaft's static weight to assist foil bearings only at low speeds

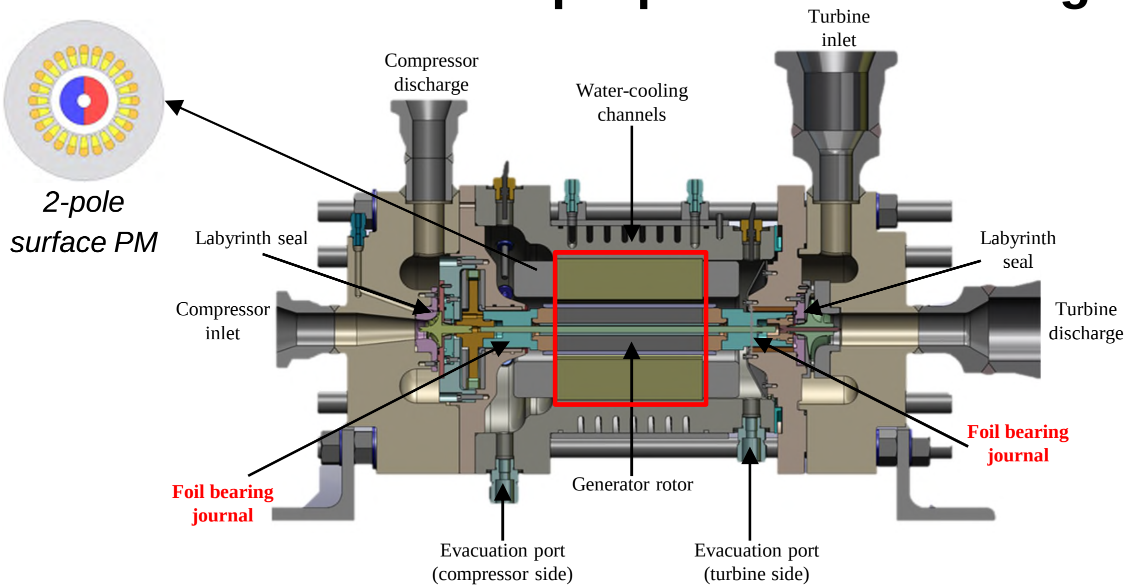


The goal of this paper is to investigate the practical implementation of foil-bearing unloaders in sCO_2 turbomachinery.

[2] S. Saleh, T. Noguchi, L. Rapp and E. L. Severson, "Design of Bearingless Motors to Unload Static Forces from Foil Bearings," ECCE, 2025.

Case Study Machine

We considered an existing hermetic turbomachinery as the application for the proposed foil bearing unloader concept



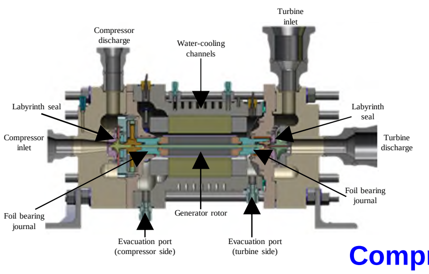
The case study machine was originally designed by Barber Nichols and later tested in an sCO_2 loop at the Brayton Lab at Sandia National Laboratories.

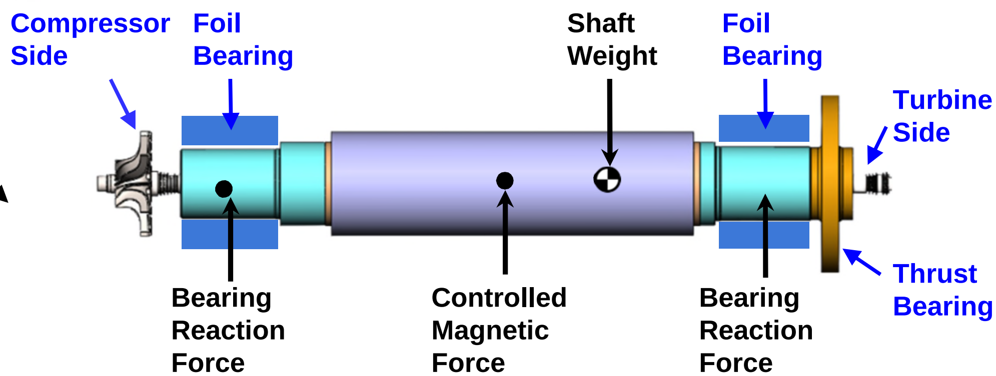
Parameter	Specification
Rated power	100 kW
Rated speed	75 kRPM
Rotor	2-pole surface PM
Bearing	Foil bearings
Working fluid	sCO_2

We are demonstrating this concept in an existing turbomachine

Ability to Unload Foil Bearings in Case Study Machine

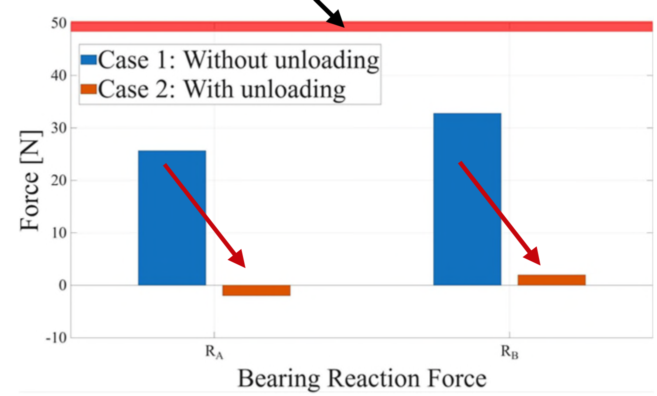
A force and moment study was conducted on the prototype machine to understand the impact motor-generated forces can have on the bearing loads





Free body diagram of prototype machine

Shaft weight of 50 N



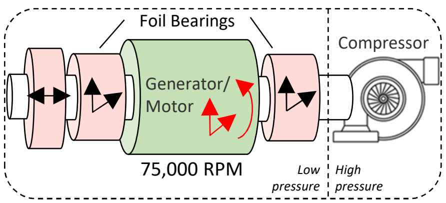
We are able to reduce foil bearing loading by creating radial magnetic force with the electric motor/generator

Foil bearing load significantly reduces when magnetic unloading force applied

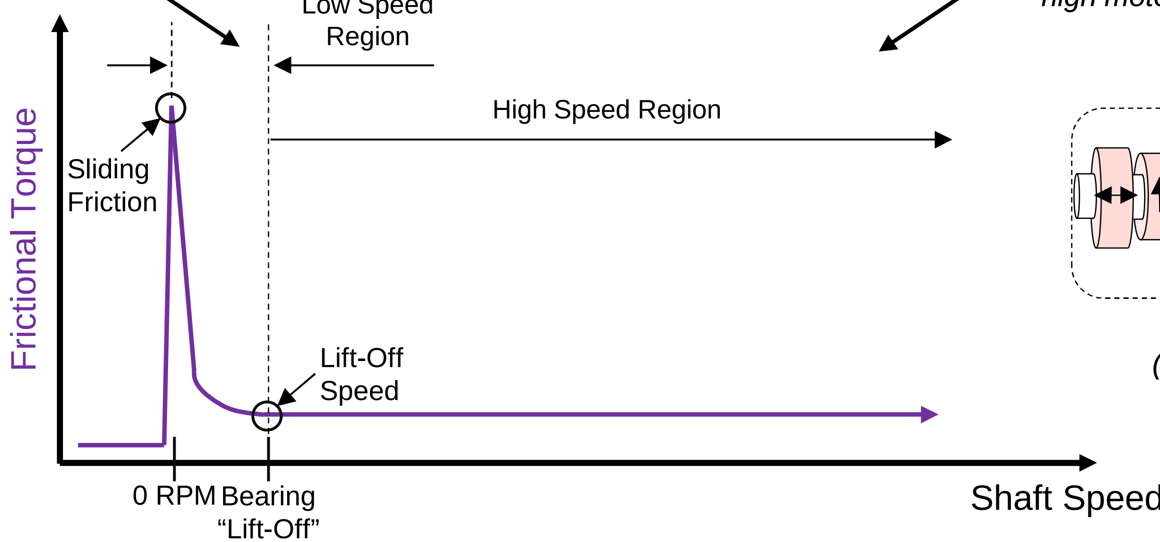
High Speed Performance for Foil Bearing Unloader

Because foil bearing limitations occur at low speeds, the proposed foil bearing unloader for the case study machine should generate force only during low speeds

At low speeds, the electric machine generates force to reduce high sliding friction in this region

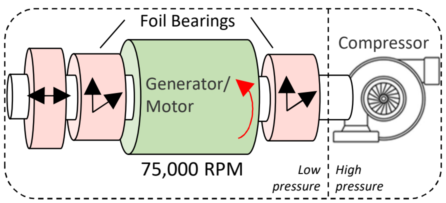


Bearing Unloading
(Creates torque and unloading force)



Foil-bearing frictional torque versus shaft speed

After lift-off speed, the unloading force will be will deactivated to retain high motor/generator performance.



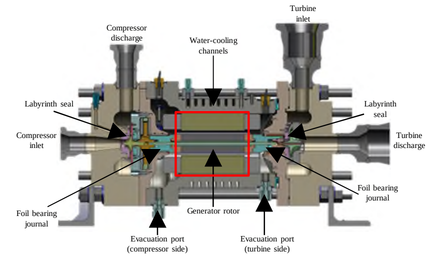
Normal Operation
(creates only torque)

The proposed foil bearing unloader creates forces only at low speeds

Design Space Exploration of the Case Study Machine

[2] S. Saleh, T. Noguchi, L. Rapp and E. L. Severson, "Design of Bearingless Motors to Unload Static Forces from Foil Bearings," ECCE, 2025.

Winding Configurations

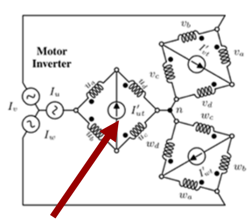


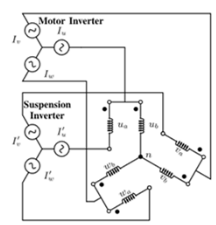
There are several plausible winding configurations that can make electric motors produce unloading force

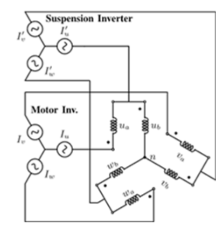
Our team has design, control, and sensing innovations across all of these winding types

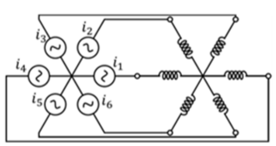
Winding Config.	Bridge	Parallel	MCI	MP	Separate
Custom motor drive required?	✅ No	🟧 Maybe	🟧 Maybe	❌ Yes	✅ No
Torque rating reduced when unloading force is deactivated	✅ No	✅ No	✅ No	✅ No	❌ Yes

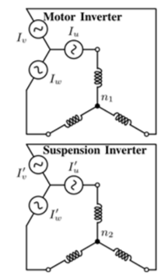
MP: Multi-phase
MCI: Mid-point current injection











Bridge converter: unloading forces created by adding "bolt-on" force drive electronics to an otherwise standard motor system

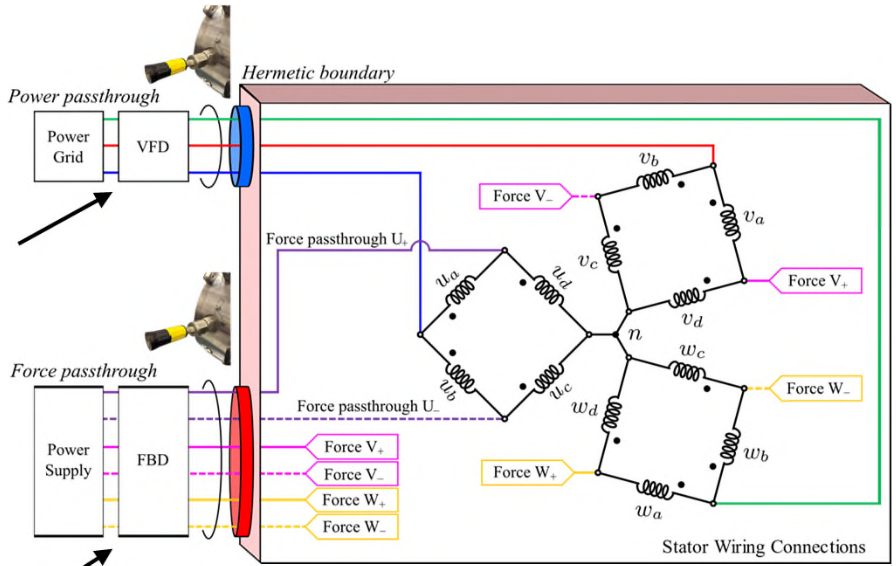
We selected the bridge winding for demonstration because this allows the motor/generator to be operated by a standard variable frequency drive

[2] S. Saleh, T. Noguchi, L. Rapp and E. L. Severson, "Design of Bearingless Motors to Unload Static Forces from Foil Bearings," ECCE, 2025.

Bridge Winding for the Case Study Machine

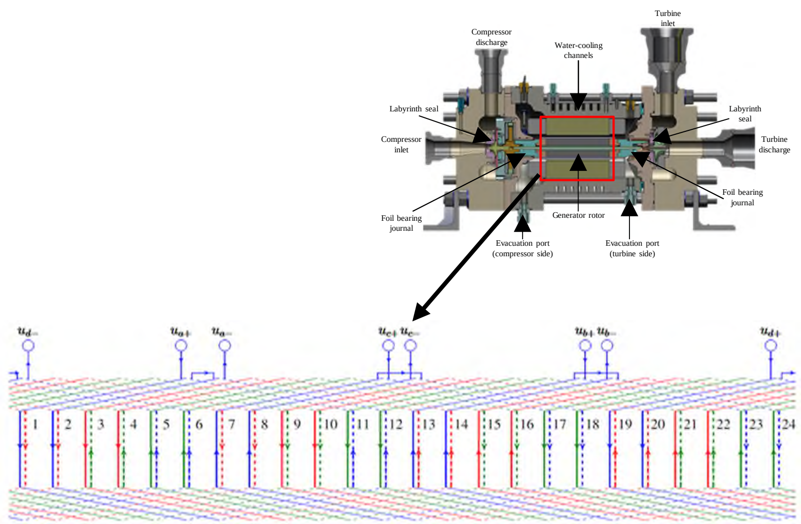
We proposed replacing the existing winding of the case study machine with a bridge winding capable of producing both torque and force.

Standard Motor Drive (100 kW)



Our "Bolt-on" Force Drive (only 23 W required for example 100 kW motor!)

Coil connections for the bridge winding configuration



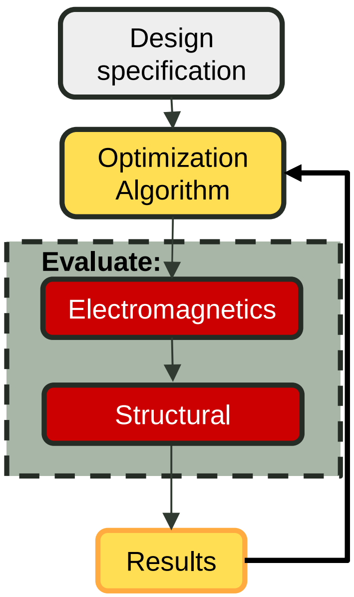
Winding layout for the case study machine

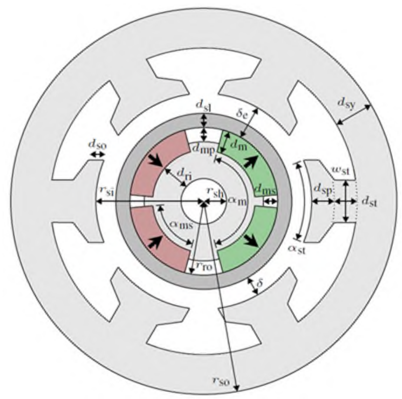
We only need to add a 23 W "bolt-on" force drive to unload the foil bearings of this 100 kW electric machine

[2] S. Saleh, T. Noguchi, L. Rapp and E. L. Severson, "Design of Bearingless Motors to Unload Static Forces from Foil Bearings," ECCE, 2025.

Optimizing the Case Study Machine

We created a modeling framework to optimize case study machine to study the performance implications of adding force capability





Objective functions:

a. Maximize power
b. Maximize efficiency
c. Minimize weighted ripple

Specification parameters used in the optimization study

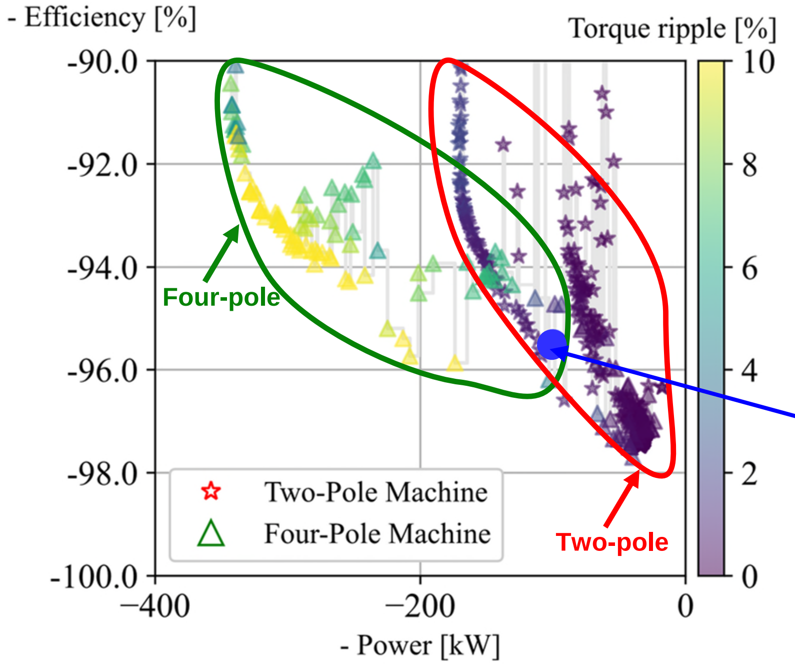
Parameter	**Pole Count**
Rated speed	75 kRPM
PM material	Recoma 26
Sleeve material	Carbon fiber
Stator lamination	Arnon5
# of stator slots	24

We developed modeling and optimization approach to explore design space of electric motors that make force

[2] S. Saleh, T. Noguchi, L. Rapp and E. L. Severson, "Design of Bearingless Motors to Unload Static Forces from Foil Bearings," ECCE, 2025.

Feasibility of Adding Force Capability on Motor Performance

Evaluated the motor performance of electric machines capable of generating forces at high speed when the unloading forces are disabled.



Key Findings:

1. Adding force capability to assist foil bearings is feasible without compromising the machine's nameplate ratings
2. No design with efficiency > 96 % and power 100 kW due to windage loss in sCO2 environment.

This is the case study machine before rewinding (i.e., creates only torque)

Adding force capability to assist foil bearings is feasible without compromising the machine's nameplate ratings (power and efficiency)

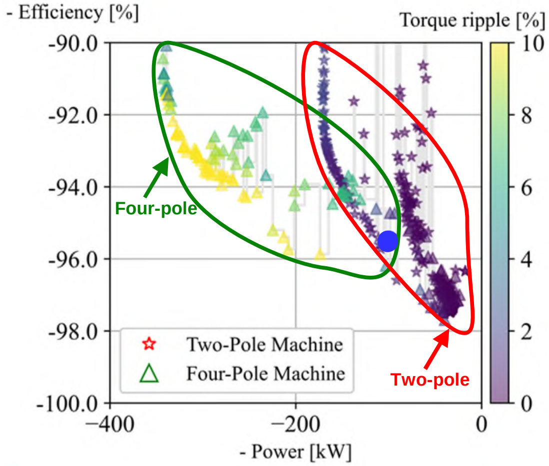
Performance Analysis of Selected Machines from the Design Space

Detailed Analysis of Motor Behavior While Unloading Bearings

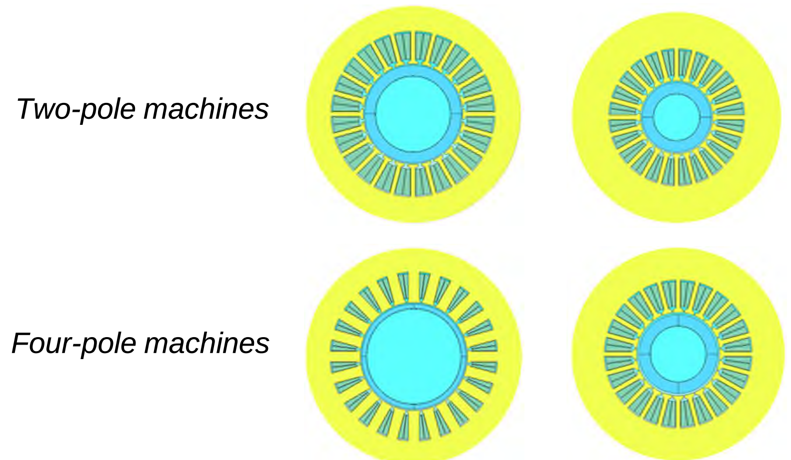
Explored implementation challenges of applying the unloading concept in sCO_2 environments:

1. Thermal and loss study → Illustrate practical thermal management techniques to maintain the motor within safe thermal limits
2. PM demagnetization study → Identify allowable temperature limits for PMs
3. Force performance study → Show force performance during the unloading event

Select machines optimization



Detailed analysis



This paper presents detailed analysis of four maglev unloader machines

The Selected Machines

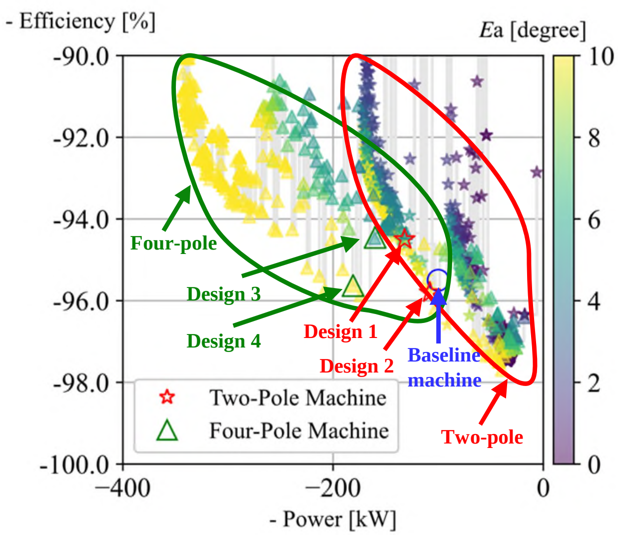
Selected four machines from optimization study to be evaluated in sCO2 environment for detailed analysis

Parameter	Pole Count	Power [kW]	Efficiency [%]	Torque ripple [%]	Ea [deg.]
Design 1	Two-pole	124	94.5	0.7	6.4
Design 2	Two-pole	109	95.8	0.3	15.8
Design 3	Four-pole	152	94.2	6.5	4.9
Design 4	Four-pole	181	95.7	14.6	49.6
Baseline machine	Two-pole	100	95.6	0.2	-

Ea: Error angle
Ea is used to evaluate force ripple during unloading event

$$E_a = \max\left(|\phi - \phi_{\text{avg}}|\right)$$

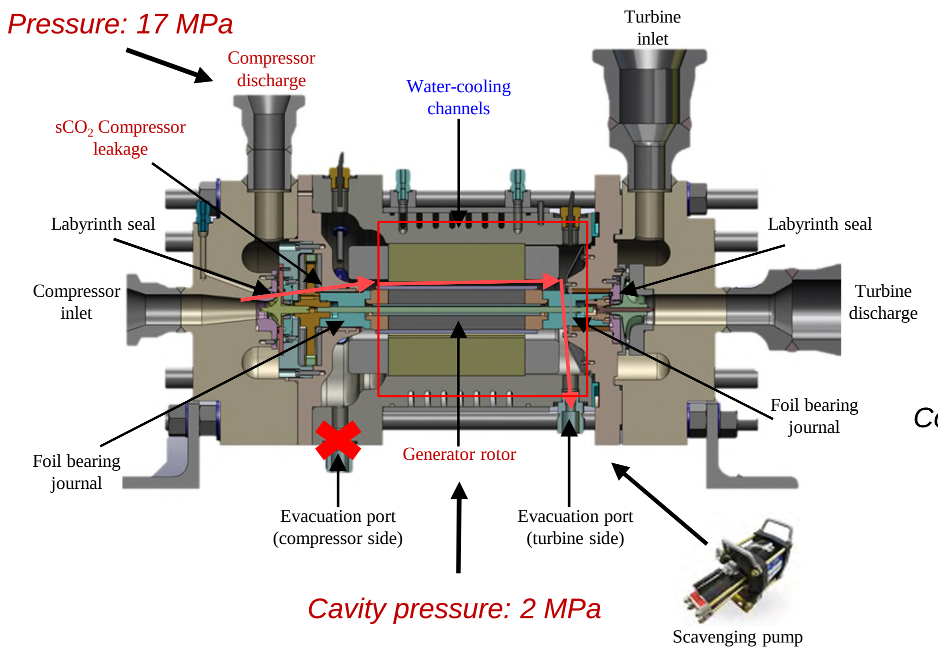
Design 1 & 3 are selected for thermal considerations analysis

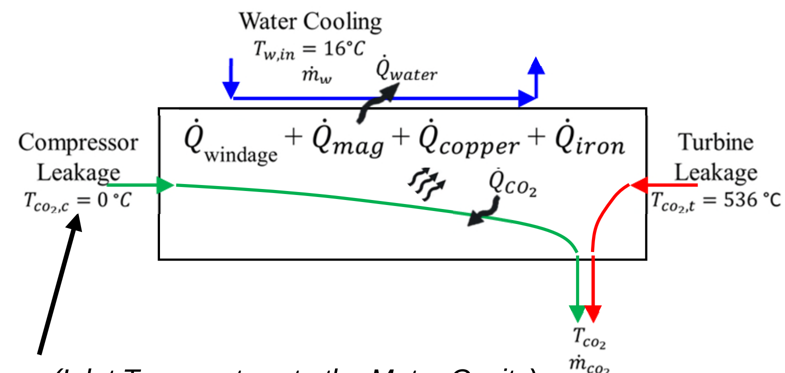


Selected designs are highest power/efficiency, have range of force performance

Thermal modeling for the Case Study Machines

- **Thermal resistance networks were used to estimate the temperature distribution in the motor cavity using Anays-MotorCAD.**
- **CO_2 compressor leakage flow and water jacket used for cooling.**



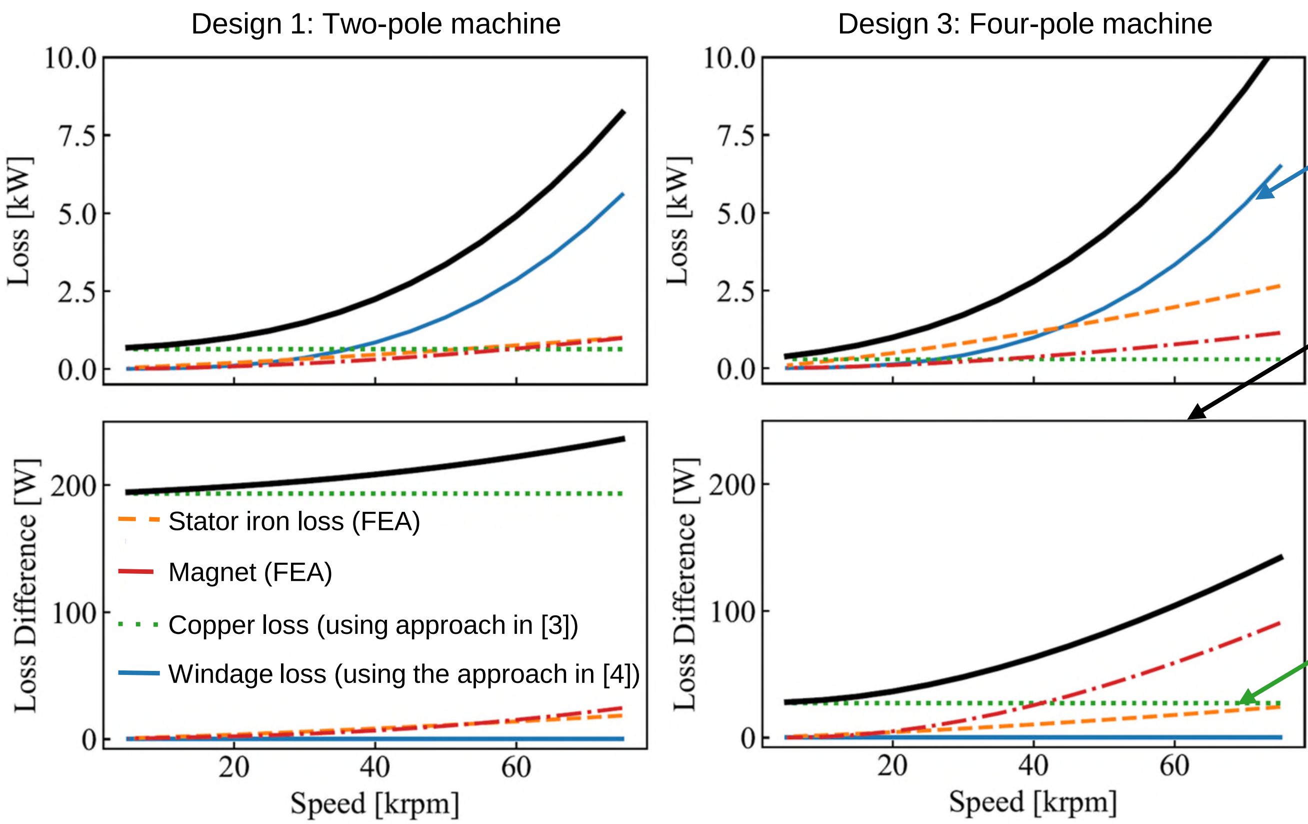


Compressor Leakage (Inlet Temperature to the Motor Cavity)

- *The inlet temperature of the compressor leakage is estimated using the Joule–Thomson effect, assuming that isenthalpic expansion occurs across the labyrinth seal.*
- *The temperature drop is calculated based on the pressure drop. This pressure drop results in a temperature decrease to 0 °C.*

Compressor leakage is utilized to cool the motor air gap

Loss Analysis Results of Designs 1 and 3



Windage is the dominant loss

Loss Difference: $\mathrm{Loss}_{\mathrm{motor}} - \mathrm{Loss}_{\mathrm{Unloader}}$

- *Motor: creates only torque*
- *Unloader: creates torque and unloading force*

Key Findings:

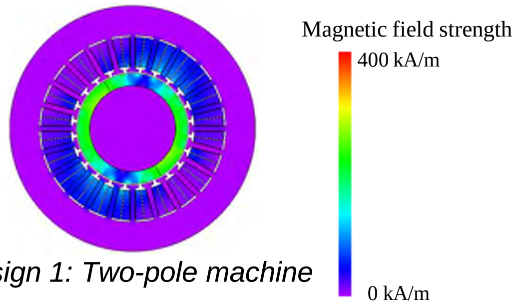
1. No significant difference due to unloading bearings
2. Interestingly, copper loss is slightly reduced during unloading bearings

Unloading the bearings does not increase motor loss / thermal load

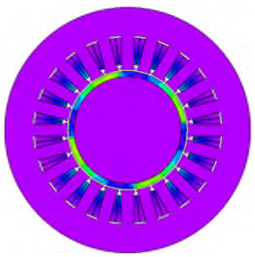
[3] N. Bianchi, S. Bolognani, and P. Frare, "Design criteria for high-efficiency spm synchronous motors," IEEE Transactions on Energy Conversion, vol. 21, no. 2, pp. 396–404, 2006.
[4] J. E. Vrancik, "Prediction of windage power loss in alternators," NASA Technical Note D-4849, NASA Lewis Research Center, Cleveland, OH, October 1968

PM Demagnetization Analysis

Analyzed the magnetic strength of PMs for Design 1 & 3 during two conditions: motor and unloader

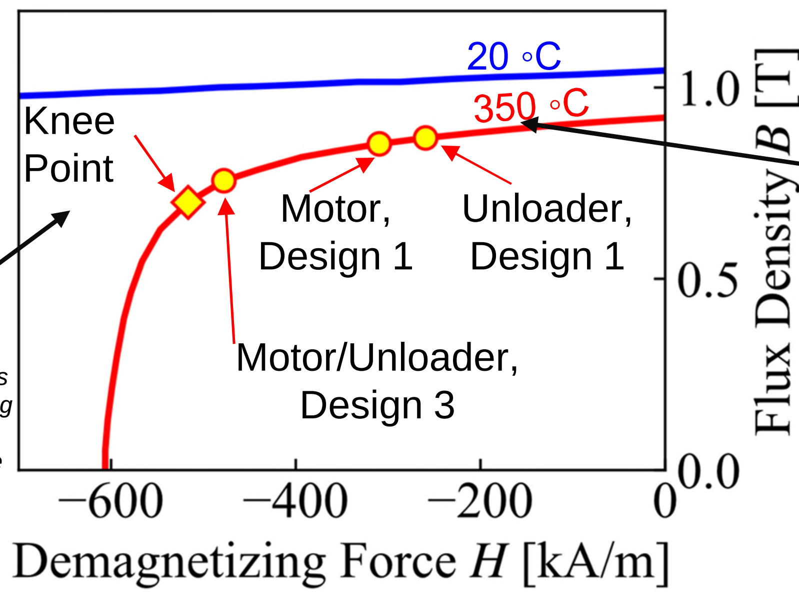


Design 1: Two-pole machine



Design 3: Four-pole machine

The allowable temperature of PMs depends on the machine operating points on the magnet B–H curve relative to the onset of irreversible demagnetization(the knee point)



To avoid demagnetization, a 10 % safety margin is adopted; that is, the allowable PM temperature is set to 315 ℃.

The magnetic field needed to unload the bearings does not introduce significant magnetic stress nor does it cause excessive magnet heating

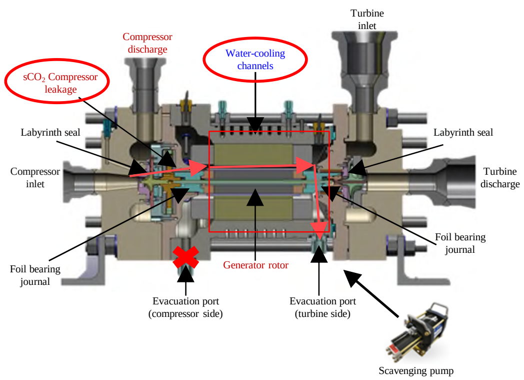
Slide 24

1 @saleh097@umn.edu -- in the paper we use this analysis to establish that we should operate at a max of 315C, right? It seems like that should be indicated on here because we see 315C on the next slide.
Reassigned to Sayed Saleh
Eric Severson, 3/2/2026

1 I annotated to this point here.
Sayed Saleh, 3/2/2026

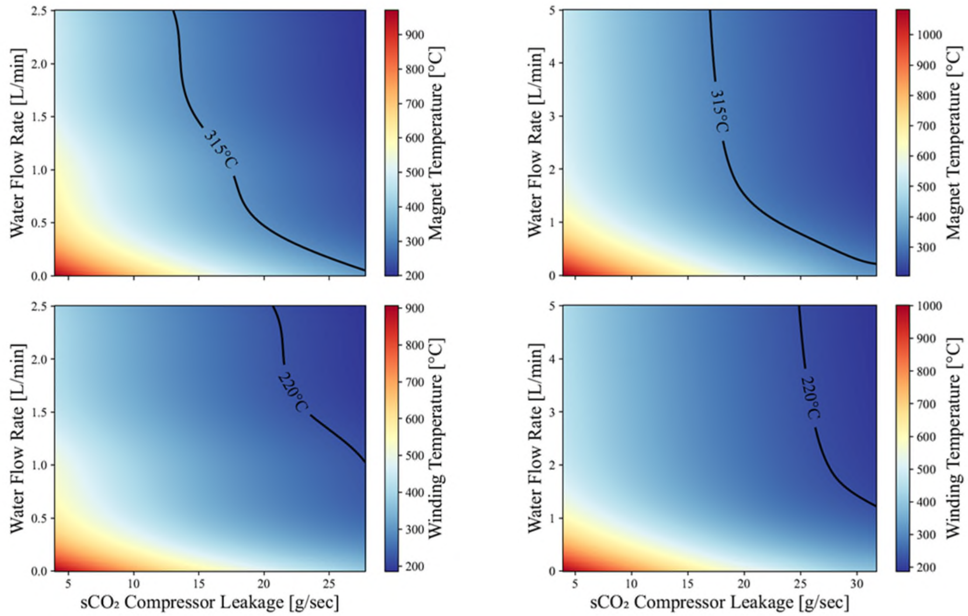
Temperature Distribution of the Selected Machines

Calculated the temperatures of the PMs and windings for Designs 1 & 3 using thermal resistance networks



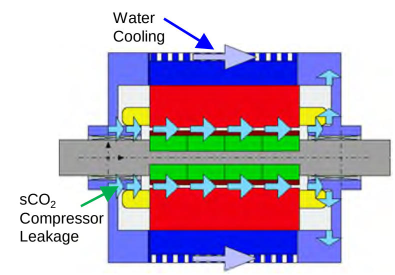
Design 1: Two-pole machine

Design 3: Four-pole machine



Temperature Limits:

- *Magnet: 315 °C*
  (from demagnetization study)
- *Windings: 220 °C*
  (coil type: NW-71, Class 220)

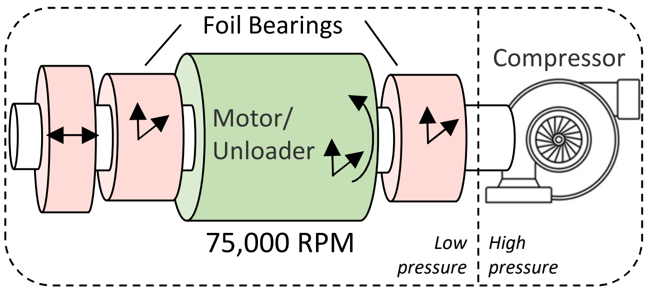


Ansys- MotorCAD model

Either design can be cooled by using leakage flow through the compressor seal + the cooling jacket already installed on this case-study machine.

Conclusion

- **High performance electric machines can be used to unload foil bearings**
  - Only one additional passthrough port
  - No additional sensors



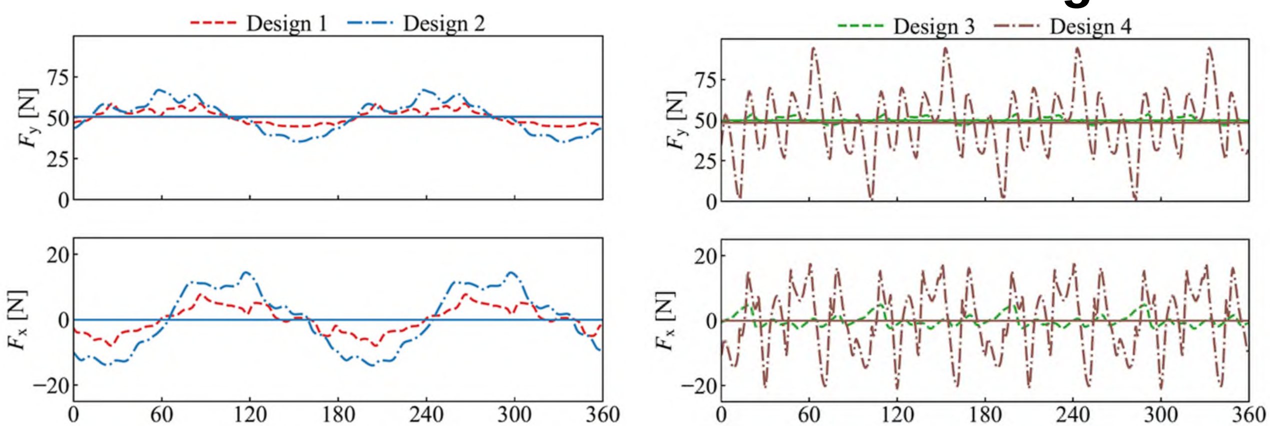
- **Can use standard drive electronics**
  - Plus a small “bolt on” force drive
- **Does not add thermal load**

This is a cost-effective concept to enable foil bearings in significant power sCO_2 turbomachinery without compromising efficiency or power

Next steps: we are looking for demonstration partners! Come talk to us.

Force Performance During Unloading Bearings

Examined force ripple of all selected machines during unloading bearings



	Power [kW]	Eff. [%]	Torque rip. [%]	Ea [deg]
Design 1 two-pole	124	94.5	0.7	6.4
Design 2 two-pole	109	95.8	0.3	15.8
Design 3 four-pole	152	94.2	6.5	4.9
Design 4 four-pole	181	95.7	14.6	49.6

Key Findings:

1. Two-pole machines achieved the required unloading force with minimal disturbance.
2. Four-pole machines with higher power and efficiency suffer from a higher error angle, leading to greater oscillations in radial forces.

While four-pole machines have higher power and efficiency, they suffer from greater force ripple

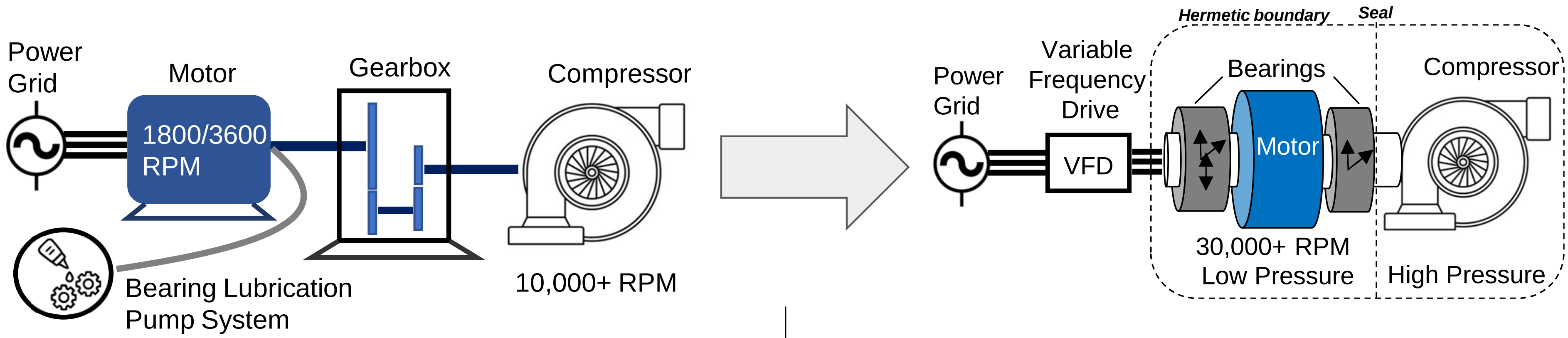
Conclusion

- Foil Bearing Challenge in Hermetic sCO_2 Turbomachinery
  - Startup and shutdown wear limits practical power capability.
  - Bearing unloading mitigates wear during low-speed operation.
- Design Space Exploration for Proposed Foil Bearing Unloader
  - Bearing unloading preserves the machine's nameplate power and efficiency.
  - Windage losses in sCO_2 constrain power and efficiency (no design with power > 100 kW and efficiency > 96%)
- Thermal Management for the Proposed Foil Bearing Unloader
  - Unloading bearings does not increase thermal loading
  - sCO2 compressor leakage can be utilized to cool the machines

The proposed electric machine enables foil bearing implementation in high-power sCO_2 turbomachinery without compromising efficiency or power

Problem: Closed Brayton Cycles Limited by Bearings

Need for cost-effective bearings that operate in hermetic environment



- Large size → *compromises the power density advantages of fluids like sCO2*
- High cost → *dry gas seals*
- Maintenance, reliability concerns

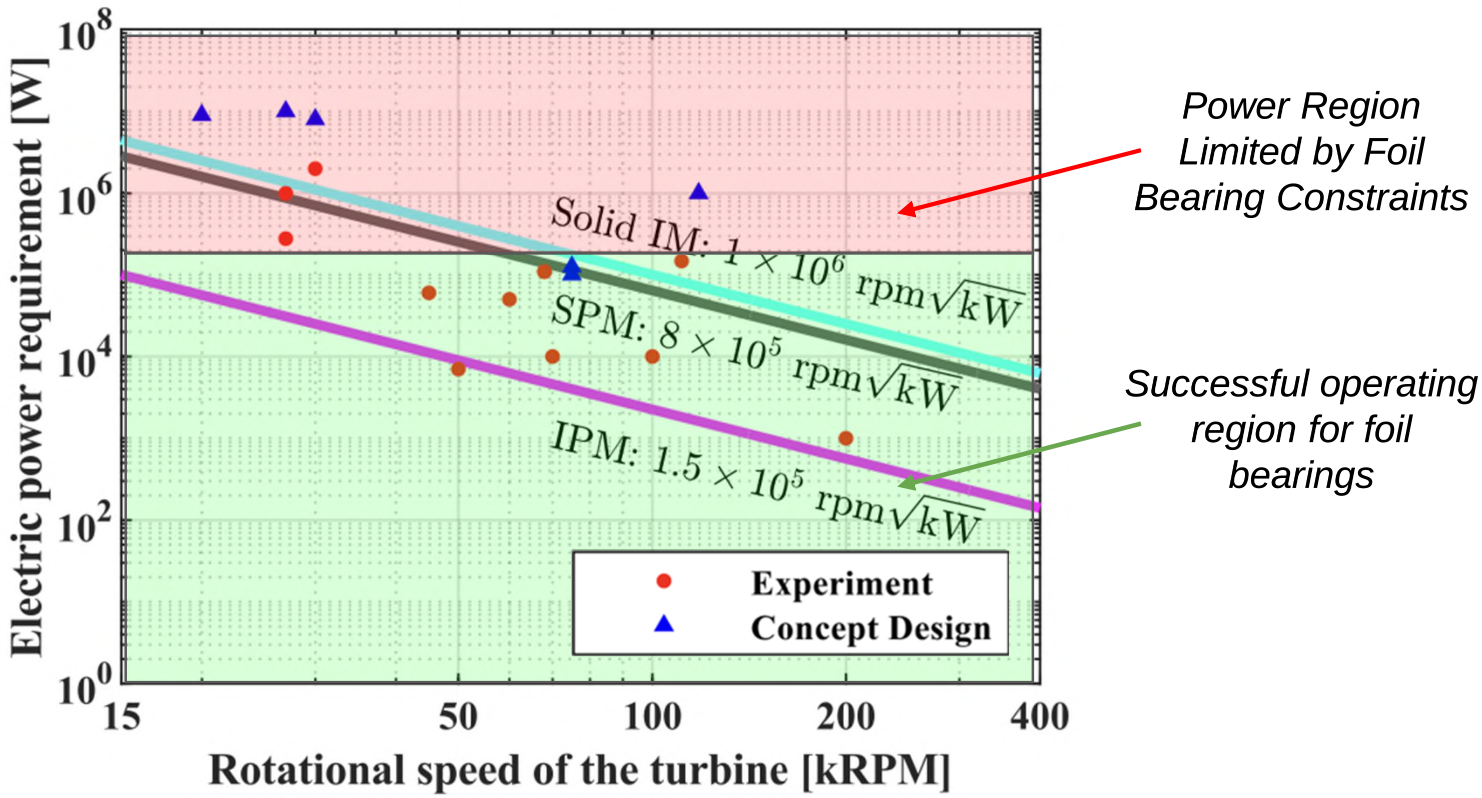
- Compact and highly integrated
- Needs oil-free bearings
  - *Gas: foil or externally pressurized*
  - *Maglev*
- Current technology has shortcomings

[1] T. Noguchi, W. Chan, N. Petersen, L Rapp, E L Severson, "Opportunities to Enhance sCO2 Power Cycle Turbomachinery with Bearingless Motor/Generators," *Solar Compass*, 2024.

Foil Bearings Limit Achievable Power in sCO_2 Turbomachinery

- Direct-drive sCO_2 turbomachines: **10 kW – 8 MW potential**
- Foil bearing wear restricts practical operation to < **200 kW**

Published speed-power for sCO2 turbomachinery designs [1]



[1] T. Noguchi, W. Chan, N. Petersen, L Rapp, E L Severson, "Opportunities to Enhance sCO2 Power Cycle Turbomachinery with Bearingless Motor/Generators," *Solar Compass*, 2024.