# “Brushless and Permanent Magnet Free Wound Field Synchronous Motors for EV Traction”

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**University of Wisconsin - Madison**

**June 9th, 2015**

**Project ID: EDT065**

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# Overview

## Timeline: 2 years

- Project start date: October 1st, 2014
- Project end date: September 30th, 2016
- Percent complete: 33% as of today

## Budget: $616,567

DOE - $493,247

FY1 $279,245

FY2 $214,002

UW & IIT - $123,320

## Partners

- Prof. Dan Ludois – University of Wisconsin – Madison
- Prof. Ian Brown – Illinois Institute of Technology

## Barriers

- Magnet cost (about $200) is about 75% of the 2020 motor cost target; eliminating PMs reduces motor cost by 30%
- The back EMF of Interior PM machines requires a boost converter, which brings the power electronics cost above the 2015 or 2020 cost targets; eliminating the boost converter saves 20% in power electronics cost
- Poor power factors for Interior PM machines cause larger currents, increasing size and cost of PE; improved power factor saves 15% PE cost

# Background Motivation - Relevance

- Commercial & societal detractions of permanent magnet synchronous machines (PMSMs)
  - Rare earth PMs are significant fraction of EV motor cost
  - Rare earth PM market is volatile
  - Rare earth PM extraction and refinement environmentally hazardous
  - Rare earth PMs are largely single source from a foreign power

# Background Motivation - Relevance

- PMSM's operational detractions in a traction application
  - PMs have a fixed flux level, non variable, always "on"; safety concerns during inverter faults.
  - Interior PMSMs typically operate with negative d-axis current (especially during field weakening operation);
    - Power factor lowered because of the reactive current
    - Traction inverter oversized to supply reactive current
    - Increased losses in inverter and stator (ohmic)

<u>Wound Field Synchronous Machines (WFSM) stand to overcome the limitations of PMSMs via electromagnets</u>

# Project Objective – Relevance

- Design, develop, and demonstrate a prototype wound field synchronous motor (WFSM) with brushless rotor excitation via capacitive power transfer (CPT) capable of replicating the performance of commercially available Interior PM motors for EV traction.
- Two WFSM prototypes have the following technical targets:

DOE USDRIVE AND WFSM PROTOTYPE TARGETS

| Attribute | Units | USDRIVE 2015 Target | USDRIVE 2020 Target | WFSM Prototype 1 Target | WFSM Prototype 2 Target |
|---|---|---|---|---|---|
| Peak Power | kW | 55 | 55 | 55 | 55 |
| Cont. Power | kW | 30 | 30 | 30 | 30 |
| Specific Power | kW/kg | 1.3 | 1.6 | 1.3 | 1.6 |
| Power Density | kW/l | 5 | 5.7 | 4.5 | 5 |
| Specific Cost | $/kg | 7 | 4.7 | - | - |

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# Budget Period 1 Milestones

| Milestone | Type | Description |
|---|---|---|
| Initial Electrostatic Design Complete | Technical | Analytical and finite element confirmation of capacitive coupler transferring average field power [≥300 W] and peak field power [≥600W] with limited electric fields [<1.5 MV/m] |
| Development of Combined Thermal and Electromagnetic WFSM Multi-objective Optimization Code Complete | Technical | Optimization results for sample designs match detailed finite element modelling results within 15% for average torque, torque ripple, phase flux linkage and within 20% for stator core losses. |
| Multi-objective Optimization and Selection of Candidate Designs for Prototyping Complete | Technical | Candidate designs meet the following technical goals: 55 kW peak power for 18 sec., 30 kW power continuous, specific power >1.3 kW/kg, power density >4.5 kW/l in optimization analysis. |
| Construction WFSM Prototype 1 Complete | Technical | Selected design for prototype 1 constructed and ready for bench testing. |
| Capacitive Coupling Bench Test Complete | Go/No Go | Experimentally confirm capacitive coupling transfers average field power [≥300 W] and peak field power [≥600W] to dummy load. |

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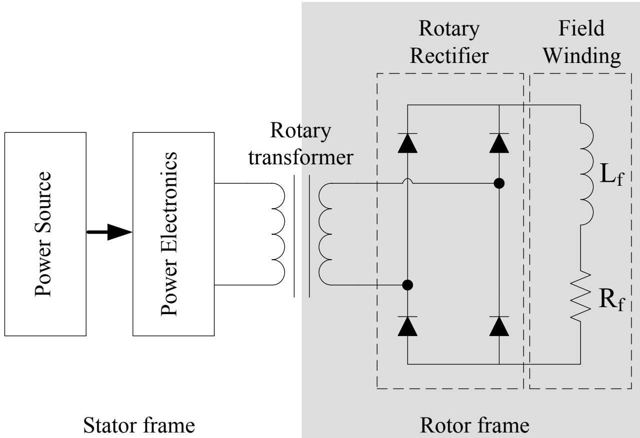
# Budget Period 2 - Milestones

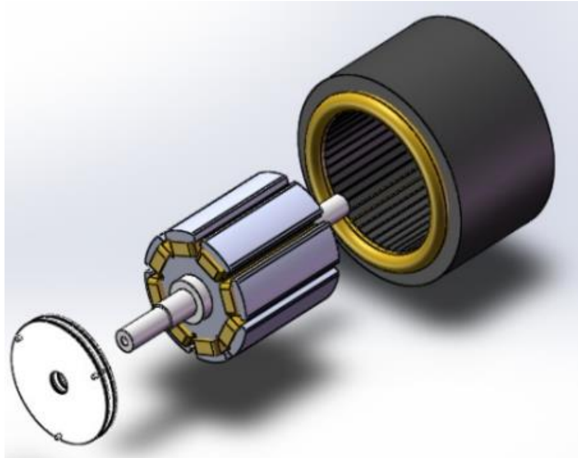
| Milestone | Type | Description |
|---|---|---|
| WFSM Prototype 1 Initial Dynamometer Testing with Brushes Complete | Technical | Design for prototyping meets the following technical goals 55kW peak power for 18 sec., 30 kW power continuous, specific power ≥1.3 kW/kg, power density ≥ 4.5kW/l |
| Dynamometer Testing of WFSM and Capacitive Coupler Prototypes 1 Complete | Technical | The measured performance of the WFSM Prototype 1 meets or exceeds the following specifications: specific power density [≥1.3 kW/kg], volumetric power density [4.5≥kW/l]. |
| Simulation Validation Complete | Technical | The simulation demonstrates that the WFSM stator terminal voltage can be regulated with CPT without the need for the main traction drive. |
| WFSM Performance – Prototype 2 Achieved | Technical | The measured performance of the WFSM meets or exceeds the following specifications: specific power density [≥ 1.6 kW/kg], volumetric power density [≥ 5 kW/l]. |
| Performance in CERTS Micro-grid Achieved | Go/No Go | The WFSM is able to transfer real and reactive power to the micro-grid. |

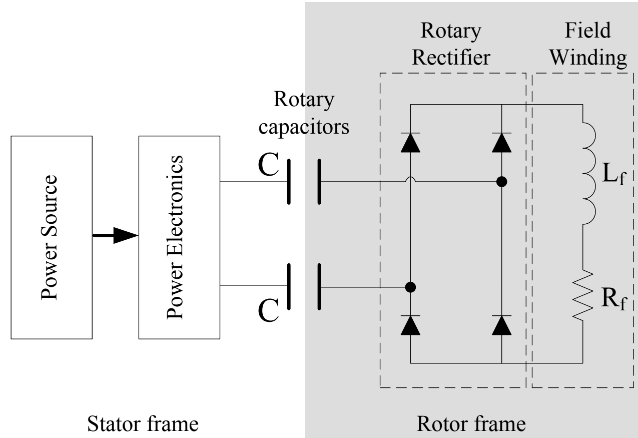
# Approach/Strategy
# Potential WFSM Advantages

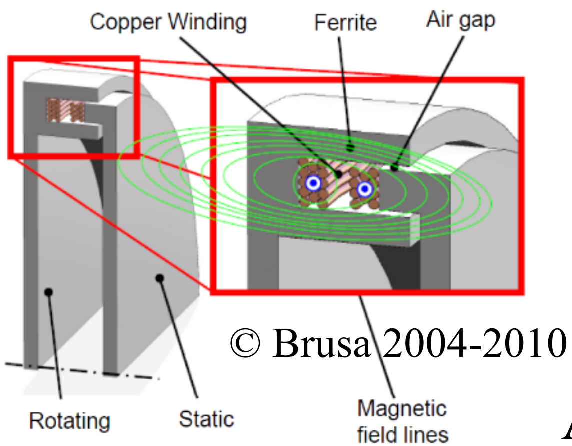
- Wound field synchronous machines (WFSMs) require no PMs
- WFSM have complete control of field excitation
  - Third control variable $i_q$, $i_d$, $i_f$
  - WFSM have potential for optimal field weakening and a large constant power speed range
  - Loss minimization control
  - Rapidly de-energize field in the case of inverter fault
  - Traction inverter downsizing and improved efficiency
- Potential for power take off (generator operation) and grid support when used in a hybrid vehicle application

# Approach/Strategy
# Inductive (IPT) vs. Capacitive (CPT) Coupling

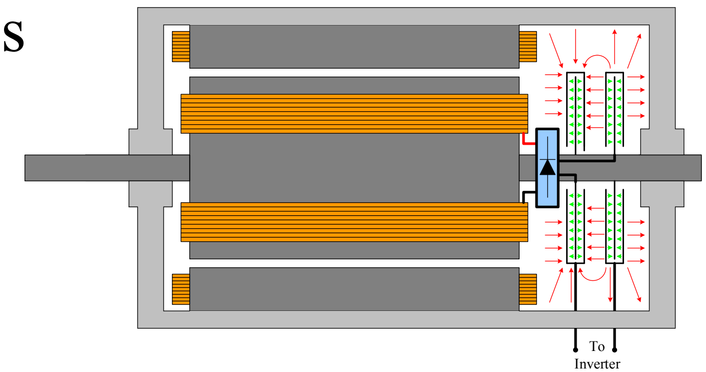





Basic idea: replace PMs with electromagnets




## Approach to Critical Challenges

- Design of the rotor and stator for max power density
- Non-contact rotor field power, i.e. brushless Capacitive Power Transfer

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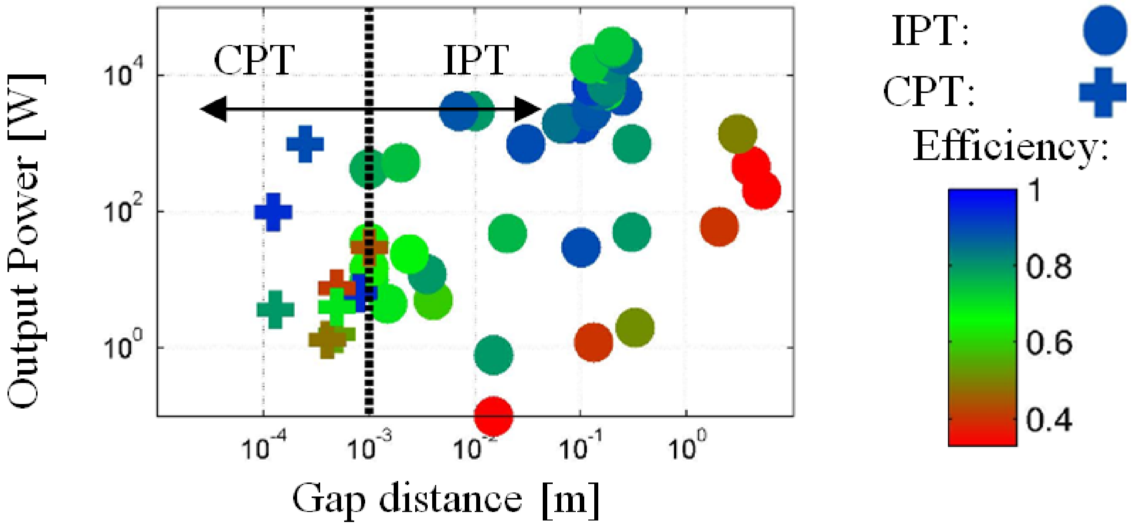
# Approach/Strategy
# CPT in WFSM Advantages




Dai, J.; **<u>Ludois, D</u>**., "A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications," *Power Electronics, IEEE Transactions on*

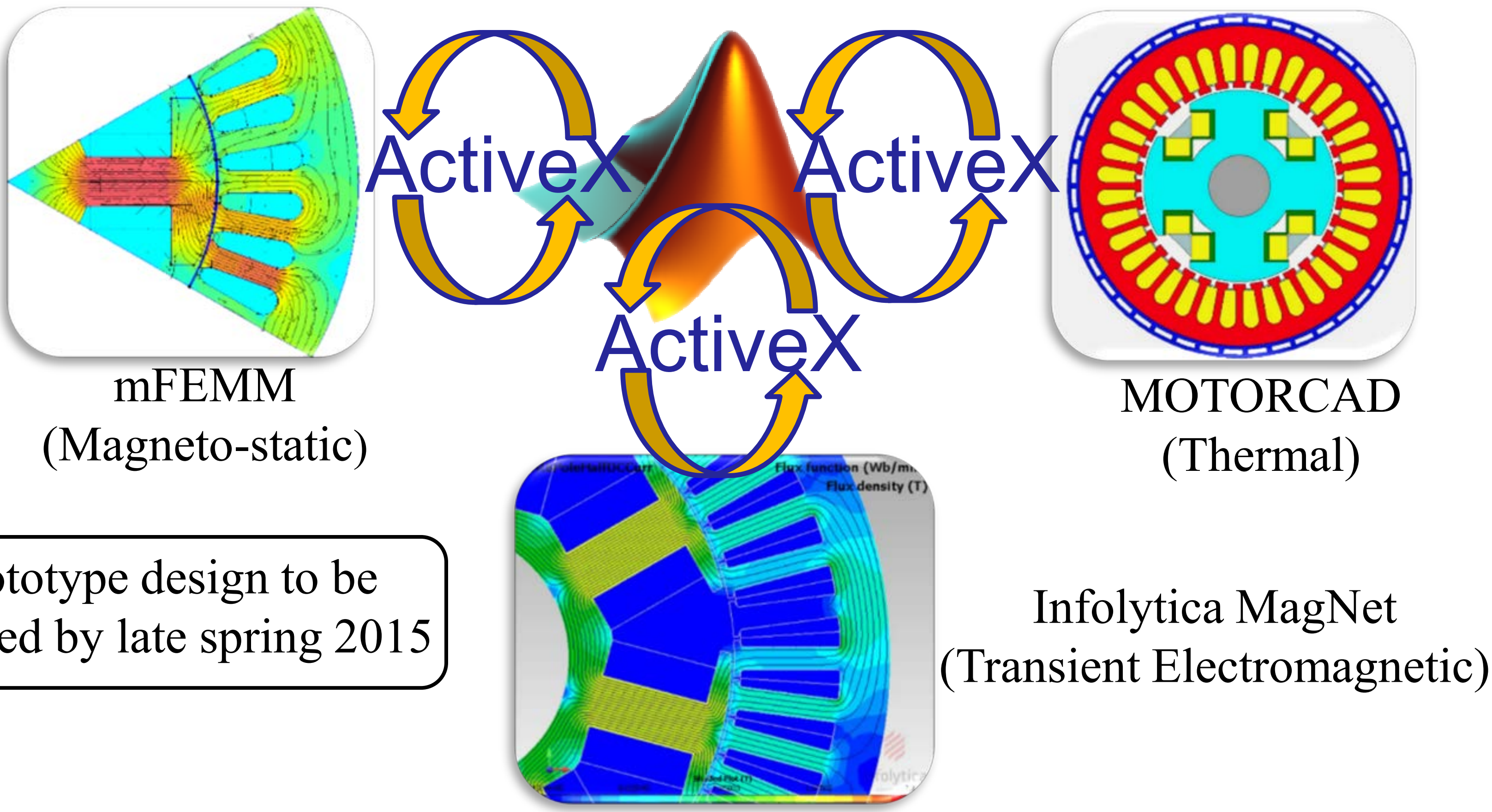
-CPT has comparable power capability to IPT for small gaps

- CPT Advantages for WFSMs: less shaft length, high structural integrity
  - No need for back iron, vs. closed magnetic path in transformers
  - Electric flux lines terminate on charge, field cancels outside gap
  - Metal disks naturally suited for high speed
  - No composite materials or brittle materials (like ferrite)
  - Air dielectric works well at high frequency
  - Light weight, low cost: No magnetic grade steel, ferrite or copper windings

# Approach/Strategy
# WFSM Flexible Design Environment

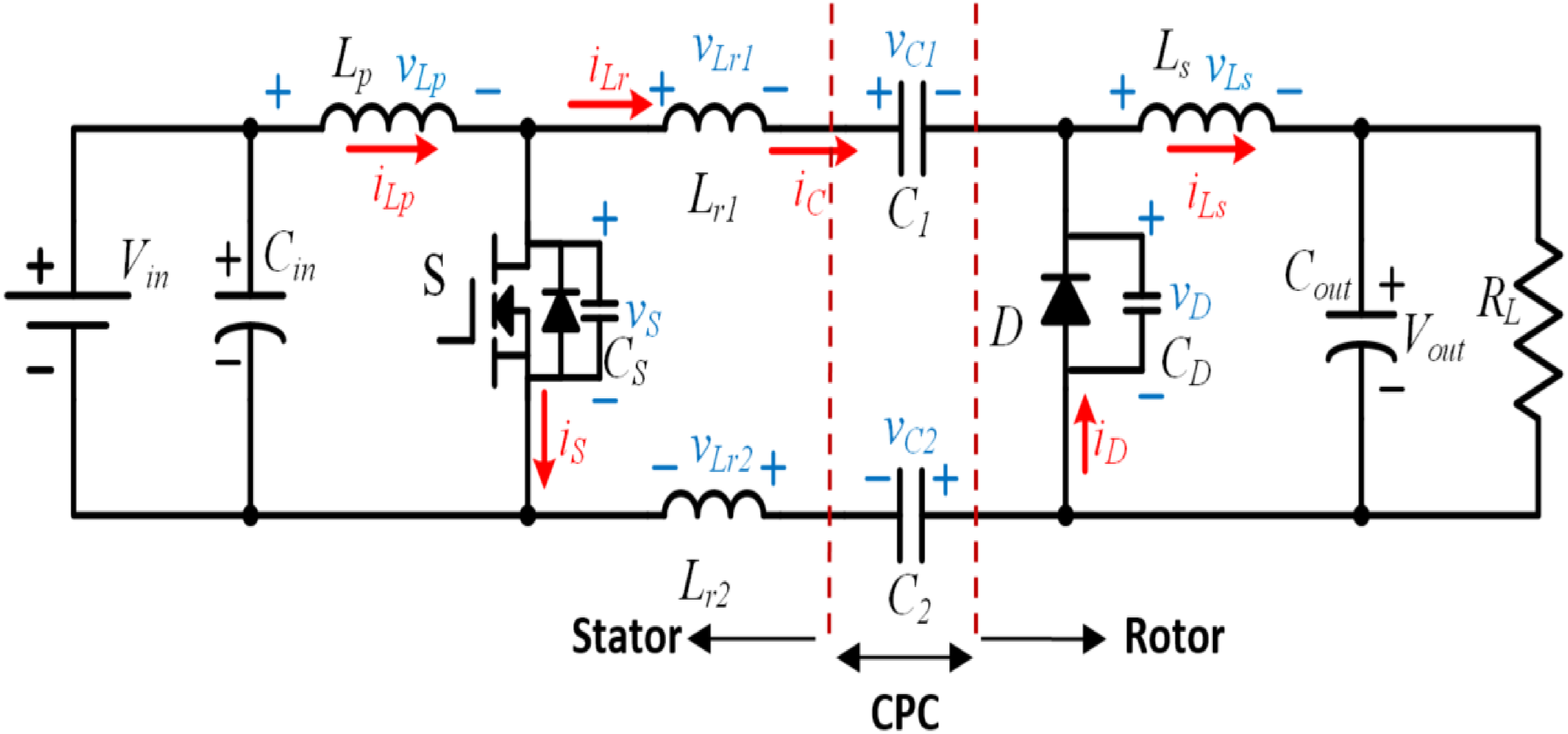
A combined WFSM electromagnetic and thermal design optimization environment has been created

MATLAB(Geometry engine, program control, optimization)



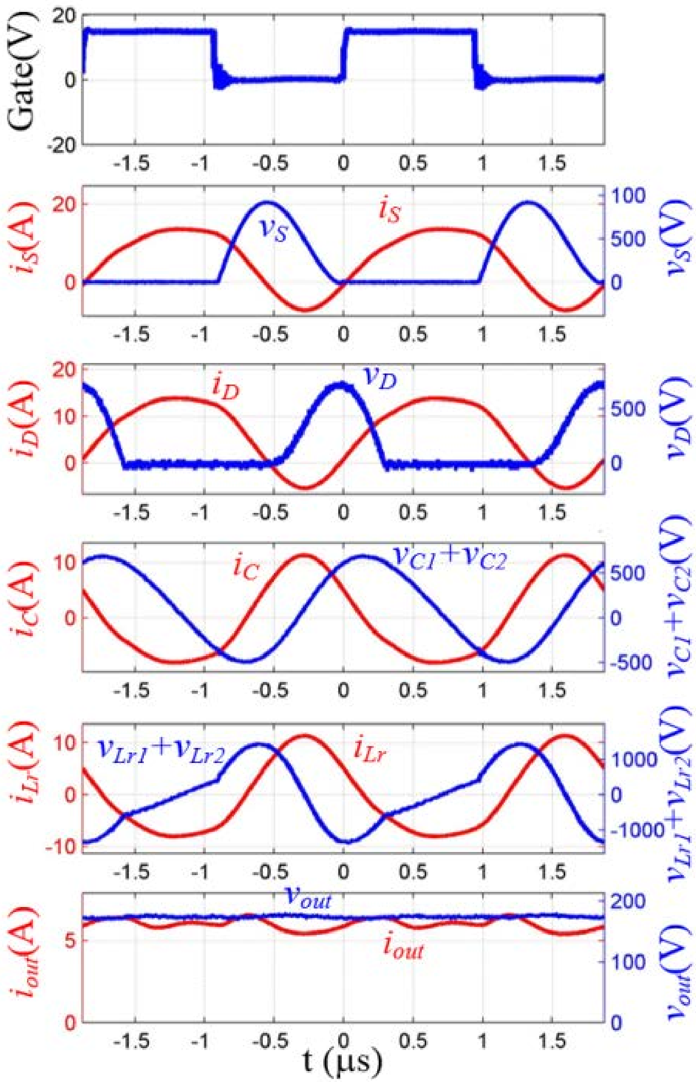

First prototype design to be completed by late spring 2015

# Technical Accomplishments/Progress
# Milestone 1: Initial Electrostatic Design

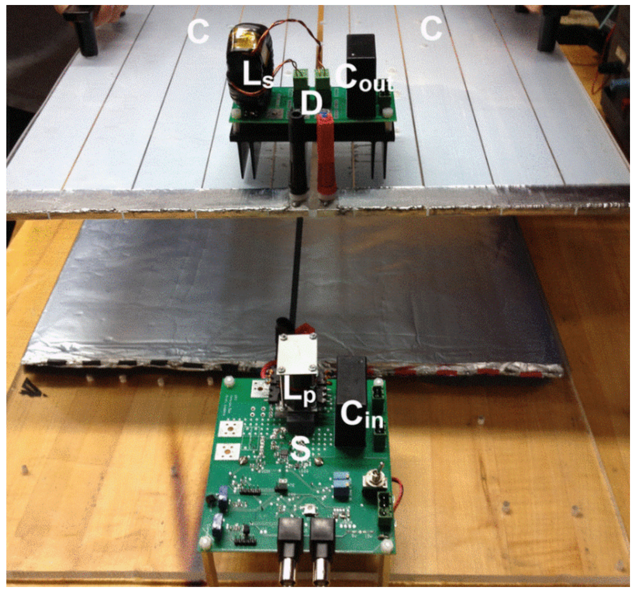



- Class E amplifier and rectifier, "class $E^2$"
- 2.5 kW capable, 550kHz switching, 1200V SiC switches
- Requires ~10nF of coupling capacitance for C1, C2

# Technical Accomplishments/Progress
# Milestone 1: Initial Power Electronic Circuit Results

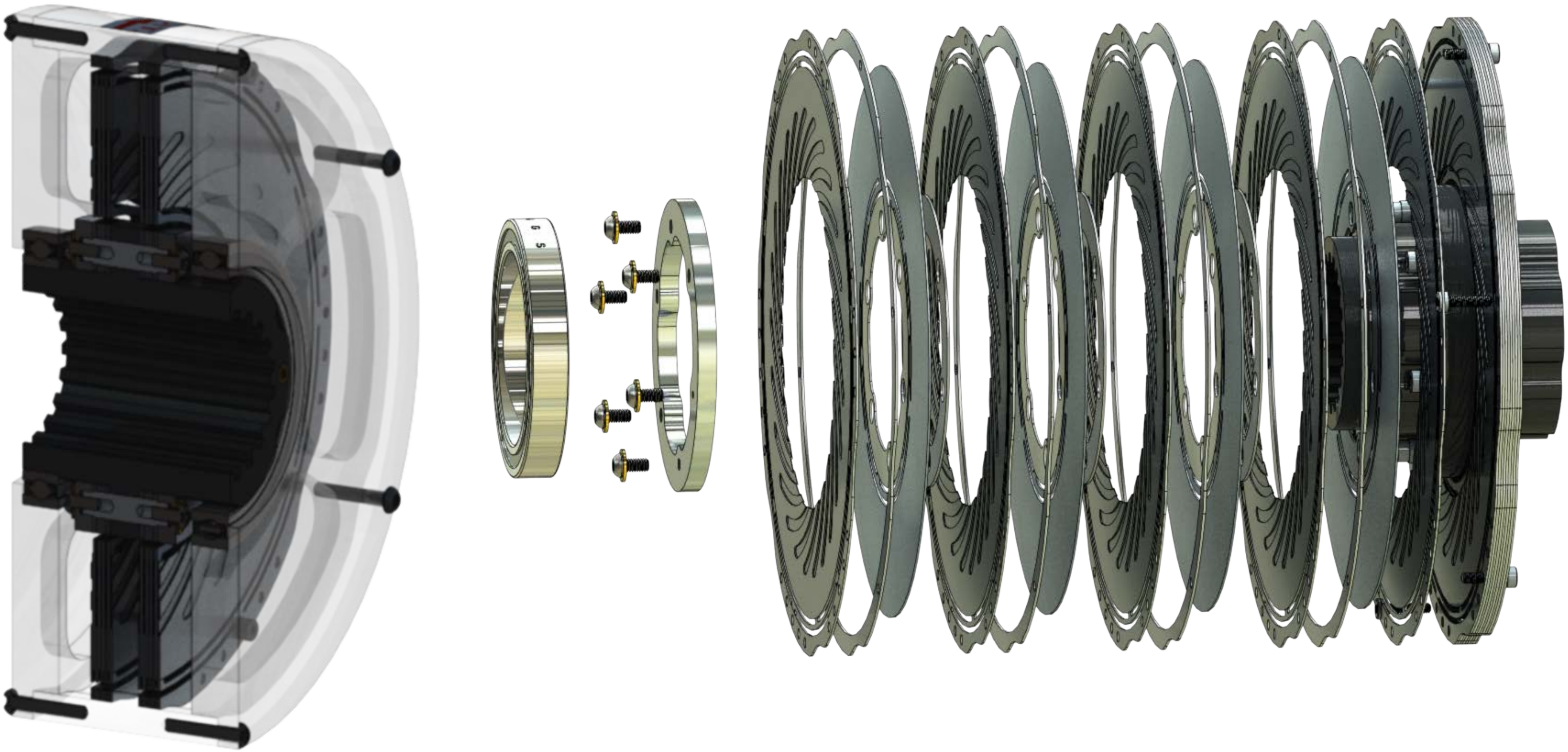



- General pad implementation (prior to WFSM)
- 1100W, 92% efficient (DC to DC)
- Output: 165V and 7A
- 9nF coupling capacitance (C1, C2)
- 540kHz soft switching
- Peak device voltage ~0.85kV (1.2kV SiC parts)



# Technical Accomplishments/Progress

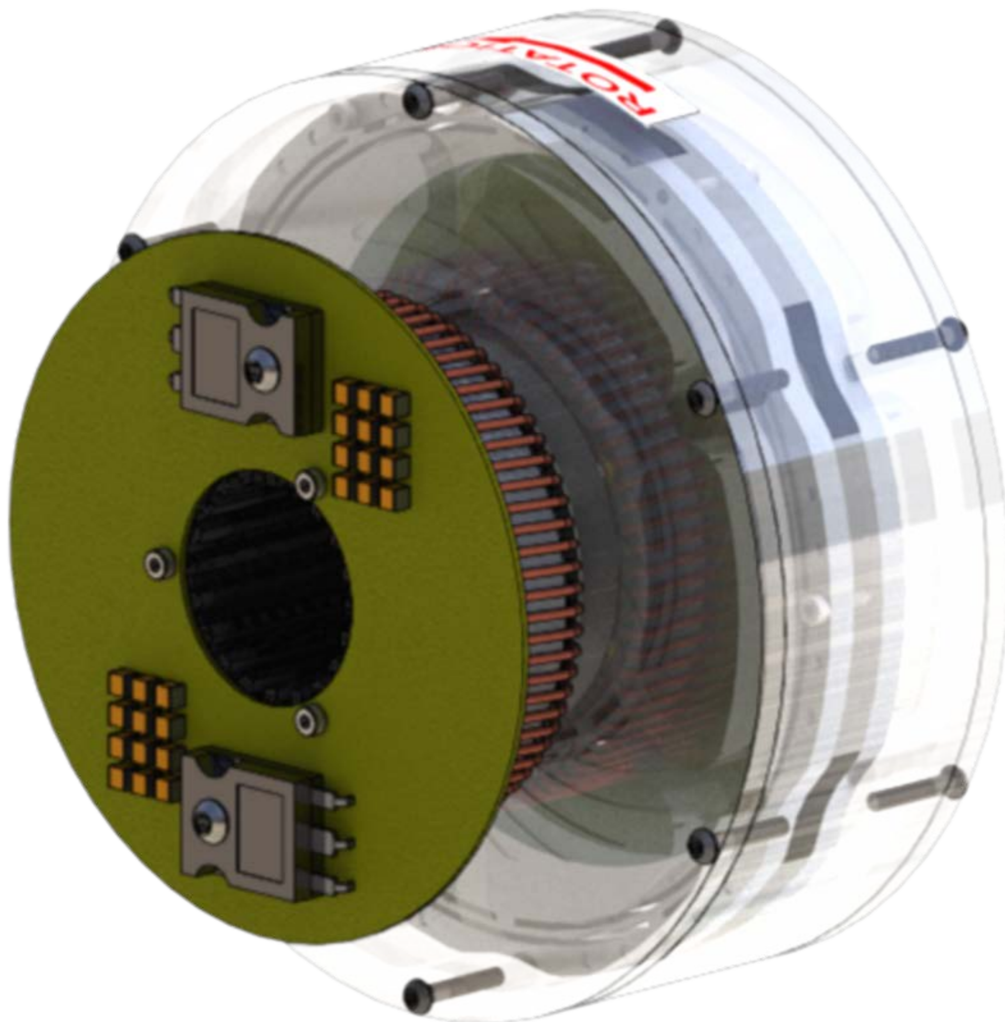
## Milestone 1: Axial Flux Hydrodynamic Coupling Capacitors



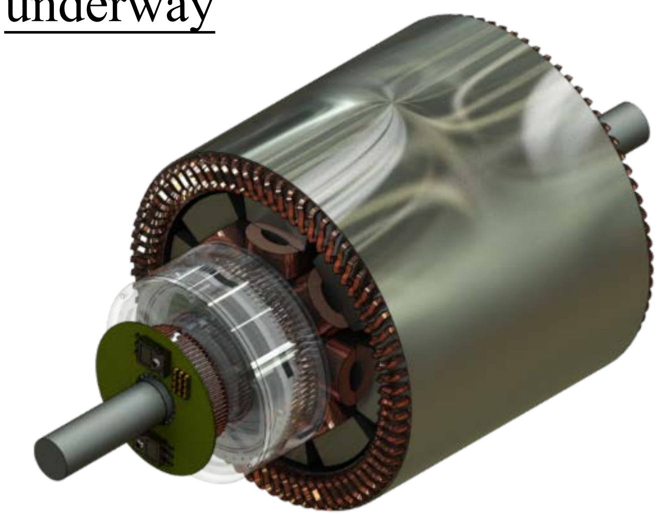
- Spiral groove thrust bearing design, air is working fluid
- 100mm diameter, 50 micron gap, 10nF realized for C1 & C2

# Technical Accomplishments/Progress

## Milestone 1: Initial Electrostatic Design, CPT Coupling



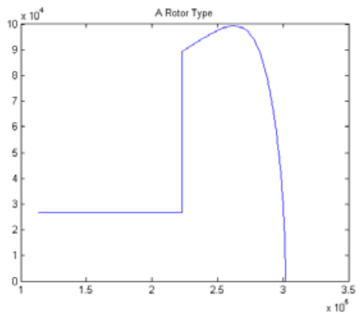
- <1/3 the axial length of a traditional brushless exciter for this machine rating
- 2.5 kW throughput
- Mass: 600 grams
- Mechanically stable to high speeds
- <u>Prototype construction underway</u>



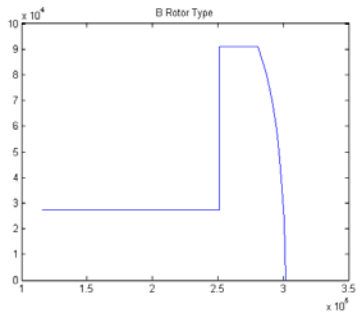
# Technical Accomplishments/Progress

## Milestone 2: Parametric Geometry and Structural Analysis

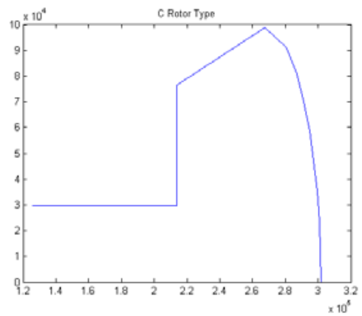
- Geometry (stator and rotor) is parameterized to allow full exploration of design space
  - Geometry engine allows for points to merge and collapse
  - Single and double layer windings



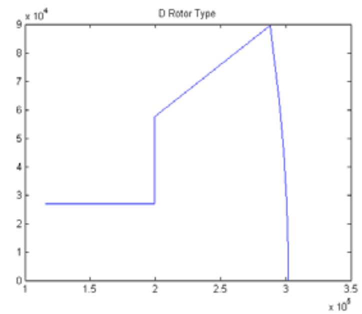
(a) Rotor Type A



(b) Rotor Type B

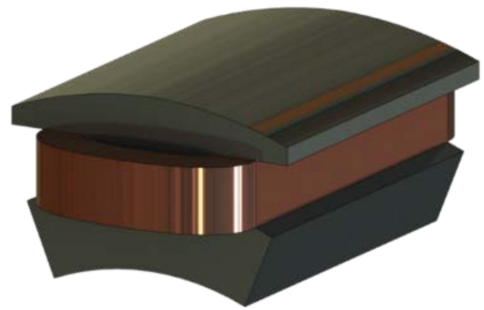


(c) Rotor Type C

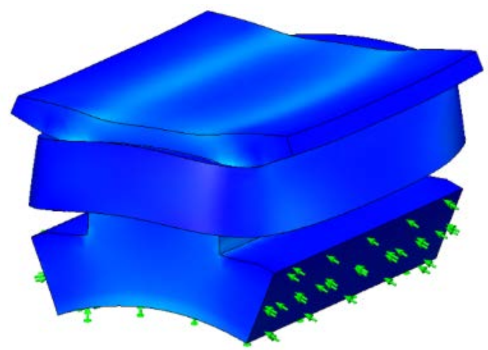


(d) Rotor Type D

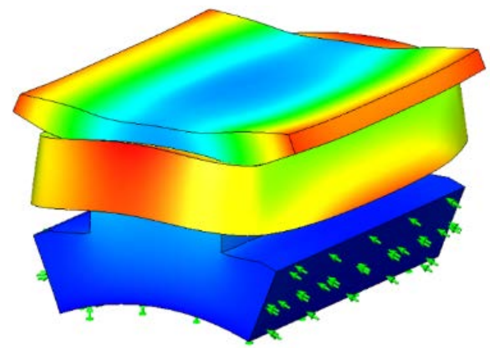
- Design of experiments structural analysis
  - Determine rotor geometric design variable limitations



Von-Mises Stress



Strain

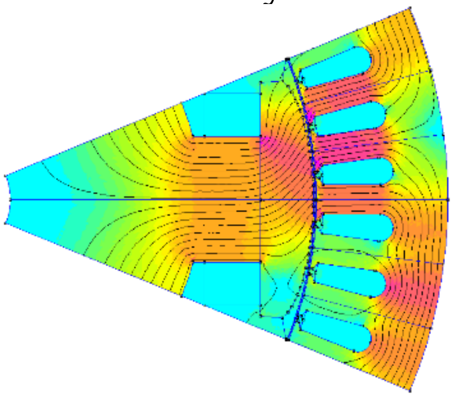


# Technical Accomplishments/Progress

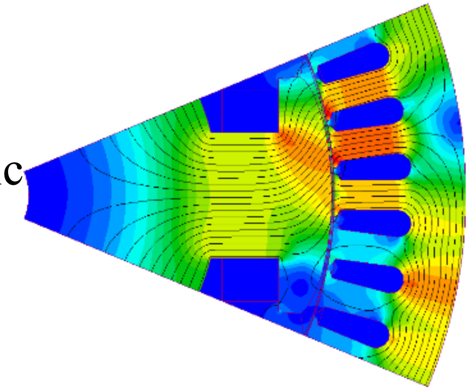
## Milestone 2: Rapid Transient Magnetic Behavior Reconstruction

- Using a series of magneto-static simulations and fully exploiting magnetic and electric symmetries to reconstruct transient behavior rapidly
  - Enables multi-objective population based optimization
  - Coupled with thermal analysis

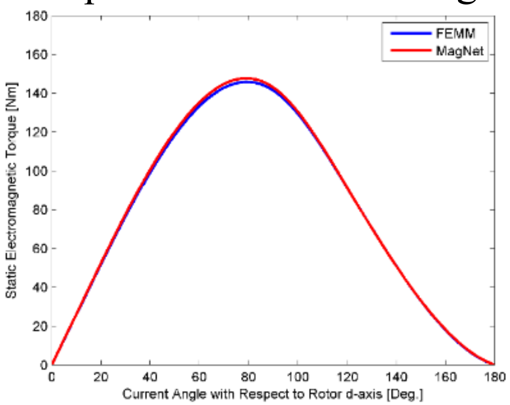
Rapid magneto-static reconstruction
FEMM



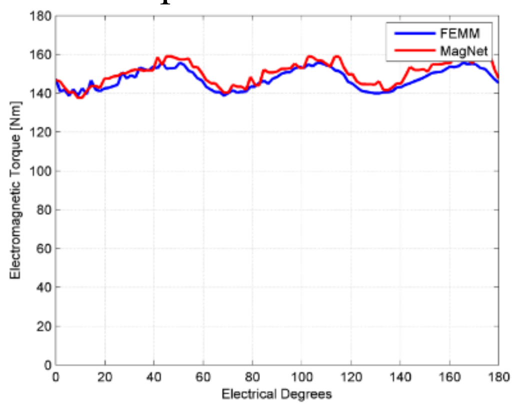
Transient magnetic
MagNet



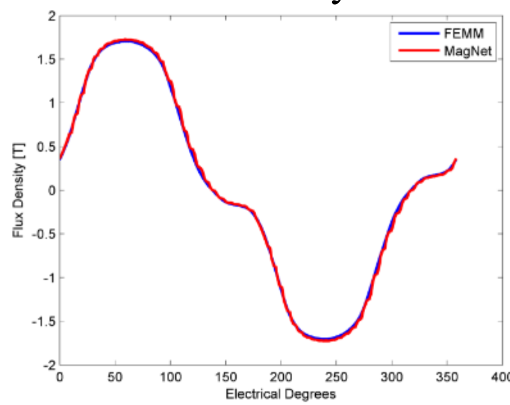
Torque versus Current Angle




Torque versus Position




Radial Flux Density Mid-Tooth

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# Response to Previous Year Reviewers' Comments

- This project is a new start

# Partnerships/Collaborations

- Lead Institution (PI) – University of Wisconsin - Madison
- Sub-award Institution – Illinois Institution of Technology
  - Weekly meeting between project institution leads (Ludois, Brown)
  - Biweekly joint teleconferences between teams (includes students)
  - Site visits for hands on collaboration
- C-Motive Technologies Inc. (Madison WI based startup)
  - C-Motive advising UW on CPT deployment
  - Lending capacitive surface coating and annealing know how
  - Desires to participate in future commercialization effort if project is successful

# Future Work & Activities

## Budget Period 1 (Through 9/30/2015)

- Complete construction of WFSM Prototype 1
- Control code development and dynamometer testing of WFSM Prototype 1
- Complete construction of Capacitive Coupler Prototype 1
- Bench testing of Capacitive Coupler Prototype 1

## Budget Period 2 (10/1/2015 - 9/30/2016)

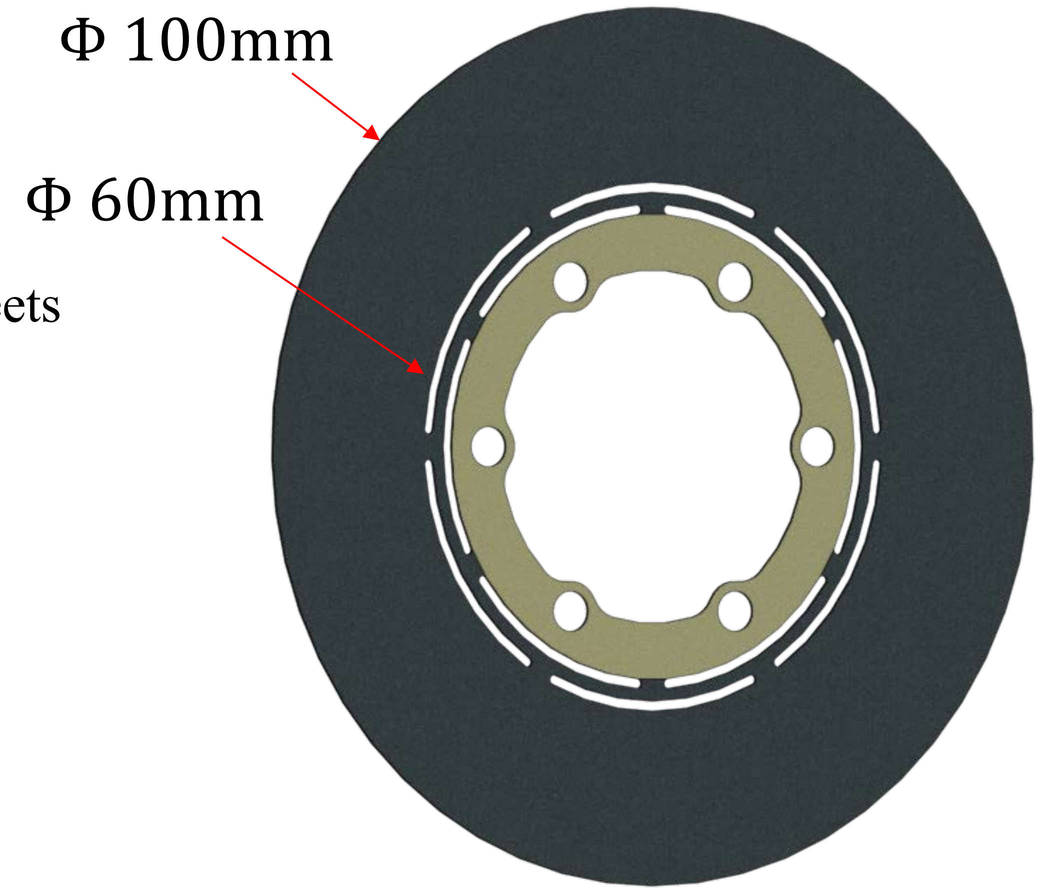
- Dynamometer testing of WFSM and Capacitive Coupler Prototypes 1
- Design of WFSM Prototype 2 from lessons learned with Prototype 1
- Design of Capacitive Coupler Prototype 2 from lesson learned
- Construction of WFSM and Capacitive Coupler Prototypes 2
- Dynamometer testing of WFSM and Capacitive Coupler Prototypes 2
- Investigation of power take-off capability and microgrid support

# Summary

- Relevance
  - Develop a high performance wound field synchronous machine for EV traction
    - Brushless & permanent magnet free
  - Reduce EV motor and traction inverter cost
- Approach
  - Capacitive power transfer for compact brushless rotor excitation
  - Combined electromagnetic and thermal multi-objective optimization for WFSM
- Technical Accomplishments
  - Initial capacitive coupler design complete, power electronics functionality confirmed experimentally at >1kW and 92% efficient.
  - Parametric geometry engine, rapid reconstruction of transient magnetic behavior from static simulations, to enable population based optimization
- Future Work
  - Construction and dynamometer testing of WFSM and Capacitive Coupler
  - Design refinement and 2nd prototype development from 1st prototype lessons learned
  - WFSM control algorithms and deployment in a microgrid environment

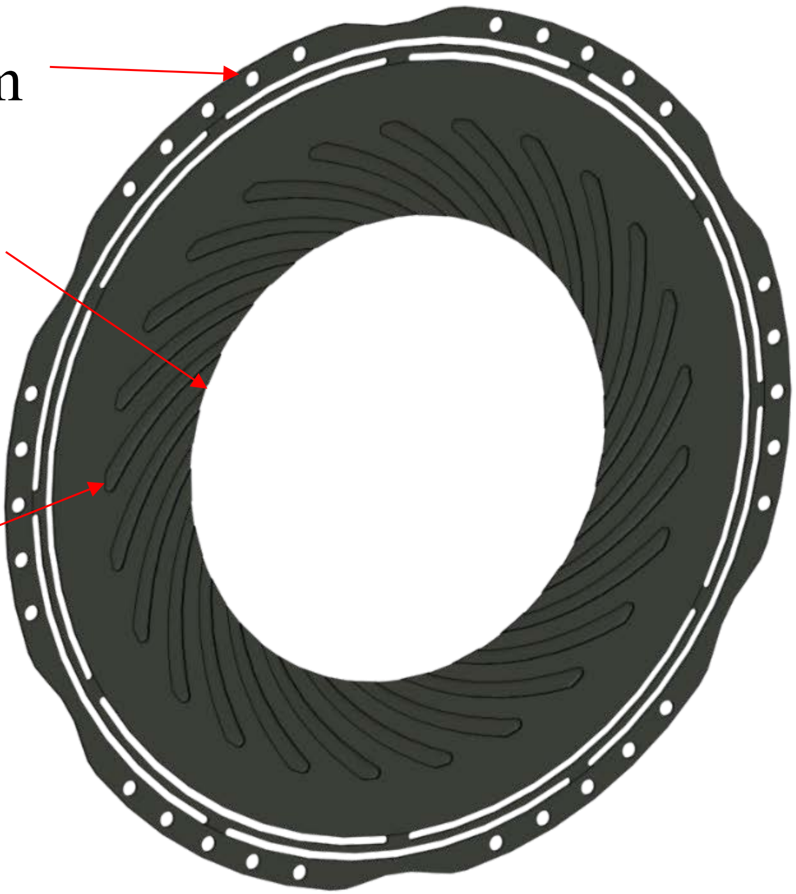
# Technical Back-Up Slides

# Coupling Capacitor Rotors




- 0.016in. thick 3003-O Aluminum sheets
- Hard anodized beyond flexures
- Torque transmitted through featured I.D. and nylon 6/6 alignment pins
  - 3003-O
  - Resistivity – 3.649E-8 [Ohm-m]
  - Yield Strength – 144.78 [Mpa]
  - 6061-T6
  - Resistivity – 4.066E-8 [Ohm-m]
  - Yield Strength – 241.31 [Mpa]

# Coupling Capacitor Stators




- 0.016in. thick 3003-O Aluminum sheets
- Designed as outwardly pumping spiral groove bearing
- Supported on flexure beams at OD

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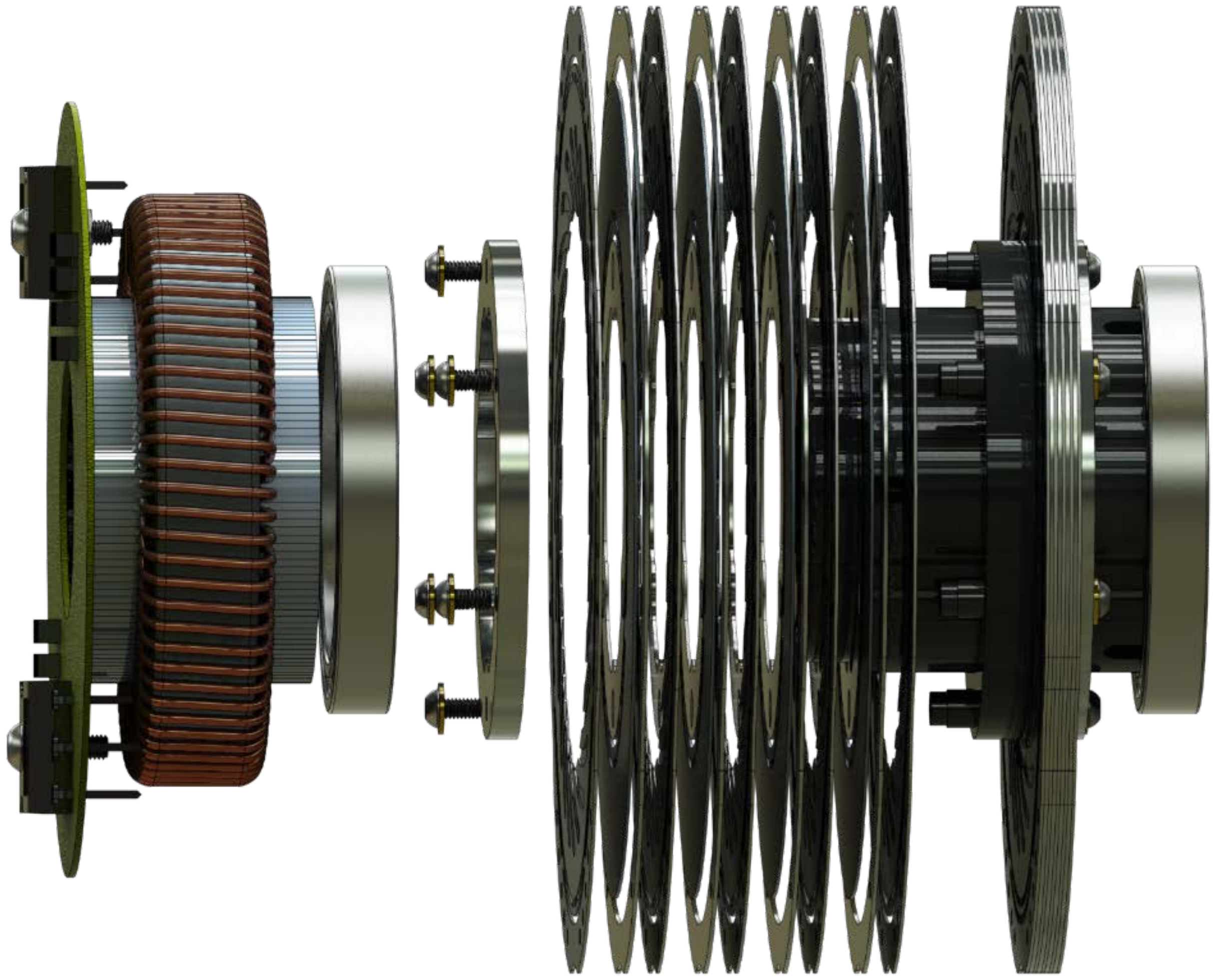
# Capacitive Power Coupling Exploded View



- 2 coupling capacitors, C1, C2
- Rectifier board