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Superconductor Manufacturing Technology for Next-gen Electric Machines

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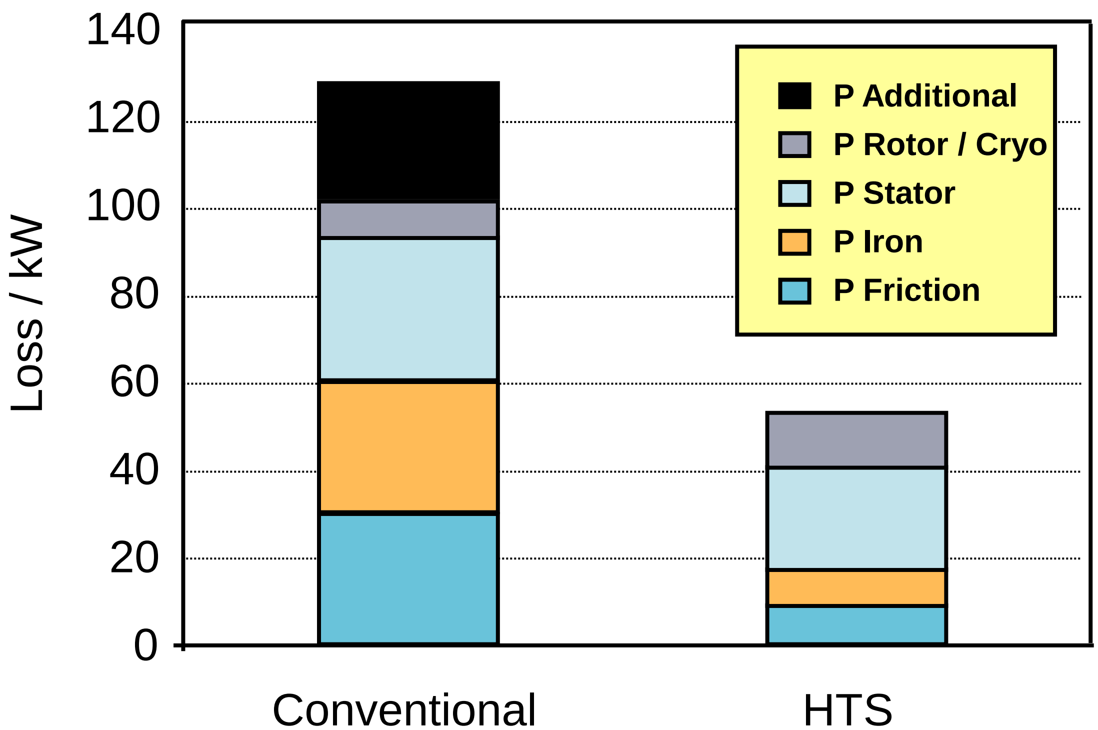
Outline

- Higher efficiencies achieved in HTS Rotating Machines
- Advantages of HTS Rotating Machines compared to LTS Rotating Machines
- Status of HTS Wire
- Economics of HTS Rotating Machines
- HTS Wire Manufacturing for Industrial Motors: Challenges & Goals

Higher efficiciencies achieved in HTS Rotating Machines

2% efficiency improvement in Siemens' 4 MVA HTS Generator



Picture: Siemens

Efficiency at rated operation

cos φ	Conv.	HTS
0.8	96.1 %	98.4
1.0	97 %	98.7

- Higher power density → higher magnetic field in armature winding → less Cu and steel → less overall losses

Klaus et al. Design Challenges and Benefits of HTS Synchronous Machines, *IEEE Transactions* 2007

97 - 98% efficient G.E.'s 1.3 MW HTS Generator

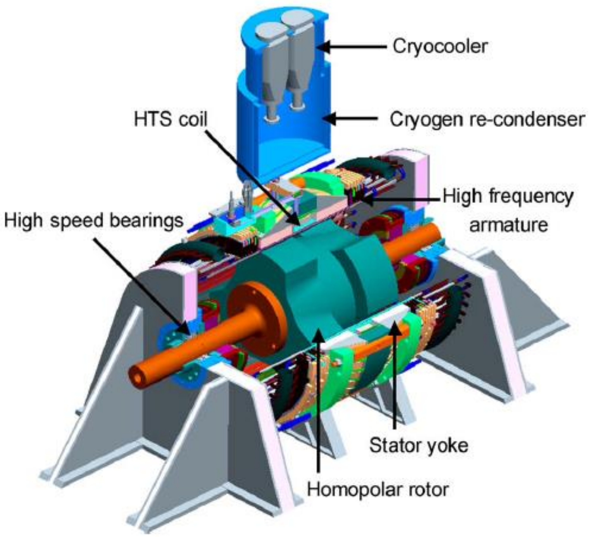
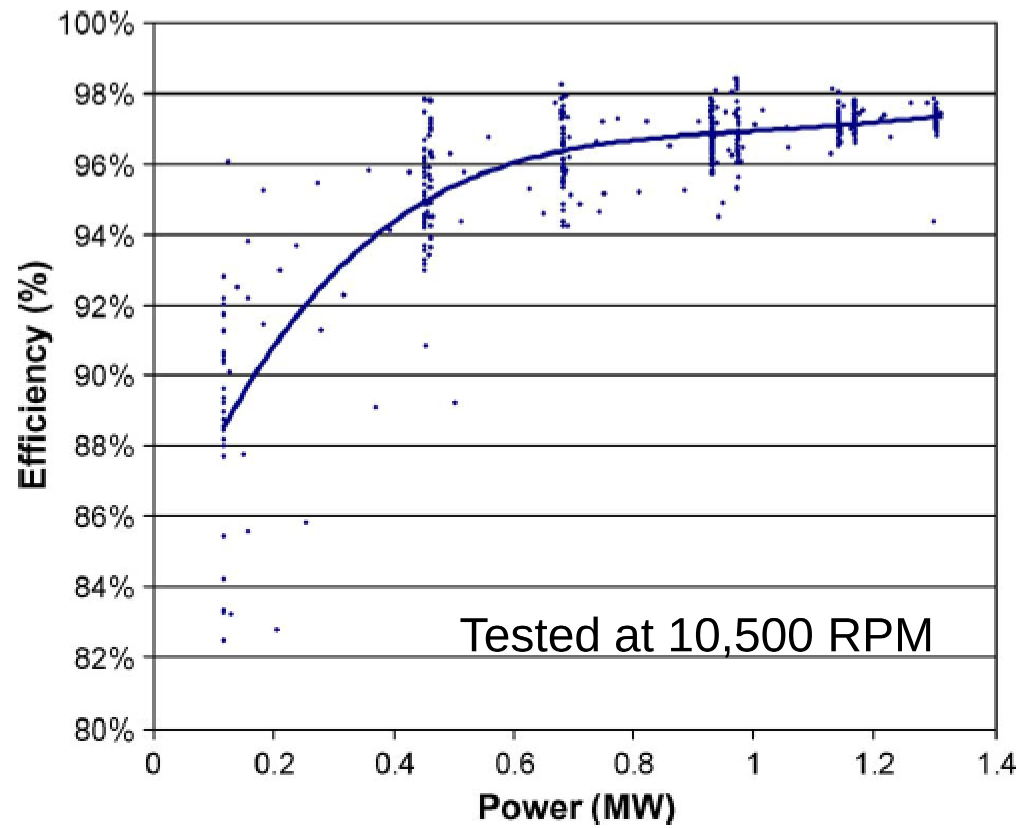


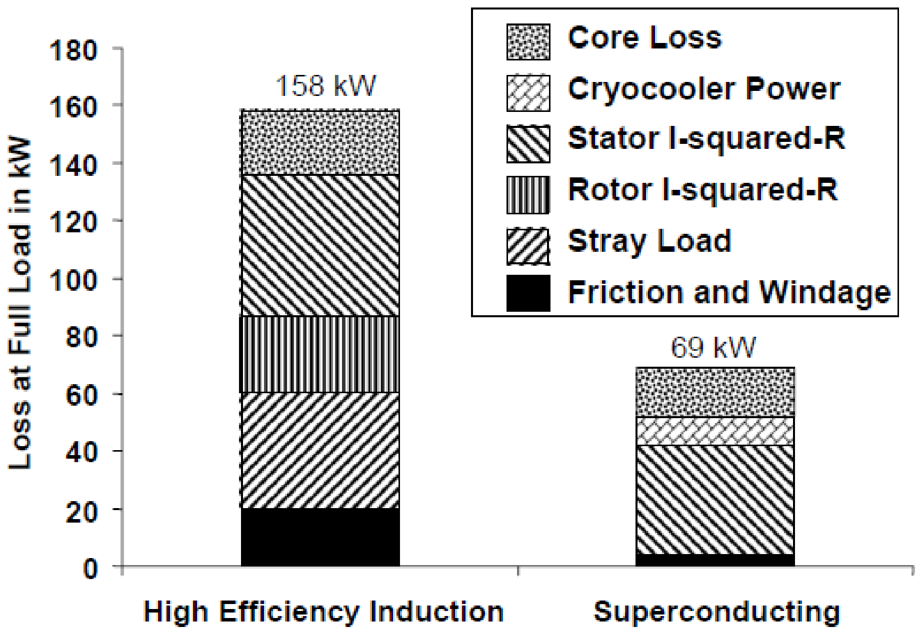
Fig. 2. Homopolar inductor alternator with HTS field winding.

Power, MW	5
Rated speed, rpm	35000
Voltage, V	670
Poles	6
Frequency, Hz	1750
Efficiency at FL, %	98
Synch reactance, p.u.	0.7
Gap flux density, T	1.8
Field Ampere-Turns	45,000
Diameter, cm	50
Length, cm	50
Active Length, cm	21.6
Machine weight, kg	500
Cryogenic weight, kg	45.5
Total Machine weight, kg	545



K. Sivasubramaniam et al., "Development of a High Speed HTS Generator for Airborne Applications" *IEEE Trans. Appl. Supercond.* 19, 1656, (2009)

2% higher efficiency in Rockwell Automation 6000 h.p. motor (design)



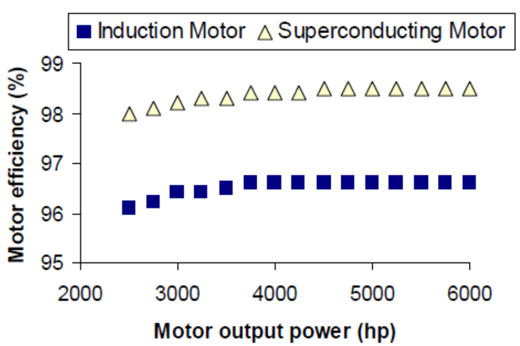


Fig. 4 Efficiency vs output power for 6000 hp, 3600 rpm, 2 pole motors at rated speed.

TABLE I
6000 hp, 3600 RPM, 2 POLE MOTOR COMPARISONS

		HTS	Induction
1.	Full load efficiency [%]	98.5	96.6
2.	Active length [m]	0.81	0.99
3.	Rotor OD [m]	0.26	0.45
4.	Stator-core OD [m]	0.67	0.79
5.	Active Volume [m^3]	0.28	0.48
6.	Overall Volume Without Stator Heat Exchangers [m^3]	1.70 Including Cryocoolers	2.21
7.	Overall Volume Including Stator Heat Exchangers [m^3]	3.34 Including Cryocoolers	7.95

Advantages of HTS Rotating Machines compared to LTS Rotating Machines

More economical, more reliable and less complex cryogenics with HTS machines

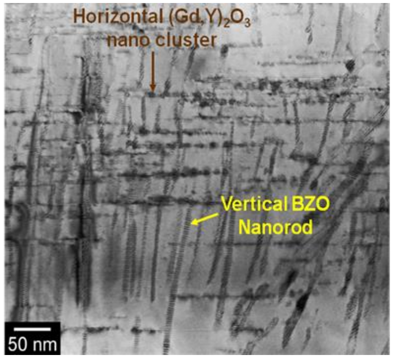
- The cost to cool superconducting coils is roughly proportional to the inverse of the operating temperature in Kelvin[1].
- A 5 MW motor operating with LTS wire at 4 K would require at least 1.2% of its rated power for cooling the superconducting coils[1] → severely cuts into the 2% efficiency improvement benefit
- A 5 MW HTS motor will require ~ 0.1% of its rated power for cooling at 40 – 65 K.
- Much less complex cooling at 40 – 65 K using single stage cryocooler
- Cryocoolers for 5 MW motor have maintenance intervals of 10,000 hours
- HTS wires have substantial temperature margin (10s of Kelvin) compared to ~ 1 K for LTS wire → higher reliability with HTS machines (important to user)
- HTS wires have much higher heat capacity compared to LTS wires → minimum quench energy in LTS < 10 mJ @ 4.2 K → HTS motors will be far less susceptible to quench → higher reliability which is critical to user

[1]R. Schiferl et al. “High Temperature Superconducting Synchronous Motors: Economic Issues for Industrial Applications” IEEE Trans. Paper No. PCIC-2006-31

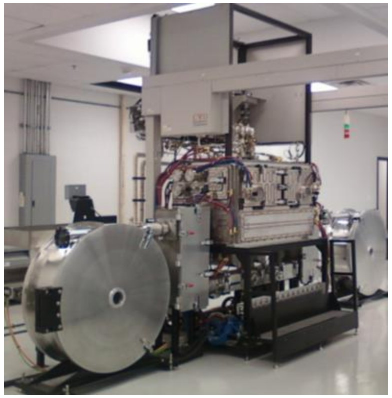
Status of HTS wire

4X HTS wire performance improvement targeted for high power wind generators

- ARPA-E REACT program targeted 10 MW wind generator operating at 30 K, 2.5 T
- Improved approaches to engineer nanoscale defects in coated conductors
- Scale up 2X improved wire technology to long-length manufacturing.



Engineered nanoscale defects

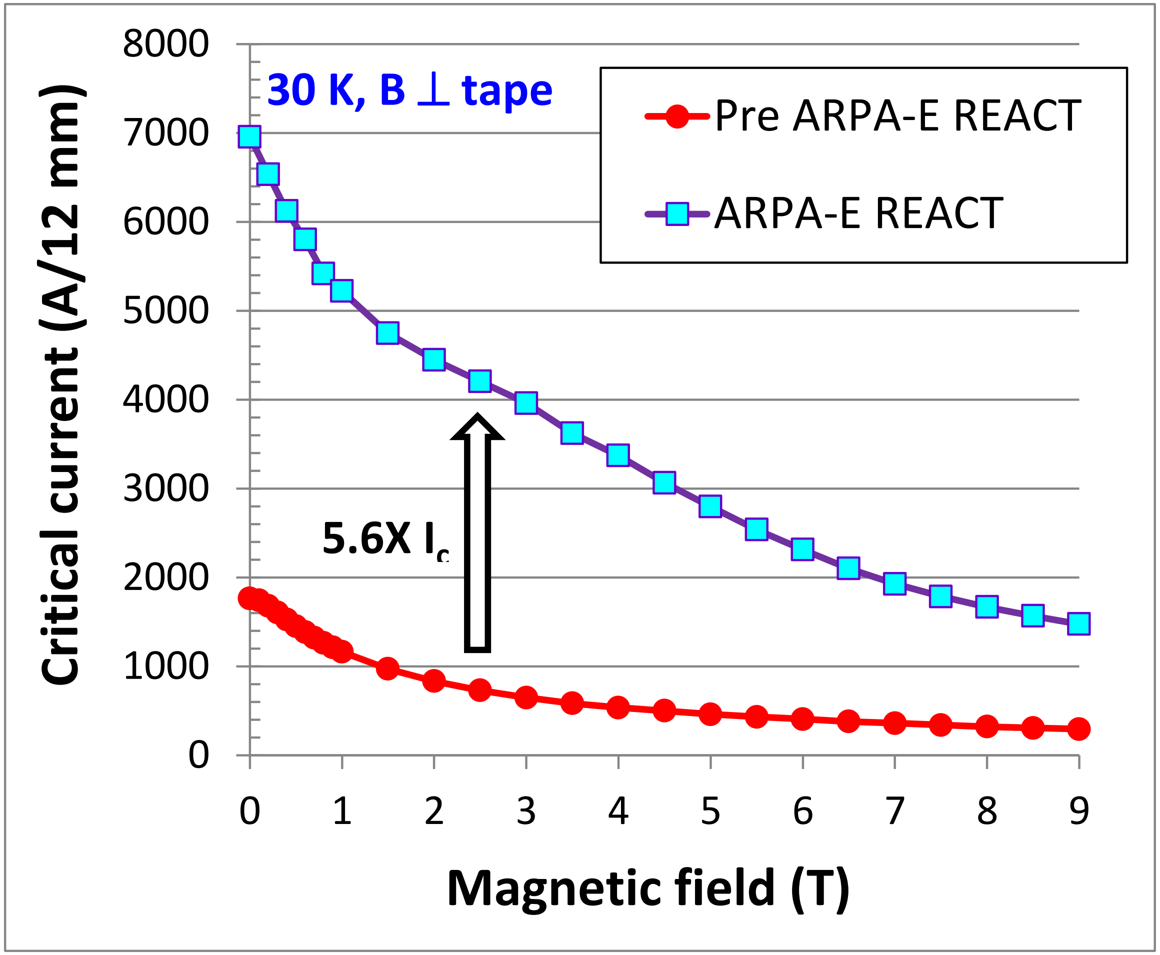


Improved wire manufacturing

High-power, Efficient Wind Turbines

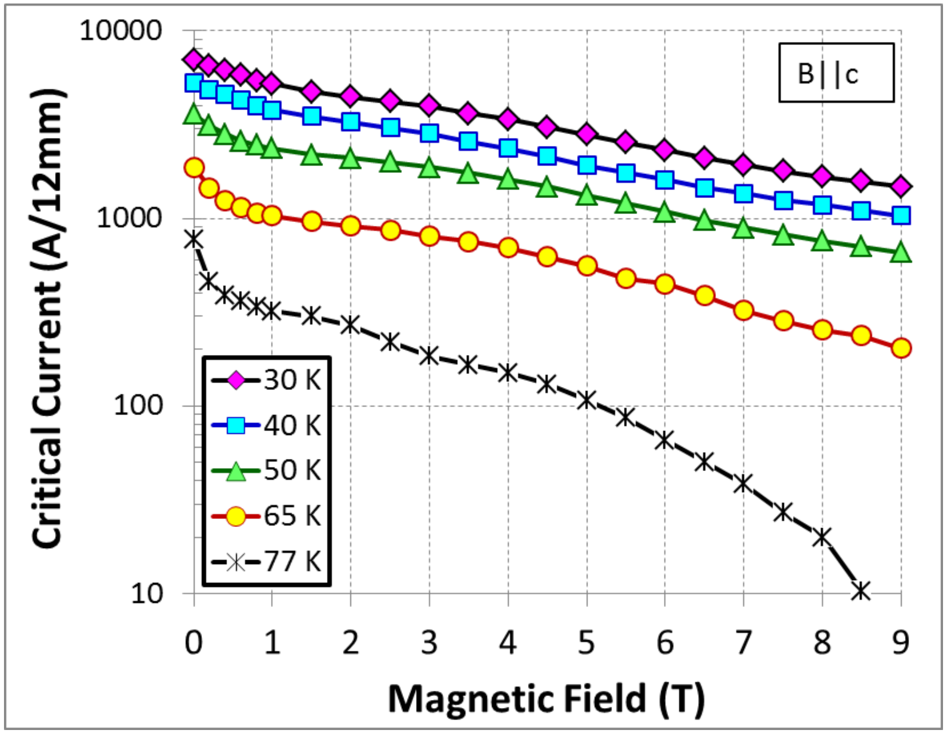
- *Quadrupling superconductor Performance at 30 K, 2.5 T for commercialization of 10 MW wind generators to reduce wire cost by 4x*
- *Advances will also lead to high-performance HTS conductors for other applications*

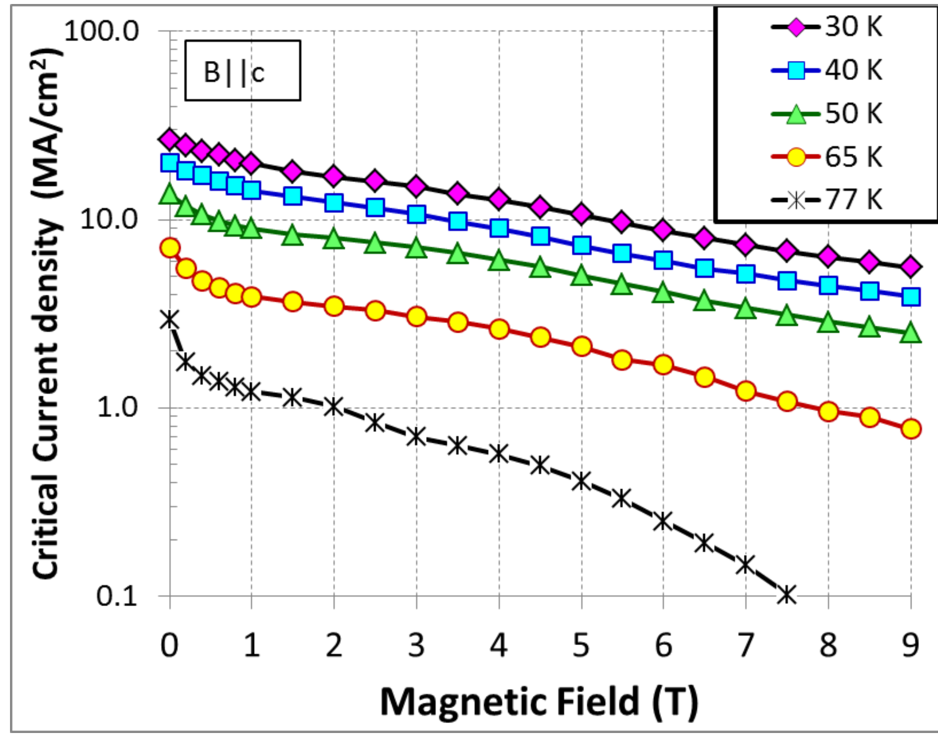
5.6X I_c achieved at 30 K, 2.5 T in ARPA-E REACT program, exceeding goal of 4X performance



4X Ic wire → 4X less wire required in motor → significant cost reduction

Very high critical currents over a broad temperature range





	30 K, 3 T	40 K, 3 T	50 K, 3 T	65 K, 3 T	77 K, 3 T
I_c (A/12 mm)	3963	2833	1881	805	184
J_c (MA/cm^2)	15	10.1	7.1	3.1	0.7

Opportunity: *Use 4X Ic wire at higher temperatures → eases cryogenic requirement*

Economics of HTS Rotating Machines

Key metrics required for use of HTS in industrial motors

1. Competitive capital cost → short term for ROI
2. Reliability → Simple cryogenics → higher operating temperature
3. Predictability → Consistency in performance
4. Availability → high volume production

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Design of 5 MW, 15000 RPM HTS Rotating Machine using 5.6X I_c ARPA-E REACT wire

Stator Parameters (Air core)	
Electrical loading (kA/m)	74.89391
Armature thickness (mm)	24.9
Armature current (Arms)	1735.5
Armature voltage (Vrms)	1056.37
Rotor Parameters (Double Helix)	
Total length (mm)	455.7144
Conductor length (m)	2407.28
Conductor margin (%)	50.00%
Rotor peak field (T)	0.62523
Rotor current (A)	185.11
Other Parameters	
No load field (T)	0.99
Synchronous reactance (p.u.)	0.11
Frequency (Hz)	750
Number of pole pairs	3
Rotation speed (RPM)	15000
Efficiency (%)	99.84%

Calculated Machine Parameters		
	Power (kW)	5,500
	Power (HP)	7383
	Torque (Nm)	3.501E+03
	Specific Torque (Nm/kg)	12.70
	Specific Power (kW/kg)	19.95
	Shear stress (Nm/m2)	1.268E+04
Overall Dimensions		
	Rotor HTS inside radius (mm) r1	184.68
	Rotor HTS outside radius (mm) r2	190.70
	Armature inner radius (mm)	202.70
	Armature outer radius (mm)	227.60
	Back iron inner radius (mm) rs	228.60
	Back iron outer radius (mm)	269.81
	Rotor Shaft Radius	125.00
	Active length (mm) La	230.41
	Total length (mm) Ltot	455.71
Machine Mass		
	Rotor HTS weigth (kg)	13
	Armature winding weight (kg)	100
	Back iron weigth (kg)	106
	Total active weigth (kg)	**219**
	Shaft weight (kg)	59
	Weight of mechanical structure (kg)	20
	Cryogenic components (kg)	12
	Total weight (kg)	**310**

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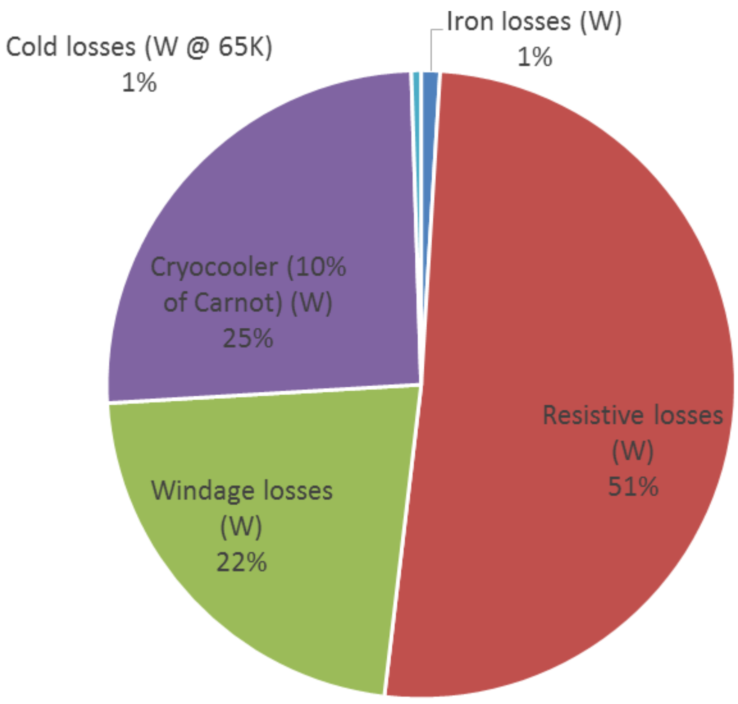
High Performance wire enables a compact, light motor with substantially-reduced losses

- 5.5 MW, 15,000 RPM
- Total weight ~ 310 kg
- Total losses at 65 K ~ 50 W
- Efficiency ~ 99.8%

Cryogenics for HTS rotating machine at 65 K within capability of standard cryocoolers

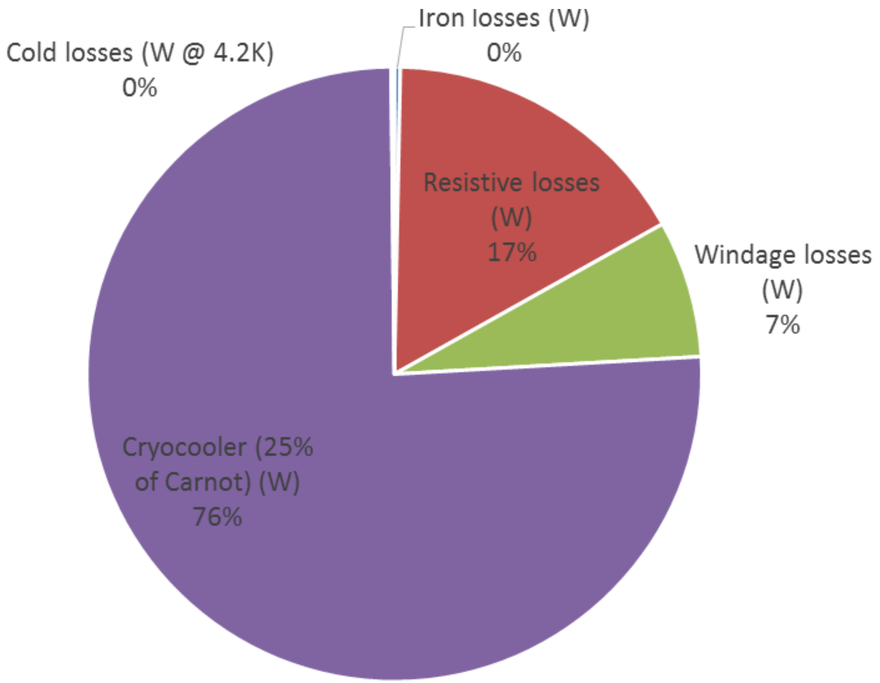
- Cooling at 65 K to address 25% of all losses
- Cooling required = 50 W at 65 K
- Cooling capacity required at room temperature = 1.3 kW → within the capacity of commercial single-stage cryocoolers



Qdrive 2s226K-FAR

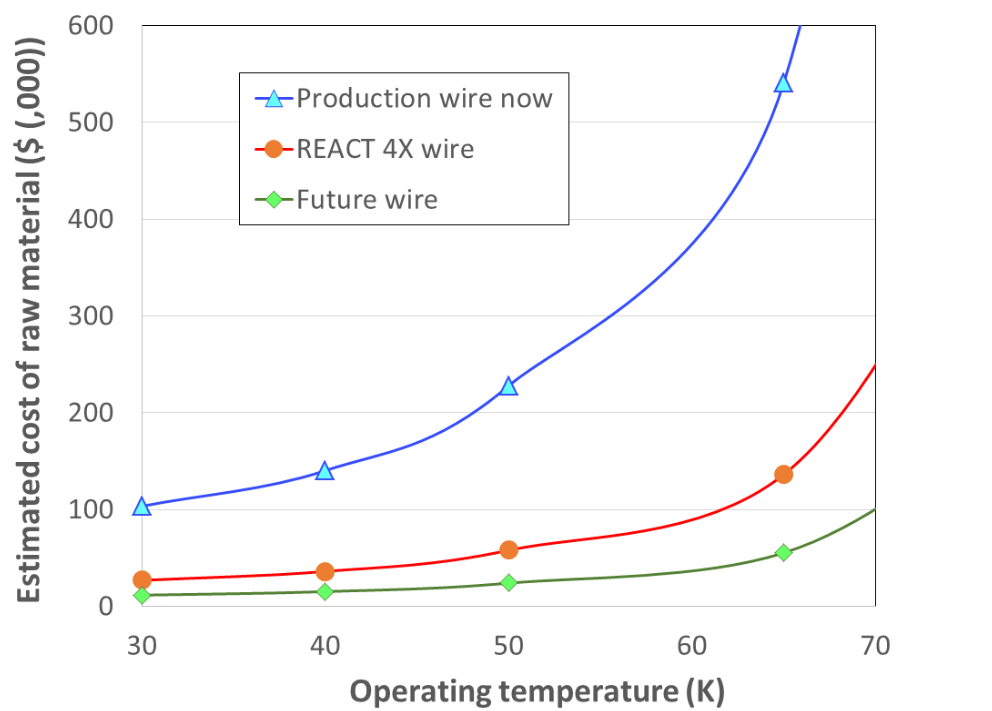
Substantial heat load at 4.2 K makes LTS rotating machines untenable

- Cooling required = 55 W at 4.2 K
- Highest cooling capacity of commercial cryocoolers at 4.2 K = 5 W
- Need an expensive and complex cooling plant to handle 55 W of losses at 4.2 K. Also heat leaks at 4.2 K are more difficult to handle



High Performance HTS wire can enable low-cost superconducting motor at 65 K

	Prod. Wire now	REACT 4X wire	Target wire
Ic @ 65 K, 1.5 T (A/12 mm)	175	700	1750
Wire quantity for 5.5 MW motor* (km)	13.5	3.4	1.3
Wire cost for 5.5 MW motor† ($(,000))	540	136	55
% of motor cost**	154%	39%	16%



* 4 mm wide wire
† Same wire cost of $40/m
** using a conventional 6000 HP synchronous motor cost ~ $350K

Commercial superconducting motors can become feasible with high performance, low-cost HTS wires

- HTS wire for 5 MW, 15000 RPM superconducting motor ~ $ 55,000
- Cryocooler for 5 MW, 15000 RPM superconducting motor ~ $ 25,000
- Additional costs of superconducting technology ~ $ 20,000
- Increased cost of superconducting motor ~ $ 100,000
  (cost of replaced copper wire in rotor is not subtracted)
- Cost savings/year with superconducting motor ~ $ 47,000
  (2% improved efficiency, 90% up time, $ 0.06/kW-h)
- ROI ~ 2 years

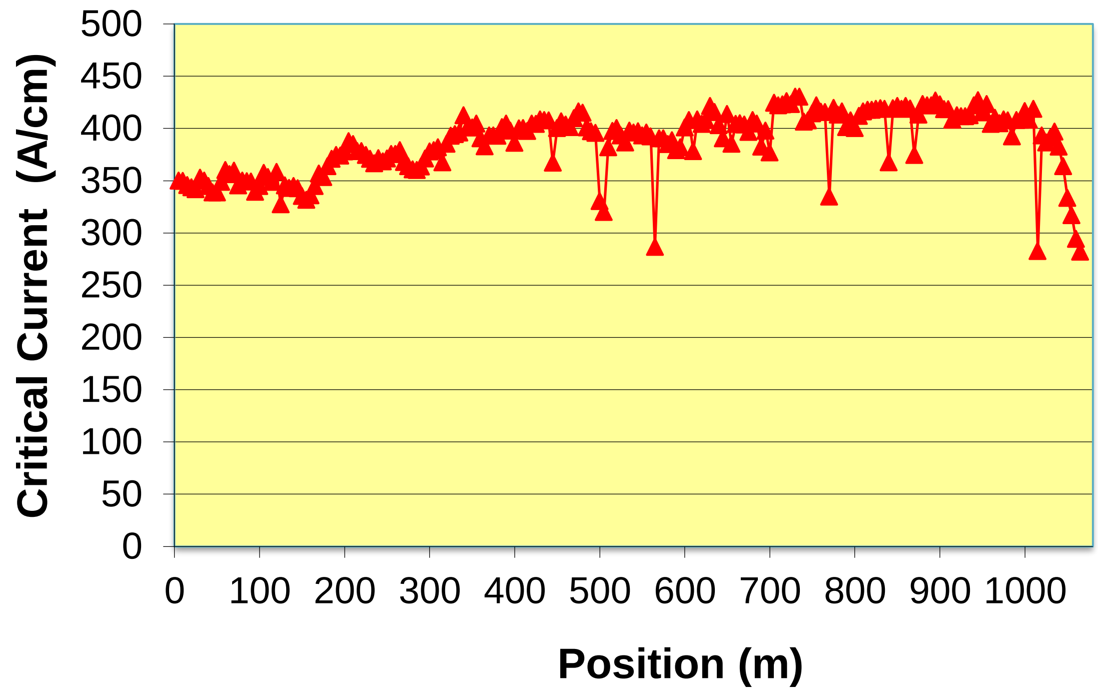
HTS Wire manufacturing for industrial motors: Challenges & Goals

Key challenges in HTS wire manufacturing for industrial motors

- **Higher performance wire at 65 K, 1.5 T**
  - Need higher amperage at 77 K
    - Thicker films; now 1.5 µm; 5 µm feasible
  - Higher amperage at device operating condition
    - Improve in-field performance (lift factor) at operating condition
      - Can be adjusted independent of amperage at 77 K (two knobs to turn)
- **Lower manufacturing cost ($/m)**
  - Improve manufacturing yield in long lengths
    - Yield based on 77 K, 0 T performance
      - Eliminate drop outs in critical current
    - Yield based on in-field performance
      - Improve consistency in in-field performance
  - Reduce major cost components
    - MOCVD precursor cost (low precursor to film conversion efficiency)
- **Higher manufacturing throughput**

Manufacturing yield based on 77 K, 0 T performance affected by drop outs in Ic

- Yield decreases with increasing critical current and increasing piece lengths
- Major yield detriments are defects on substrate and buffer surface, cleanliness of substrate and buffer surface and process stability over long runs



Yield of 200 m piece lengths

- Ic > 250 A/cm = 100%
- Ic > 300 A/cm = 80%
- Ic > 350 A/cm = 60%

Industry is making steady progress towards eliminating drop outs

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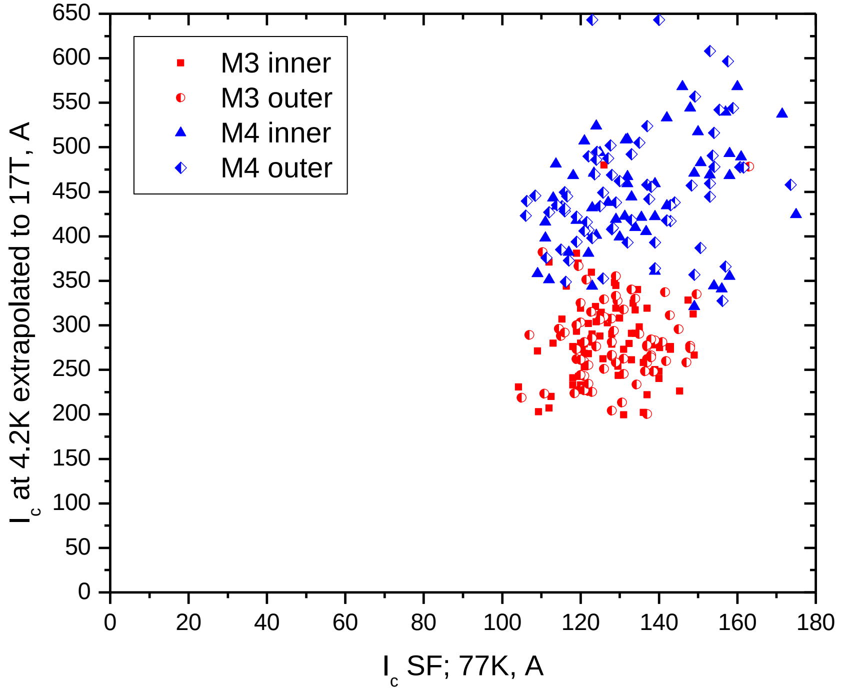
Manufacturing yield based on in-field performance: Wide scatter in I_c in high fields at lower temperatures



D. Abraimov et al. NHMFL, reported at WAM-HTS, Hamburg, May 2014

- For high yield manufacturing, consistent wire performance is needed
- Uniformity of Ic at 77 K, 0 T does not guarantee consistency in in-field performance

Manufacturing targets for commercial HTS wire for superconducting motors

	Production wire now	REACT 4X Ic wire now	Goal
Performance – in-field Lift factor @ 65 K, 1.5 T	0.5	1.25	1.25 (in thick film)
Performance @ 77 K, 0 T Ic (A/12 mm)	350 A in 1.5 µm film	560 A in 2 µm film	1400 A in 5 µm film
Performance @ 65 K,1.5 T Ic (A/12 mm)	175	700	1750
Precursor conversion efficiency	15%	15%	50%
Consistency in in-field performance	± 50%		± 5%
Throughput	1X	1X	3X

Target performance, efficiency, consistency and throughput targets will enable HTS wires to meet the key metrics for industrial superconducting motors