IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Thu-Mo-PL5-01 given at MT26, 22 – 27 September 2019; Vancouver, Canada.

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Superconducting Rotating Machines

T A Coombs

27/09/2019

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Outline

- Ancient History
- Recent History
- Future ?

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View from the 70's

New Scientist 16 December 1971 157

Industrial promise of the 'super-motor'

The world's largest superconducting motor—a 3250 horsepower dc machine—has just completed its test programme driving a water pump at Fawley power station. The lessons learned are helping to provide new propulsion systems for the navy and ac generating sets in the 2000 megawatt class

Anthony Appleton
is head of the electrical engineering department at International Research and Development Ltd, Newcastle-upon-Tyne

It is now five years since the world's first superconducting motor—a 50 horsepower machine operating at 2000 rpm—was successfully demonstrated by International Research and Development at Newcastle upon Tyne. The success of this contract, for the Ministry of Defence (Navy), led the National Research Development Corporation to back further work to construct and test a full scale prototype machine. The objective in this case was to build a motor of sufficiently large rating to bring out the major development problems, and to test it in an industrial environment. The suggested rating was about 3000 hp at a few hundred rpm. Given the ability to pass heavy electrical currents through superconducting coils, the design engineer will then be able to take advantage of the zero power loss and be free of the limited fields achievable with conventional iron magnets.

After examination of a number of possible alternatives, the most convenient application for the big motor was found to be at Fawley power station near Southampton. This station has four 500 megawatt turbo-generator sets served by four large cooling water pumps, each with a rating of 3250 hp at 200 rpm. With the close co-operation and assistance of the Central Electricity Generating Board it was arranged that the superconducting motor would be installed to drive one of these pumps for a limited period before the station became fully operational. The design of the motor subsequently began in May 1967 and the works tests were completed in the IRD laboratories by the end of 1969. The motor is a homopolar machine with a superconducting field winding which provides nearly three million ampere turns to give a maximum flux density of 3·7 tesla. The winding is maintained at the very low temperature of 4·4°K by means of liquid helium supplied by a closed cycle refrigerator. The armature of the machine is at ambient temperature and is a segmented Faraday disc. An idealised diagram of the motor is shown left (Figure 2) and the principle of operation is demonstrated in the diagram over page (Figure 3).

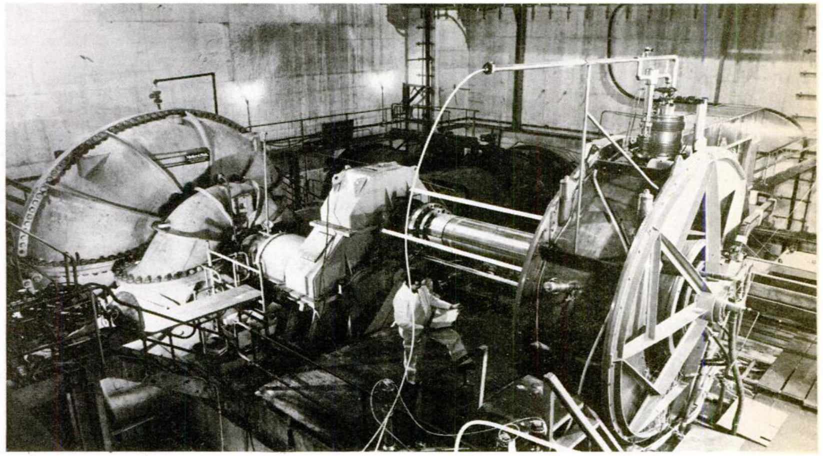

Figure 1 IRD's 3250 hp superconducting homopolar motor, installed at Fawley power station has successfully completed its demonstration trials driving a cooling water pump

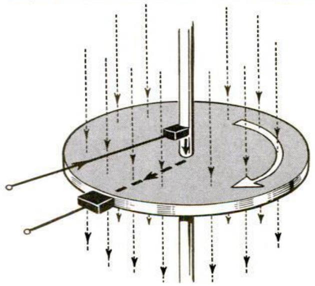

Figure 2 All homopolar machines are based on the Faraday disc. Made of conductive material, this rotates on a shaft aligned with a magnetic field (dotted lines), while current is passed through the disc radially, causing it to rotate and so develop power

The Fawley motor was first operated in

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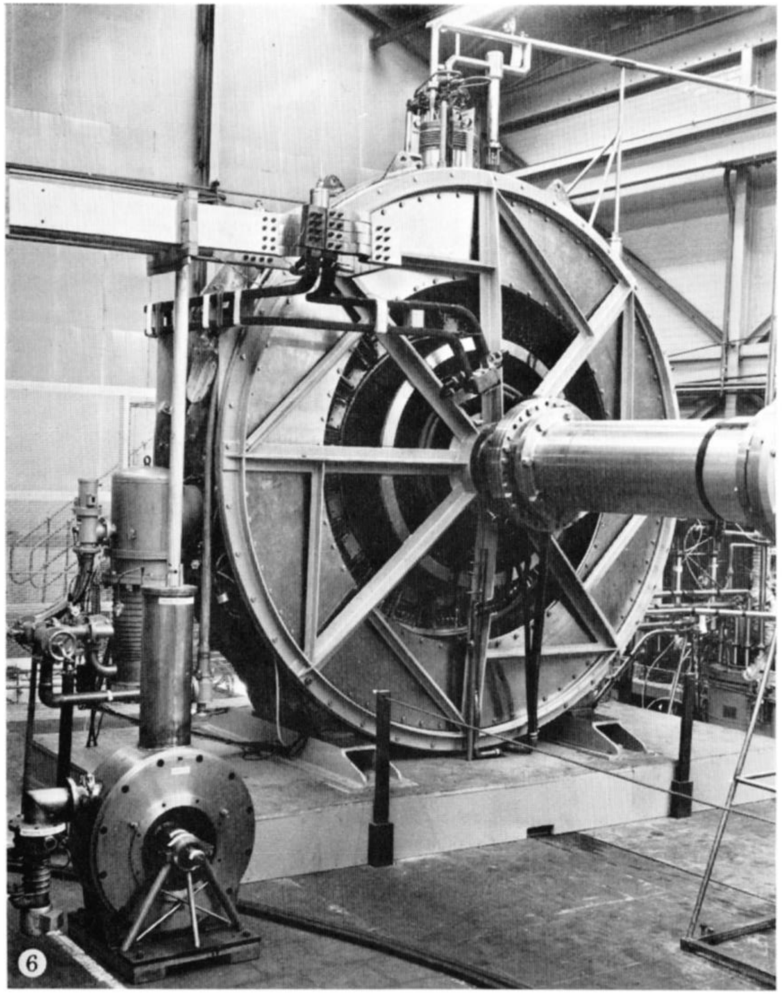

FIGURE 6. The 2.4 MW, 200 rev/min superconducting d.c. Fawley motor with the 37 kW model motor in the foreground.

FIGURE 7. Superconducting d.c. generator field coils being fitted into coil support structure.

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CONCLUSIONS

1. The industrial application of superconductivity in the United Kingdom will be realized in the near future with the superconducting dc motors and generator developed at IRD.

2. The continuing development towards practical superconducting ac transmission cables is assured through the large team engaged on this work at CERL.

3. Further work on superconducting transformers at any significant level is unlikely in the foreseeable future.

4. The development of superconducting ac generators is expected to increase, although the many formidable problems which must be overcome will necessitate a very substantial financial investment.

5. The development of superconductors will continue, but as far as rotating machines are concerned, the order of priority is lower costs, improved techniques for fabricating windings, and improved performance.

6. Improvements are required in the cryogenic field, particularly in the size and efficiency of helium-refrigerator components and in the cost of the refrigeration plant.

7. There is no longer any doubt that superconductors will be employed increasingly in electrical power plants, and we may look forward hopefully to the not-too-distant future when every large rotating machine, ac or dc, will be superconducting.

ACKNOWLEDGMENTS

The author acknowledges discussions on superconducting ac cables with Dr. Norris, Dr. Baylis, and Mr. Maddock of CERL, and with Mr. Edwards of BICC; and discussions on the reciprocating ac generator with Mr. Harrowell of CERL.

The author thanks the Ministry of Defence (N), the National Research Development Corp., and the International Research and Development Co. for permission to present this paper.

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2. E. C. Rogers, E. C. Cave, and R. Grigsby, in: *Conference on Low Temperatures and Electric Power*, Inst. Intern. du Froid, Annexe 1969–1 (1969), p. 127.
3. A. D. Appleton, in: *Conference on Low Temperatures and Electric Power*, Inst. Intern. du Froid, Annexe 1969–1 (1969), p. 207.
4. R. V. Harrowell, *Nature*, **222** (5193): 598 (1969).
5. H. O. Lorch, *Cryogenics*, **9** (5): 354 (1969).
6. D. A. Swift, in: *Proceedings of XII Intern. Congress of Refrigeration*, Inst., Intern. du Froid (1967), p. 173.
7. A. D. Appleton and R. B. MacNab, in: *Conference on Low Temperatures and Electric Power*, Inst. Intern. du Froid, Annexe 1969–1 (1969), p. 261.

DISCUSSION

Question by P. H. Morton, Imperial Metal Industries: Would you comment on the merit and future potential of hollow conductors. Will they be used generally or only in particular applications, and if so why?

Answer by author: The introduction of hollow conductors was a useful improvement over strip conductors because it enabled coil systems to be designed with a much lower helium requirement; it also removed some of the mechanical stress problems. However, as far as rotating electrical machines are concerned, there are even greater benefits to be derived from the use of the intrinsically stable superconductors. Since the latter do not require intimate contact between the helium and the superconductor, an even smaller amount of helium can be employed and the manufacturing problems are simplified.

7. There is no longer any doubt that superconductors will be employed increasingly in electrical power plants, and we may look forward hopefully to the not-too-distant future when every large rotating machine, ac or dc, will be superconducting.

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A. D. Appleton

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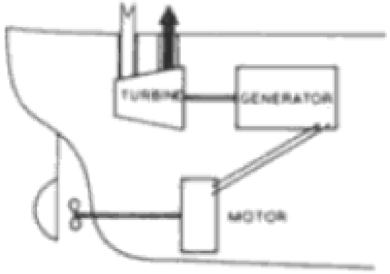
1. ELECTRICAL PROPULSION GIVES BETTER CONTROL.
   CONVENTIONAL D C MACHINES CANNOT BE MANUFACTURED IN THE RATINGS REQUIRED.

2. GAS TURBINE MAY BE LOCATED AWAY FROM PROPELLER SHAFT TO EFFECT IMPROVEMENT IN LAYOUT. THE PROBLEM WHICH IS SOLVED IS THE SPACE TAKEN BY LARGE AIR INLET AND EXHAUST DUCTS TO GAS TURBINES.



3. ONE TURBINE CAN DRIVE BOTH PROPELLERS DURING CRUISING TO IMPROVE RUNNING COSTS AND LIFE OF TURBINES. IT ALSO ALLOWS EASIER MAINTENANCE.

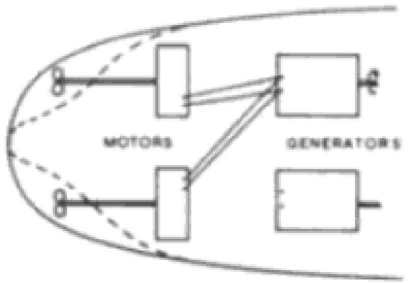
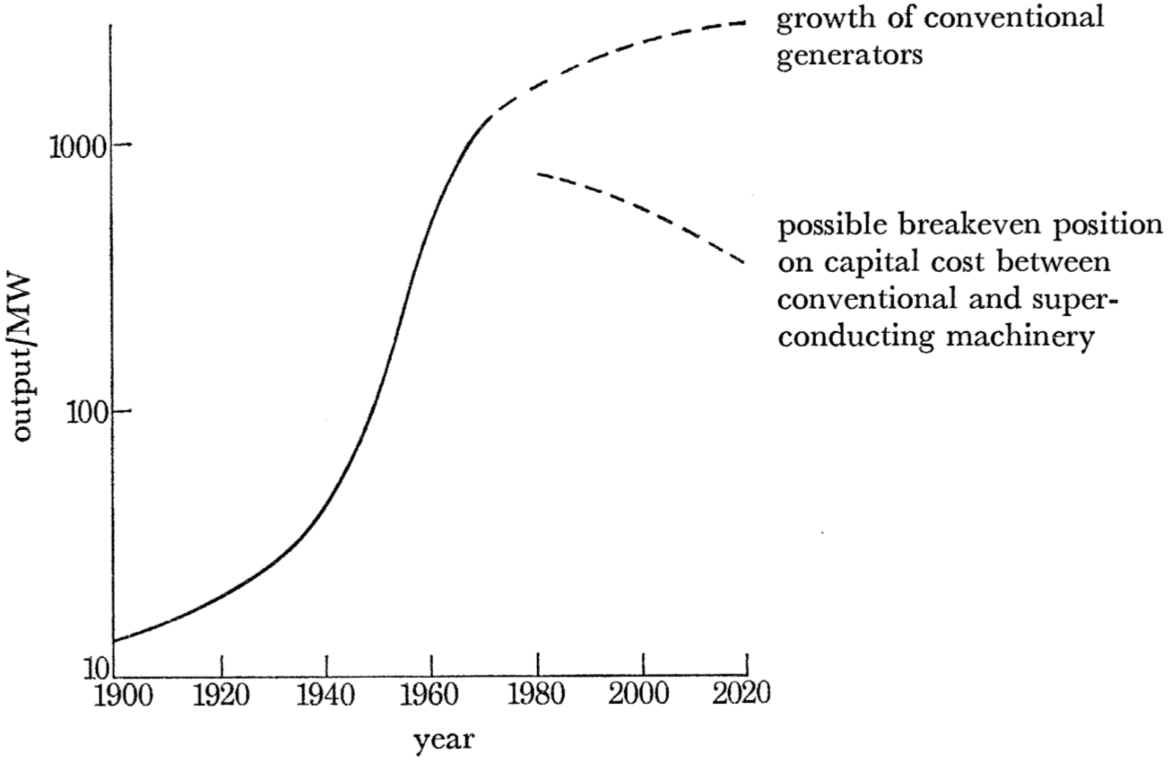


Fig. 5. Advantages of superconducting propulsion systems.

A. D. APPLETON



1000 MW) significantly lower than conventional generators.

(3) On reasonable estimates they appear to be more efficient than conventional generators.

Of course, there is the overriding requirement that, on reasonable engineering judgement, the development problems of the superconducting generators are not insuperable; it is the concensus of informed opinion that this is the case.

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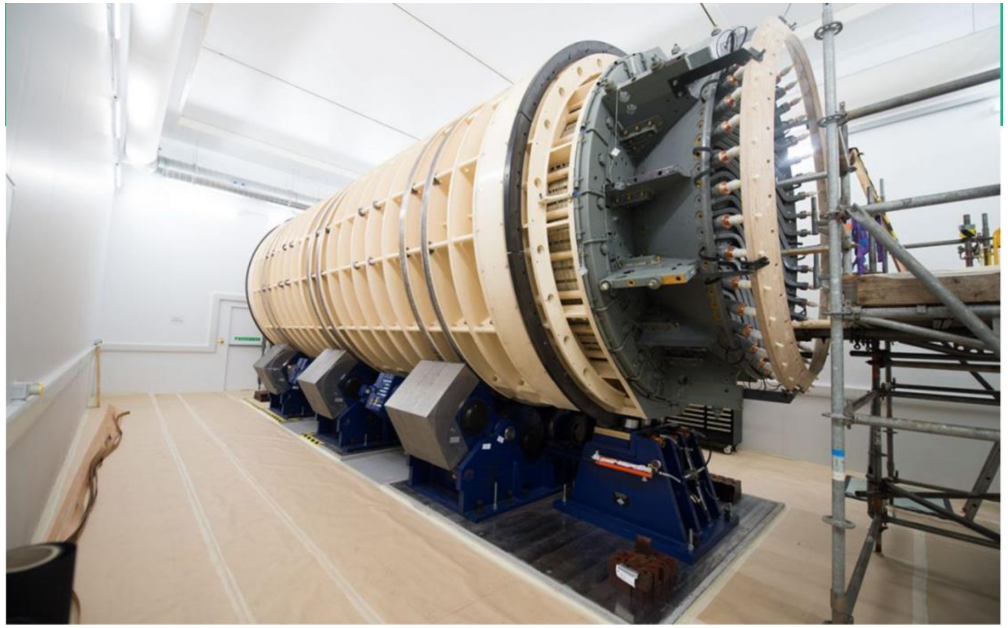

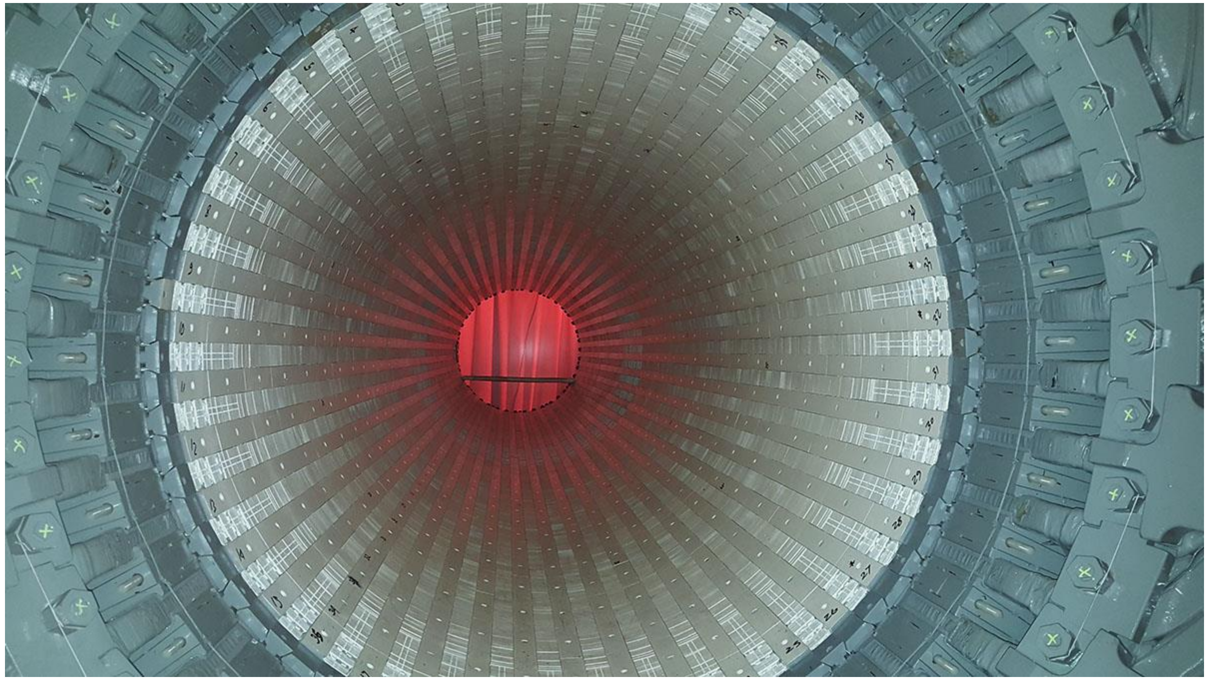

Drax 660 MW-300 tonne
https://www.drax.com/technology/refurbishing-300-tonne-generator-core-within-heart-power-station/

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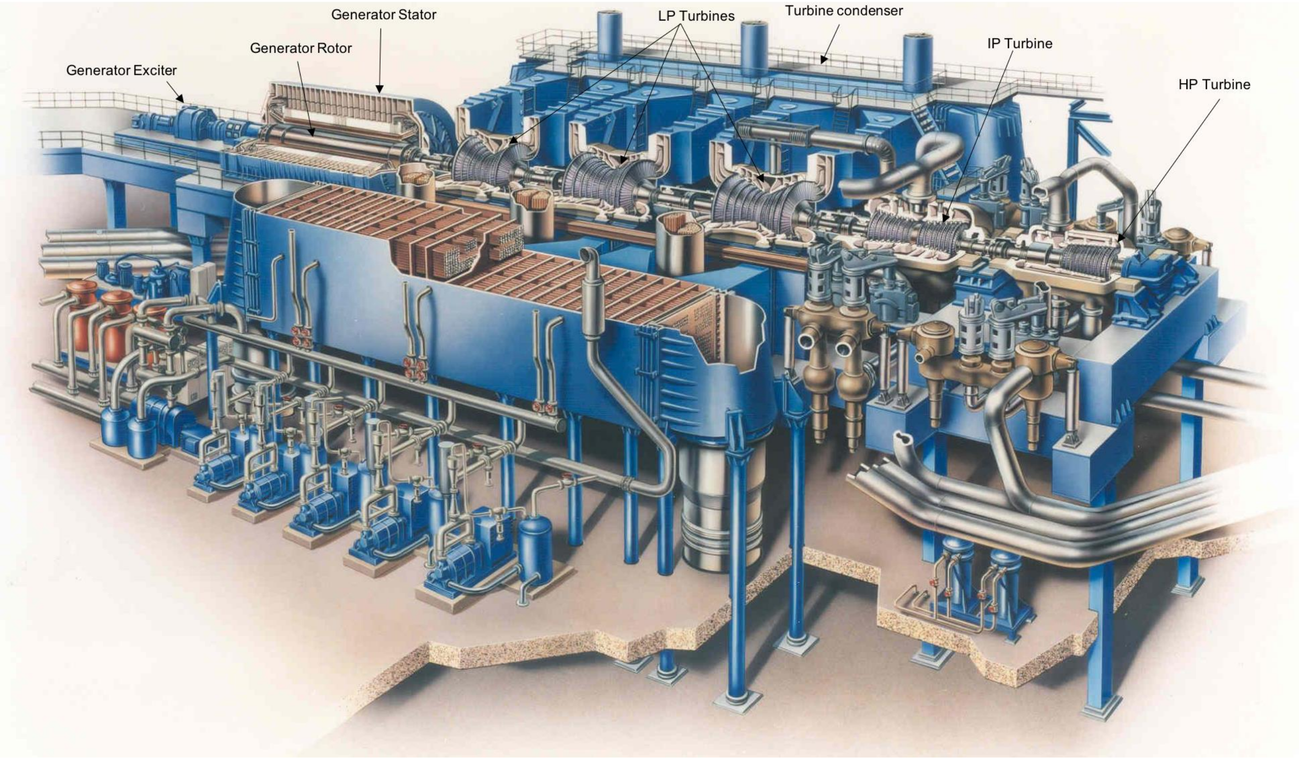

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Early motors – Tended to Be Homoplolar

United States Patent [19] **Sakuraba et al.**

[11] **Patent Number:** **5,032,748**

[45] **Date of Patent:** **Jul. 16, 1991**

2107937 5/1983 United Kingdom 310/178

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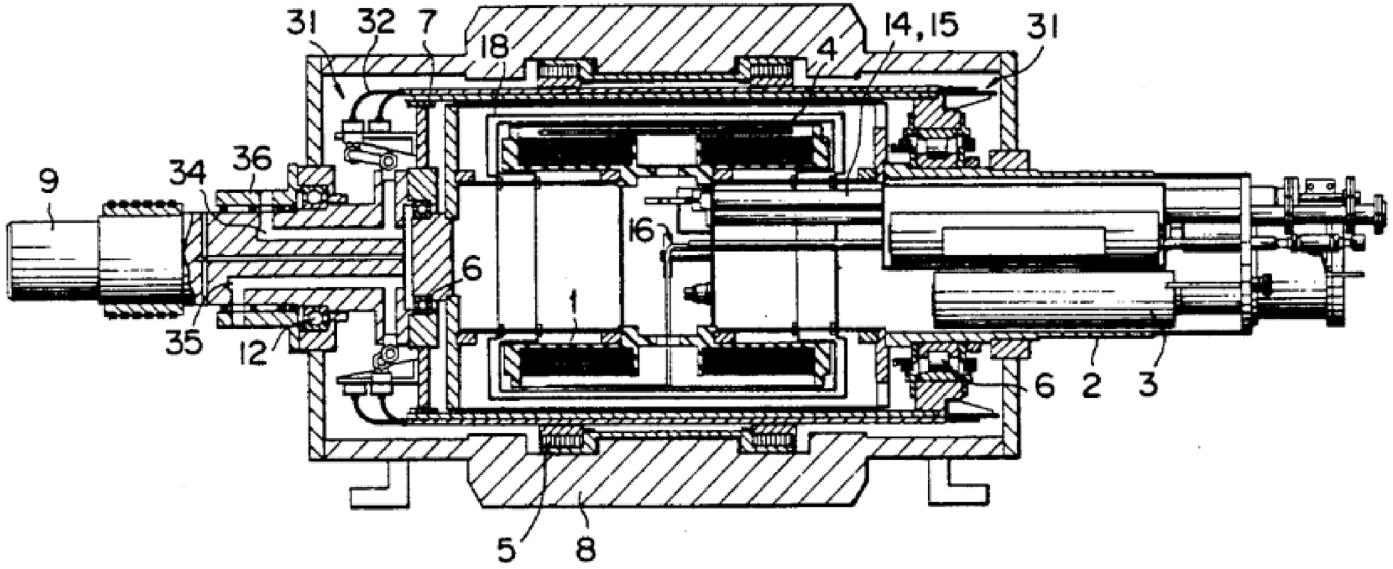
"Large Superconducting DC Motor Drives" by A. D. Appleton et al, Int. Research & Development Co: Ltd, Newcastle upon Tyne, NE 62YD, IEEE Conf. Publ. No. 170, pp. 163–170, (no month 1978).
"Shaped Field Superconductive DC Ship Drive Sys-

other longitudinal end of the same segment of the armature drum and also to the one at the longitudinal opposed end of an adjacent segment in diagonal fashion progressively.

16 Claims, 9 Drawing Sheets



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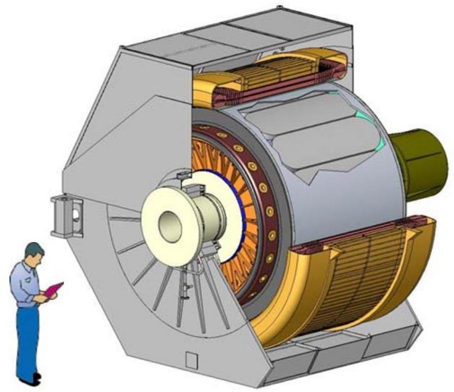
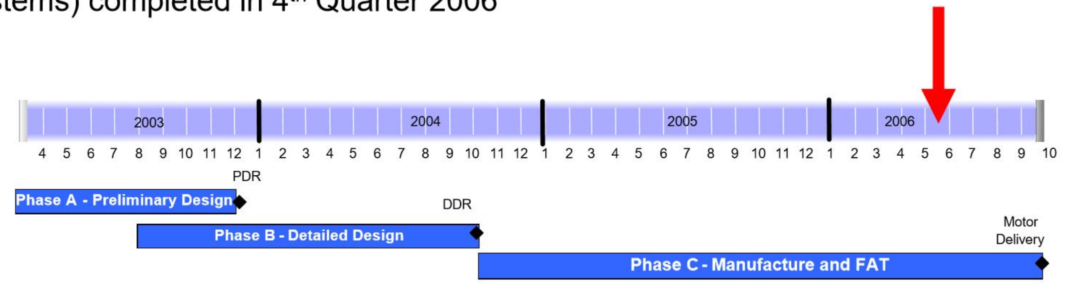
36.5 MW HTS Propulsion Motor Development

ONR Program

- *Objective*: Develop a Full Scale, High Power Density, Lightweight, Advanced 36.5 MW Propulsion Motor and Drive System compatible with naval applications
- Contract Awarded to AMSC February 2003
- *Design Drivers*: Low Weight, High Power Density, Improved Efficiency and Low Noise
- Detail Design Completed October 2004 – Design meets MIL-S-901D Shock and DD(X) Acoustics
- Factory Acceptance Testing (Marine Systems) completed in 4th Quarter 2006





Design leverages features successfully tested on 5 MW HTS motor

American Superconductor

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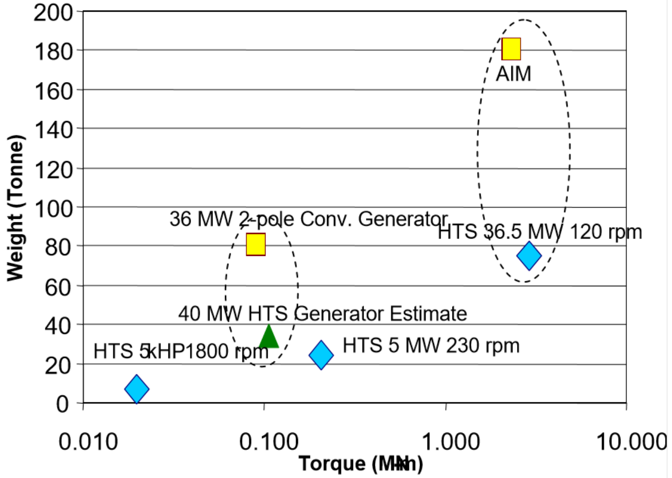
36.5 MW HTS Propulsion Motor Development

Summary and Power Density Comparison

- HTS Motors are multi-phase synchronous machines with active field control, large airgap, and the flexibility to utilize a variety of drives.
- HTS wire used in the actively cooled rotor is presently 1G; starting migration to 2G wire
- The 36.5 MW motor is based on experience from multiple HTS electric machines.
- The ONR 5 MW motor provided the basis for the components used in the 36.5 MW motor.
- The program is on track to deliver a high power density75 metric ton motor to the Navy in September of this year.
- The rotor has been tested and the stator assembly is almost complete.
- No load testing at the NGC Philadelphia facility this summer.
- HTS is also applicable to generators.



HTS motors offer the next generation in power density for naval propulsion

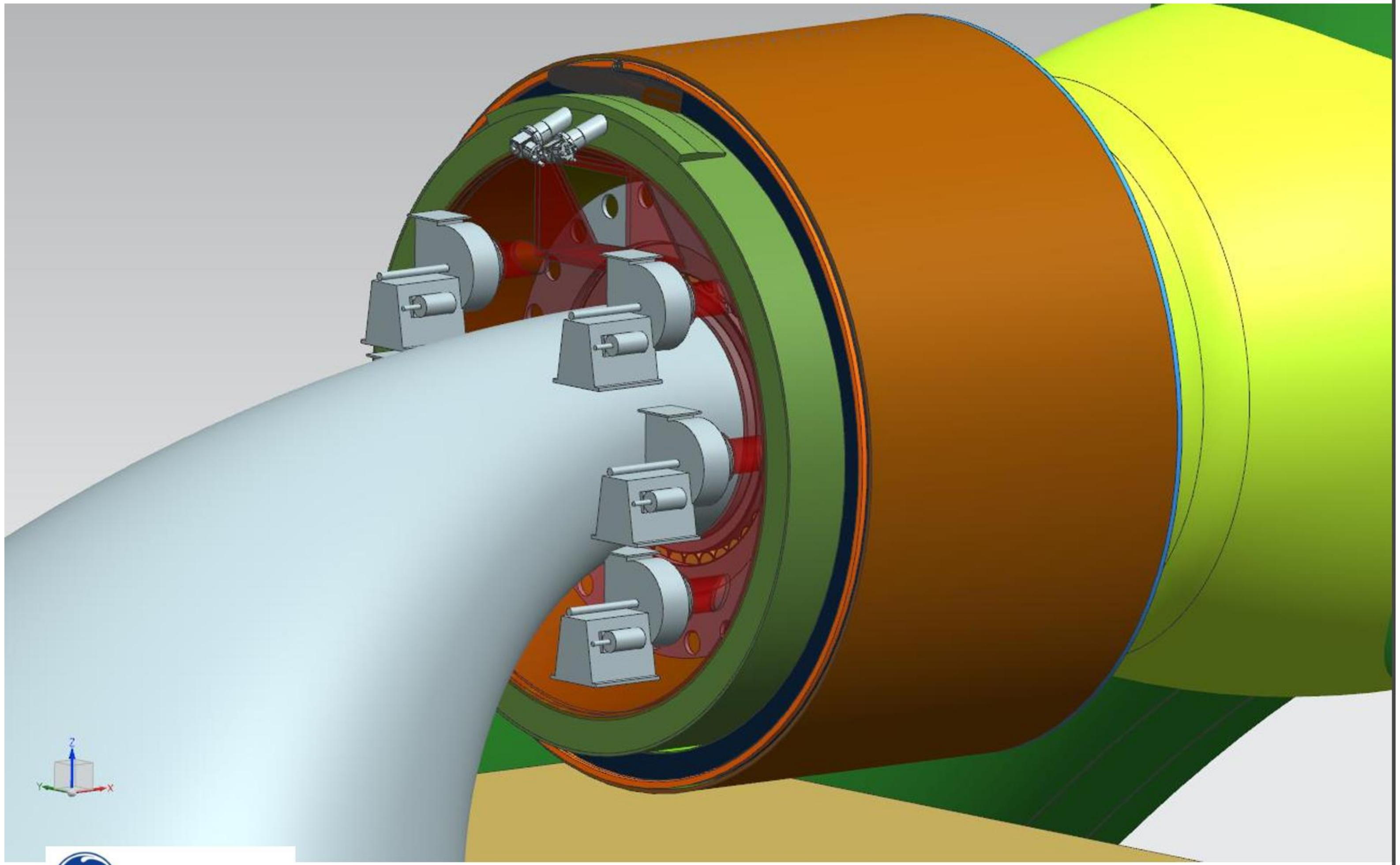
American Superconductor

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Thu-Mo-PL5-01 given at MT26, 22 – 27 September 2019; Vancouver, Canada.

Recent History – Focus Shifts to Synchronous Generators

IEEE/CSC & ESAS EUROPEAN SUPERCONDUCTIVITY NEWS FORUM, No. 22, October/November 2012.

Generator external view



imagination at work

5 of 29

5
Oct 11th 2012

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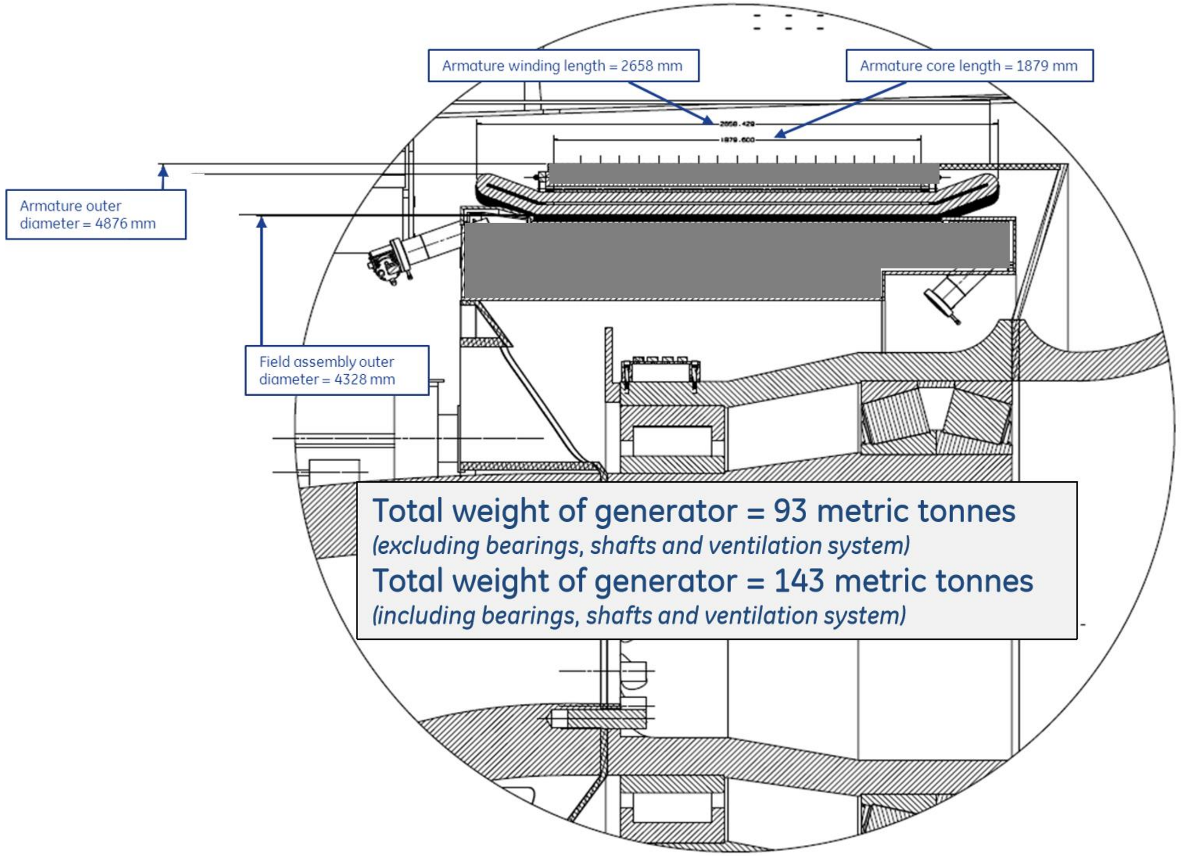
Key Generator Dimensions

GE proposed
This machine
which uses LTS



Total weight of generator = 93 metric tonnes
(excluding bearings, shafts and ventilation system)
Total weight of generator = 143 metric tonnes
(including bearings, shafts and ventilation system)

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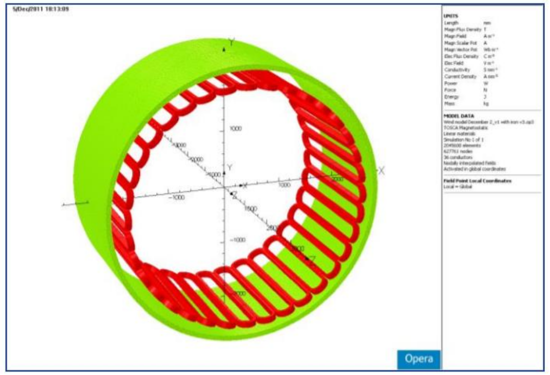
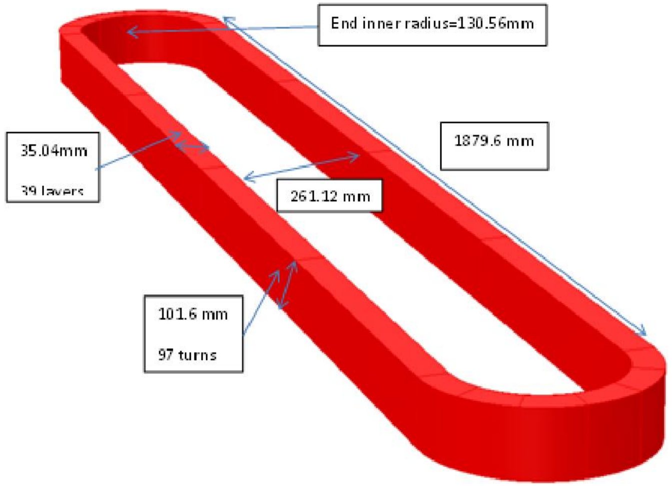
Paper study but a lot of useful info produced

SC coil optimization





- Optimization parameters
  - Width of the coil
  - Height of the coil
  - End radius of the coil
  - Operating current in the coil
  - Short sample percentage for coils
  - Current sharing temperature for the conductor
    - A sufficient margin is required for the stable operation of the coils. Current sharing temperature depends on the maximum field in the coil, critical current at maximum field, ratio of operating current to critical current at maximum field and ratio of maximum field in the coil to critical field of the conductor

imagination at work

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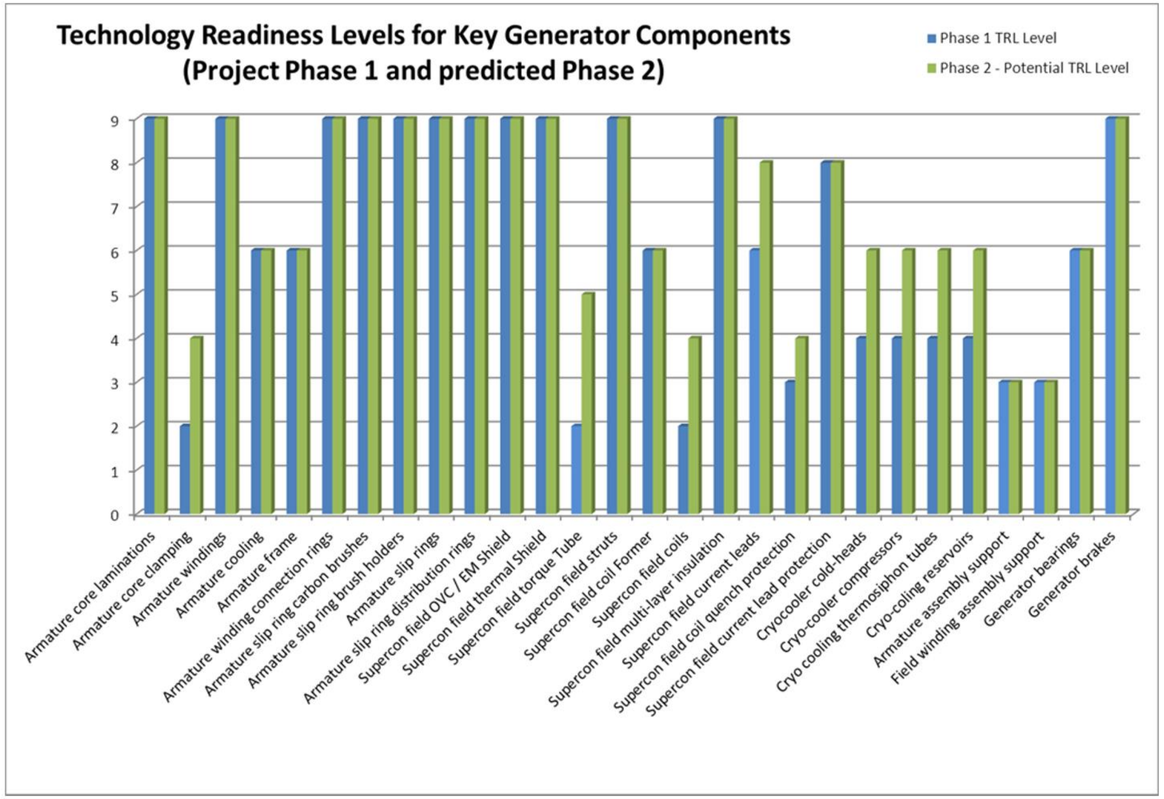
Technology Readiness Level Analysis



	PHASE 1	PHASE 2 projected
Sub-System	% lower than TRL4	% lower than TRL4
Armature	10 %	0 %
Superconducting Field	28 %	0 %
Cryogenic Cooling	0 %	0 %
Mechanical	43%	28 %

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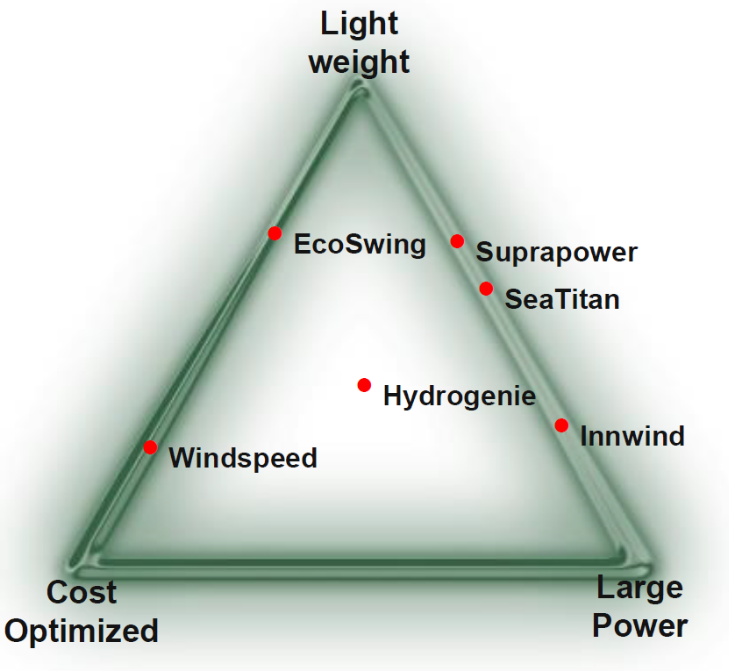
Various Recent Projects – variety of conductors used.

Review of Activities in Superconducting Generators



- Focus mostly on European activities and sort by ambition
  - *Hydrogenie* (Converteam/GE)
    - 2 MW fullly tested, 8MW, 10 MW planned
  - *Innwind* 10…20 MW DD (Siemens)
    - Components demonstrated, CoE comparison @ EWEA
    - Comparing HTS to PM and to pseudo DD
  - *SeaTitan* 10 MW DD (AMSC)
    - Design complete, hardware de-risking complete
  - *Suprapower*, 10 MW DD (Tecnalia, ex Acciona)
    - Design complete, hardware in progress
- Trend is a bit towards *lower* power rating (as price of superconductors comes down).
  - *Windspeed*. 3.5 MW DD (ECO 5)
    - Design basics published
  - ***EcoSwing*, 3.6 MW DD (Envision)**
    - Plans to be first on a turbine

ECO 5

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Dates to Around 2010 and uses BSCCO as this was the most mature conductor of the time

Hydrogenie, First Superconductor Hydro Generator

- Partners: Converteam, E.On
  - Technology platform
  - 1789 kVA, 1700 kW, 5250 V, 28 poles, 0.95 pf, 214 rpm
- The generator tested successfully and exceeded expectations
  - Tested to 2500 kVA under nominal and under short-circuit load.

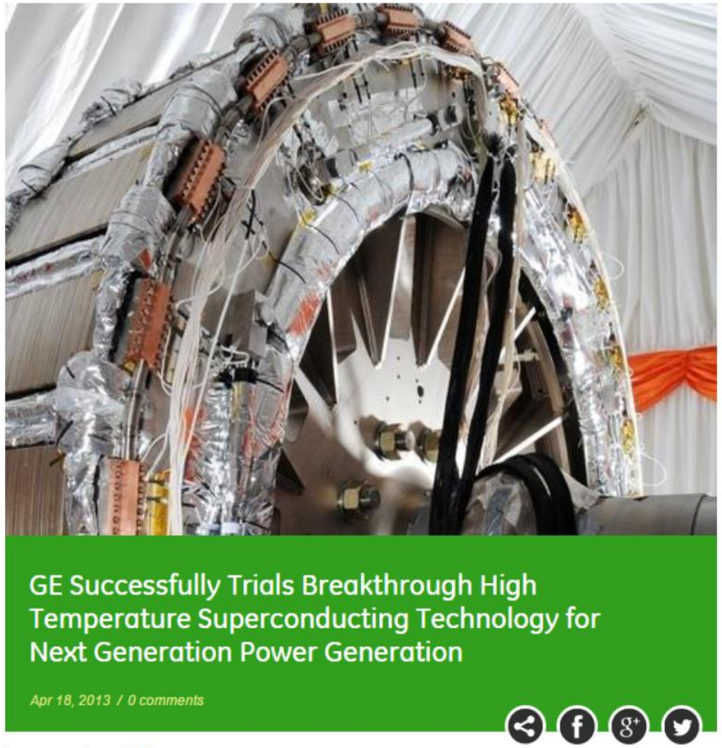
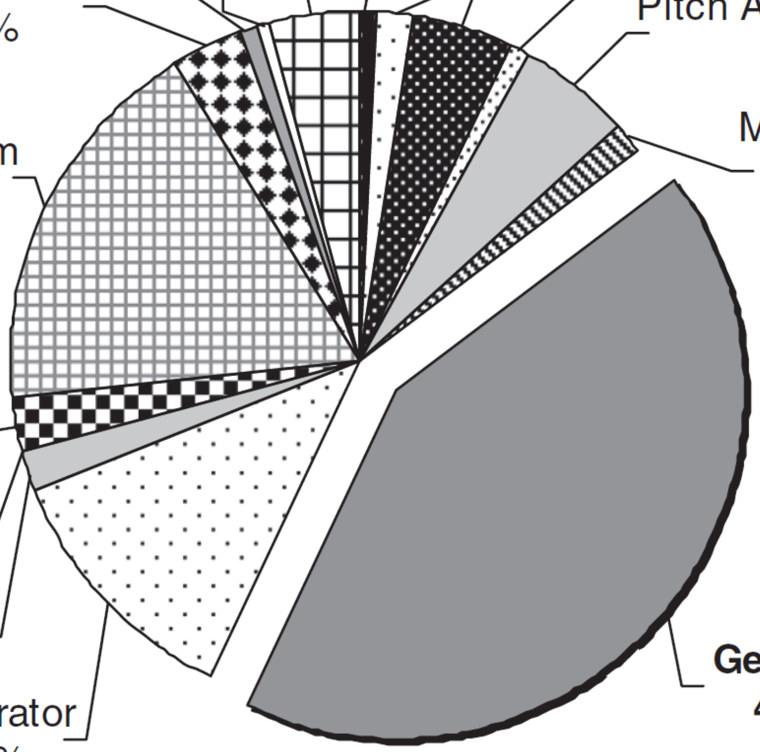


Image courtesy of GE

ECO5

Clive Lewis in his book identifies a clear motivation




NO SMOKING
WITHIN 20 FEET
OF THIS SIGN
EUROSPRAY

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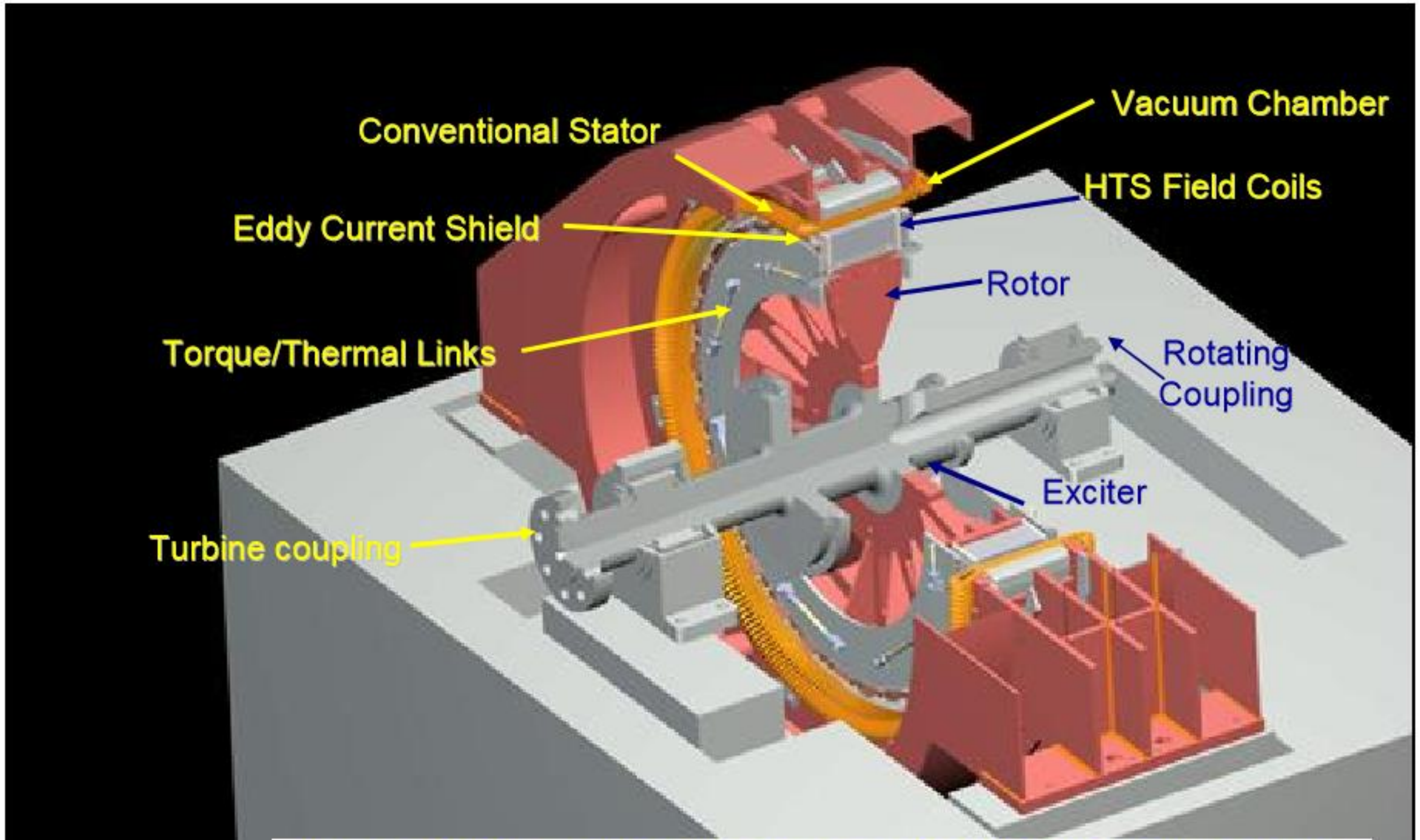
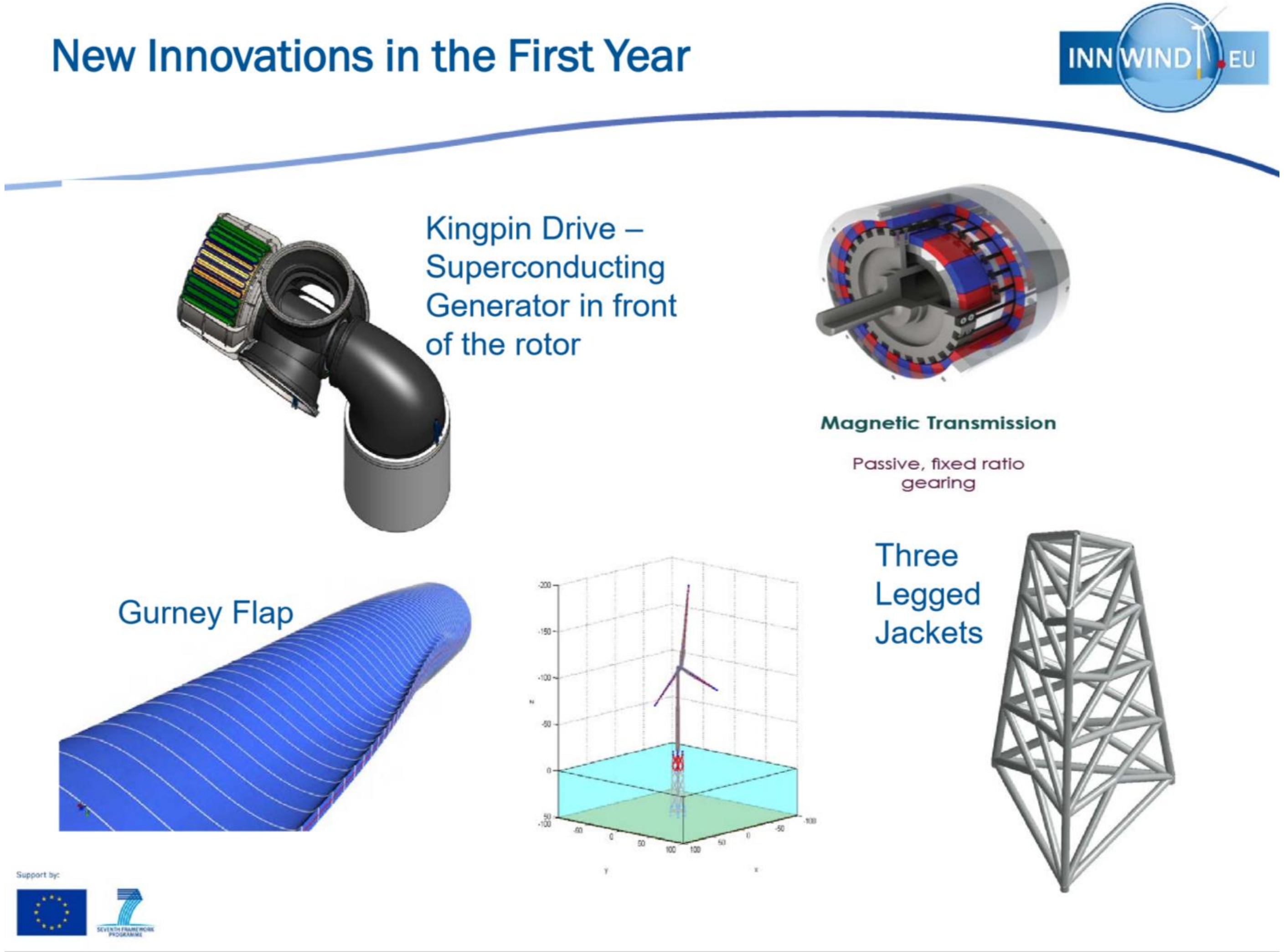


Horizontal shaft machine driven by a Francis double turbine with integral thrust bearing. Back-of-core diameter = 3m. Axial length = 1m.

Innwind Picks up on the need for direct drive but MgB2 has now taken over as the conductor of choice



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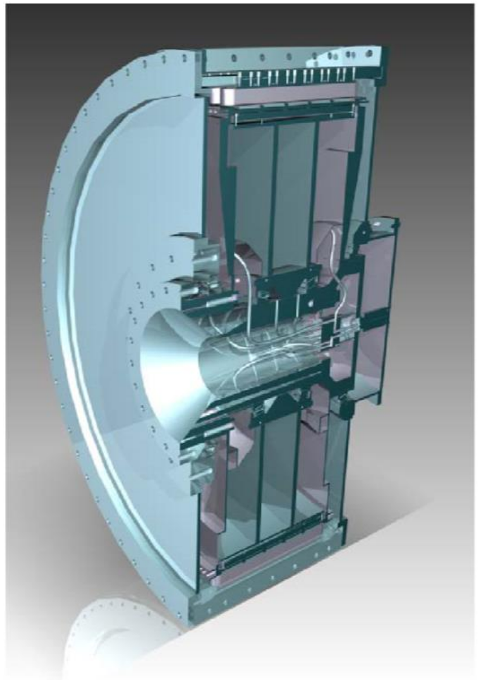
Direct drive trains

INNWIND.EU



Pseudo direct drive (Magnomatics)

10 MW superconducting (DTU)

Support by:

INNWIND LEAFLET www.innwind.eu

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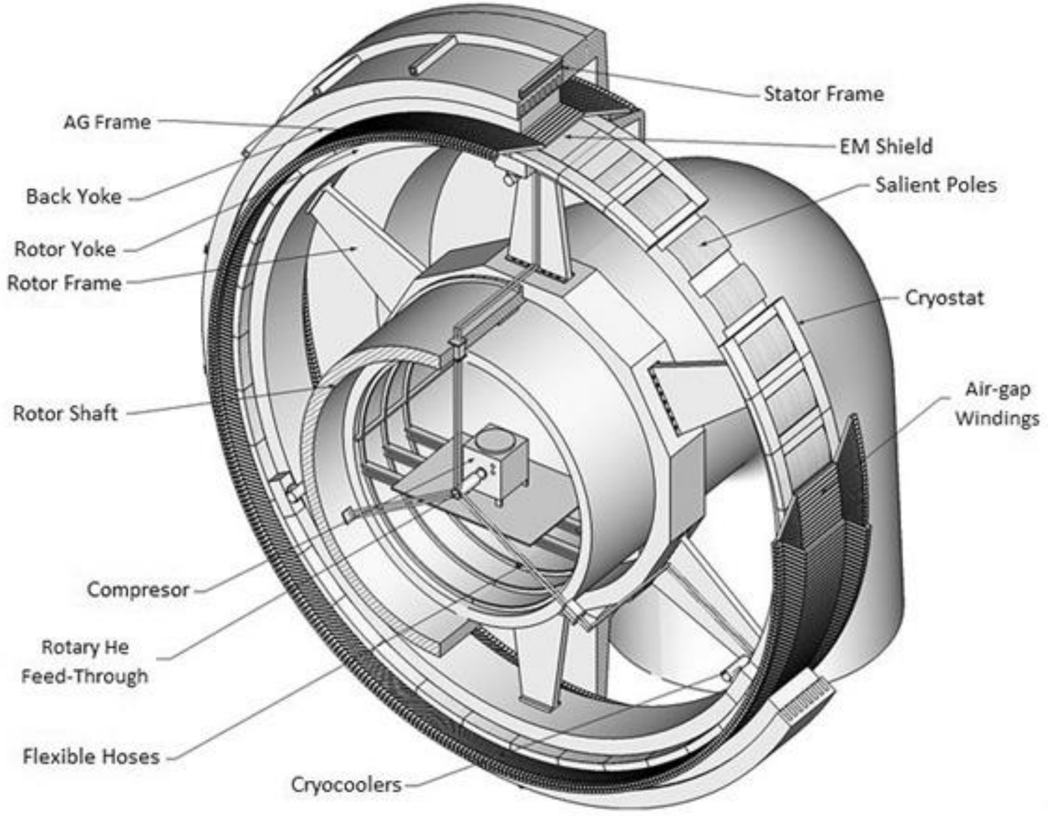
Suprapower SUPerconducting, Reliable, lightweight, And more POWERful offshore wind turbine – 10MW Mgb2 -



Partners

tecnalia Inspiring Business | solute | Ingeteam | Columbus Superconductors | ELÚ | University of Southampton | KIT Karlsruhe Institute of Technology | d2m Engineering

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Another Paper study again using MgB2

Basic Design Windspeed - Rotor

- Various rotor designs were constructed in Windspeed (see report for details)
- Rotor option 5a (cold rotor yoke) is shown here
- Vacuum enclosure, thermal shield and MLI are omitted for clarity

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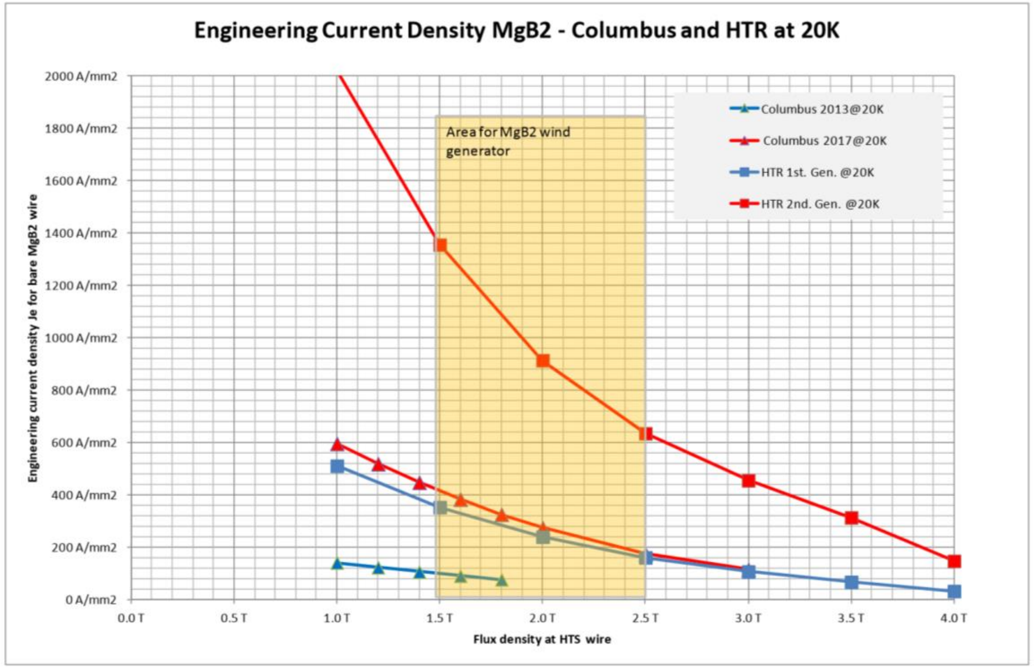
MgB2 Wires – Critical Currents

- Engineering current densities improve over time
- Actual current densities are high enough for DD wind generators
- Higher current densities lead to more compact & lighter generator design, with lower first costs



ECO5

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EcoSwing

(RE)BCO has arrived !

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Fig. 1: EcoSwing generator (right) next to the original permanent magnet generator (left) in a CAD generated image. Note the considerably smaller diameter of the EcoSwing.

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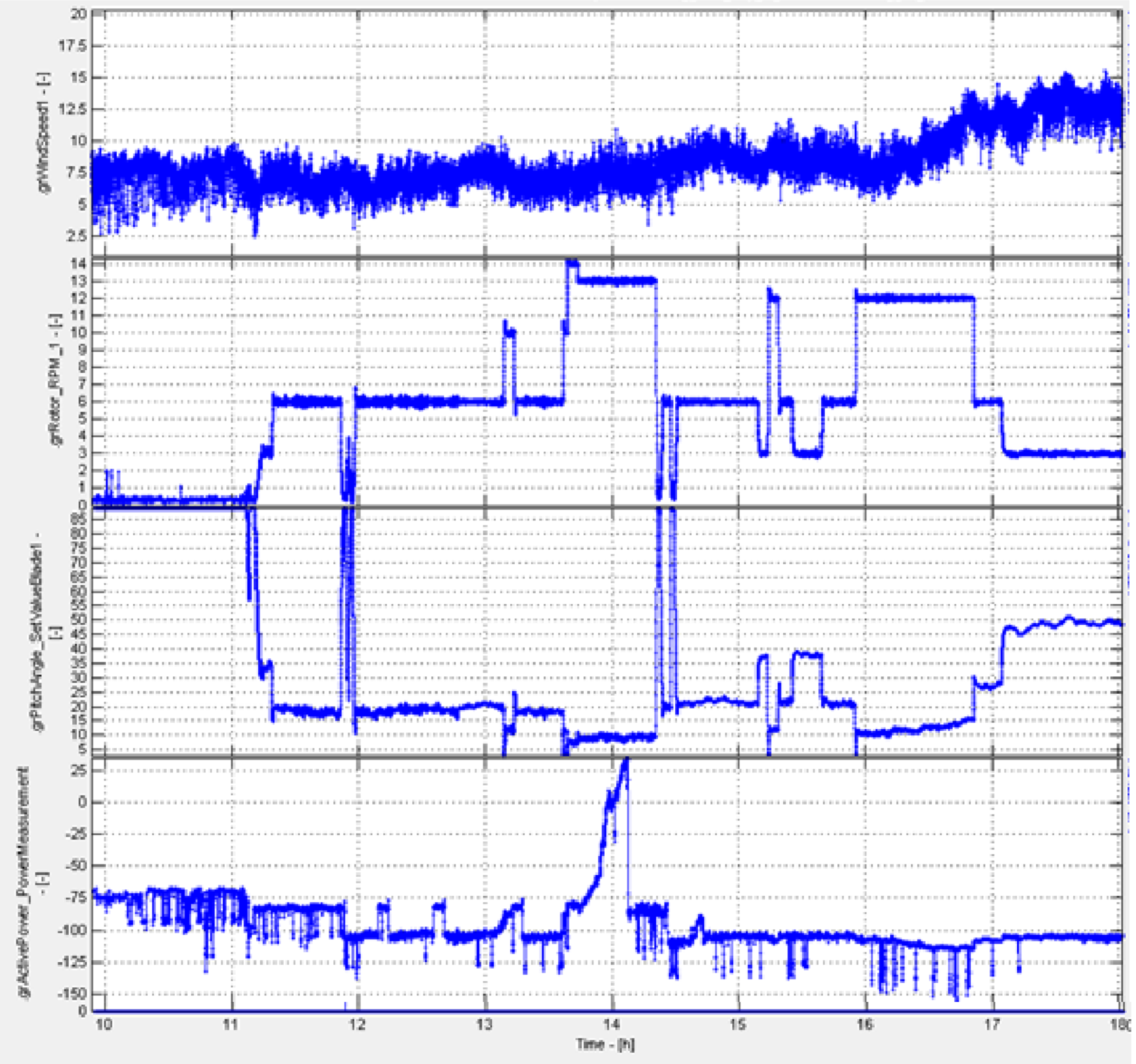
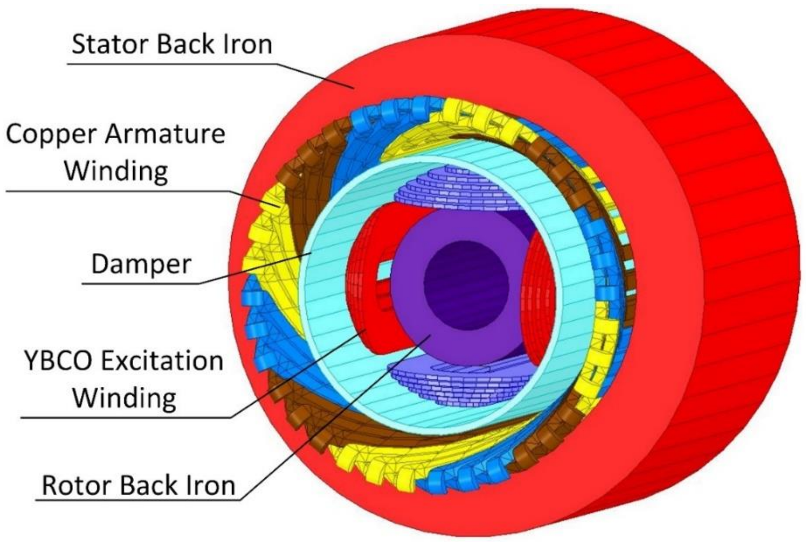


Fig. 3: First power production from EcoSwing on December 6, 2018 at 14:00. The plot shows from the top: wind speed, rotor speed, pitch angle of the blade, measured power to the grid.

10 Mvar HTS synchronous condenser (2018-2021)

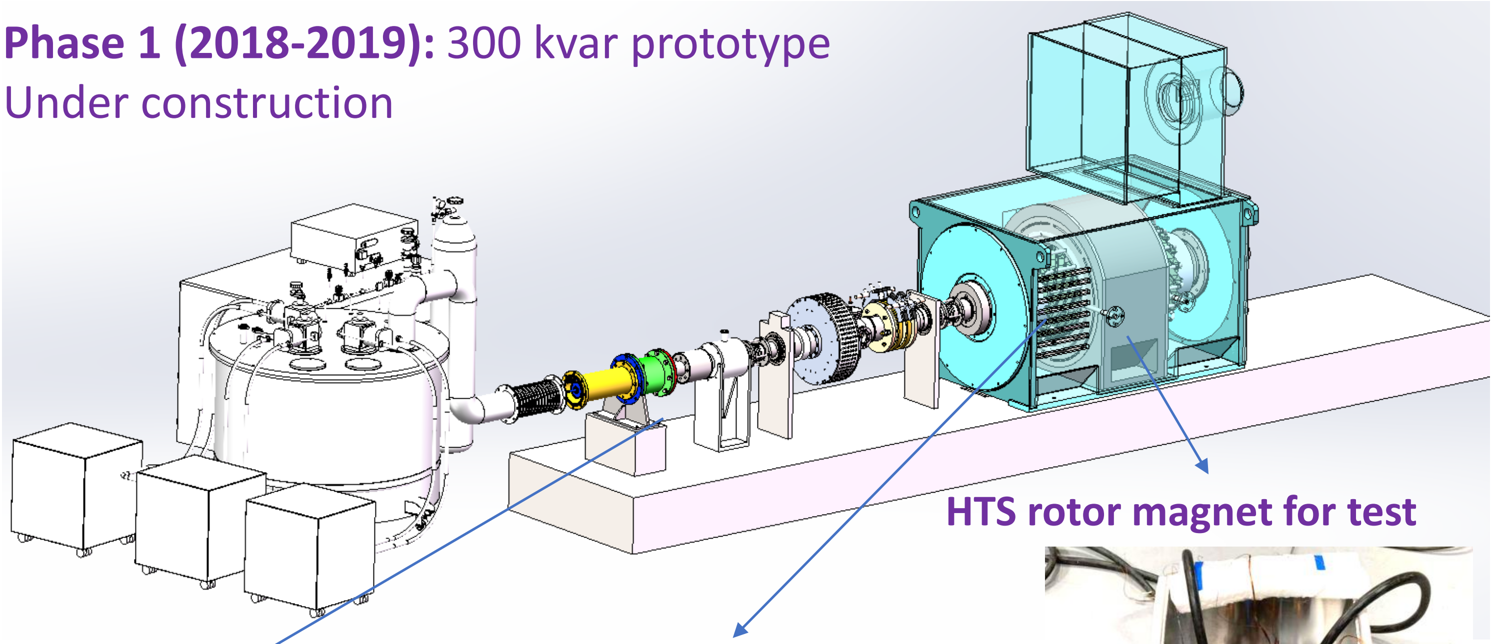
Funded by China Southern Power Grid

Designed by Tsinghua University

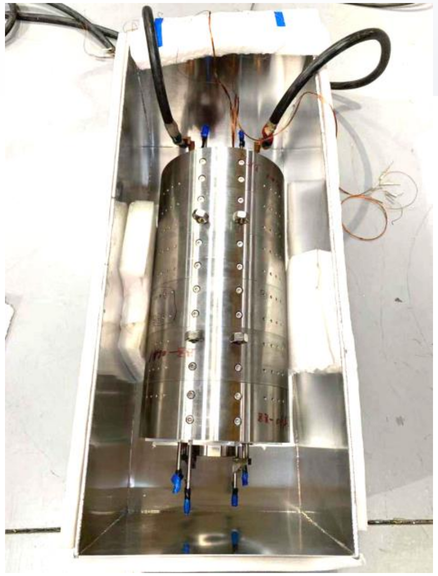


- 10 Mvar, 1500 rpm
- REBCO rotor magnets
- Gap field > 1.4 T
- Non-ferro teeth
- Cooled by 20 K gas helium

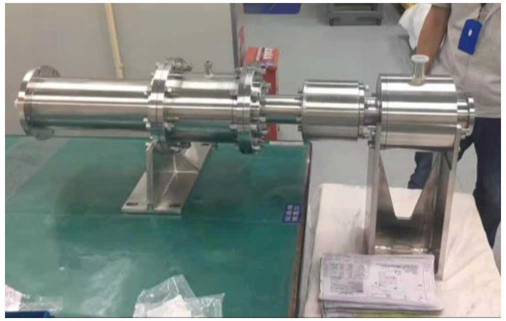
Phase 1 (2018-2019): 300 kvar prototype
Under construction



HTS rotor magnet for test



Cryogenic rotary joint



HTS rotor coils

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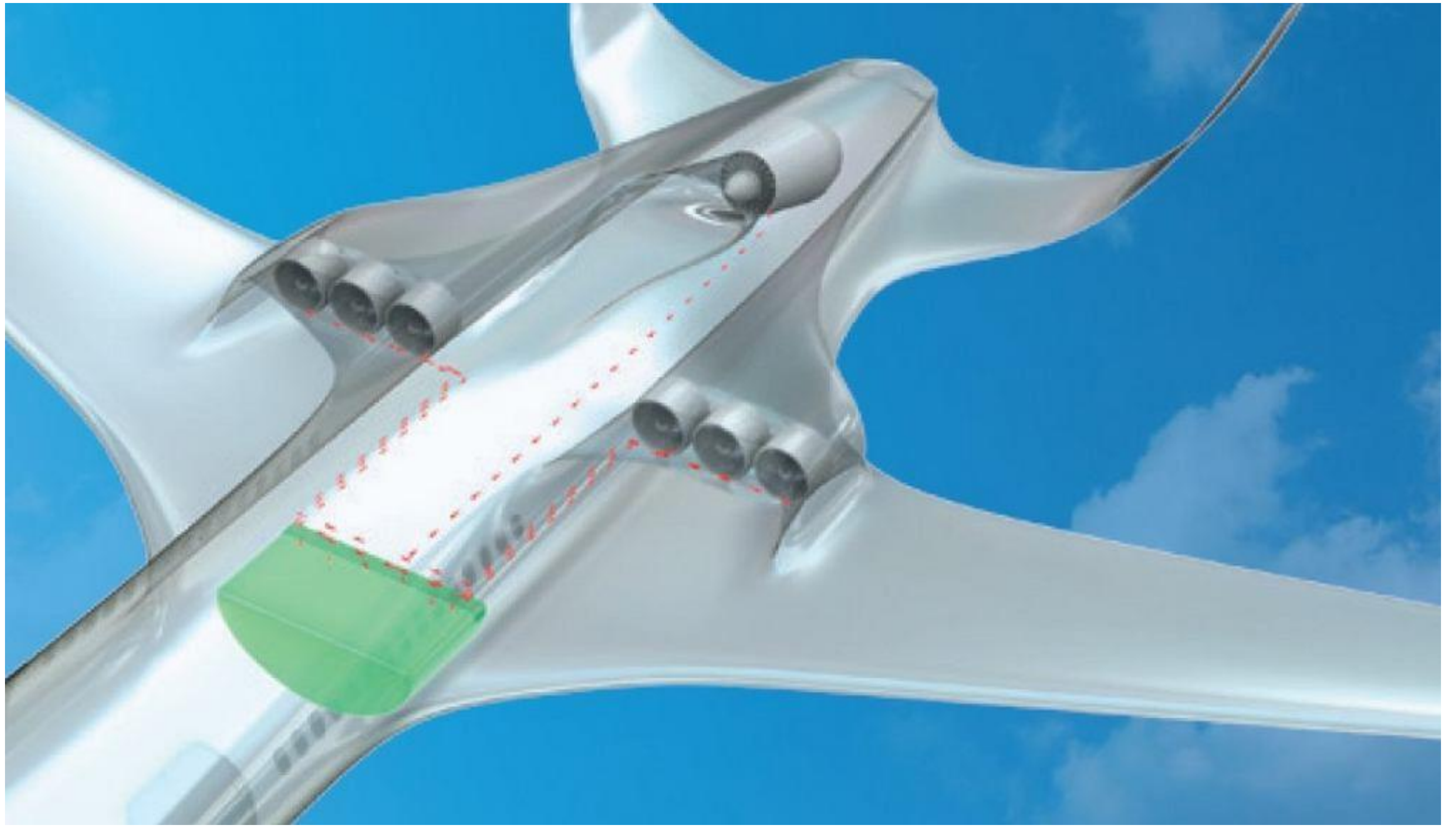
EADS E-Thrust

Focus Swings to Motors – Driven by initiatives such as Flightpath 2050



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EADS E-Thrust

Focus Swings to Motors – Driven by initiatives such as Flightpath 2050

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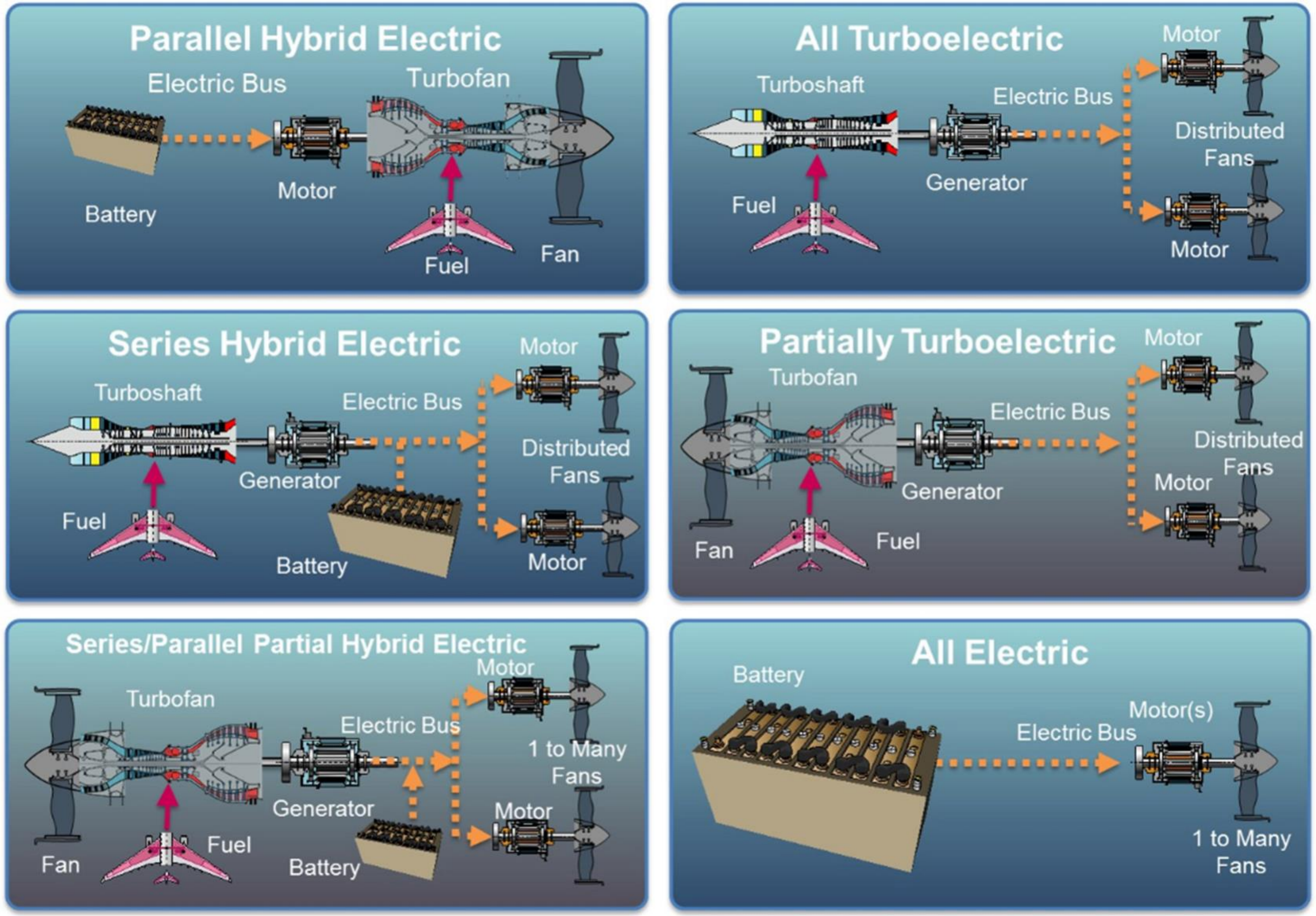

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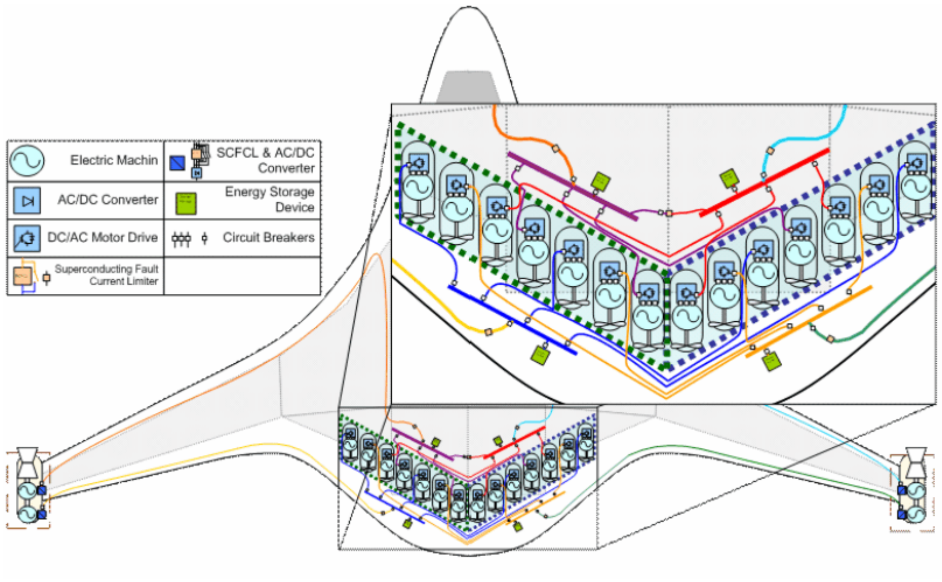
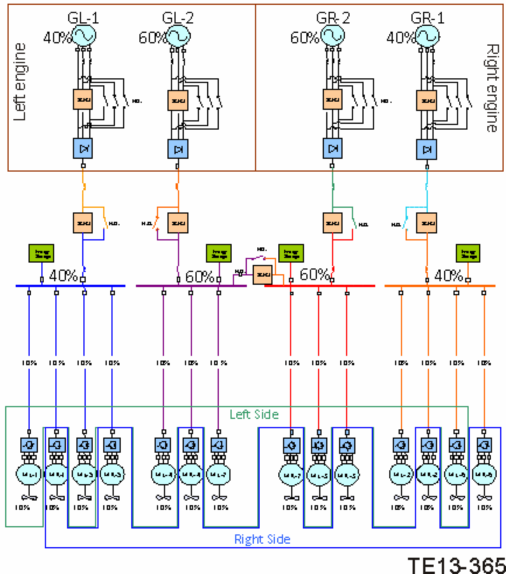
Rolls-Royce Turbo-Electric Distributed Propulsion (TeDP) System Architecture Concept.





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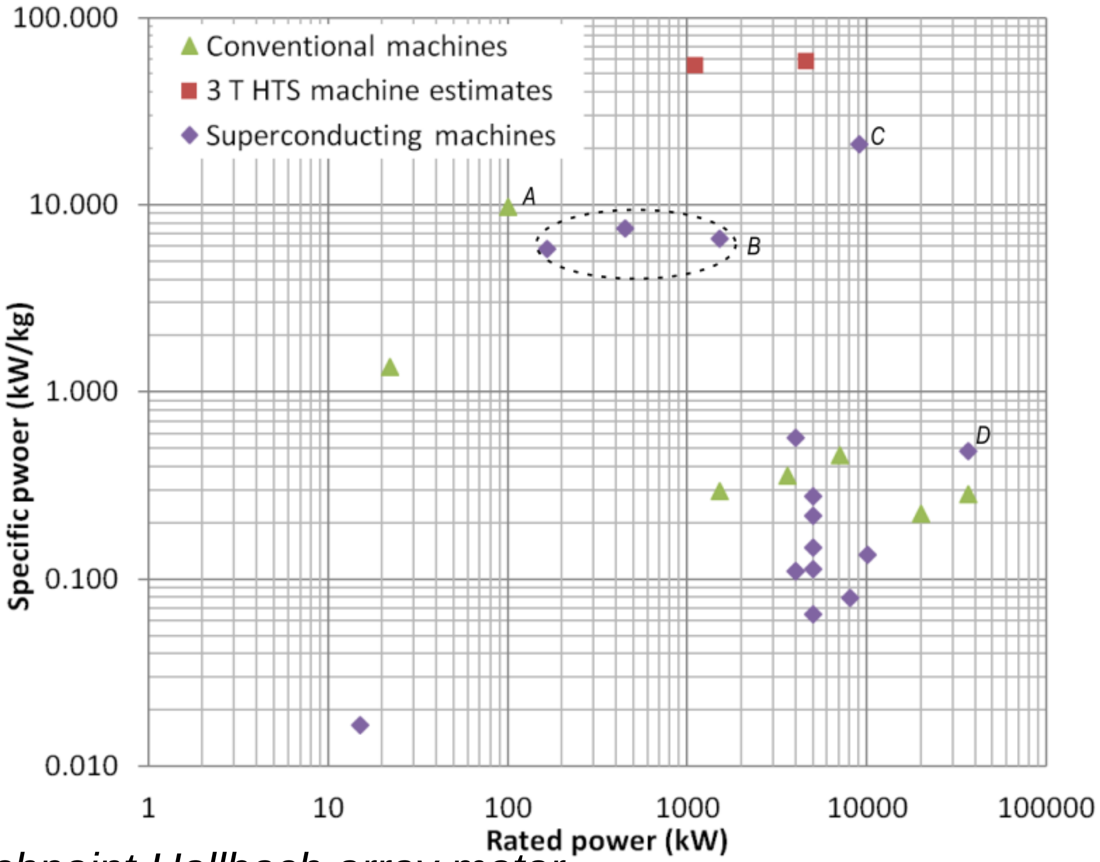
Historical Electrical Machines



A: Launchpoint Hallbach array motor
B: Masson et al. aerospace HTS machines
C: Westinghouse LTS generator (1977)
D: AMSC 36.5 MW HTS marine motor

Data supplied and presented at EUCAS 2015 by F. Berg of Airbus Group

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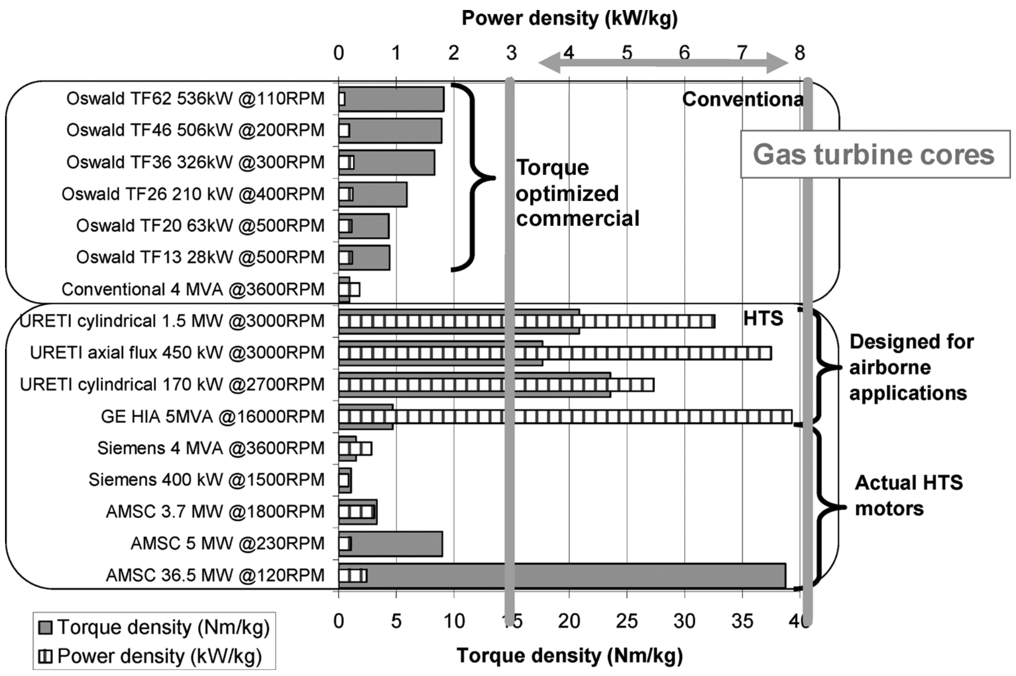
Summary of recent large superconducting motors



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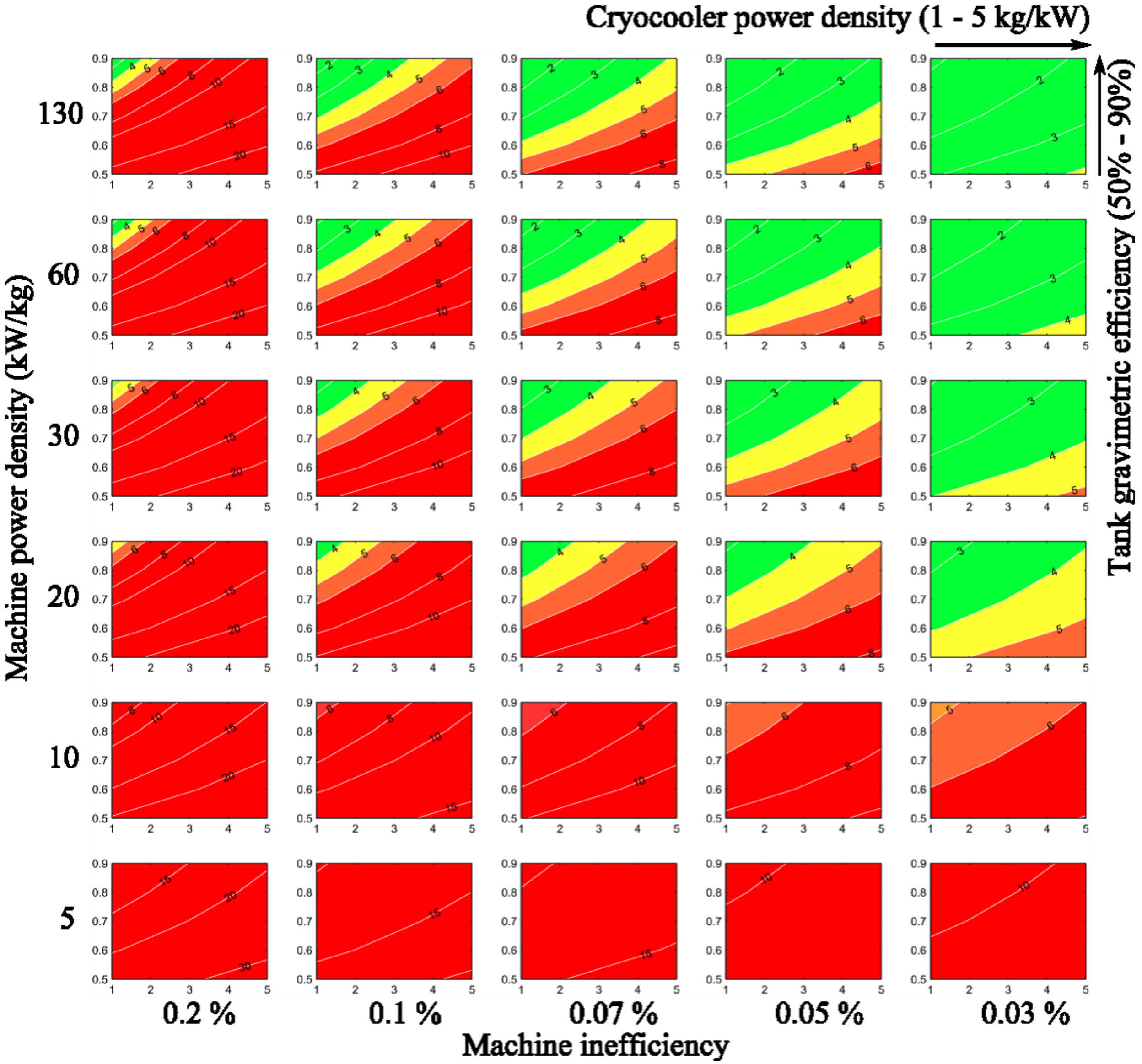

Courtesy :
F. Berg - EADS

Model of Motor

Early mock-up of a Superconducting motor using bulk YBCO

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MAGNIFYE
MAGNETS. THE NEXT GENERATION.

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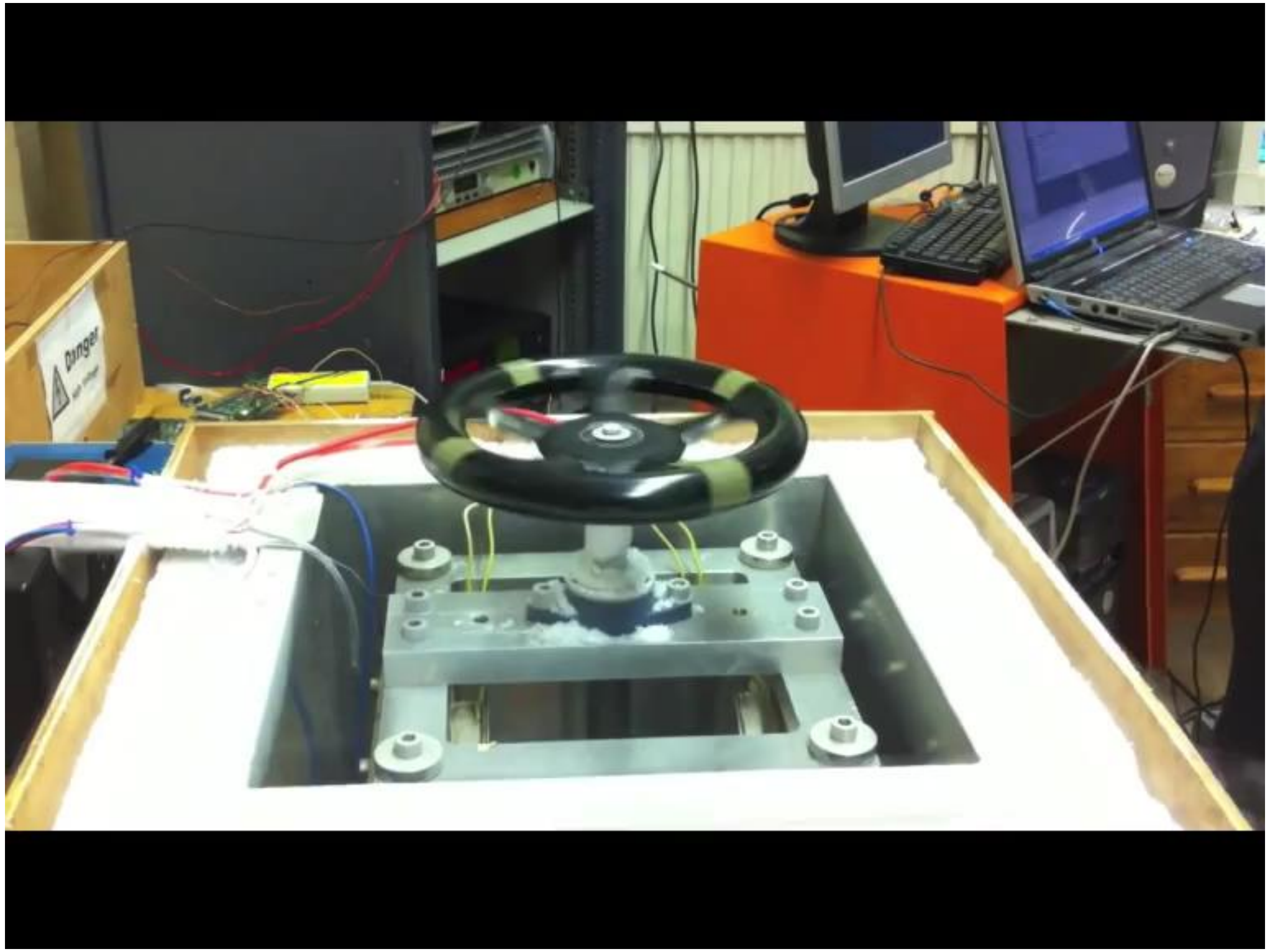
The PSAM – all HTS motor



IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
Plenary presentation Thu-Mo-PL5-01 given at MT26, 22 – 27 September 2019; Vancouver, Canada.

ASuMED - Advanced Superconducting Motor Experimental Demonstrator

- ASuMED is building the first fully superconducting motor prototype tests evaluate the technology´s benefits and allow its integration into designs for future aircraft.
- Target 1MW machine having specific power density of 20kW/kg

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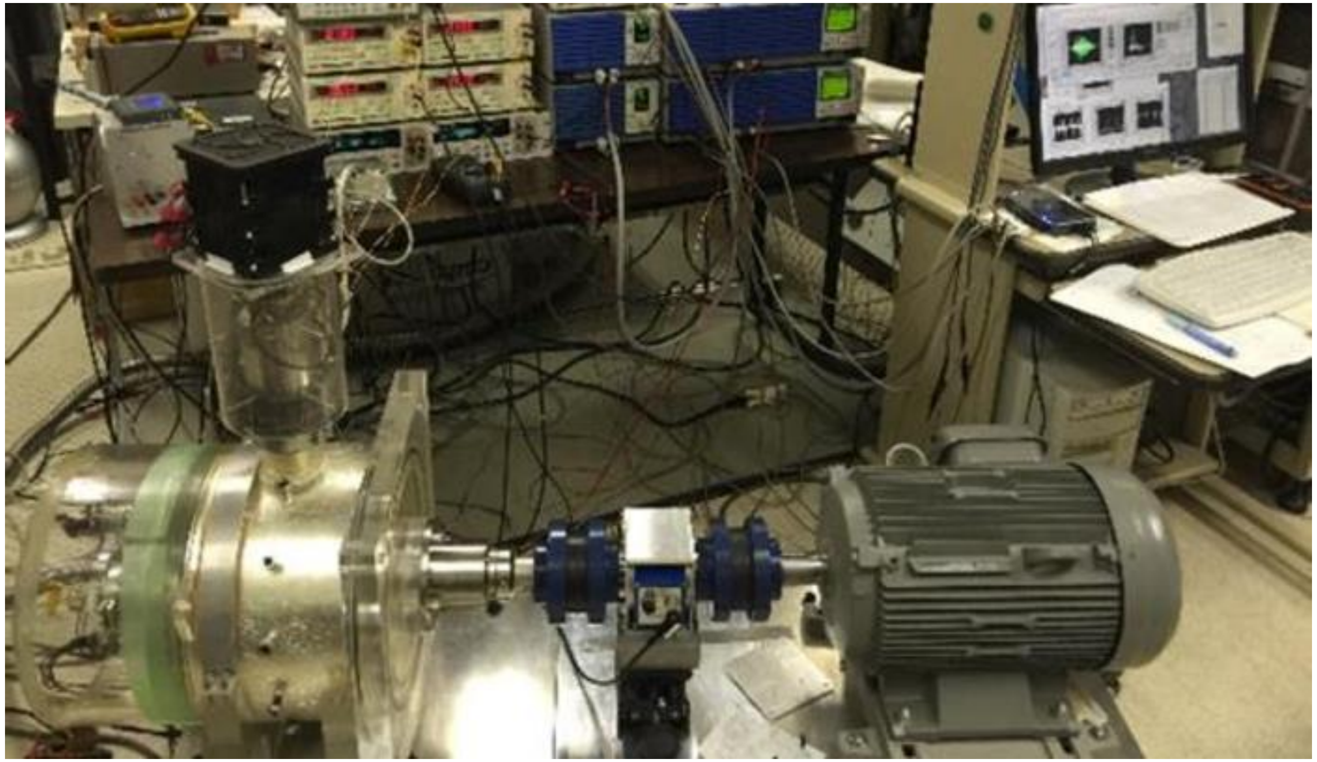

Sutor – Precursor to ASumed

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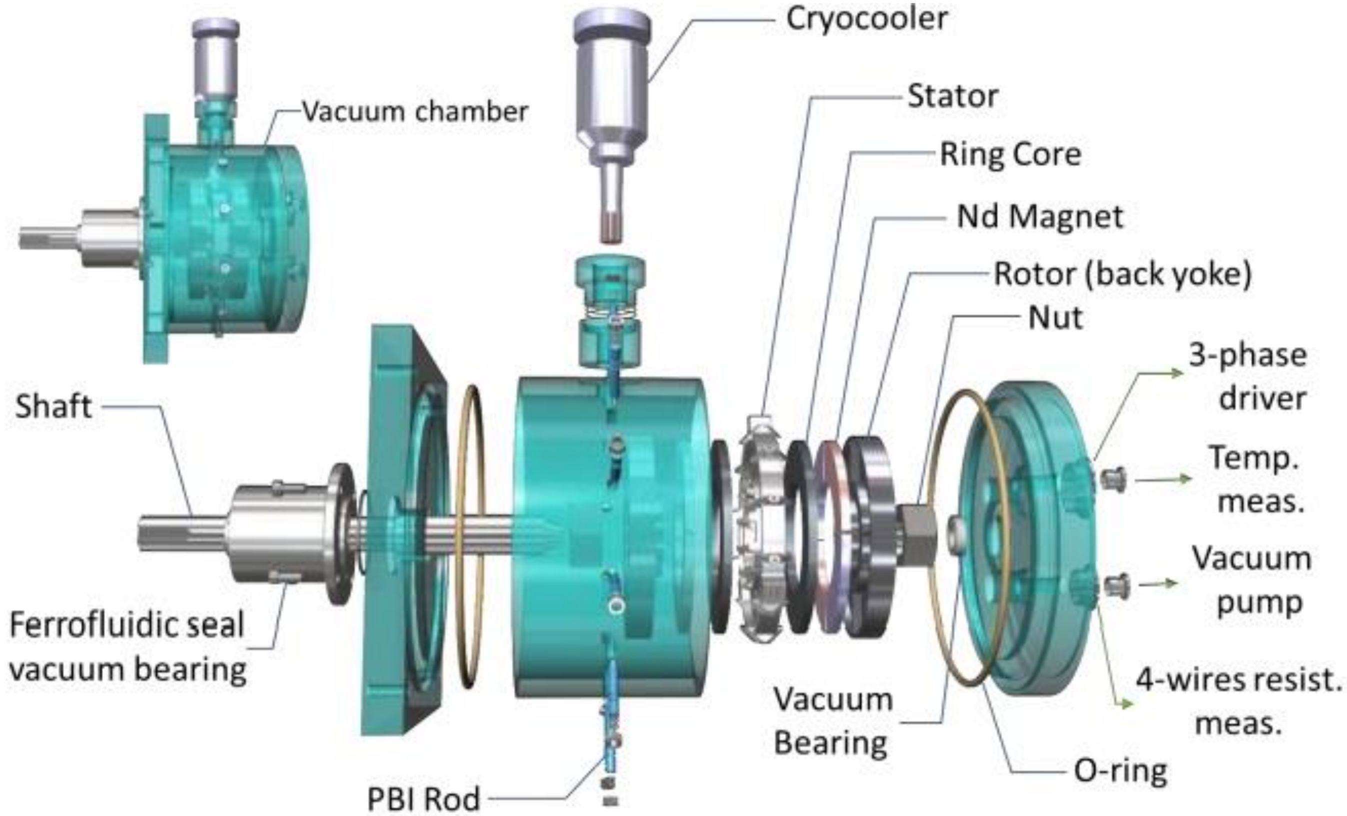

Schematic diagram of the prototype super motor/generator (SUTOR) which is a synchronous four-pole machine and is topologically the same as Asumed

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ASuMED

Purpose

- Demonstrate benefits of a new fully superconducting motor with a power density of 20kW/kg. In particular:
  - design an appropriate motor topology
  - develop a high-temperature superconducting (HTS) stator with an electric loading of >450kA/m
  - develop a rotor using HTS stacks operating like permanent magnets providing an average magnetic loading of >2.5 T
  - integrate a magnetization system into the stator area
  - implement a highly efficient cryostat for motor combined with integrated cryogenic cooling system and associated power converter
- Demonstrate above technologies in a prototype with approximately 1 MW power at 10.000rpm and a thermal loss <0.1%
- Design innovative modular inverter topology with enhanced failure protection, to realize highly dynamic and robust control of superconducting machines.

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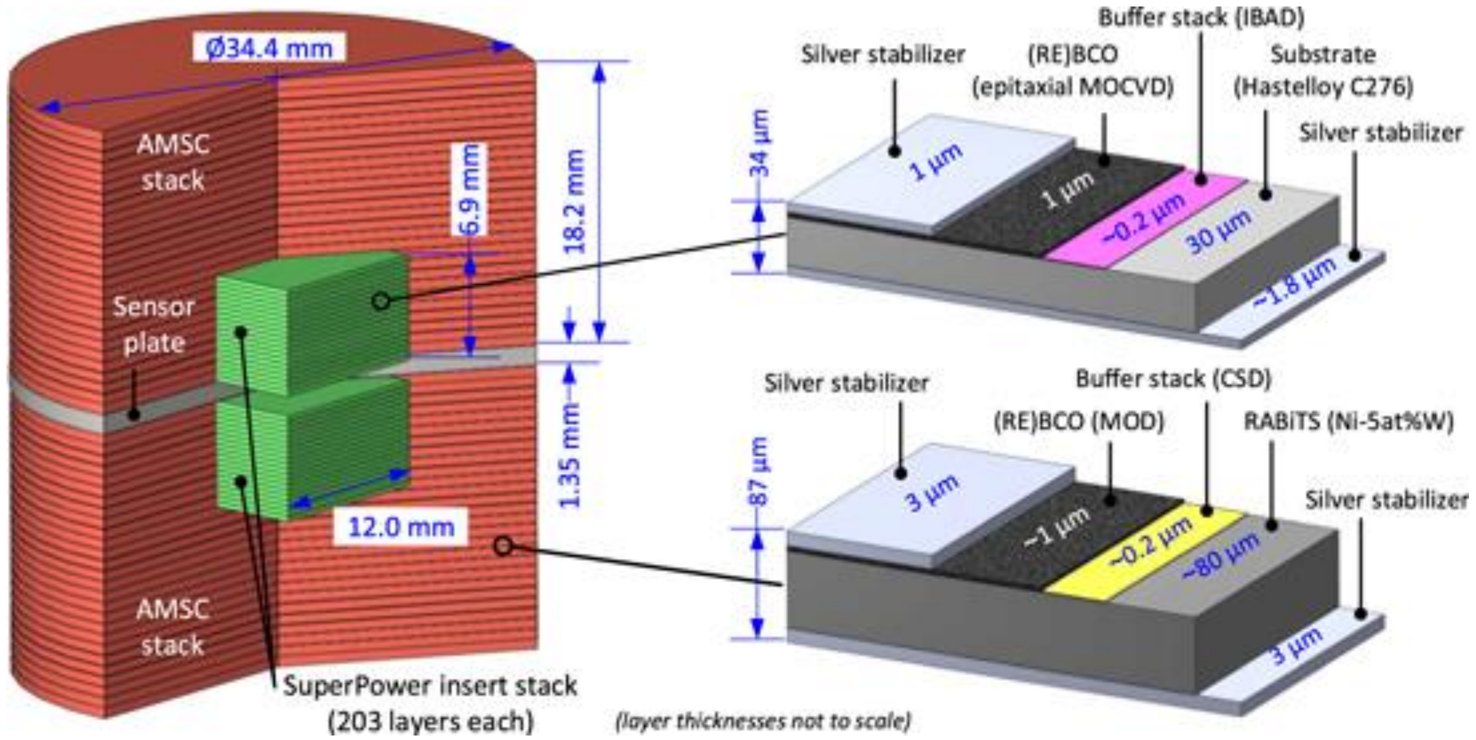
World Record Fields



A trapped field of 17.7 T in a stack of high temperature superconducting tape

Anup Patel[1], Algirdas Baskys[1], Tom Mitchell-Williams[1], Aoife McCaul[1], William Coniglio[2], Jens Hänisch[3], Mayraluna Lao[3] and Bartek A Glowacki[1,4]

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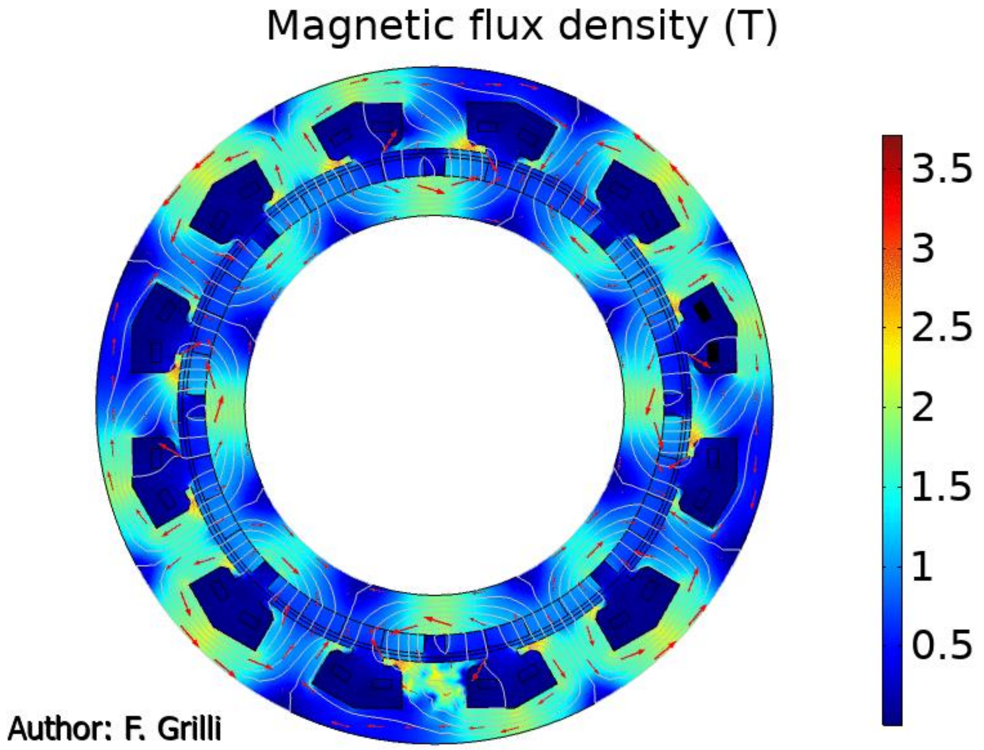

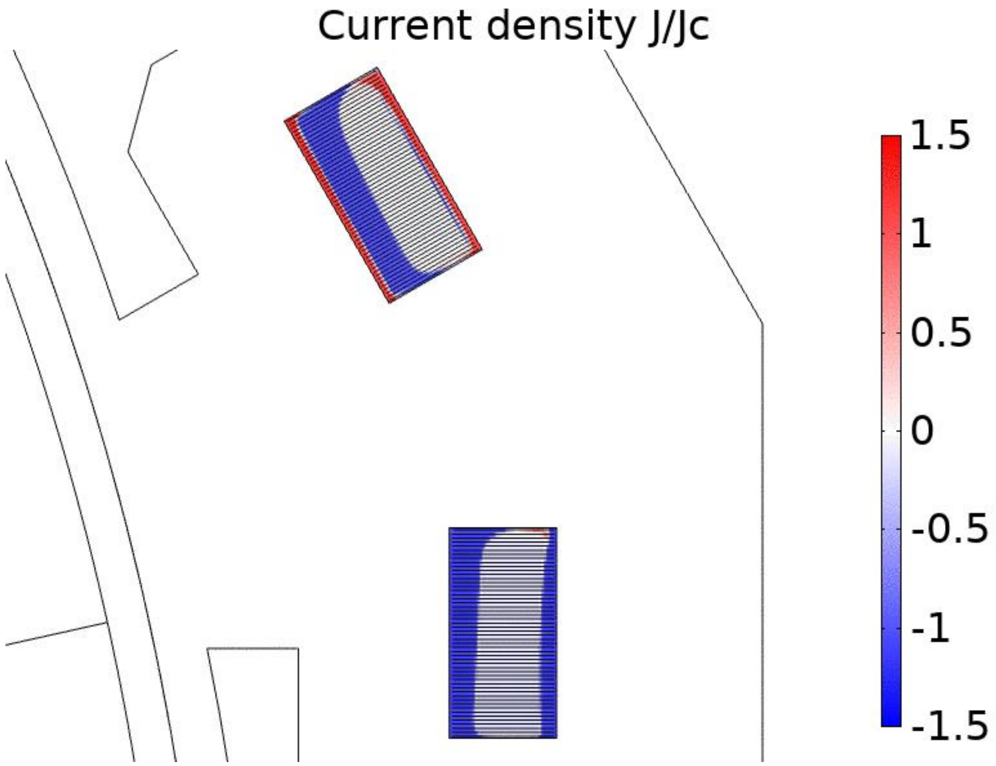

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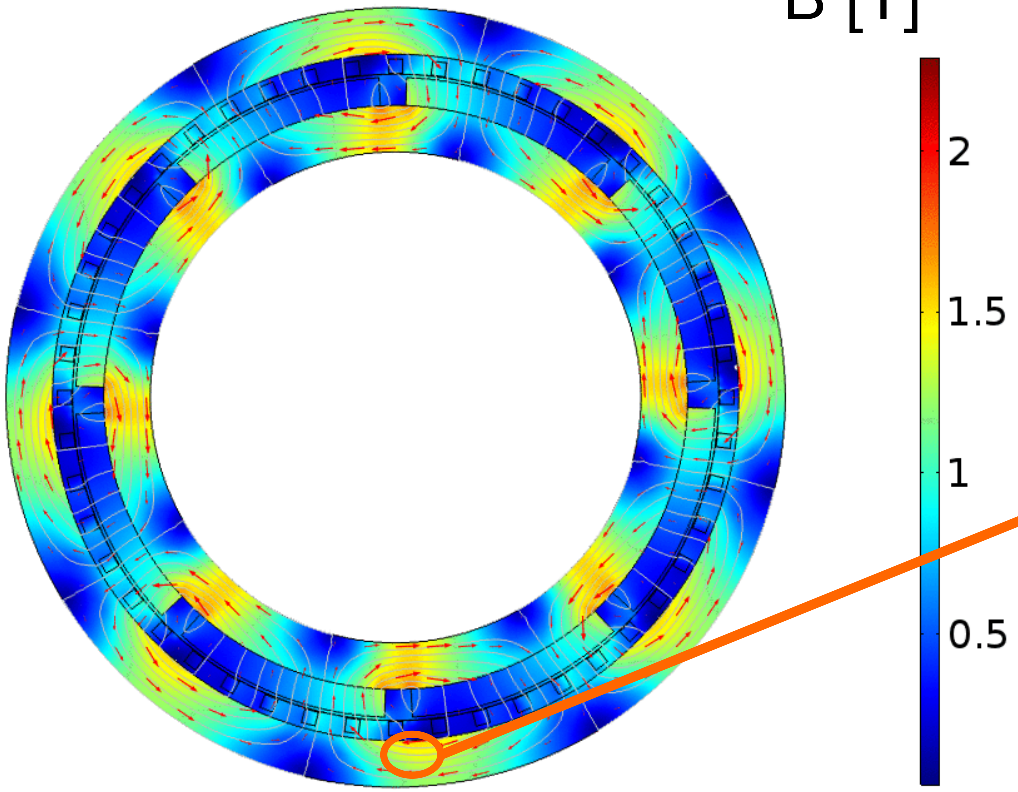
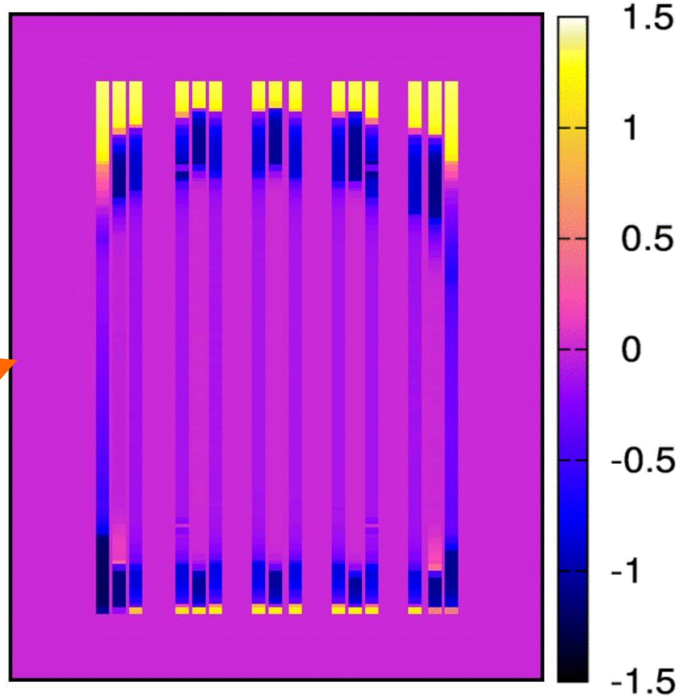
Non-linear eddy currents and AC loss

ASuMED
Funded by the European Commission Grant No 723119

B [T]



more than 1000 tapes



Machine Efficiency

- Highest power Densities only achievable with all superconducting machine … Stator will see alternating field and current
- AC conditions lead to loss in superconductors

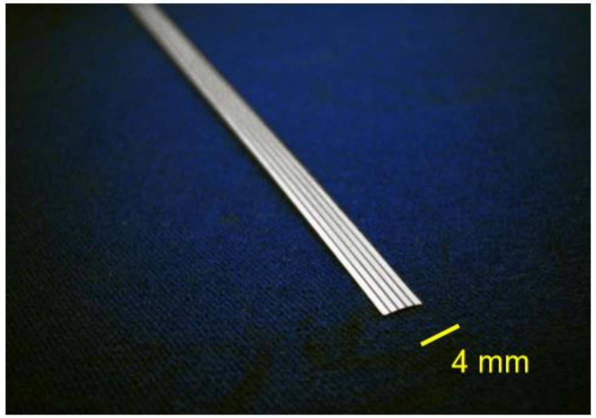
Mitigations

Flux Divertors

Roebel Cables

CORC

Striation



- 600 μm stripe / 200 μm trench (5 stripes)

Striation of Superpower's tape led to 5x reduction on loss

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Roebel Cables

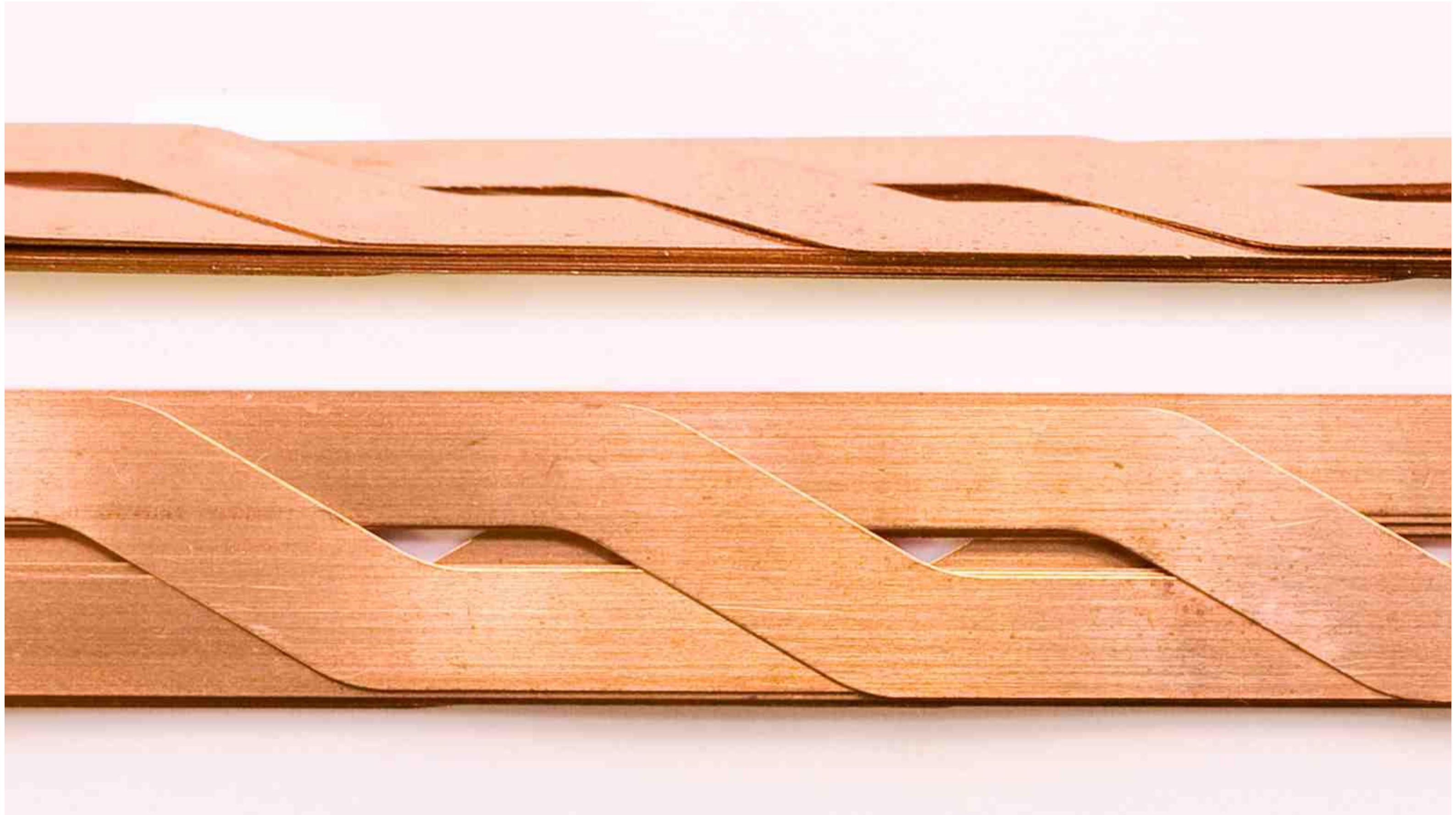

Image Courtesy of: The Robinson Institute Wellington University

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), November 2019.
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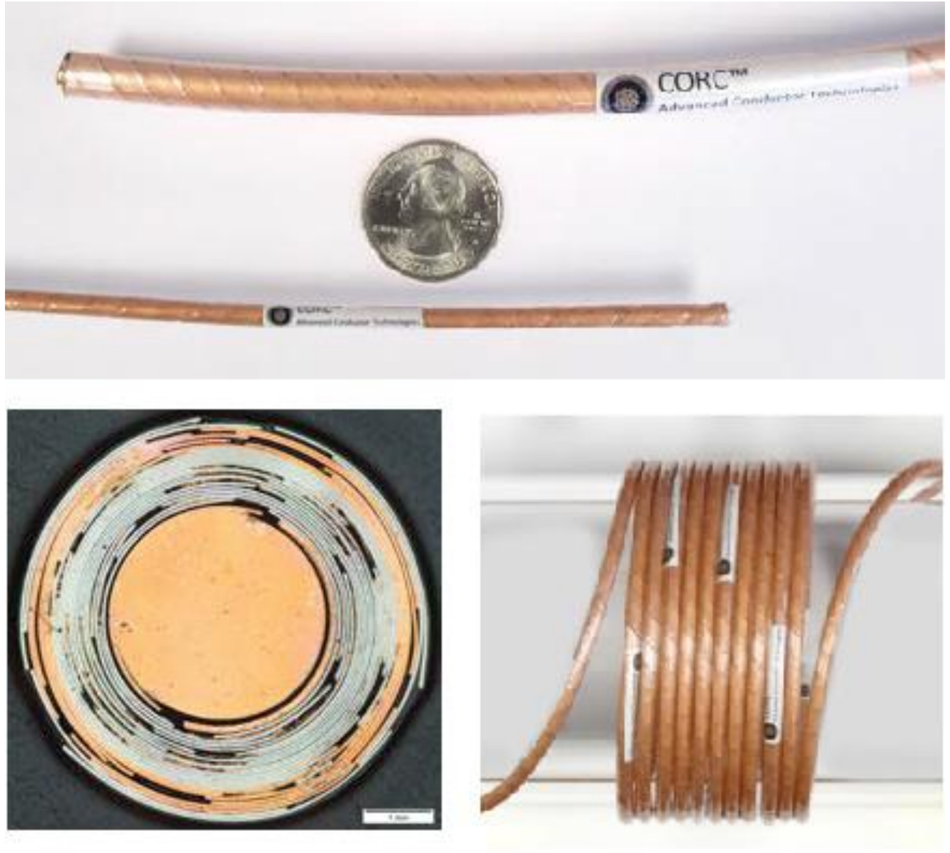
Conductor on Round Core (CORC®) cable



- *Graphic image courtesy of Advanced Conductor Technologies*

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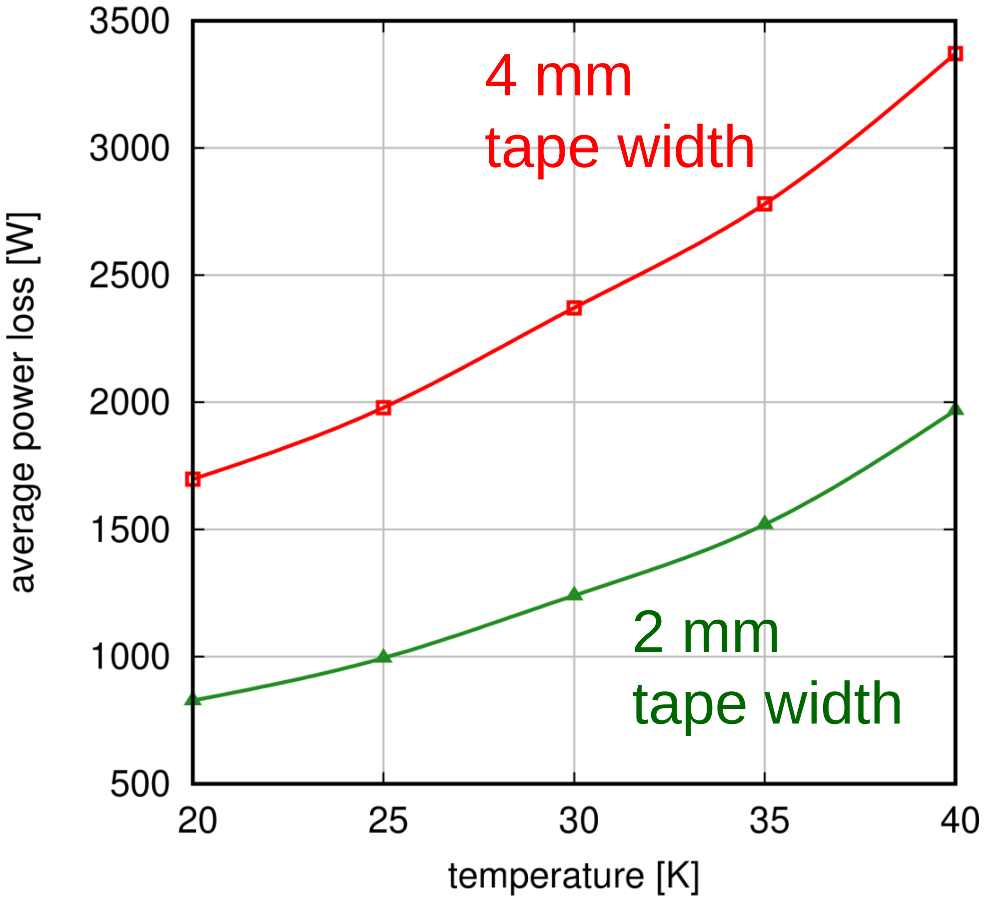
Narrower tapes decrease AC loss

ASuMED
Funded by the European Commission Grant No 723119



Narrower tapes with the same J_c are very interesting!

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Superconducting machines: stator

	Design 1	Design 2	Design 3
Power	2.67 MW	2.67 MW	2.67 MW
Operational temperature	25/65 K	25/65 K	25/65 K
Stator HTS width	1 mm	0.5 mm	0.25 mm
AC loss of stator @50Hz	107 kW	29.9 kW	13.1 kW
Stator efficiency	95.9%	98.8 %	99.5%

Narrow multi-filament HTS cables are essential for fully HTS machine applications.

- Soldering stack of narrow HTS strip *
- Diffusion stack of HTS (SuNam)
- Striated HTS without copper/Ag coupling
- Bi2212

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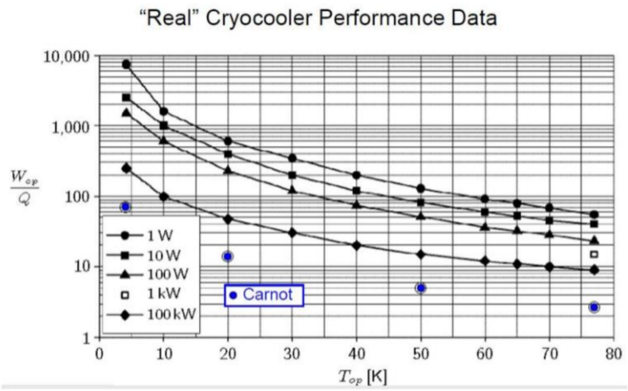
Superconducting machines: cooling

	Design 1	Design 2	Design 3
Stator HTS width	1 mm	0.5 mm	0.25 mm
AC loss of stator	107kW	29.9 kW	13.1kW
Stator efficiency	95.9%	98.8 %	99.5%
Machine efficiency @ 100 kW cooling station	59.9%	88.8%	95%



Conclusion:

1. A 2.67 MW fully HTS propulsion machine was designed as a baseline case.
2. The up limit of this machine is 54 kW/kg using current 2G HTS technology.
3. HTS multi-filament cables <= 0.5 mm are essential for stator winding to maximum machine efficiency.
4. Active magnetic shielding will help to improve power density.

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Summary

Early Seventies optimism dampened by failure to realise ever larger generators removing original driver for innovation

Development of Generators mirrors the development of conductors

EcoSwing is a significant step forward and indicates that the technology is essentially mature

All superconducting machines need to be developed if the next big market (air travel) is to be realised. This is leading to developments in the conductor geometry rather than the material itself in an effort to bring AC losses down to an acceptable value