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Lessons learned from EcoSwing

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on behalf of the EcoSwing consortium;
author list & references on final slide

iFAST

iFast Industry workshop on HTS developments and applications, Trieste, 18 April 2023

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- *What?*
  - Introduction
- *Why?*
  - Motivation
- *How?*
  - Results
- *Conclusion / lessons learned*

EcoSwing: *what?*

A **successful** H2020 project (2015-2019) with as main aims:

- To design, develop and manufacture a **full-scale** multi-MW direct-drive **superconducting wind generator** ;
- to install & **operate this drive train in** an existing modern **wind turbine** in Thyborøn, DK (3MW-class, 14rpm, 128m rotor) ;
- To prove in a harsh operational environment that such a superconducting drive train is **robust** & **cost-competitive,** …

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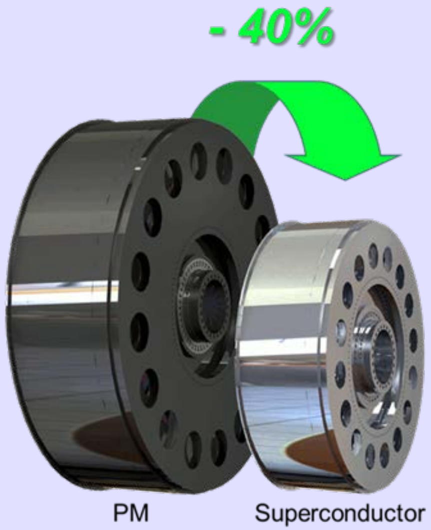
ENVISION	ECO5	JEUMONT Electric
Coordination / demonstration	*Core design / engineering*	*Stator / integration*
DELTA ENERGY SYSTEMS	THEVA	SHI Cryogenics Group
Power convertor / control	*ReBCO conductor / coils*	*Cryogenics*
Fraunhofer	UNIVERSITY OF TWENTE.	DNV·GL
Ground-based testing	*Validation / rotor assembly*	*Pre-certification*

Envision's 3.6 MW test turbine



EcoSwing's ambition

… thereby addressing multiple **perceived challenges** :

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

EcoSwing: *what?*

Direct-drive synchronous generator w. cold rotor / warm stator

	Design Specification
Generator terminal power	3.6 MW
oD generator frame	4,000 mm
Rated speed	15.0 rpm
Stator type	With iron core sheets
Stator primary cooling	Radial air cooling
Stator voltage	710 V
Axial core length	1,142 mm
Stator coils	Form wound copper, mica insulation, VPI, class F
Bearings	2 main
Free mechanical air gap	13 mm
HTS wire dimensions, bare	12 x 0.2 mm^2
Current density in HTS pack	~ 100 A/mm^2
Efficiency (rated)	~ 92%
Current loading	132 kA/m
Cogging torque	< 0.5%
Load torque ripple	< 1.5%
THD stator voltage	~ 1 %

<u>DC rotor</u> design:

- 40 DP racetracks @ 30K;
- Theva *Re*BCO tape
  TPL2100 w. 100μm stabilizer
- Common cryostat;
- Conduction-cooled w. SHI SRDK-500B rotating cold-heads (& rotating He gas coupling);
- Cold back-iron
  (<u>cryogenic</u> properties critical!)

<u>AC stator</u> design:

- Strongly increased J_{cu}
- Cooling challenge

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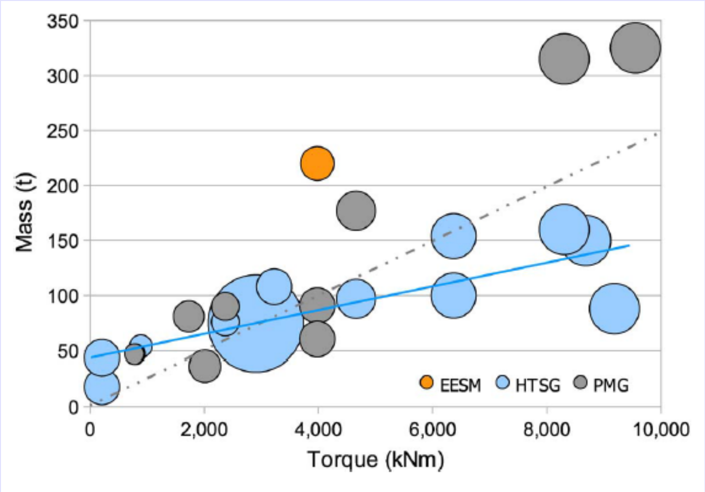
Trends in *wind convertors*

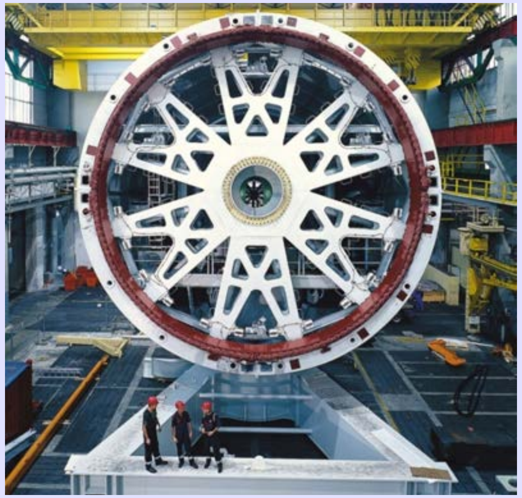
- Towards **higher-power-rated convertors** ;
- direct-drive (no gear box) → **high-torque** machines ;
- synchronous generators (DC rotor) ;
- state-of-the-art based on PM technology (NdFeB)

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)**

EcoSwing: *why?*

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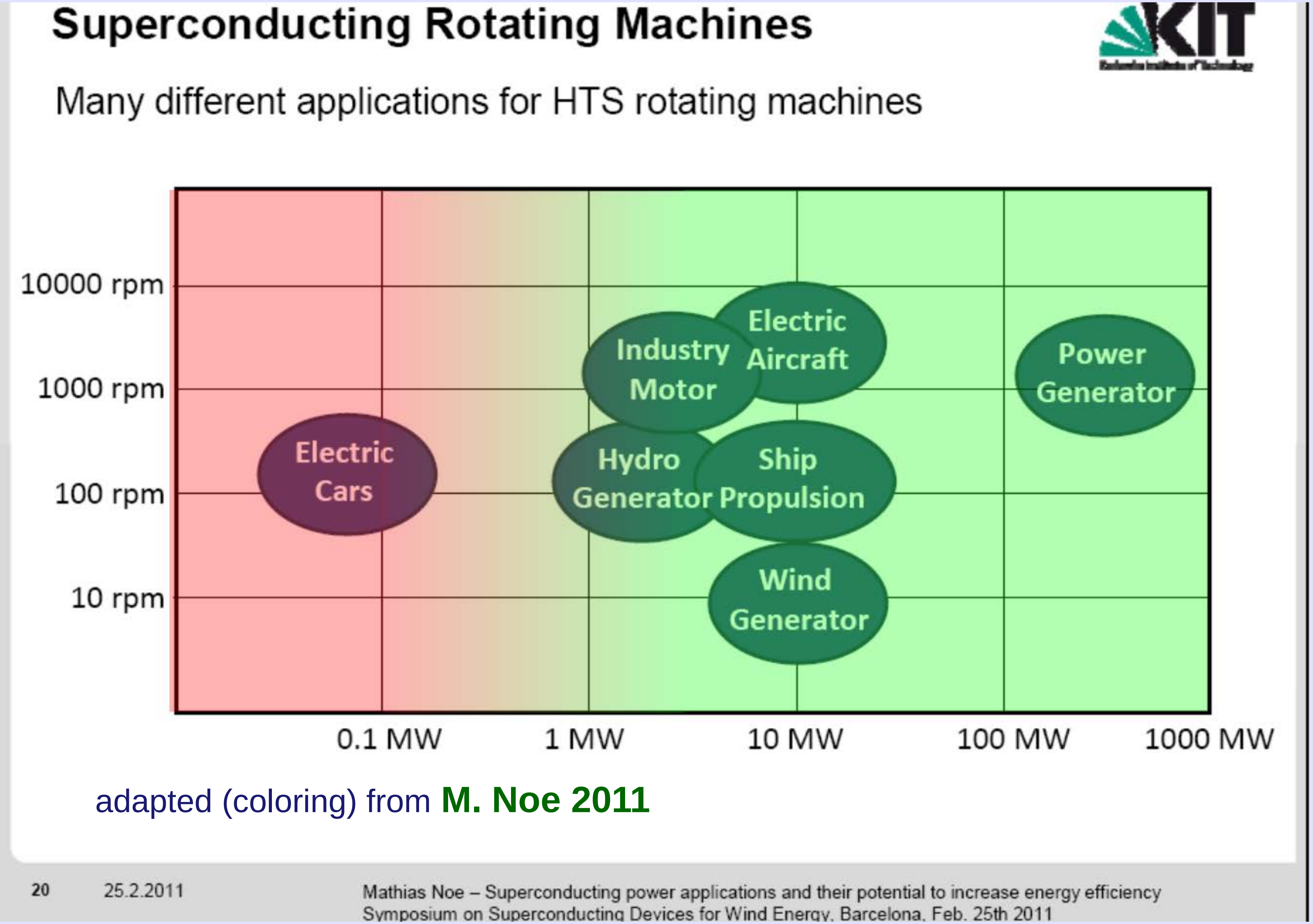
In general for SC machinery: often "economy of size" :

- 'costs' (cryostat, heat inleak, connections, etc.) tend to scale with surface;
- 'benefits' (current, field, …) tend to scale with volume:

⇒ *Increased* ***power density*** especially pays for ***larger*** systems where weight is key :

transport / wind conv.

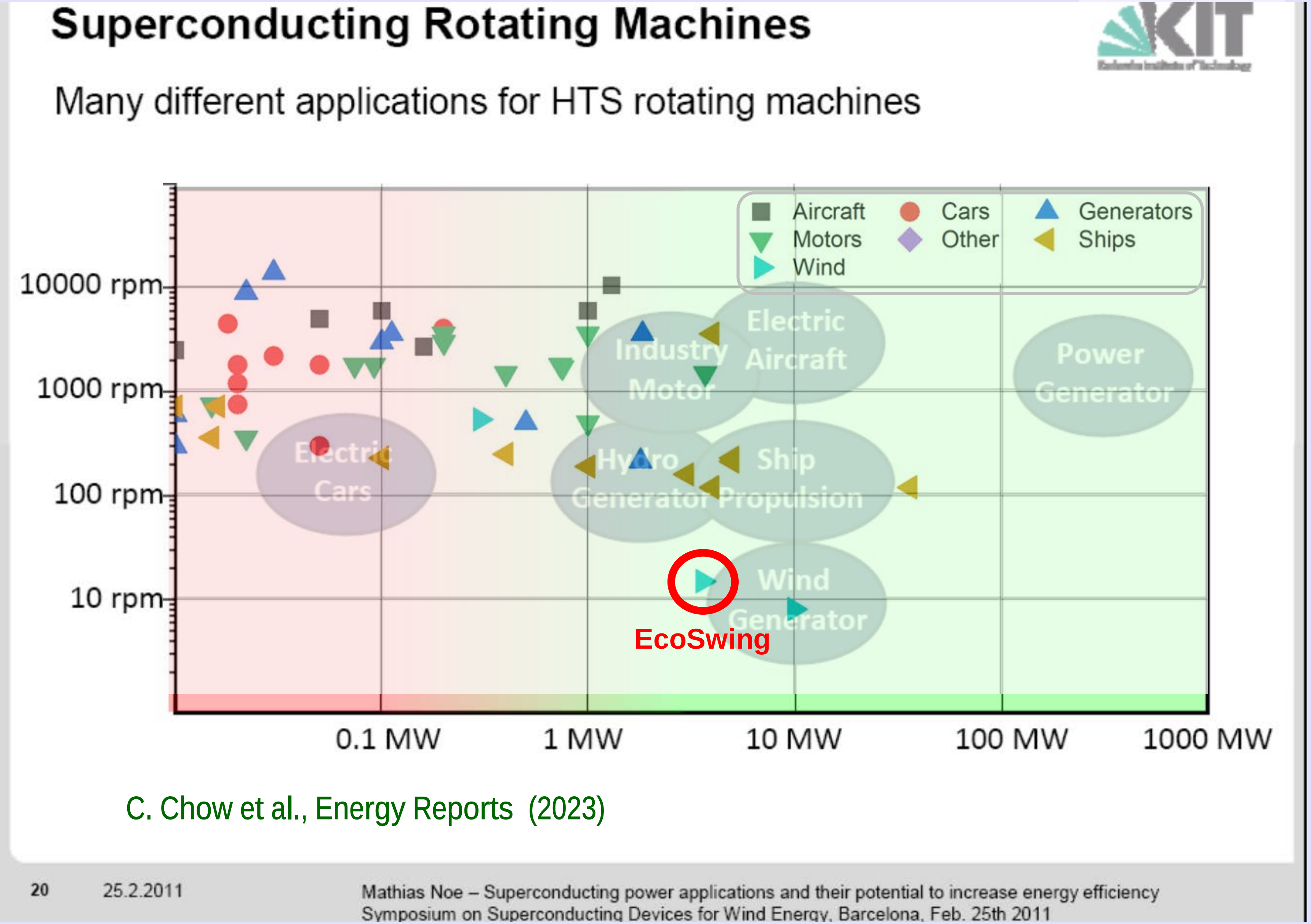


EcoSwing: *why?*

Nonetheless many SC demonstrators since then, also ‘smaller’ ones.

- Application-specific benefits
- R&D risk mitigation?
- Availability of funding? (~ 1-2 €/W)

Comprehensive review from the IEE Hong Kong / KC London groups



C. Chow et al., Energy Reports (2023)

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EcoSwing: *how?*

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Superconducting rotor assembly

SHI Cryogenics Group

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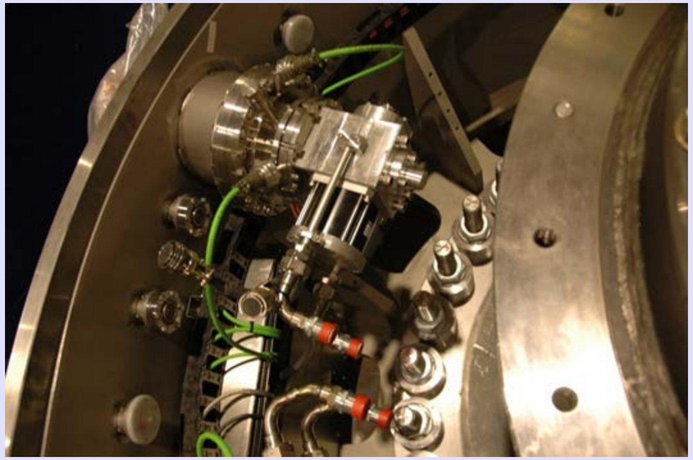
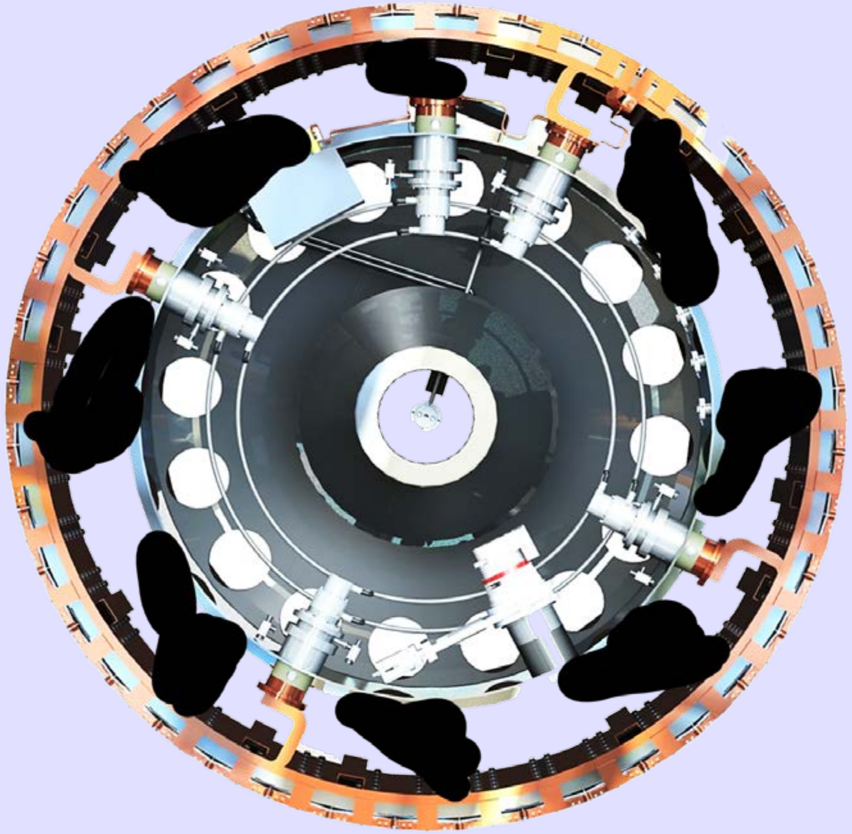
JEUMONT Electric



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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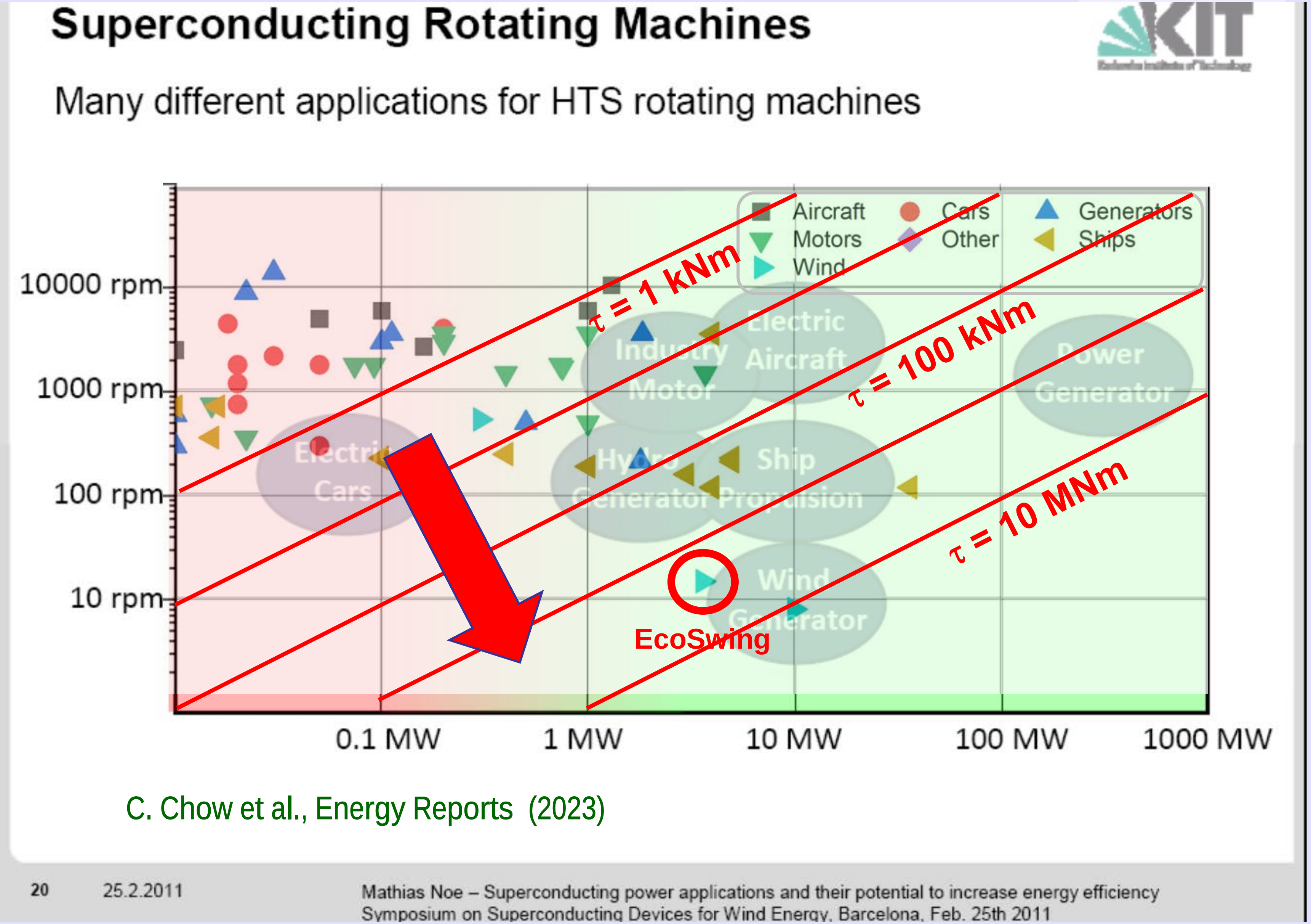
What about the perceived ***transmission bottleneck?***

How to transfer high ***mechanical torque*** levels from an ambient mechanical system to the cryogenic rotor without creating too high a ***heat leak***`?

$$P = \omega\tau$$



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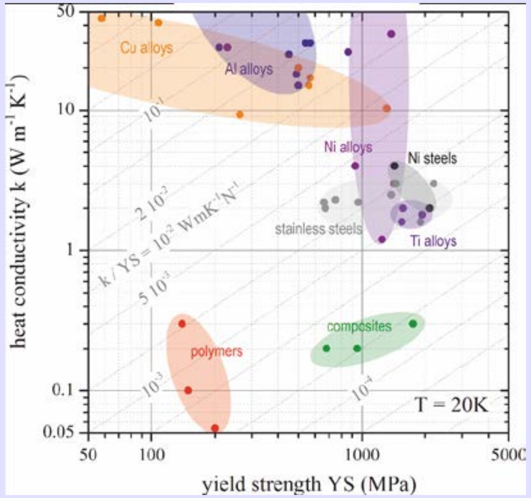
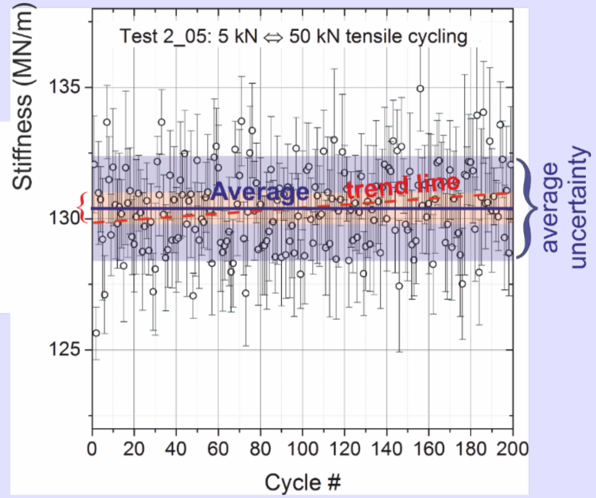
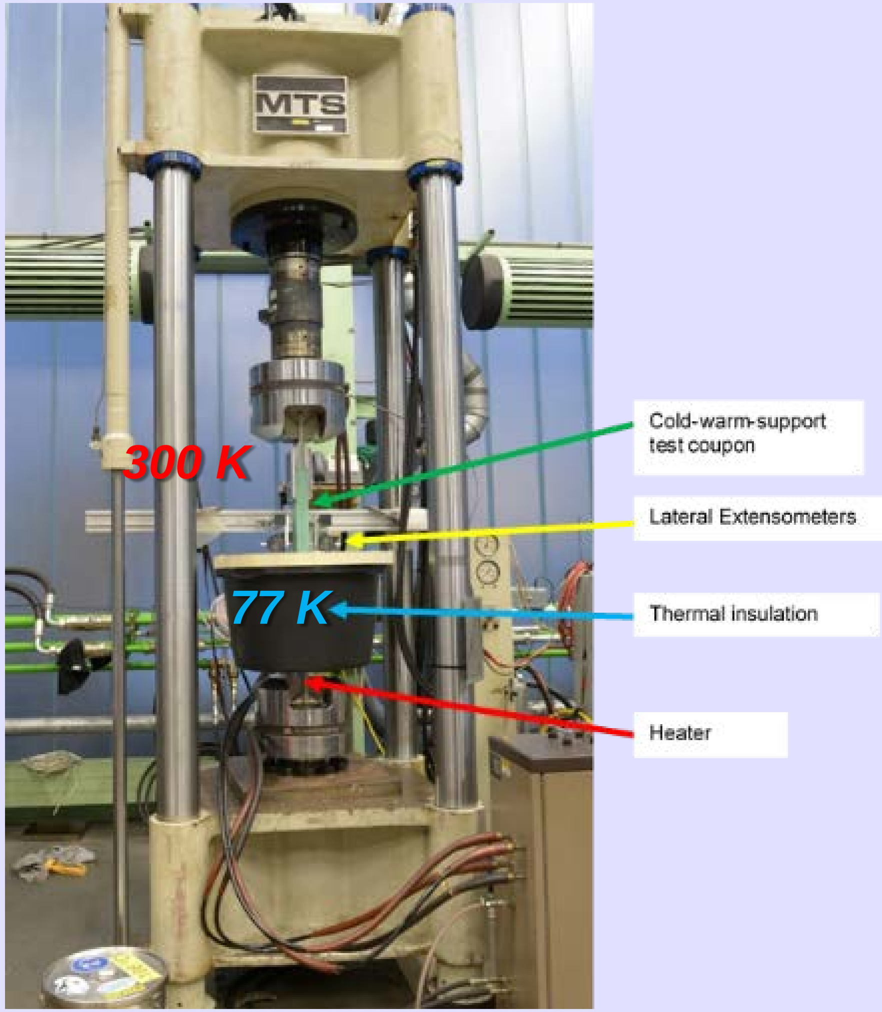
Answer: *reinforced polymer composites*



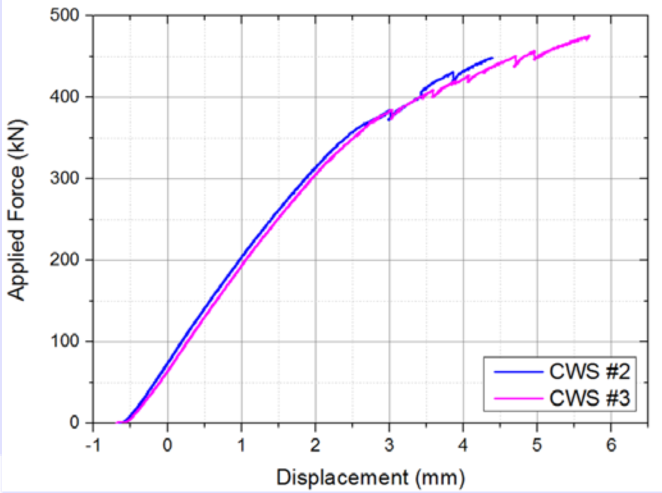
Cryogenic strength vs heat conductivity



Representative fatigue testing



Tensile / compressive loading test coupons @ TNO Delft



Tensile yield test

Yielding on warm side,
not on cold side

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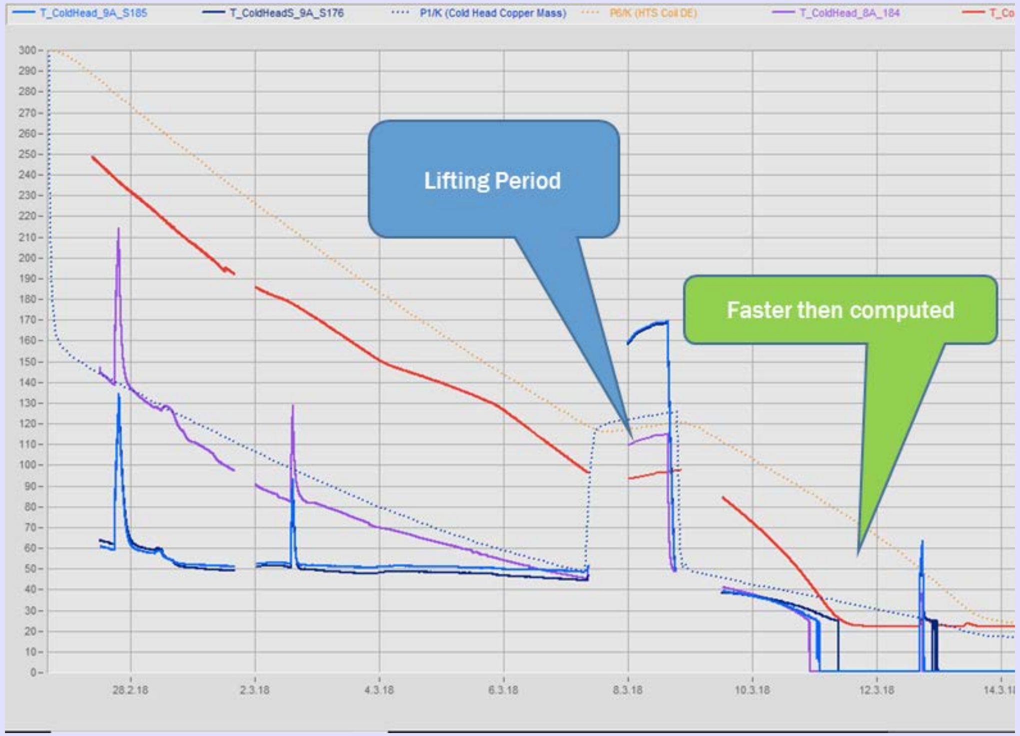
Ground-based testing at Fraunhofer IWES

Arrival at Bremerhaven



First cool-down (2 weeks)

Connecting with test drive

Better cryogenic performance than designed-for (rotating cooling power > static)

EcoSwing: *how?*

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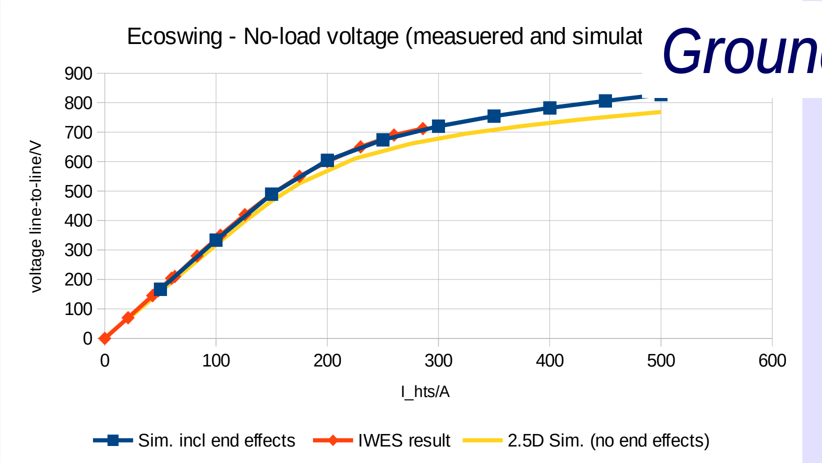
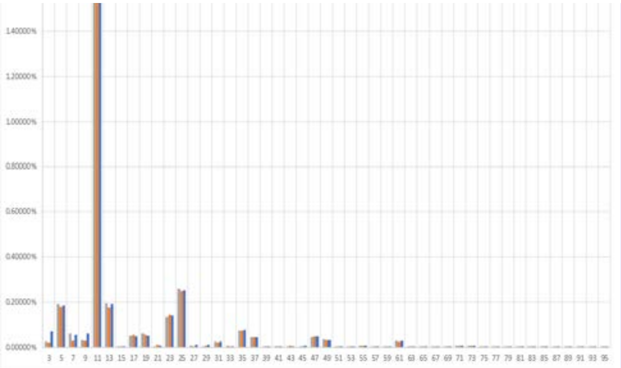
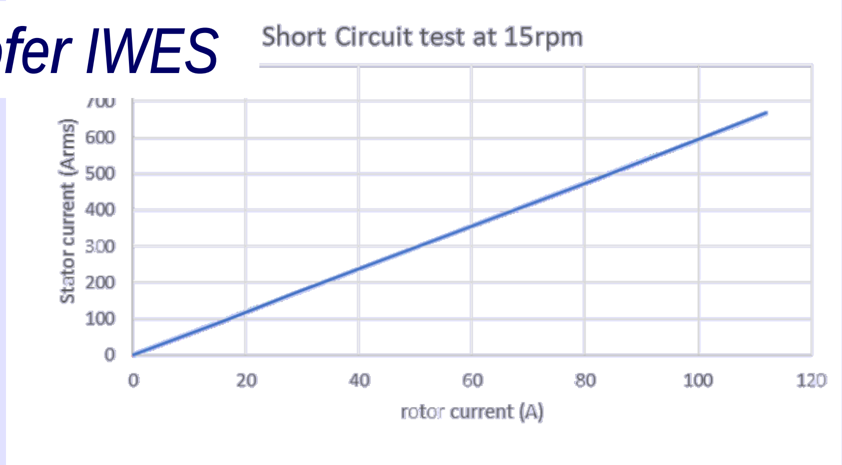
Ground-based testing at Fraunhofer IWES



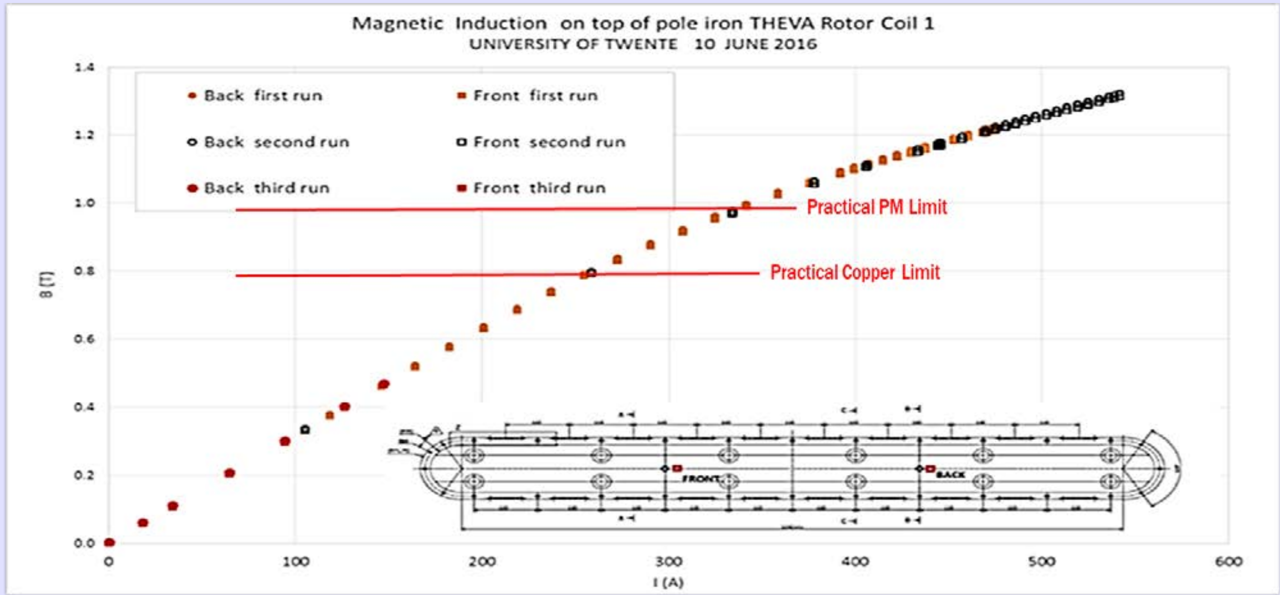
Confirmed no-load voltage



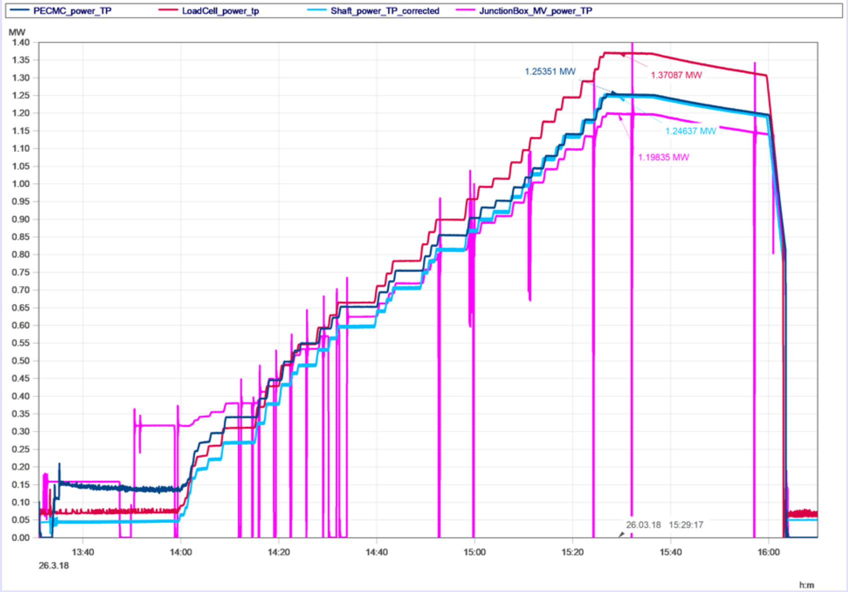
Very low-harmonic distortion (air gap)



Confirmed synchronous reactance

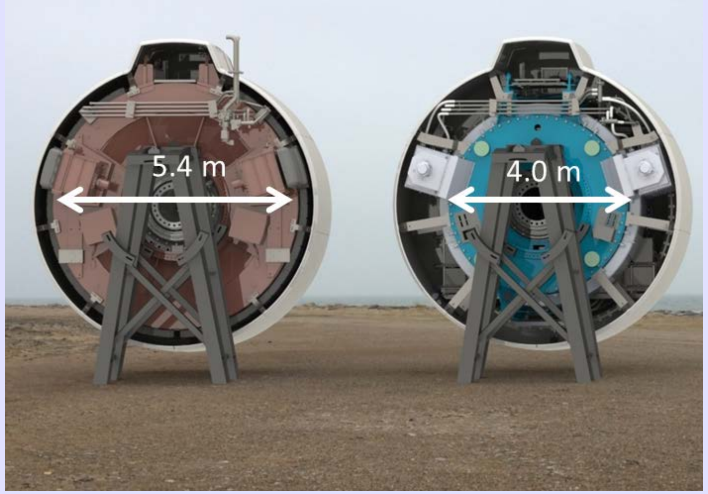


Confirmed air-gap field



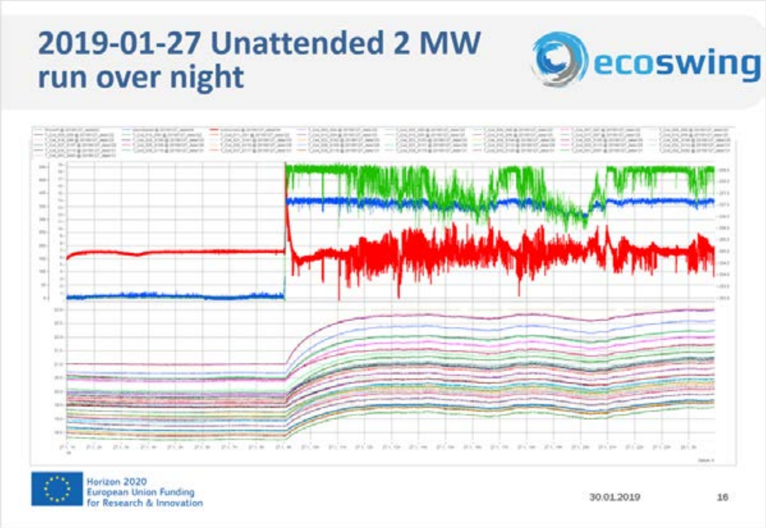
First power generation

In-turbine installation and successful operation in Thyboron DK



Arrival at Thyboron

Lifting onto the Envision turbine



Operational experience

Outline

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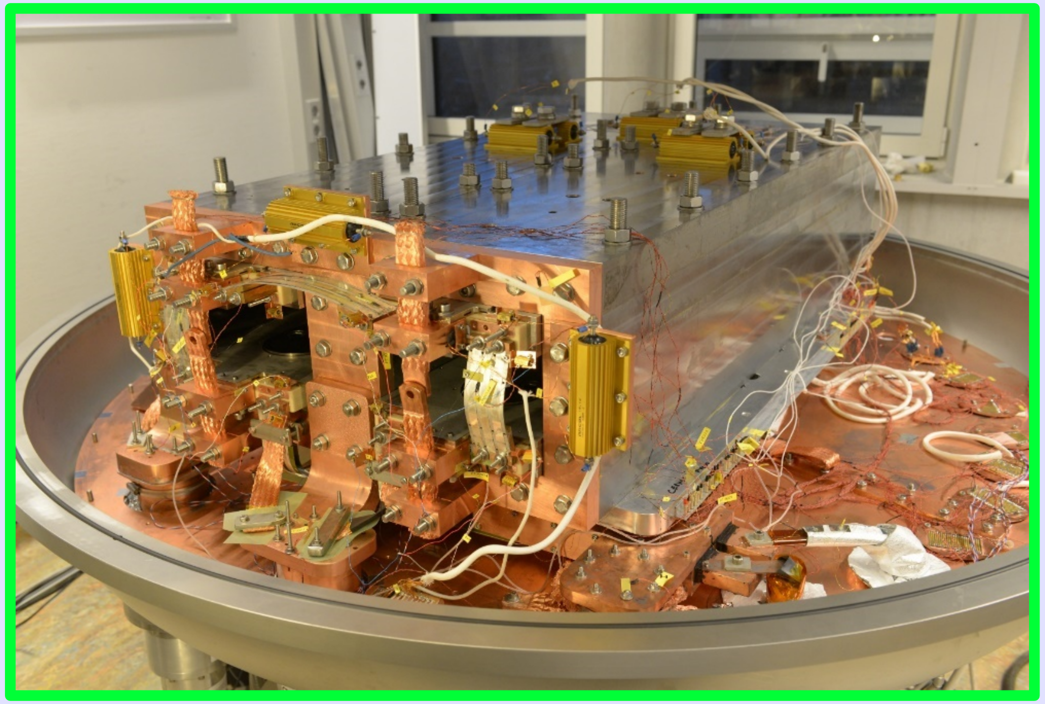
Ground-based testing & coil 'quench' event



- Coil acceptance tests (in batches of 4) @ full operational conditions;
- Optimal ***de-risking***, but ***time-consuming***

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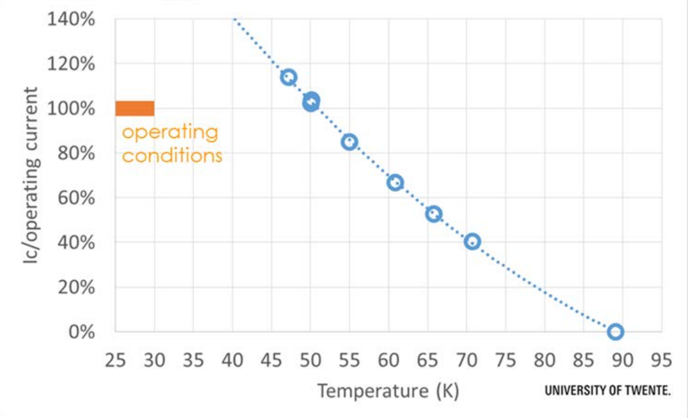
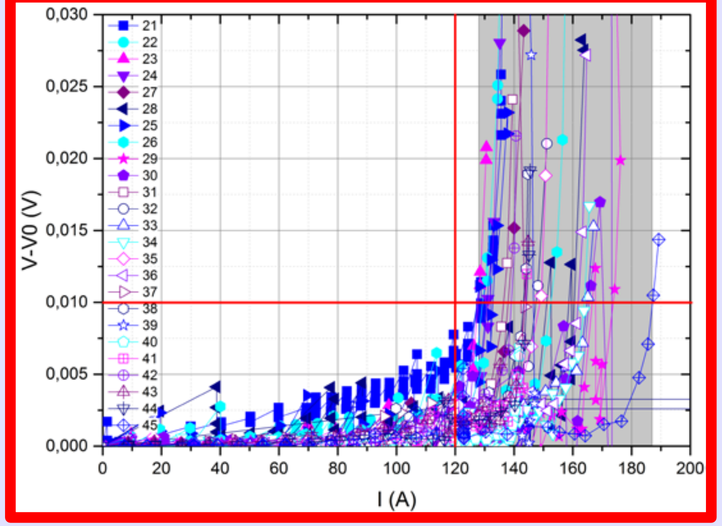
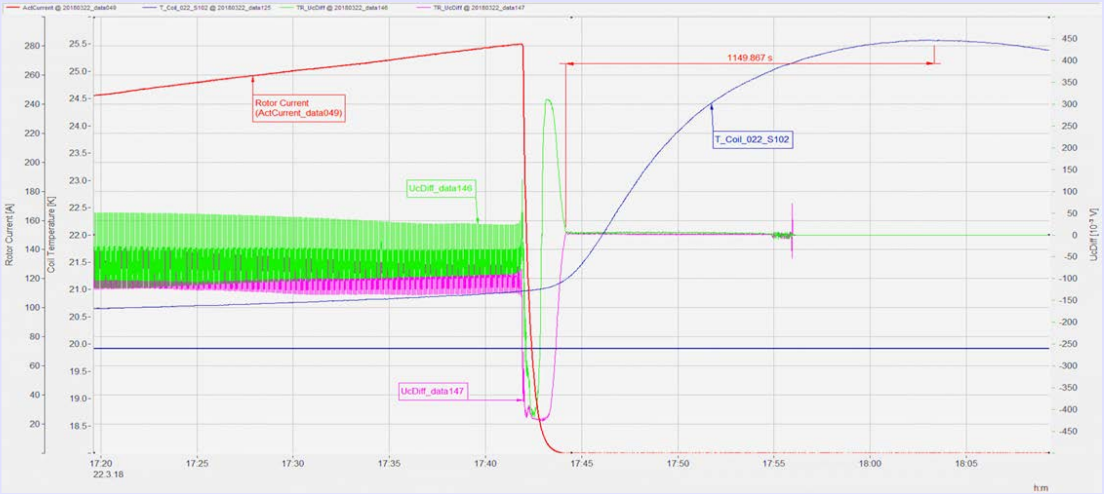




- 'Accelerated' acceptance tests @ 77K at winding shop (~30% of coils);
- Relies on ***precise knowledge of lift-factor*** !

Ground-based testing & coil 'quench' event



Temperature rise sub-standard coil after quench

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

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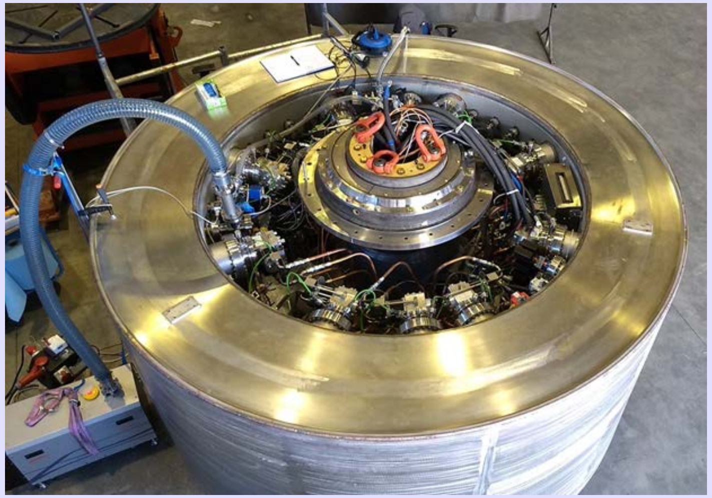

Repair action at Boessenkool Almelo

EcoSwing: *lessons learned*

- *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 'e' 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*** – even better than expected - *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,…).*
- *Detailed knowledge of* ***cryogenic*** *functional* ***materials properties*** *critical.*
- *Attention to* ***quality control*** *& a healthy* ***design margin****: how to narrow-down lift-factor predictions (77K $\neq$ 20-30K)?*
- *Continuing attention to* ***detection & protection*** *in 'messy' environments: false positives cost money, false negatives even more !*

Acknowledgement and references

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- 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)