Superconducting Rotating Machines

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

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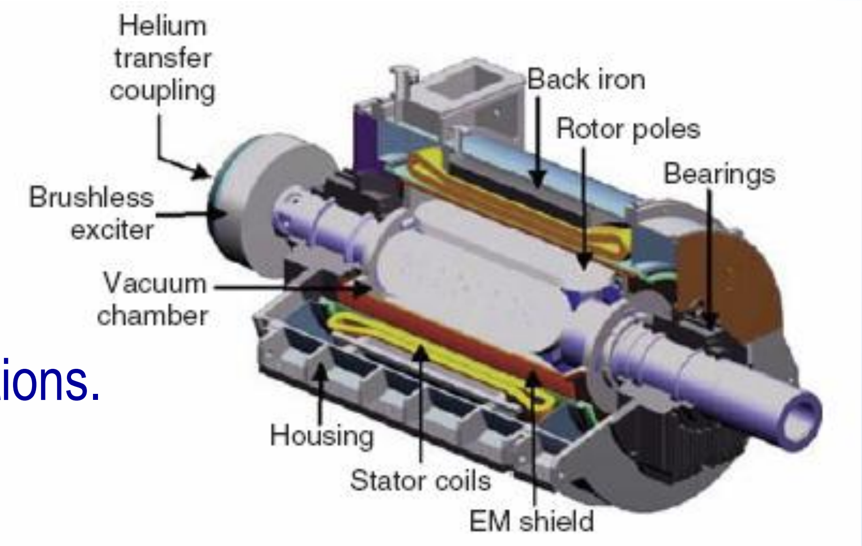
Topology and advantages of SC Machines

- <u>High magnetic field in the air gap (1.5 – 2 Tesla) and no iron core in SC rotor</u>
  - Low synchronous reactance,
  - Robust during the transient faults.
  - Superior damping
  - Improved reactive power (VAR) for both over- and underexcited operating conditions.
  - Compact and lighter



- Virtually no harmonics in the terminal voltage.
- Potentially longer rotor life due to the elimination of thermal load cycling for field winding current changes.
- Higher efficiency, even under partial load conditions, with potential for significant operating cost savings.
- Structure-related vibrations and noise are lower than conventional machines

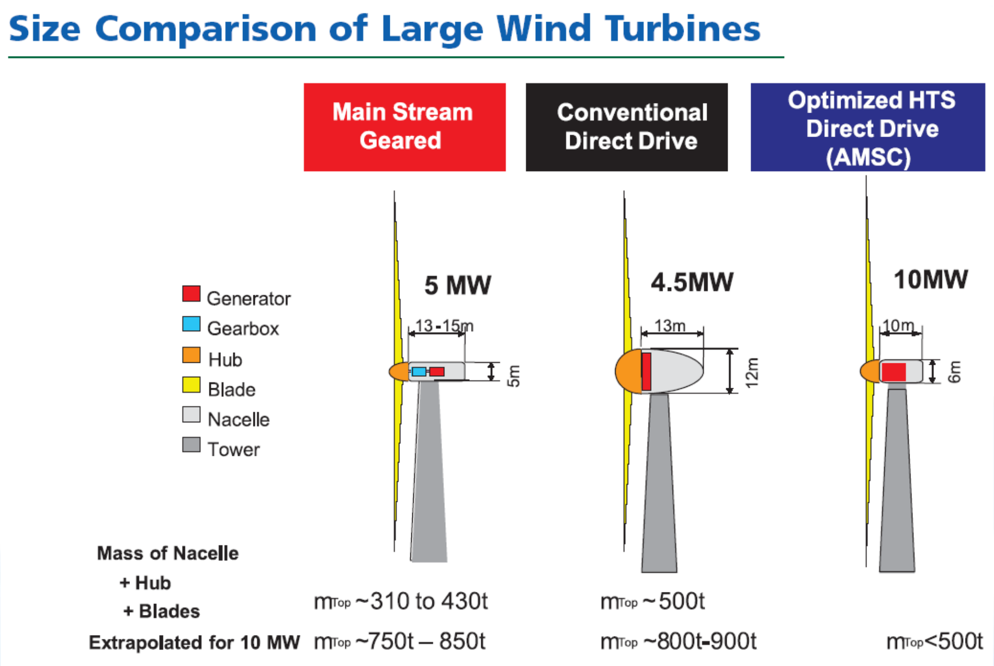
Kalsi, et al Proc. of IEEE 2004

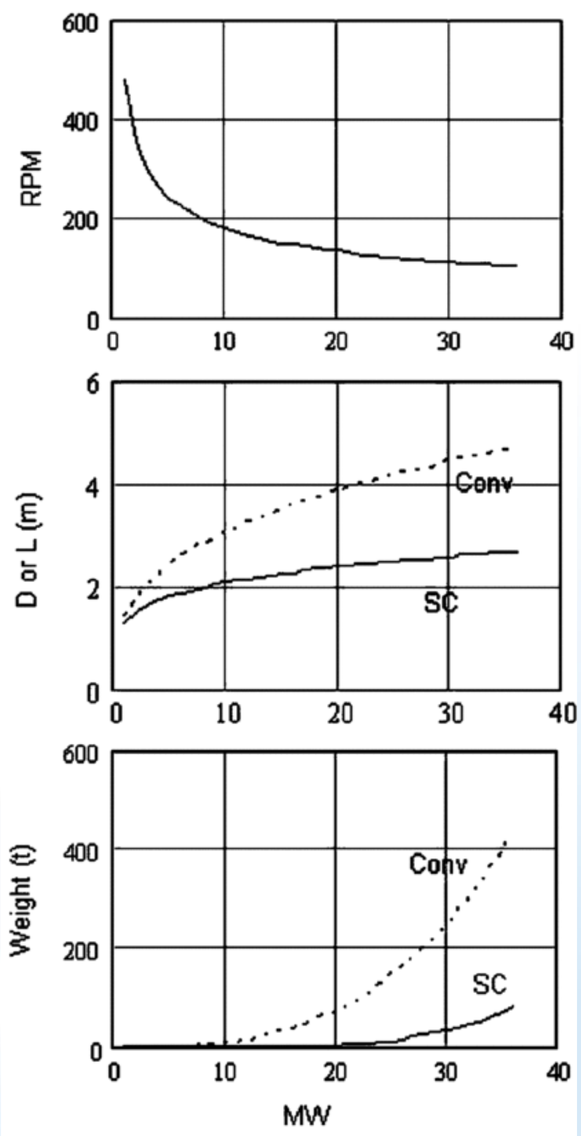
Scaling relationship

for ship propulsion motors
- low speed, high torque

P ~ D^5 – SC Motors

P ~ D^3 – Conventional motors





Kalsi, et al Proc. of IEEE 2004

LTS SC Machines

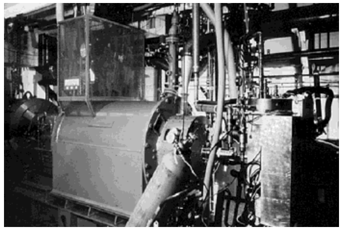
Mid 1960s

- Multifilamentary NbTi
- Development of nuclear power

LTS SC machine R&D (1970s-1990s)

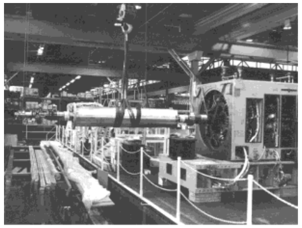
Westinghouse

- 5MV utility generator
- 5/10-MVA SC generator for the US Air Force



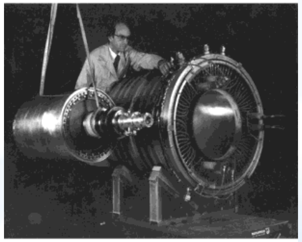
GE built 20 MV generators

- Two-pole 60 Hz



(a)

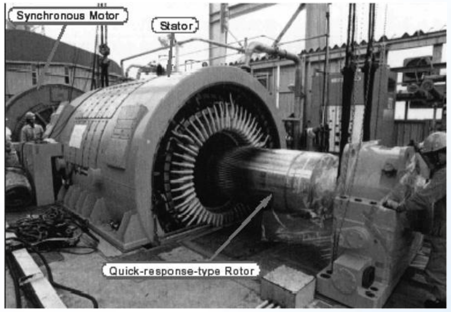
- Four-pole high frequency



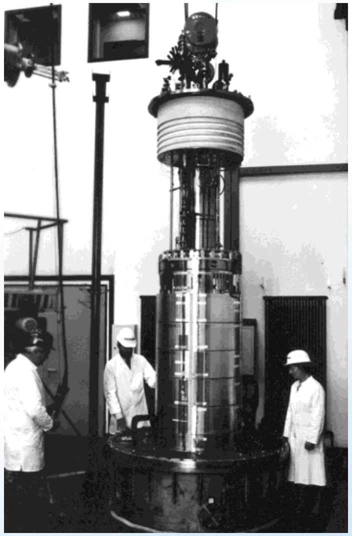
(b)

Kalsi, et al Proc. of IEEE 2004

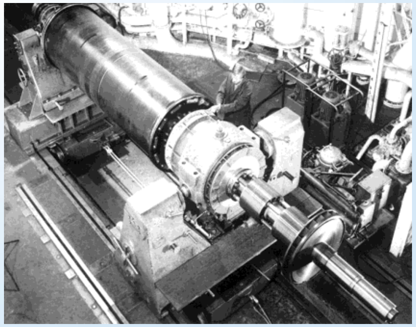
Super GM (Japan)-built generator—70-MW two-pole 60-Hz machine. Three SC rotors tested in a common stator. (12 years project started in 1988)



Siemens/KWU
SC Rotor model ready for cooldown



Alstom prototype rotor - a 1200-MW



LTS SC Machines

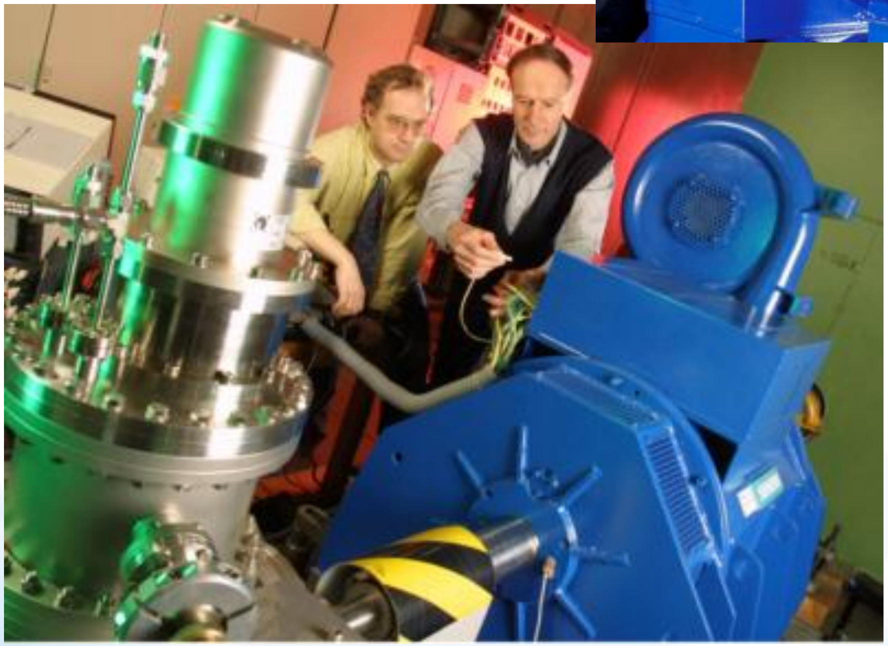
- Difficulty of transporting liquid helium to the rotor with inlet and outlet temperatures within a band of 4–6K.
- Small thermal margin of LTS windings, which were prone to quench with slightest local rise in temperature.
- Reliability concerns relating to liquid helium refrigerators.

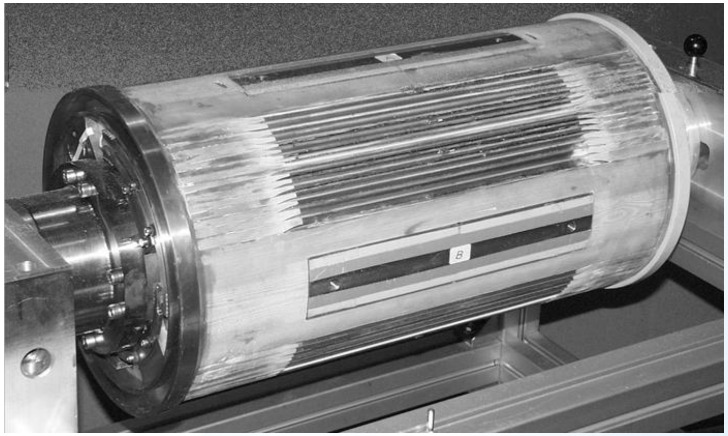
HTS SC Machines

- Only ambient-temperature helium is transferred to the rotor
- Cryocooler cold heads are located on the rotor for cooling the HTS windings.
- Windings operating at 30–40K have large thermal margin.
- Cryostat (thermal barrier on the rotor) design is much simpler
- Available off-the-shelf cryocoolers are reliable and mean time between failure (MTBF) is estimated to be >*9 years.*

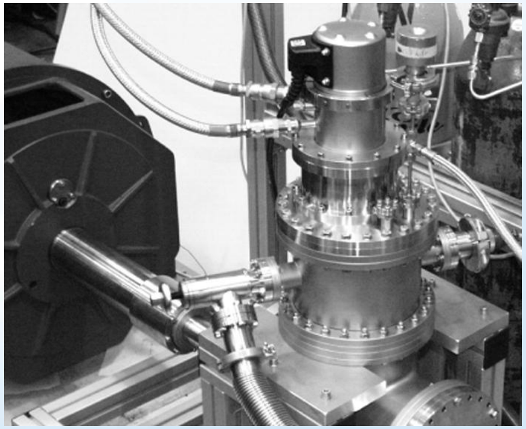
HTS SC Machines

Neon-operated commercial GM crycooler (thermosiphon) in the foreground of a Bi-HTS race-track coil for a 400 kW synchronous motor (in blue) (Siemens).





Completed cold mass of rotor (SC coils and filler pieces) on pole former before bandaging and application of superinsulation.



Closed-cycle rotor cooling system, GM cryocooler inserted from top, motor shaft on the left.

HTS Wire Development

1) SuperPower-Inc., Schenectady, NY – 2G (ReBCO) coated conductor
2) AMSC, Devens, MA – 2G (ReBCO) coated conductor
3) SuNAM, Korea – 2G (ReBCO) coated conductor
4) Sumitomo Electric Industries (SEI), Japan – 1G (DI-BSCCO-2223) wire
5) Hypertech Research, Columbus, OH – MgB_2 wire.

Table 5.6.2 Summary of HTS wire characteristic data in 2013.

Parameter	Super power	AMSC	SuNAM	DI-BSCCO	MgB_2
Material type	ReBCO	ReBCO	ReBCO	BSCCO-2223	MgB_2
Critical current, I_c (A)	480	500	390	200	2000
Temperature at quoted I_c (K)	77	77	77	77	20
Wire width (mm)	12.2	12.3	12.2	4.6	1
Wire thickness (mm)	0.1	0.32	0.20	0.26	1
Copper stabilizer thickness (mm)	0.045	0.1	0.09	—	—
Critical tensile strength at 77 K (MPa)	550	150 (RT)	700	130	—
Critical axial tensile strain at 77 K (%)	0.45	—	0.4	0.2	—
Critical bend diameter in tension at RT (mm)	11	100	30	70	—
Critical bend diameter in compression at RT (mm)	11	100	30	70	—

Operating Temperature

ReBCO
30–35K

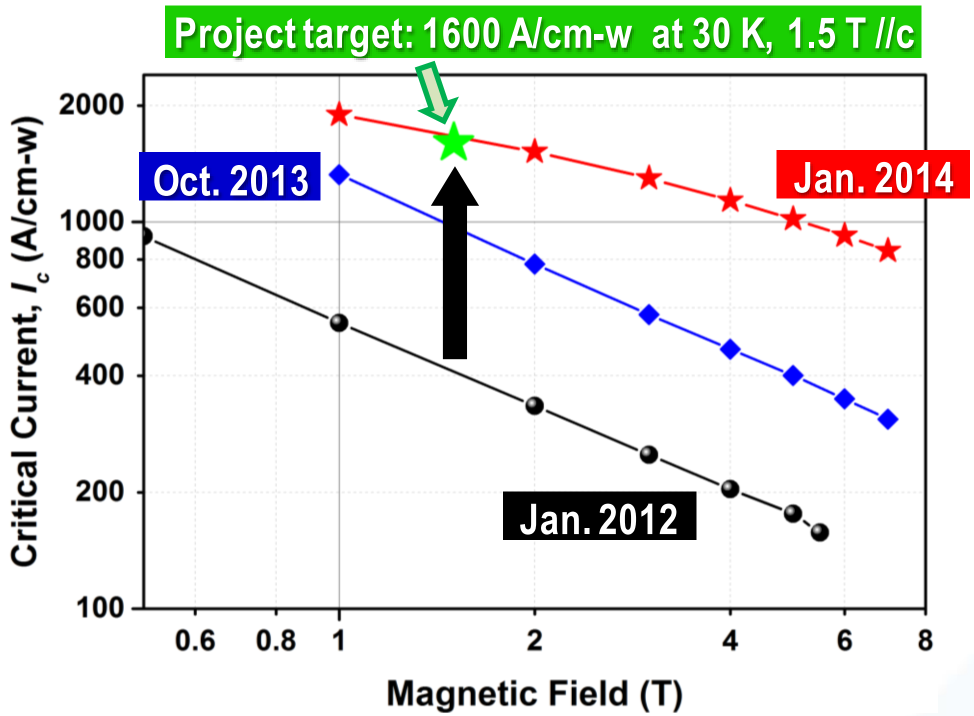
DI-BSCCO
30K

MgB_2
20 K

"Applied Superconductivity", ed. Paul Seidel, 2015

Superconducting Wires for Direct-Drive Wind Generators

Qiang Li (PI) - Brookhaven National Lab



Superconducting Direct Drive Wind Generator (10MW+)

BNL scientist Qiang Li discusses next-generation superconducting wires with US Energy Secretary Ernest Moniz at February 2014 ARPA-E Energy Innovation Summit

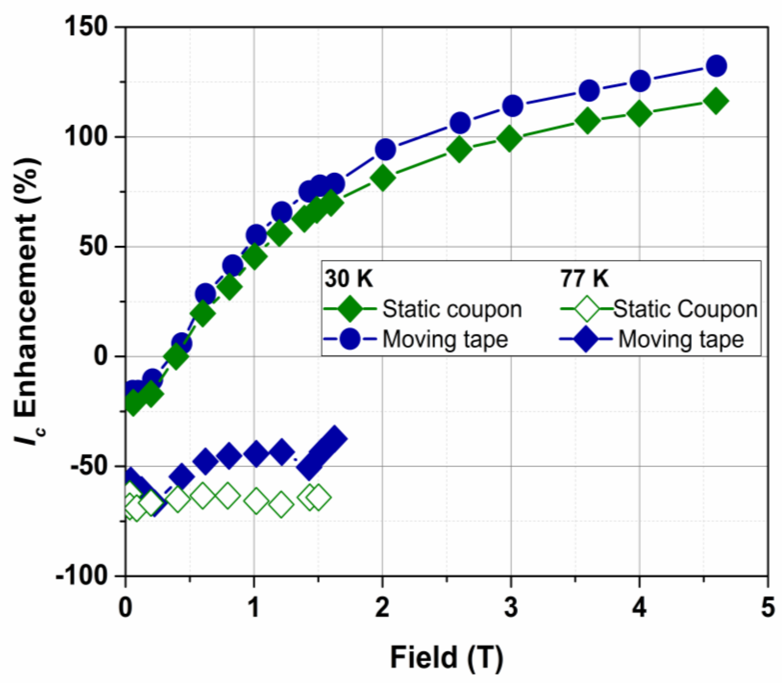
ARPA-E REACT Project kick-off in Jan. 2012

http://www.bnl.gov/newsroom/news.php?a=24697

Superconducting Wires for Direct-Drive Wind Generators

Qiang Li (PI) - Brookhaven National Lab

At Brookhaven National Laboratory, we demonstrated a **roll-to-roll irradiation process**[1] on an AMSC's production length 2G wire (46 mm wide and over 80 meters long) that resulted in doubling the critical current in the 4 – 50 K operating regime targeted for rotating machine applications and high field magnet applications.[2] The roll-to-roll irradiation was carried out with ion energies readily accessible with commercial electrostatic generators.



I_c enhancement at 30 and 77K (relative to an unirradiated control sample) of a stationary short sample and a moving tape after irradiation with 18 MeV Au to a dose of $6x10^{11}$ Au/cm^2

References
1. Patent pending (BNL/AMSC)
2. To be presented at EUCAS 2015

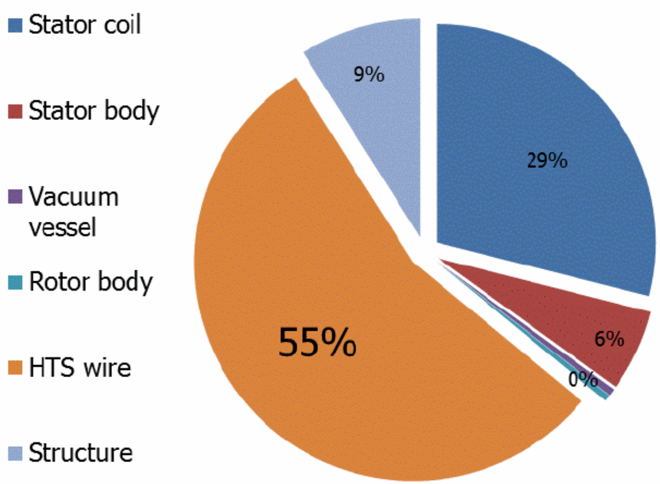
HTS 2G wire price (current $150-250/KA-m)

Total cost of a 12 MW SCSG (Future price of HTS wire; 50 $/kA-m)

Material	Cost
Copper	20.5 $/kg
Stainless steel	1.5 $/kg
Silicon steel plate	4.1 $/kg
HTS wire	5 $/m (100 A @ 77 K)

Active parts	Weight	Material
Stator coil	48 ton	Copper
Stator body	50 ton	Silicon steel plate
Vacuum vessel	12 ton	Stainless steel
Rotor body	11 ton	Stainless steel
Total length of HTS wire		
HTS wire	375 km	

Parts	Cost
Stator coil	985 k$
Stator body	206 k$
Vacuum vessel	18 k$
Rotor body	16 k$
HTS wire	1,873 k$
Structure	306 k$



Total cost of the 12 MW SCSG
=3,403,709 $, ~4M$
~15% of total system price

Ref. Design of direct-driven permanent-magnet generator for wind turbines, Anders Grauers
Ref. SuperPower (4mm HTS wire)

Challenges for HTS motors

Applications

- **slow speed (<20 r/min)**

  wind generators, ship propulsion motors

- **(100–250 r/min)**,

  Industrial motors, generators

- **(1200–3600 r/min)**
  synchronous condensers, high-speed generators

- **(15000-r/min)**
  direct coupling to gas turbines.

- Rotor winding and cooling

  (3D winding, pancake coils?)

  (MgB_2 wire is better)

- Coolant transfer to rotor (solved)

- Stator winding consideration

- User acceptance

- HTS wire cost, in field performance

Superconducting Motors

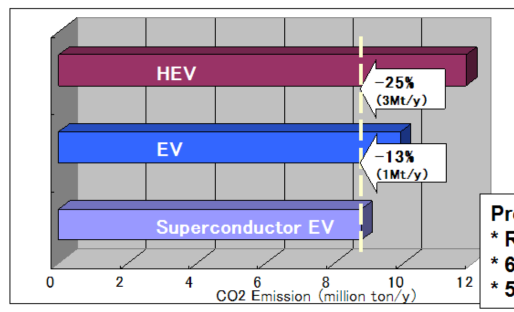
Q. Li – Brookhaven National Lab
ARPA-E Advanced Motor Drive Commercialization, March 15, 2012, Orland, FL

HTS Electric Vehicle

To validate the potentials and challenges of DI-BSCCO, the Electric vehicles droved by HTS Motor were developed.

< Verified performance >

1. Max Speed 85 km/h
2. Max Torque 120 Nm
3. Max Power 31 kW



Precondition
* Route bus
* 600 thousands
* 50,000km/y

Expected Energy Loss Reduction >10%

HTS Motor

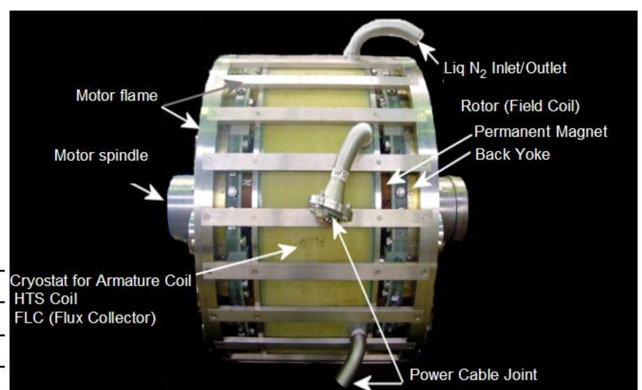
HTS Electric Vehicle (June 2008)

Superconducting Motor for Ship propulsion

HTS motor : Small & Light, Cooled by liquid Nitrogen, High efficiency, Low CO_2 Emission

World's Largest L Nitrogen cooled HTS Motor with High Torque Density: 1.8×10^4 Nm/m^3

Rated Output	400 kW (365 kW)
Rated Speed	250 rpm
Rated Torque	15.3 kN·m (14 kN·m)
Dimension	1.2 m(Dia.) -0.8 m(Length)



Ingenious Dynamics

Figures and Photos - Courtesy of Dr. K. Sato, Sumitomo Electric Industries, Japan,

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