



2018 IDAJ为中国新能源汽车加速  
整车 / 新能源汽车关键性仿真技术

无人驾驶 | 新能源整车EMC | 动力性及能量管理 | 动力锂电池 | 结构可靠性

武汉 | 重庆 | 上海 | 广州 | 北京 | 长春巡回研讨会



# ANSYS新能源汽车电机多物理场 仿真解决方案

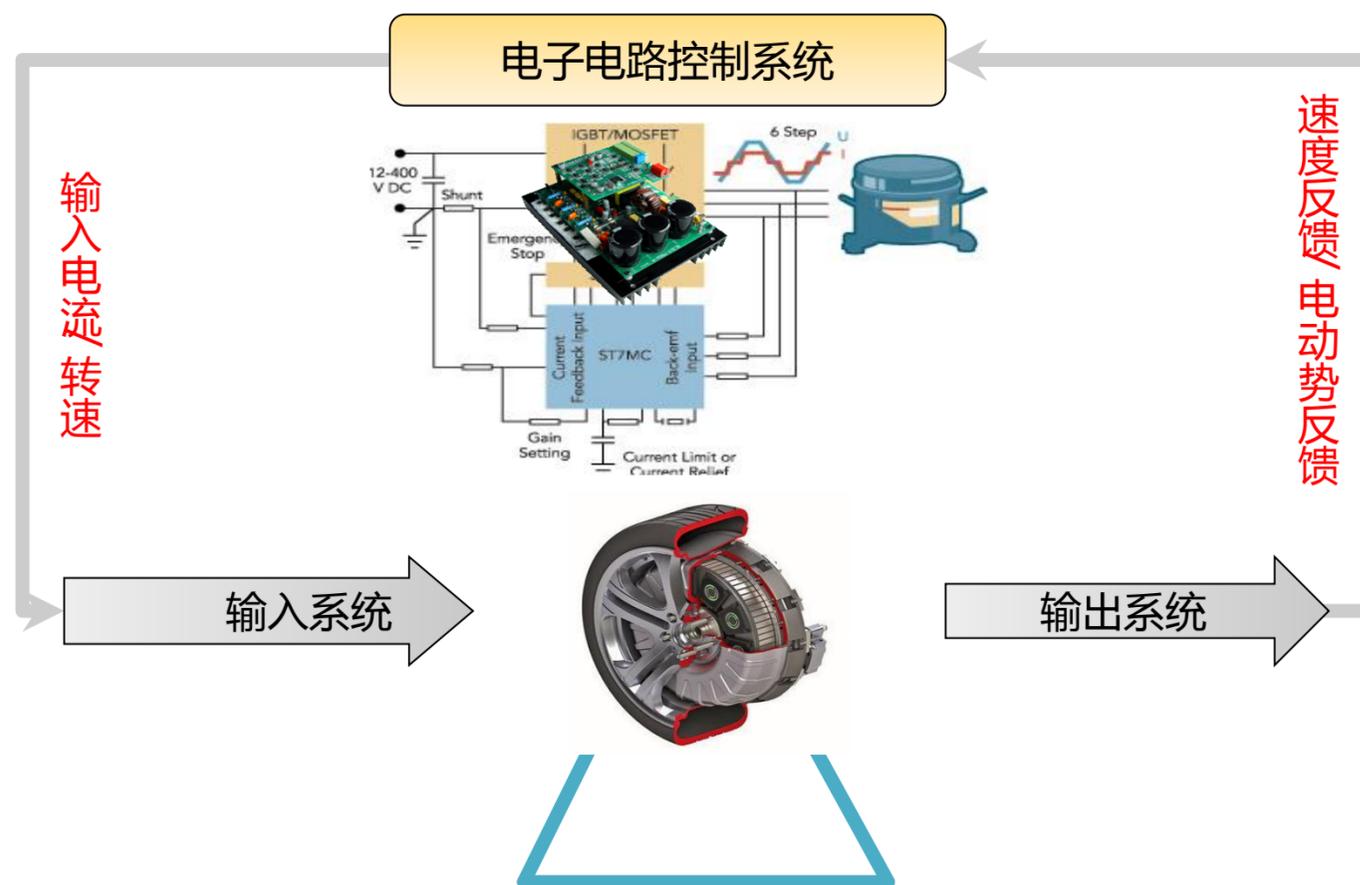
IDAJ中国  
技术部 魏仁委

# 目录

1. 新能源汽车电机研发关注的问题及其多物理场特性
2. ANSYS新能源汽车电机多物理场仿真的解决方案
3. 电机仿真案例介绍
4. 小结

# 电机设计中的多物理场问题

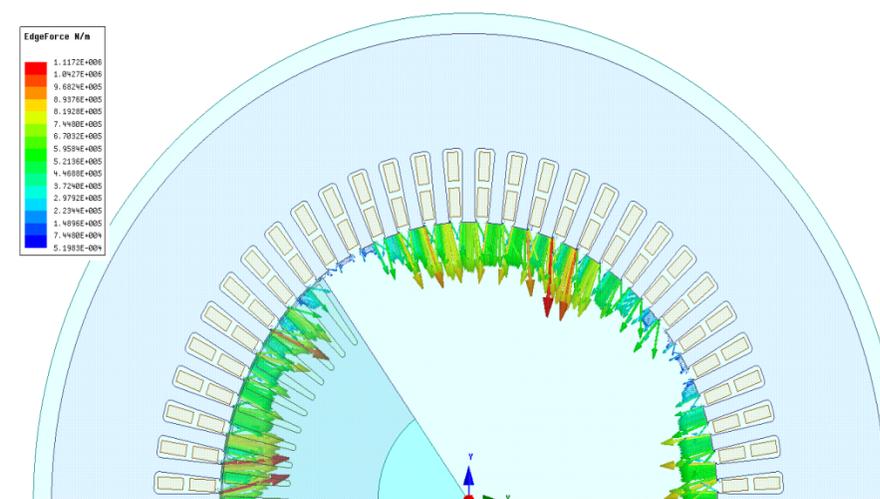
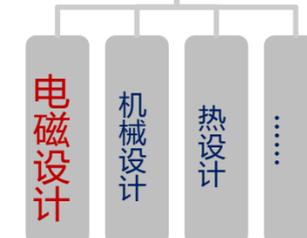
- 电机是一个集电气、机械、动力学、散热、电子电路、控制系统等众多学科综合于一体的复杂系统。



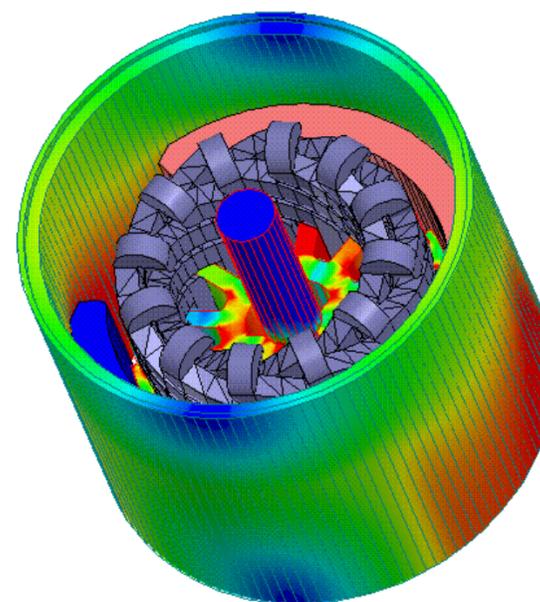
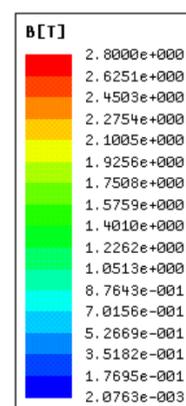
# 电机设计中的多物理场问题

## ■ 电机电磁场分析问题

- 电机空间磁密分布、气隙磁密分布
- 电机损耗（铜损、铁损）
- 电机电磁力/力矩计算
- 扁线电机导体的涡流损耗分析
- 电机磁铁的退磁分析
- .....

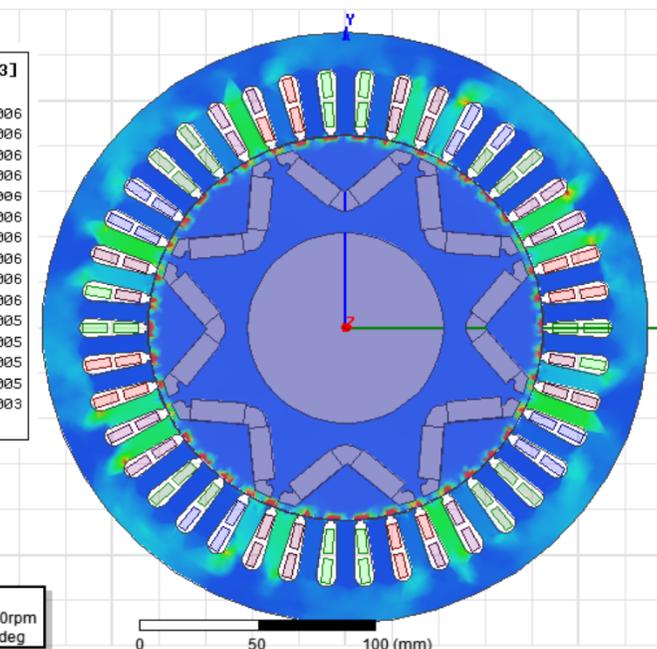
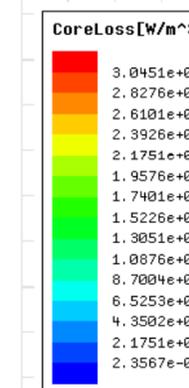


电磁力矢量云图



磁通密度云图

Time = 0.015s

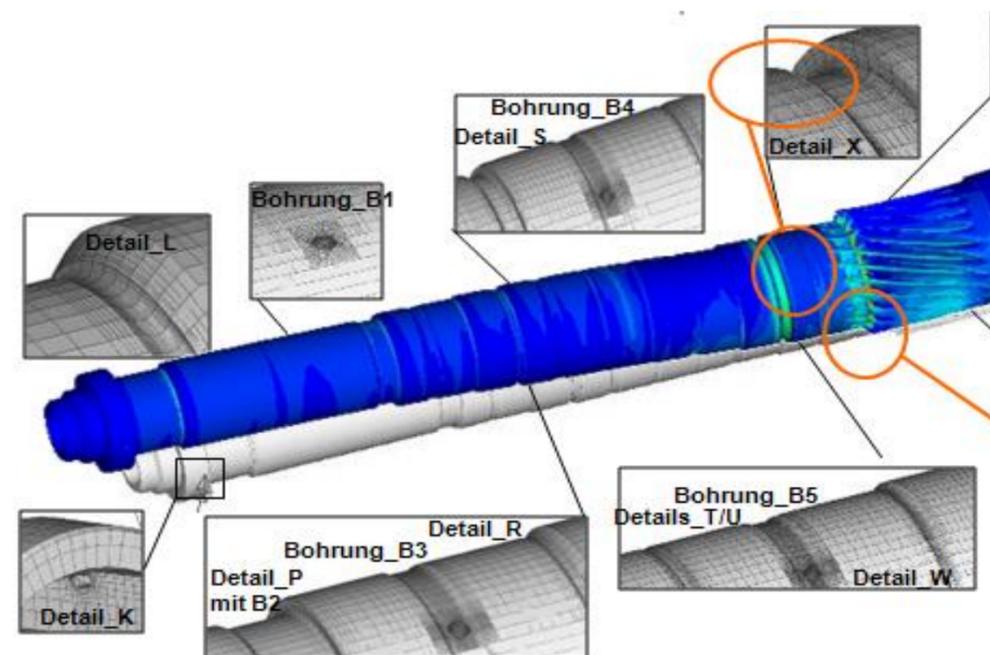
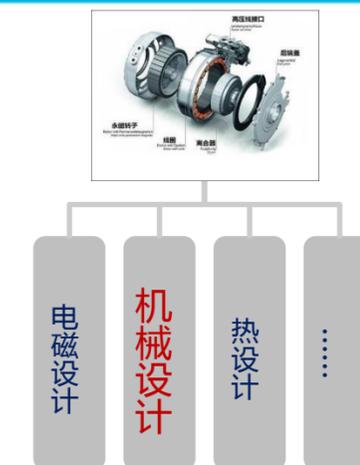


铁损云图

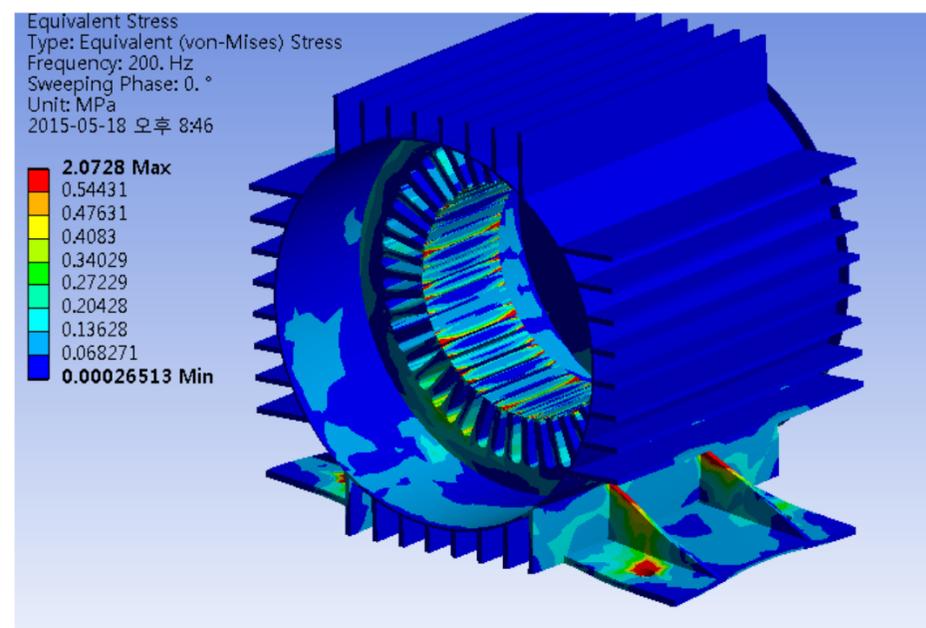
# 电机设计中的多物理场问题

## ■ 电机机械结构分析问题

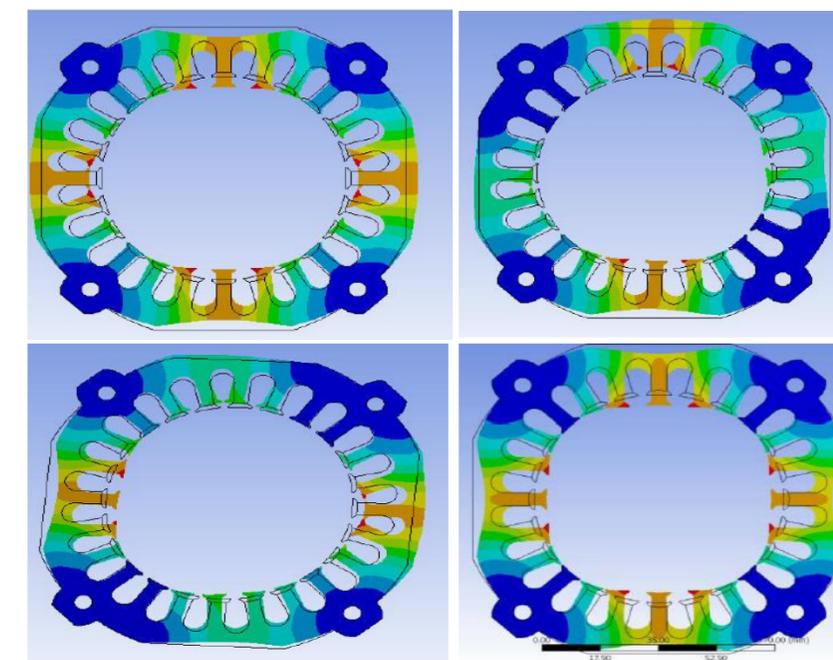
- 定转子\机壳应力和变形
- 定转子、机壳等结构的振动
- 电机装配（过盈配合、螺栓预紧）
- 结构疲劳寿命
- .....



转子疲劳寿命



定子机壳的应力

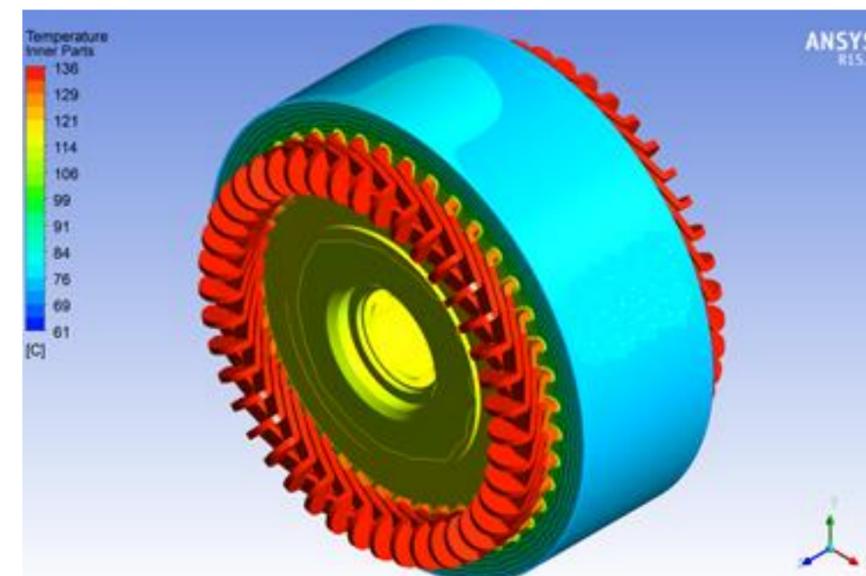
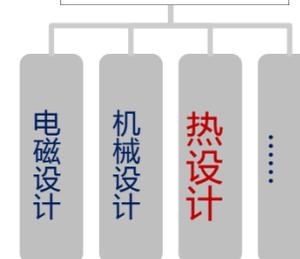


定子固有频率及振型

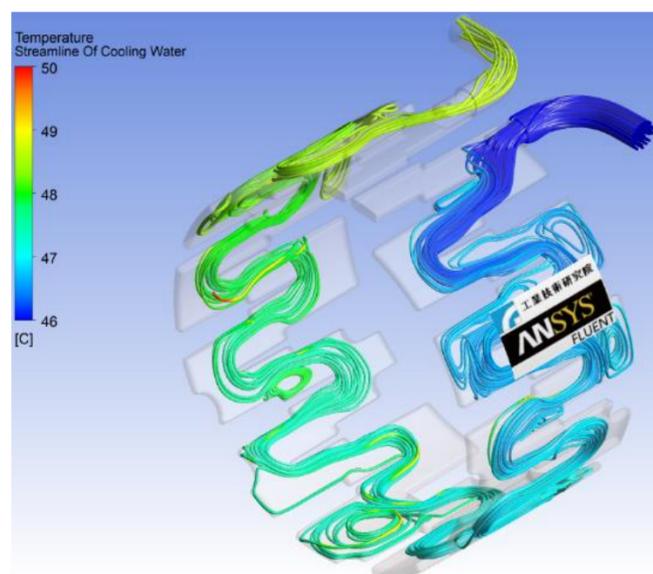
# 电机设计中的多物理场问题

## ■ 电机散热流动分析问题

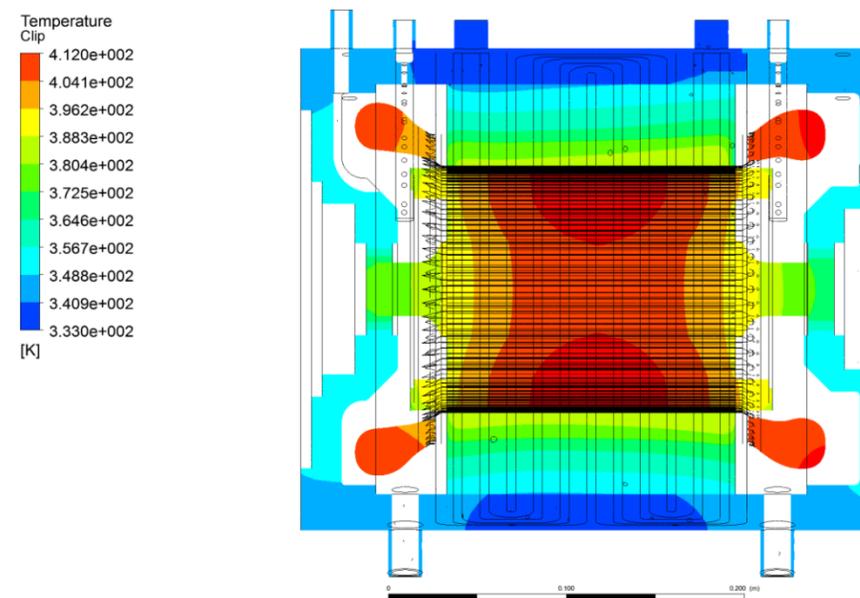
- 冷却系统（风冷、水冷）设计
- 结构传热与流体散热分析
- 电机结构温升(热变形和热应力)
- .....



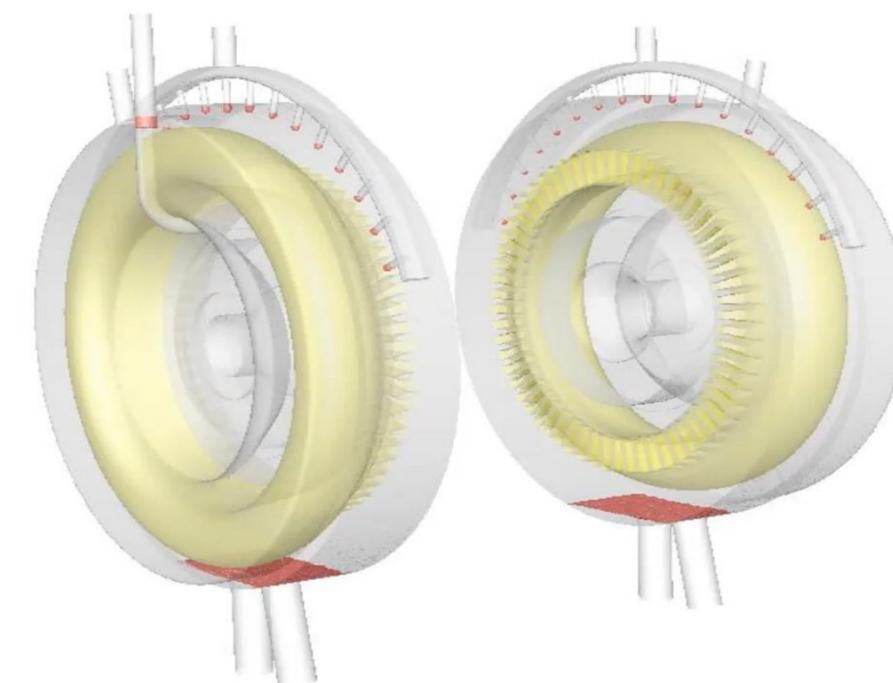
电机结构的温度云图



水套中冷却水的流线



剖面显示电机结构的温度云图



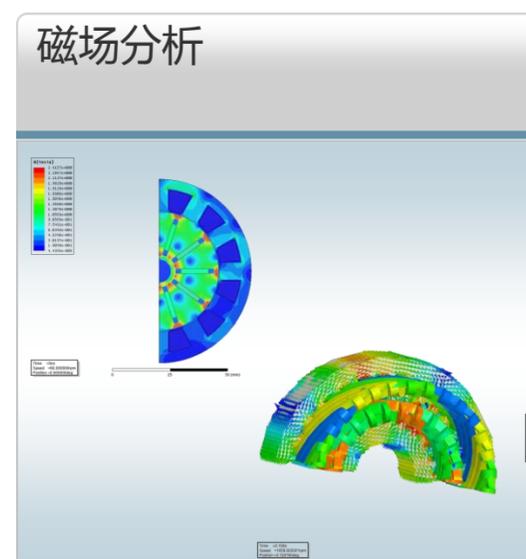
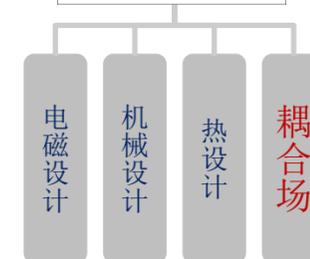
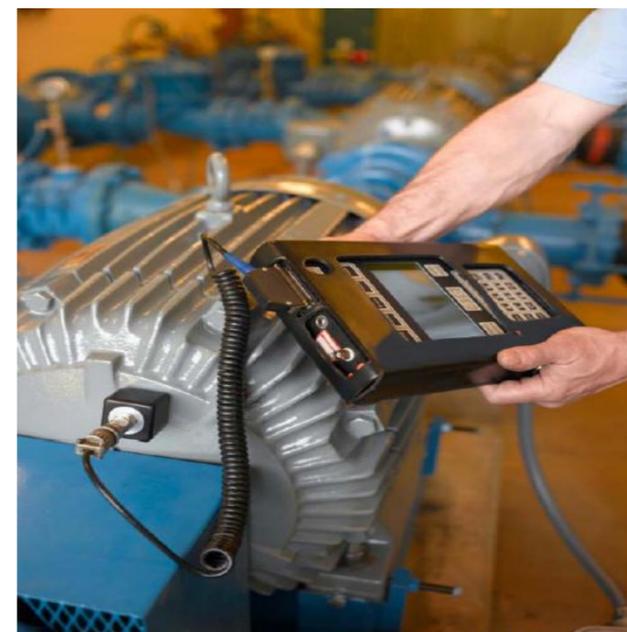
e=5.0000e-03)

绕组端部区域润滑油流动冷却

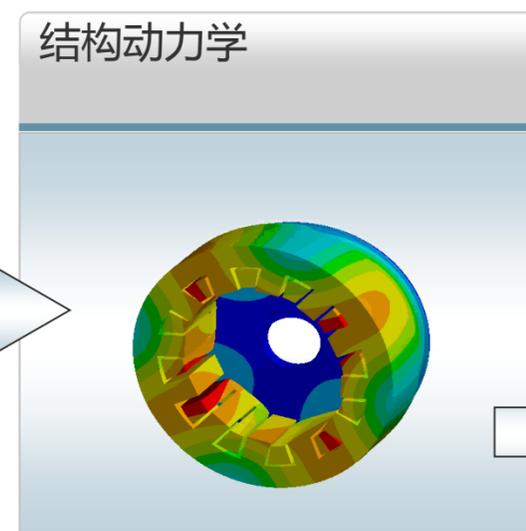
# 电机设计中的多物理场问题

## ■ 电机多物理场耦合分析问题

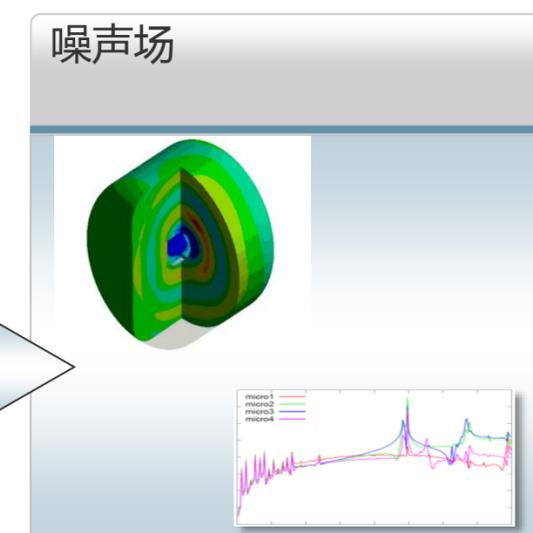
- 电机电磁-结构振动分析
- 电机电磁-温升散热分析
- 电机温升-结构热应力热变形
- 电机电磁-结构振动-噪声分析
- 电机气动-噪声分析...



力



位移



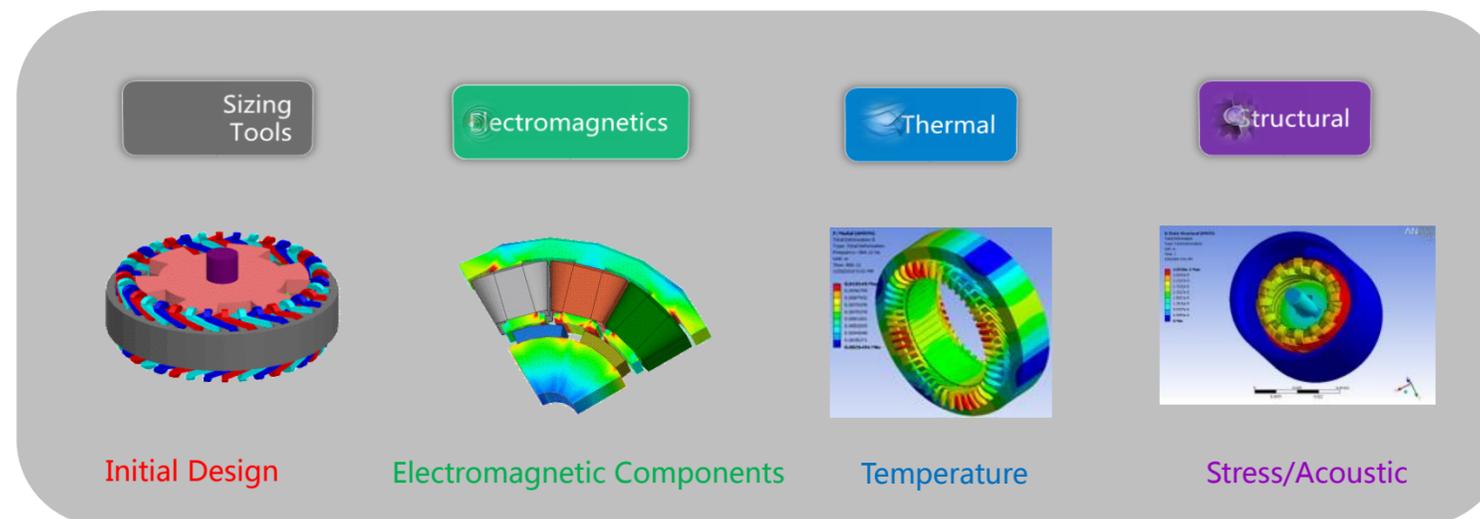
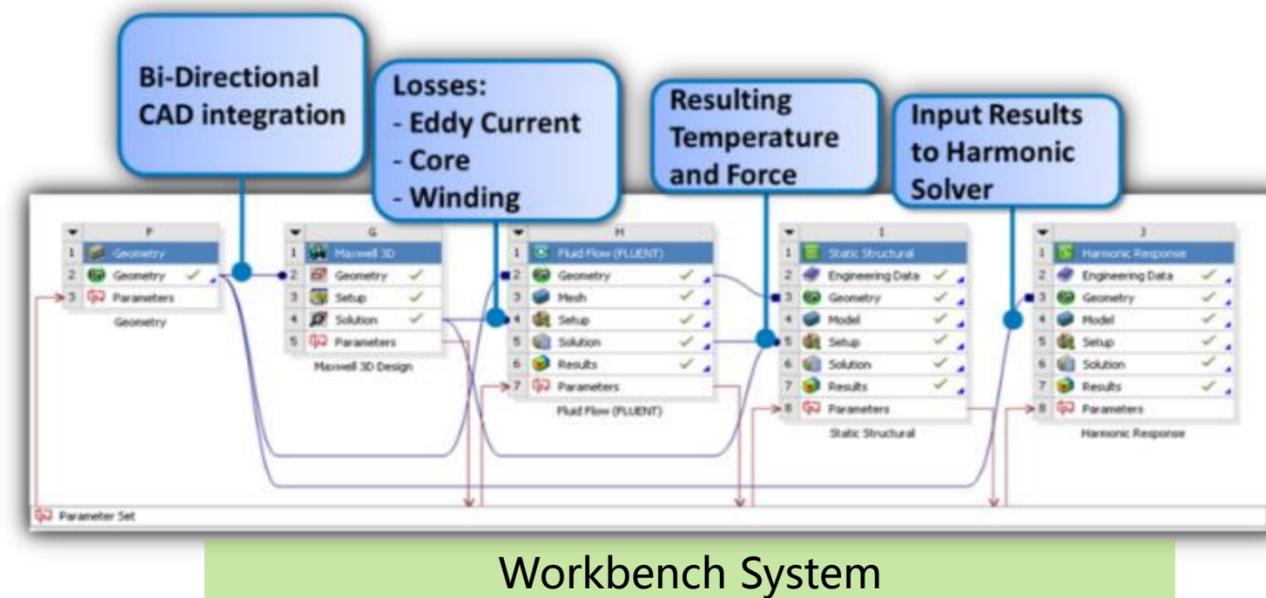
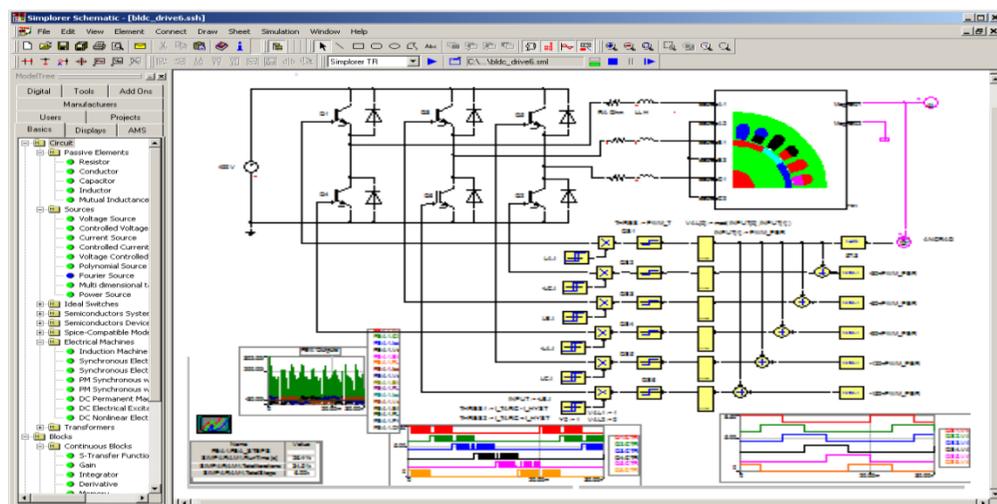
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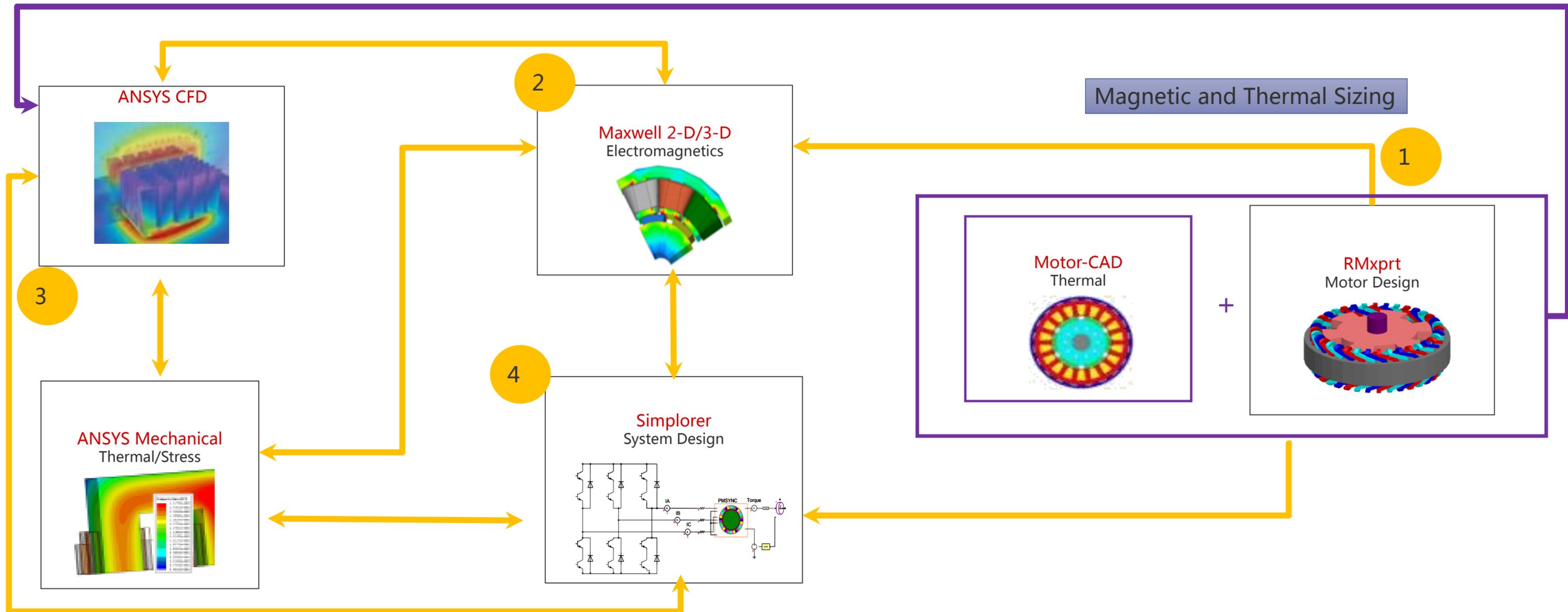
## ■ 什么是ANSYS电机设计多物理场仿真系统?

1-D System



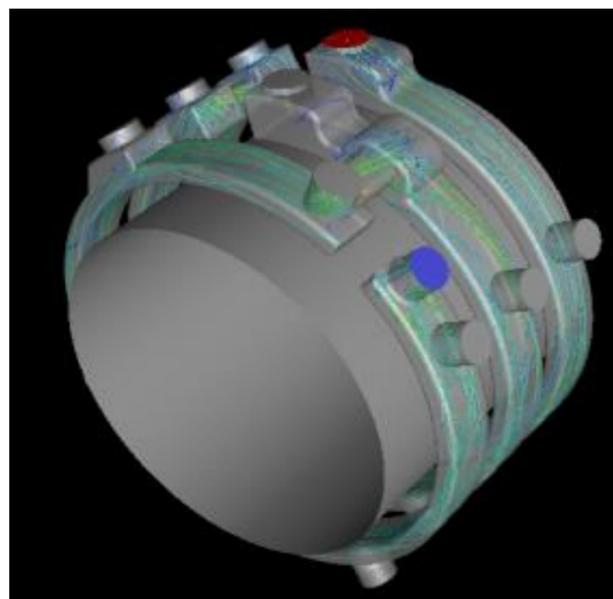
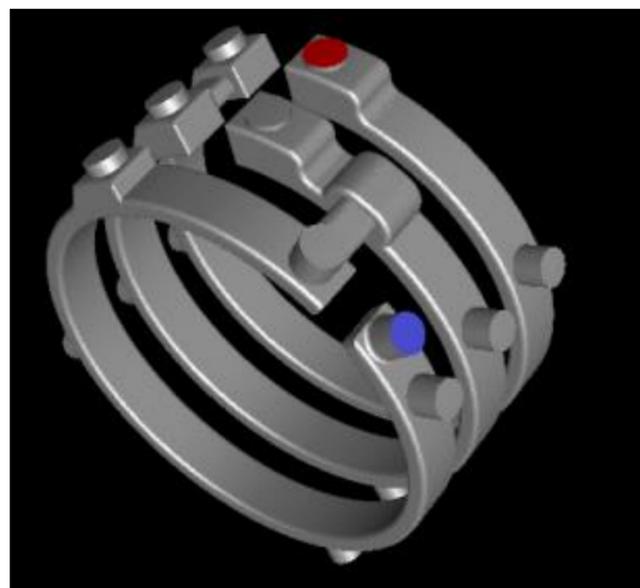
# ANSYS新能源汽车电机多物理场仿真解决方案

## ■ ANSYS电机设计多物理场系统如何耦合仿真？

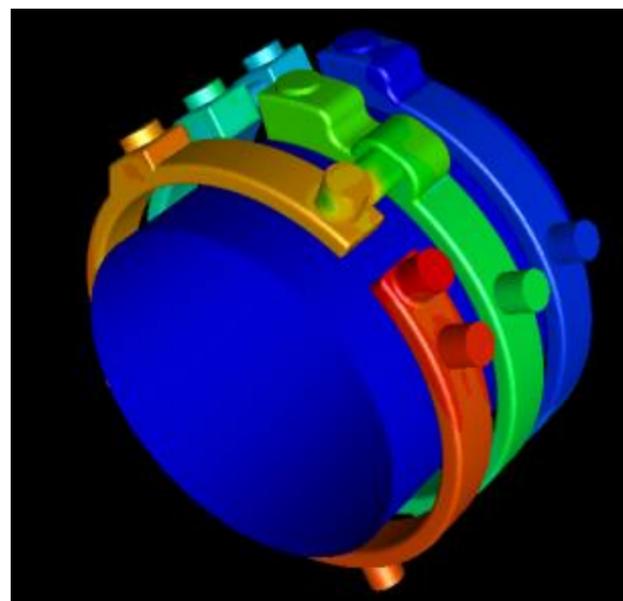


# ANSYS新能源汽车电机多物理场仿真解决方案

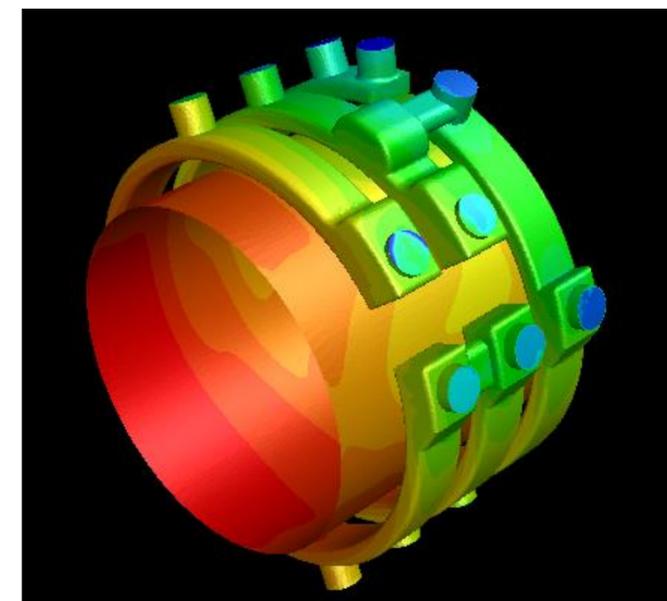
## ■ 水冷电机水套性能模拟



Path Lines



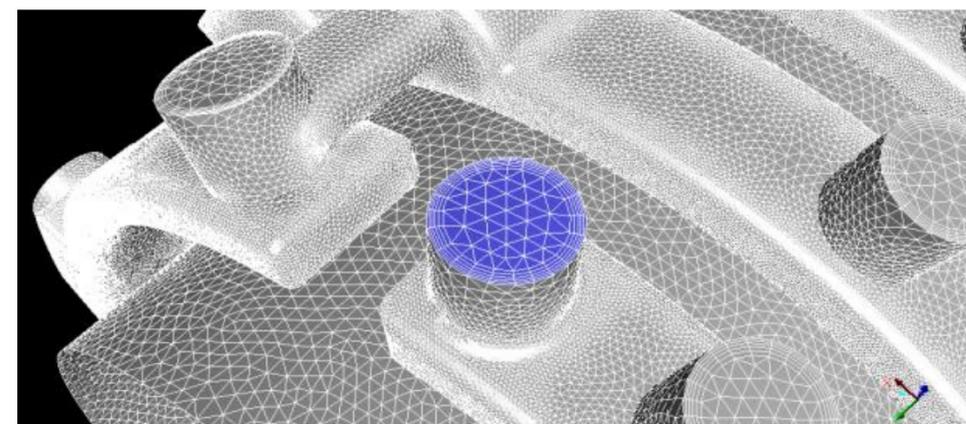
Static Pressure



Temperature Profile

Maxwell3D

Fluent



冷却通道不同布置时的冷却液分布

# ANSYS新能源汽车电机多物理场仿真解决方案

## ■ 电机NVH性能分析

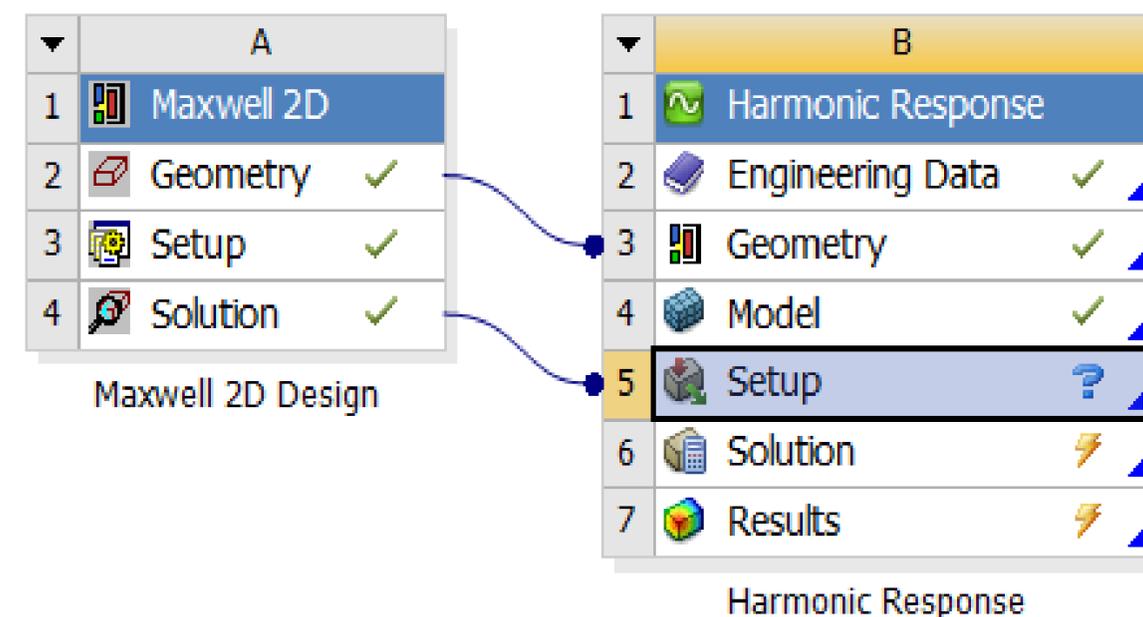
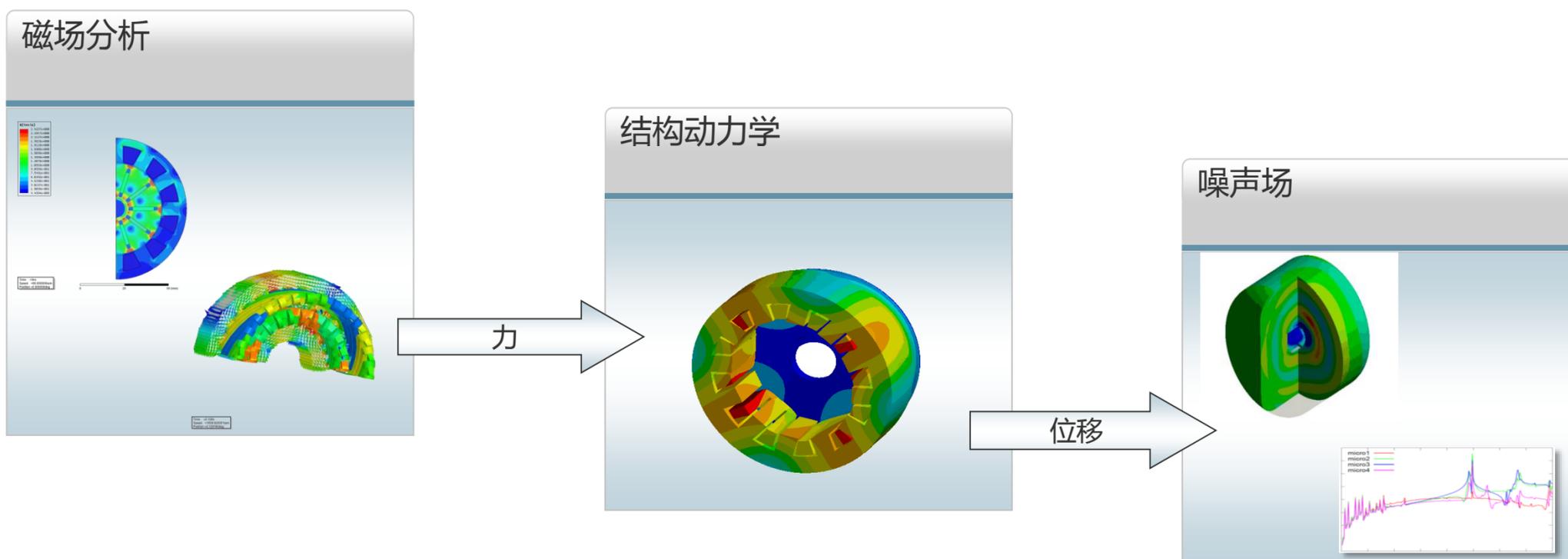
### ➤ 振动噪声

瞬态Maxwell 2D/3D单向耦合Harmonic stress

Maxwell

+

Mechanical

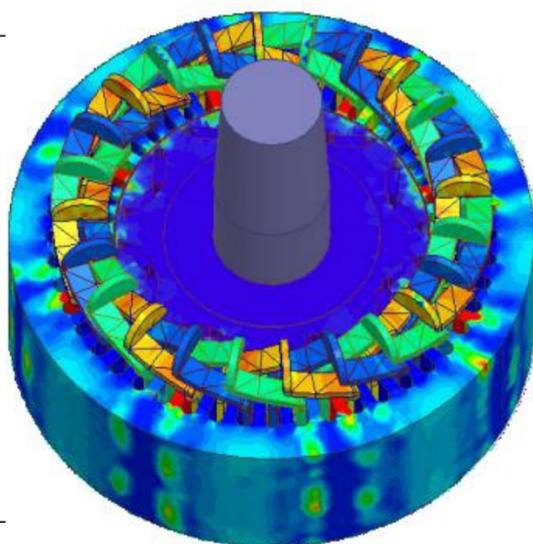
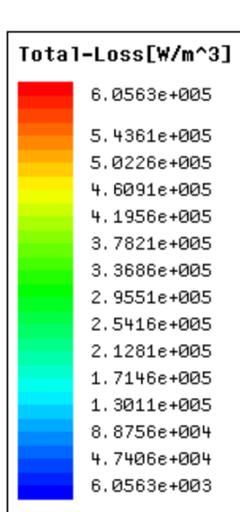
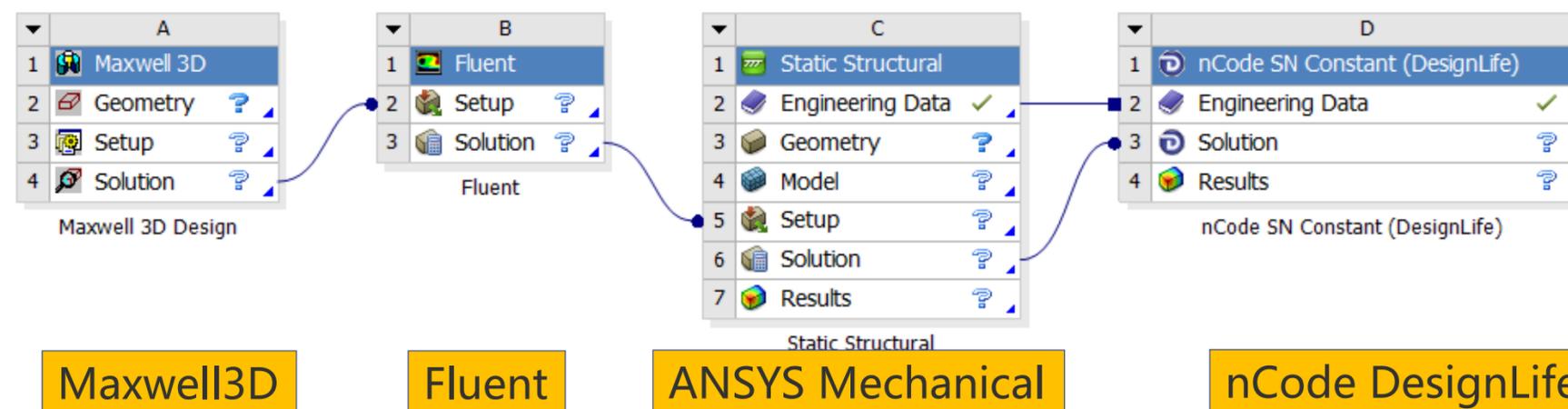


# ANSYS新能源汽车电机多物理场仿真解决方案

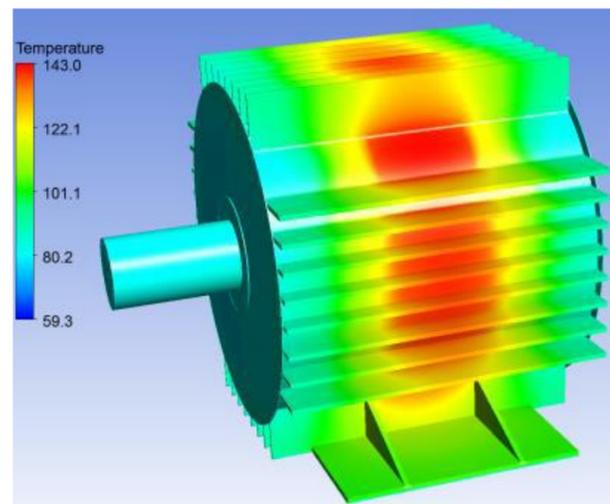
## 电机综合性能设计

### 多物理场耦合仿真

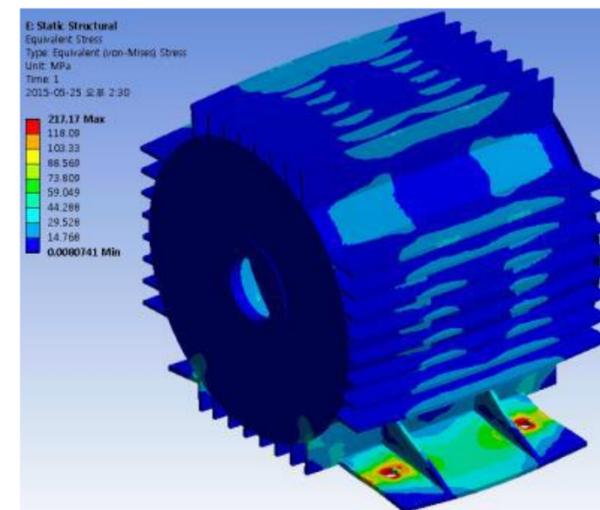
## Electric – Fluid – Mechanical (Thermal Stress) - Fatigue



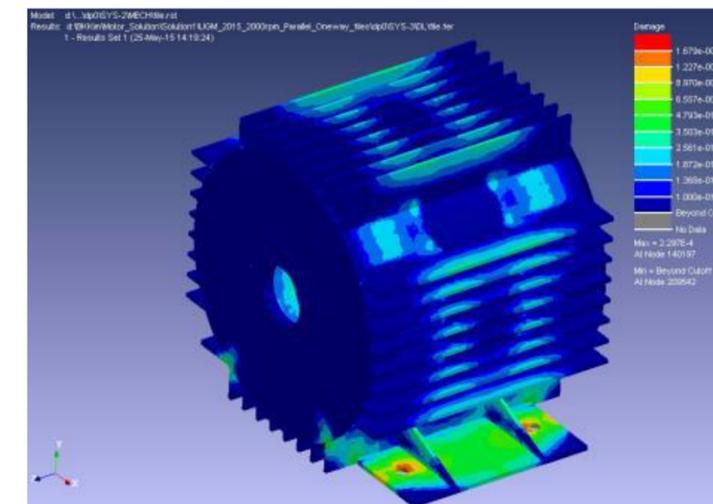
Loss



Temperature



Stress

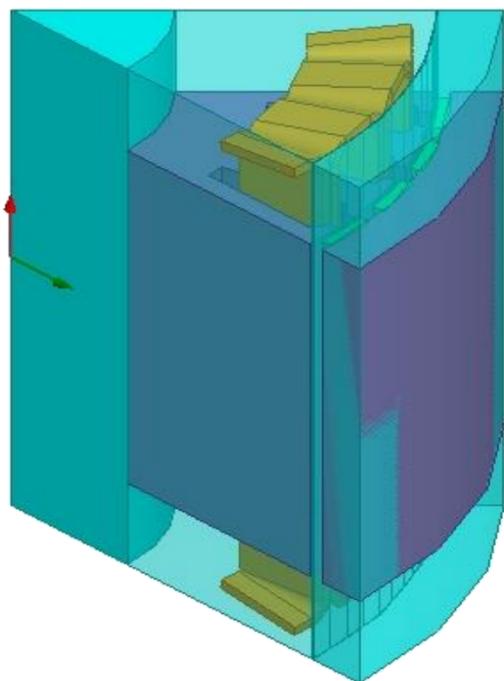
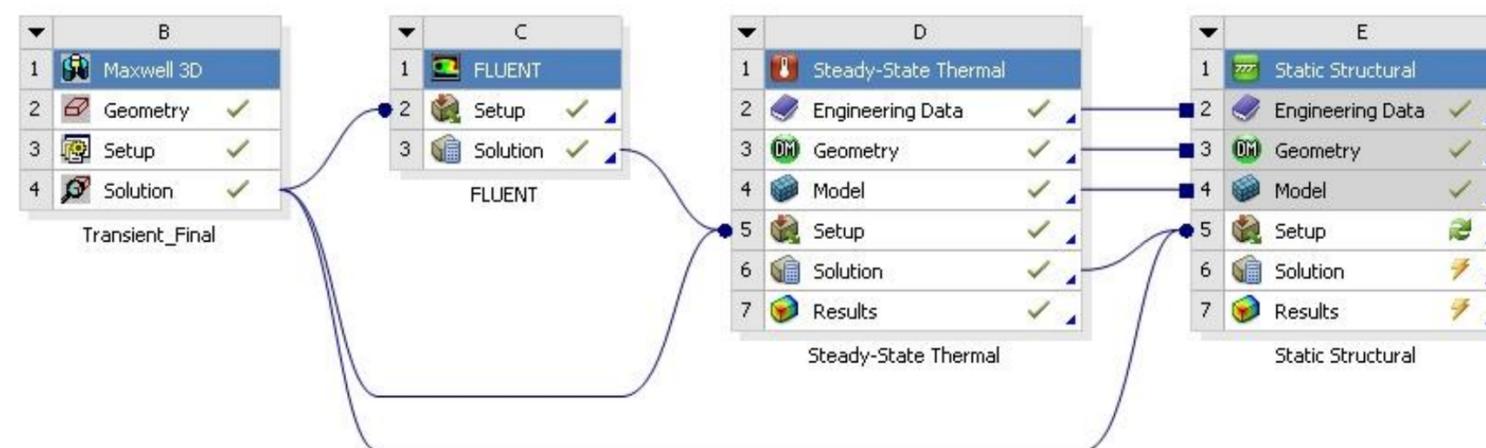


Damage

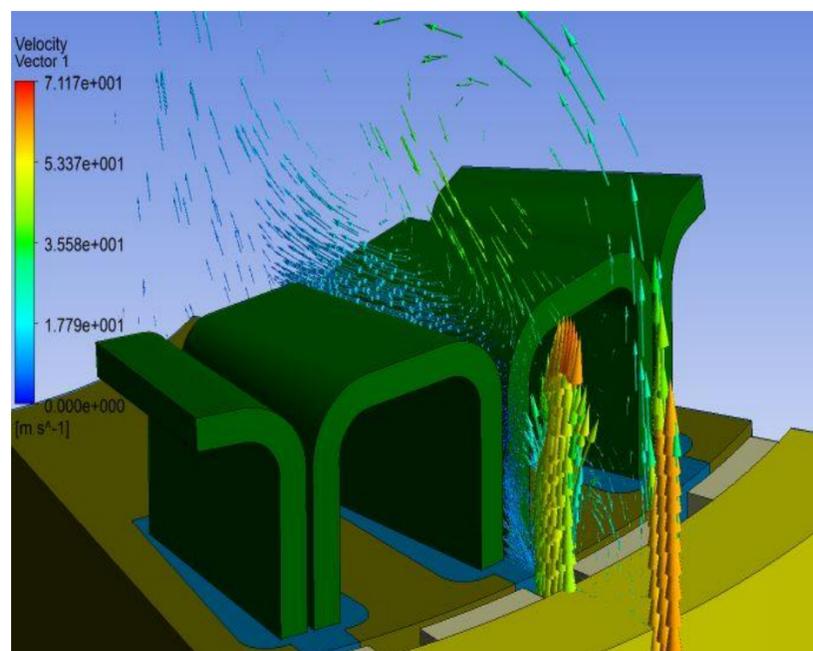
# ANSYS新能源汽车电机多物理场仿真解决方案

## ■ 成熟且高效的ANSYS Workbench平台

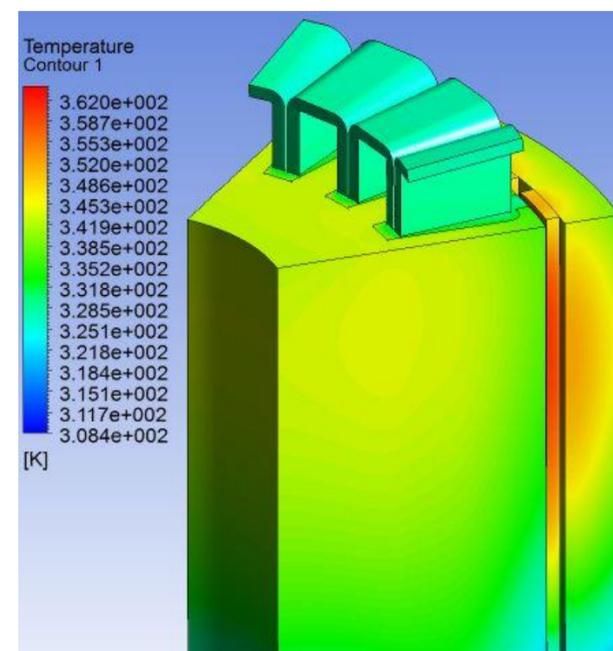
➤ 横向耦合：电磁场、流场、温度场及应力



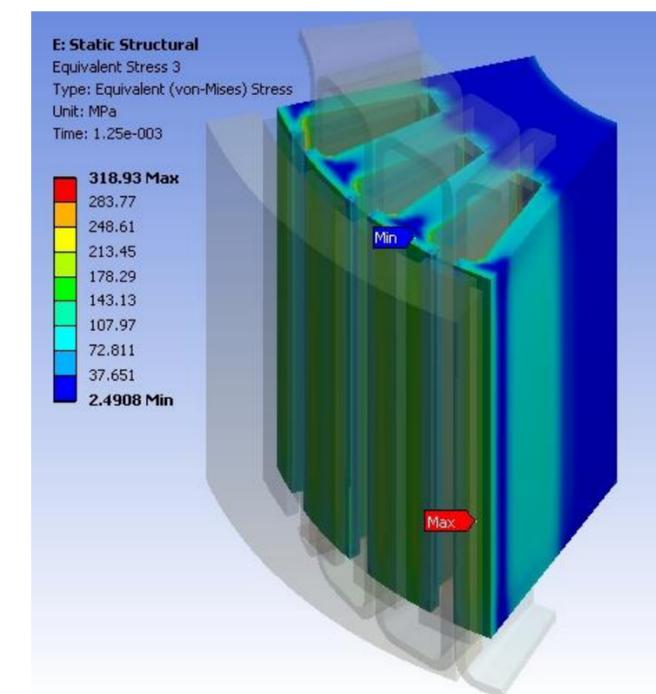
Electromagnetic field



Thermo-fluid



Heat transfer



Stress

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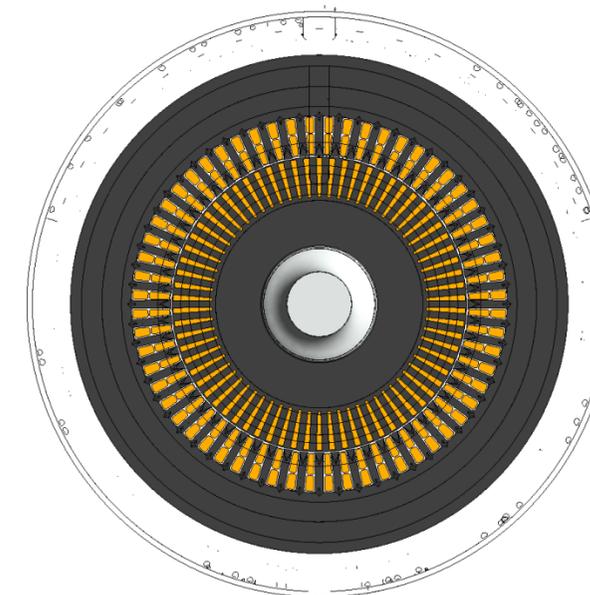
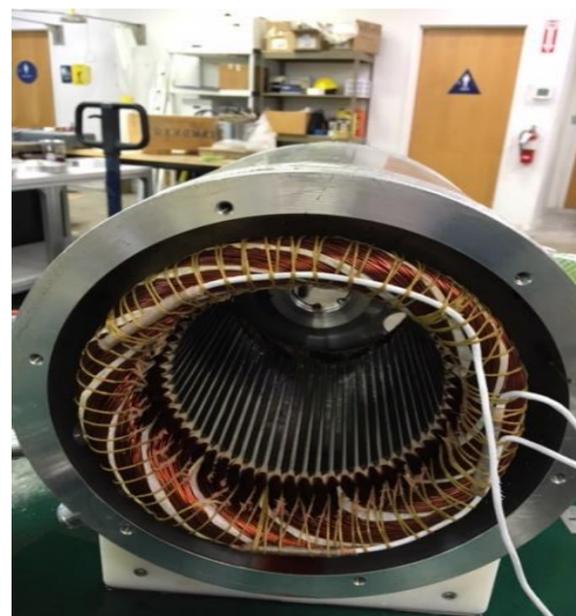
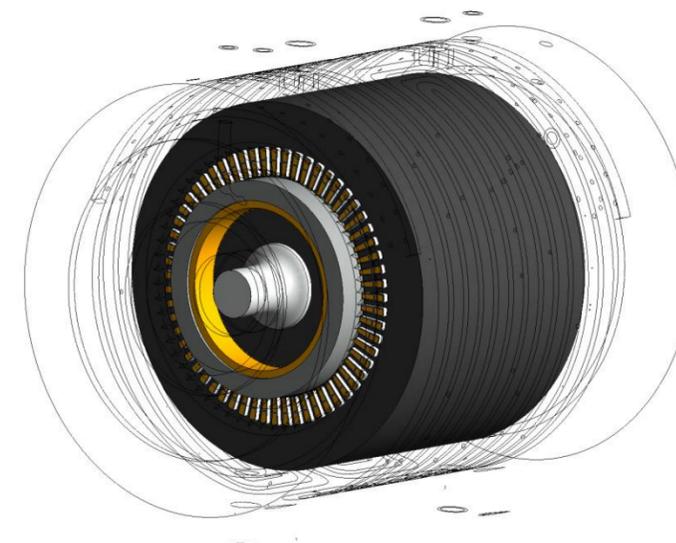
## 3. 电机仿真案例介绍

- 模型介绍及仿真策略
- 电-磁分析
- 热分析
- 结构分析

# 模型介绍及仿真方案

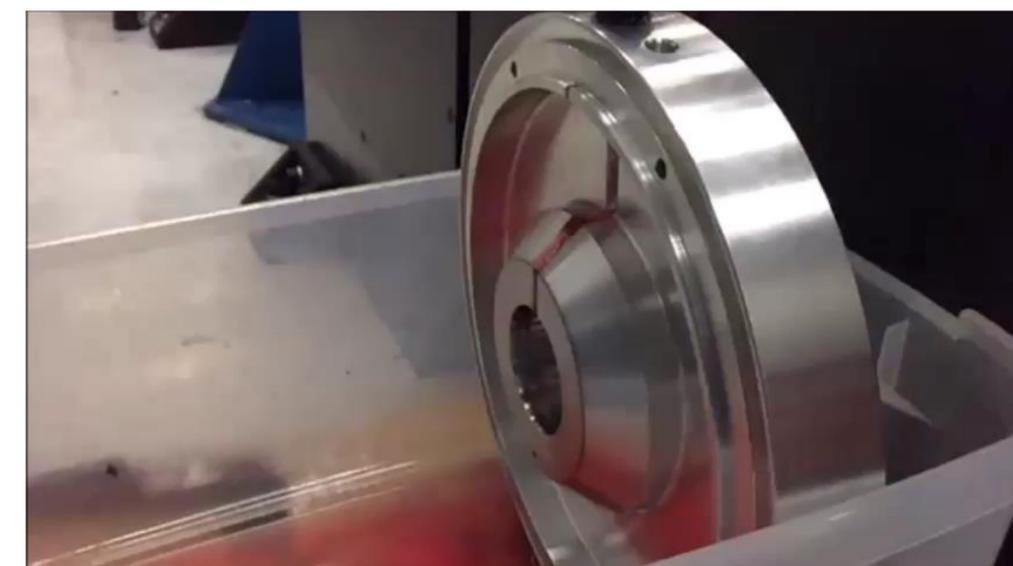
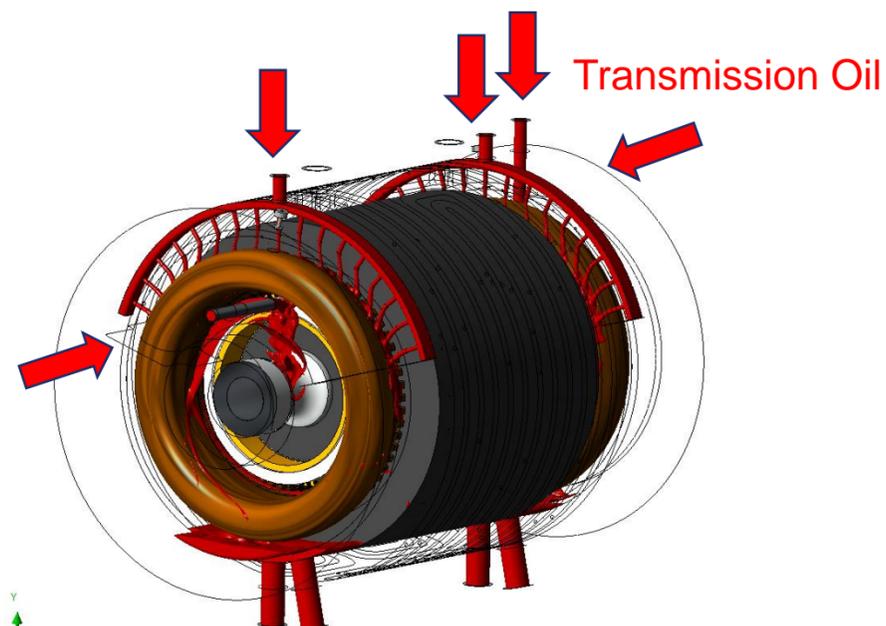
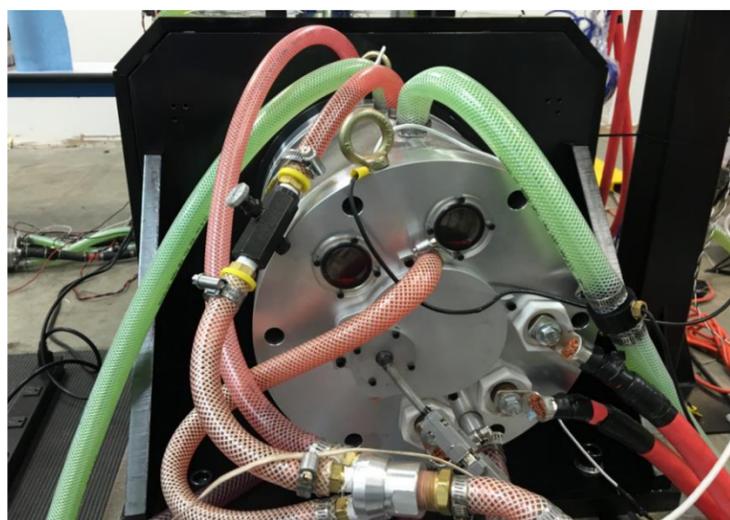
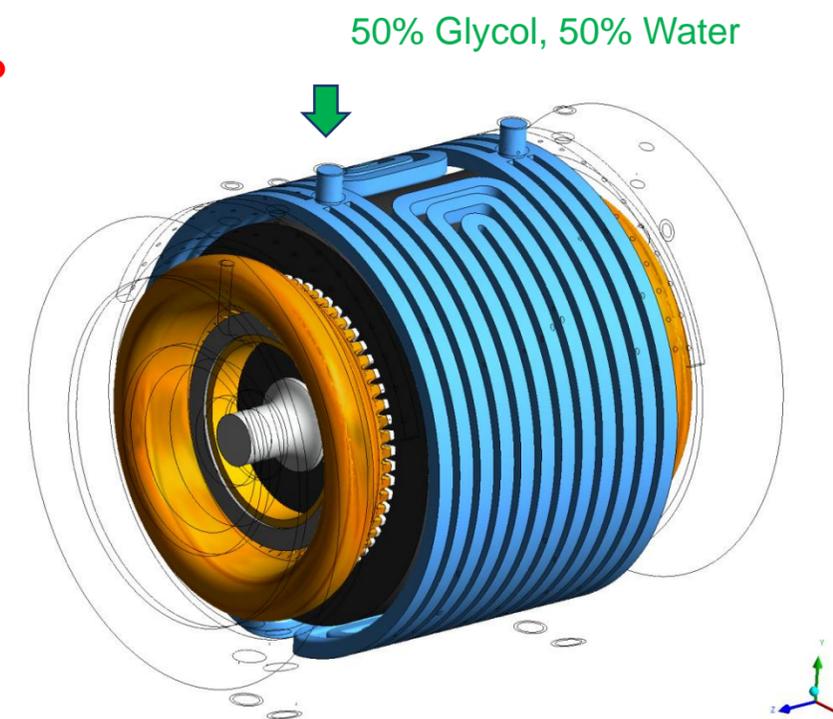
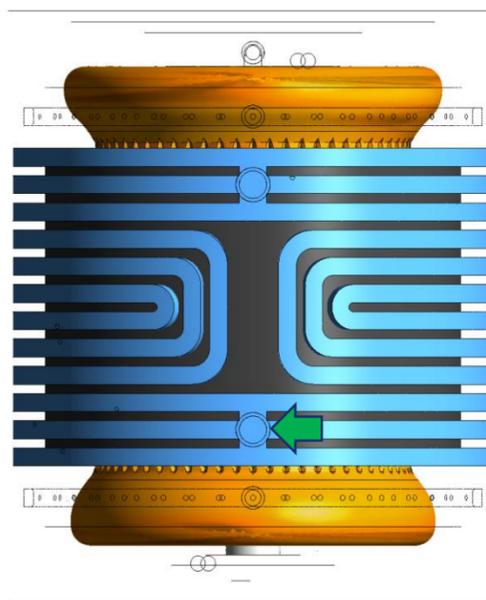
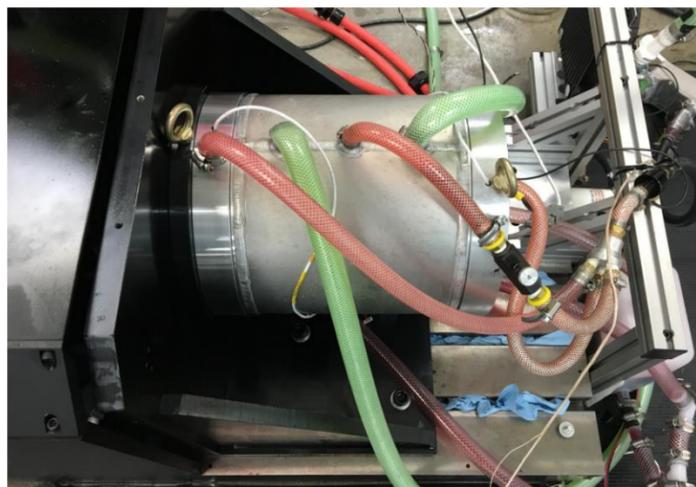
LUCID

## ■ Lucid 四极三相逆变器驱动感应电机



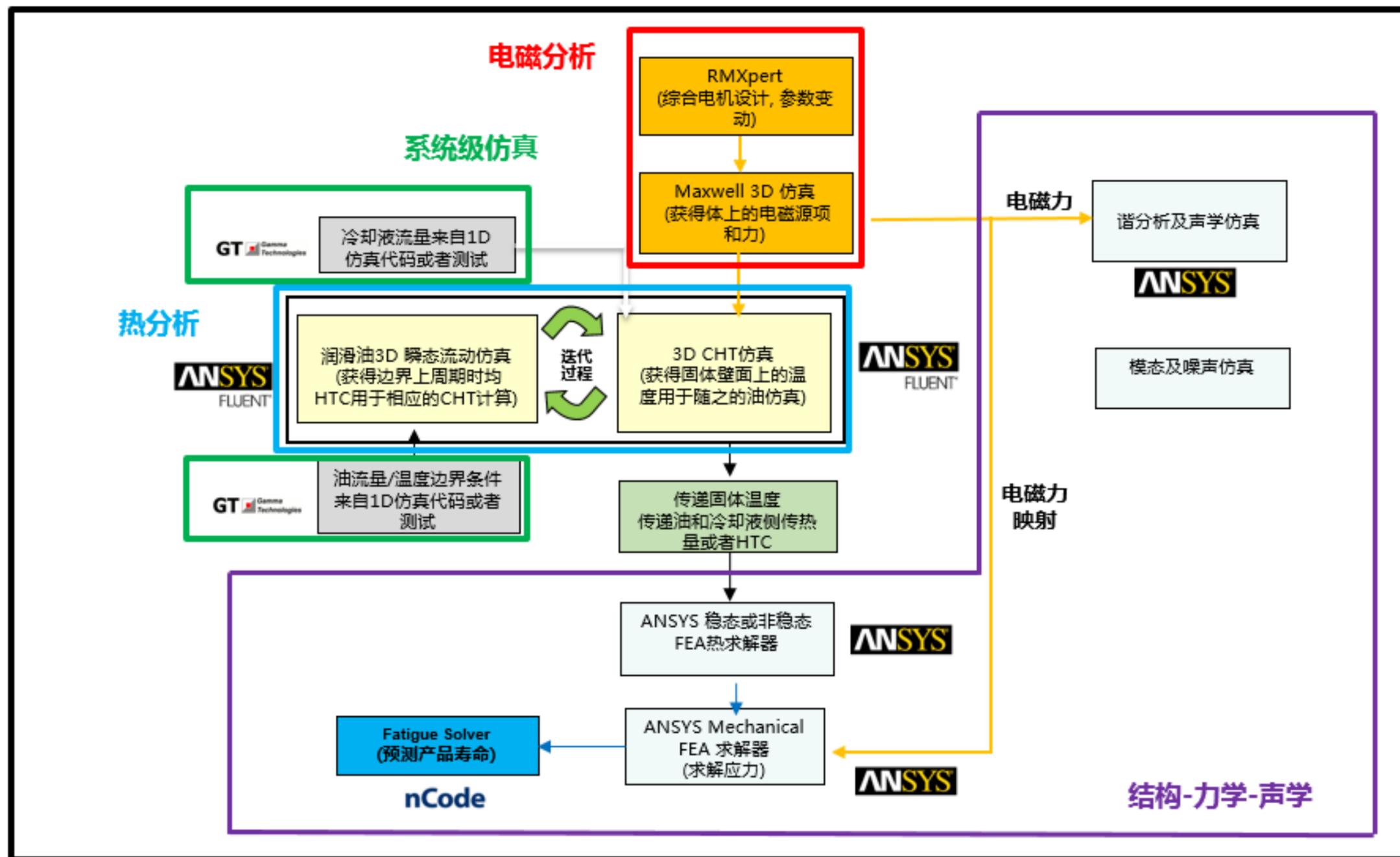
# 模型介绍及仿真方案

- 两种冷却方式：**电机外壳中有水套**；**末端绕组和转子上喷油**。

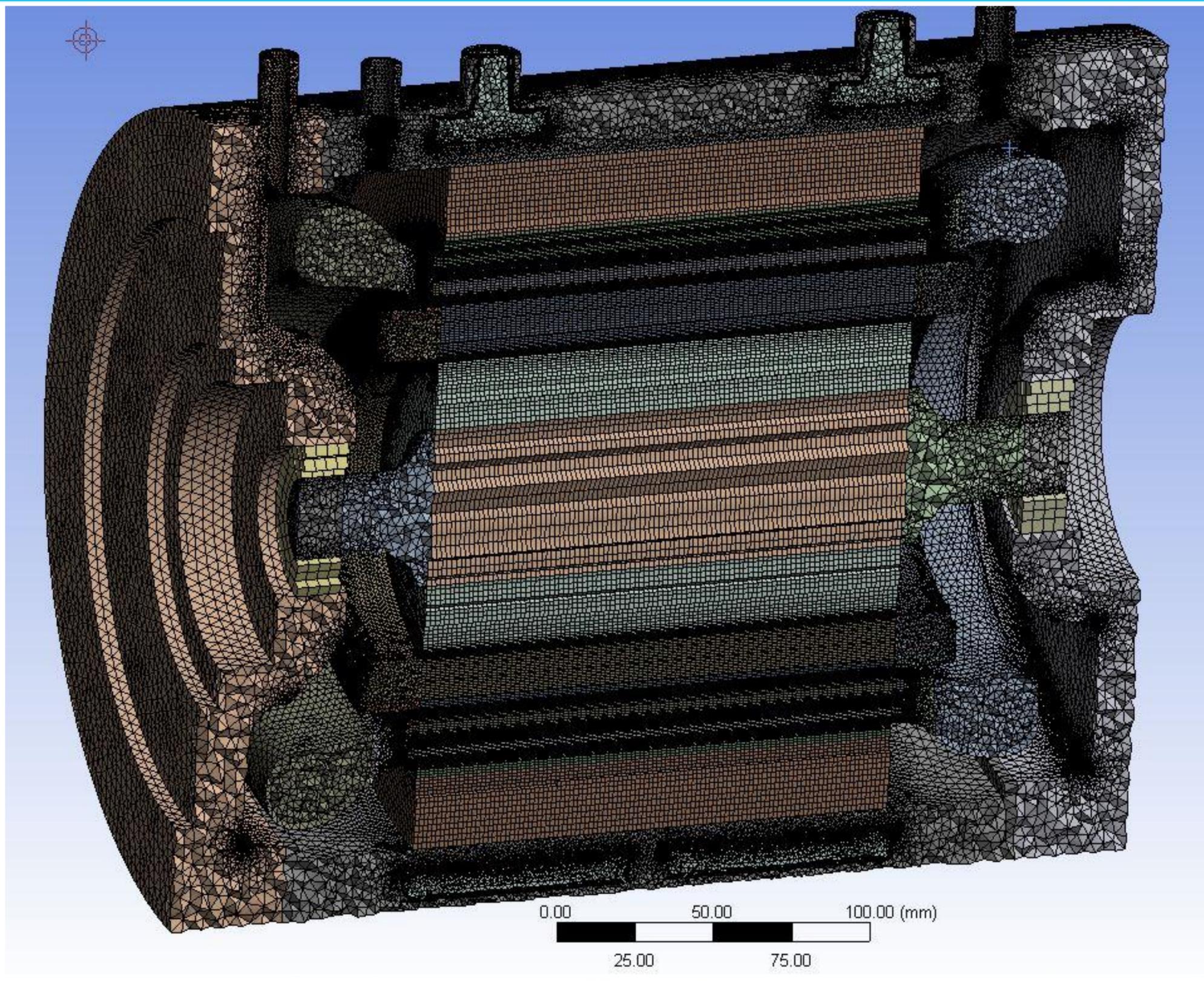


Transmission Oil @ 90C

# 模型介绍及仿真方案

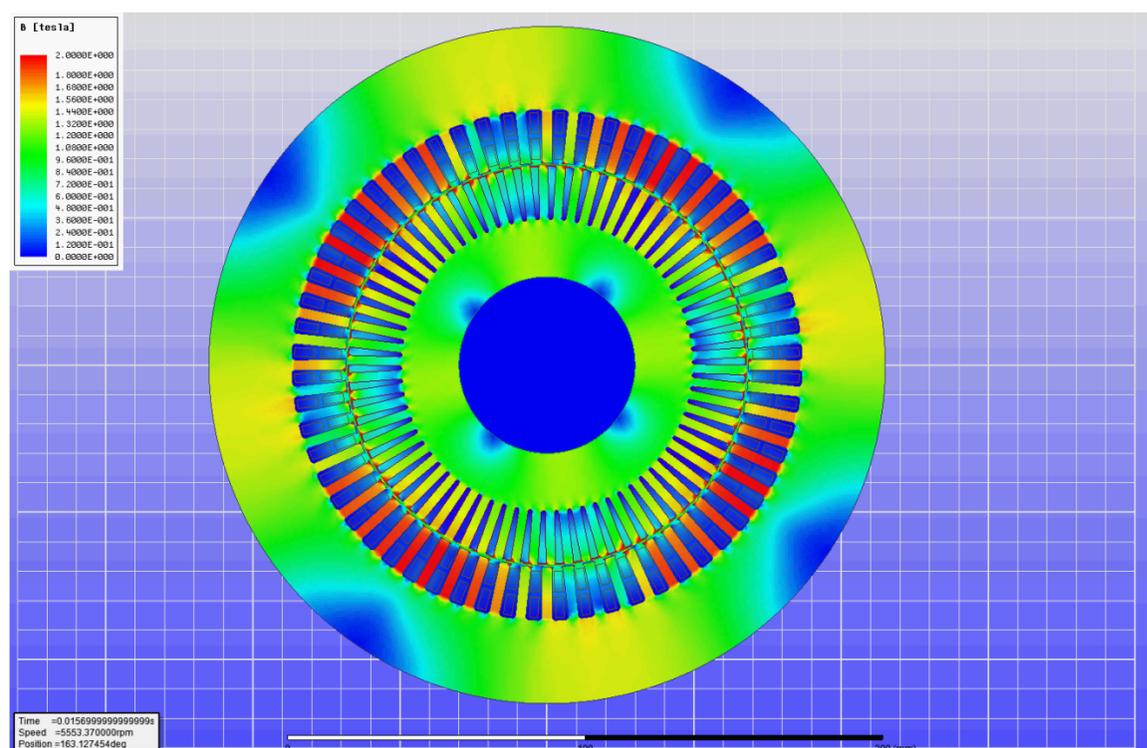


整个动力系统的系统级仿真在SIMPLORER中完成

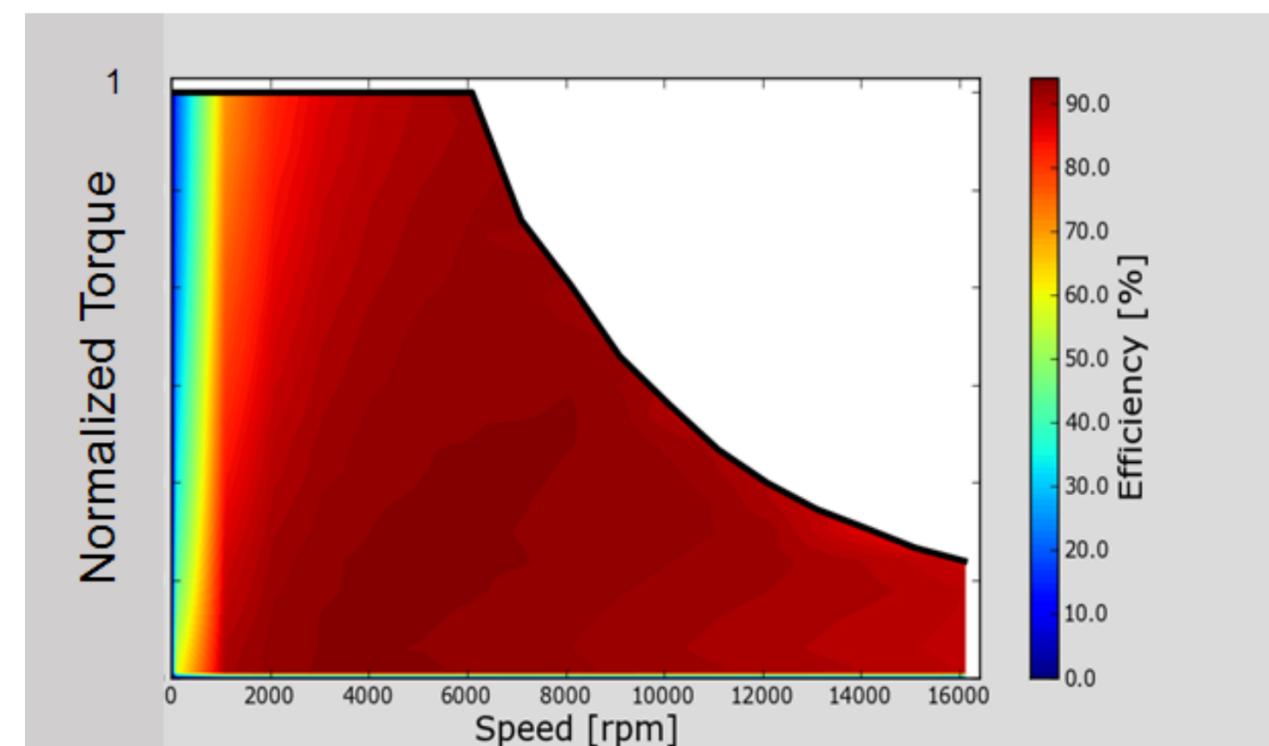


# 使用Maxwell进行2D/3D FEA设计优化

- 使用Maxwell的参数化设计探索 (Optimetrics)以及并行处理 (DSO)功能，在评估了数百种不同的设计形式后，确定了最佳的电机设计形式。



磁通密度 B [Tesla]  
最终优化的四极三相逆变器驱动感应电机

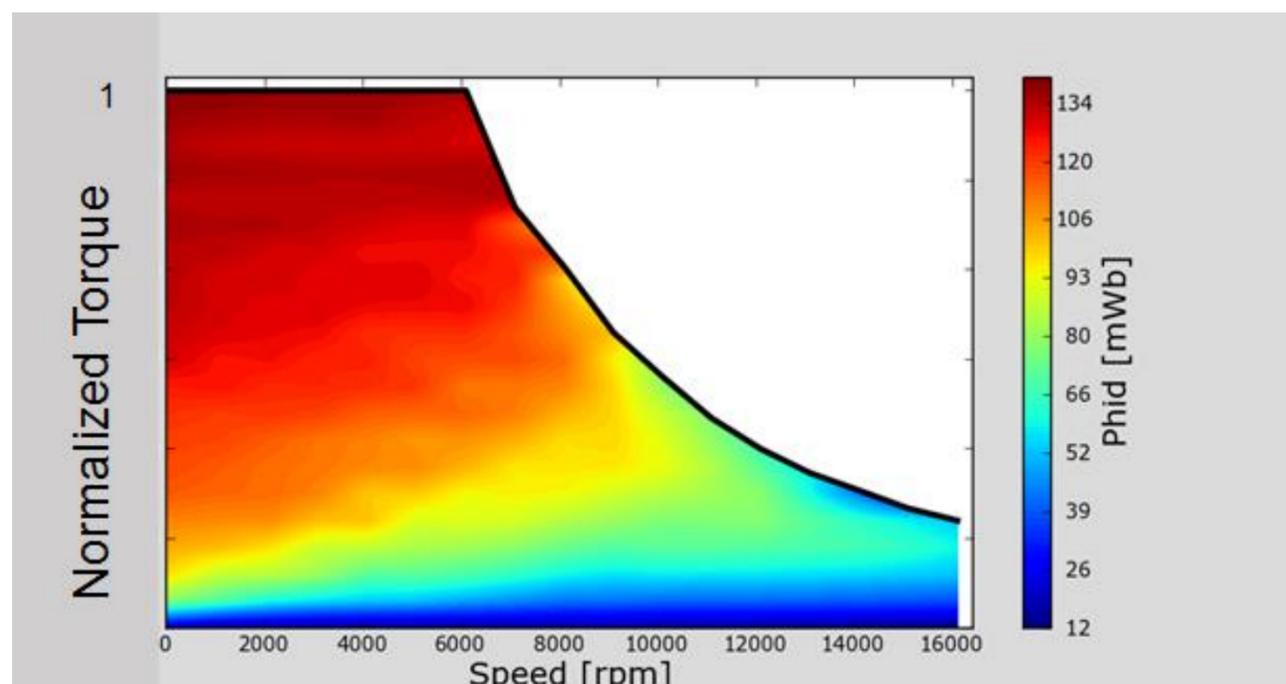


使用Maxwell Motor Toolkit获得最优电机优化设计效率图，考虑了多种参数变化的影响，如频率、滑差和输入电流

# 使用Maxwell进行2D/3D FEA设计优化

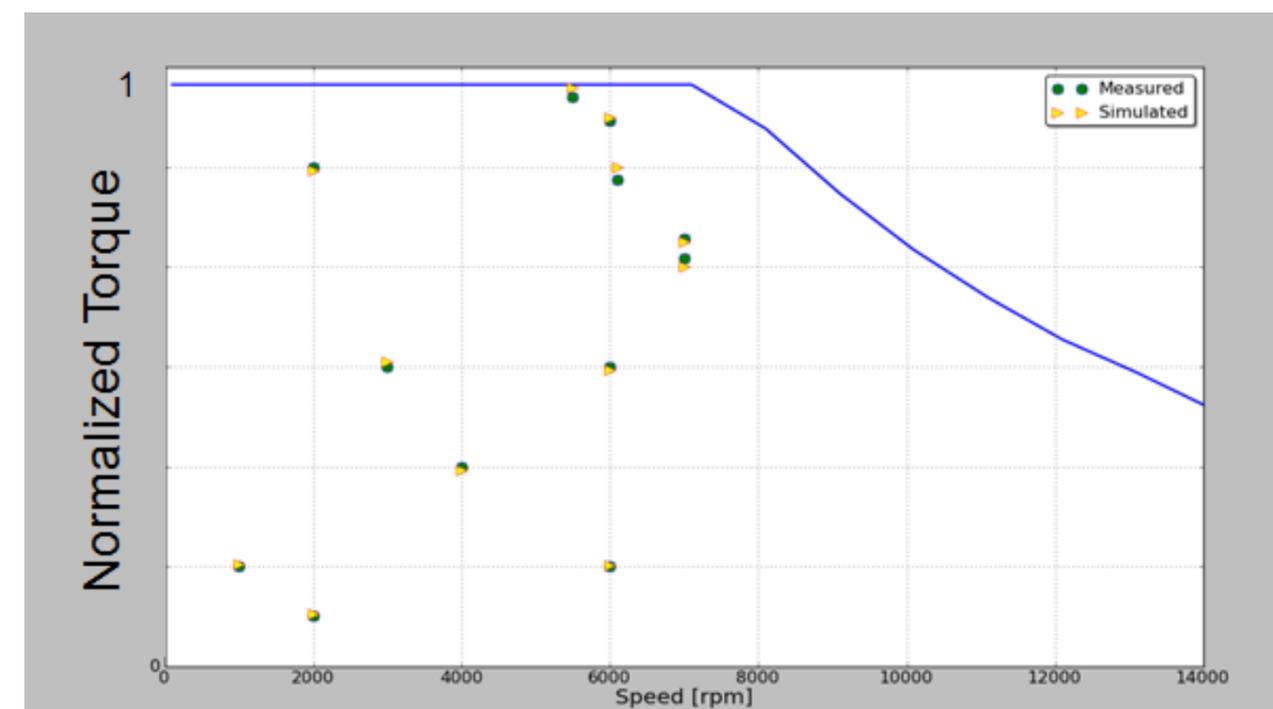
- 使用转子磁通映射图(Rotor Flux Map, 通常由Dynos试验标定) 在本例中直接由FEA计算获得, 以获得最小损耗 (最大效率)。

Rotor Flux Map



通过FEA计算获得磁通和车辆参数可以直接通过电机控制软件/算法用于车辆控制单元 (VCU)

仿真 vs. 试验

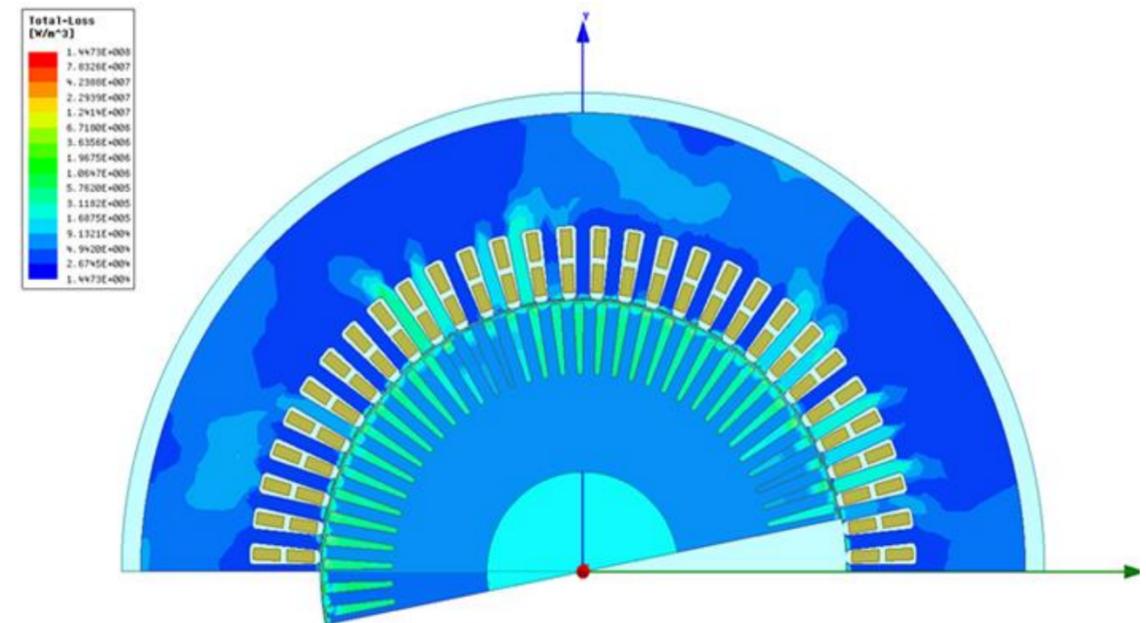


FEA可以**缩减80%**的Dyno标定时间, 同时获得更好的驾驶感受

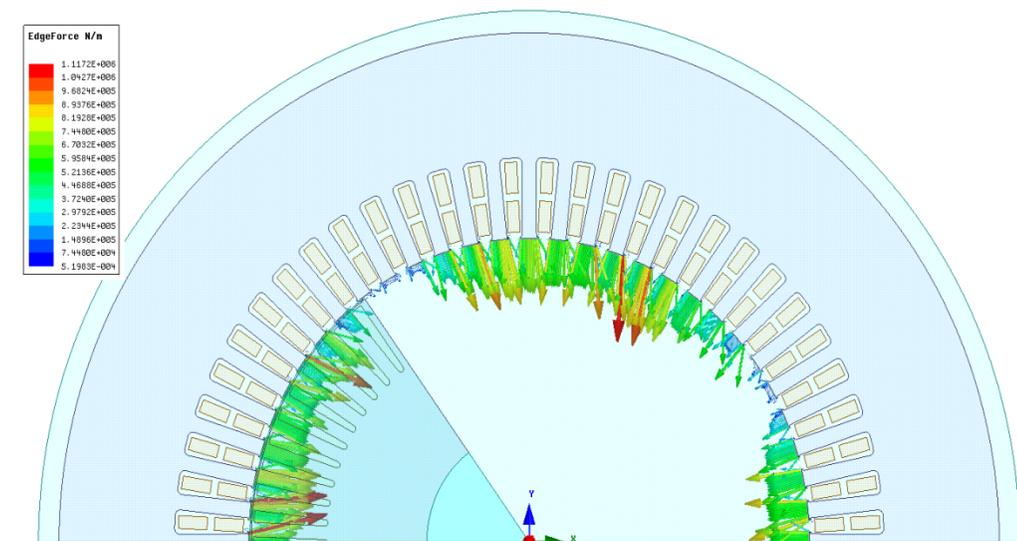
# 使用Maxwell进行2D/3D FEA设计优化

## ■ 电磁场计算结果输出给CFD/ 结构

- Maxwell损耗结果输出用于 **热分析**:
- 总损耗在0.594秒 (结束时间),  $W/m^3$



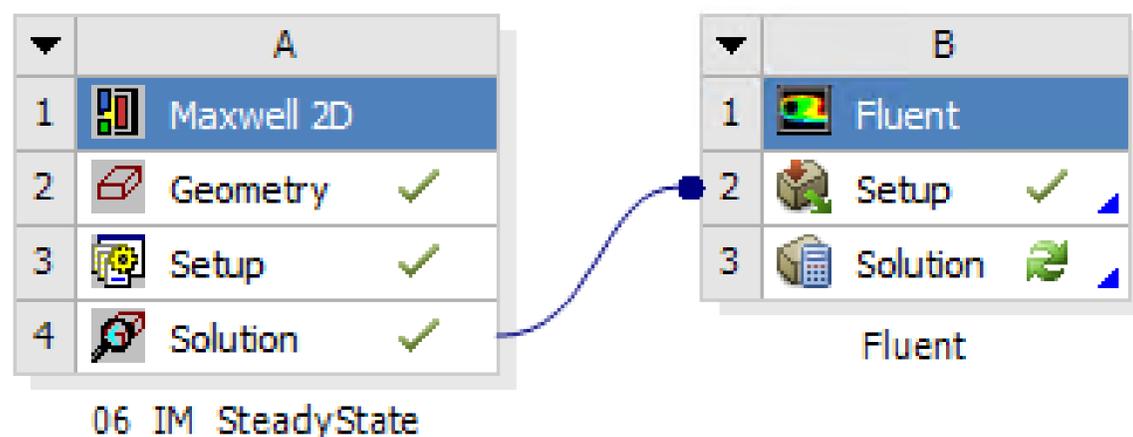
- Maxwell电磁力场结果输出用于**结构分析**:
- 定子齿尖端力,  $N/m$



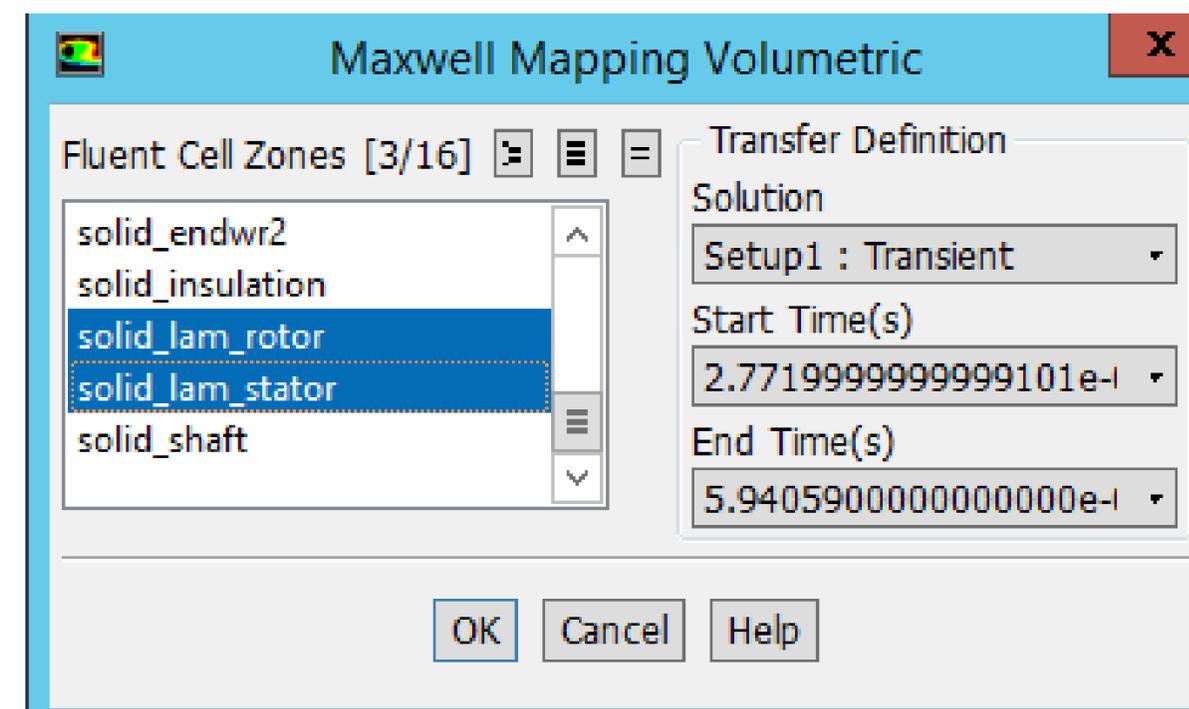
# 热源的获得：从Maxwell到Fluent

- 将体损耗由Maxwell映射给Fluent可以通过Workbench内嵌选项实现。

Workbench原理图



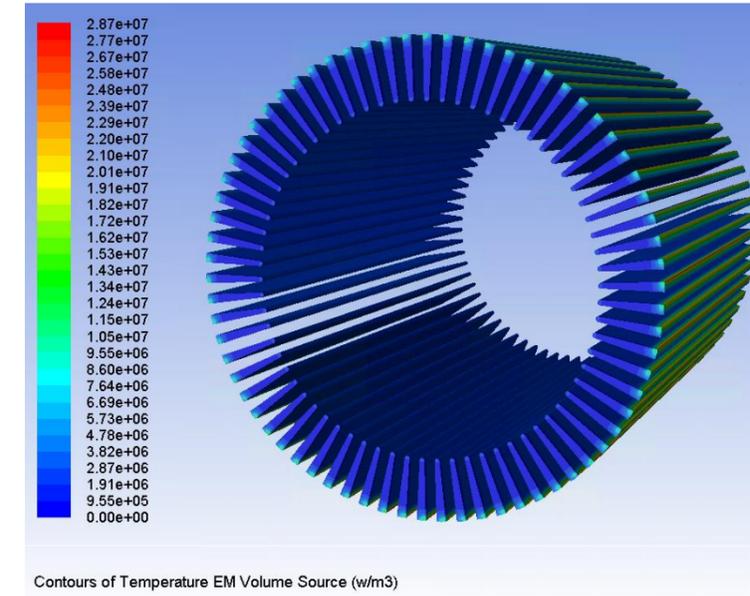
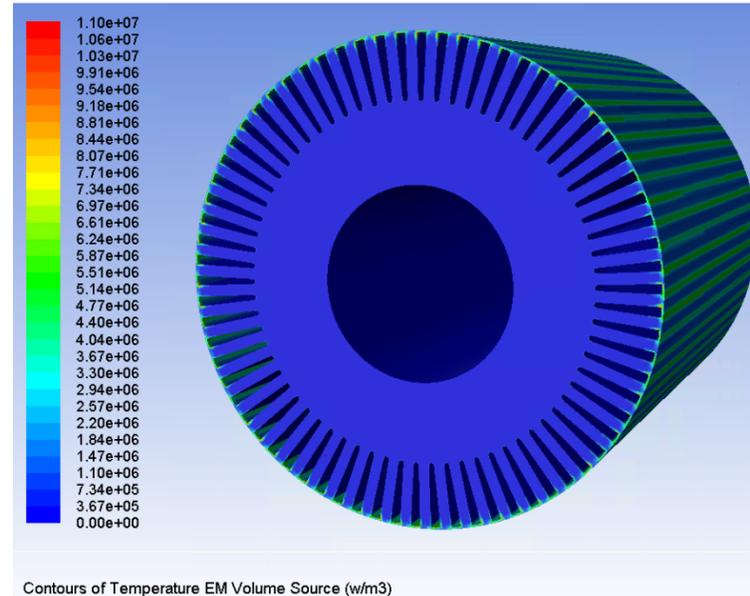
损耗(Watts)	Maxwell模型计算结果	映射入Fluent的值
定子和转子叠片 (铁心损耗)	477	497
转子铜棒 (固体损耗)	1175	1197
电磁映射损耗总量	1652	1694*
绕组损耗	2749	2749



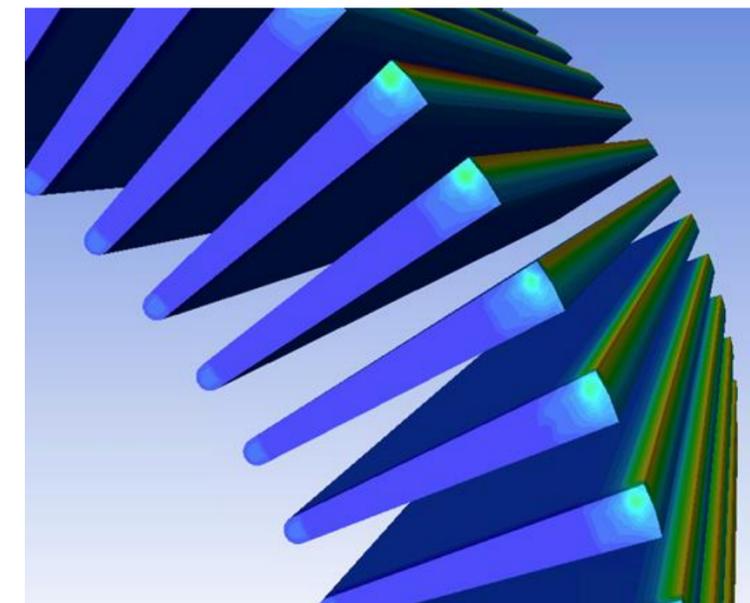
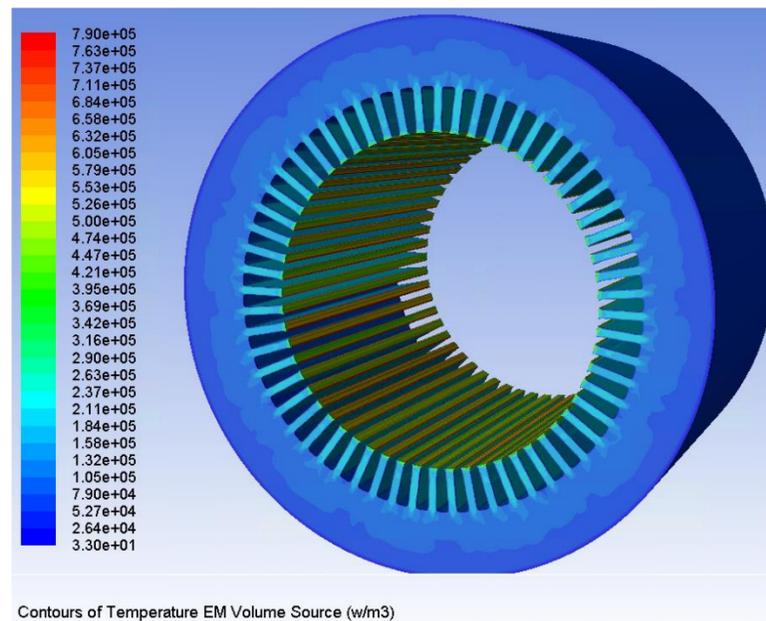
Fluent中的体映射

# 热源的获得：从Maxwell到Fluent

- 将体损耗由Maxwell映射给Fluent可以通过Workbench内嵌选项实现。

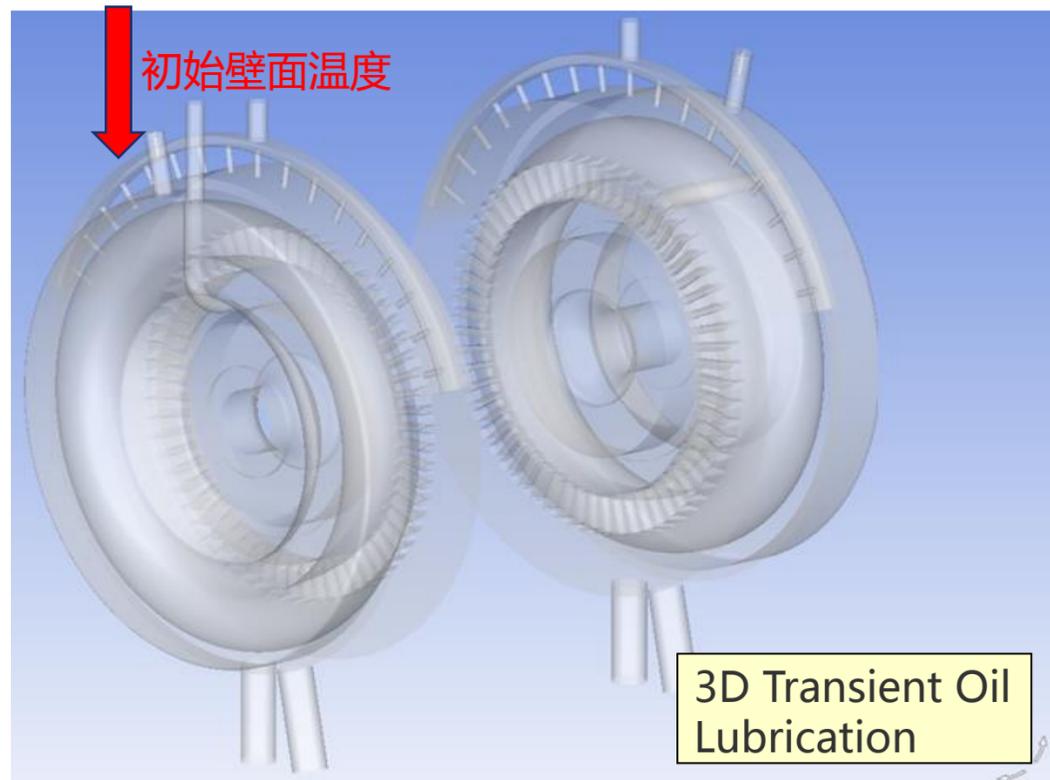


Fluent的电磁体积源云图正确显示了3D损耗的分布。

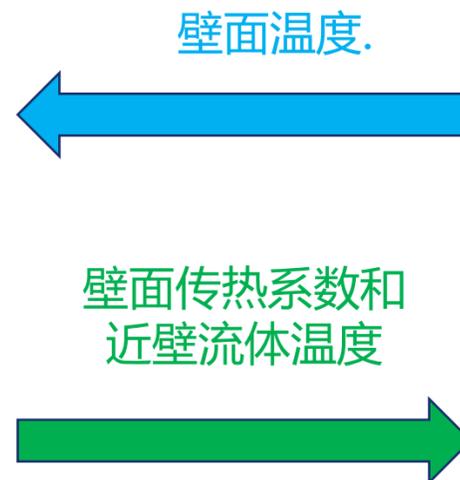
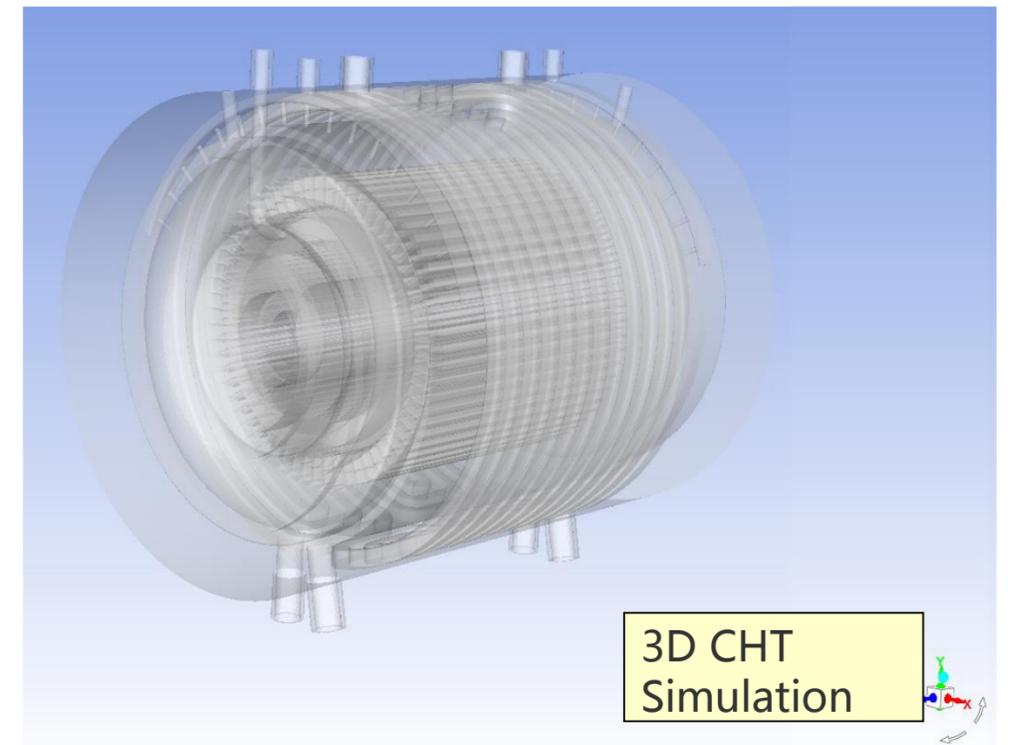


# 两种散热方式仿真：喷油冷却及水套散热

油流动模型: Multi-Phase (VOF, Air + Oil)  
(Transient)



CHT模型: Solids + Water Jacket Fluid  
(Steady State)

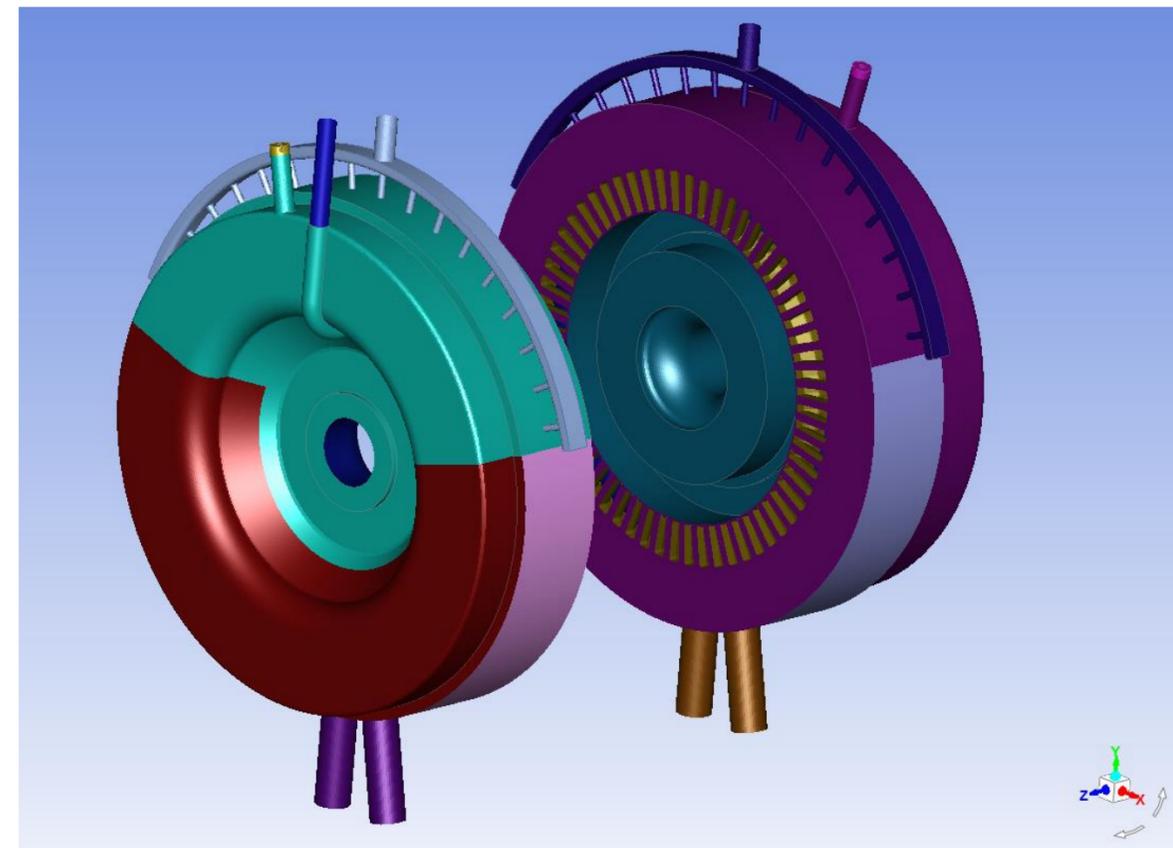
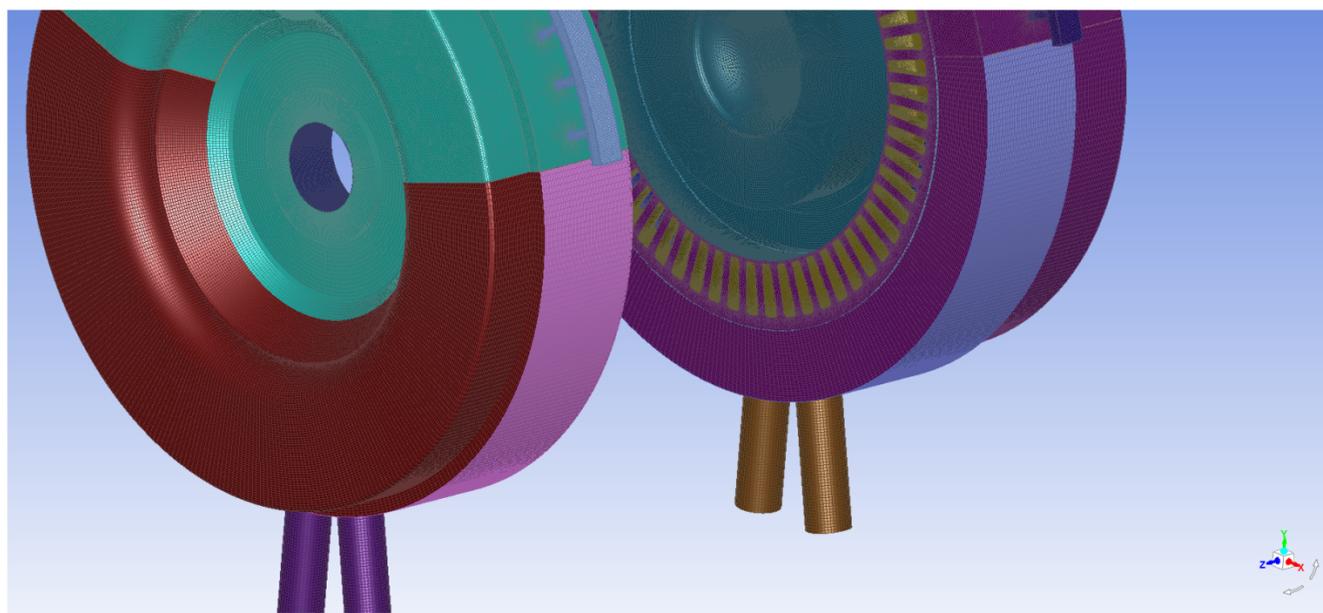
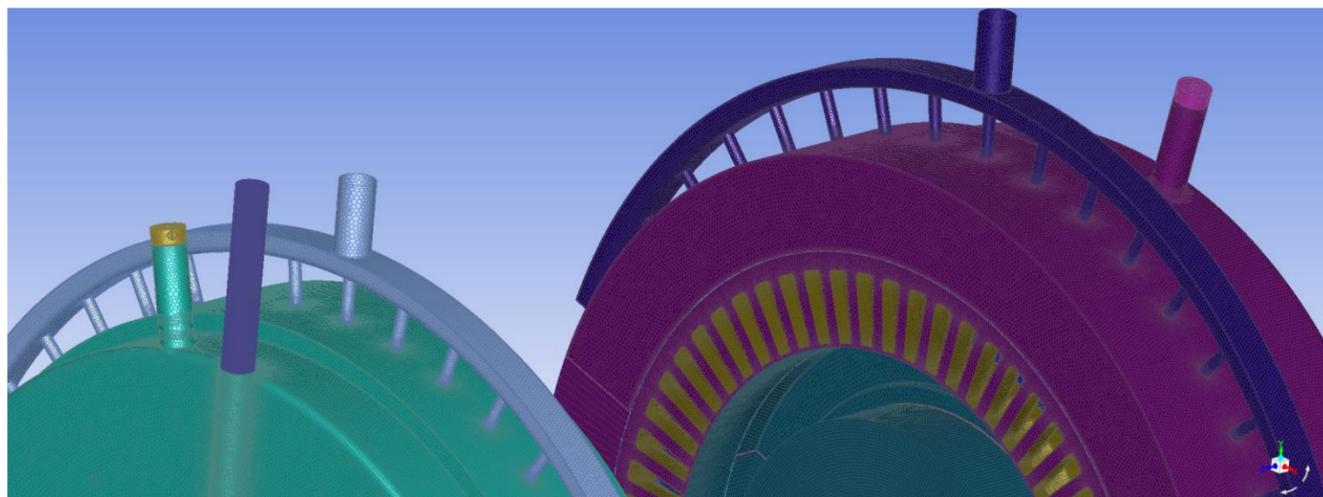


- Step 1: 假设初始状态壁面温度，进行油流动计算（瞬态）；
  - Step 2: 将壁面周期平均传热系数和近壁处流体温度作为边界条件传递给CHT模型；
  - Step 3: 计算CHT模型（稳态），将壁面温度作为新的热源边界回传给油流动模型
- 反复迭代直到油流动模型中的壁面温度不再变化

最终结果

# 网格(Mesh)

## ■ 网格：油流动模型

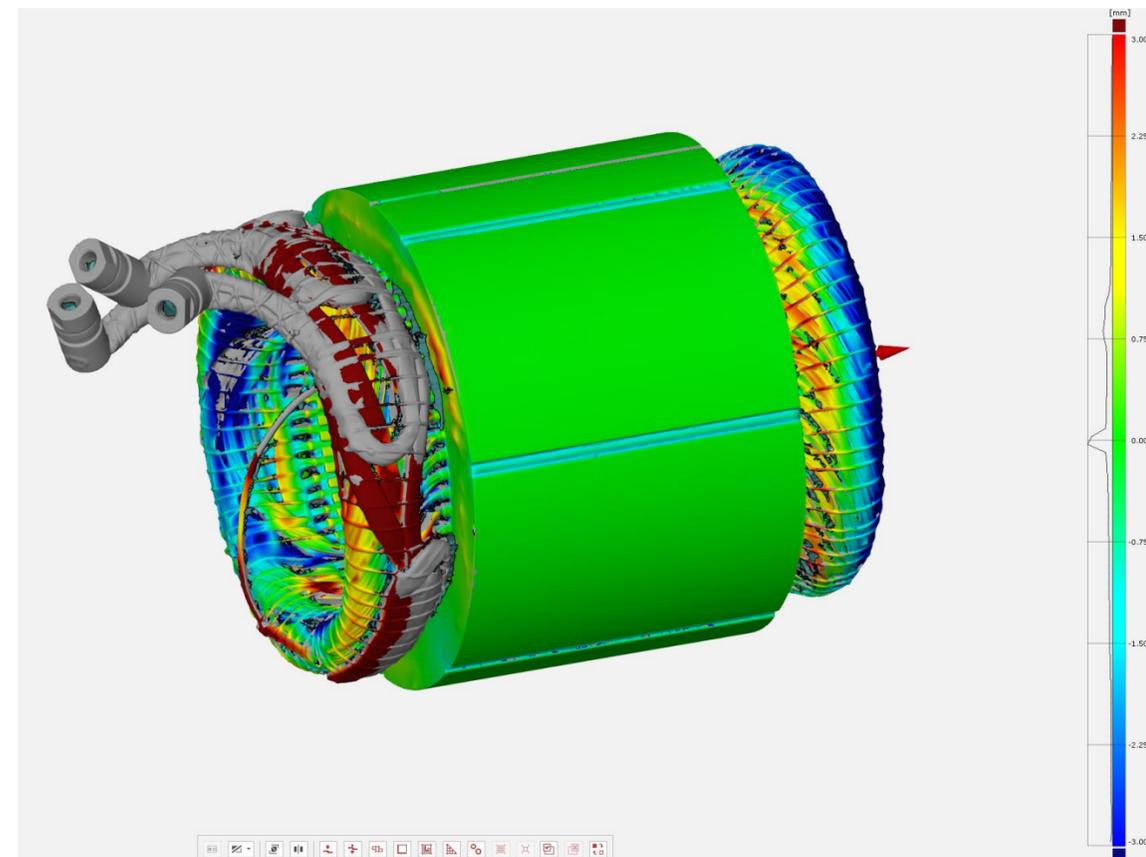
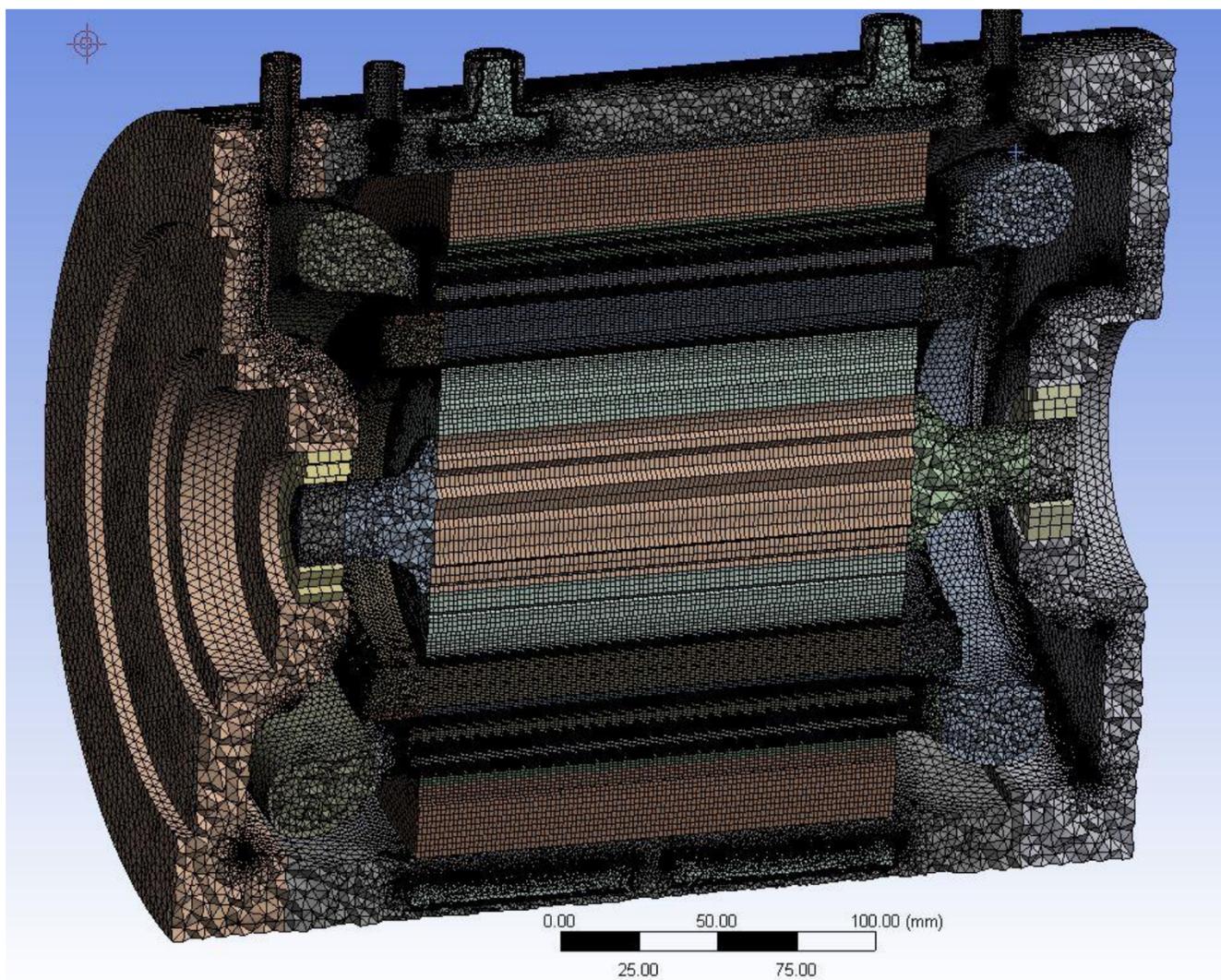


### 网格统计

- 网格数: 77M混合网格, ~19M多面体(转化后)
- Max Skewness = 0.93
- Min Orthogonal Quality = 0.15
- Max aspect ratio = 34
- 喷油打击面5层, 其他面3层
- 接触面大部分采用节点对应网格

# 网格(Mesh)

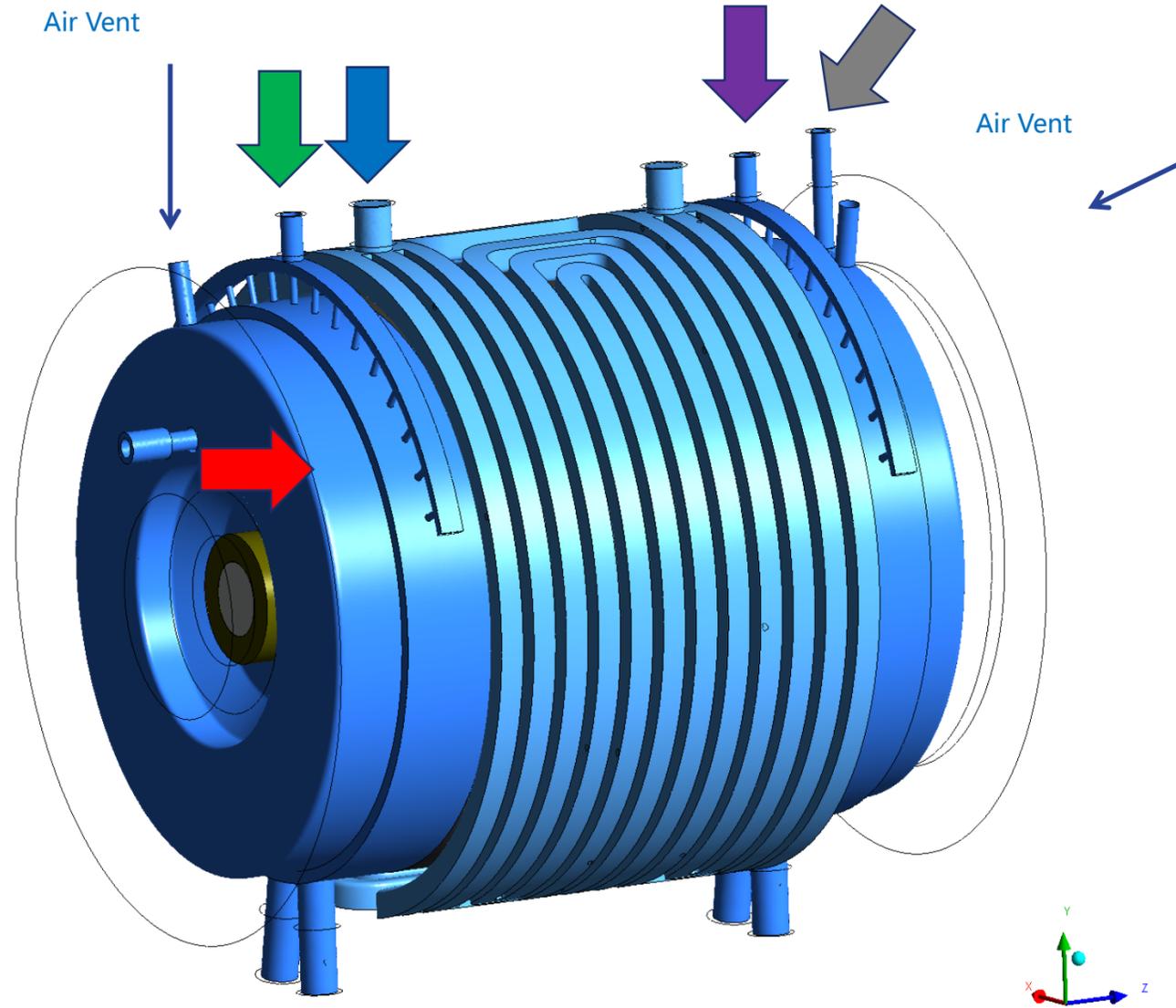
## ■ 网格：水套CHT模型



### 网格统计

- 网格数：41M混合网格, 转化为18 M多面体
- Max Skewness = 0.93
- Min Orthogonal Quality = 0.12
- Max aspect ratio = 52
- 水套内5 prism layers
- 定子/转子部位采用 hex/prism.
- 接触面大部分采用节点对应网格.
- 气隙部位设置为固体

# 边界条件



Water Jacket:  
 - 0.27 kg/s (15 Liters/min) of 50% Glycol 50 %  
 Water @ 60 C

Oil to the Top of the Drive Side:  
 - 0.45 Gallons/min @ 60C

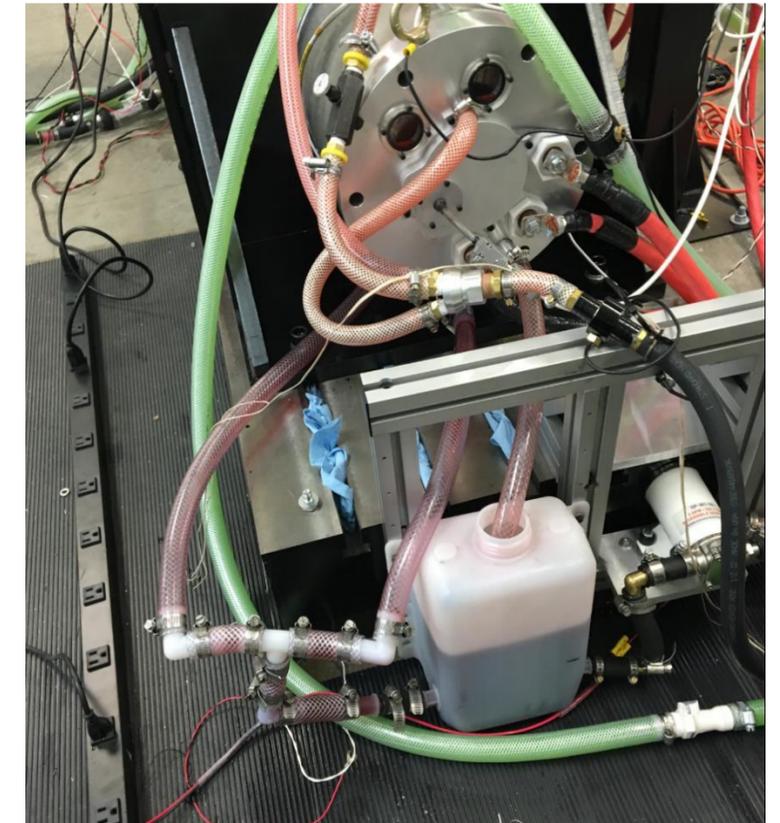
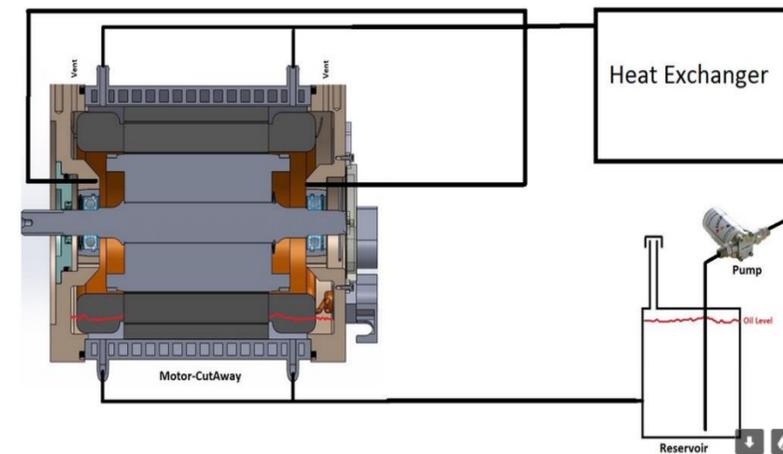
Oil to the Rotor on the Drive Side:  
 - 0.8 Gallons/min @ 60 C

Oil to the Top of the Non-Drive Side:  
 - 0.45 Gallons/min @ 60C

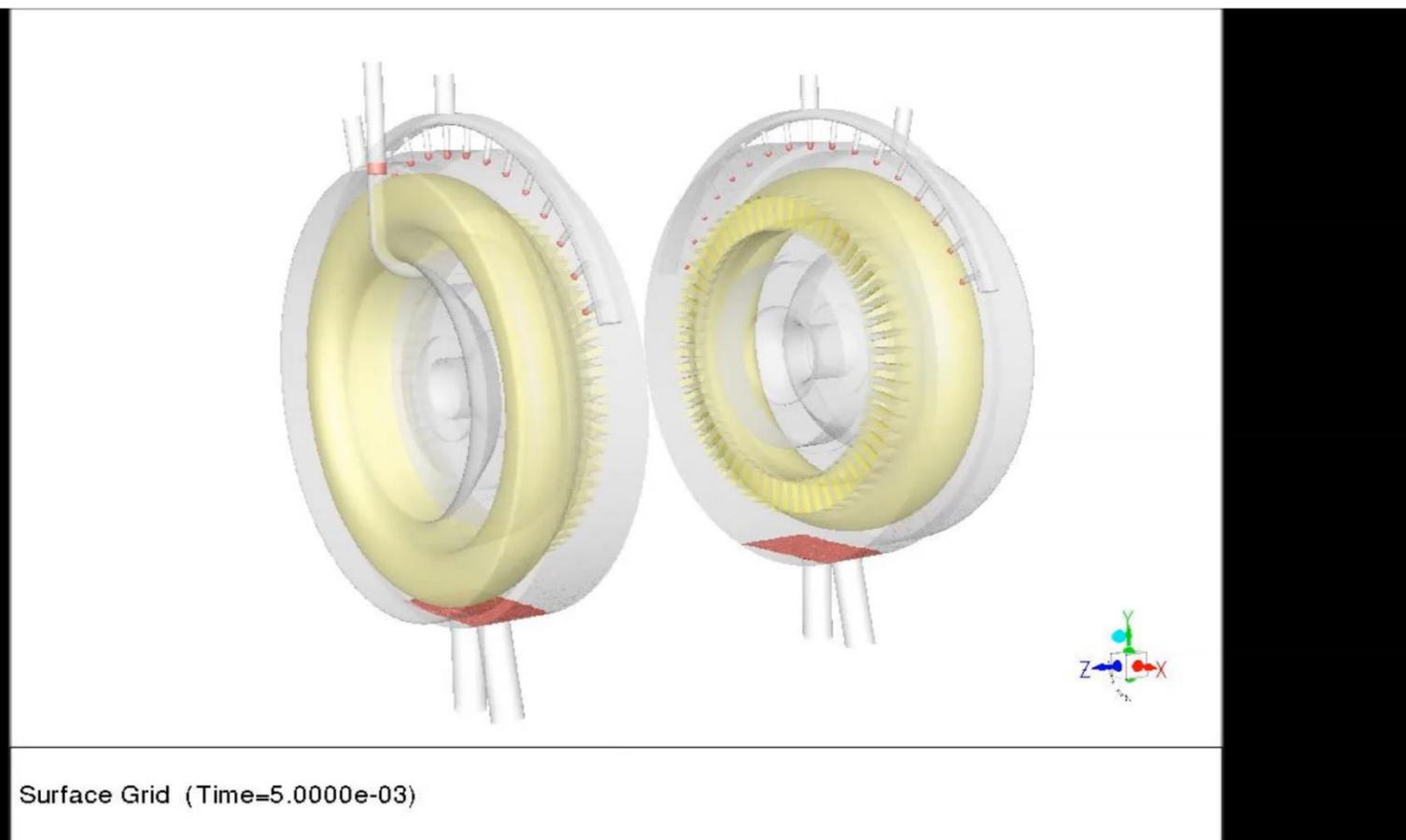
Oil to the Rotor on the Non-Drive Side:  
 - 0.65 Gallons/min @ 60 C

其他热边界条件:

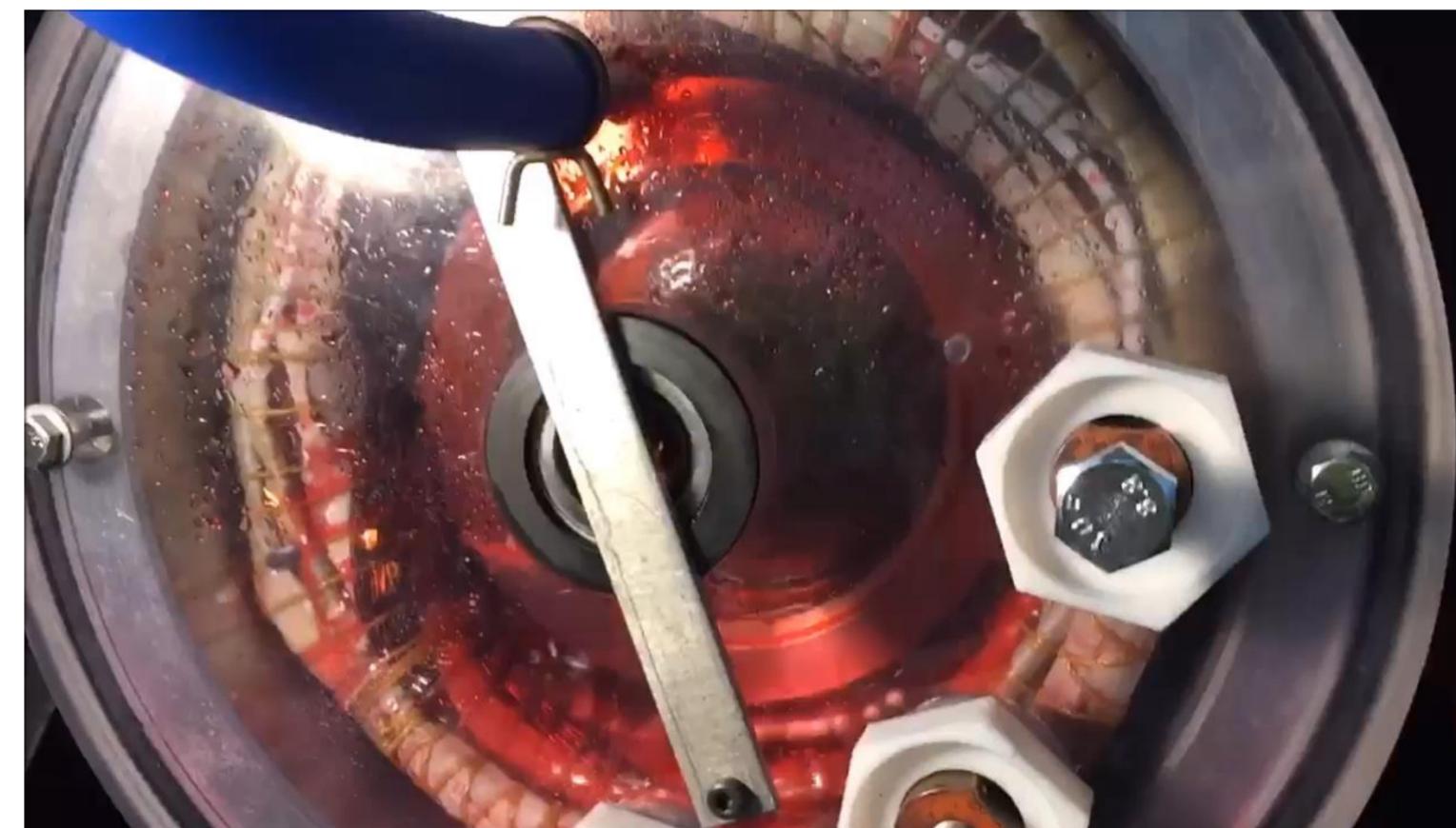
环境温度 25 C, 传热系数  $6 \text{ W/m}^2\cdot\text{K}$  ( wall-case, 右侧壁面、轴和轴承 )



# 仿真结果



润滑油流动仿真结果动画  
(VOF 0.1 Iso-Surface, 0 - 0.5s)

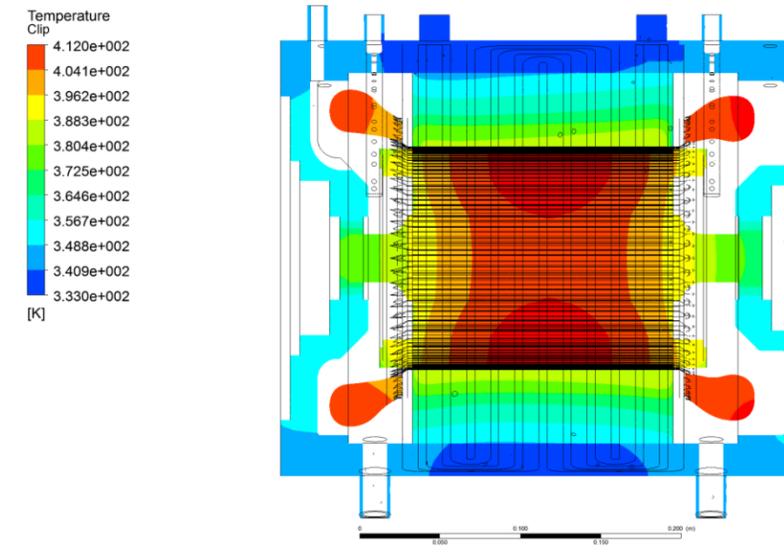
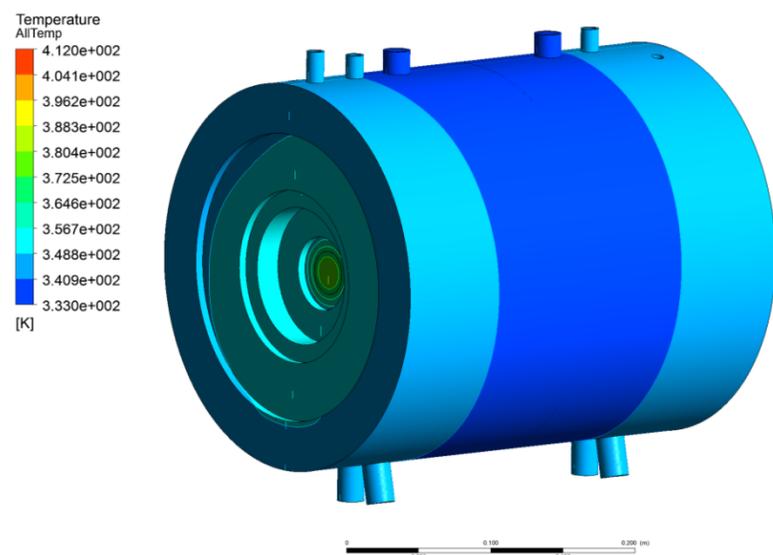


试验中油的喷射流动 @ 90C

# 仿真结果

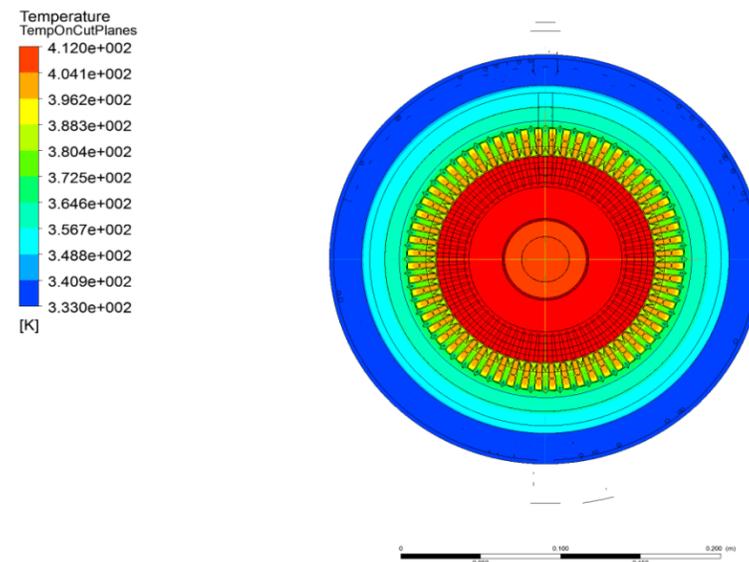
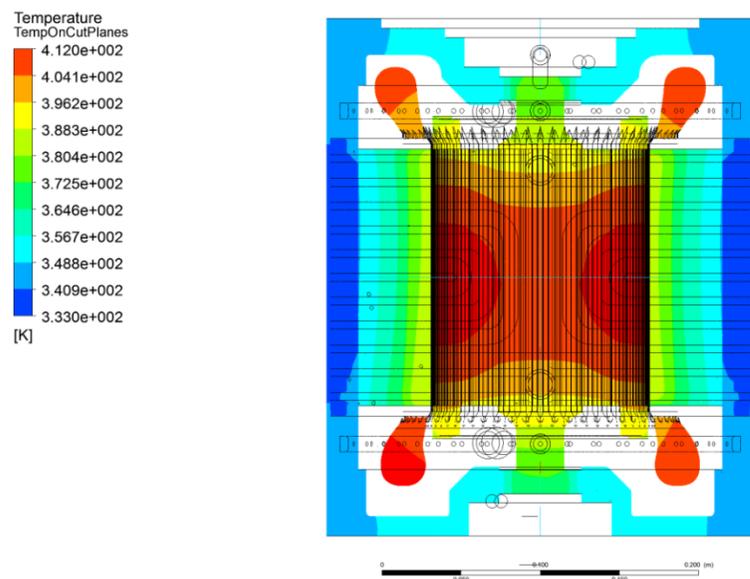
■ CHT模拟结果：结果取自五次映射迭代之后

Iso Global View



Lateral Cut View

Top Cut View

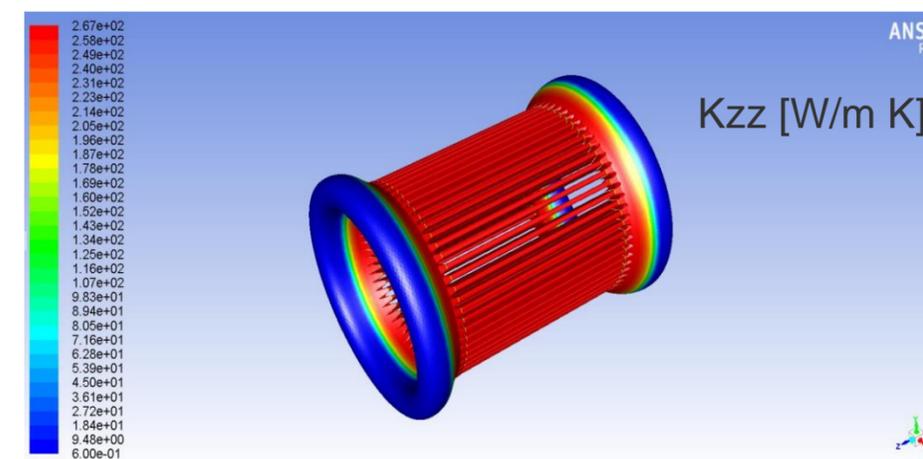
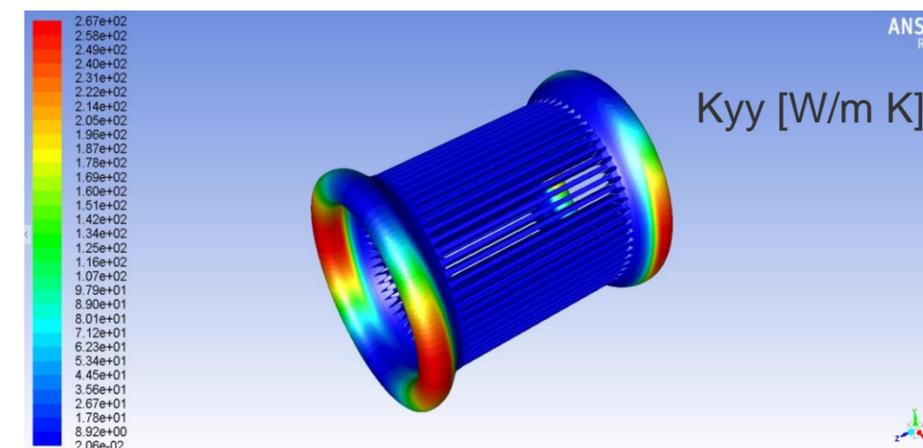
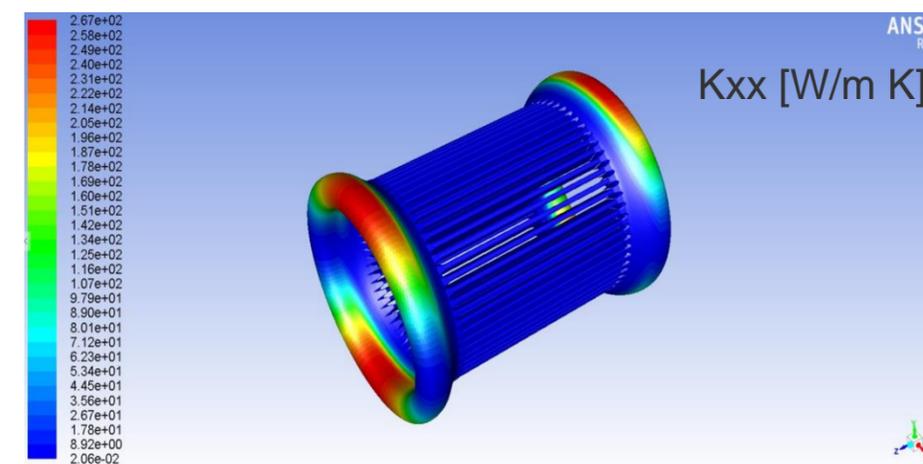
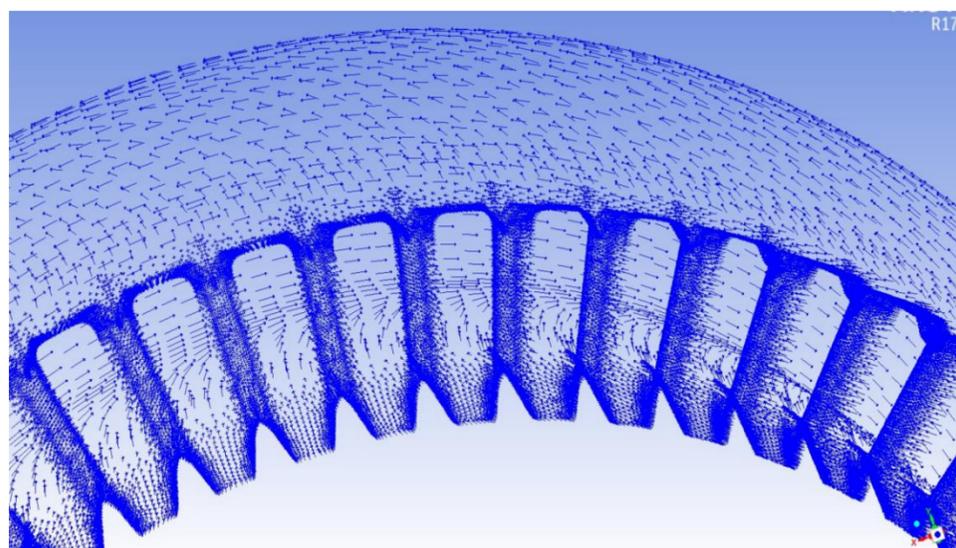


Axial Cut View

# 仿真结果

- 使用UDF定义定子和端部绕组各向异性导热系数

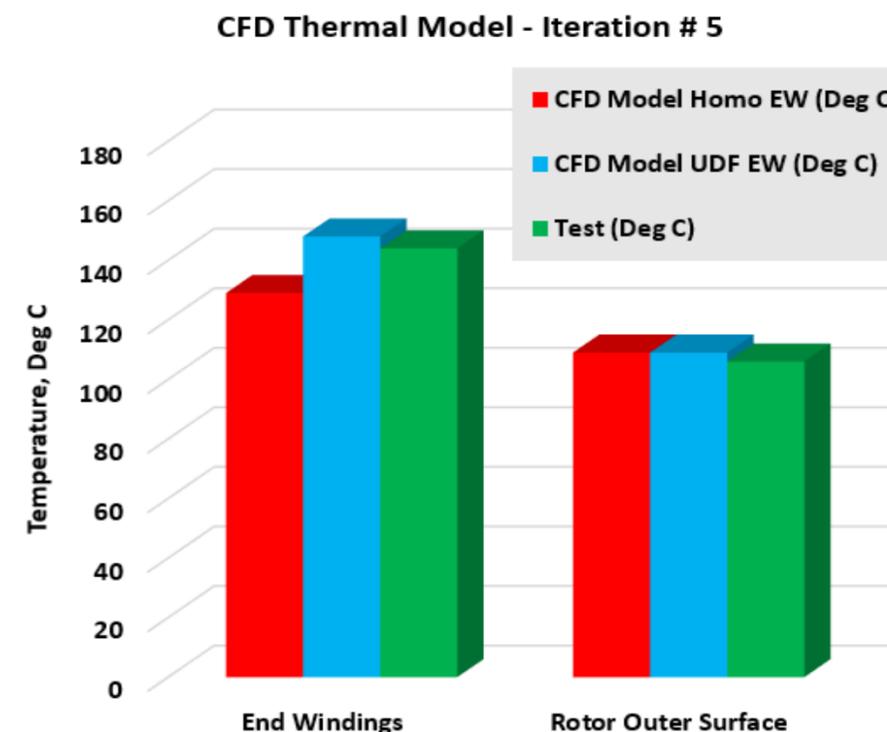
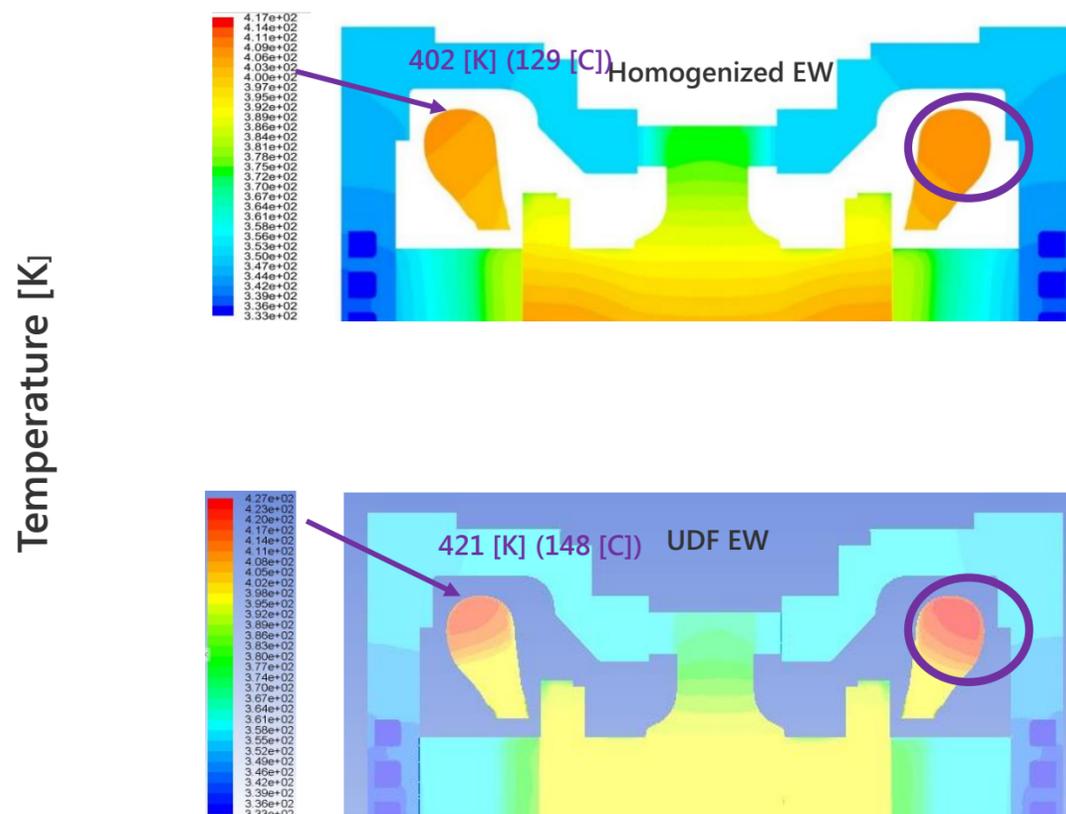
绕组主要方向



# 结果对比

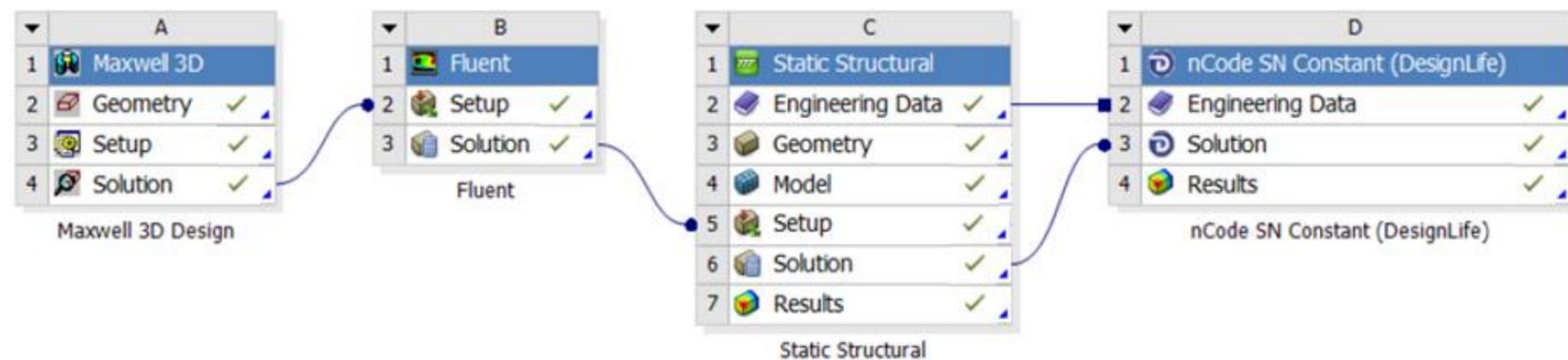
## ■ CHT模拟结果：试验结果 Vs 不同导热系数设置(各向同性/异性)

Wall Temperature	Test (Deg C)	CFD Model Homo EW (Deg C)	CFD Model UDF EW (Deg C)	CFD Model Homo EW Error %	CFD Model UDF EW Error %
Steady state winding temp	144	129	148	-10.42	2.78
Steady state rotor temp	106	109	109	2.83	2.83

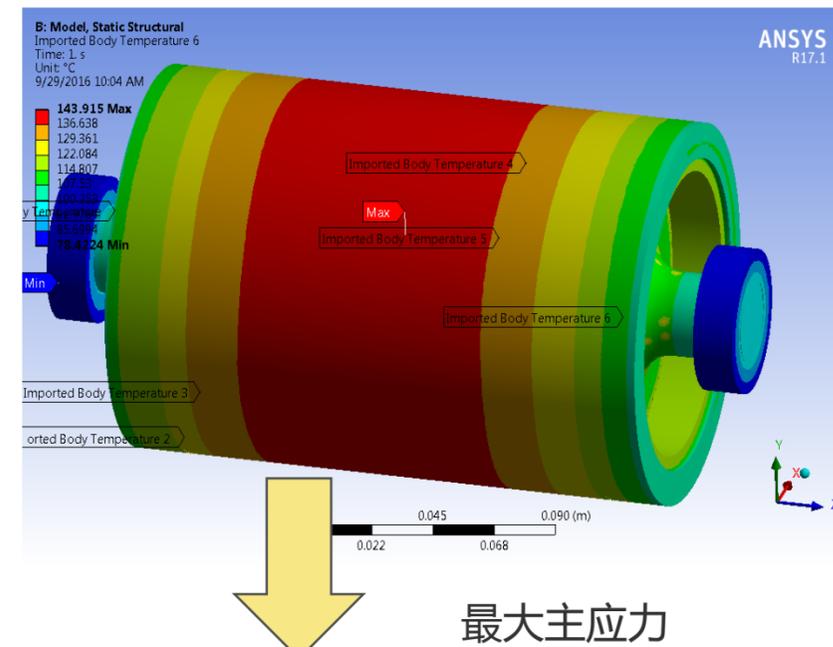


# 转子应力/疲劳计算

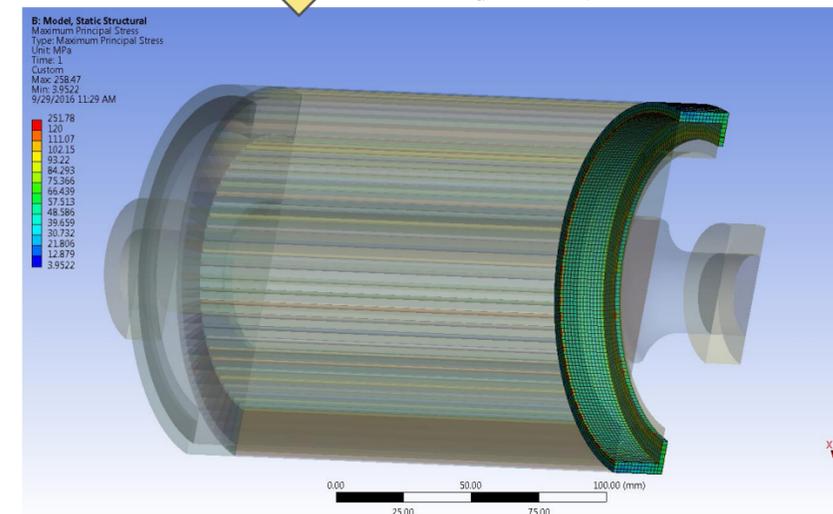
- CHT计算出的最终温度结果被映射到转子上以预测其遏制环的应力和疲劳寿命。



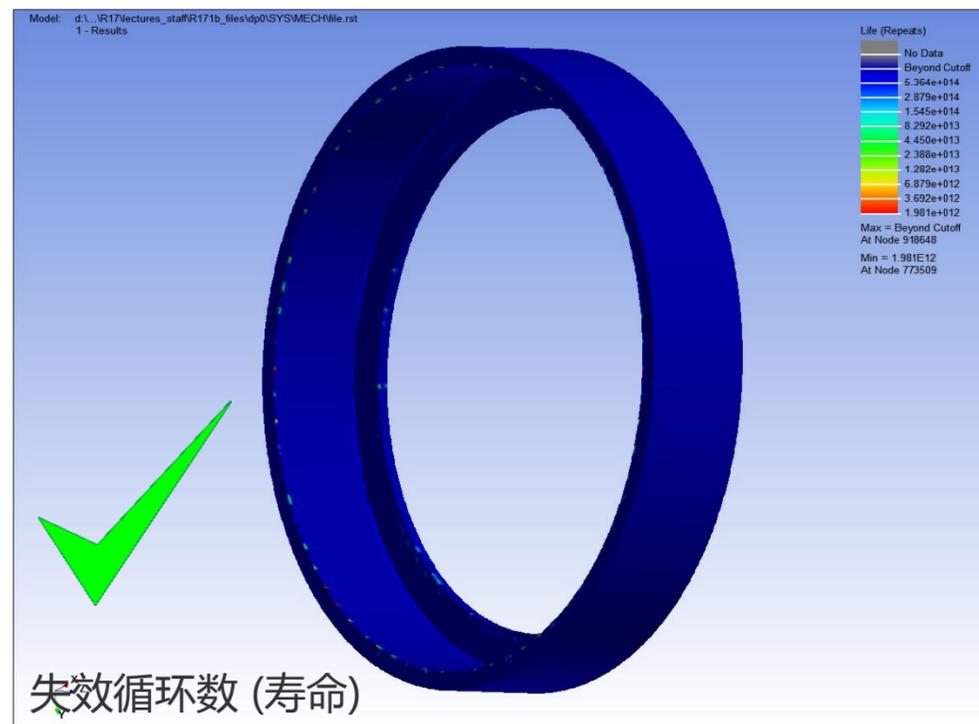
固体温度来自CFD结果的映射



最大主应力



疲劳寿命  
(nCode)

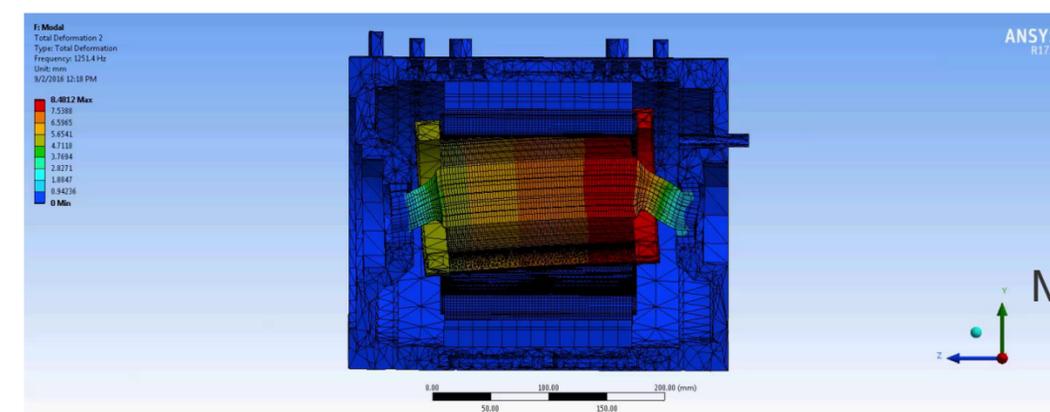
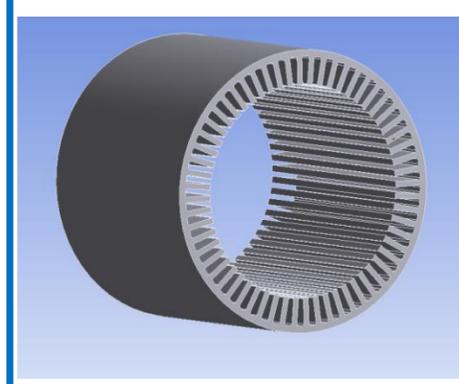
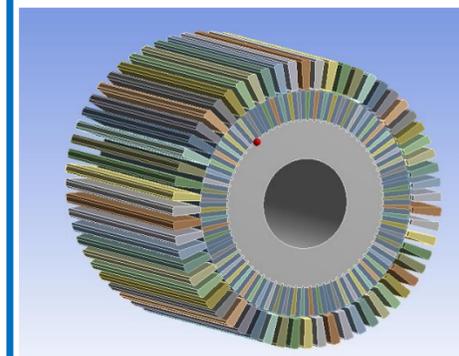
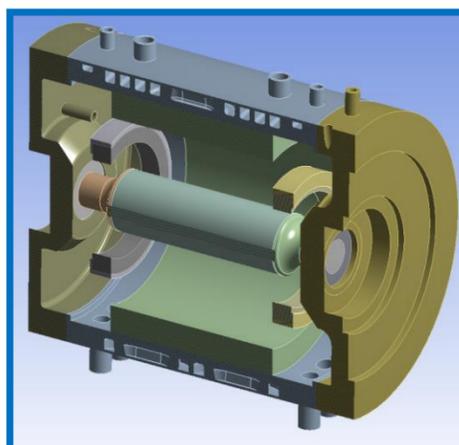
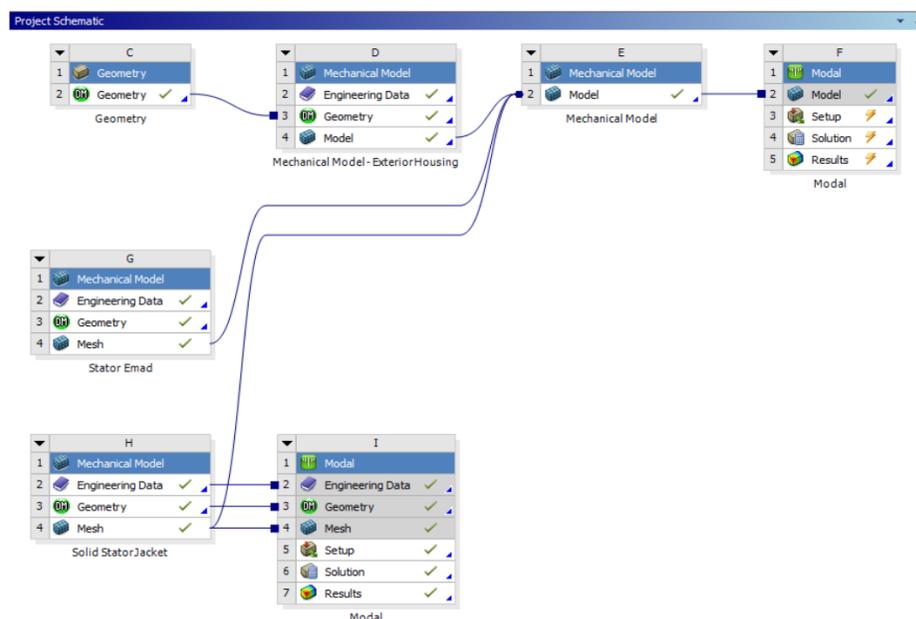


失效循环数 (寿命)

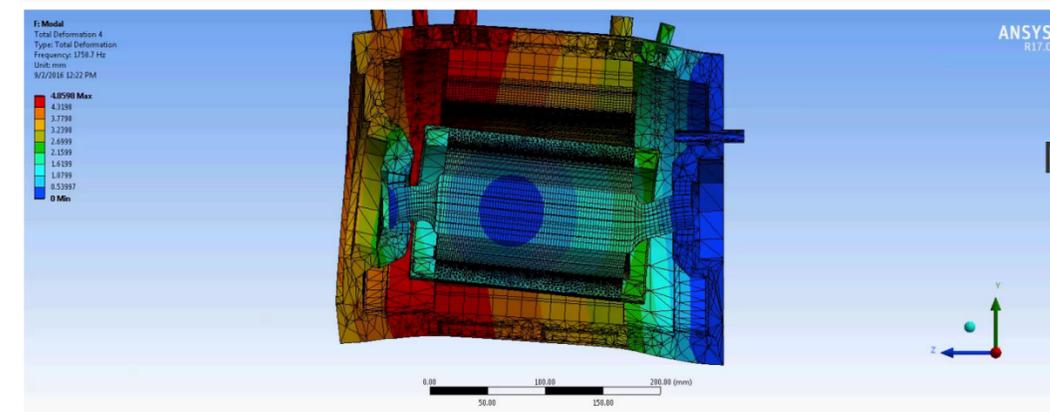
# 模态及谐分析

## ■ 使用Assembly modeler来创建全电机可管理模态模型

模态形状和频率

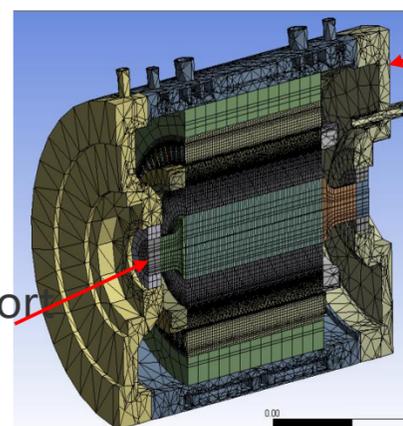


Mode 2 – 1250 Hz

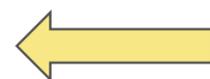


Mode 4 – 1650 Hz

1.3m nodes



Fixed Support

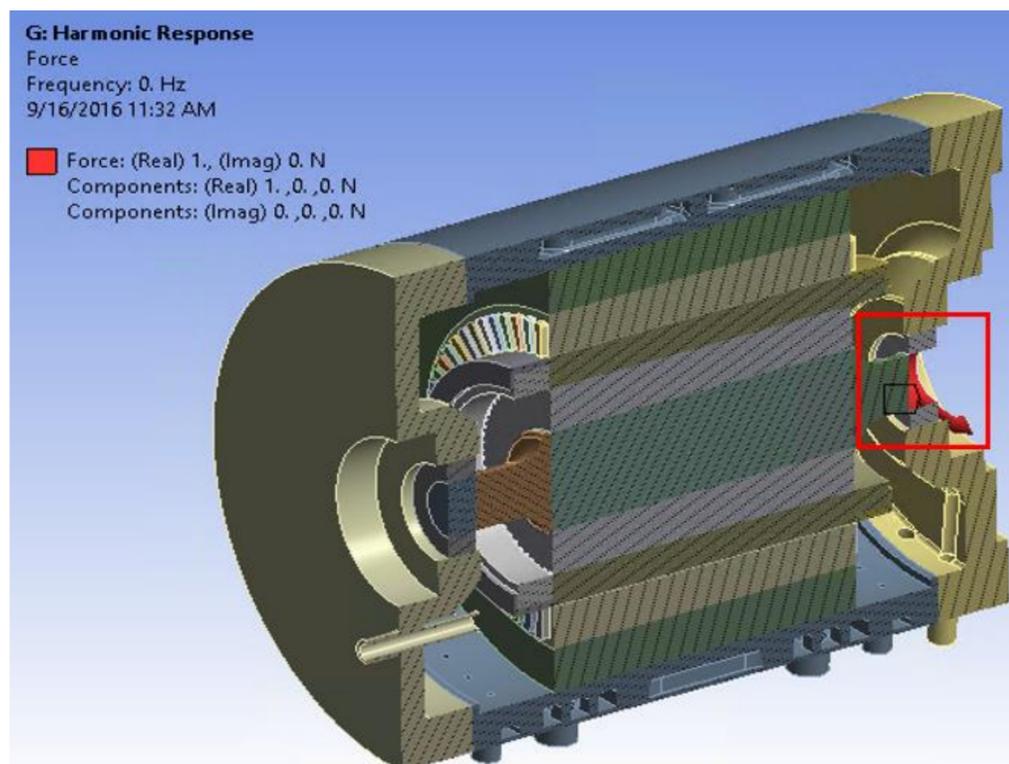
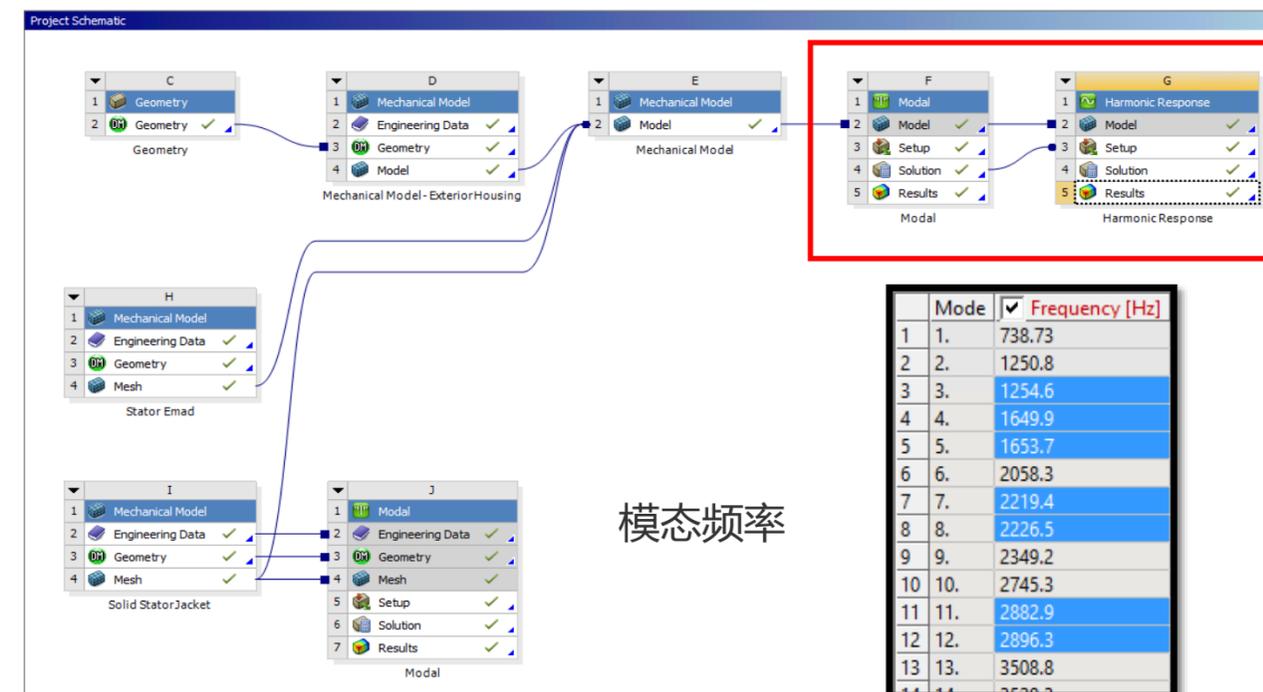


Fixed Support

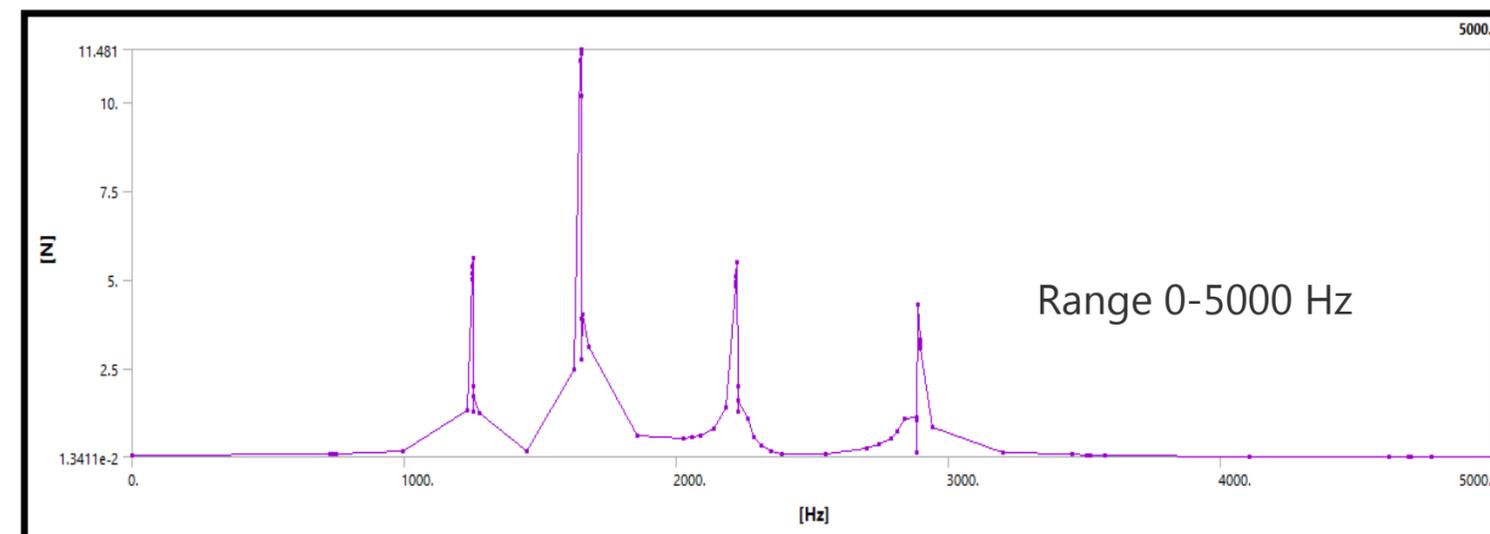
	Mode	<input checked="" type="checkbox"/> Frequency [Hz]
1	1.	738.73
2	2.	1250.8
3	3.	1254.6
4	4.	1649.9
5	5.	1653.7
6	6.	2058.3

# 模态及谐分析

- 采用模态叠加法-谐响应分析；
- 在后盖和轴端固定支撑，轴承受不平衡力；
- 谐波响应与结构的模态频率一致。



后盖受力 (固定支架)



# 目录

1. 新能源汽车电机研发关注的问题及其多物理场特性
2. ANSYS新能源汽车电机多物理场仿真的解决方案
3. 电机仿真案例介绍
4. 小结

## 小 结

- **ANSYS**产品具备新能源汽车动力电机性能分析所需的多物理场耦合解决方案。
- **IDAJ**在汽车行业深耕多年，将与ANSYS携手为您提供高水平的专业仿真软件和一流的技术服务，期待与您的进一步合作。

感谢倾听  
期待与您的进一步合作 😊



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