Overview

- Superconducting electrical machines

- Benefits of superconductors & typical design
- Use of high temperature superconducting (HTS) conductors •

AMSC ship propulsion motors

  - EcoSwing wind generator
- Use of bulk HTS materials
- Future outlook & challenges

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Superconducting electrical machines

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Synchronous (radial) machine ��

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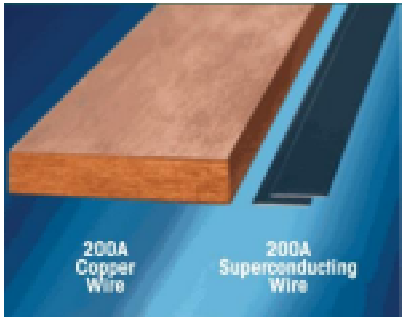
Supercondutors can increase magnetic / electric loading of an electric machine



- Higher current density, higher magnetic field

Partial or complete removal of iron

→ increased torque / power density ↔ reduced size & weight

- Lower wire resistance

→ lower losses & higher efficiency = better performance FEMM Hub

Superconducting electrical machines

Over many decades, various superconducting machines shown to be technically feasible over wide range of power ratings

First attempted in the 1960s, replacing copper windings with low temperature superconductors (LTS)

- Improved efficiency (about 1%) was expected, but the main rationale was the size / weight reduction
- Operated at liquid helium temperature (4 K)
- Large AC losses in armature winding → unacceptable heat load • Complexity & cost of 4 K cryogenics prohibitive
  - Only DC field winding feasible

Superconducting electrical machines

Optimal configuration for AC superconducting machines from studies using LTS conductors in the 1960s & 70s

ROTOR	Superconducting DC field winding (rotating)
	External excitation current supply
	Liquid helium coolant
	High vacuum cryogenic insulation
	Normally-conducting eddy current shielding system (conducting shell)
STATOR	Normally-conducting armature winding (stationary)
	Cooling system rejecting heat at ambient temperature
	Laminated back-iron flux shield

Superconducting electrical machines

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Discovery of high-temperature superconducting (HTS) materials in 1987 renewed enthusiasm!

- Expectation that materials could be exploited at higher temperatures, e.g., liquid nitrogen @ 77 K
- Reduced capital costs for & complexity of refrigeration system
- Refrigeration efficiency ~100 times greater than at 4.2 K
- Carnot efficiency (ideal):

$$\eta_c = \frac{T_{op}}{T_{amb} - T_{op}} \qquad P_{in} = \frac{1}{\eta_c}\frac{dQ}{dt}$$

1 W heat @ 77 K = 2.8 W

@ 4.2 K = 68 W

- <u>Multiplication factor incl. cryocooler inefficiency: 20-50 @ 77 K</u>

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Superconducting electrical machines

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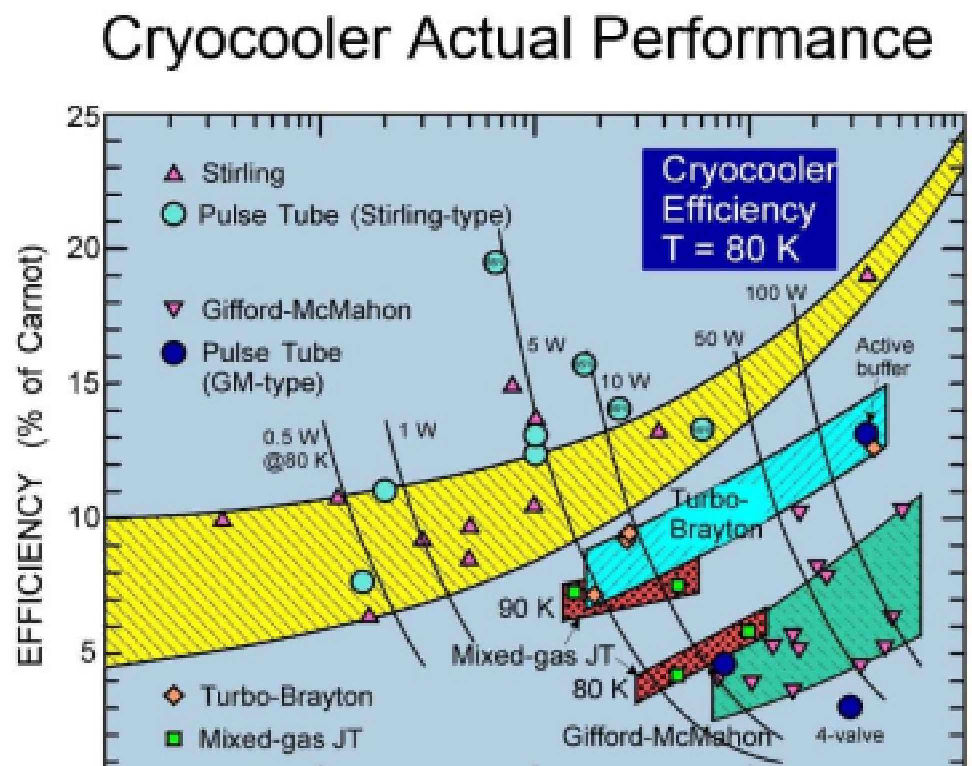

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Superconducting electrical machines

Advantages only appear over critical, "break-even" size or rating due to cryogenic system(s)

• i.e., the refrigeration penalty (size, weight, cost) becomes negligible • Critical / "break-even" size reduces with increasing operating temperature

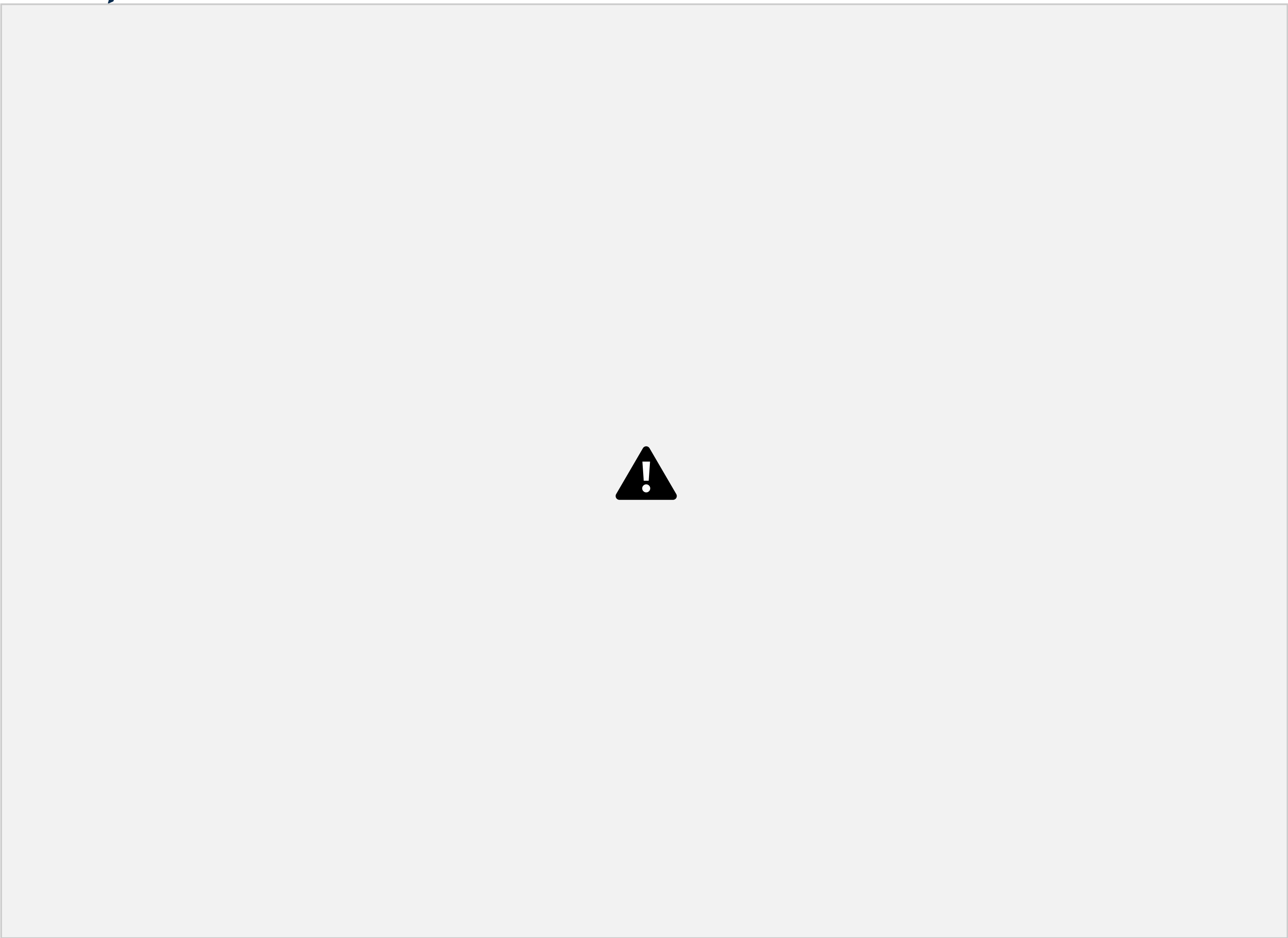
Improved thermal properties

• Assuming Cu stabiliser, specific heat increases

• Critical heat flux (nucleate → film boiling) much higher for 77 K than 4 K

For 2G HTS (RE)BCO, much improved in-field critical current density

Superconducting electrical machines



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AMSC ship propulsion motors

American Superconductor (now AMSC) HTS ship propulsion motors

- U.S. Navy moving towards all electric ship systems including propulsion

- Requirements difficult to achieve using conventional technology
- 2001-2004: 5 MW / 230 rpm [1]
- 2003-2008: 36.5 MW / 120 rpm [2]

[1] Snitchler et al., IEEE Trans. Appl. Supercond. 15 (2005) 2206-2209
[2] Gamble et al., IEEE Trans. Appl. Supercond. 21 (2011) 1083-1088

AMSC ship propulsion motors (AMSC)

Rotor

- HTS field winding at 32 K
- BSCCO-2223 (1G) wire
- Helium gas cooled,

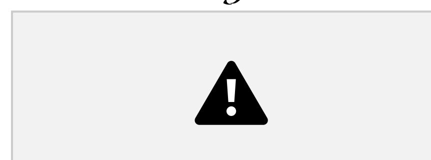
external cryocooler module

- EM shield

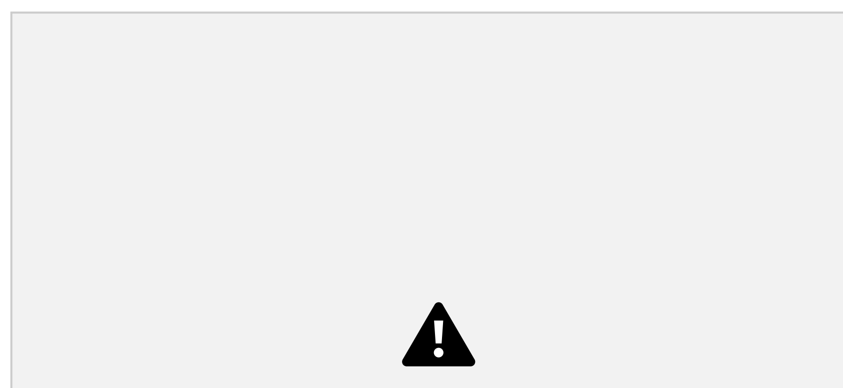
Stator (Alstom)

- Dielectric oil cooled Litz wire
- Air-gap winding, non-magnetic support structure

AMSC ship propulsion motors



Rotor integrated with stator at Alstom for full factory testing (2003)



- Operated for 21 hours at Center for Advanced Power Systems, FSU (2005)
- Achieved specified performance & power ratings under full operating conditions (full load, full speed)

5 MW, 230 rpm HTS motor (left) with 2.5 MW load motor (right) at Alstom, UK

AMSC ship propulsion motors

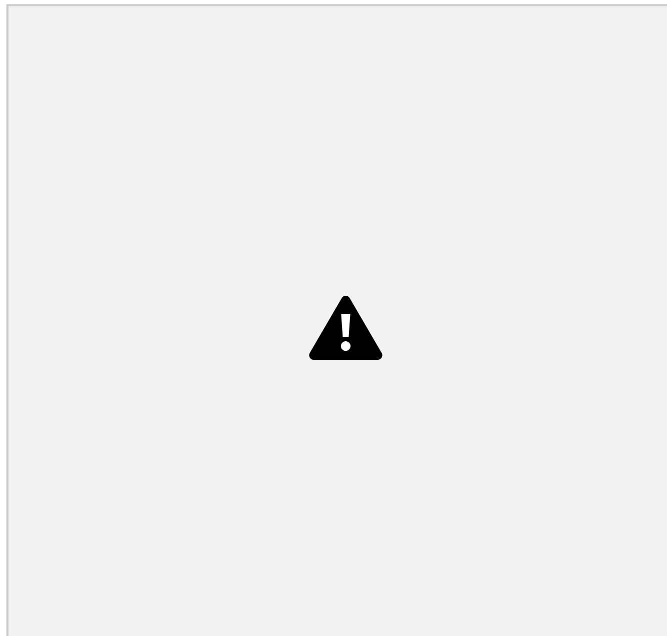
Extended to 36.5 MW HTS motor

- 14:1 torque increase over 5 MW machine
- Passed full power tests by end of 2008
- Achieved specific target of 75 metric tonnes

1/3 weight

of traditional copper-based propulsion systems

1/2 size



EcoSwing wind generator

- 4 year, EU-funded (Horizon 2020) project, ended April 2019
- Full-scale, multi-MW direct-drive superconducting wind generator
- Install superconducting drive train in existing modern wind turbine in Denmark (3.6 MW, 15 rpm, 128 m rotor)

EcoSwing wind generator

- Design according to IEC61400 (wind turbines) & IEC60034 (rotating electrical machinery) series
- 3.6 MW, 2.46 kNm, 690 V, 50 Hz

General requirements:

- Turbine system mechanical load
- Vibrations (fore-aft, side-side, roll, nod, yaw)
- Restricted space request for

EcoSwing wind generator

Stator assembly

- Insulation class F

compact design

- Max. temperature rise class B
- Temperature (external): -20°C +30°C
- Altitude: 2000 m
- Humidity: <95%, 100% for 10% of life

- Serviceable wear parts
- Minimum 1 year service interval
- Lighting protection IEC61400-24

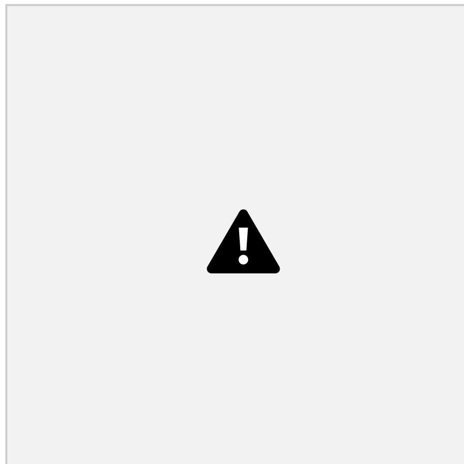
Conventional stator assembly with iron core sheets

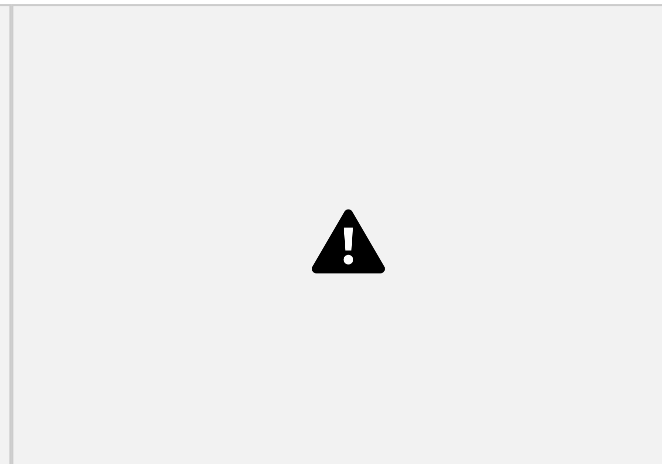
Form wound copper, mica insulation, VPI, class F

EcoSwing wind generator

Rotor assembly

THEVA TPL2100 Pro-Line wire
12 mm wide, 0.2 mm thick, GdBCO
Non-magnetic Hastelloy C-276 substrate
1 μm silver surround
100 μm copper stabliser on HTS side





200 turns, 500 m wire
Double pancake, insulated, potted with commercial resin,
glass-fibre reinforcement

Operating temperature <30 K
Conduction-cooled: SHI Cryogenics cryocoolers

EcoSwing wind generator

Testing

- Generator & power converter reached target range
- Generator successfully tested at Fraunhofer IWES labs (ground based testing) & certified prototype installation
- 650 hours of grid-connected operation
- Core technologies showed >7 months of stable, reliable operation

Other efforts

• Japan's Super-GM program: 70 MW-class superconducting generators (LTS) • Siemens: 380 kW (1500 rpm) motor → 4 MVA (3600 rpm) generator → 4 MW (30-190 rpm) ship motor

• Sumitomo Electric: 30 kW motor for electric passenger car • Converteam: 1.7 MW (214 rpm) hydroelectric power generator ... and more!

SIEMENS

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Bulk superconductors

machine performance

Bulks can be utilised in machines in three ways

- Flux shielding (reluctance)
- Flux pinning (hysteresis)
- Flux trapping (trapped flux)

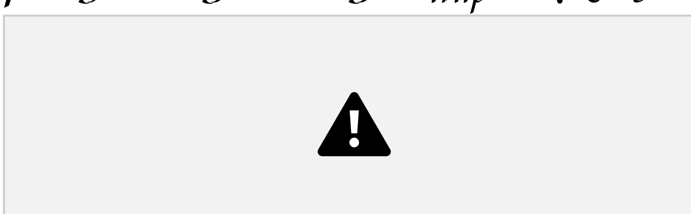
A large, single grain bulk superconductor

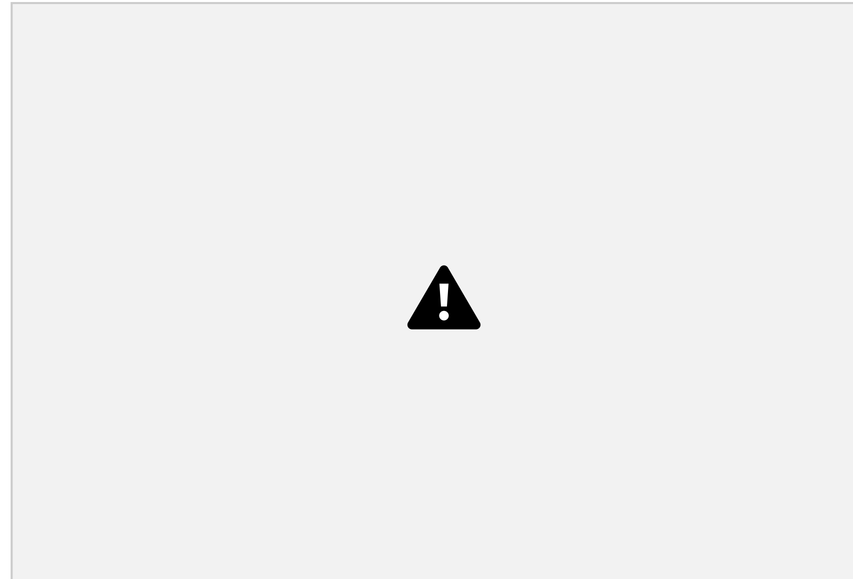
Most benefit to power density &

Trapped flux motor

Bulk HTS superconductors can 'trap' large magnetic fields >17 T

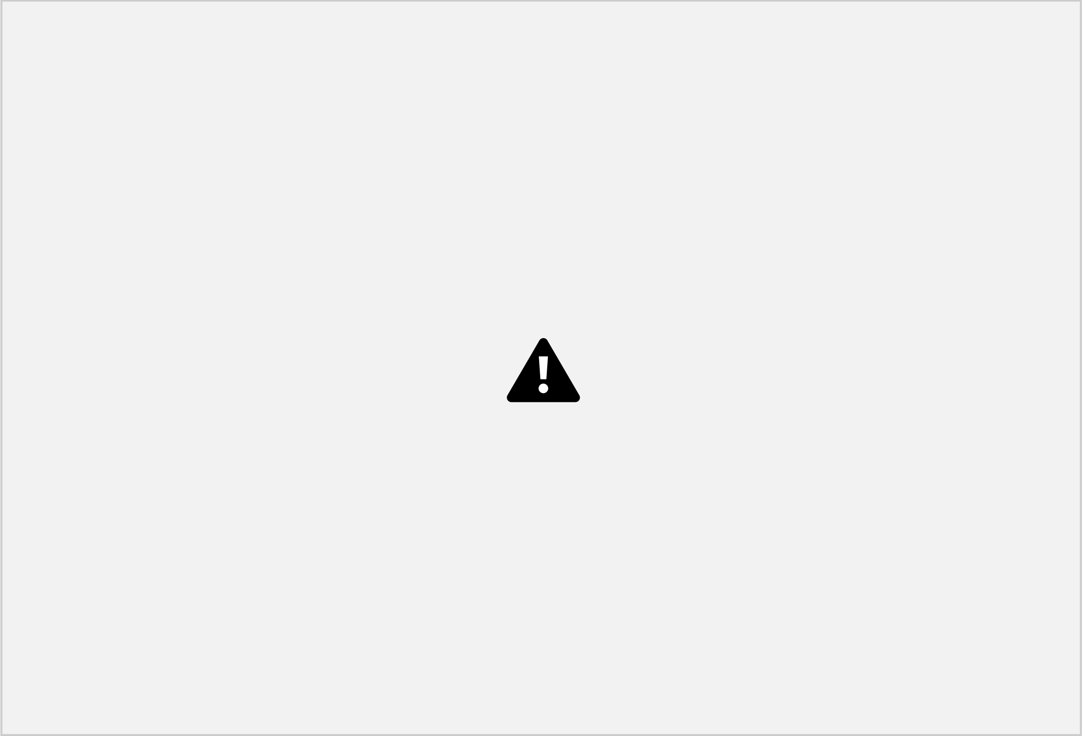
- Achieved by 'pinning' penetrated magnetic field (quantised flux lines) → macroscopic electrical current
- Magnetisation increases with sample volume
- Trapped field given by $B_{trap} = k\mu_0 J_c R$

where 



Typical trapped magnetic field profile of a bulk superconductor

Trapped flux motor



Radial-type bulk machine

Axial-type bulk machine

[Coombs et al., University of Cambridge]

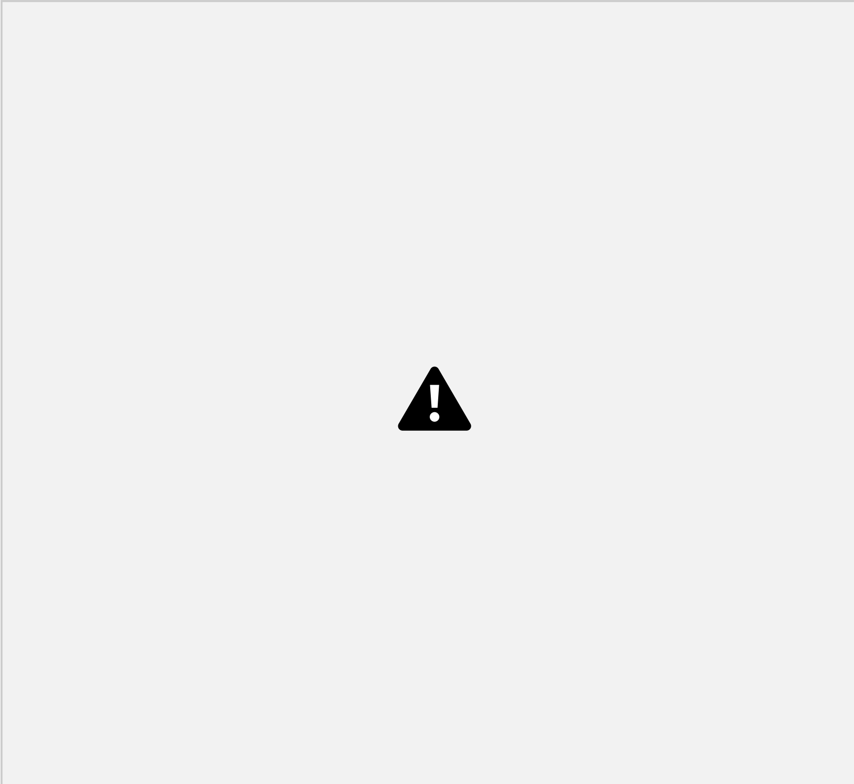
[Courtesy of M. Izumi, TUMSAT]

Magnetisation of bulks

- Three magnetisation techniques
  - Field cooling (FC)
  - Zero field cooling (ZFC)
  - Pulsed field magnetisation (PFM)

- To trap B_{trap}, need to apply $\geq B_{trap}$
- FC and ZFC require large magnetising coils + time
- Impractical for applications/devices → PFM

ZFC FC



Pulsed field magnetisation  PFM

technique: compact, mobile, relatively inexpensive • Stored energy in capacitor bank discharged through copper magnetising coil + pulse waveform control with IGBT switching

Pulsed field magnetisation PFM

technique: compact, mobile, relatively inexpensive • Stored energy in capacitor bank discharged through copper magnetising coil + pulse waveform control with IGBT switching

Issues: B_{trap} [PFM] < $B_{trap,max}$ [quasi-static]

• Temperature rise ΔT due to rapid movement of magnetic flux • Thermal time constant >> electromagnetic time constant (HTS)

Record PFM trapped field: 5.2 T @ 29 K

• 45 mm diameter Gd-Ba-Cu-O [Fujishiro et al., Physica C (2006)] • Record trapped field (quasi-static magnetisation): 17.6 T @ 26 K (2 x 25 mm dia Gd-Ba-Cu-O) Durrell et al. 2014 Supercond. Sci. Technol. FEMM Hub Conference 2024, Birmingham

Pulsed field magnetisation Many considerations!

• Pulse magnitude, pulse duration, temperature(s), number of pulses, type of magnetising coil(s), use of ferromagnetic materials • Dynamics of magnetic flux during PFM process

Promising routes for magnetisation:

• Multi-pulse, step-wise cooling (MPSC) techniques

• Using ferromagnetic materials to shape & enhance trapped fields •

Waveform-control PFM

Offers an in-situ magnetisation method for rotating machines!

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Trapped flux motor

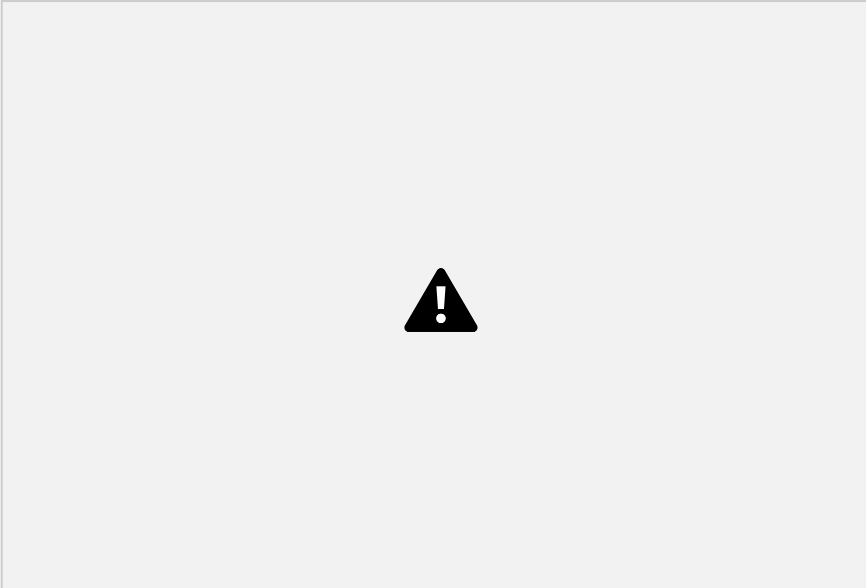
Stator coils pulse-magnetise bulks •

Dual purpose: magnetisation + armature

• Cooled with liquid N_2

Closed-cycle neon thermosyphon system with cryo-rotary joint •

Cryogen from static condenser to rotating rotor plate with bulks • Allows cooling of bulks to sub-40 K



Axial-type bulk machine [Courtesy of M. Izumi, TUMSAT]

Future outlook & challenges

- Significant body of work → 2G HTS (RE)BCO coated conductor, MgB_2
- Most designs have focused on isolated, cryogenic rotor + conventional stator
    - Low AC loss conductor and / or improved winding / machine design
    - All-cryogenic / all-superconducting solutions with unprecedented power

densities could be realised

- Will reduce complexity, improve reliability

- Cost still a major issue as identified by large-scale projects •

Development of numerical models

- Need cost- & time-effective design & optimisation tools
- Highly nonlinear superconducting properties, large aspect ratio or twisted multifilamentary wires make life difficult

Future outlook & challenges

- Appropriate infrastructure & knowledge required for large-scale manufacture •

  Superconducting materials, specialist coil winding & cryogenic / vacuum systems need to be available on an industrial level

- Crycooler + cryostat technology
  - Efficiency, reliability, cost, redundancy; complete engineering solution required

Bulk-based machines

- Larger diameter samples (limited to ~50-60 mm diameter) → larger field poles
- Magnetisation techniques
  - Improved in-situ PFM → 5-7 T trapped fields
- Magnetic field stability + demagnetisation
  - Time-varying fields in real machine environments → demagnetisation?
- Mechanical properties of bulks + mechanical design of machines
- Limiting factor for high field applications (>7-9 T); brittle ceramics

Electric aircraft

AIRBUS UpNext ASCEND

Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator

Next stage: CRYOPROP project

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Recommended further reading

Superconducting machines (in general)

- C.C. Chow, M.D. Ainslie & K.T. Chau, "High temperature superconducting rotating electrical machines: an overview," *Energy Rep.* 9 (2023) 1124-1156 [DOI: 10.1016/j.egyr.2022.11.173]
- K. S. Haran *et al.*, "High power density superconducting machines – development status and technology roadmap," *Supercond. Sci. Technol.* 30 (2017) 123002 [DOI: 10.1088/1361-6668/aa833e]
- J. R. Bumby, "Superconducting rotating electric machines (monographs in electrical and electronic engineering)," Oxford: Clarendon Press (1983)

Recommended further reading

Bulk superconducting machines

- M.D. Ainslie & M. Filipenko, "Ultra-light superconducting rotating machines for next generation transport & power applications," in "Bulk superconductors: a roadmap to applications," *Supercond. Sci. Technol.* 31 (2018) 103501 [DOI: 10.1088/1361-6668/aad7ce]
- Y. Zhang *et al.*, "Melt-growth bulk superconductors and application to an axial-gap-type rotating machine," *Supercond. Sci. Technol.* 29 (2016) 044005 [DOI: 10.1088/0953-2048/29/4/044005]
- D. Zhou *et al.*, "An overview of rotating machine systems with high temperature bulk superconductors," *Supercond. Sci. Technol.* 25 (2012) 103001 [DOI: 10.1088/0953-2048/25/10/103001]