ADVANCED THERMAL MANAGEMENT OF ELECTRIC MACHINES AND DRIVES

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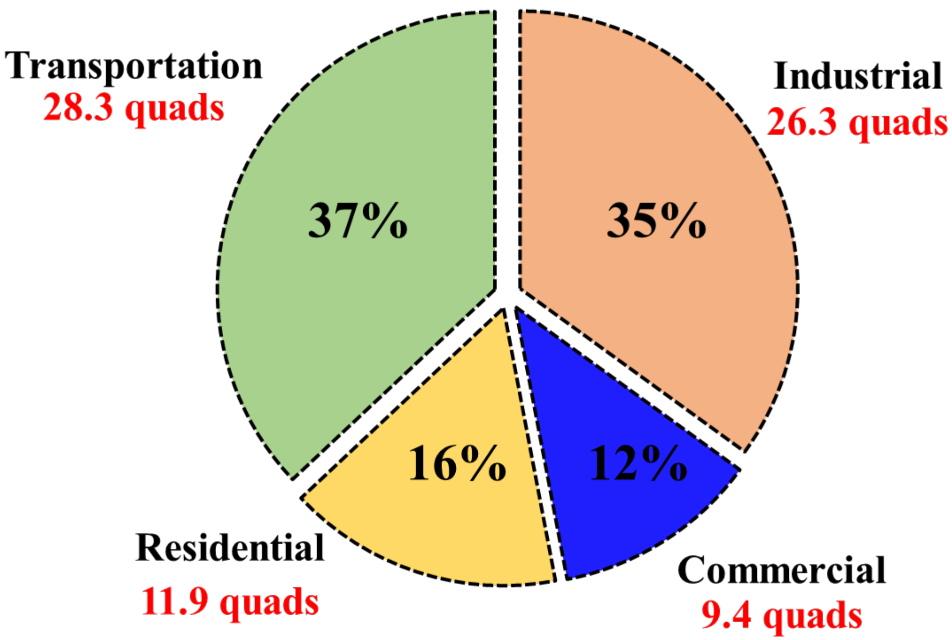
Outline

- Introduction
- SOA Thermal Mgmt. Techniques
  - Direct stator cooling techniques
  - Slot cooling techniques
  - Integrated Thermal Management
- Liquid Cooling and Co-design
  - Direct Winding HEx. and Evaporative Cooling via Liners
  - Comparison of In-Slot Cooling Techniques
- Conclusions, Challenges and Opportunities

Why Efficient Motors/Drives are Critical for Energy ?

✓ **End user energy consumption in USA**

➢ **Total = 75.9 quads**



$1\text{quad} = 1.055 \times 10^{18}\text{J}$

https://www.eia.gov/energyexplained/us-energy-facts/

✓ Motor driven source energy well represented in each of the four major US energy consumption sectors.

✓ Motor systems account for

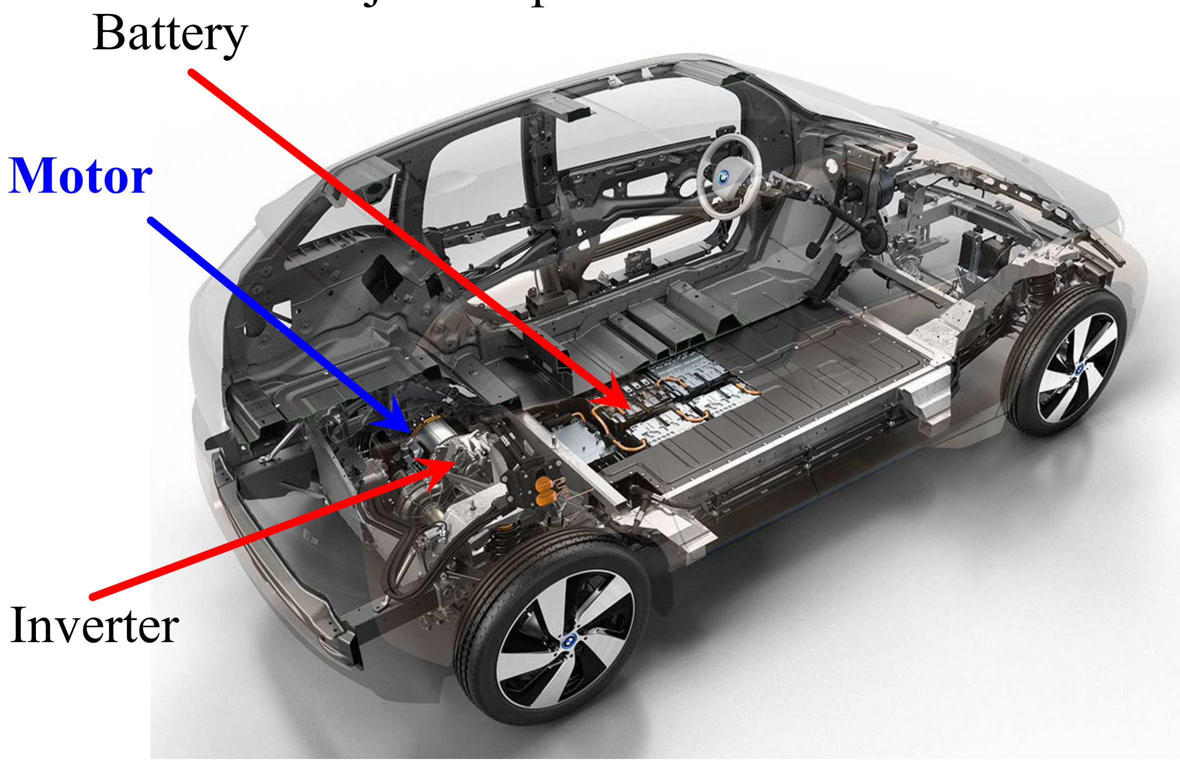
- ➢ ~50% of U.S. electricity consumption.
- ➢ ~47% of global electricity consumption.

✓ >7 millions of electric vehicles contributes a major transportation share.

Electric Motors and Drives for EVs

❖ Electric Vehicle

- ✓ Major components of **BMW i3**



https://x-engineer.org/wp-content/uploads/2017/01/BMW-i3-anatomy.jpg?41ab8b&41ab8b

- ➢ High efficiency.
- ➢ High power and torque density.
- ➢ Compact: Size, Weight

✓ **Challenges**

- ➢ Motor performance is limited by wire insulation and impregnation thermal limit.
- ➢ 10°C above the thermal limit reduces the life time by 50%.

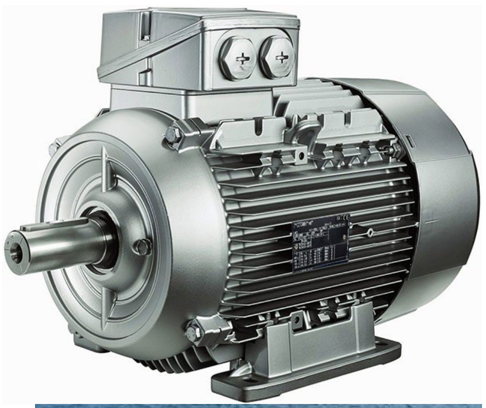
✓ **Possible solutions**

- ➢ Enhanced thermal management.
- ➢ Lower electro-magnetic losses.

Applications

✓ **Electric Motor/Drives**

Electrical energy → Mechanical energy



https://www.norfolkwaterfrontvenues.com/manufacturer-of-electric-motor/

- ❖ Transportation
  - ✓ Electrical vehicle
  - ✓ Aviation
  - ✓ Marine
- ❖ Industrial applications
- ❖ Households
- ❖ Defense sector

✓ **Electrification of transportation sector is a major drive**

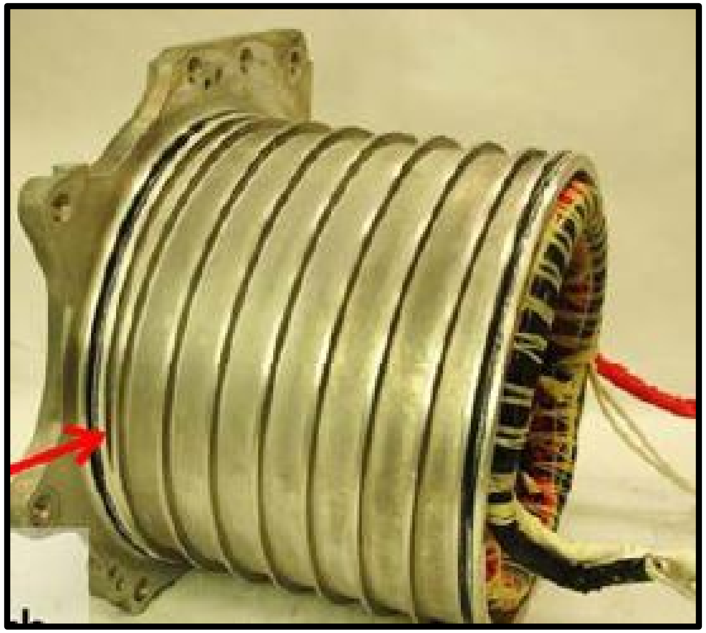
State of Art Cooling Technologies: Electric Motors

Cooling Method: Jacket Cooling

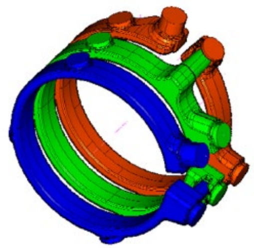
❖ Jacket cooling via spiral coolant channel

2016 BMW i3 motor

Coolant- Water Ethylene Glycol 50/50

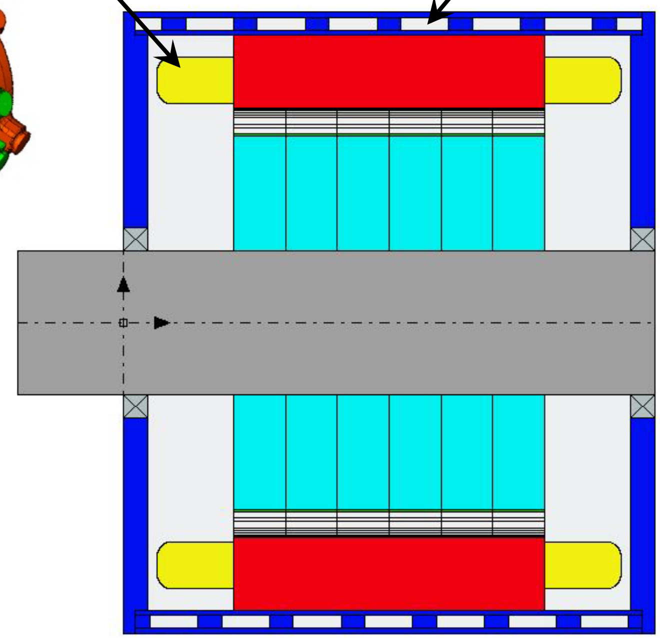


Isometric view



End-winding

Coolant channel
(20 mm × 5 mm)

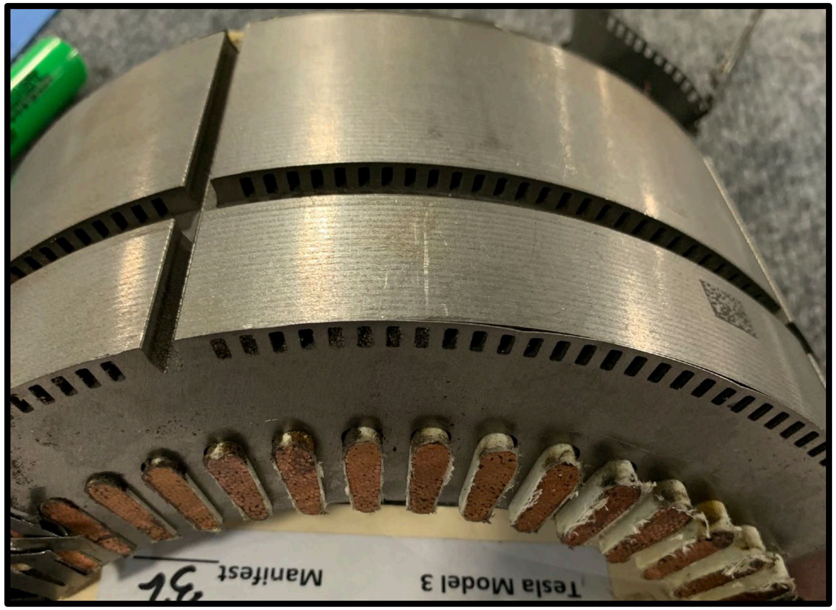


Side view

✓ Inadequate to dissipate heat from the end winding and rotor

Cooling Methods : Channels in Stator

❖ Direct stator cooling methods

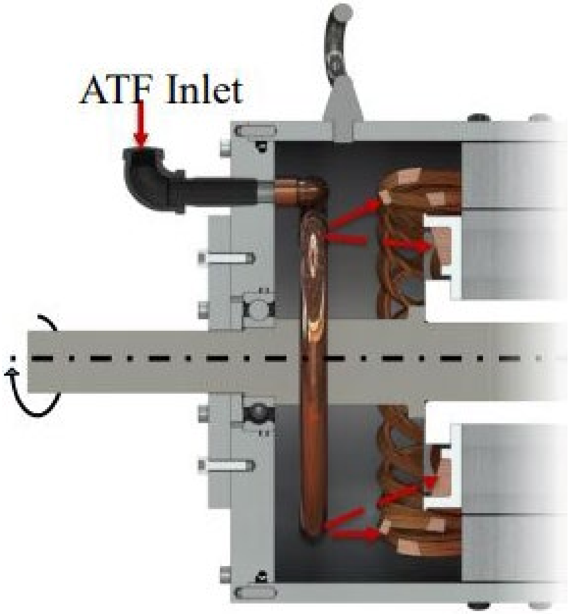


Tesla Model 3

- ✓ Rectangular channels in the stator core
- ✓ Coolant: Ethylene-glycol 50/50 or Engine oil
- ✓ Coolant gets closer to the windings and laminations

- ✓ Direct stator cooling channel may saturate the stator core.
- ✓ Care needed to prevent disturbance in the magnetic flux in the stator core
- ✓ Care needed to prevent the liquid from entering the air gap

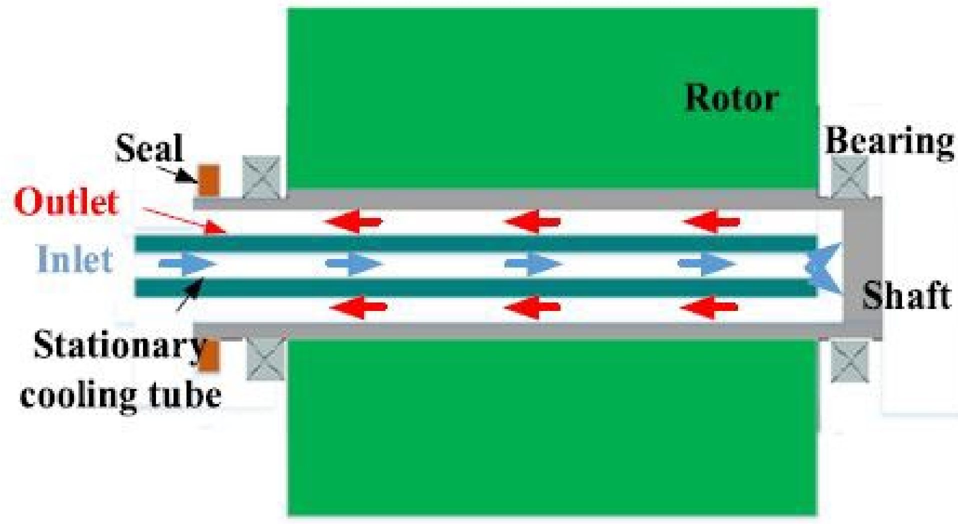
Cooling Methods : Spray Cooling



Spray cooling for end-winding

Ludois et al.

(Univ. Wisconsin-Madison, Tech. Rep. DOE-Wisconsin-6849, 2017)



Rotor cooling

EL-Refaie et al.

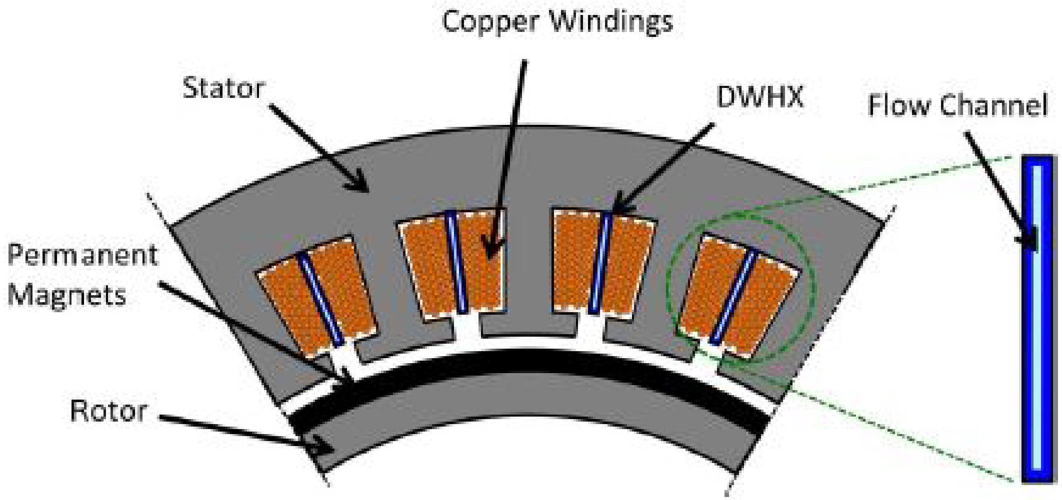
(ECCE, 2013)

- Cooler liquid is sprayed onto the end windings and/or rotor via nozzles
- Coolant is partially evaporated and need to be condensed
- High complexity; Non-uniform temperature

Cooling Methods : DWHX

❖ Direct winding heat exchanger (DWHX)

- ✓ DWHX first proposed by **Semidey and Mayor** (IEEE Transactions on Industrial Electronics, 2014).



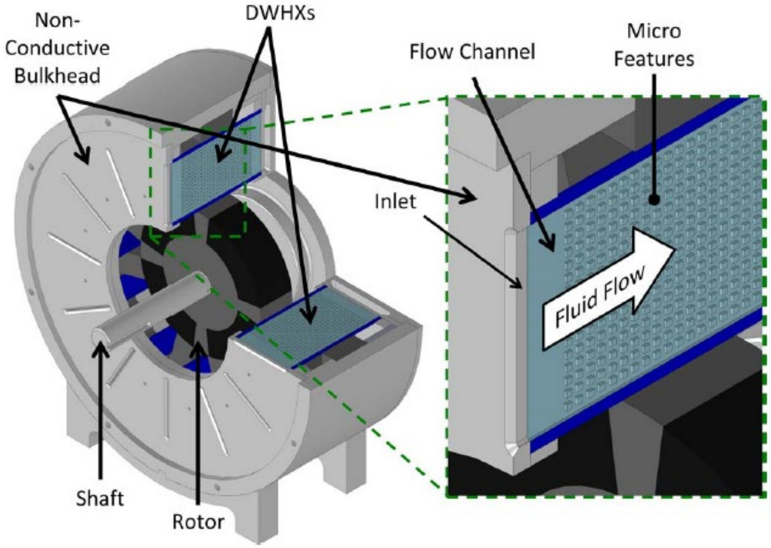
Schematic of DWHX placement in winding

DWHX wound motor

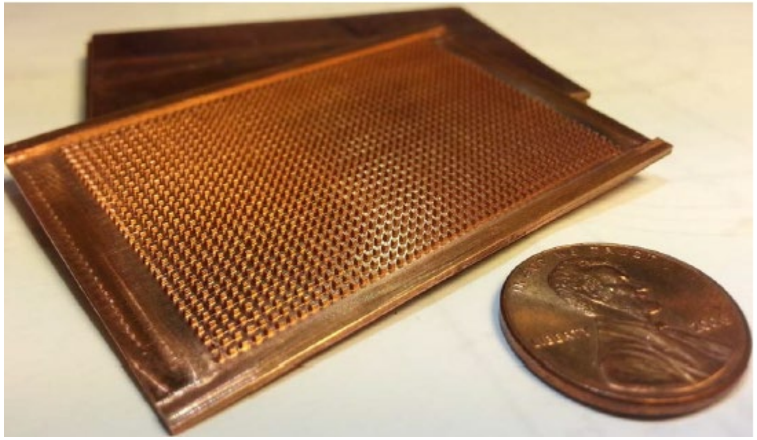
- ✓ DWHX can significantly reduce the thermal resistance between the winding and coolant.
- ✓ DWHX may reduce the copper fill factor.

Cooling Methods : DWHX

✓ **Semidey and Mayor** (IEEE Transactions on Industrial Electronics, 2014).



A Cross-Section of DWHX

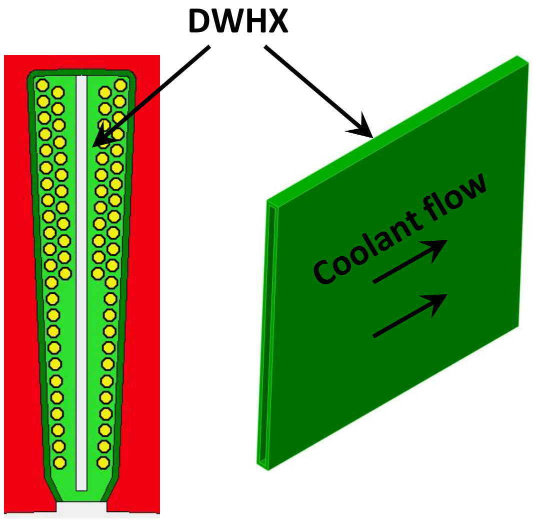


Micro-features in DWHX

- ✓ 500 μm × 500 μm microstud array
- ✓ 5.14 kPa at a flow rate of 5300 cc/min
- ✓ 8.24 A/mm^2 → 24.7 A/mm^2

In-slot Cooling Technique

❖ **Direct winding heat exchanger (DWHX)**

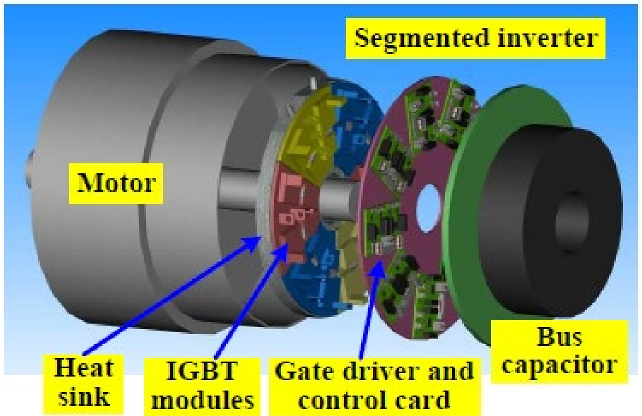


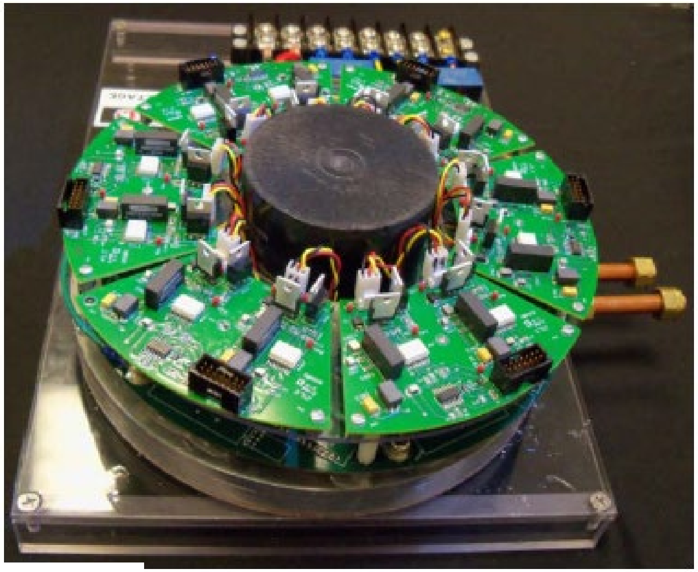
Mayor et al.
(TIE, 2014)

- ✓ DWHX significantly reduces thermal resistance between the winding and coolant.
- ✓ Water can be used as coolant.
- ✓ DWHX offers high heat transfer area between the winding-coolant increased.
- ✓ Additive manufacturing enables mass production of DWHX.
- ✓ DWHX reduces copper fill factor.
- ✓ Special end-winding design would be needed to incorporate DWHX in a distributed wound machine.
- ✓ Non-conductive endcap need to be used to prevent eddy current generation in the DWHX .

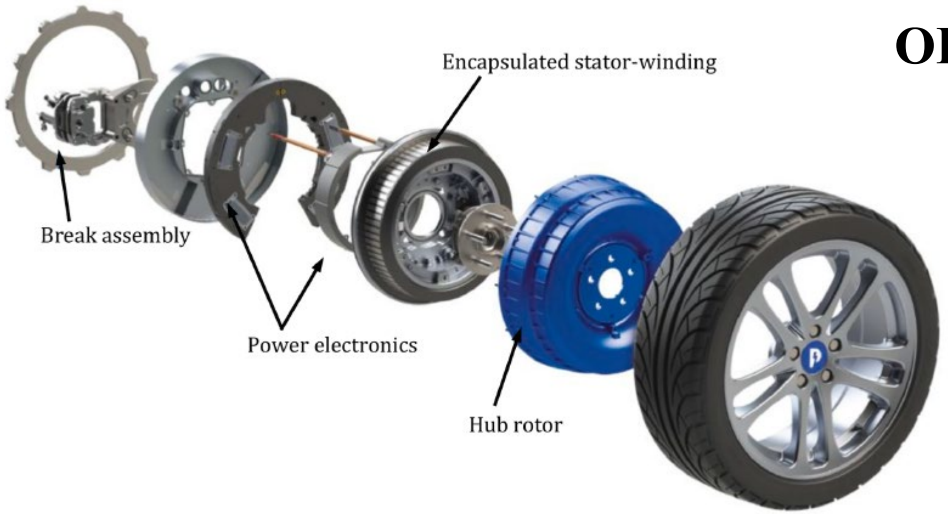
Integrated Thermal Management of Electric Machines/ Motor Drives

❖ **Axial Mounted**





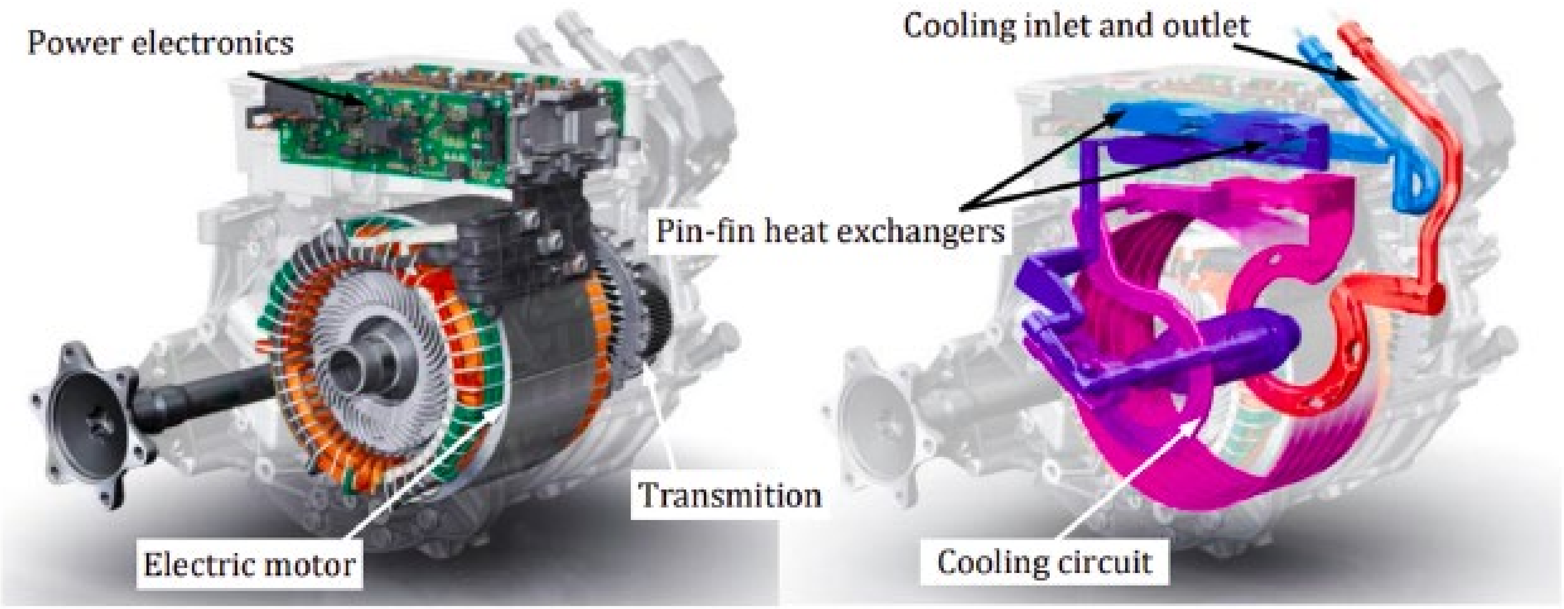
ORNL



Protean Electrics: In wheel traction application (60 kW, 1600 rpm)

Integrated Thermal Management of Electric Machines/ Motor Drives

❖ **Radial Mounted**

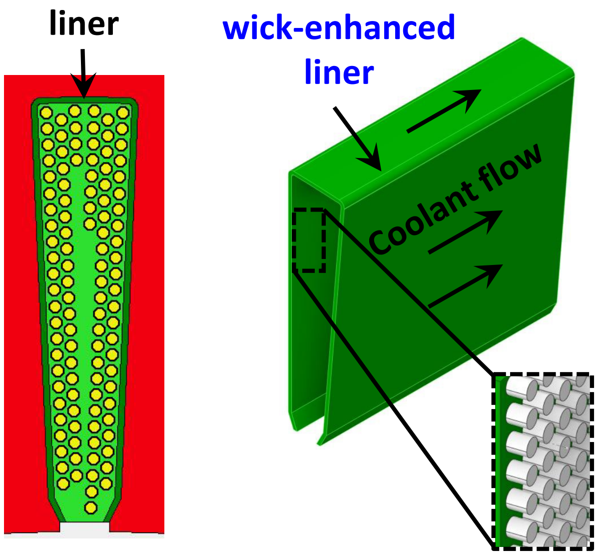


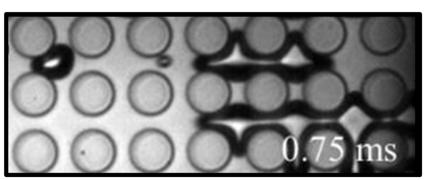
Audi e-tron: Liquid cooled (125 kW)

In-Slot Motor Cooling

In-slot Cooling Technique

❖ Slot-liner confined evaporative cooling (EC)





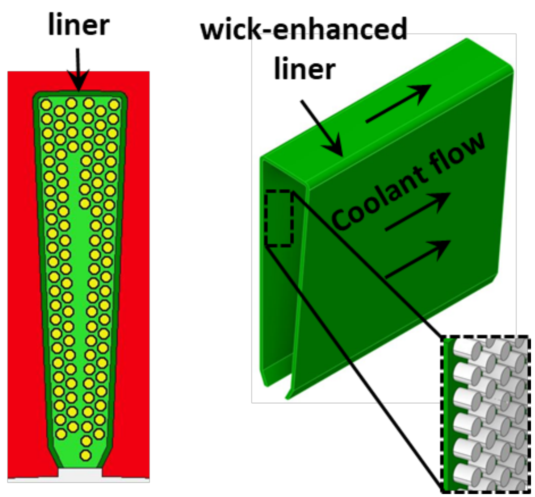
Wenming et al.
(Langmuir, 2020; TTE, 2021)

- ✓ EC dramatically reduces thermal resistance between the winding and the coolant
- ✓ EC can be applied irrespective of the winding layout, i.e., distributed or concentrated winding
- ✓ In case of EC, heat transfer area between the winding-coolant can be significantly increased.
- ✓ In case of EC, required coolant and coolant inventory mass can be significantly reduced.
- ✓ For EC, dielectric coolant need to be used .
- ✓ Special coolant delivery arrangement and stator sleeve may be required to prevent coolant leakage.

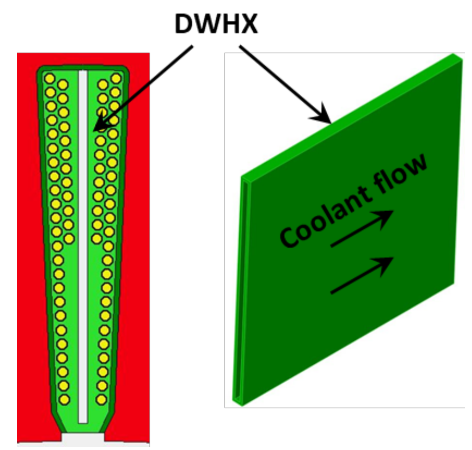
In-slot Cooling Technique

❖ EC from side and middle liner (EC-SML)

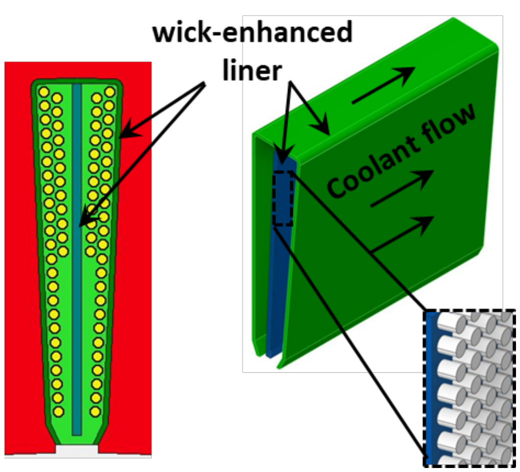
EC



DWHX



EC-SML

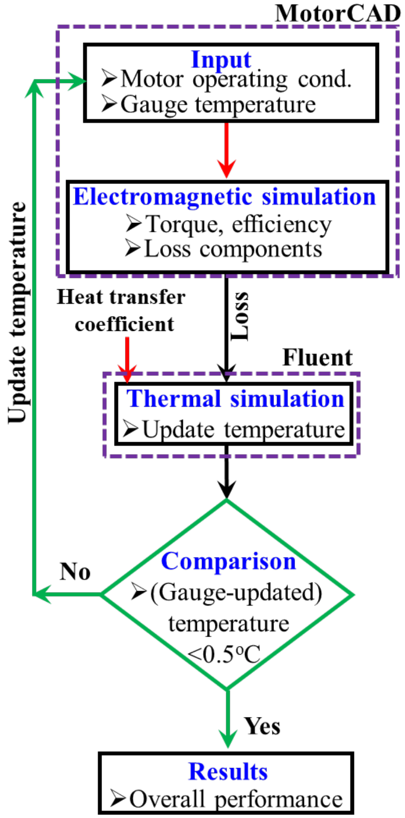


- ➢ Electro-thermal performance of EC, DWHX, and EC-SML has been compared with JC
  - ✓ EC-SML offers high heat transfer area between the winding-coolant.
  - ✓ EC-SML reduces copper fill factor.

Electro-Thermal Model Coupling, Contact Resistances and Winding Thermal Conductivity

❖ Two-way coupling

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k_r r \frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(k_\theta r \frac{\partial T}{\partial \theta}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + q''' = 0$$



❖ Contact resistance

Interface	Equivalent air gap thickness (mm)
Rotor lamination - magnet	0.005
Stator lamination - housing	0.0057
Winding - liner	0.045
Liner – stator lamination	0.015

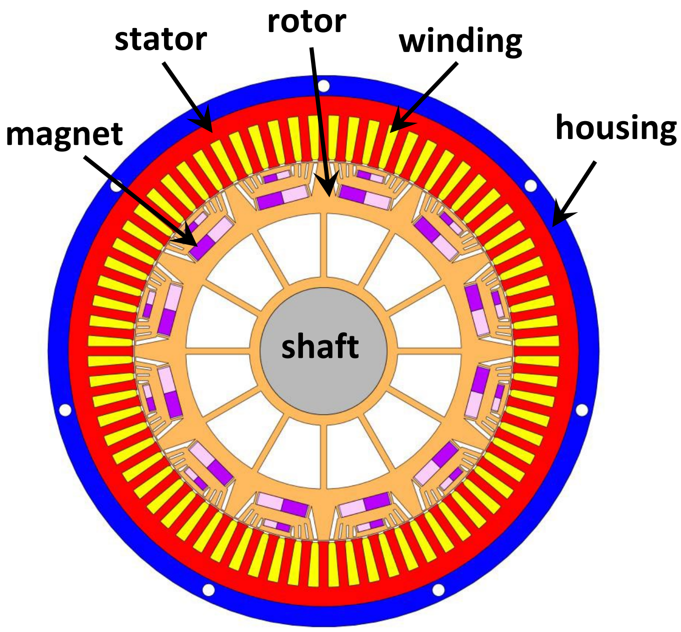
✓ In case of EC and EC-SML, there is no contact resistance between the winding and liner.

❖ Winding thermal conductivity

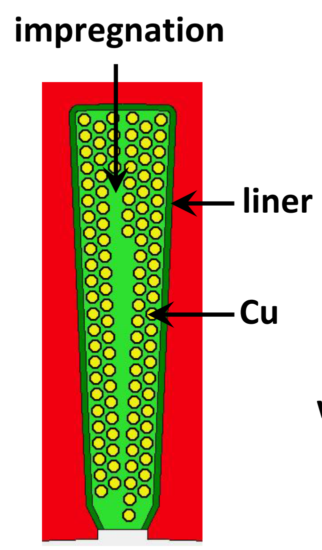
Cooling method	k_r $(W/m.K)$	k_θ $(W/m.K)$	k_z $(W/m.K)$
JC and EC	0.50	0.50	166
DWHX and EC-SML	0.48	0.48	159

Jacket Cooled BMW i3 Motor

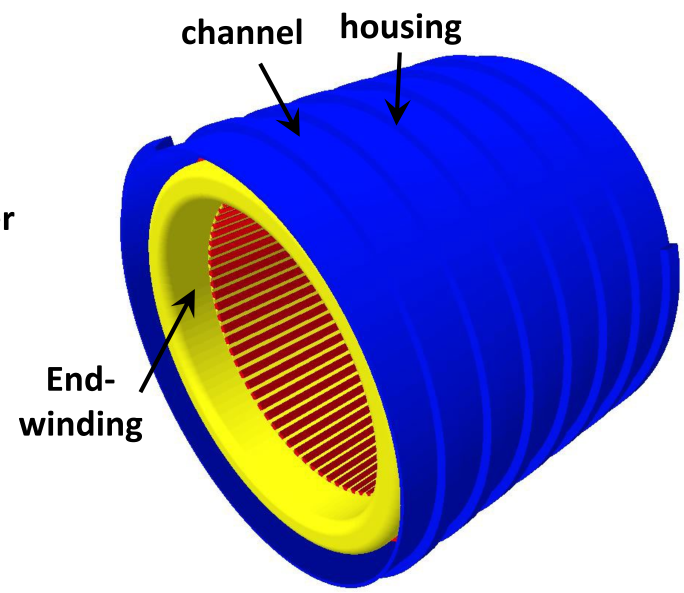
❖ **125 kW interior permanent magnet synchronous motor**



Front view



Winding Front view



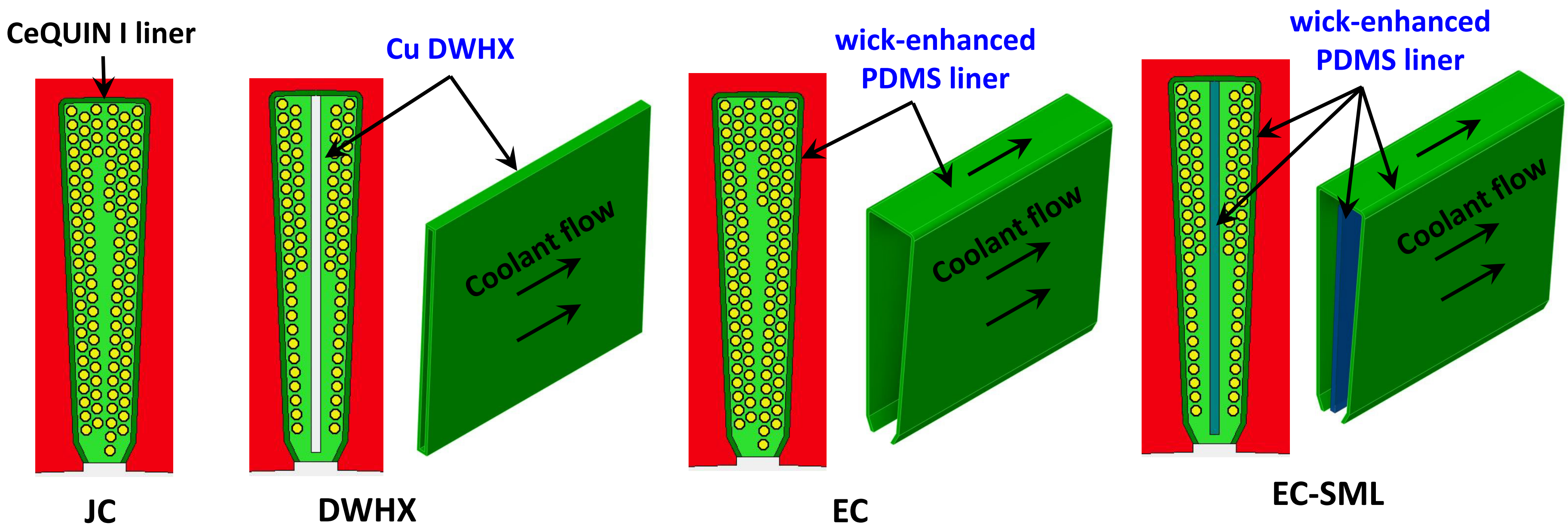
Spiral cooling channel

Number of turns per coil	9
Number of strands in hand	12
Total number of wire	108
Copper slot fill factor	0.33

✓ ethylene-glycol 50/50

In-slot Cooling Techniques

❖ **Integration of in-slot cooling techniques in BMW i3 motor**



✓ **~4-folds** heat transfer area increment

✓ **~3.8-folds** heat transfer area increment

✓ **~7.8-folds** heat transfer area increment

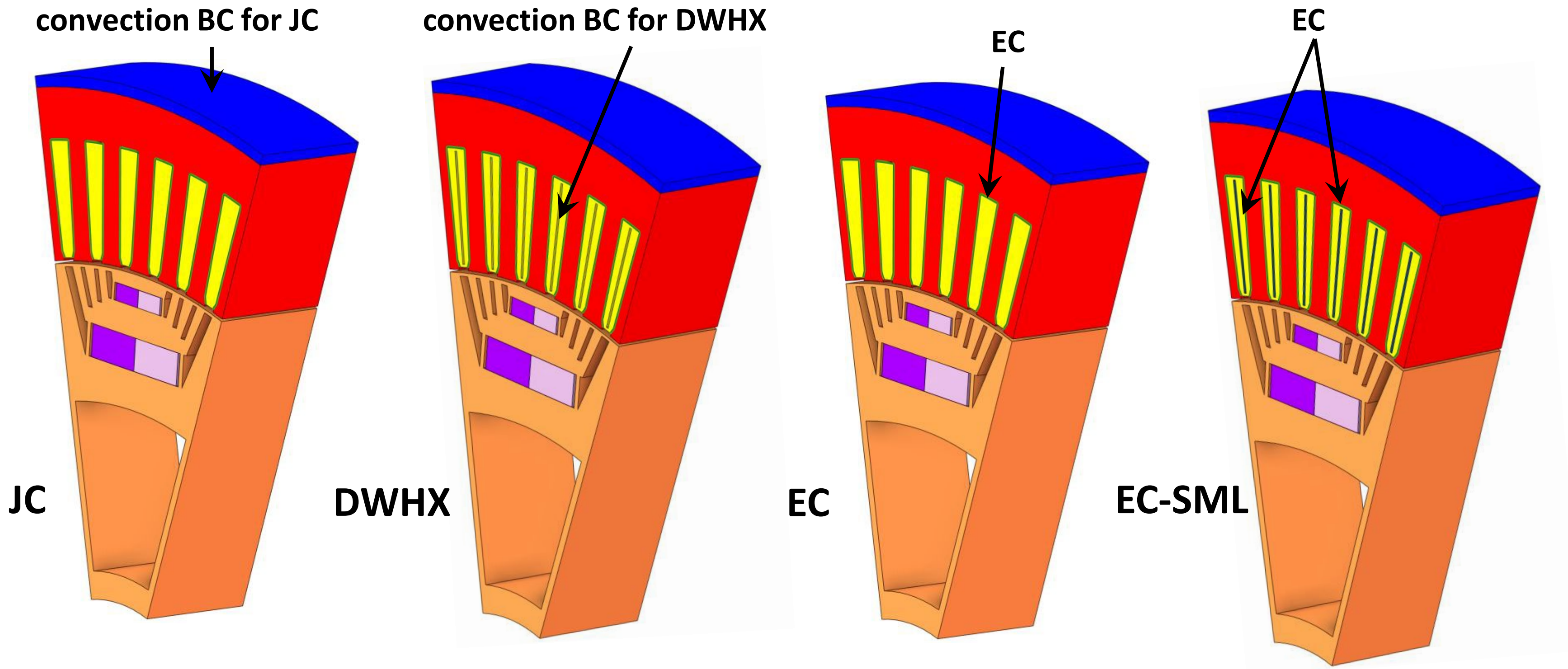
Number of turns per coil	9
Number of strands in hand	12
Total number of wire	108
Copper slot fill factor	0.33

Number of turns per coil	9
Number of strands in hand	**8**
Total number of wire	**72**
Copper slot fill factor	0.22

~33%

Numerical Modeling

❖ **Heat transfer modeling procedure**



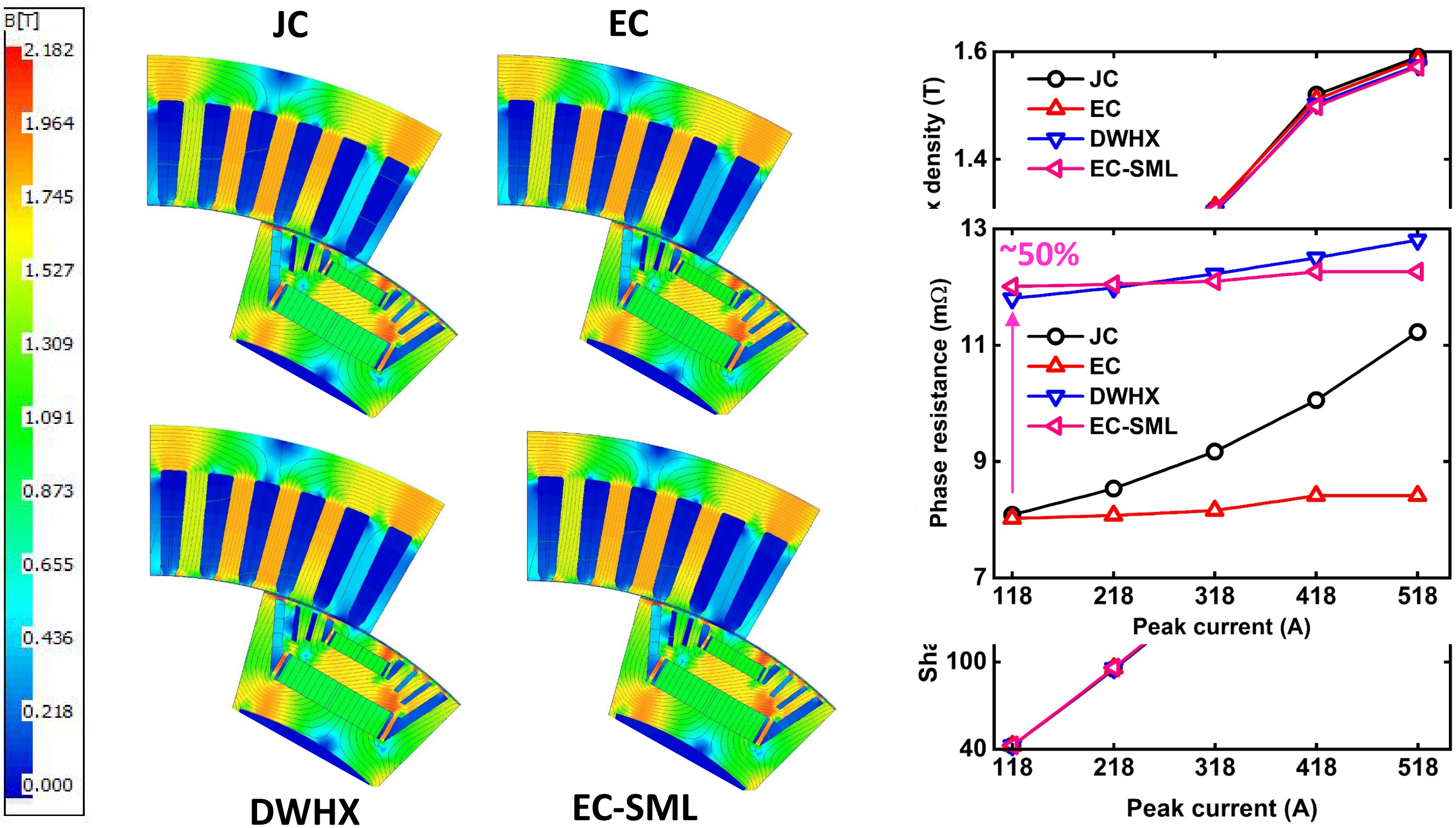
$$-k\frac{\partial T}{\partial r} = h(T_{surface} - T_{coolant})$$

$$Q'''_{eva,sl} = -h_{eva}A_{s,l-wind,o}(T_{wind,o} - T_{sat})/V_l$$

Amitav, T. et al, ITherm, 2022

Results and Discussion

❖ Electro-magnetic performance

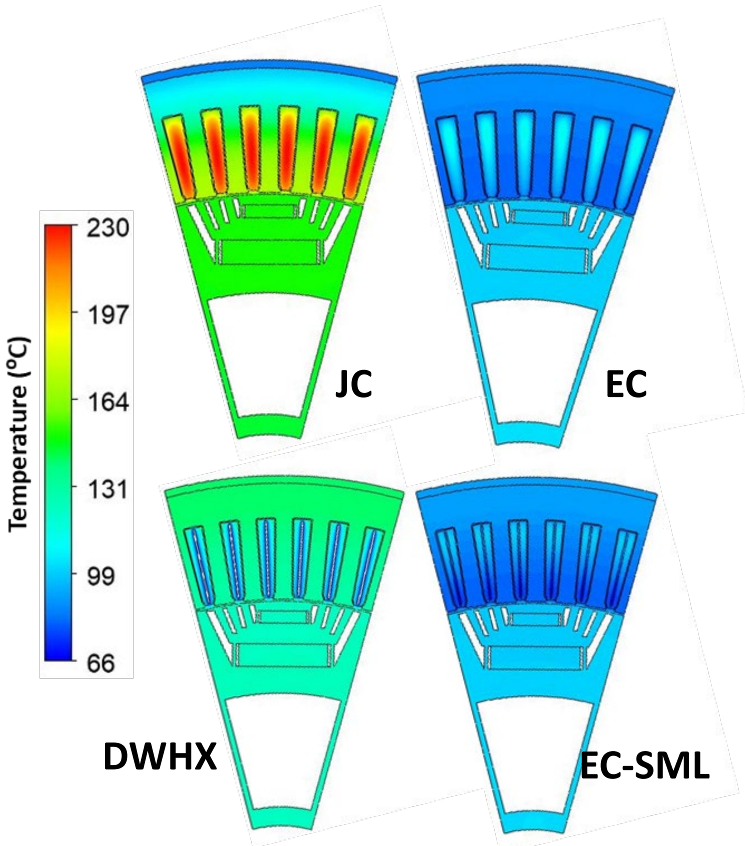


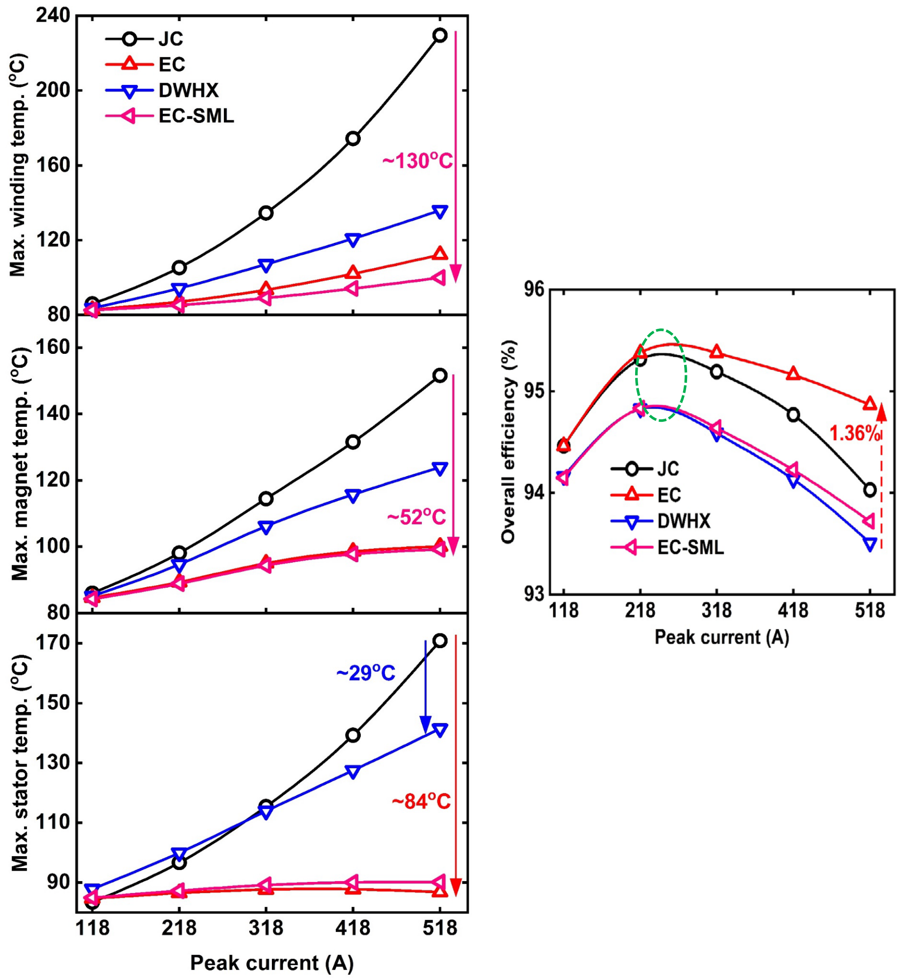
Peak current = 518 A

Speed = 4500 rpm, phase advance = 45 EDeg, h = 5000 W/m^2.K

Results and Discussion

❖ Thermal performance

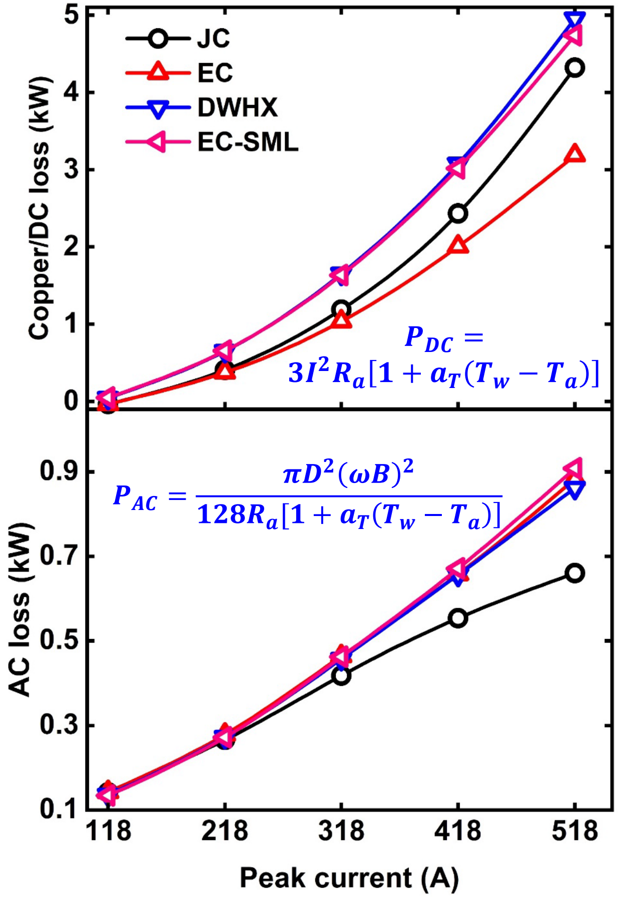


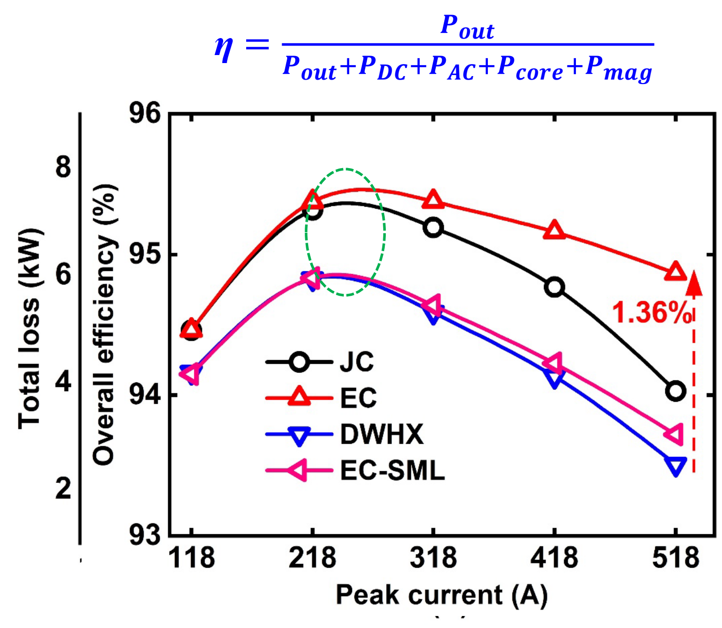


Speed = 4500 rpm, phase advance = 45 EDeg, h = 5000 W/m².K

Results and Discussion

❖ Power loss and overall efficiency

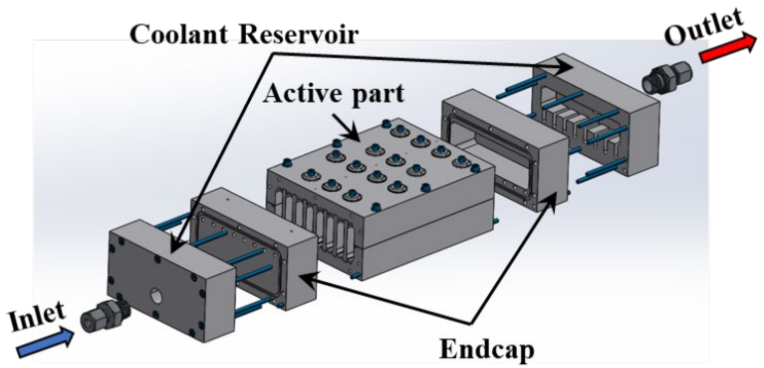


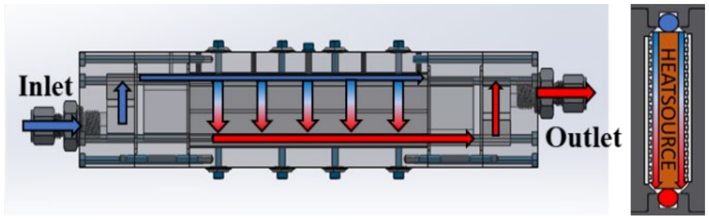


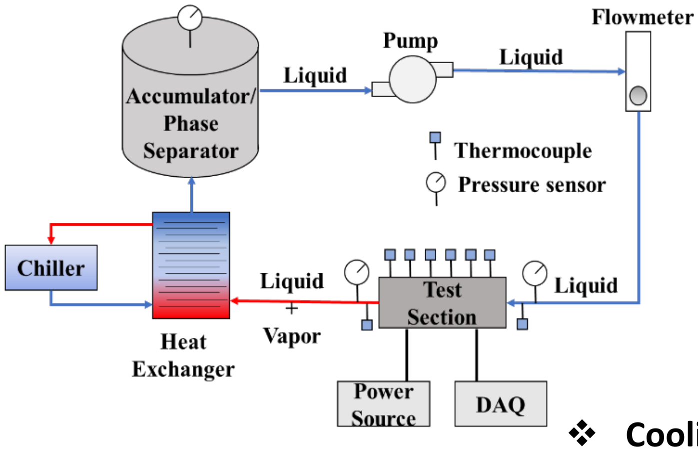
Speed = 4500 rpm, phase advance = 45 Edeg, h = 5000 W/m^2.K

Experimental Validation

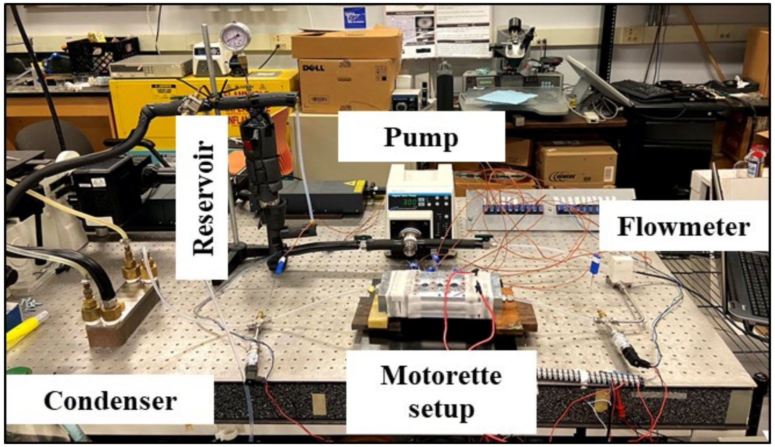
❖ Motorette test setup







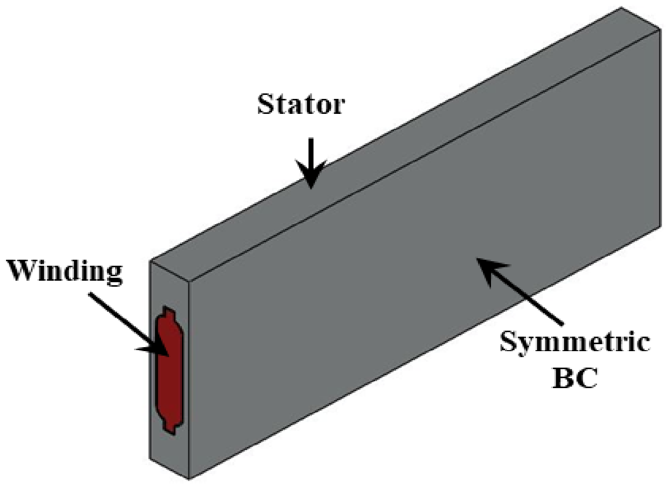
❖ **Cooling loop**



- ✓ A 2 kW DC motorette with **8 slots** is designed and fabricated.
- ✓ Slot size was **identical** to the **BMW i3** motor slot.
- ✓ Solid **Al** has been used and motorette was hand-wound with 108 turns **AWG 21** copper wire.
- ✓ **Coolant** **(T_{sat}= 76°C)**

Experimental Validation

❖ CFD/HT model

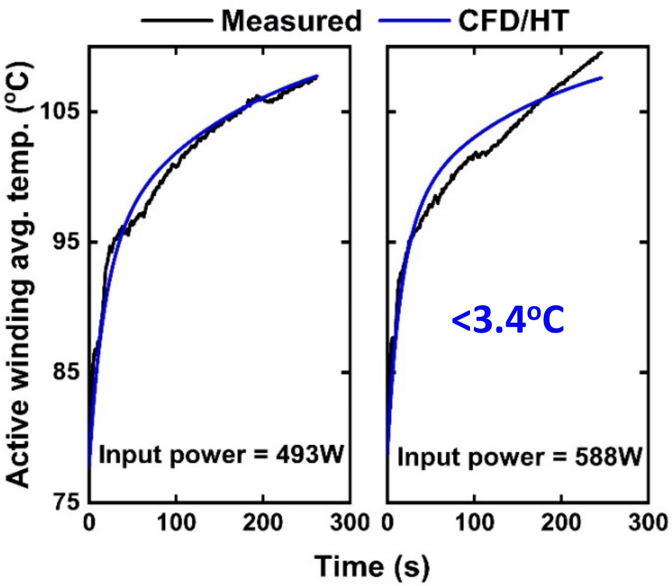


3D CFD/HT computational domain

- ✓ CFD/HT model has been modified to mimic the motorette.

Amitav, T. et al, IEEE Trans on Transportation Electrification, 8,1 2021

❖ Transient results comparison

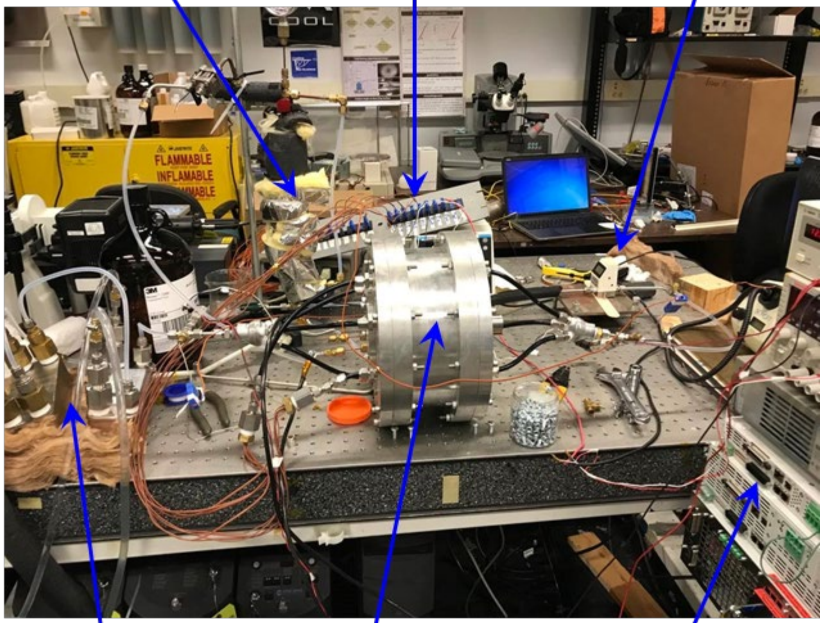


❖ Steady state results comparison

Power (W)	Flow rate (mL/min)	Average active-winding temperature (°C)	
		Measured	CFD/HT
702.9	330	113.80	113.80
1106	440	126.82	126.82
1500.7	520	137.40	137.39
1606.3	520	149.10	149.10
1702.9	640	135.20	135.19
2001.6	640	145.20	145.19

Motor Prototype

❖Thermal Testing



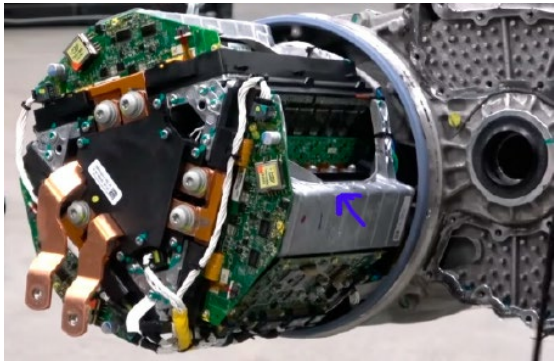
2 kW DC power.

Conclusions

- ✓ Based on EC and DWHX, a new cooling concept, namely EC-SML has been proposed.
- ✓ Electro-thermal performance of EC, DWHX, and EC-SML has been numerically evaluated and compared with JC.
- ✓ In case of DWHX and EC-SML, copper fill factor reduced by ~33% compared to the JC and EC.
- ✓ EC-SML provides best thermal performance followed by EC, DWHX, and JC.
- ✓ EC provides the lowest power loss and the highest efficiency.
- ✓ DWHX and EC-SML provides higher power loss and consequently lower efficiency, compared to the JC and EC.

Challenges and Opportunities

- ✓ Co-design: Electro-magnetic, thermal and mechanical performance



- ✓ Innovative cooling technologies
- ✓ Borrow techniques from other disciplines
- ✓ Efficient integration of motor, power electronics and drive
- ✓ Encapsulation Materials- high conductivity, and temperature tolerant
- ✓ Relevant Metrics- kW/Kg; kW/L; $/Kg

Acknowledgement

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- Owen Sullivan, McKenney's Inc.
- Kam Y Lee, Pablo Salazar, Intel
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- David Brown, Raytheon
- Jilauo Chen, Ansys

NSF DARPA Office of Naval Research ONR Science & Technology SRC Oak Ridge National Laboratory Air Force Research Laboratory Integrity ★ Service ★ Excellence

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