UNIVERSITEIT TWENTE.

Power-dense Superconducting Generators for Wind Converters

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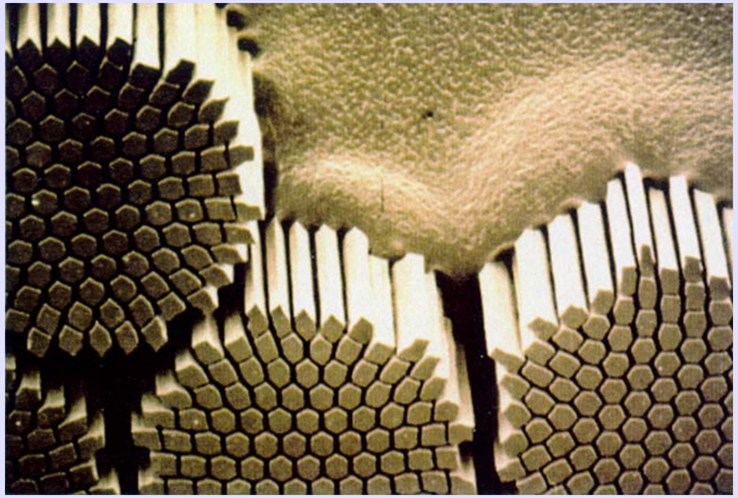
4TU.HTM Meeting Materials 2020

(*) on behalf of the EcoSwing Consortium, team and references on final slide

Background *Superconductivity*

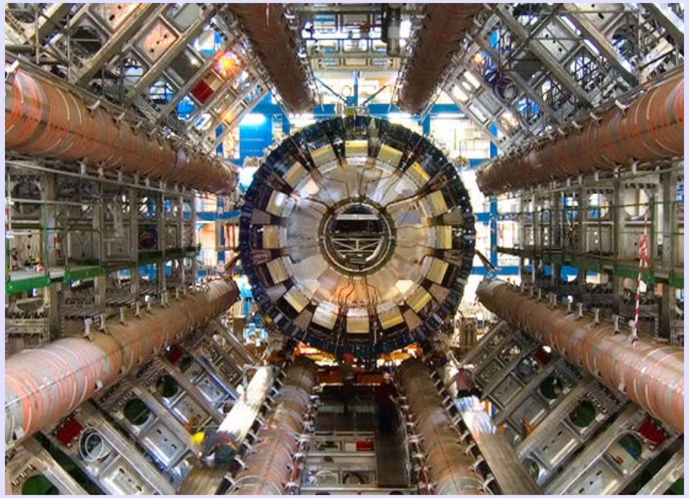
- Zero resistance below $T = T_c$
- **Dissipation-free current transport**
  up to $J_c\ (B,T) \approx 100 - 1000\ \mathrm{A/mm^2}$
  (~ 10 – 100 times higher than Cu)
- In the 20th century: metal alloys
  or intermetallics, cooled in liquid He (4.2 K)

- Applications: **superconducting *magnets***
- Cu + Fe electromagnets $B \lesssim 1.5\ \mathrm{T}$
- Nb_3Sn electromagnets $B \lesssim 15 \sim 20\ \mathrm{T}$
- Enabling technology, mainly for NMR, MRI and ‘Big Science’



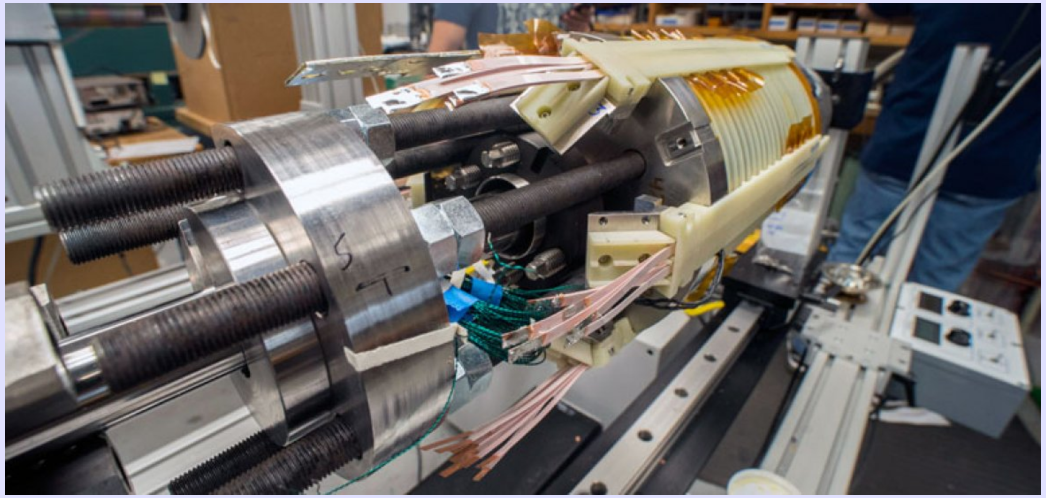
NbTi filaments (ϕ 7μm) in composite wire

State-of-the-art MRI system (Philips)



ATLAS detector magnets (CERN)

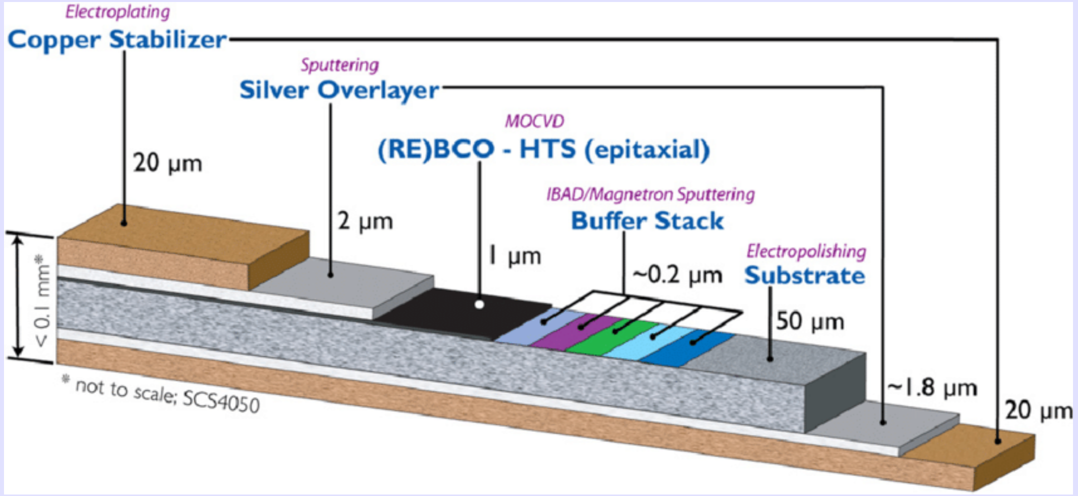
- 1986: discovery of **superconductivity in ceramic CuO-compounds**
- $T_c \sim 10 - 100$ K ; $B_{c2} > 100$ T
- Anisotropic materials
- Further developed into highly textured epitaxial coatings ('coated conductors')



*Re*BCO 32 T magnet (NHFML Tallahassee)

Manufacturer	ReBCO layer	Buffer layers
American Superconductor	MOD	RABiT
Bruker HTS	PLD	ABAD
Deutsche Nanoschicht	CSD	RABiT
Fujikura	PLD	IBAD
MetOx	MOCVD	RABiT
Oxolutia	CSD	IBAD + ABAD
SuNAM	RCO	IBAD
Superconductor Technologies Inc.	RCO	IBAD + ABAD
SuperOx	PLD	IBAD
SuperPower	MOCVD	IBAD
Theva	RCO	IBAD + ABAD

Properties: http://htsdb.wimbush.eu/



Layout *Re*BCO Coated Conductor (SuperPower)

*Re*BCO Roebel cable (KIT / CERN)

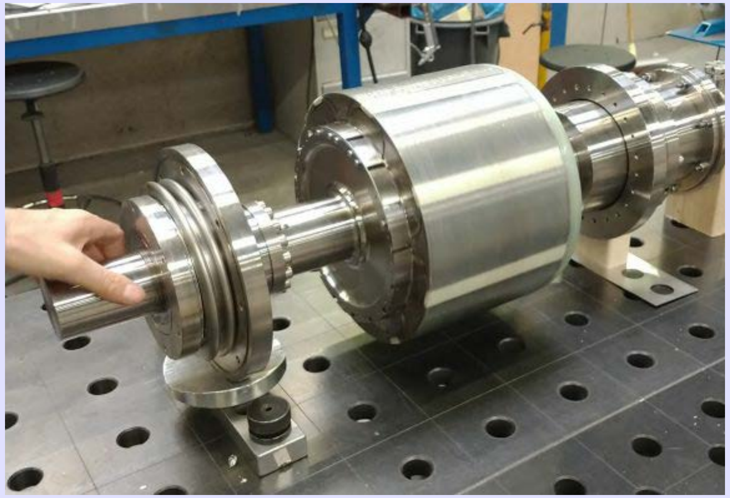
Background *Superconductivity*

- In parallel: steady progress in **liquid-cryogen-free cooling** technology
- New s.c. materials + user-friendly cooling → unlocks new application areas
- **Main driver = power density** $\propto I^2 \; or \; B^2$
- Enables smaller and/or more powerful devices (transport / motors / actuators)

Gifford-McMahon cryocooler (Summitomo)

Grid powercable (AmpaCity, Essen)

36.5 MW ship propulsion engine (AMSC)

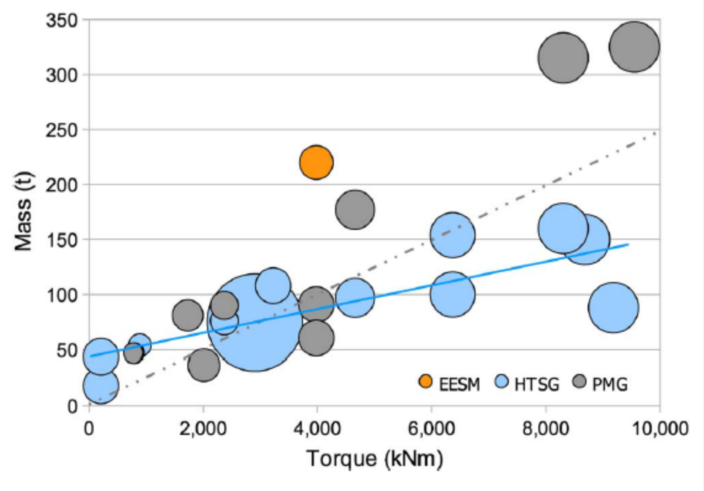


All-electric airplane? (ASUMED, Demaco)

Background *Wind convertors*

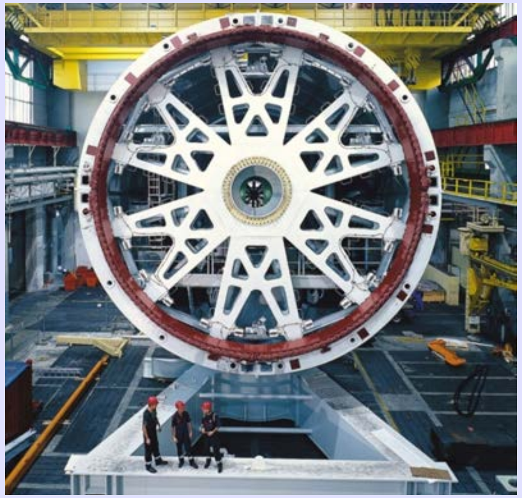
- Trend towards **higher-power rated convertors**
- Direct-drive (no gear box) → high-torque machines
- Synchronous generators (DC rotor)
- State-of-the-art based on PM technology (NdFeB)
- **Scaling advantage for superconducting** machines

($P \propto D^5$ instead of D^3, S. Kalsi 2003)



Mass vs. torque scaling (O. Keysan 2011)

PM rotor (Arnold Magnetic Technologies)



7.5 MW PM rotor (Enercon)

Haliade-X 12MW converter (GE, Rotterdam)

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Horizon 2020 European Union Funding for Research & Innovation

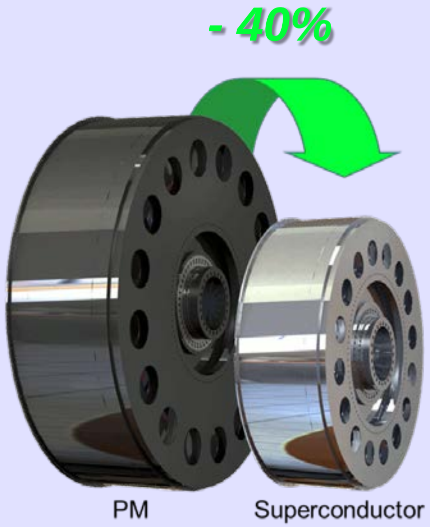
ecoswing (2015-2019)

However: perceived challenges

- Availability / cost superconductor.
- Cryogenics reliability;
- Mechanical torque transmission; from warm to cold environment

- Design, develop and manufacture a **full scale** multi-MW direct-drive **superconducting wind generator**;
- Install and **operate this drive train in** an existing modern **wind turbine** in Thyborøn, DK(3 MW Class, 14 rpm, 128 m rotor);
- Prove in an operation environment that such a superconducting drive train is **cost-competitive**.

Envision's 3.6 MW test turbine



EcoSwing's ambition

ENVISION Coordination / demonstration	ECO 5 Core design / engineering	JEUMONT Electric Stator / integration
DELTA ENERGY SYSTEMS Power convertor / control	THEVA *Re*BCO conductor / coils	SHI Cryogenics Group Cryogenics
Fraunhofer Ground-based testing	UNIVERSITY OF TWENTE. Validation / rotor assembly	DNV·GL Pre-certification

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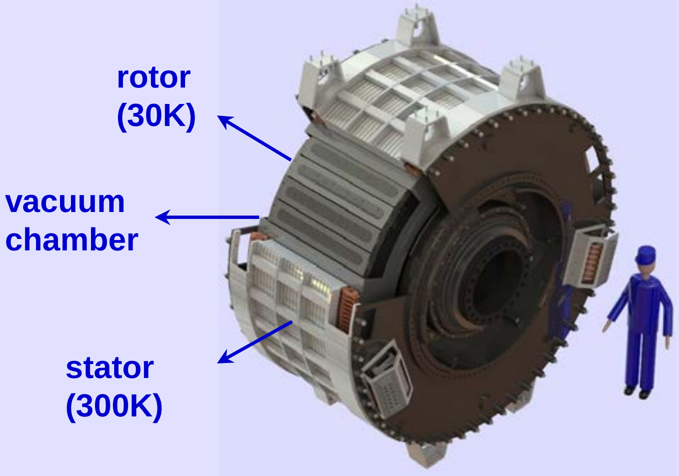
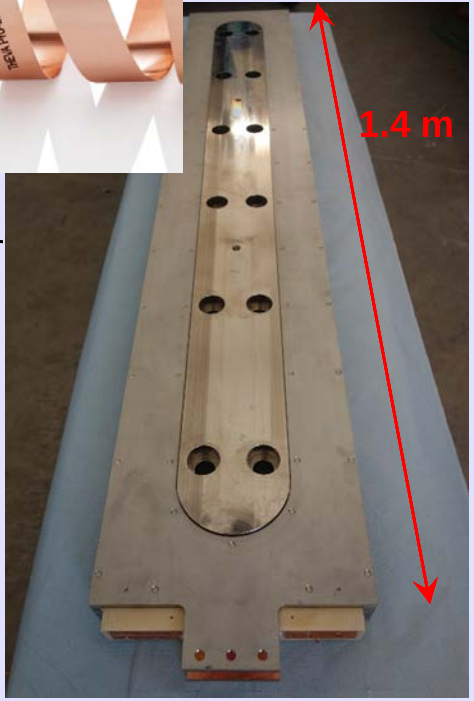
Validation conductor & coils / Ramp-up production capacity

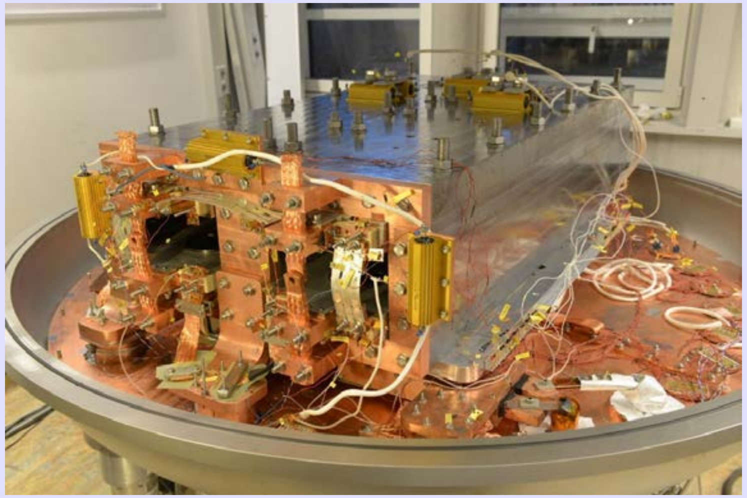


Cutaway generator design

Theva coated conductor



full-scale prototype coil

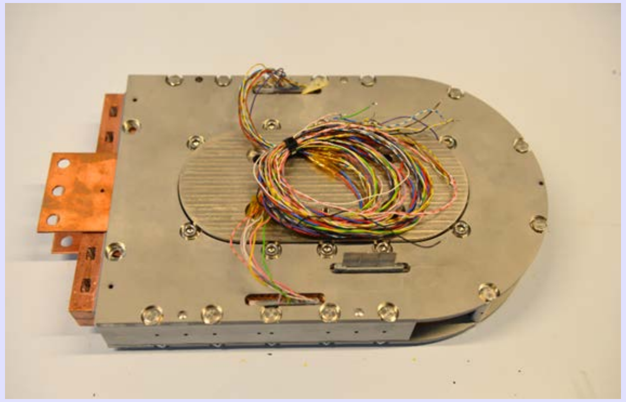


Conduction-cooled full-scale coil test rig (20K)

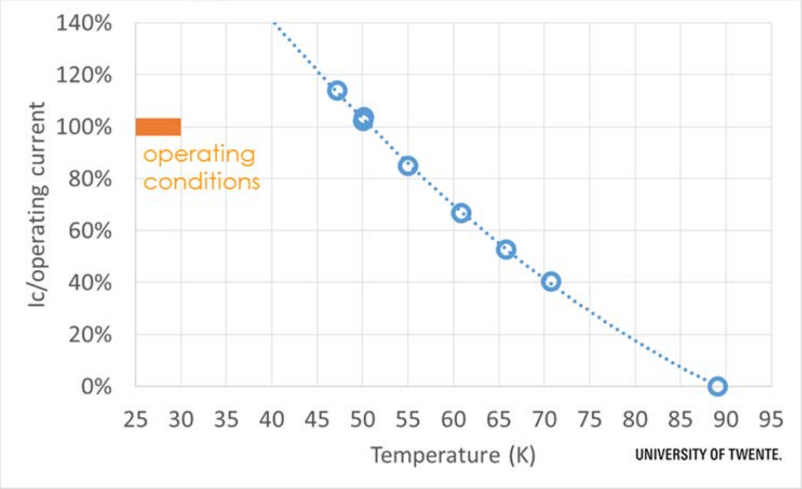
ECO5

THEVA

UNIVERSITY OF TWENTE.



Sub-scale test coil (design validation)



Prototype coil performance test

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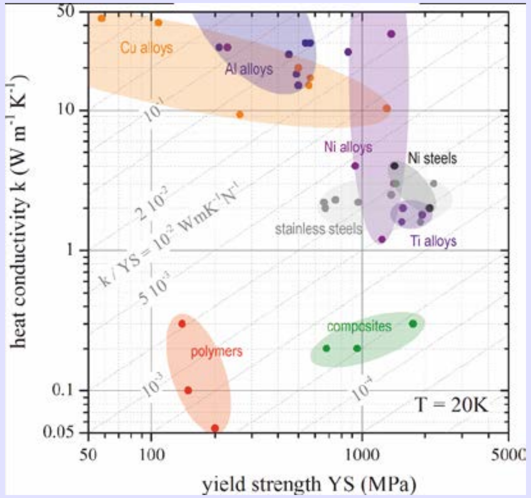
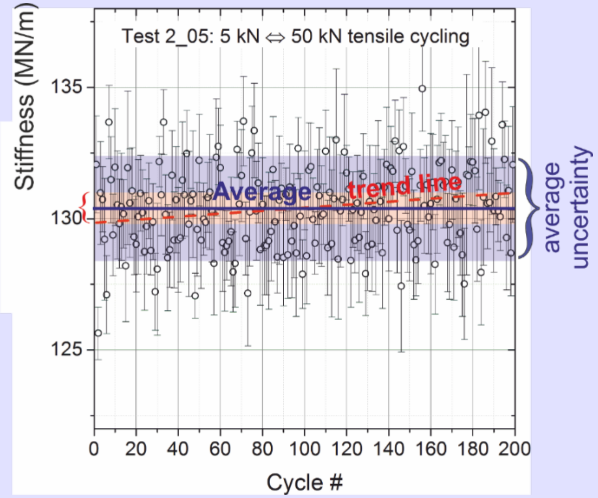
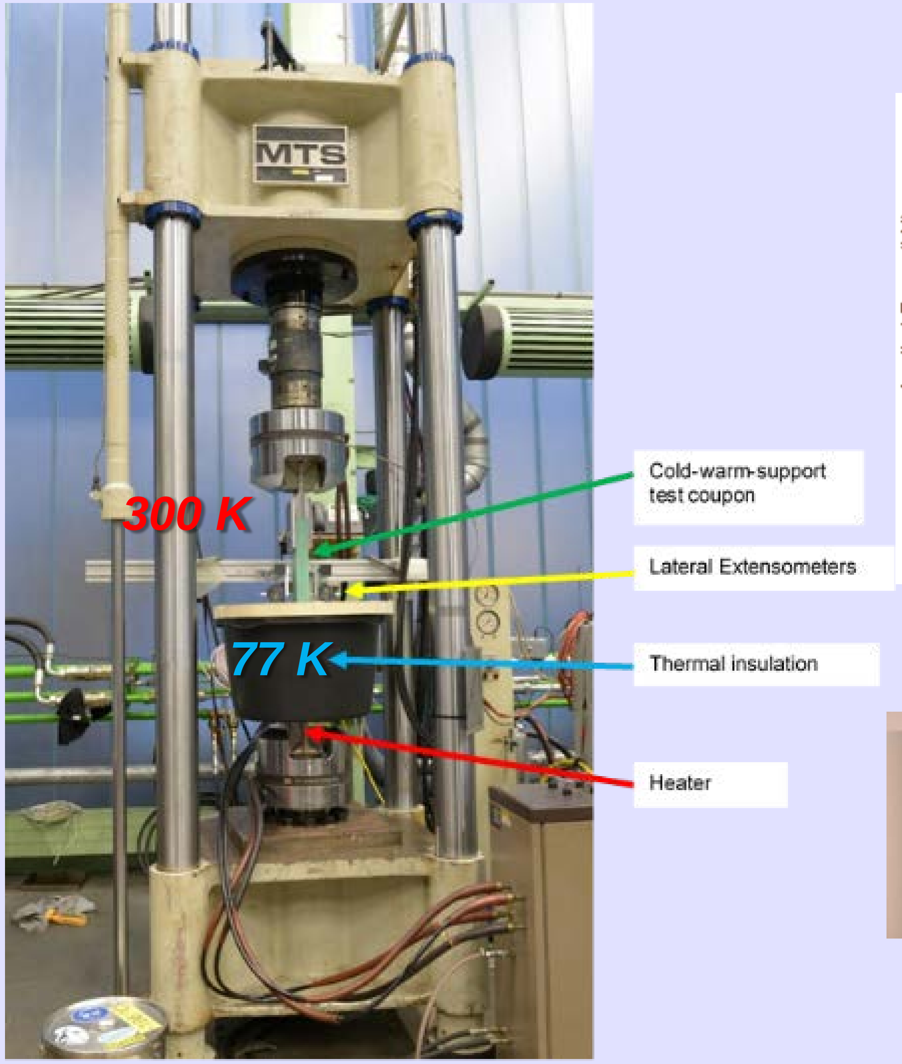
Cryogenic mechanical testing



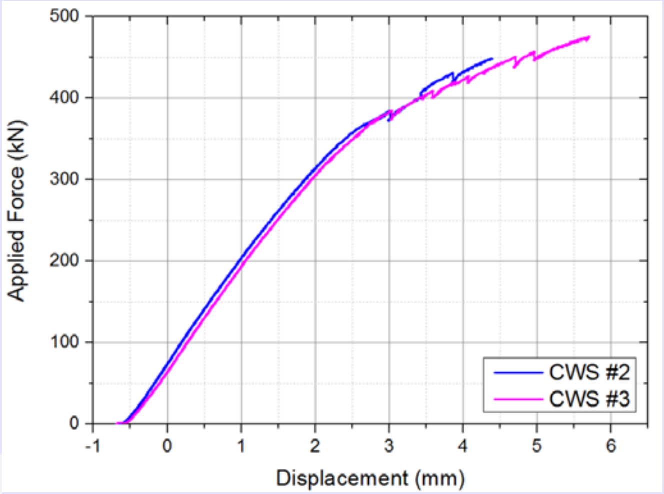
Cryogenic strength vs heat conductivity



Representative fatigue testing



Tensile / compressive loading test coupons @ TNO Delft



Tensile yield test

Yielding on warm side, not cold side

EcoSwing: *Superconducting rotor*

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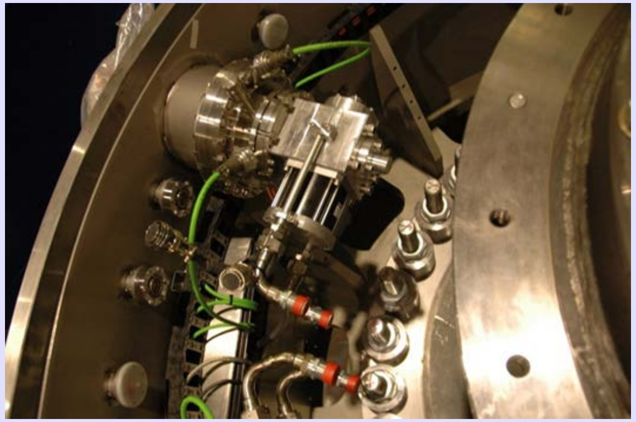
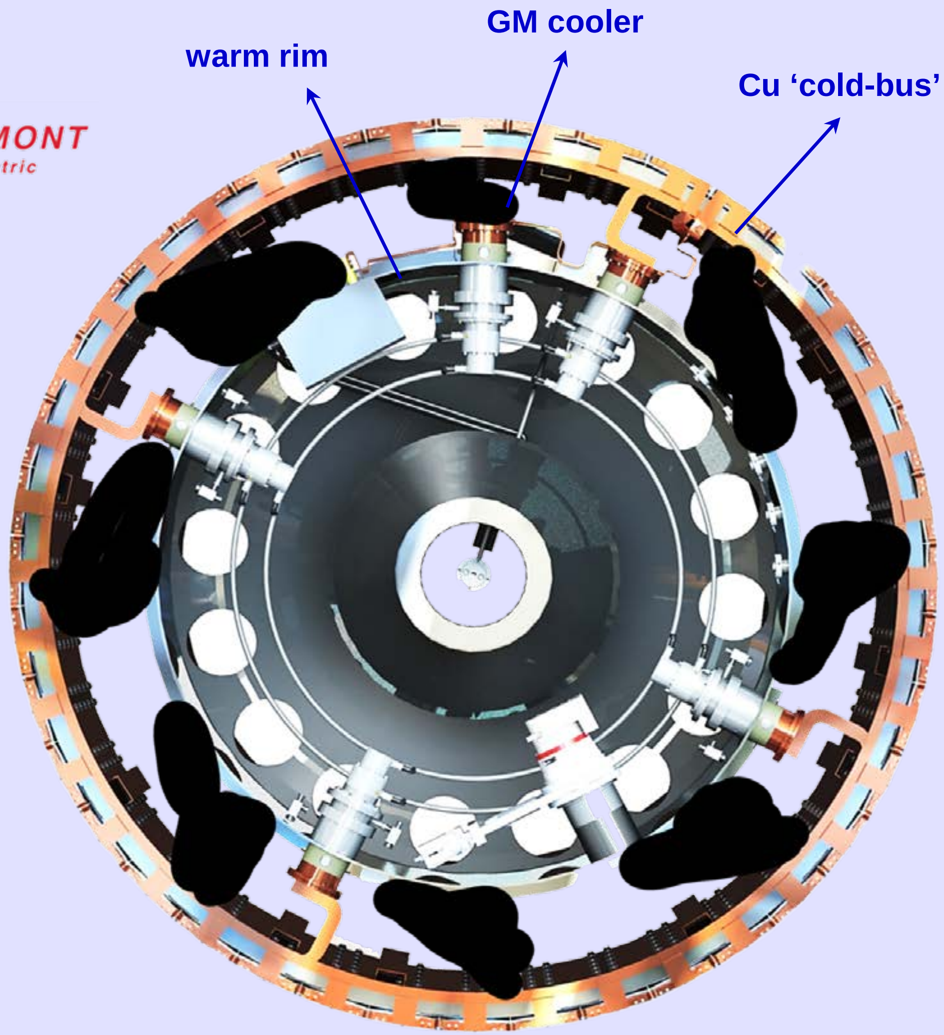
Cryogenic rotor assembly

SHI Cryogenics Group — UNIVERSITY OF TWENTE. — JEUMONT Electric



GM cold-heads & compressors



Cryogenic rotor design
(Cu cold-bus, distributed coolers)

Rotor assembly by mixed
UT – JE team (technology transfer)

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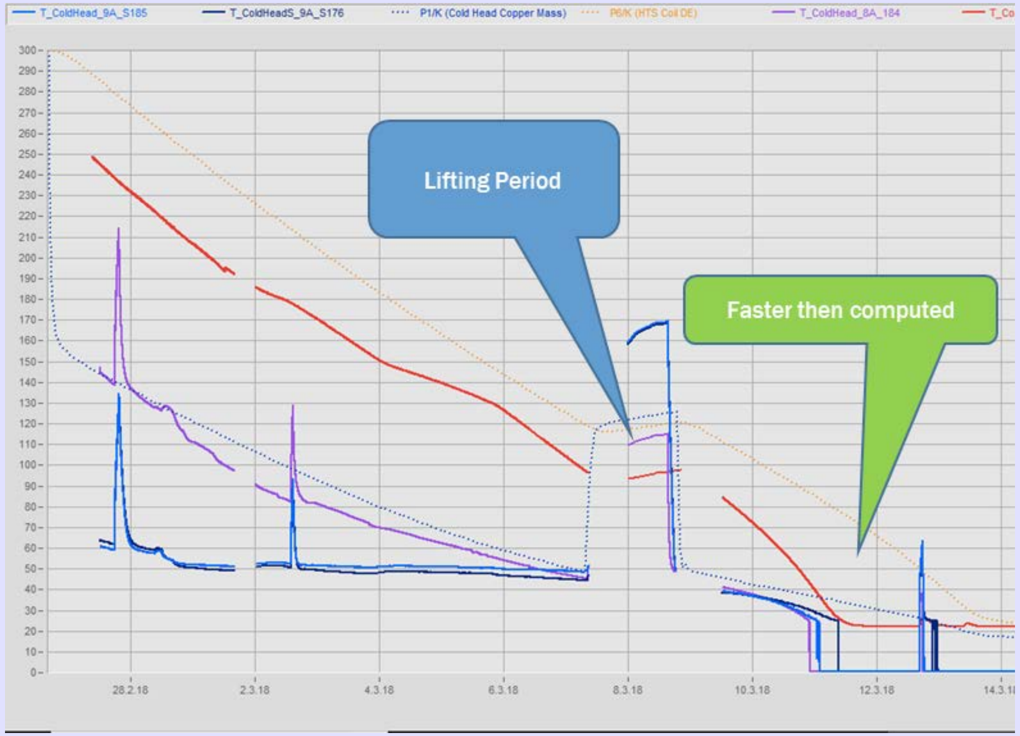
Generator integration & 1st cool-down

Fraunhofer
DELTA ENERGY SYSTEMS
ENVISION
JEUMONT Electric

Arrival at Bremerhaven



First cool-down (2 weeks)

Connecting with test drive

EcoSwing: *Ground-based testing at Fraunhofer IWES*

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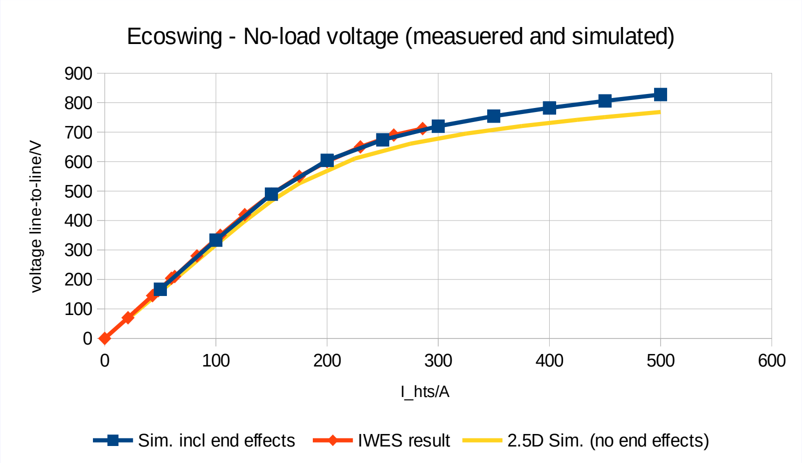
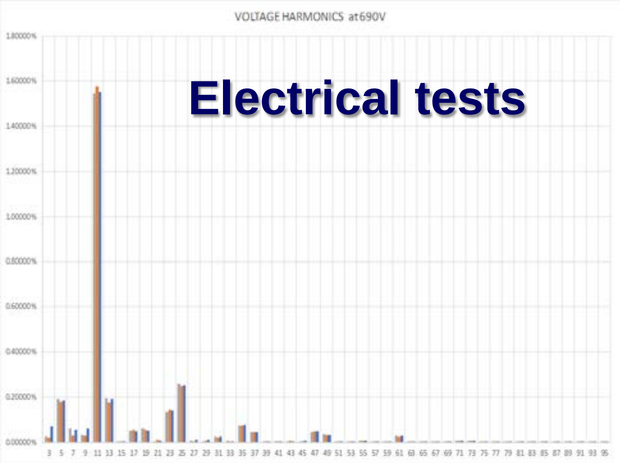
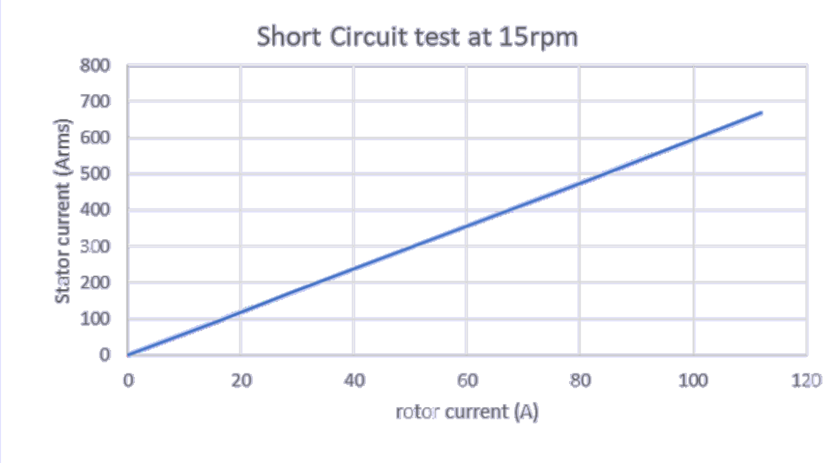
Electrical tests



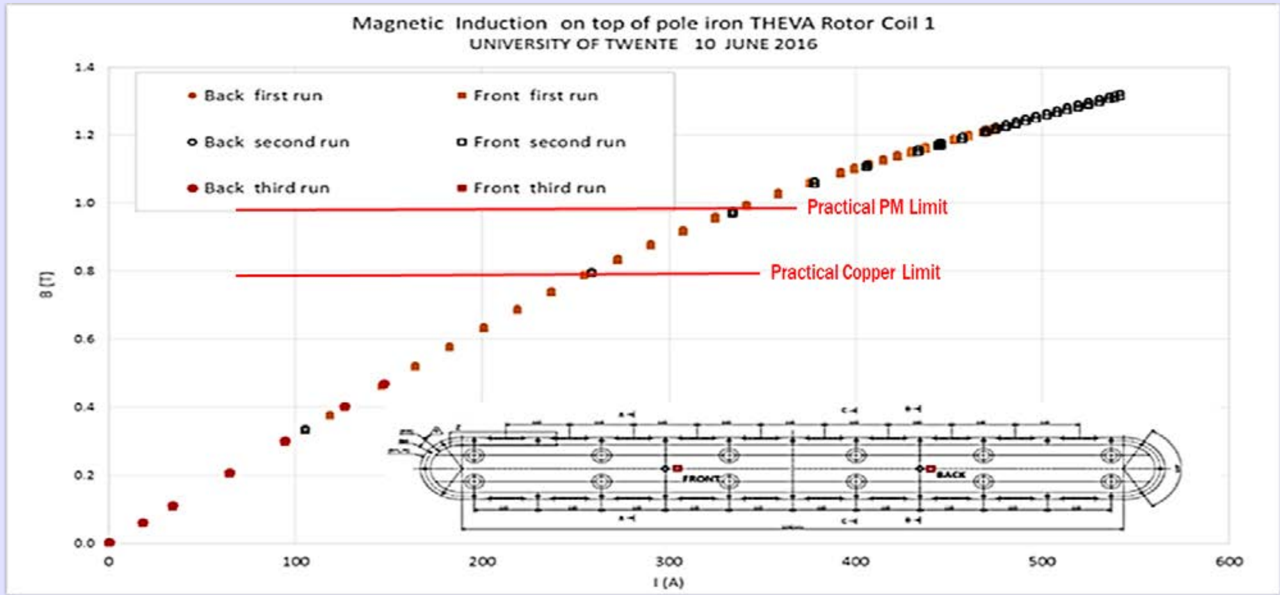
Confirmed no-load voltage



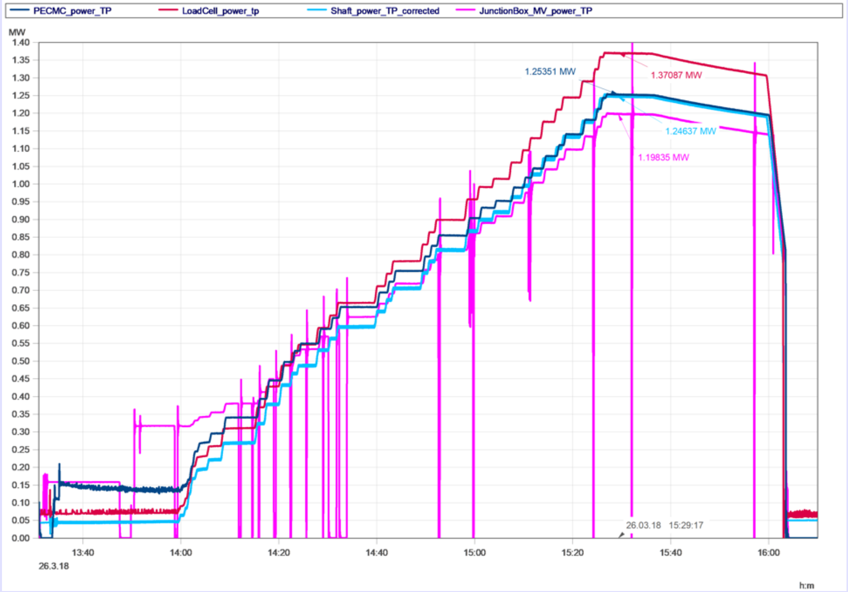
Very low-harmonic distortion (air gap)



Confirmed synchronous reactance



Confirmed air-gap field



First power generation

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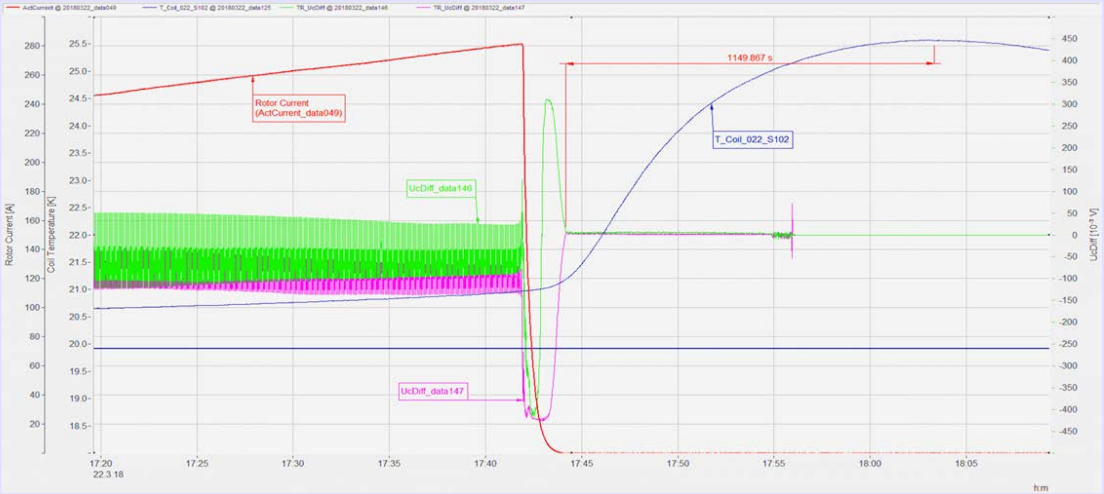

Temperature rise sub-standard coil after quench

- Sub-standard coil had passed (accelerated) acceptance test …
- … and failed during power-up ramp;
- Inadequate ‘quench-detection’ (EM interference)
  - ➢ **Required coil replacement & upgrade protection system**

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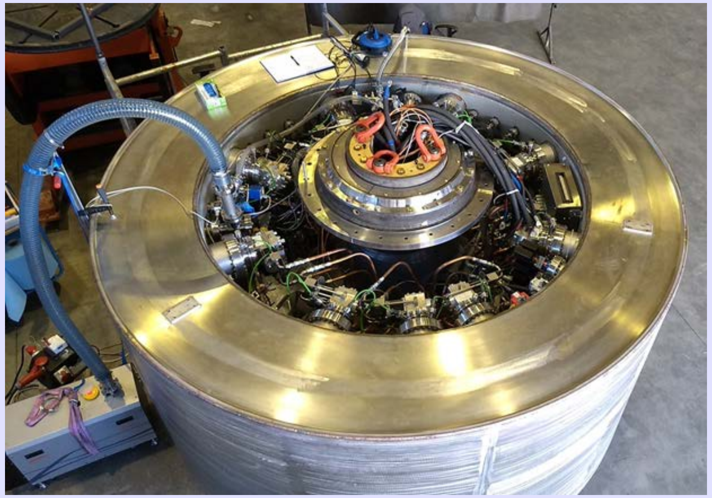

Repair action at Boessenkool Almelo

EcoSwing: *In-turbine installation & operation in Thyboron DK*

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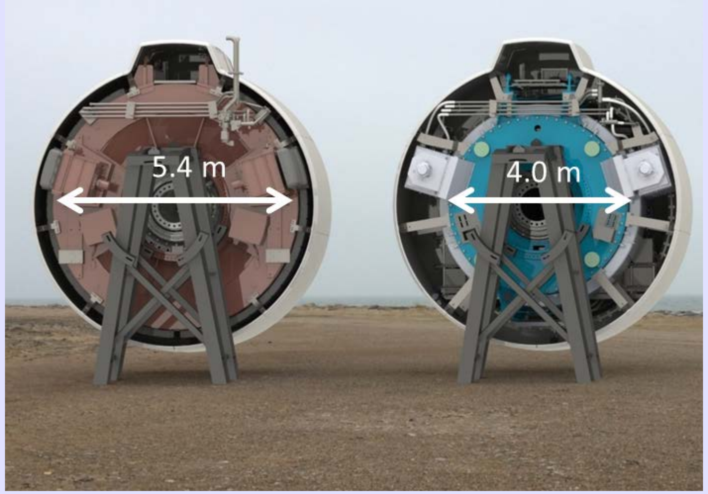
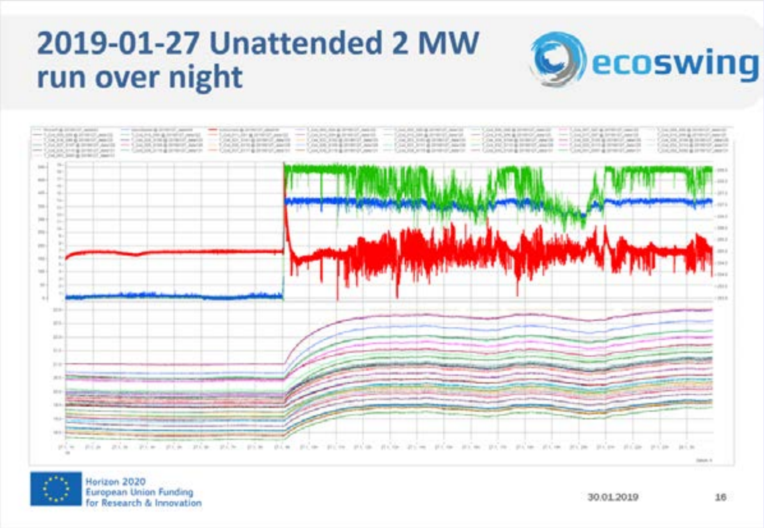
> 650h grid-operation



Arrival at Thyboron

Lifting onto the Envision turbine



ENVISION

DELTA
DELTA ENERGY SYSTEMS

Operational experience

Conclusion

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- *The EU H2020 project EcoSwing successfully designed, developed, manufactured and field-tested the **world's first full-size superconducting generator** for a 3.6 MW wind turbine.*
  - *HTS **wire manufacturing capability** stepped-up from meters to kilometers per week;*
  - *Material **properties are sufficiently stable** to allow for reliable design predictions;*
  - *HTS coil production - at a 'normal' winding shop - was achieved with a **yield > 90%;***
  - *HTS generator assembly was carried out at a **'normal' industrial generator** producer;*
  - ***Problem-free** GM-based **conduction-cooled operation** was achieved > ½ year;*
  - ***Targeted grid-connected power generation** was demonstrated > 650 h, a sizeable part of which in stand-alone mode.*
- *These successes lifted **superconducting generators for wind converters to TRL 7**, demonstrating compatibility of superconducting technology with all real-life impacts associated with a demanding environment (vibrations, variable speed, grid faults,…).*
- *Continuing attention to Quality Control and Protection are among the lessons learned.*
- *The Consortium is seeking new collaborations to bring this technology to the 10 MW+ level, where the **weight- and size-advantage** offered by increased power density are even more disruptive.*

Thank you for your attention, also on behalf of the EcoSwing team

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Torben Jersch
Trevor Miller
Werner Prusseit
Xiaowei Song
Yoichiro Ikeya
Yves Debleser

- https://ecoswing.eu/
- A. Bergen et al. "*Design and in-field testing of the world's first ReBCO rotor for a 3.6 MW wind generator*", Supercond. Sci. Technol. 32 (2019).
- X. Song et al. "*Commissioning of the World's First Full-Scale MW-Class Superconducting Generator on a Direct Drive Wind Turbine*", IEEE Trans. on Energy Conversion 35 (2020).
- A. Bergen, "*Conduction-cooled ReBCO coils for a wind converter*", PhD thesis Univ. Twente (2020)