Superconducting Motor

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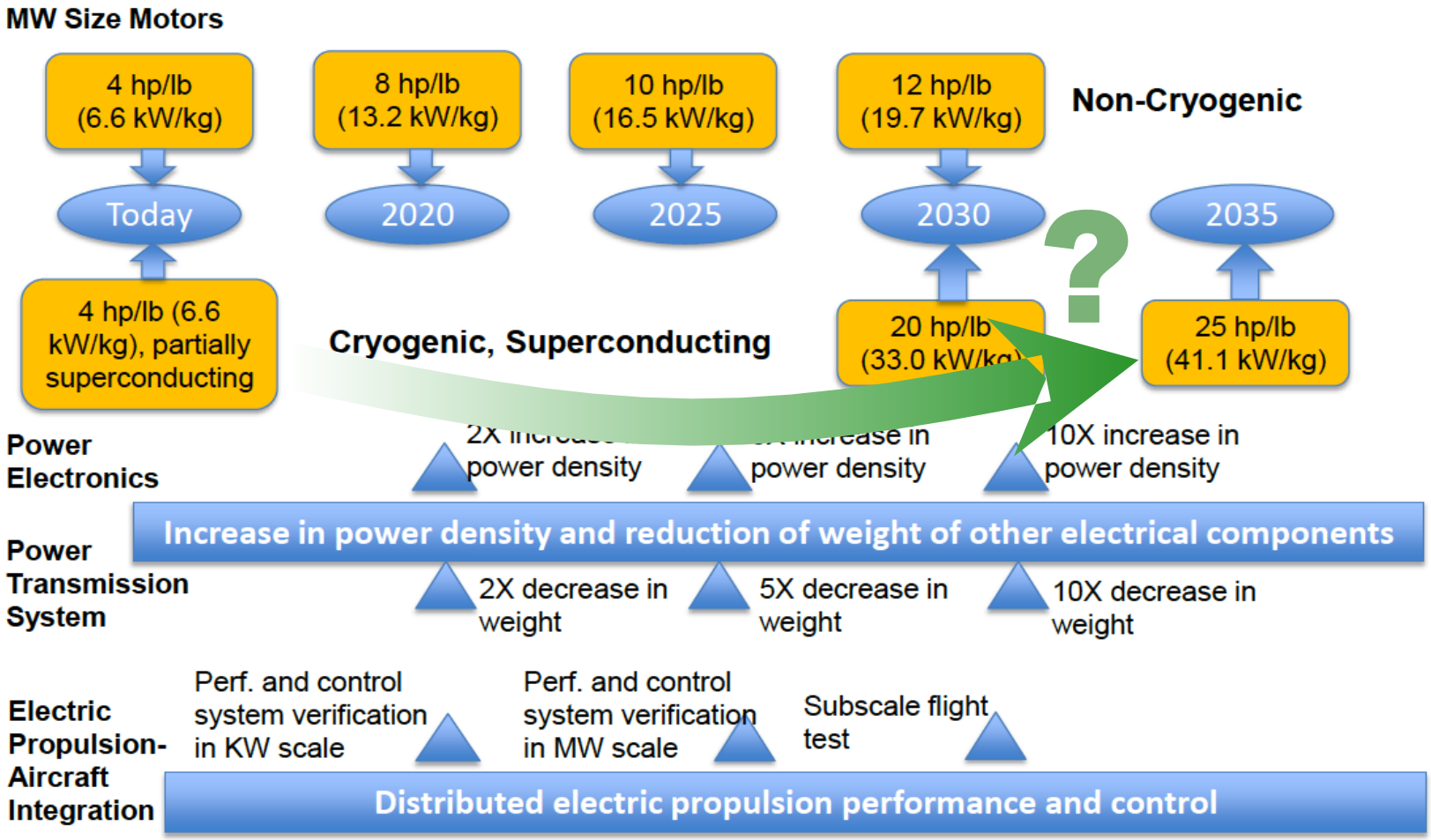
NASA FW/AATT HEP Technology Roadmap



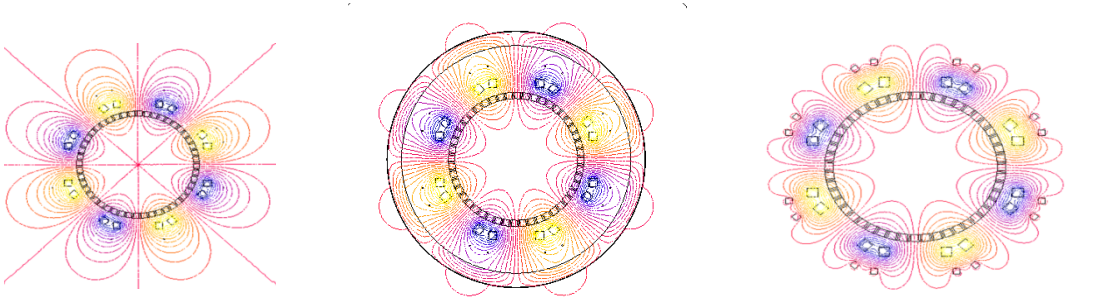
N. Madavan, September 2014

Fixed Wing Project
Fundamental Aeronautics Program

Approach

NASA LEARN Phase 1: Establish feasibility of superconducting motor with:

- Stationary field winding assembly to utilize MRI technology
- Explore peak fields up to 10T
- High field superconductor (e.g. Nb_3Sn)
- Active magnetic shield to eliminate field outside while maximizing ”air gap” flux density



Unshielded With passive shielding With active shielding

Key Technical Questions

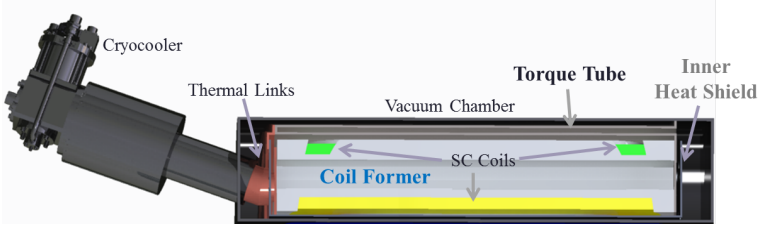
High field SC coils
- racetrack coils, stability, current ramps, quench protection

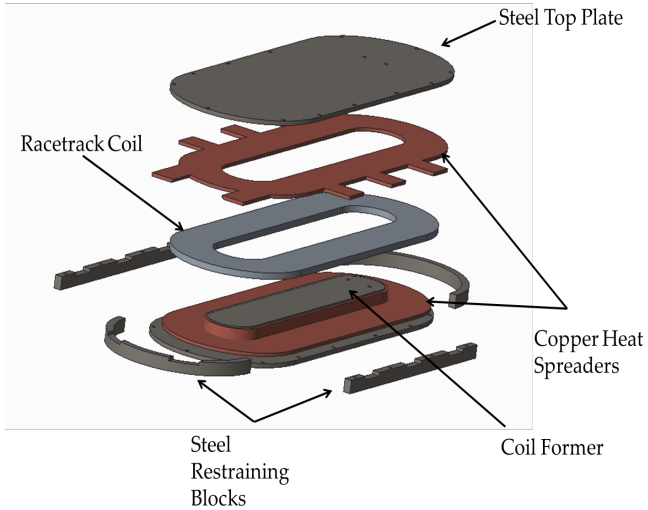
Cryogenic Thermal Management System
- heat loads, reliability, cryogen free systems

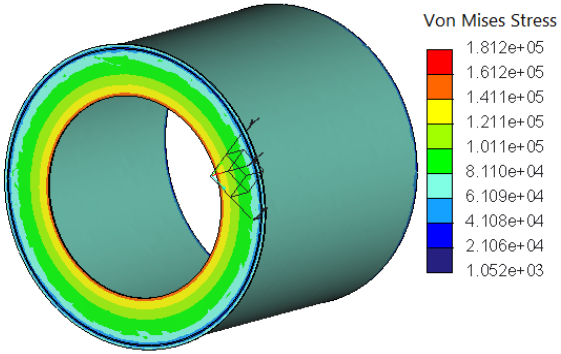
Structural integrity
- higher internal stresses, suspension system

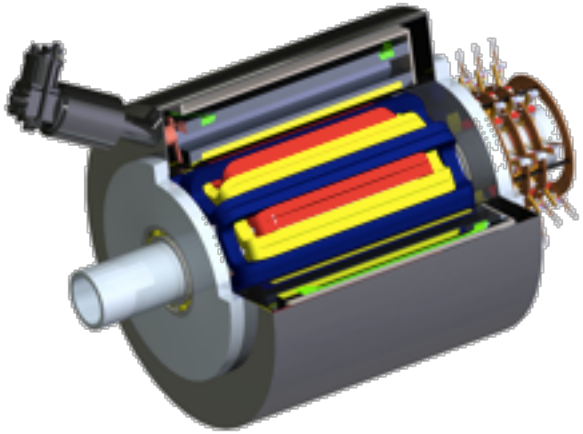
Motor Power Density
- overall motor configuration, auxiliaries, “conventional” components

Concept Design

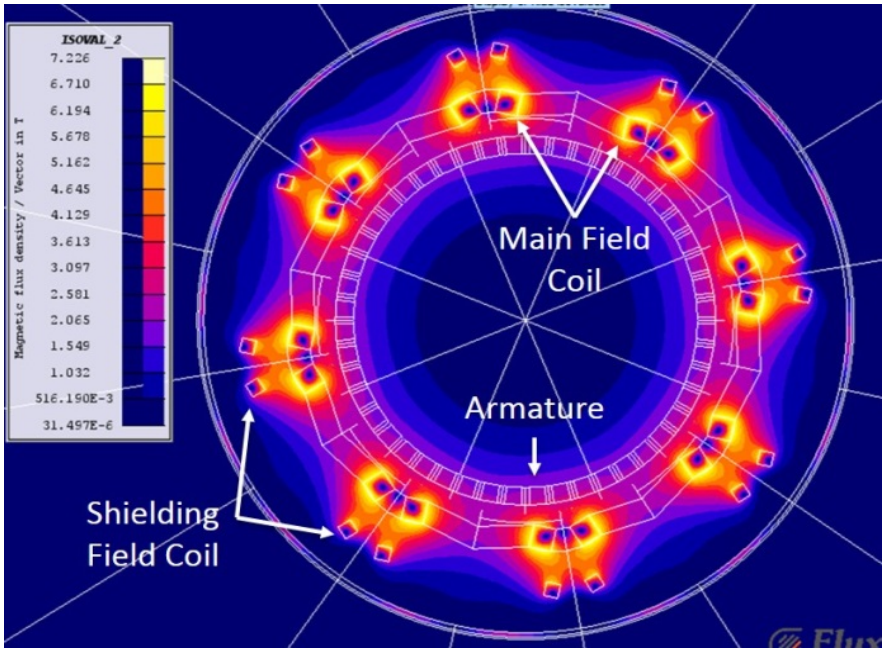




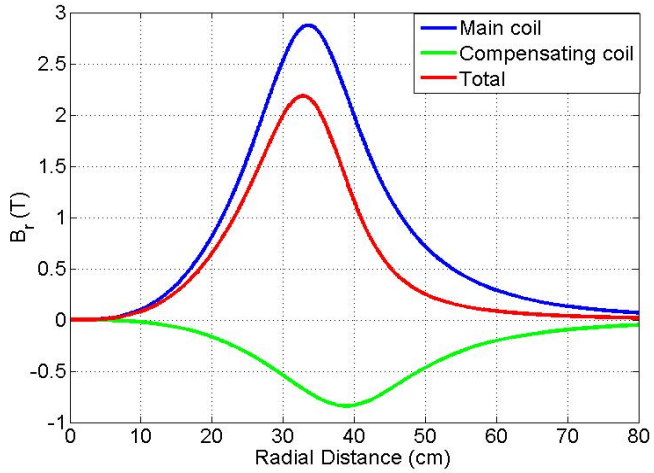




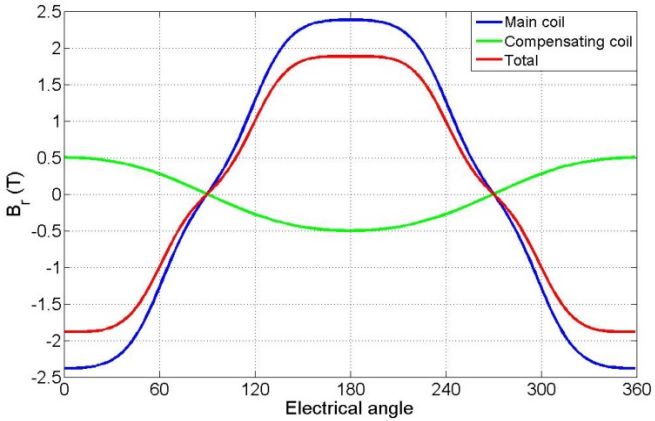
Electromagnetics



Magnetic field in cross-section of active region

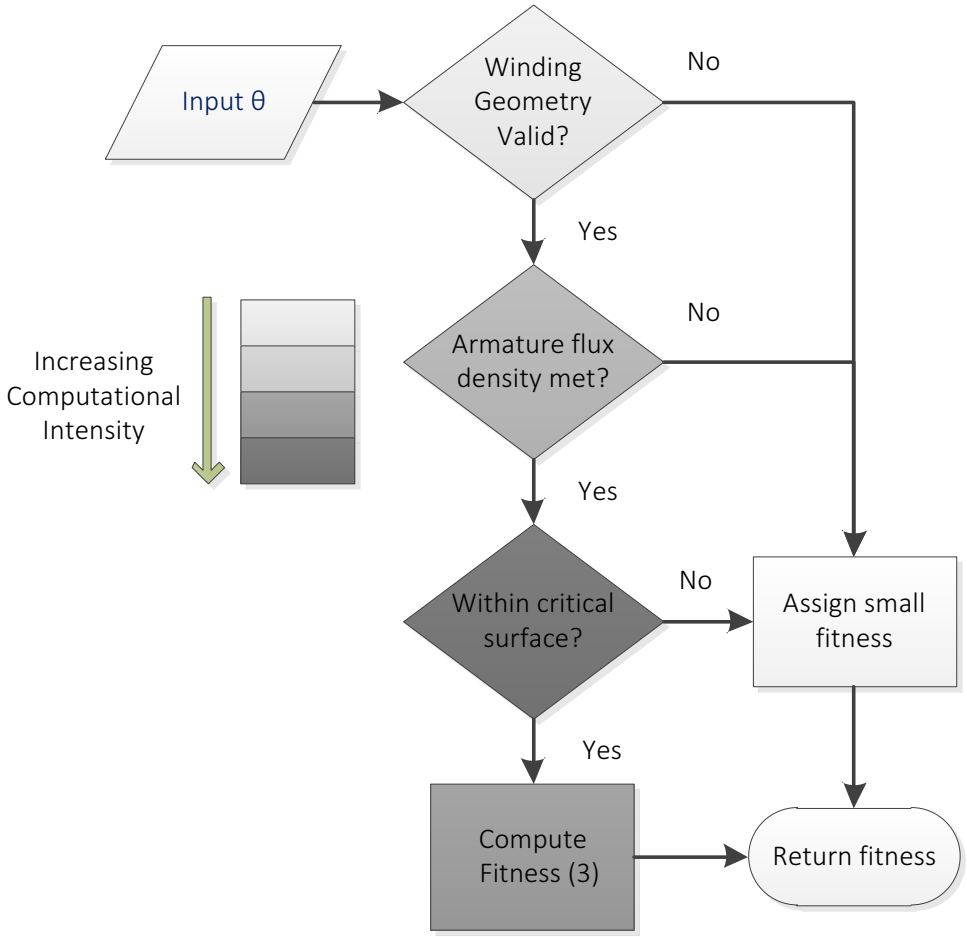


Radial Flux Density along D-axis



Radial Flux Density at Armature

Multi-Objective Optimization

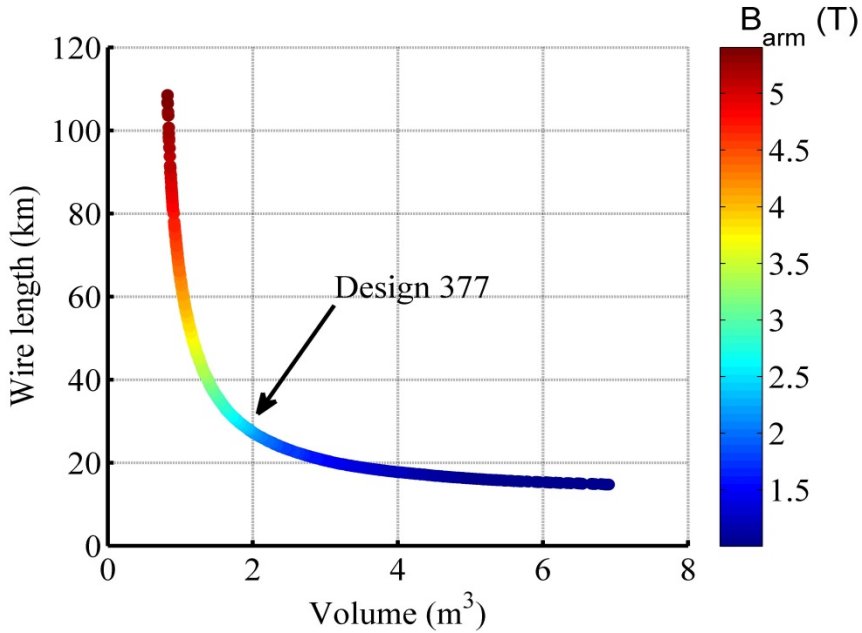


Fitness Formulation for Genetic Algorithm[1]

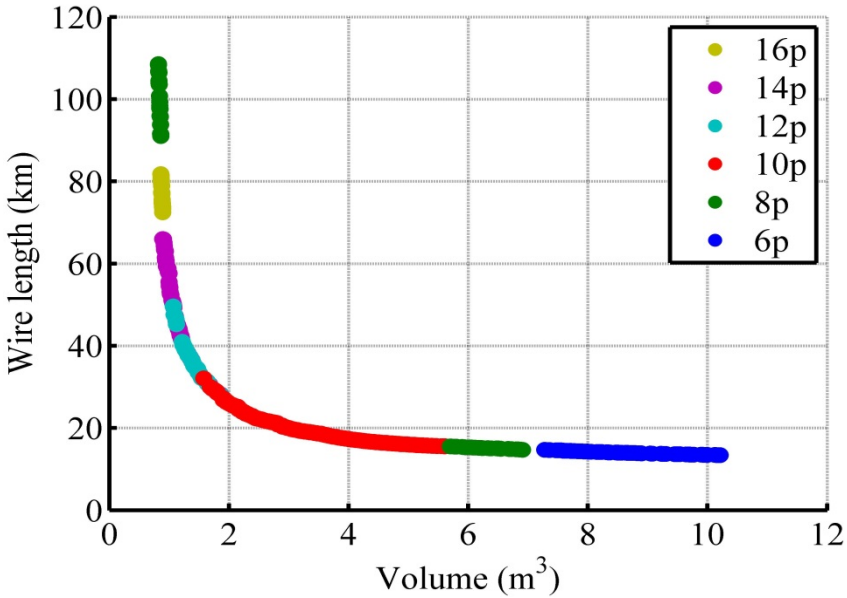
- Impose constraints on candidate designs
  - Limit Design Space
  - Critical Surface
- Define fitness vector to:
  - Maximize Volumetric Power Density
  - Minimize Superconductor
  - Minimize Far Field
- Fitness function -> Genetic Algorithm

1. S.D. Sudhoff. *Power Magnetic Devices: A Multi-Objective Design Approach.* Hoboken, New Jersey: Wiley, 2014.

Results



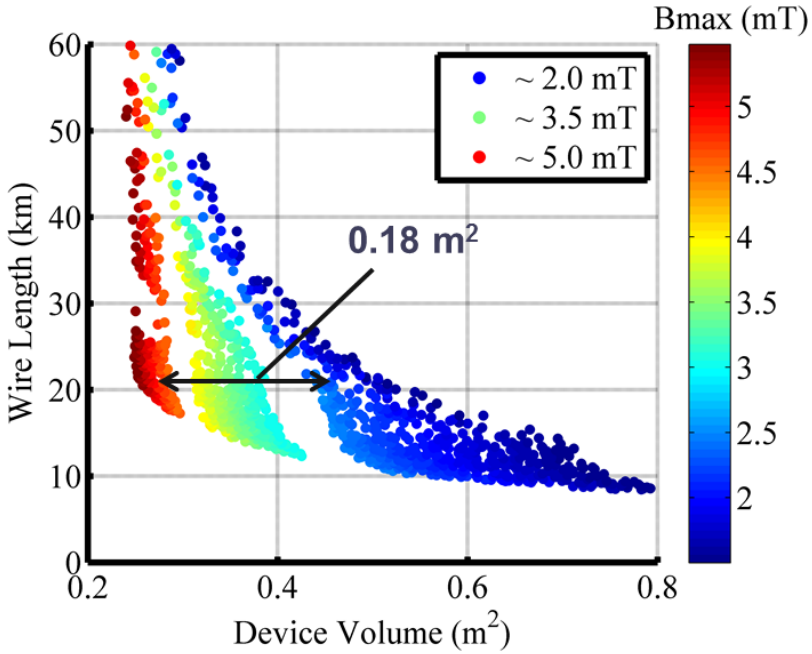
Pareto-Optimal Front for 8 pole designs



Aggregated Pareto-Optimal Front
Pole Counts 6-18 included

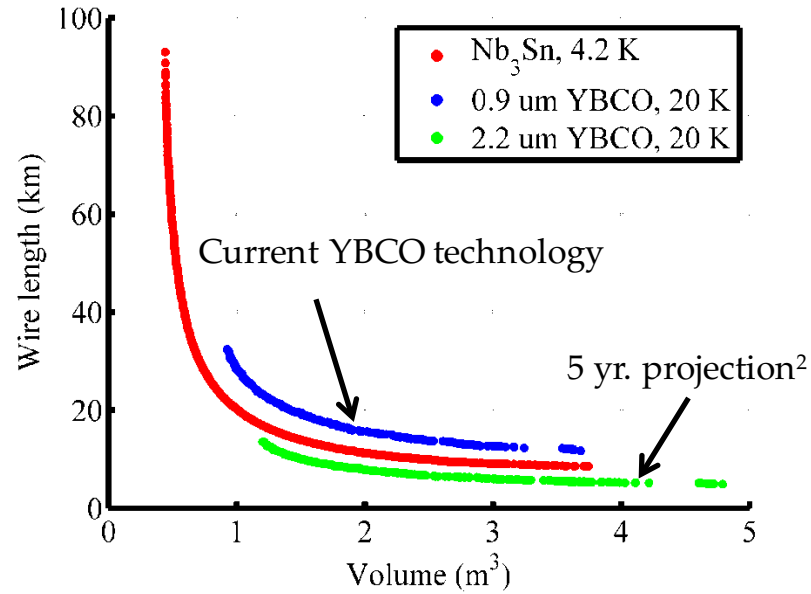
- External Field Requirement: 0.5 mT (MRI Industry)
- High Armature Flux Density Achievable (> 5 T)
- Pole Counts > 8 yield minimal improvement

Field Requirement and HTS



External Field Requirement Study

-Up to 0.18 m^3 (40%) reduction in machine size

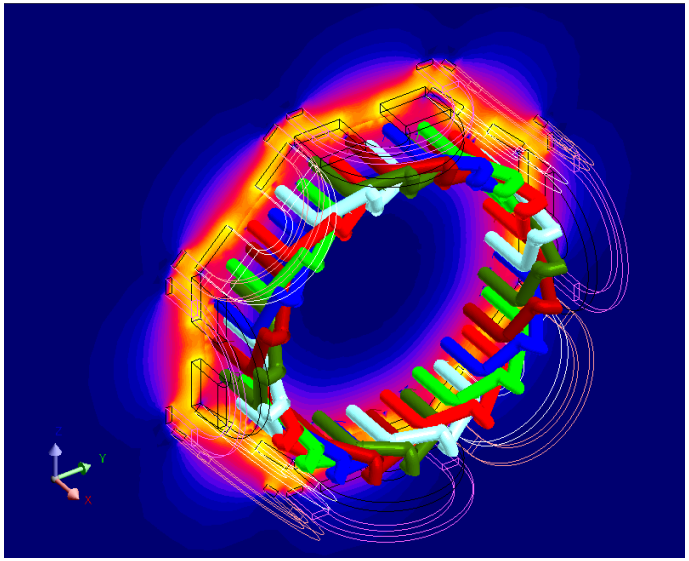


Comparison with YBCO

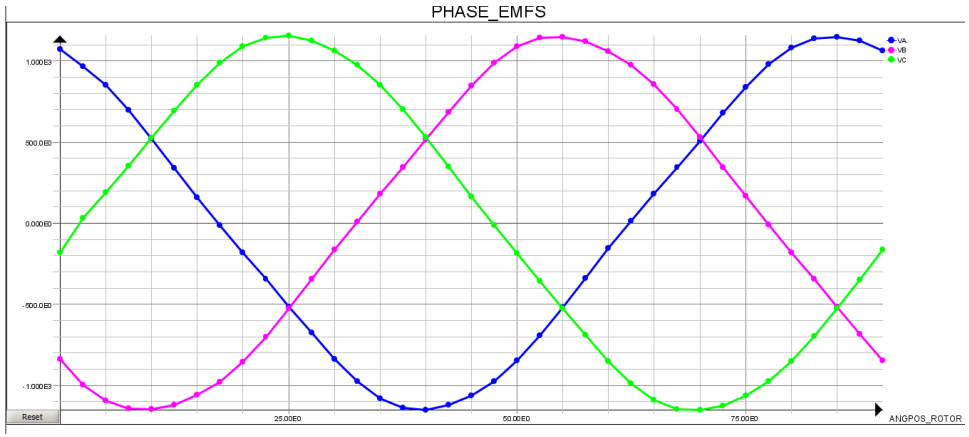
-YBCO nearing competitive performance

2. Critical current density above 15MAcm−2 at 30K, 3T in 2.2μm thick heavily-doped (Gd,Y)Ba2Cu3Ox superconductor tapes

3D Field Analysis - Magsoft



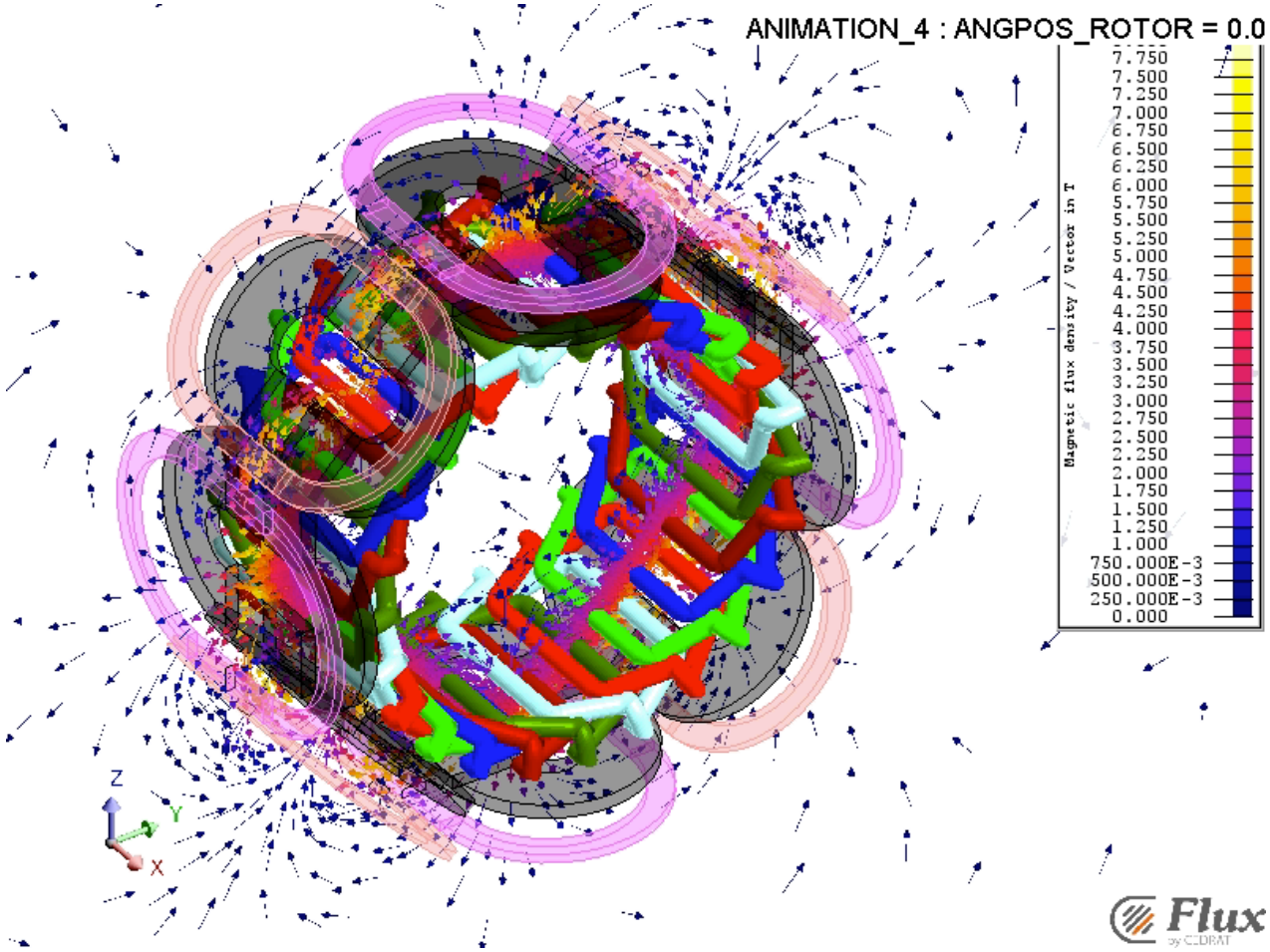
Full 3D Time-stepping Model to validate EM performance



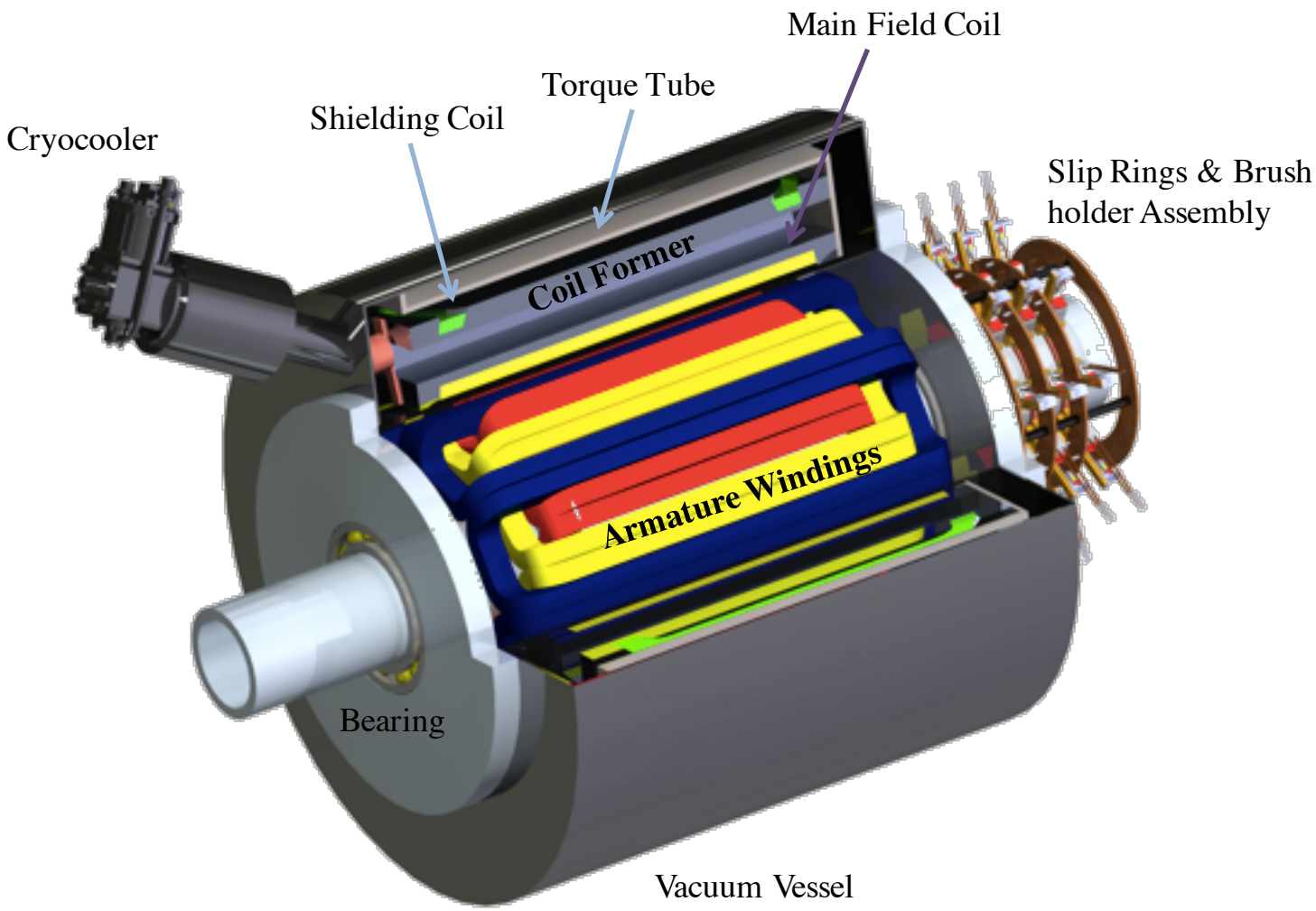
Phase EMFs at 3000 rpm

Torque: 44.2 kNm
39% higher than 2D prediction because of extra coupling in end turns.

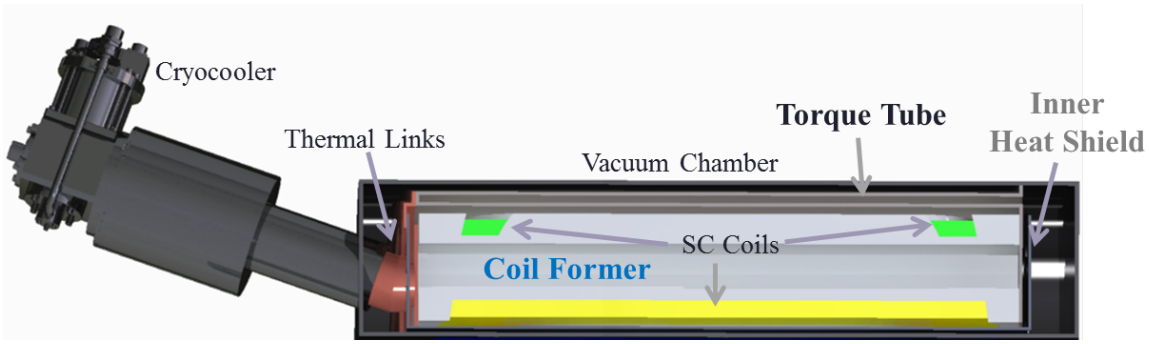
3D EM Simulation



Motor Configuration



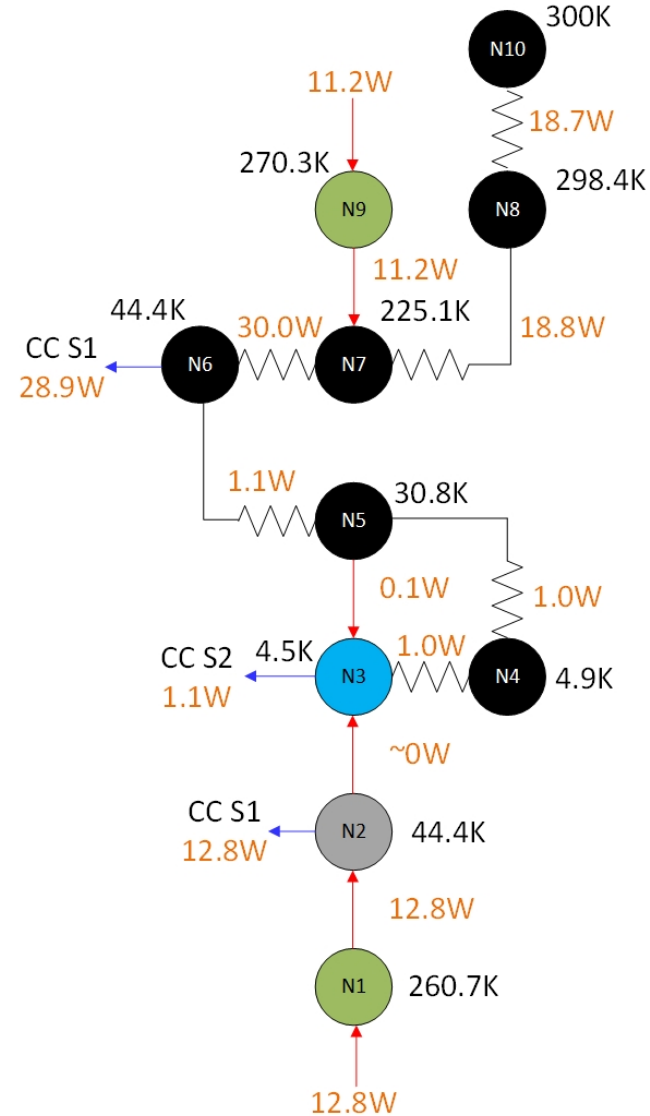
Thermal Design and Analysis



Stator Cross-Section

Table: Heat Load Summary

	Heat Load (W)
Stage 1 Cryocooler	
Radiation	12.785
Conduction with Torque Tube	28.885
Current Leads	13.90
Total Stage 1	**55.6**
Stage 2 Cryocooler	
Radiation	0.029
Conduction with Torque Tube	1.061
Current Leads	0.2
AC Losses	TBD
Total Stage 2	**1.1**



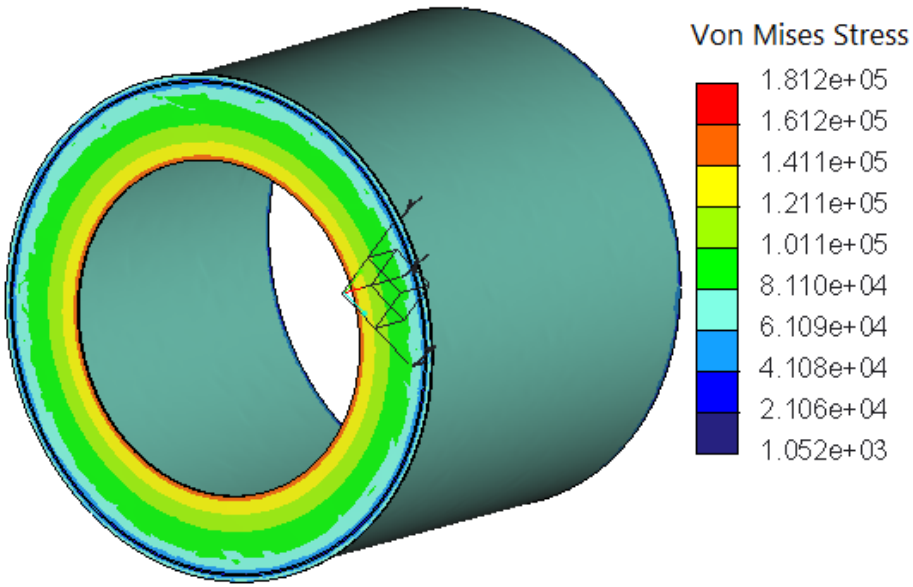
Lumped Parameter Thermal Model

Acceptable Heat loads

Structural Analysis

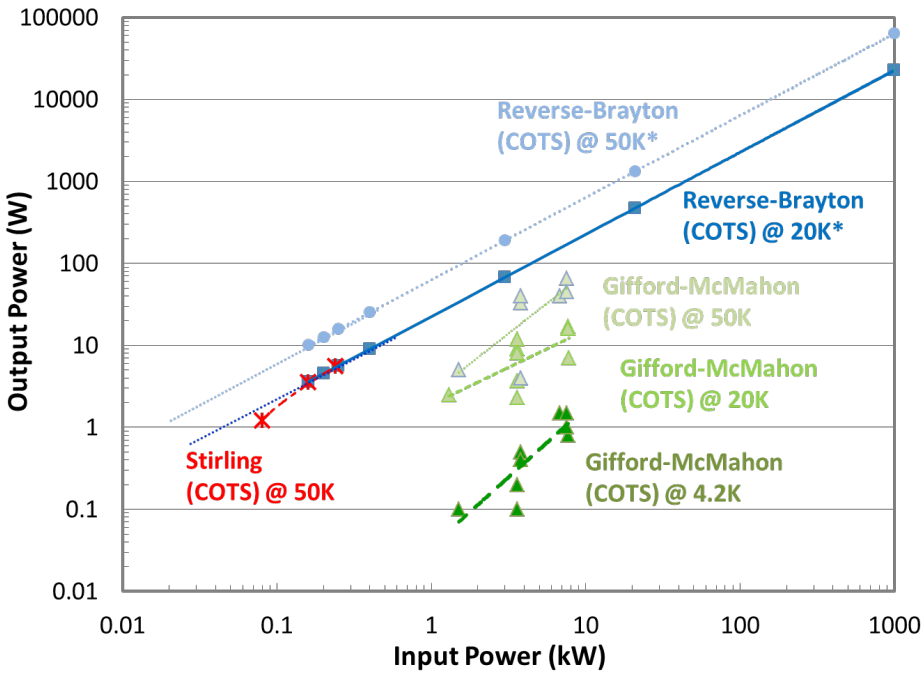
- Structural Members
  - Coil Former
  - Torque Tube
  - Vacuum Vessel

- Torque Tube Stress
- Double Turn, 5 mm thick
- (10x nominal torque)
  - Maximum Stress: 170 MPa
  - Maximum Displacement: 1.7 mm
  - Yield Strength of Titanium: 225 MPa



Mechanical Stress on Torque Tube

Cryocooler Selection



T_{op}(K)	Type/Company	Model	P_{in} (kW)	Mass (kg)
4.2K	GM, SHIcryogenics	SRDK-415D-A61D	7.5	189
4.2K	GM, ARS	DE-215S	6.8	121
20 K	GM, ARS	DE-202PE	1.5**	80***
20 K	Brayton	COTS	0.1**	11***
50 K	GM, SHIcryogenics	SRDK-101D-A11B	0.3**	49***
50 K	Brayton	COTS	0.02**	11***
50 K	Sterling, Sunpower	Cryo-tel GT	0.1	3.1

Cryocooler Options for the 1.5 W Thermal Load of the Magnet – the machines for 4K also have a 2nd stage capable of handling the 45-50W load at ~ 50K.

* This is from an over-power machine, not optimized for that heat load.

** Assumes first-order estimate for efficiency ~30% of Carnot for all size machines; exact numbers are not available yet.

*** This is COTS available, not optimized for lower power.

Ref. Reverse-Brayton cycle machines: F. Berg, et al, IEEE TAS **25(3),** 5202705 (2015)

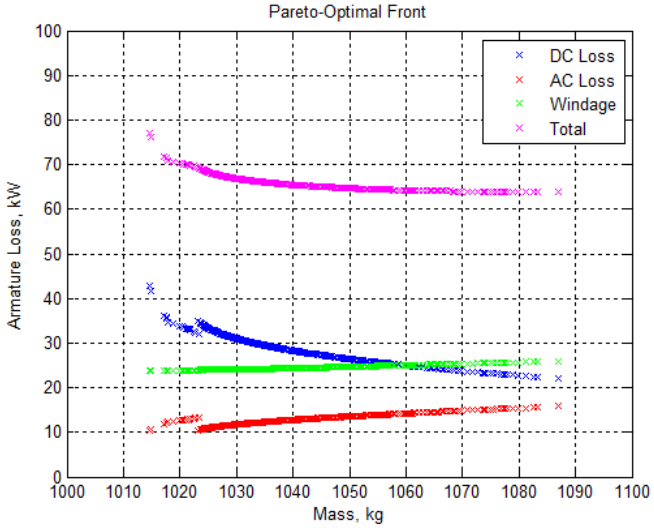
Armature Winding Optimization

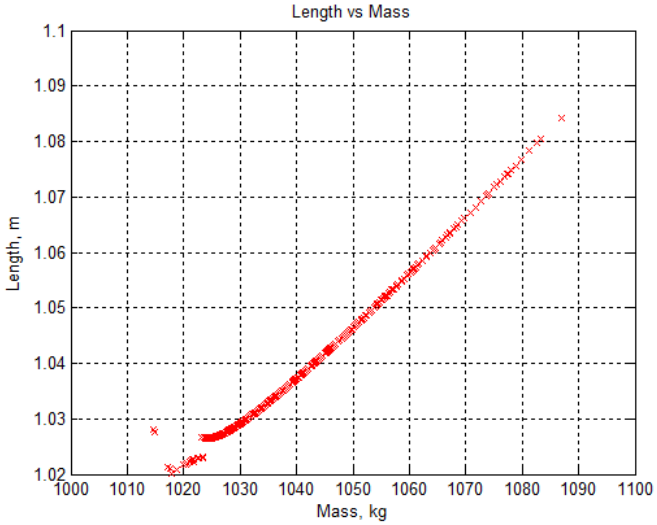
- Degrees of freedom
  - Width of each ‘slot’
  - Depth of each ‘slot’
  - Active length of machine
  - Strand radius
  - Q- and D-axis current
- Constraints
  - Geometry
  - Torque
  - Peak winding temperature
  - Maximum loss and maximum mass
- Metrics
  - Total Loss (DC, AC, Windage)
  - Total Mass

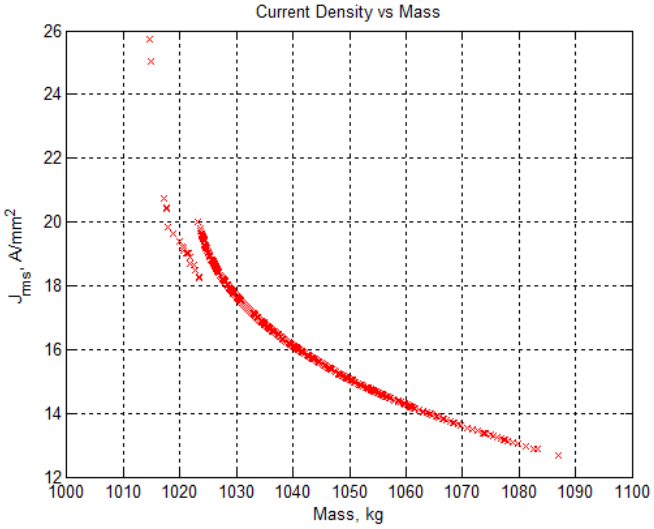
Armature Winding Optimization

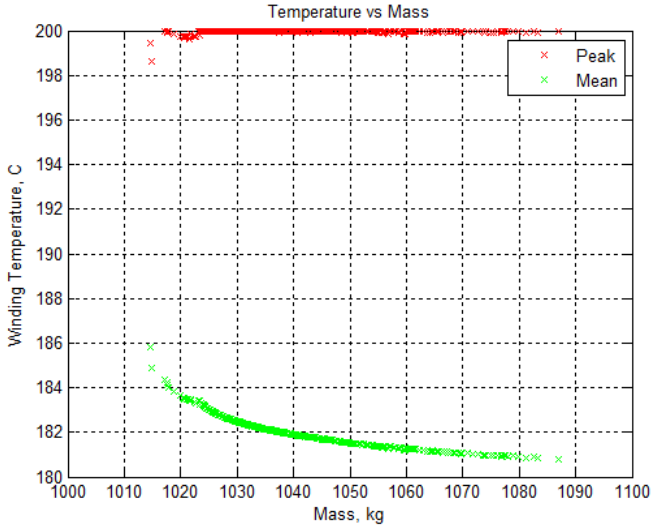
- Field analysis: 2D Biot-Savart Law in with conductive regions represented as sets of conductors
- AC Loss:
  - Driven by eddy currents in armature winding due to superconducting field which is time varying as seen by moving armature
  - Loss calculated using temporal average of spatial mean of square of the time derivative of flux density
- Thermal model
  - Based on 1-D thermal analysis with parabolic temperature distribution within each conductive region

Properties vs. Mass along P.O. Front



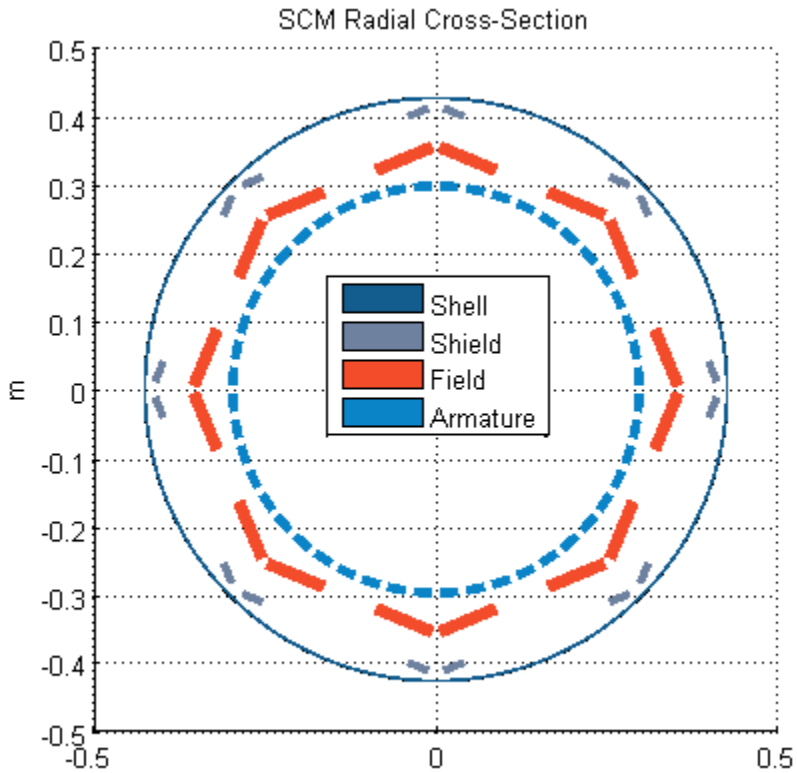






Design 111

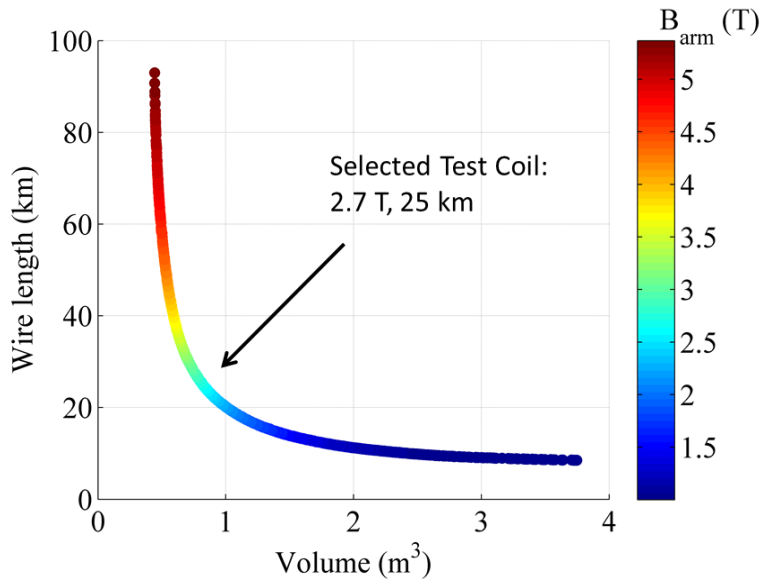
Enter design number of solution to report on (0 to skip): 111
Length (m): 1.05
Active Length (cm): 77.8
Armature Mass (kg): 38.2
Structural Mass (kg): 1010
Total Mass (kg): 1050
Slot Width (cm): 2.80
Slot Depth (cm): 1.40
Strand Guage: 40
Q-Axis Rotor Current (A): -1540
D-Axis Rotor Current (A): 0
Current Density (A_rms/ mm^2): 15.1
DC Resistive Loss (kW): 26.5
AC Proximity Loss (kW): 13.6
Windage Loss (kW): 24.7
Total Armature Loss (kW): 64.7
Efficiency (%) : 99.7
Mean Winding Temperature (C): 182



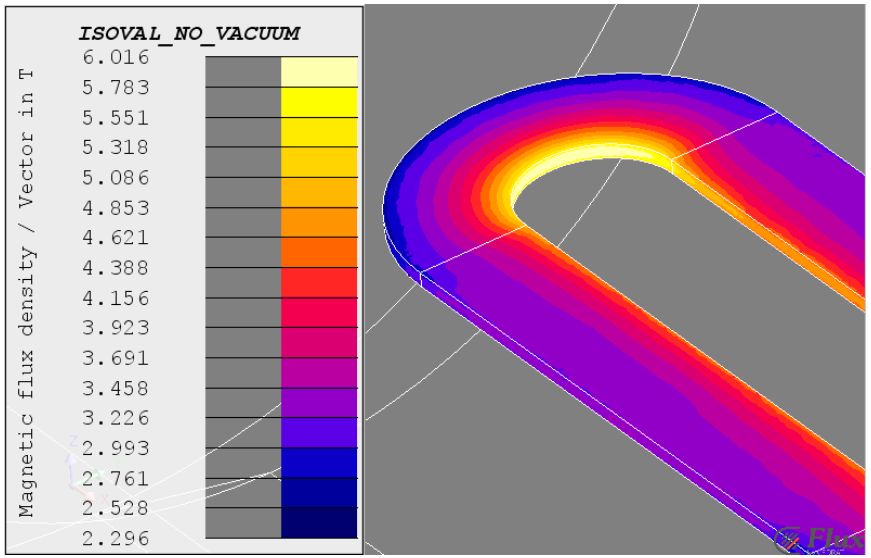
Power Density Estimates

		20 MW @ 6000 rpm, 99.6% Efficiency	
Mature Materials	Nb_3Sn coil, Titanium Torque Tube, Steel Cryostat, Al Coil Former	12	20
	↓		
Advanced Composites	Fiber Reinforced Composites Torque Tube, Cryostat, and Coil Former	24	40
	↓		
HTS Coils	Cryocooler weight reduced Reduced Torque Tube mass Eliminate radiation shield	**33**	**54**
		hp/lb	**kW / kg**

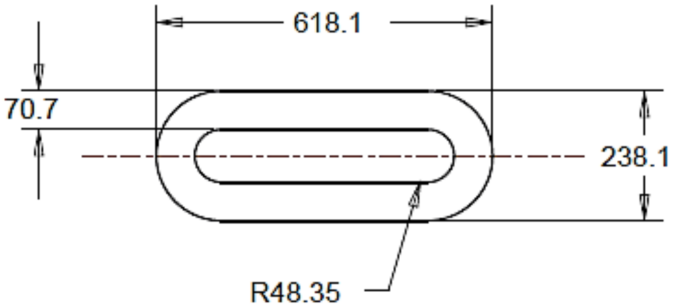
Coil Selection for Bench Test



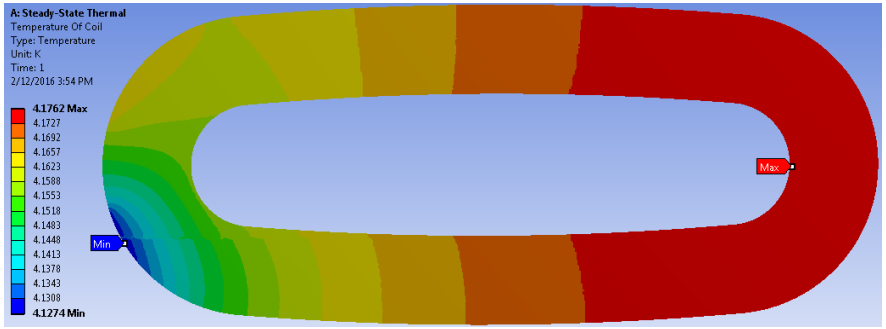
Selected Coil for 2.7 T Armature Field



3-D Field Distribution - Peak 6 T

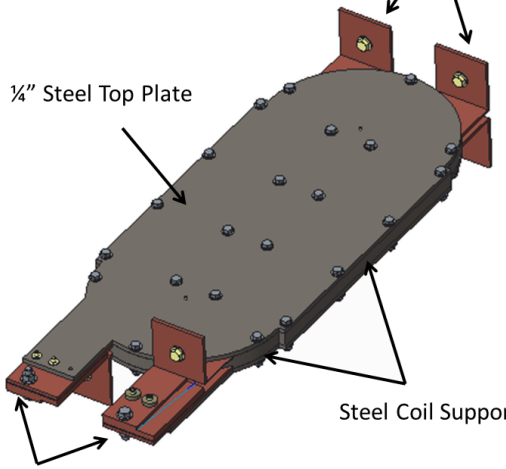


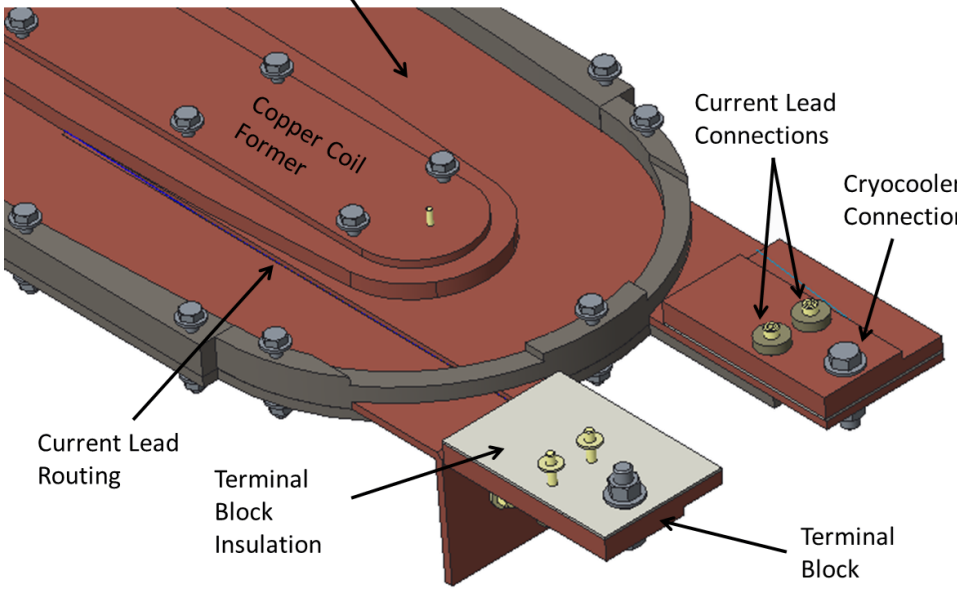
Winding Dimensions (in mm)

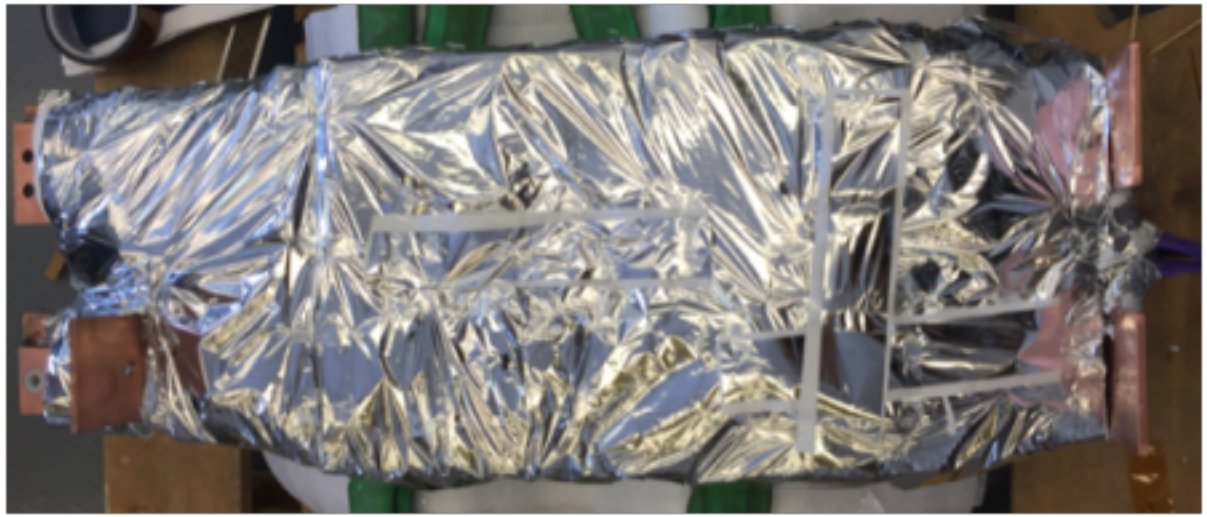


Temperature Distribution – Tmax <4.2K

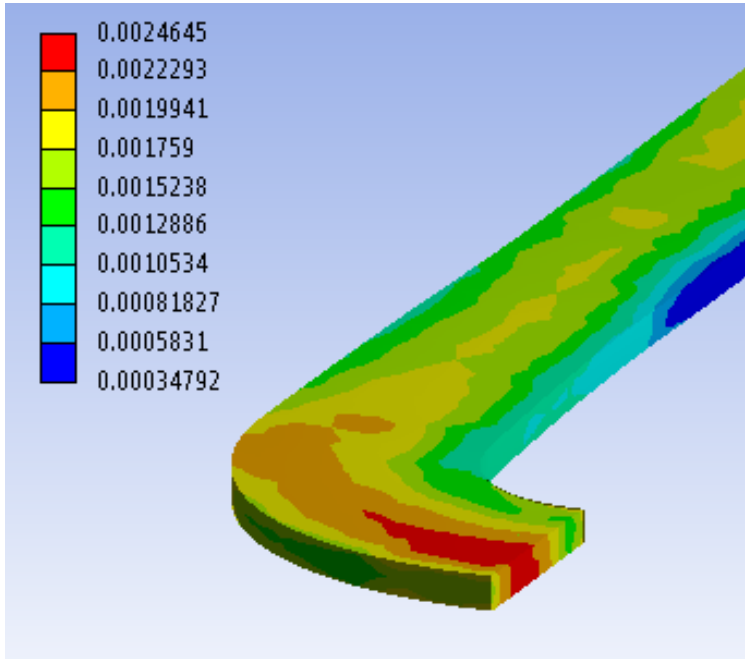
Coil Assembly



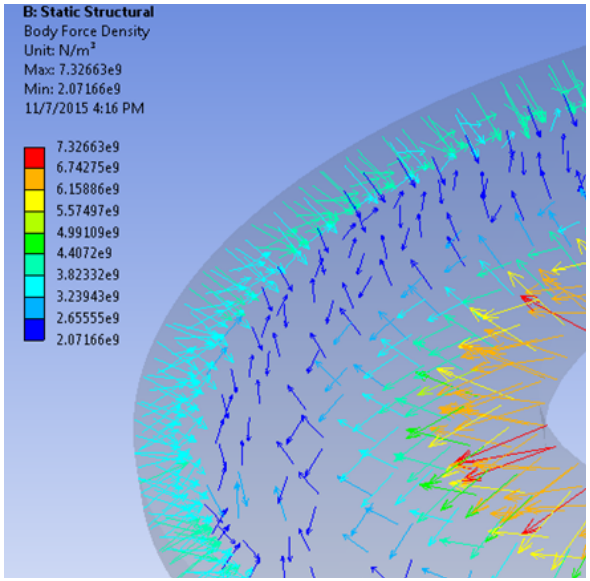


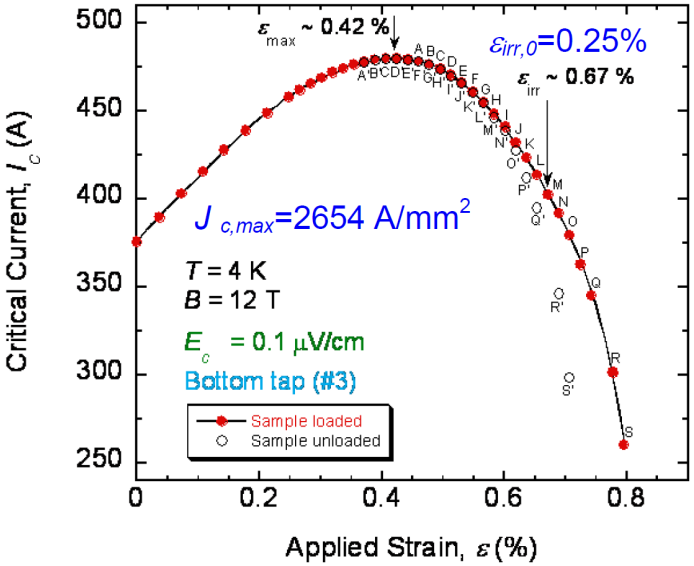


Strain Analysis



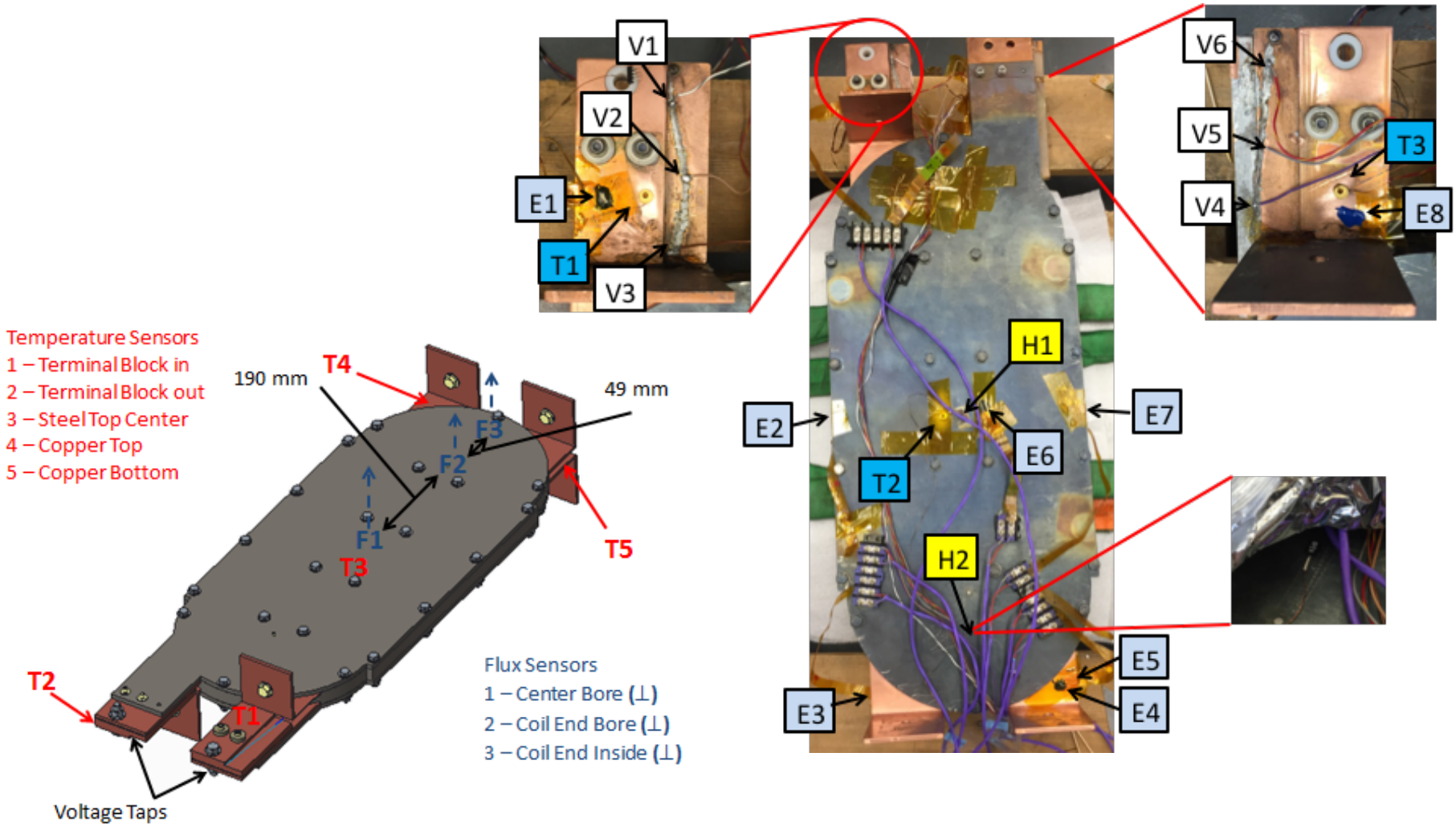
Strain Distribution in ANSYS



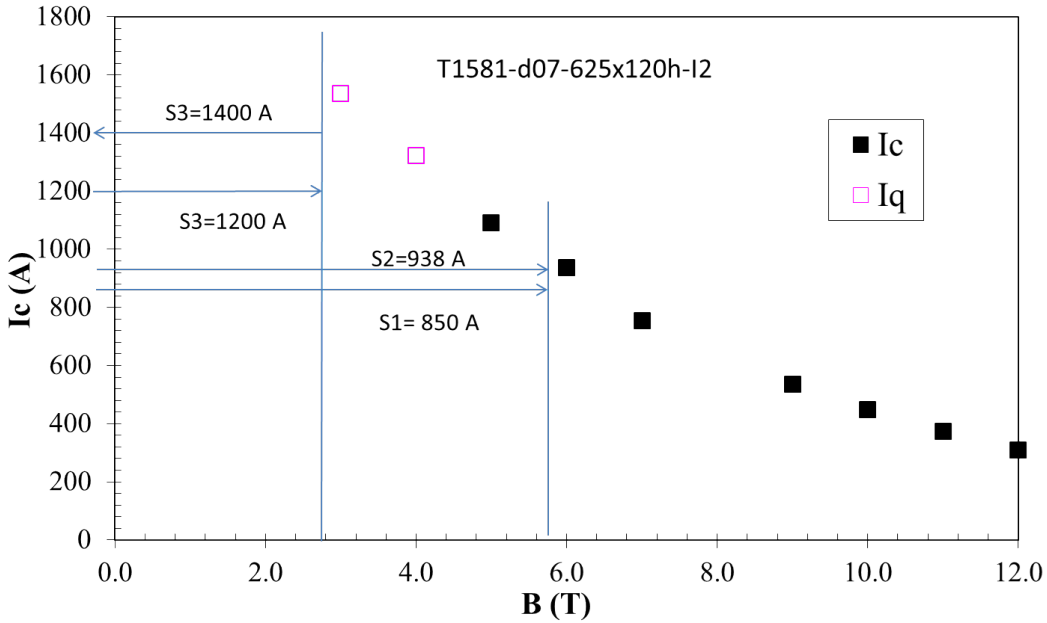


Tensile Strain < 0.2 %

Instrumentation

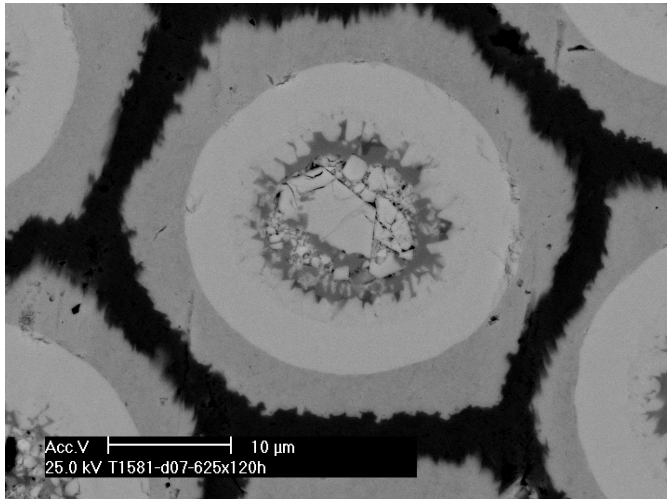


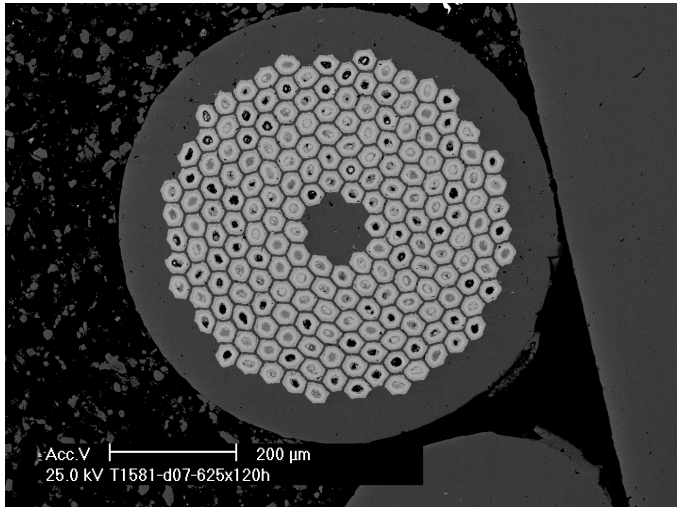
Strand Stability



Critical Current Test
(Voltage Criterion: 10 μV/m)

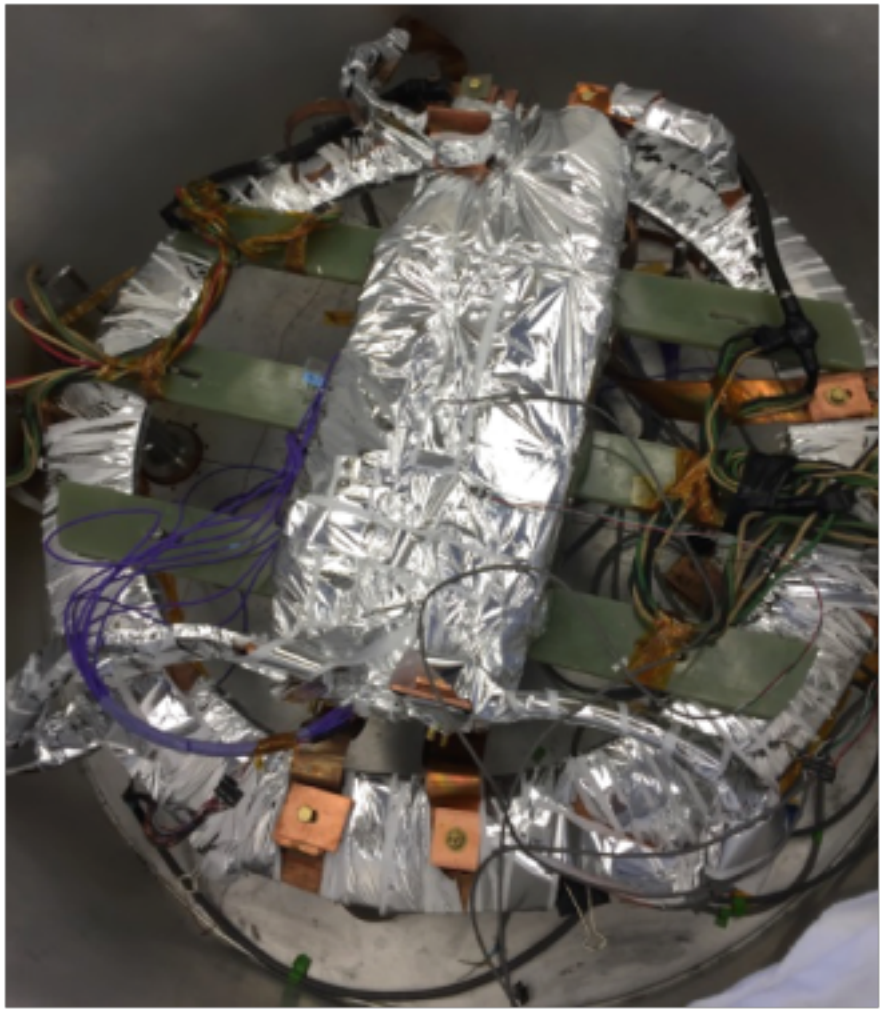
$$\frac{Iop}{Ic} = \frac{435\ A}{850\ A}$$





SEM views of cross-section

Coil Test Setup



Coil tests in progress

LEARN Phase I Plan vs Status