Commercial Rules for Making Money with Superconducting Applications (Does it pass the $ test)

Use Superconductors when you cannot figure out any other way to do the application, and you really need the application (Accelerators, MRI, NMR, resistive fault current limiters).

Use Superconductors when weight and size is an issue, and you are will to pay for those advantages (fuel savings-eliminating a gear box) or offer a cost savings verses the non-superconducting approach (aircraft, ship, train, truck & bus, inductive fault current limiters, wind turbine generators)

Use Superconductors if energy (or electric) efficiency justifies higher initial equipment costs and you are willing to live with the payback (ROI) period.

Use superconductors when project is of a size, that selling price will be lower (manufacturing cost) than the non-superconducting version (generators, motors, transformers, cables

Hyper Tech

What is state of the art in superconductors that are suitable for motor applications?

Active Generator- Motor Programs -Wind (8), Aircraft (4), Ship (2), Train, (1), Land based-stationary

Variety of Designs at least (7) on Wind Turbine Generators alone

Most common - Superconducting rotor- Cu stator or reversing it with superconductor stationary on outside.

Recently all cryogenic –(stator designs with low loss MgB_2 wires)

For all cryogenic machine -Trade off of stator speed superconducting (2-8000 rpm) vs non-superconducting (20,000 rpm plus)

Superconductor options NbTi, Nb_3Sn, MgB_2, BSCCO, YBCO

Iron based machine `1,2 or 3 T field on wire at 4K, 8K, 20K, 30K

Air core machine – starting at 6T on wire, 4K, 8K, 15K, 20K

Hyper Tech

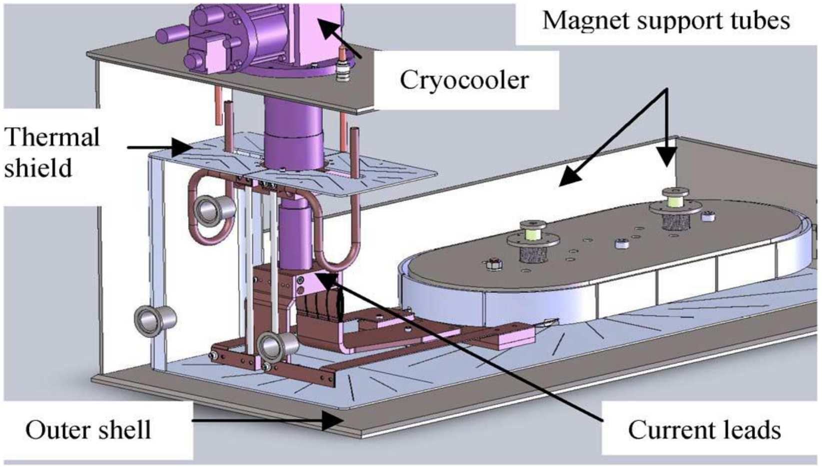
Potential for Large Conduction Cooled Nb3Sn Coils

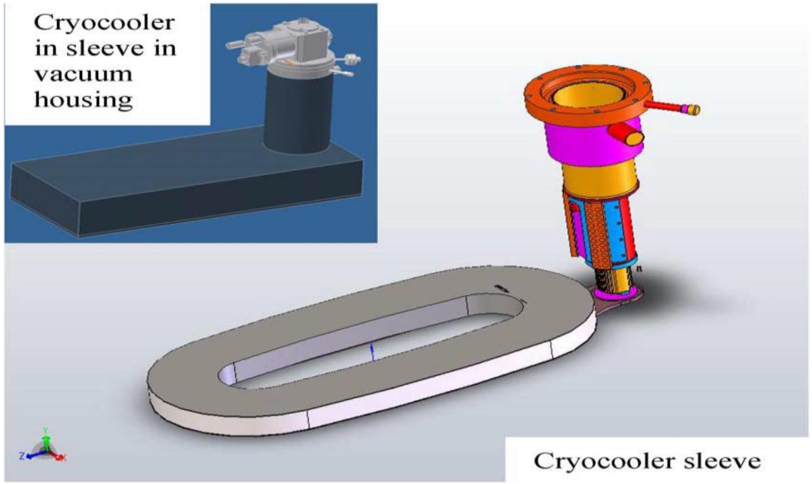
Motivation (conduction cooled 2-10 tesla on the wire)

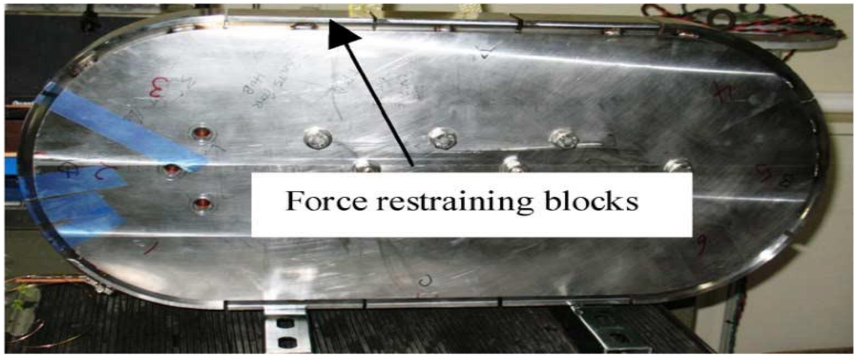
1. In the last few years the Jc of Nb_3Sn has increased from 1000A/mm2 -12T-4K to 2500 A/mm2 -12T-4K,
2. The filament sizes have gotten smaller so Nb_3Sn wires are stable in the 1-10T range.
3. The $/kA-m of Nb_3Sn can drop below NbTi at 10T-4K
4. Nb_3Sn can offer temperature margin 4-8 K for Conduction Cooled Large Magnets thus eliminate He bath cooling.

What is the potential for conduction cooled motors and generators using Nb_3Sn ?

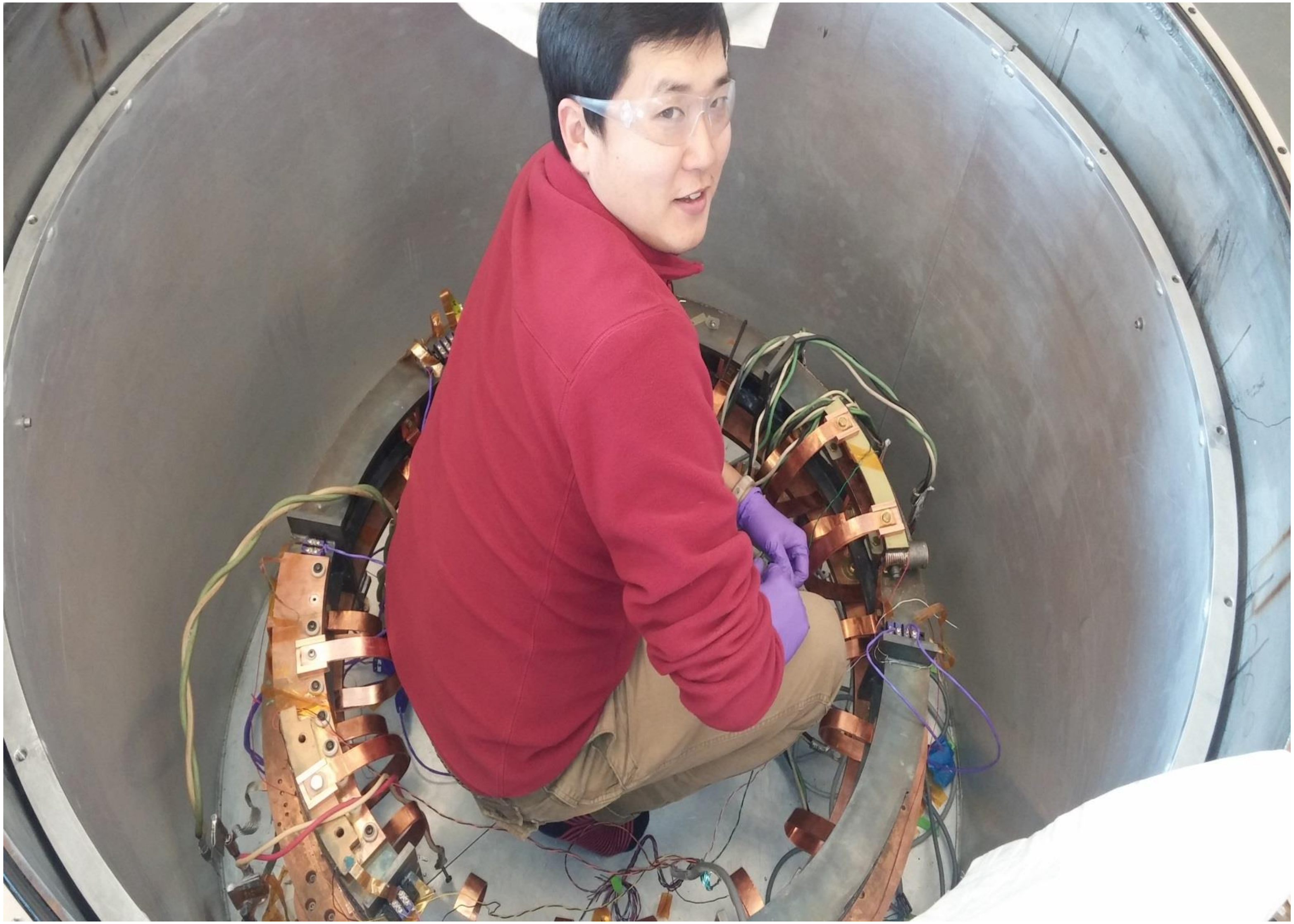
GE –Reported ASC -2010 . GE used ITER Nb3Sn Wire . There is now Nb3Sn wire available with 3- times the Jc at 4K-12 T. Much more margin to operate at 8K, Considerable manufacturing capacity available worldwide



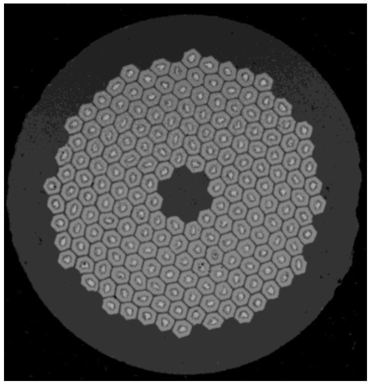




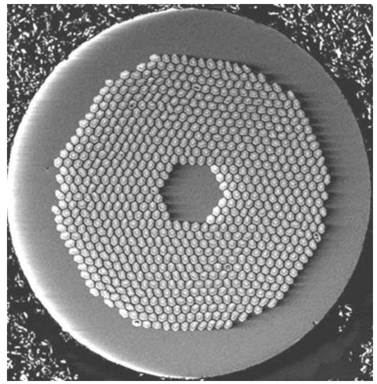
Hyper Tech



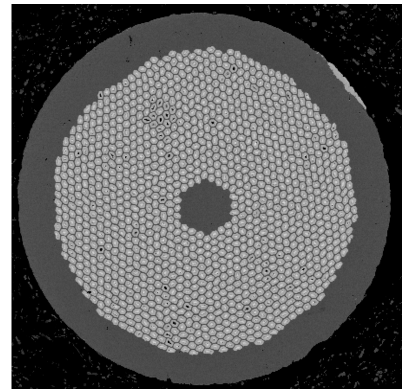
Smaller Filament Size (d_{eff}) for 0.7 mm Strands



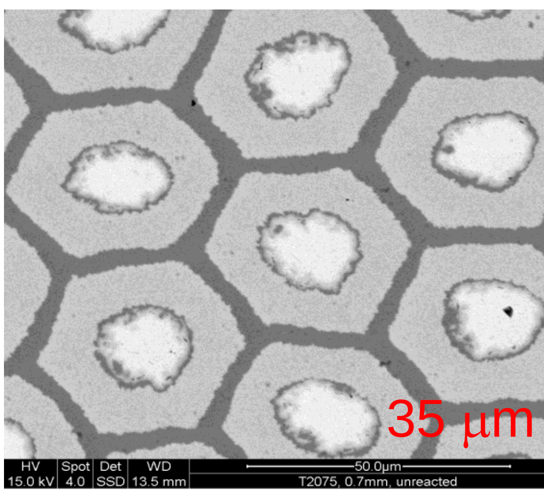
36 µm, 192

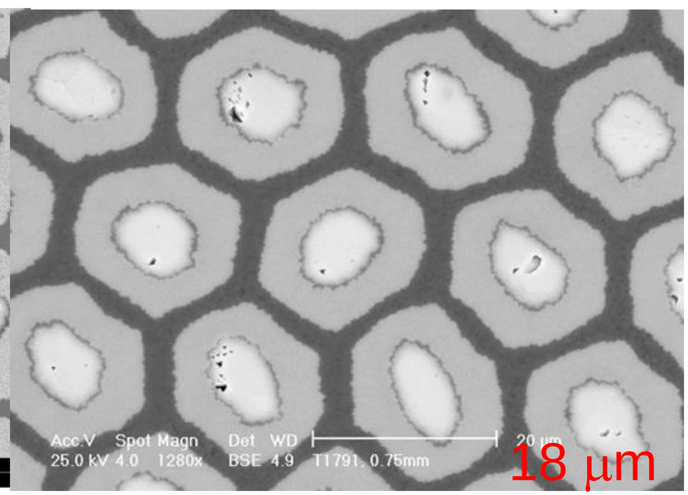


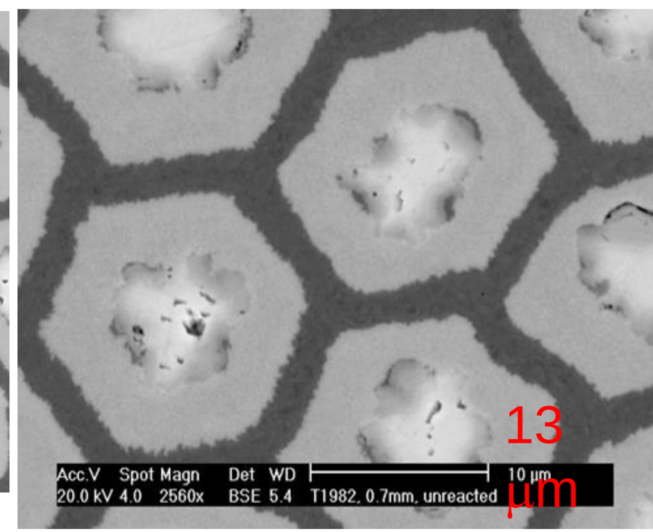
18 µm, 744



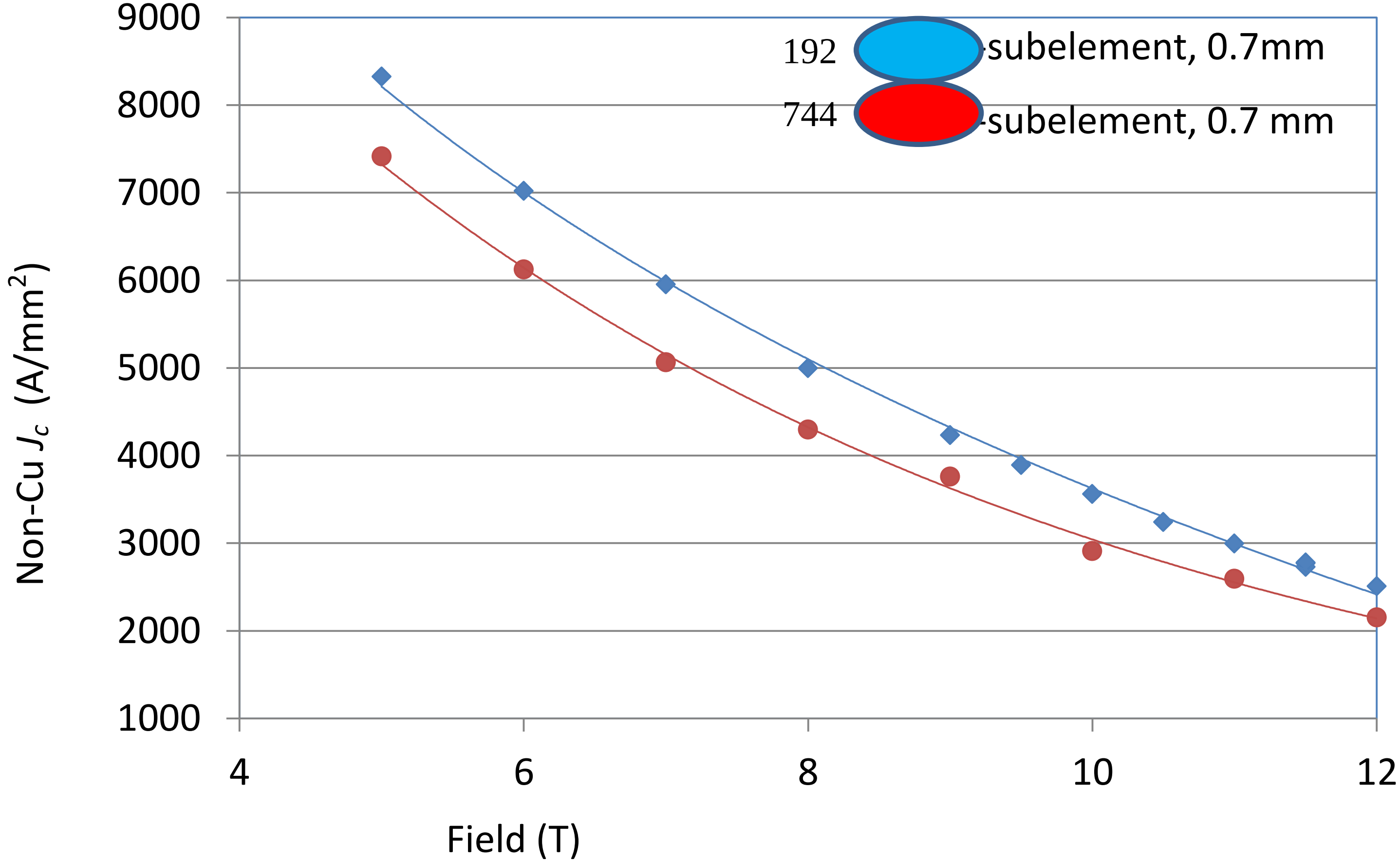
12 µm, 1248







J_cs Results



192
-subelement, 0.7mm
744
-subelement, 0.7 mm
9000
8000
7000
6000
5000
4000
3000
2000
1000
Non-Cu J_c (A/mm^2)
4
6
8
10
12
Field (T)

Future Potential for Hyper Tech's Nb3Sn APC Wires

Hyper Tech's current and future APC Nb3Sn compared to CERN's desired future specification

Patent Pending

. Red- Indicates meeting the CERN specification requirements

Manufacturer	Type Assuming 50% Cu and 50% non-copper	Jc – A/mm2 12T-4K	Jc-A/mm2 16T-4K	Jc-A/mm2 20T-4K	Diameter 0.8 mm Filament Size, microns	RRR	Length , m
Desired Specification			1500 minimum	500-1500	Less than 20	Greater than 150	Greater than 5000
Hyper Tech	Tubular Approach Solid Sn	2000-2600	900-1100	200-400	10-80	50-200	500-5000
Experimental							
Hyper Tech APC (1) not optimized	Binary Needs R&D funding	3050	1780	1200	20	200	5000
Hyper Tech APC (2) optimized	Ternary Calculated potential Needs R&D funding	12400	9000	5600	20	200	5000
Potential Improvement		4 X	6X	14X			

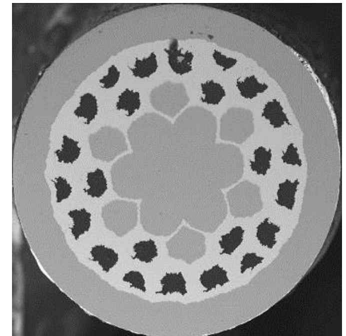
(1) Demonstrated –Non optimized layer Jc of 9,600 A/mm2 at 12T-4K in Binary Nb3Sn, normal layer Jc in binary is 3500 A/mm2 at 12T-4K, in ternary normal layer Jc is 5000A/mm2 at 12T-4K.

(2) Calculated- Optimized Jc in Ternary Nb3Sn

Hyper Tech

Standard 1st Gen MgB_2 wire products

- Up to 5 – 6 km (25 kg billets)
- C-doped B, Nb, Cu, Monel

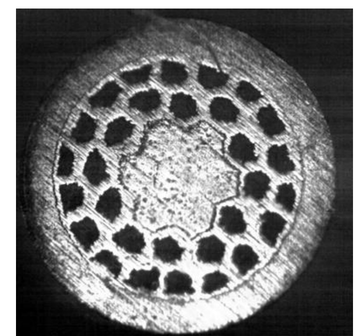


24-NM

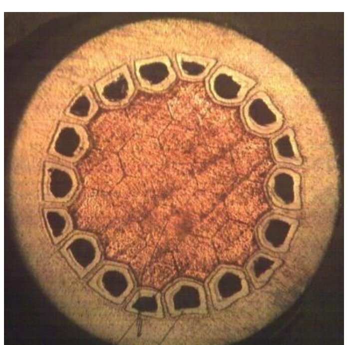
36-CM

Lock-in conductor design

- J_c (4K, 4T) = 200,000 A/cm^2
- J_c (20K, 2T) = 140,000 A/cm^2

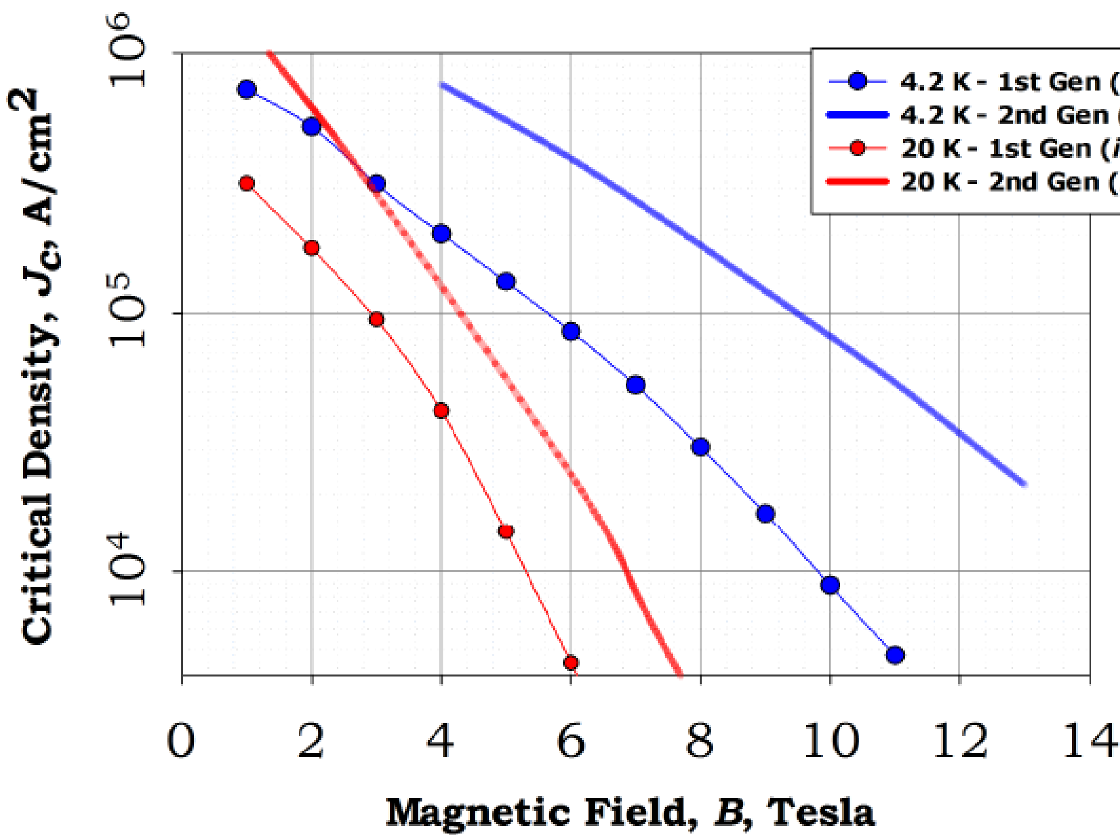


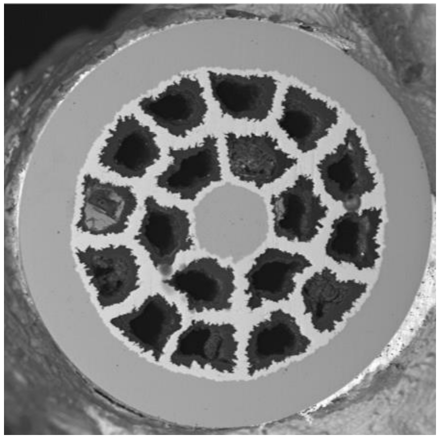
30-NM



18-MS

2nd Generation (AIMI) MgB_2





Comparison of 1st Gen (*in-situ*) and 2nd Gen (AIMI) J_c at 4K and 20K

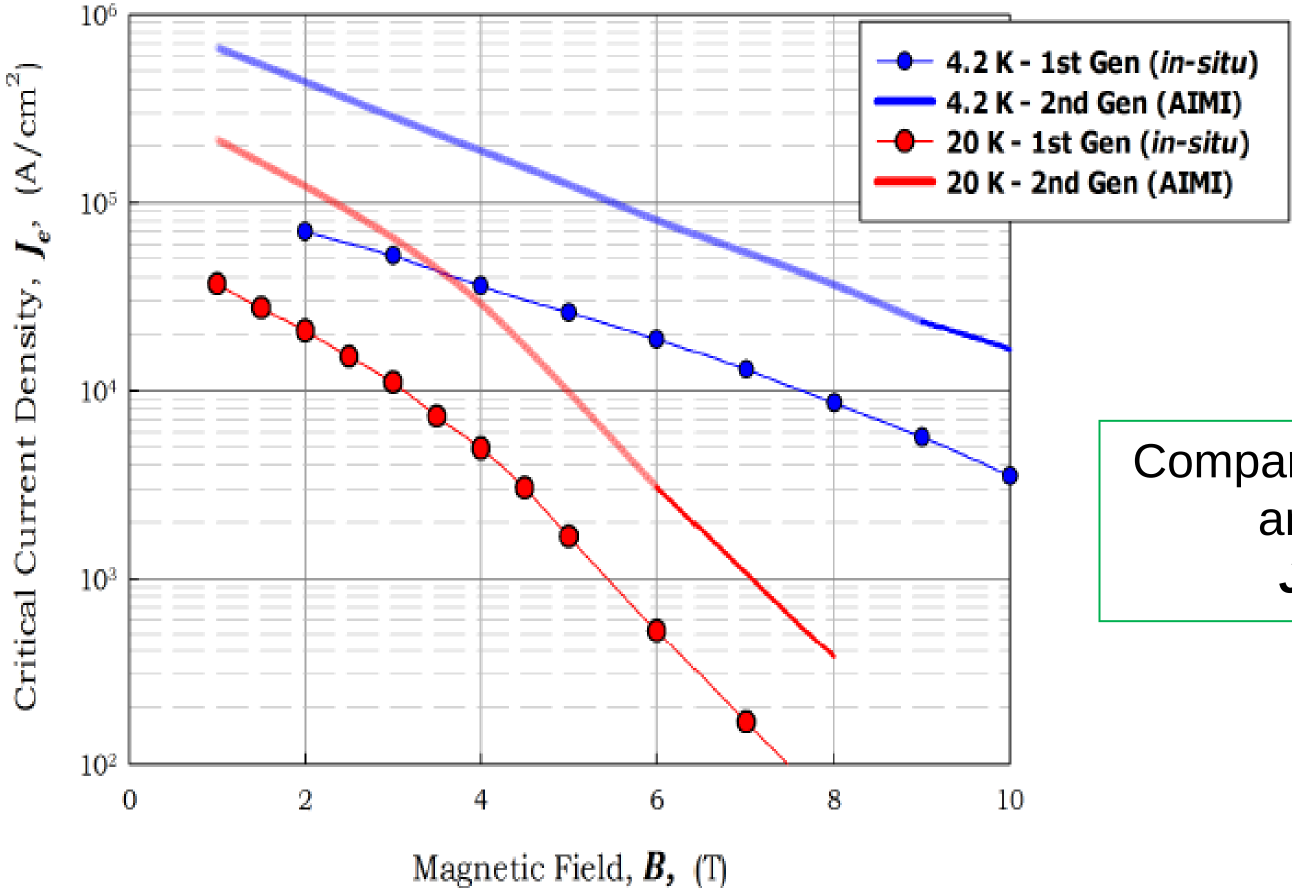
- 2nd Generation: Higher layer J_c; lower MgB_2 fill factor.
- 1st Generation: Lower layer J_c; higher MgB_2 fill factor.

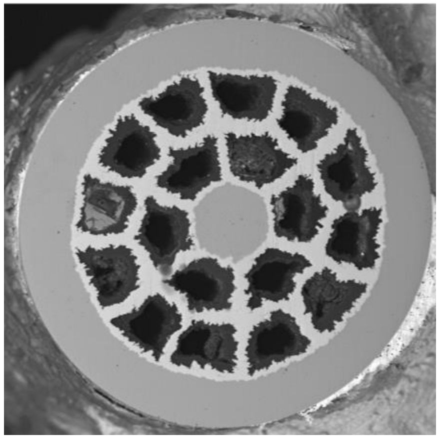
As with 1st Gen MgB_2, C doping introduces substantial B_{c2} enhancement,.

Hyper Tech

2nd Generation (AIMI) MgB_2

"AIMI" refers to Advanced Internal Magnesium Infiltration





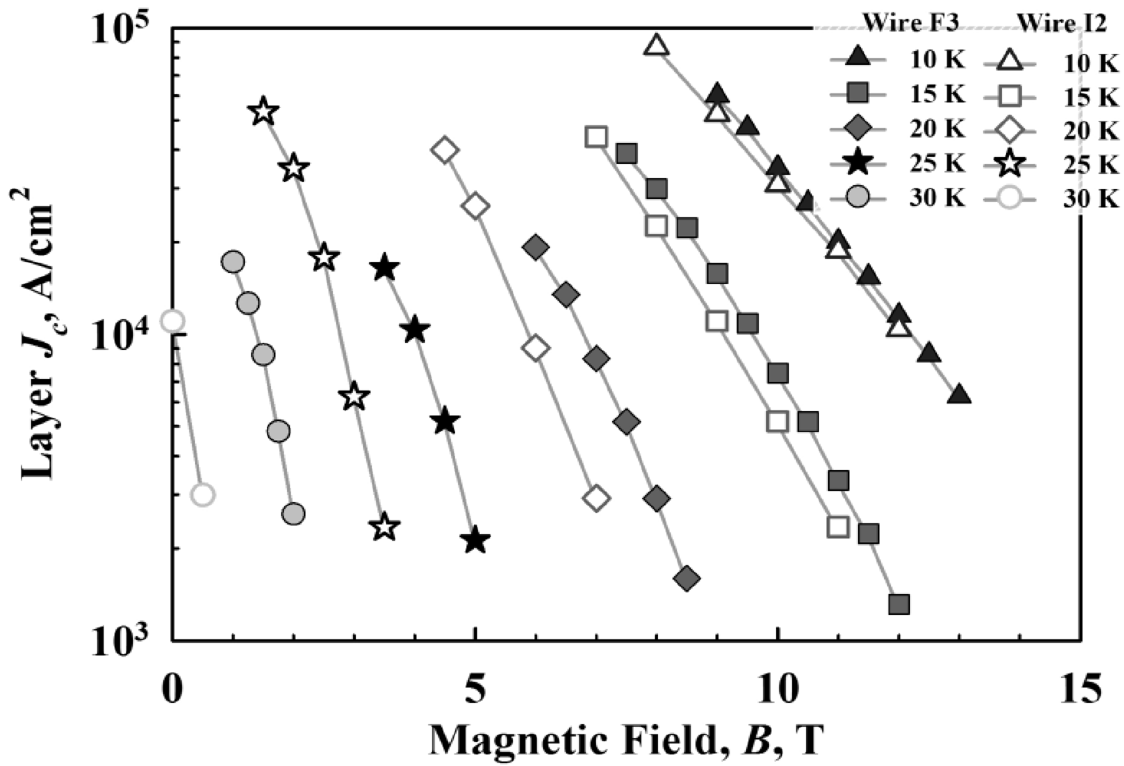
Comparison of 1st Gen (*in-situ*) and 2nd Gen (AIMI) J_e at 4K and 20K

Hyper Tech

Increasing B_{c2} at 20 – 30 K

Comparing PIT (1st Gen) to AIMI (2nd Gen)

- C-doping increases B_{c2} at 4 K
- Dy_2O_3 does at 20-30 K



G Li, APL 105 (2014) 112603

Strand	10 K	15 K	20 K	25 K	30 K
Dy_2O_3/C co-doped, F3	14.7	11.4	8.2	4.9	2.0
C-doped, I2	14.4	10.9	7.0	3.4	0.4

What is the present performance when compared to today's cost optimized Nb_3Sn (i.e., price in $/kA-m)?

Price Performance Comparisons at 2T (considering iron in machine)

Price –Performance $/kAm for motors and generators	Present $/kAm	Projected future 3 years- $/kAm	Projected Future 6 years $/kAm
MgB2 4K-2T	7	0.5-1.5	0.5
MgB2 10K-2T	10	0.7-2.30	0.7
MgB2 15K -2T	15	1-3	1
MgB2 -20K -2T	20	1.5-5	1.5
YBCO -4K-2T	50	25	10
YBCO -20K -2T	100	50	20
YBCO -30K -2T	150	75	40
BSCCO 2223 30K-2T	125	125	125
Nb3Sn 4K-2T-ITER type	3.50	3.50	3.50
Nb3Sn 8K-2T-ITER type	7	7	7
Nb3Sn 4K-2T – high Jc tube type	1.42	1.42	1.42
Nb3Sn 8K-2T – high Jc tube type	2.84	2.84	2.84
Nb3Sn 8K-2T- optimized APC tube type			1.40
NbTi 4K-2T	0.5	0.50	0.50

Hyper Tech

What is the present performance when compared to today's cost optimized Nb_3Sn (i.e., price in $/kA-m)?

Price Performance at 6T and 10T – air core machine

Price –Performance $/kAm for motors and generators	Present $/kAm	Projected future 3 years- $/kAm	Projected Future 6 years $/kAm
MgB2 4K-6T	50	3.5-10	3.5
MgB2 10K-6T	70	4.9-15	4.9
YBCO -20K -6T	80	40	16
YBCO -30K -6T	120	60	25
BSCCO 2223 4K-6T	125	125	125
Nb3Sn 4K-6T-ITER type	4.90	4.90	4.90
Nb3Sn 8K-6T-ITER type	9.80	9.80	9.80
Nb3Sn 4K-10T ITER type	11.70	11.70	11.70
Nb3Sn 4K-6T – high Jc tube type	2.17	2.17	2.17
Nb3Sn 4K-10T- high Jc tube type	4.68	4.68	4.68
Nb3Sn 8K-6T – high Jc tube type	4.34	4.34	4.34
Nb3Sn 4K-6T- optimized APC tube type			0.60
Nb3Sn 8K-6T – optimized APC tube type			1.20
Nb3Sn 4K-10T optimized APC tube type			0.75
NbTi 4K-6T	1.00	1.00	1.00
NbTi 4K-10T	10	10	10

Hyper Tech

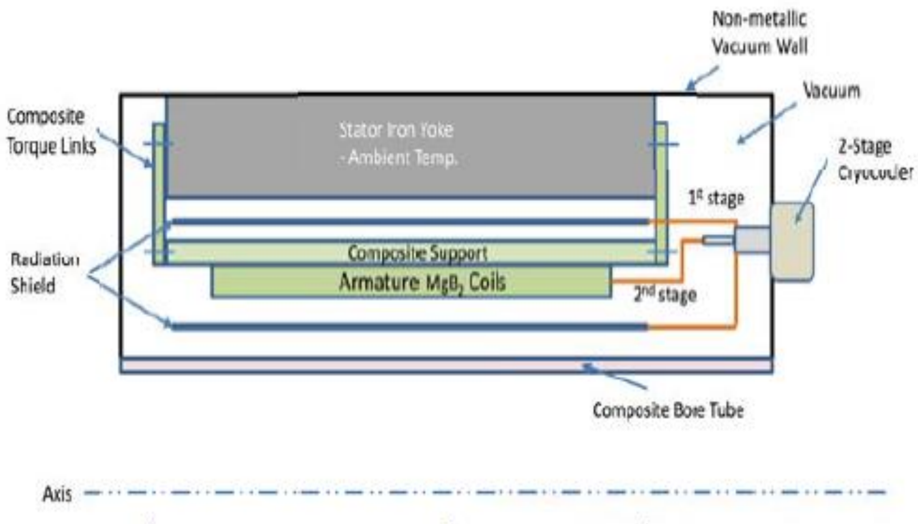
What is/are the key performance metrics (in the order of importance) if this technology is to be considered in base (land based, stationary?) industrial motors?

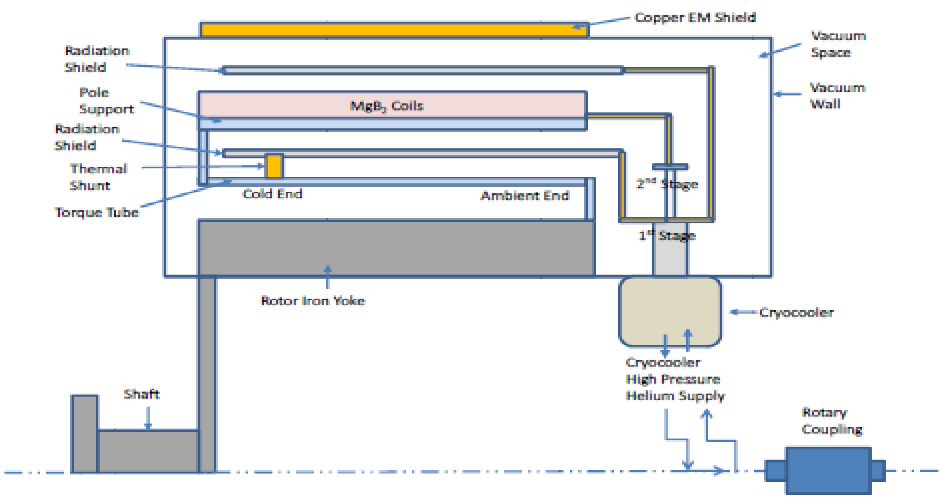
Argument and projections that there is a high probability that in 5, 10, or 15 years, that a superconducting motor of XX MW(hp) and larger, is less expensive manufacturing than non-superconducting approach, and life cycle costs (O&M) are equal or less than non-superconducting options.

Metrics:
Cost projections (multiple option to reduce risk),

Proven reliability – need commercial high end motors and generator s (Aircraft, ships) in market place

Once the high end motors are in the marketplace, price will come down for basic industrial motors.





Magnesium Diboride enables <u>all cryogenic</u>

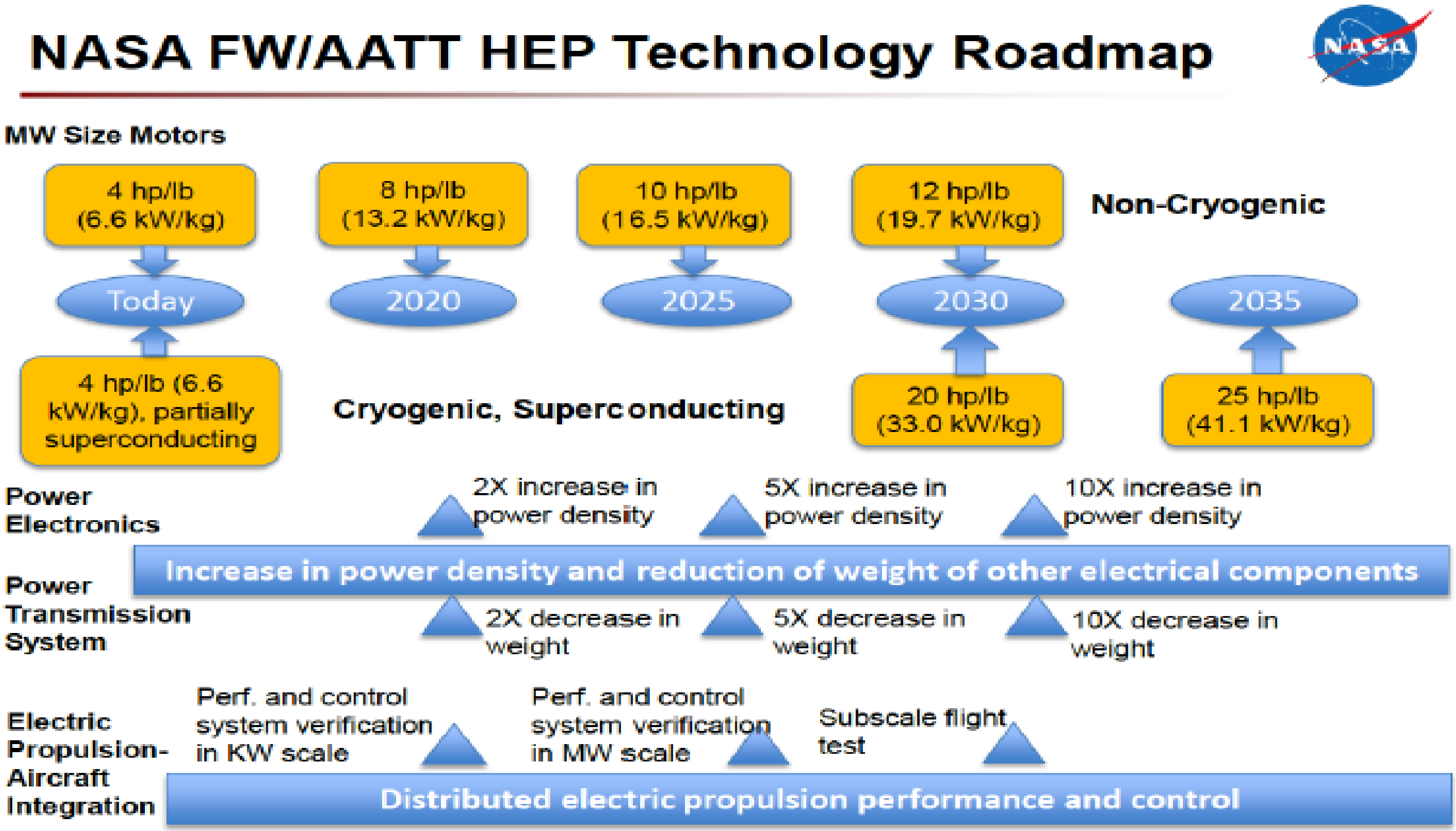
Low cost *5*-10 MW plus wind turbines for land and offshore

Design of a 10MW
all cryogenic machine with
both a superconducting
rotor and stator at 15-20K

Estimate for 10 MW is a total weight of **<u>50 metric tons</u>** and **<u>$2.0 million</u>** U.S. if build
in volume of 12 or more per
year- see article

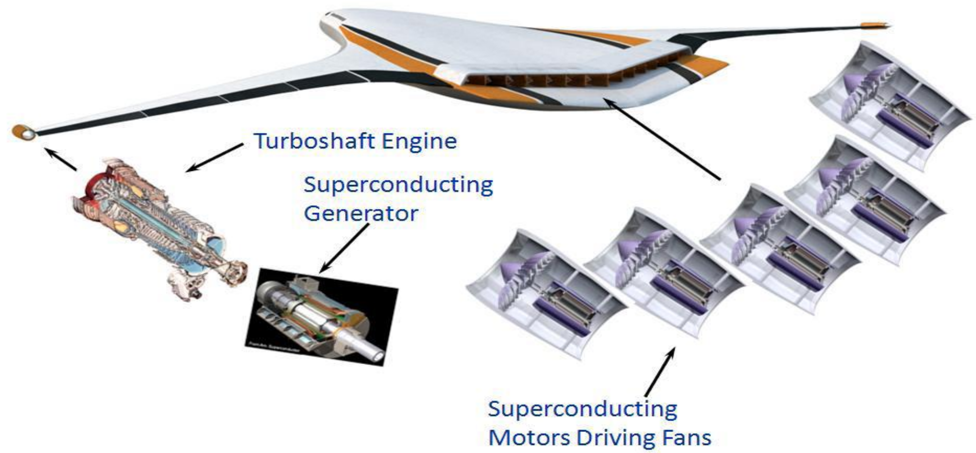
Hyper Tech

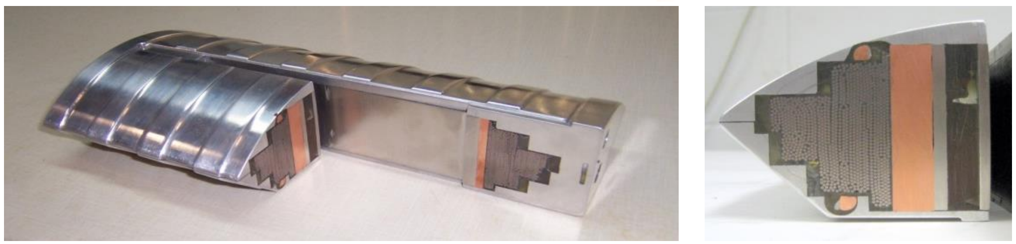
All Cryogenic Superconducting Aircraft



Fine Filament Wires Can Enable Low AC Loss Stators

- NASA is funding the development of finer filament MgB_2 wire for superconducting stators. The goal is for an all-electric aircraft that uses all cryogenic motors and generators. Achieving 10 µm filaments for stators in the 1-200 Hz range.

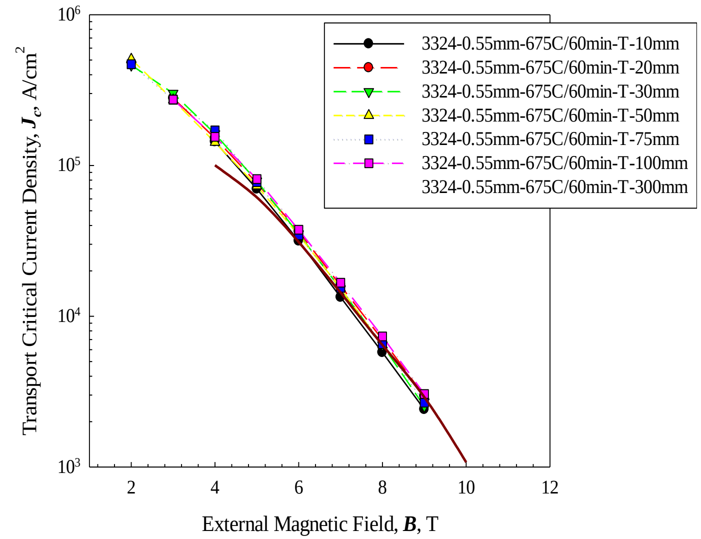




MgB_2 rotor coils have been made for NASA 2 MW 15,000 rpm generator

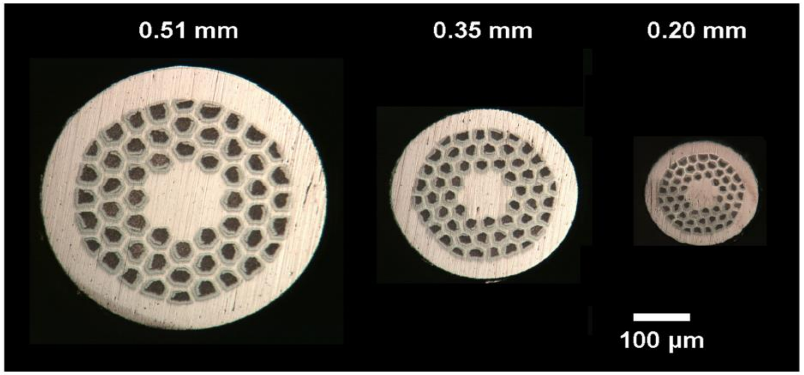
Low AC loss MgB_2 conductor development

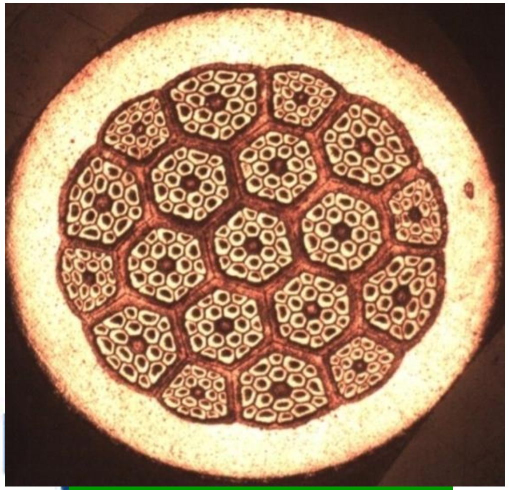
<u>Successful strand design recipe</u>:
- small d_{eff} *and* resistive matrix
- higher T_{op} (e.g. 20K);
- Small twist pitch
- Non-magnetic sheaths



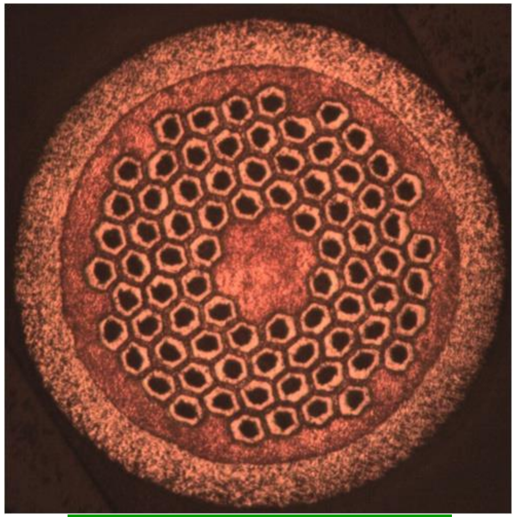
J_c measured with 10 µm filaments at 0.29 mm. Work progressing to get obtain 10 µm filaments with larger wire diameters.

J_c maintained with twist pitches as low as 5mm.





342 filaments



78 filaments

Benefit is Fuel Savings

National Aeronautics and Space Administration

Mission Fuel/Energy Consumption

	Weight lbs (kg)	Mission Fuel Consumption lbs (kg)	Mission Energy Consumption BTU(MJ)	Mission Energy Reduction
777-200LR Class Aircraft	768,000 (348.400)	280,000 (127.000)	5.2E+09 (5.5E+06)	
N3-X BSCCO/Cryocooler	515,000 (233.600)	85,000 (38.560)	1.6E+09 (1.67E+06)	70%
N3-X MgB_2/LH_2	496,000 (229.800)	76,000 (34.470)	1.5E+09 (1.55E+06)	72%

Fundamental Aeronautics Program
Fixed Wing Project

www.nasa.gov

What is an acceptable return on investment (ROI) for superconducting machine at MW range (cost and time)?

ROI -5 years or less is business standard (short term view)

ROI- 20 years electricity savings (long term view)

Need to see superconducting motor for transportation first

You have fuel savings and increased cargo & freight capacity
Over the lifetime of the mode of transportation –plane, ship,
Train, bus, and truck.

Hyper Tech

What are the key challenges in improving wire performance and/or the manufacturing process to reduce price close to Nb_3Sn (i.e., improve in critical current, increase in yield, waste reduction etc.)?

For MgB2
1st generation wire – manufacturing volume and lower cost barrier material
2nd generation wire – improving uniformity over length

For (Re)BCO
Increasing manufacturing capacity per $ of capital equipment
Increasing processing speeds of all the steps in the manufacturing
Increasing pinning and increasing superconductor thickness

For Nb3Sn (high performance Nb3Sn)
Low Jc Nb3Sn (ITER) wire- has settled out on price
Finer filaments to be more stable at lower fields 0-6 T fields
High Jc thru grain size refinement and artificial pinning

For BSCCO (2223 or 2212)
Have to dramatically reduce the Ag content (70%), this is tough because O2 needs to get in and out during heat treatment

Hyper Tech

Are there any other pre-requisites that need to be addressed prior to demonstrating the technology readiness for industrial motors?

Single cryostat vs multiple cryostats (depends on size)
Rotating seals if cryogenic portion is rotating (depends on speed)
All cryogenic or partial cryogenic (depends speed and low AC loss conductor

What would be a good power level for prototype demonstration (i.e., 1 MW or larger)?

For land based industrial, if size and weight is not an issue, commercial machine needs to be high power.

But as a stepping size demo, pick a size that has commercial benefit for transportation. Get dual use out of demonstration 1-2MW medium speed motor or generator, all cryogenic. This has immediate commercial potential.

Hyper Tech

What would be a good component level demonstration for the technology?

Depends on size, and purpose

Items to de-risk,

Cryogenics (rotating couplings –low speed and high speed)

Stator Coil fabrication (non metal, high thermal conduction materials)

Method of cooling (liquid cryogen vs conduction cooling)

Deciding on a design? Many design options to choose from in literature based on the application

Cryostat (single or each coil in own cryostat –depends on size and application).

Hyper Tech

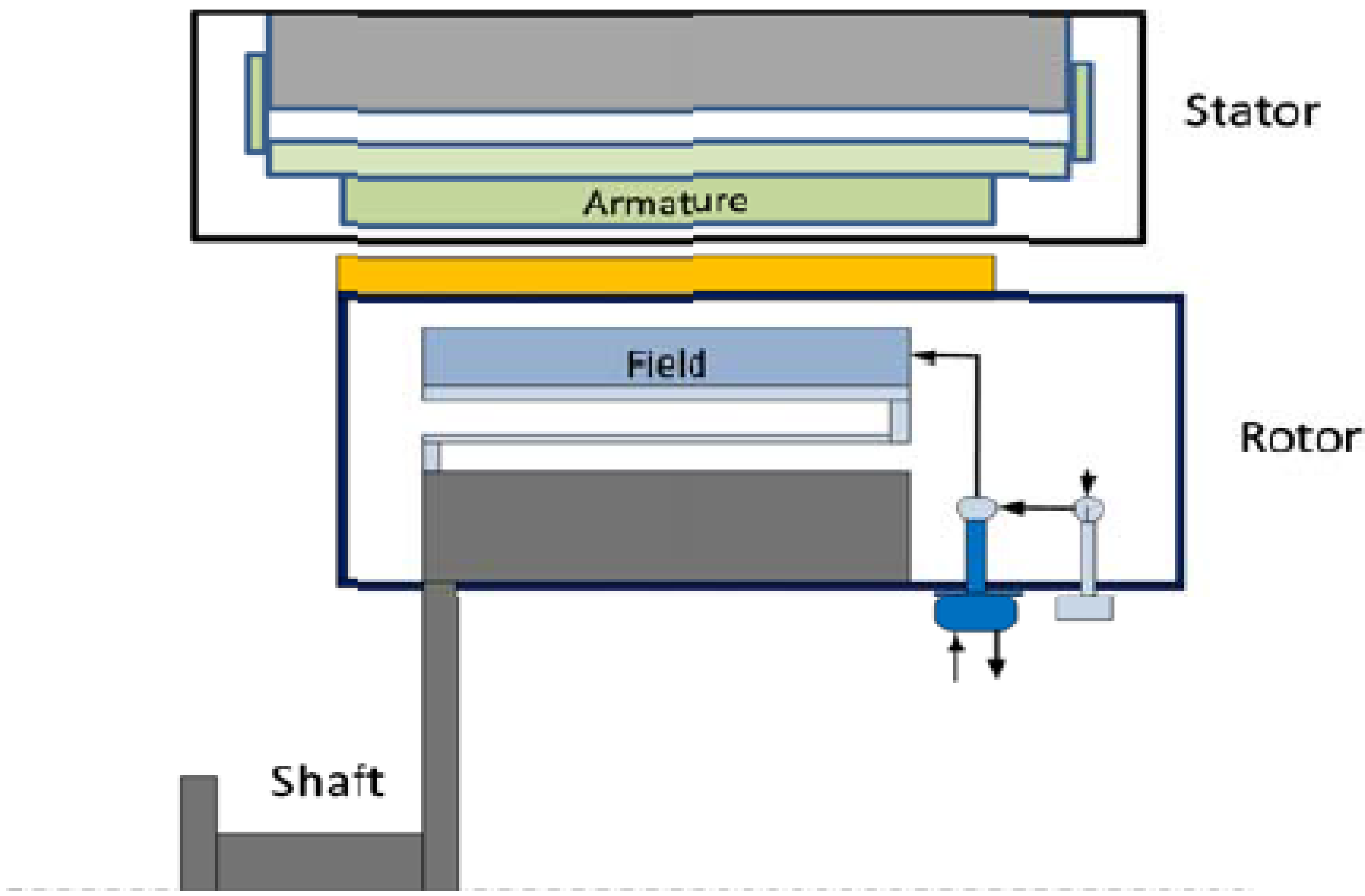


Figure 3: Overall generator configuration

Superconducting Wind Turbine Generator Employing MgB_2 Windings Both On Rotor And Stator

Swarn S. Kalsi[1], *Fellow, IEEE*

[1]Kalsi Green Power Systems, Princeton, NJ 08540 USA

Table I

SPECIFICATION FOR THE 10 MW GENERATOR DESIGN

Parameter	Value
Rated output, MW	10
Rated speed, RPM	10
Rated power factor	0.99 lag
Number of phases	3
Number of poles	24
Maximum diameter, m	<5
Maximum axial length, m	<2

Table VII

SUMMARY OF LOSSES AND EFFICIENCY AT RATED LOAD

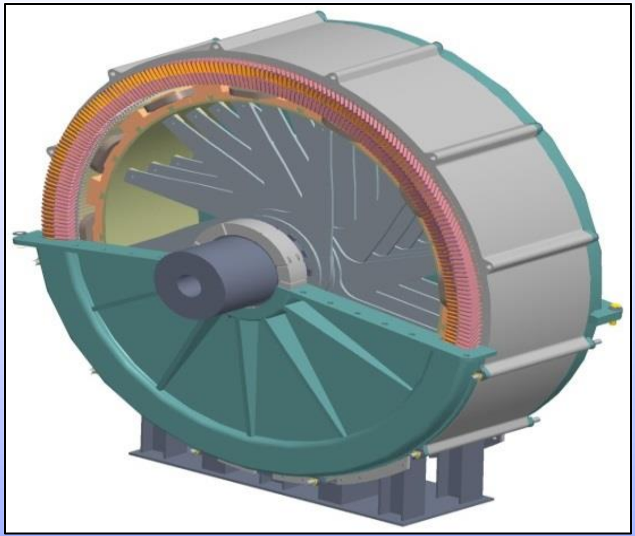
Parameter	Rotor	Stator
Winding conduction loss, W	24	216
Current lead loss at 55K, W	80	160
Radiation through MLI at 55K, W	117	124
Conduction along torque transfer components		
First stage at 55K, W	64	6
Second stage at 15K, W	21	
Safety margin for calculated losses	50%	50%
Load on the 1st stage (including safety margin), W	392	440
Load on the 2nd stage (including safety margin), W	68	324
Number of cryocoolers needed (including one spare)	9	20
Total input power to cooler compressors, kW	68	150
Iron yoke losses, W		60
Total losses at rated load, kW	218	
Efficiency at rated load	98%	

Table IX

GENERATOR AND COMPONENT COST

Component	Cost, 1000$
ROTOR	
MgB_2 winding,	746
Current leads	1.0
Cryogenic instruments	6.0
MLI insulation	0.4
Mechanical components (including iron yoke)	300
STATOR	
MgB_2 winding	142
Iron yoke	136
Torque links	12
MLI insulation	0.4
ACCESSORIES	
Brushless exciter	14
Vibration pickup	2
Cryocoolers	693
Coolant transfer system	36
ASSEMBLY & TESTING	20
COST OF POWER ELECTRONICS	1000
TOTAL GENERATOR COST	3168

Hyper Tech Generator features- 5MW design expandable to 20MW using superconducting rotor and copper stator



Designed in modules to transportable and be assembled in the field

No component weight is more than 14 tons for a 5MW -76 ton generator

Power (MW)…………………..…. 5.0

RPM ……………………….…….. 10

Configuration : Synchronous

Voltage (kVrms) ….………… 1,350

Number of Poles …………..… 24

Diameter (M) ………………... 4.87

Length (M) ………………….. 1.74

Weight (Tons) ….……..…….. 76.5

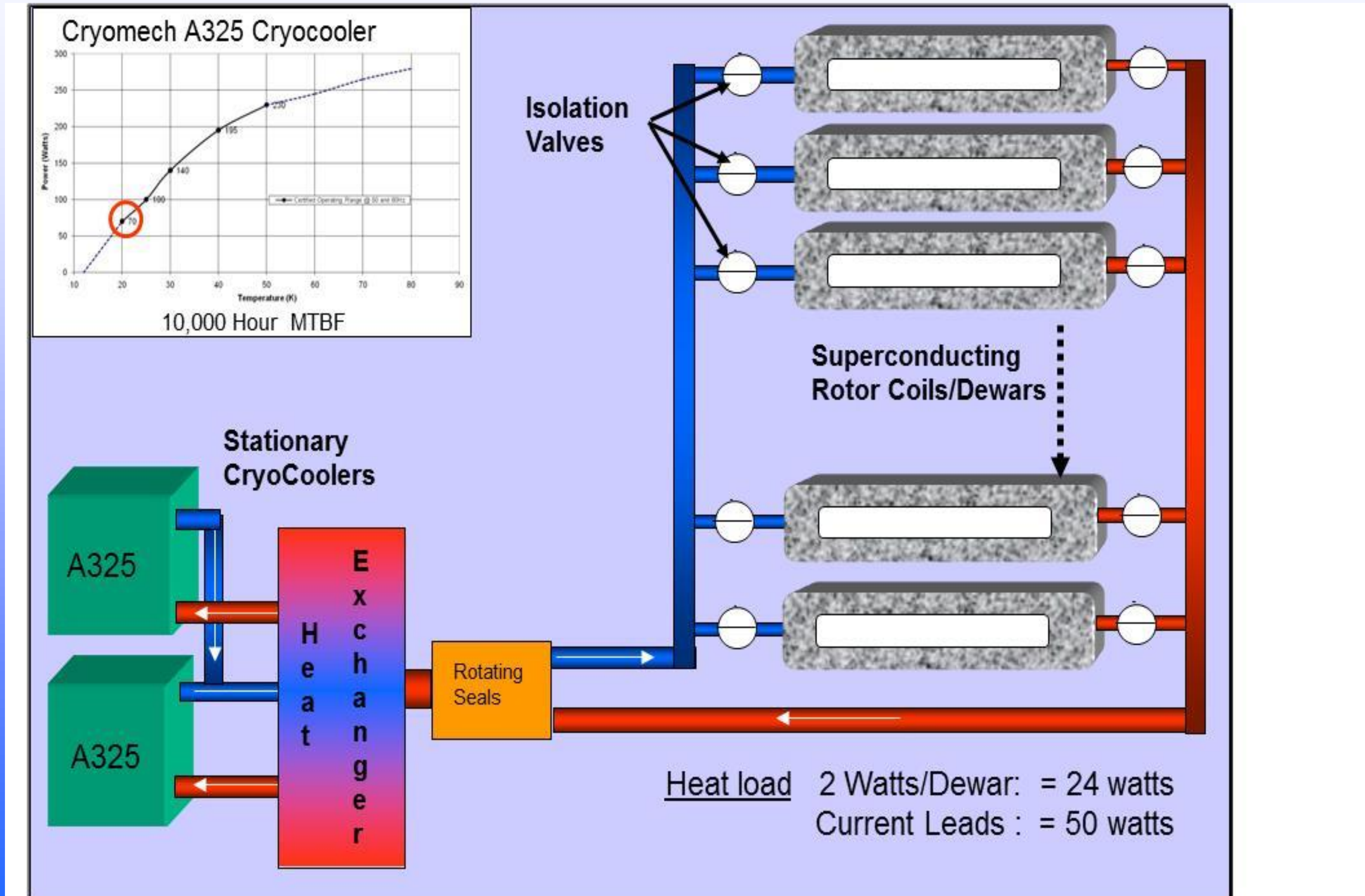
Superconductor ……..…… MgB_2

Rotor Coolant … LHe/GHe

Stator Conductor ……….Copper

Stator Coolant … Water or EGW

Cryogenics



Cryomech A325 Cryocooler
Power (Watts)
Temperature (K)
10,000 Hour MTBF
Isolation Valves
Superconducting Rotor Coils/Dewars
Stationary CryoCoolers
A325
A325
Heat Exchanger
Rotating Seals
Heat load 2 Watts/Dewar: = 24 watts
Current Leads : = 50 watts

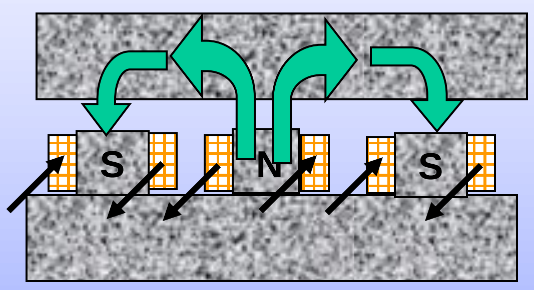
HyperTech Lightweight Superconducting Generator Technology

Generator Technology	Generator Weight (Tons)			
	5MW	**10MW**	**15MW**	**20MW**
Hyper Tech Superconducting Generator **(Preliminary)**	76.5	123.3	162.3	205.9
Km of MgB_2 wire	30	60	90	120

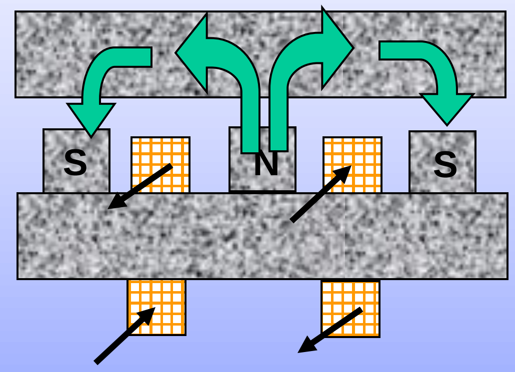
24 poles, one rotor coil was driving 2 poles
Each superconducting rotor coil (12 total) for 5 MW generator contains a single 2,293 meter long piece of MgB_2 superconducting wire (27.5km total per generator) operating at 20K-3T

For 10 MW – 55 km. 2nd generation wire

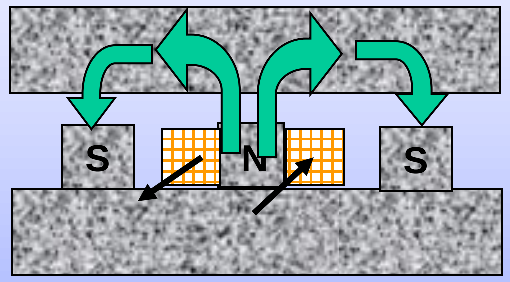
Novel Rotor Coil Configuration Eliminates Half the Typical Rotor Coils…High Reliability



Traditional Rotor Configuration
One Small Radially Oriented Coil Around each Pole

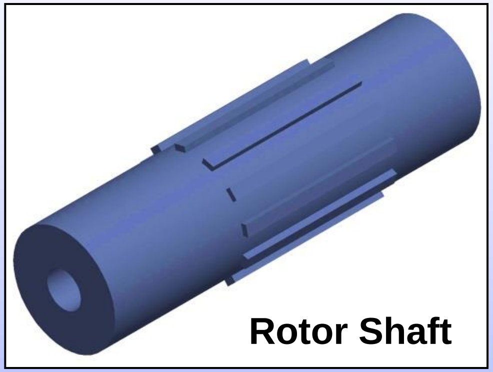


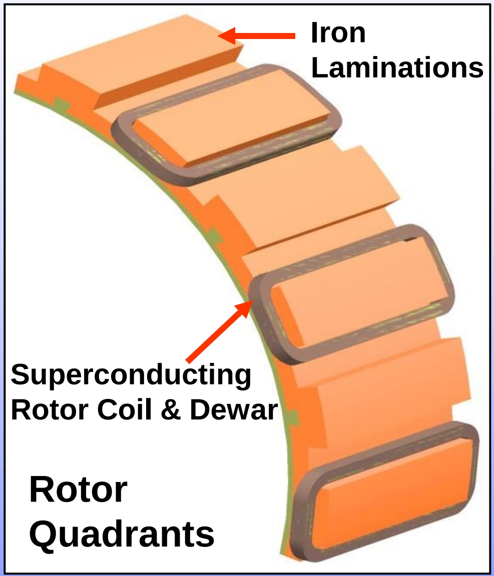
Equivalent Rotor Configuration
One Large Peripherally Oriented Coil Between Poles

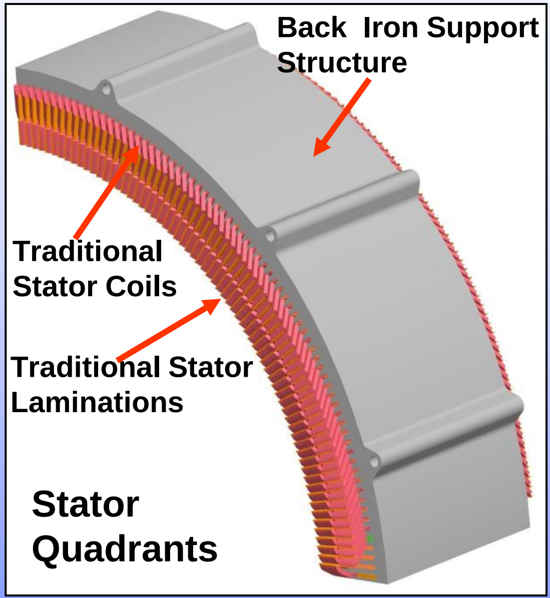


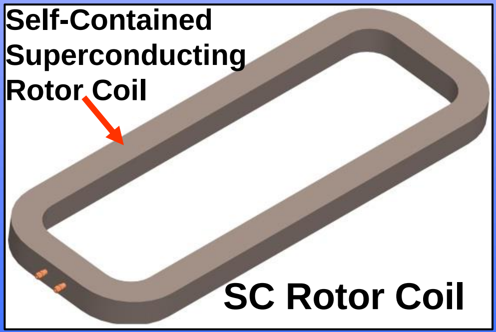
Our Equivalent Configuration
One Large Peripherally Oriented Coil on Half the Poles

5-20 MW Modular Generator Components

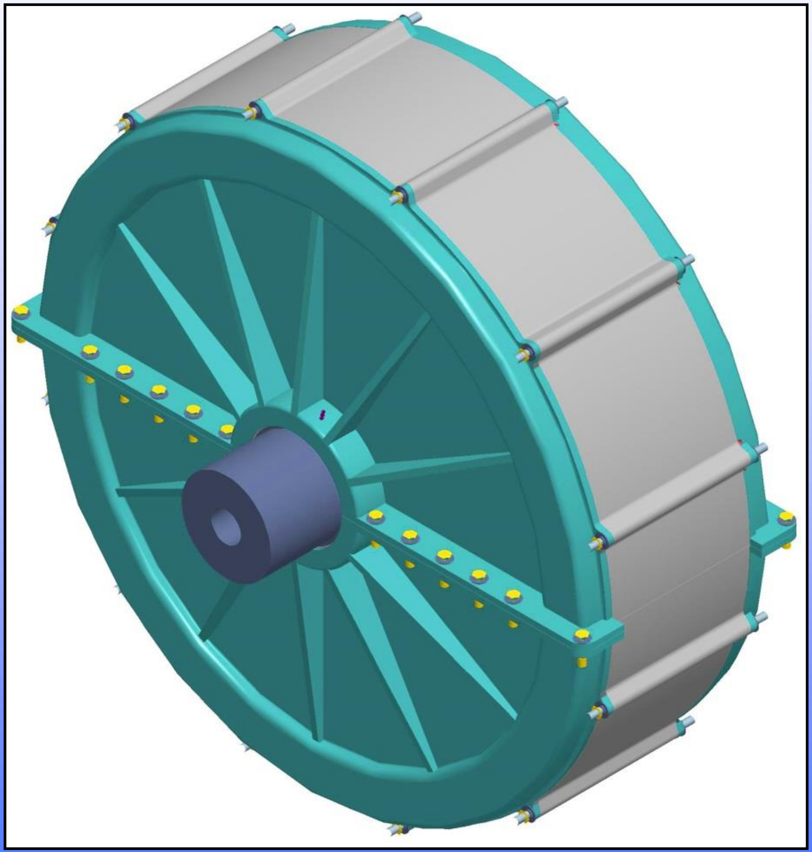








Completely Assembled Generator



Specifications

Power (MW) ……………..…… 5.0

RPM ……………………..……….. 10

Configuration ……. Synchronous

Voltage (kVrms) …………. 1,350

Number of Poles …………..... 24

Output Frequency (Hz) ……. 2.0

Diameter (M) ……………... 4.87

Length (M) ………………… 1.74

Weight (Tons) …..………..….. 76.5

Superconductor …….…… MgB_2

Rotor Coolant … LHe/GHe or LH_2

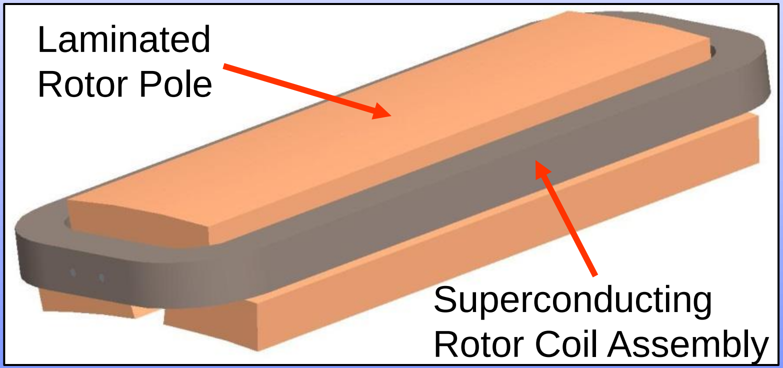
Stator Conductor ……….Copper

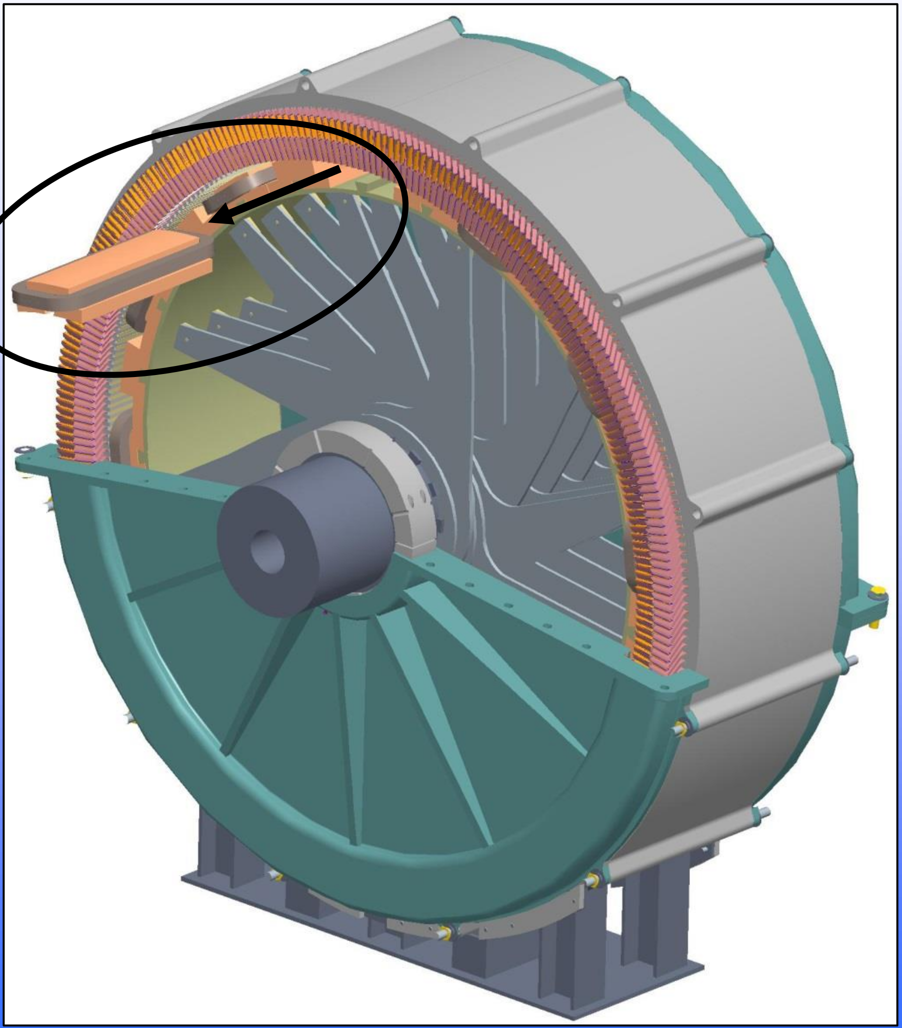
Stator Coolant … Water or EGW

Generator Repair Procedures

Remove Defective Rotor Pole/Superconducting Coil Assembly

STEP 2: Remove Rotor Pole Assembly with Defective Superconducting Rotor Coil

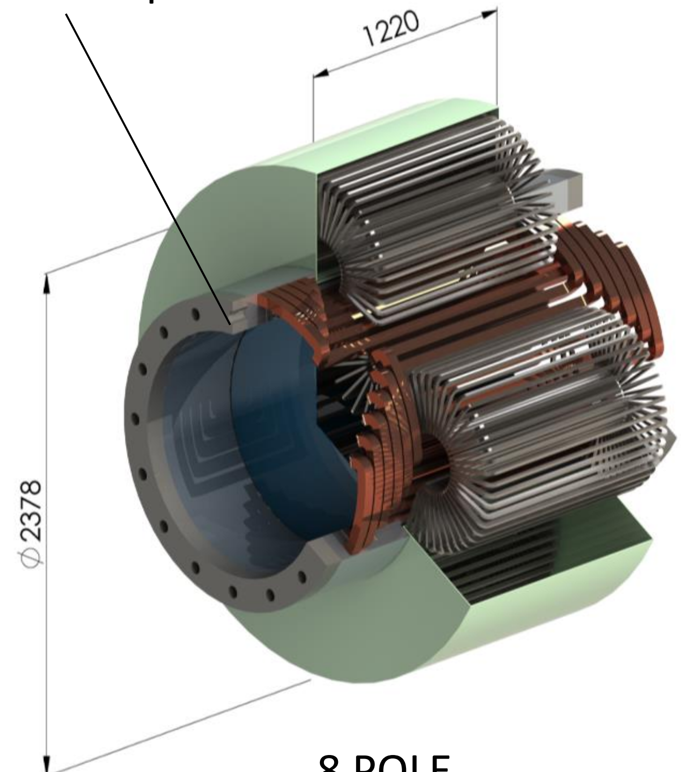




11 MW @ 150 RPM MARINE STAR TOROIDAL TECHNOLOGY

Power Total	**11 MW**	**11 MW**
Torque	**700 kNm**	**700 kNm**
Rated Rotor Speed	**150 RPM**	**150 RPM**
Rotor		
Maximum Rotor Current Density	**5 A/mm^2**	**3 A/mm^2**
Rotor Tip Speed	**9.4 m/s**	**9.4 m/s**
Rotor Diameter	**1200 mm**	**1200 mm**
No. of Independent Rotor Windings	**6**	**6**
Rotor Material	**Copper Wire**	**Copper Wire**
Rotor Weight – Copper @ 3 A/mm^2 Current Density	**3300 kg**	**1980 kg**
Rotor Weight – Copper @ 5 A/mm^2 Current Density	**1980 kg**	**1188 kg**
Rotor Weight – Copper @ 10 A/mm^2 Current Density	**990 kg**	**594 kg**
Rotor Heat Loss @ Rated Rotor Current Density	**280 kW**	**100 kW**
Estimated Efficiency - Resistive Loss Only	**97.5%**	**99.09%**
Toroid Coils		
Super Conducting Wire	**NbTi**	**Nb3Sn**
SC Wire Length based on Ø 0.76 mm wire (NbTi) or Ø 0.85 mm wire (Nb3Sn)	**251 km**	**281 km**
SC Wire Weight	**788 kg**	**1100 kg**
SC Packing Factor	**0.6**	**0.6**
Maximum Coil Current Density	**273 A/mm^2**	**304 A/mm^2**
Peak Field on Wire	**5.96 T**	**9.95 T**
Operating Temperature	**5 K**	**5 K**

Rotor Speed: 150 RPM



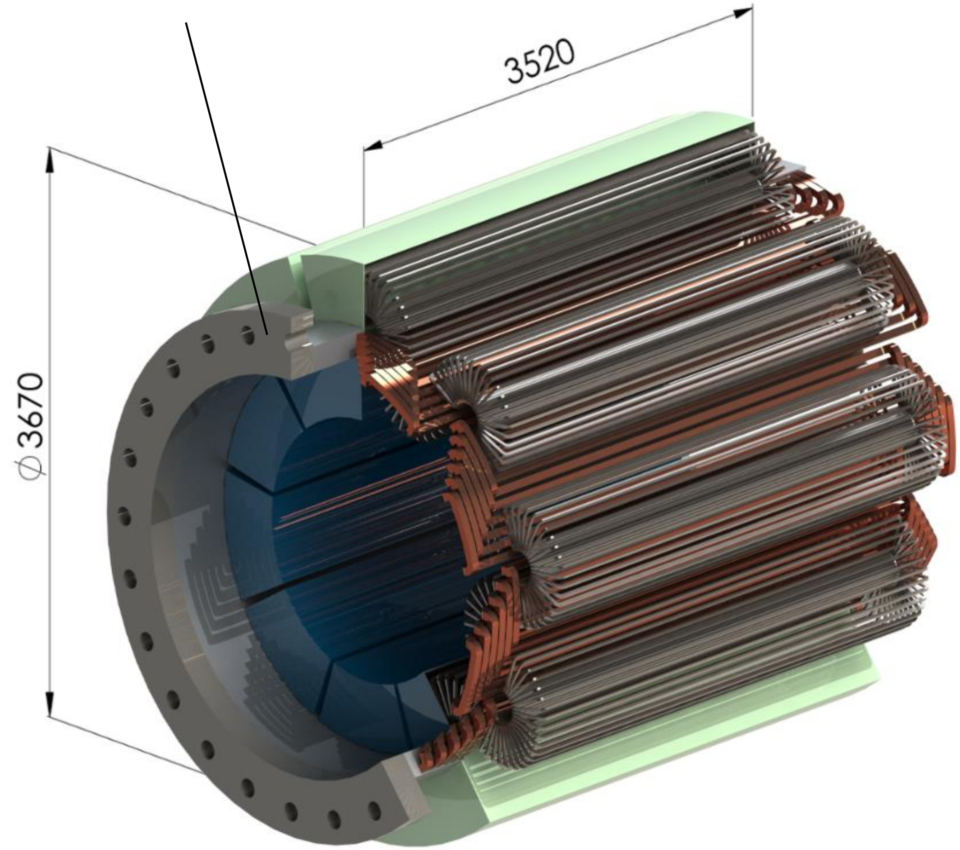
8 POLE

Note: Efficiency is quoted at maximum load and rated speed.

150 MW @ 150 RPM INDUSTRIAL STAR TOROIDAL TECHNOLOGY

Power Total	**150 MW**	**150 MW**
Torque	**10000 kNm**	**10000 kNm**
Rated Rotor Speed	**150 RPM**	**150 RPM**
Rotor		
Maximum Rotor Current Density	**5 A/mm²**	**3 A/mm²**
Rotor Tip Speed	**20.4 m/s**	**20.4 m/s**
Rotor Diameter	**2600 mm**	**2600 mm**
No. of Independent Rotor Windings	**6**	**6**
Rotor Material	**Copper Wire**	**Copper Wire**
Rotor Weight – Copper @ 3 A/mm² Current Density	**14500 kg**	**8700 kg**
Rotor Weight – Copper @ 5 A/mm² Current Density	**8700 kg**	**5220 kg**
Rotor Weight – Copper @ 10 A/mm² Current Density	**4350 kg**	**2610 kg**
Rotor Heat Loss @ Rated Rotor Current Density	**1235 kW**	**445 kW**
Estimated Efficiency - Resistive Loss Only	**99.18%**	**99.7%**
Toroid Coils		
Super Conducting Wire	**NbTi**	**Nb3Sn**
SC Wire Length based on Ø 0.76 mm wire (NbTi) or Ø 0.85 mm wire (Nb3Sn)	**1100 km**	**1440 km**
SC Wire Weight	**3385 kg**	**5640 kg**
SC Packing Factor	**0.6**	**0.6**
Maximum Coil Current Density	**273 A/mm²**	**304 A/mm²**
Peak Field on Wire	**5.96 T**	**9.95 T**
Operating Temperature	**5 K**	**5 K**

Rotor Speed: 150 RPM



Note: Efficiency is quoted at maximum load and rated speed.

Hyper Tech is also working in the area of electrical conductors that are better than copper or aluminum

Funding from Air Force (SBIR Phase I & 2)

Working on improved copper conductors using carbon nanotubes
Using a process of aligning the CNTs and electroplating.

Also working on a program funded by NASA (SBIR Phase I)

Working on Cu wires with aligned and functionalized CNTs inside the copper wires

Hyper Tech