Development of a Superconductive Wind Power Generator within the EcoSwing Project

"Energy Cost Optimization using Superconducting Wind Generators"

"EcoSwing has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 656024."
"Herein we reflect only the author's view. The Commission is not responsible for any use that may be made of the information it contains."

Core ambitions

- Design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator
- Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark
  (3.6 MW, 15 rpm, 128 m rotor)
- Prove that a superconducting drive train is cost-competitive
- **Have the generator running in 2017.**

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Platform for technology validation

- The idea is to replace a PM generator with a superconducting generator
- This includes power conversion and refrigeration equipment.

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Key technical figures

- **Generator:** Synchronous
- **Drive Train:** Direct Drive
- **Superconductor:** PVD CC (GdBaCuO)
- **Refrigeration:** Gifford-McMahon
- **Power Converter:** 4Q-IGBT
- **Turbine:** 2 Bladed, On-shore.

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Key project figures

- **Program:** EU Horizon 2020
- **Reference:** 656024
- **Start Date:** 2015-03-01
- **End Date:** 2019-03-01
- **Total Cost:** EUR 13,846,594
- **EU Contribution:** EUR 10,591,734.

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Integrated consortium

- 9 Partners from 5 countries working for a common goal

ENVISION

ECC5

JEUMONT Electric

DELTA ENERGY SYSTEMS

THEVA

SHI Cryogenics Group

Fraunhofer

UNIVERSITY OF TWENTE.

DNV·GL

- Project web site: www.ecoswing.eu

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Topics for this presentation

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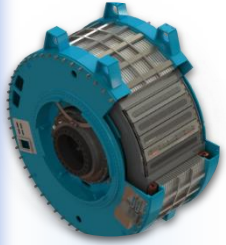
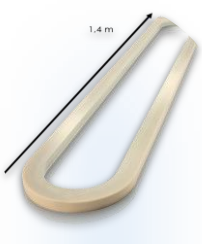
Specifications

Specs



Design

Materials



Components

Assembly

Testing

Installation

Regulatory Oversight

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Specifications start with Motivation
Market driven motivations for using HTS

- As power sizes go up Permanent Magnet Generator (PMG) beat Doubly Fed Induction Generator with gearboxes (DFIG)
  - Large DFIG becomes too heavy and too costly to maintain
  - Direct Drive (DD) have less maintenance, higher part load efficiency, better scalability
  - **The future of wind turbine drivetrains belongs to DD machines i.e. without gearboxes**
- Future wind turbines are on floating platforms i.e. top mass must go down
  - Future drivetrains must be significantly lighter relative to existing DD solutions
  - High power density, low costs and low weight are the benchmarks for the future
  - **PMG technology is at the moment the only candidate.**

Superconductor Generators shows bigger potential than PMG as the wind turbines grows in power

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General requirements

- Design according to IEC61400 and IEC60034 series
- 3.600 kW, 2.460 kNm, 690 V, 50 Hz
- Insulation class F
- Max temperature rise class B
- Temperature, external: -20 °C +30 °C
- Altitude: 2000 m
- Humidity <95%, 100% for 10% of life

- Turbine system mechanical load
- Vibrations (Fore-aft, Side-side, Roll, Nod, Yaw)
- Restricted space request for compact design
- Serviceable wear parts
- Service interval minimum 1 year
- Lightning protection IEC61400-24

Same as for conventional generators

Unique requirements

- Stability of superconductor supply
- Robust and proven cryogenics (incremental innovation)
- Risk mitigation through testing of sub components.

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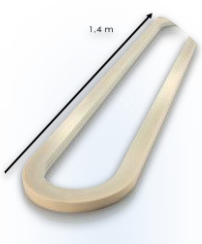
Design

Specs

Design

Materials



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Assembly

Testing

Installati
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Regulatory Oversight

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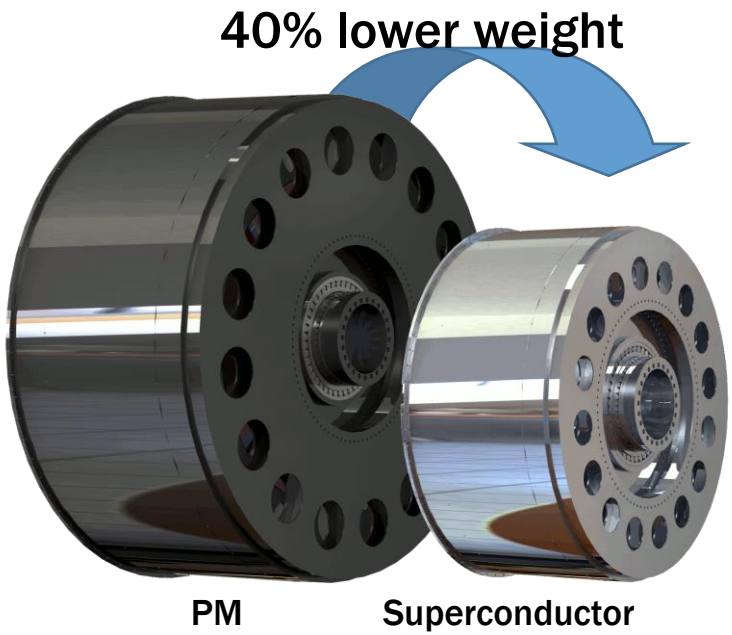
Main design goals



- **All roads capability:** diameter limited to < 4 m
- **Low cost design:** Commercial components for superconductors as much as possible
- **Low weight design:** Optimized for low top head mass
- **Mainstream markets:** 3.6 MW for on-shore and off-shore.

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EcoSwing generator
Design specifications

	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 coils, mica insulation system, 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 %

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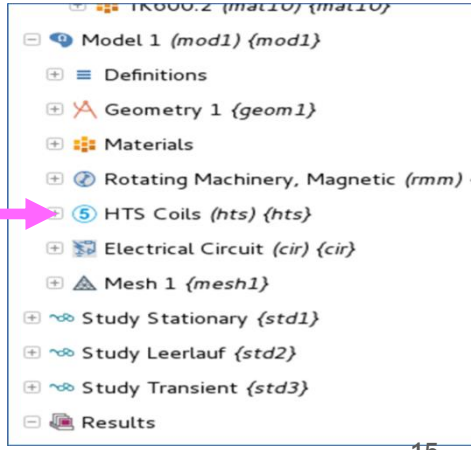
Improved AC loss computation method in HTS wire

Jens Krause et al.
https://elenia.rz.tu-bs.de/index.php?id=253

- **Starting Point:** Established methods have deficits in simulating DC and slow AC
  - Coil charging, load changes, short circuits...
  - Compare *V. Zermeno et al, "Calculation of alternation current losses in stacks and coils ...", JAP 114, 2013*
- **Goal:** Develop method to calculate dynamic behavior upon transients in 2G HTS
- **Approach:**
  - Use perpendicular components of vector potential as unknown
  - Use HTS current density as unknown
  - Use non-linear E(j) as a constraint
- **Status:**
  - "Physics Module" integrated into Comsol Multiphysics
  - For 2G wires without simplifications, including copper stabilization
  - Applicable to DC and slow AC, also to magnetizing currents
  - Works for complex applications, faster and memory efficient.



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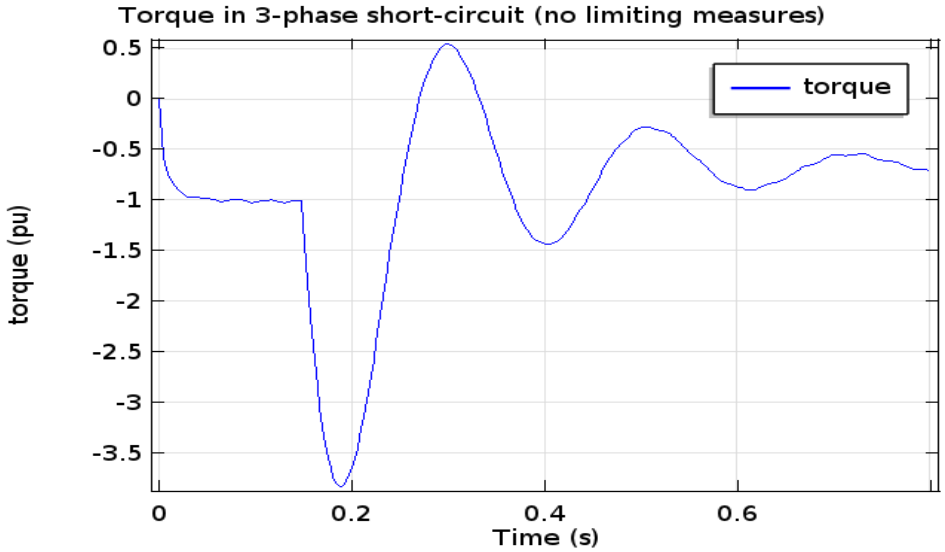
Short circuit computations

- A short circuit event in the power converter is not very likely—but a potentially disastrous event
  - It can break the generator as well as the hub and the blades
  - In the example (right) it amounts to 4x nominal torque
- Torque-limiting measures needed
  - Overrating for high torque in short circuit events counters the thermal efficiency of the HTS rotor.



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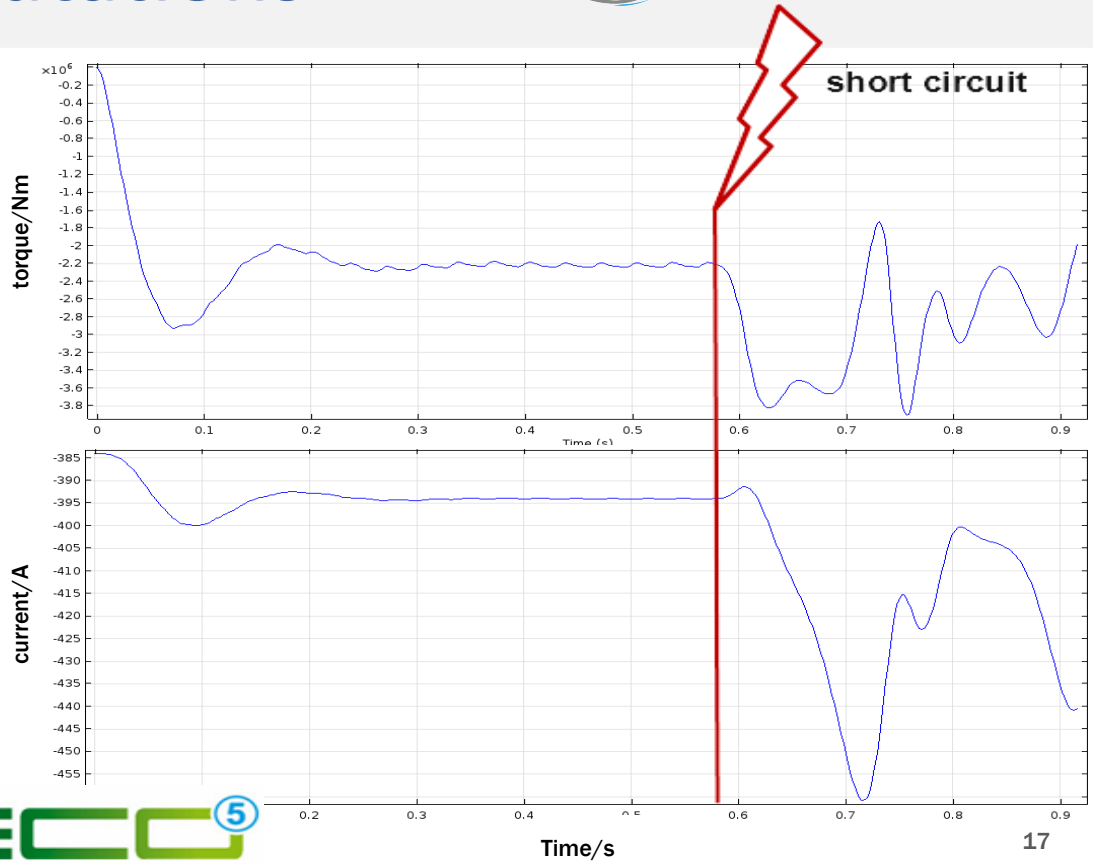
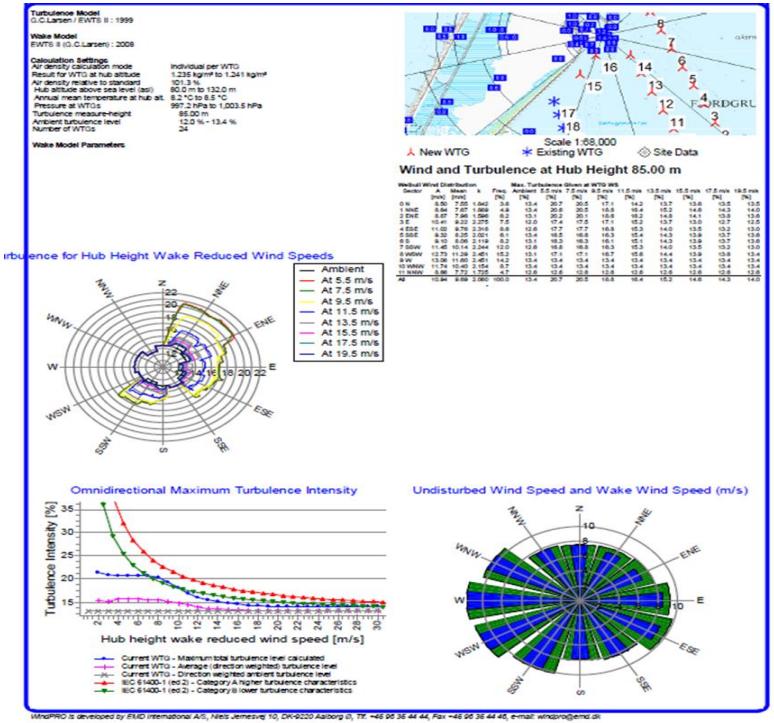
Short circuit computations

- Computation of the short circuit torque is required
  - Makes calculation of entire ring necessary (not just one pole)
  - Must include inertia of rotor and shaft as torsional spring
  - Must include stator and rotor
- Example shown (right)
- Mechanical design was made such that it sustains this short circuit, and the resulting torque levels.



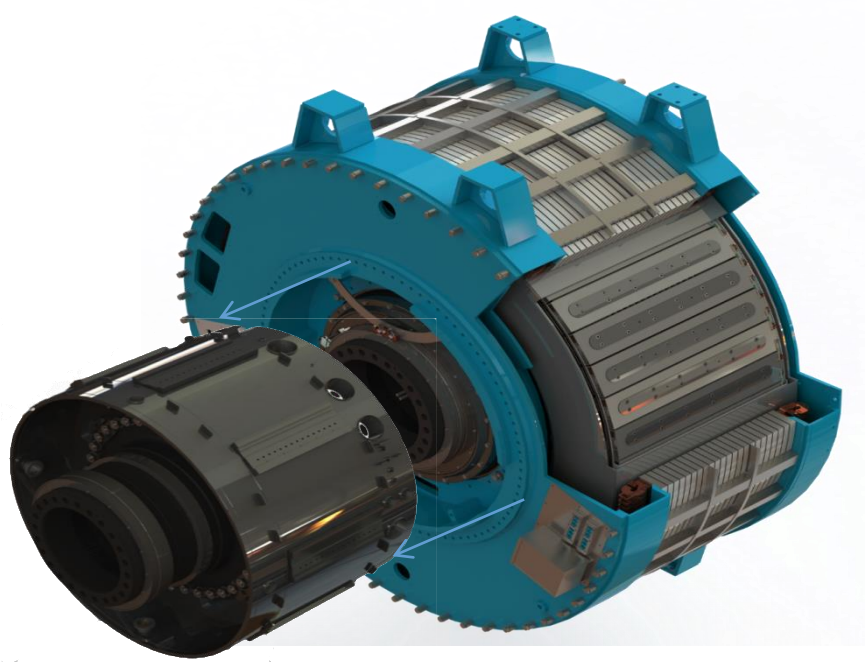
Dynamic modelling of turbine

- Mechanical and electromechanical computations for entire system
  - Site data (wind turbulence) by WindPro
  - Mechanical turbine response by BLADED
  - Generator electromechanical (and thermal) response by COMSOL
- We detected neither prohibitive resonance, nor prohibitive ac loss
- Statistical time series data will be tested during ground based test.



Dual use vacuum chamber

- Cryostat serves two purposes:
  - Thermal insulation
  - Force transmission from shaft to the HTS poles
- Here the cryostat constitutes also the inner structure
  - One piece
  - Lower cost
  - Can be made of low cost steel.



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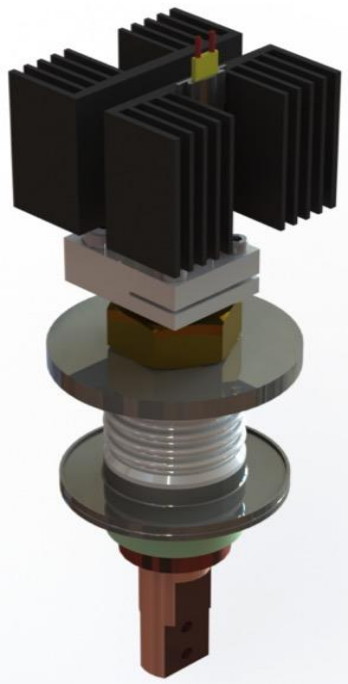
Current feed through

- Commercially available current feed throughs were considered inadequate for use in vibrating wind power environment.
- A robust system was developed allowing high current, industrial metal seals, no ceramic soldered to metal and a large cross-section allowing a small thermal gradient.



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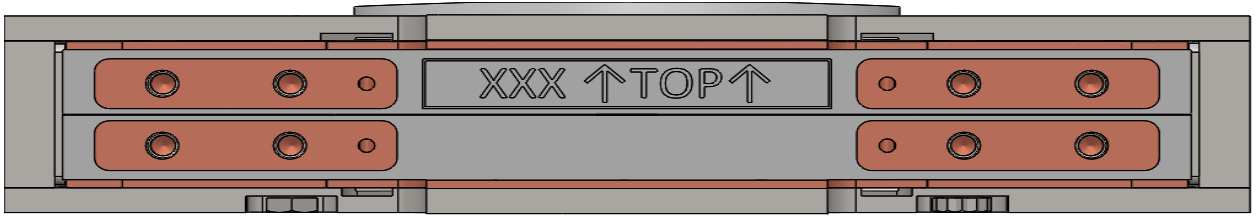
Pole connectors

- HTS coils are all the same (no difference in N and S Pole)

upper layer connection

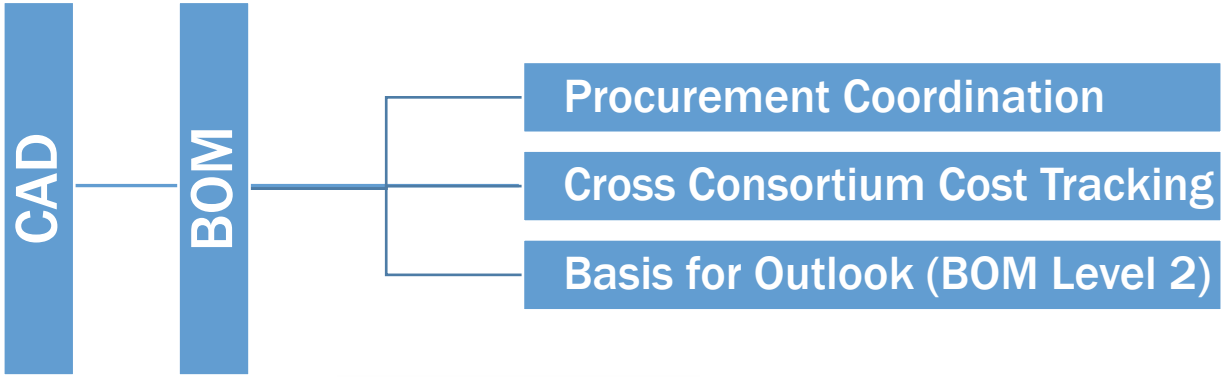
lower layer connection



- Connectors are designed such the NSNS Pole arrangement is achieved.

CAD driven Bill-of-Materials

- CAD model feeds bill-of-materials
  - Provides master list for procurement
  - Provides cost estimate under series manufacturing.



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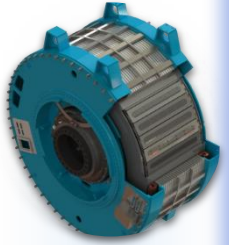
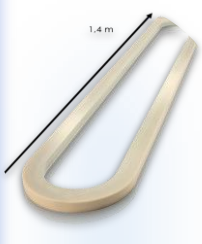
Materials

Specs



Design

Materials



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Assembly

Testing

Installati
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Regulatory Oversight

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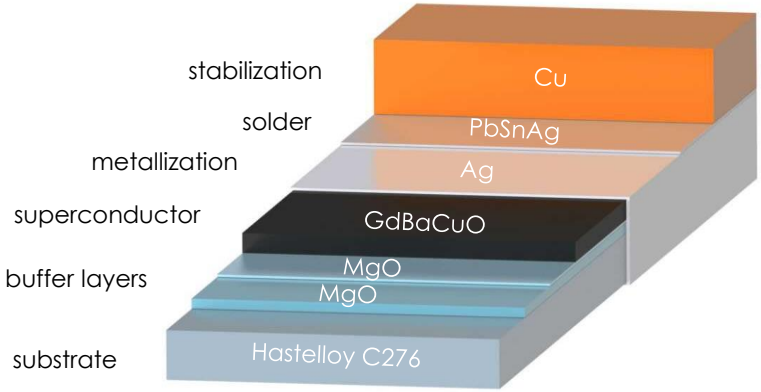
HTS tape
THEVA TPL2100 Pro-Line

Architecture	
Substrate	Hastelloy™ C-276, non-magnetic
Buffer layer	MgO
HTS layer	$GdBa_2Cu_3O_7$
Metallization	~ 1 µm Silver surround
Stabilizer	100 µm Copper on HTS side
Mechanical properties	
Thickness	0.20 – 0.23 mm
Width	12.0 - 12.5 mm
Minimum double bend diameter (RT)	60 mm
Recommended maximum handling force	150 N (15 kg)
Maximum rated stress	340 MPa at room temperature
Maximum rated tensile strain	0.3% at 77K
Electrical properties	
Minimum critical current I_c (77 K, self-field)	360 A, other current ratings upon request

Markus Bauer et al.
TUE-AF-OR17-05



TPL2100

HTS wire with thick copper stabilization for superior electrical stability and high mechanical robustness

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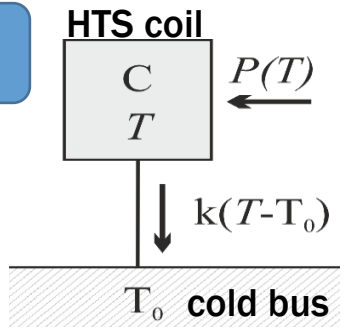
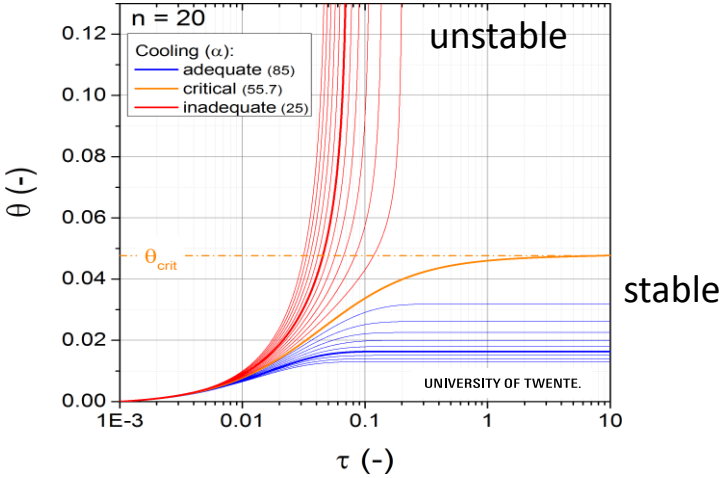
Stability & thermal drift

Anne Bergen et al.
MON-AF-OR9-03





A very straightforward thermal model, combined with non-linear self-heating …

$$P(T) = I_0 V(T) = I_0 V_c \left[\frac{I_0}{I_c(T)} \right]^n$$

… yields a non-linear 1st order differential equation for the temperature-time response:

$$\frac{d\theta}{d\tau} = \frac{1}{(1-\theta)^n} - \alpha\theta$$

$$\tau \equiv \frac{t}{\Delta t_0} = \frac{P(T_0)}{C\Delta T_0} t \quad \text{and} \quad \alpha \equiv \frac{k\Delta T_0}{P(T_0)}$$

$$\theta \equiv \frac{T - T_0}{\Delta T_0}$$

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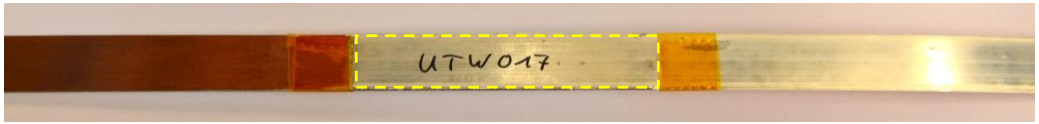
Qualification of Materials and Procedures
Just a few examples…

- Qualification of superconductive joints



- Validation of magnetic properties

- Validation of copper RRR

ECOSWING Copper pieces

Potential measured across 2.5 cm
Measurement current: 1A at low temperatures, 0.1A at 273.15 K
Operator: Jaap Kosse
Measurement date: 14/10/15

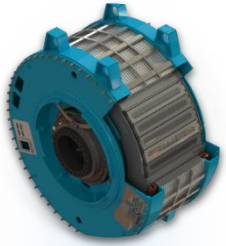
Sample	RRR (273.15/10)	RRR (273.15/30)	R at 273.15K [Ω]	R at 10K [Ω]	R at 30K [Ω]
Piece 2, Electrical connection, #1	124.2	81.6	4.403E-04	3.545E-06	5.395E-06
Piece 2, Electrical connection #2	123.5	81.8	4.575E-04	3.705E-06	5.596E-06
Piece 3, Cooling Plate, #1	78.6	59.0	9.524E-04	1.212E-05	1.613E-05
Piece 3, Cooling Plate, #2	78.7	59.2	9.471E-04	1.203E-05	1.600E-05

Qualification of Materials and Procedures
Just a few examples…

- Qualification of lubricants and adhesives
- Qualification of structural materials (w/ TNO Delft)
- Qualification of getters, sealants, procedure for affixing MLI…

Components

Specs



Design

Materials

Components

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Installation

Regulatory Oversight

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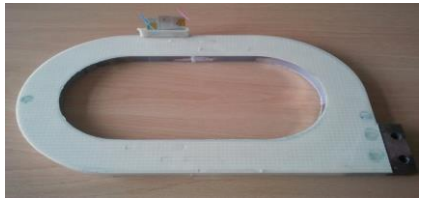
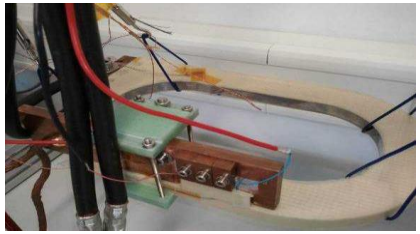
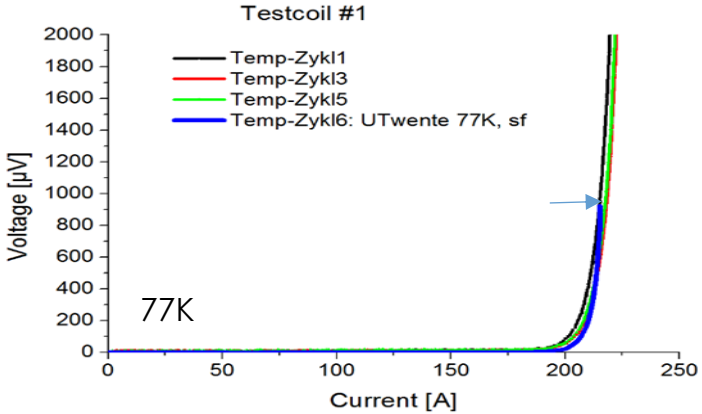
Subscale coil test



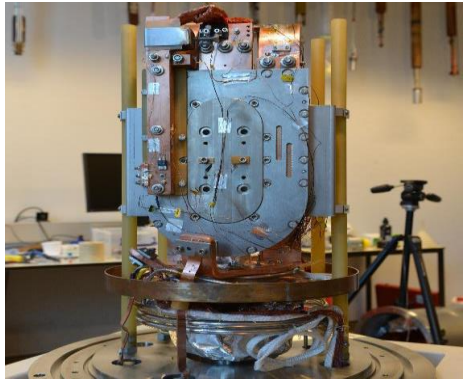
Test coil #1
- single layer
- 10 turns



LN_2 test



Markus Bauer et al.
TUE-MO-OR14-01



Pole assembly
- magnetic pole piece
- non magnetic mechanical support
- conduction cooling

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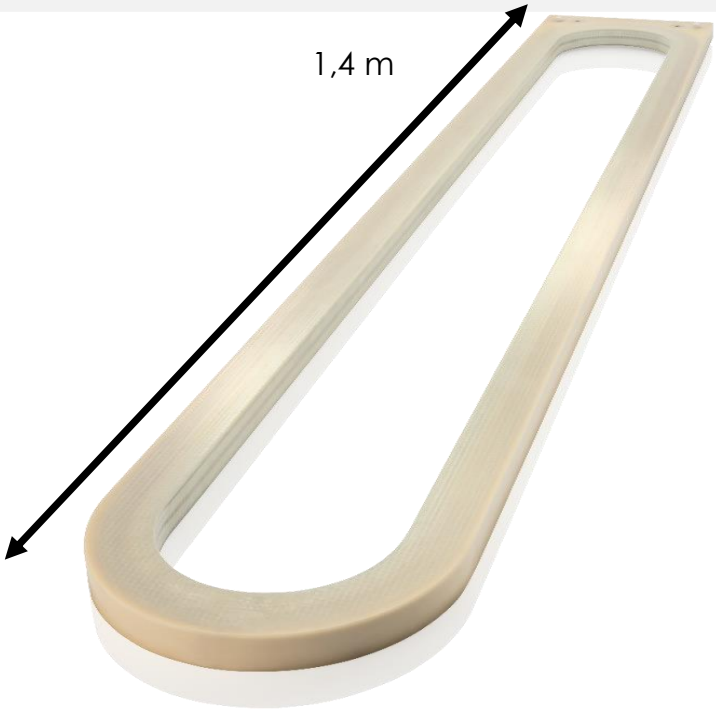
THEVA UNIVERSITY OF TWENTE.

HTS coil specifications

- ~ 200 turns with 500 m of copper laminated HTS wire
- Double pancake, insulated design, potted using commercial resin, glass fiber reinforced
- Use of casting mold for smooth surface
  - optimum mechanical and thermal contact
- Operating temperature < 30 K, conduction cooled with cold heads.



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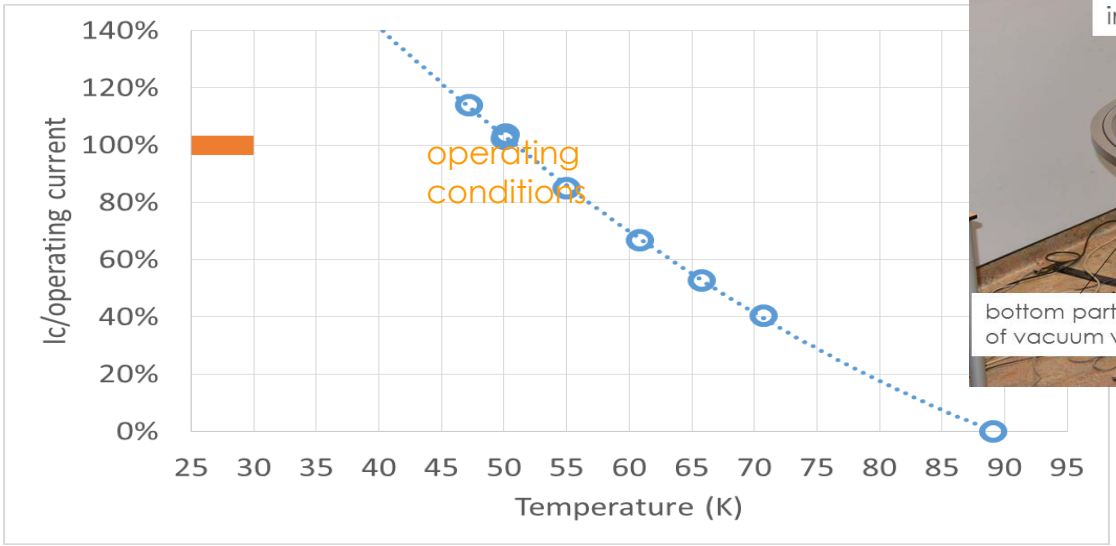
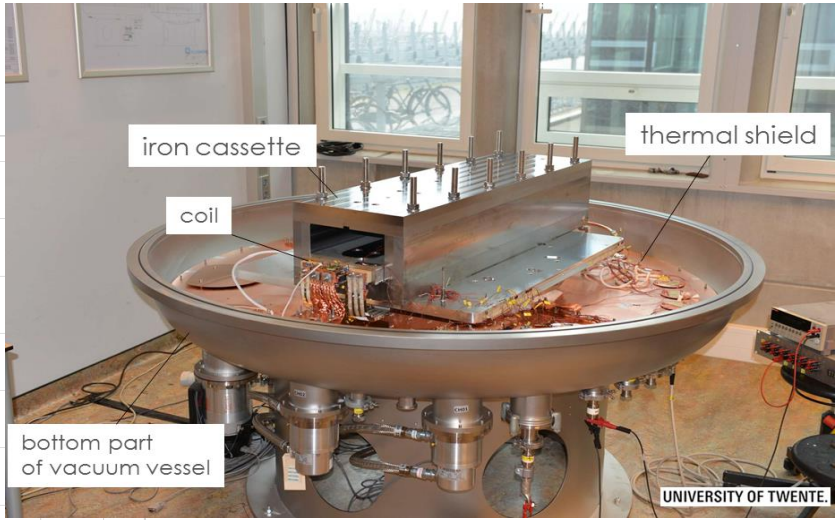
Type testing of HTS coils





Cooling

- SHI Cryogenics Group provides commercial grade cryogenic equipment
  - SRDK-500B cryocoolers
  - F-70 compressors.

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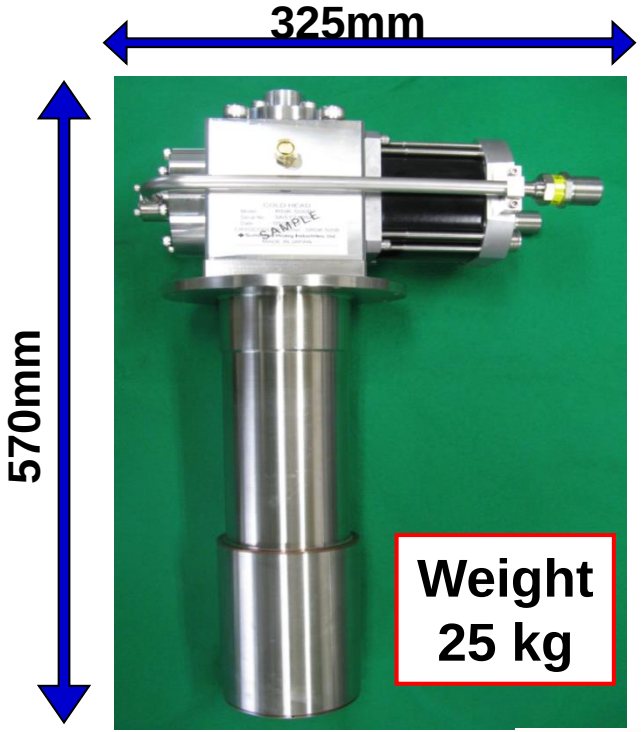
SHI Cryogenics Group

SRDK-500B coldhead



20K	40/50 W
30K	80/95 W
Compressor	F-70H
Power (50/60Hz)	7.5/9.0 kW
Maintenance	expected every 18.000 hrs
Orientational Dependence	<30%
Regulatory	UL/CE
Noise	70 dBA

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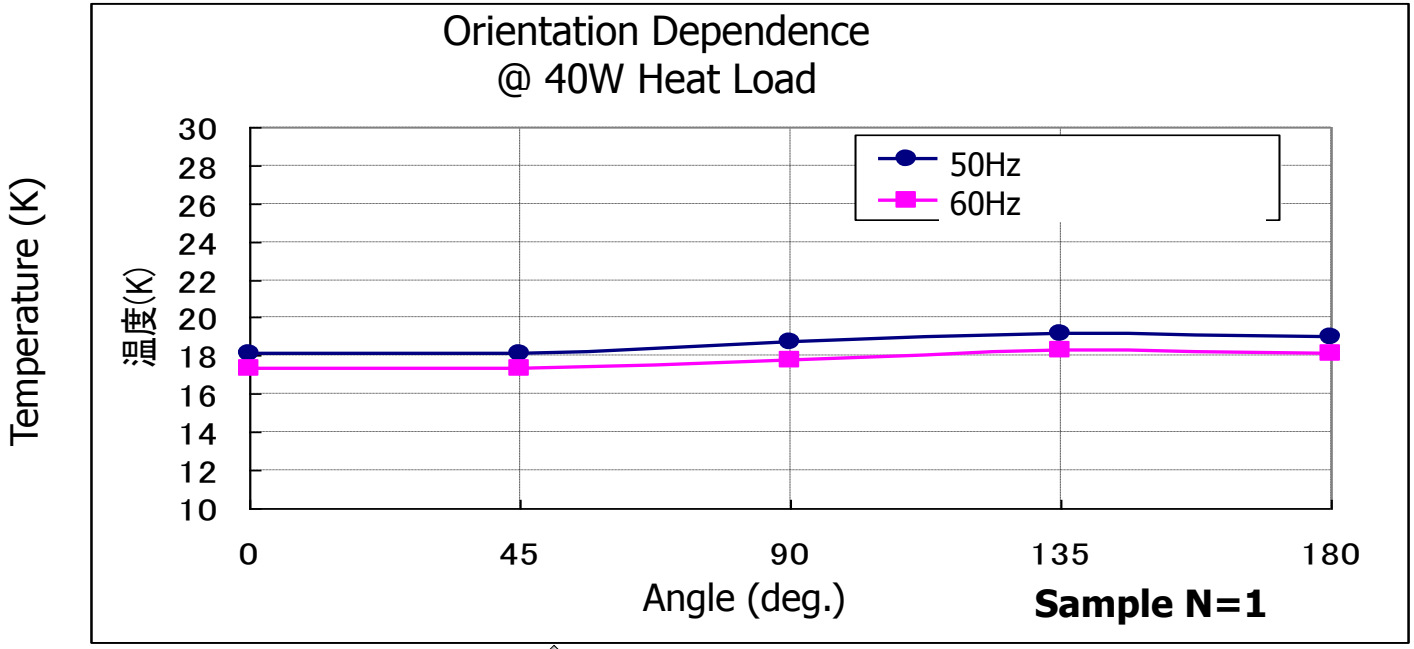
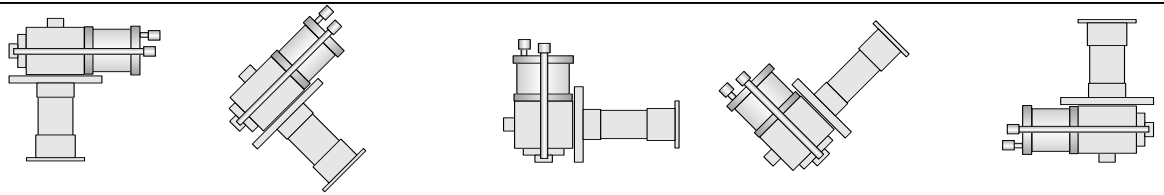
SHI Cryogenics Group

SRDK-500B
Orientation dependence





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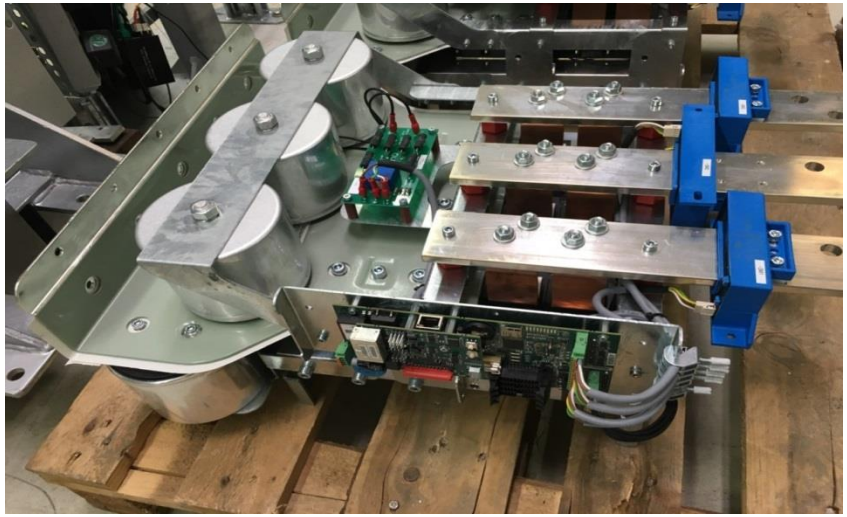
Power conversion



Power Stack

- DELTA provides the power converter
  - Latest IGBT technology
  - Assembled power stack shown on the left
- Power rating up to 1000 kVA
  - High power density design
  - Cost effective standard liquid cooling
- DELTA also provides
  - Quench protection / DAQ
  - Exciter.

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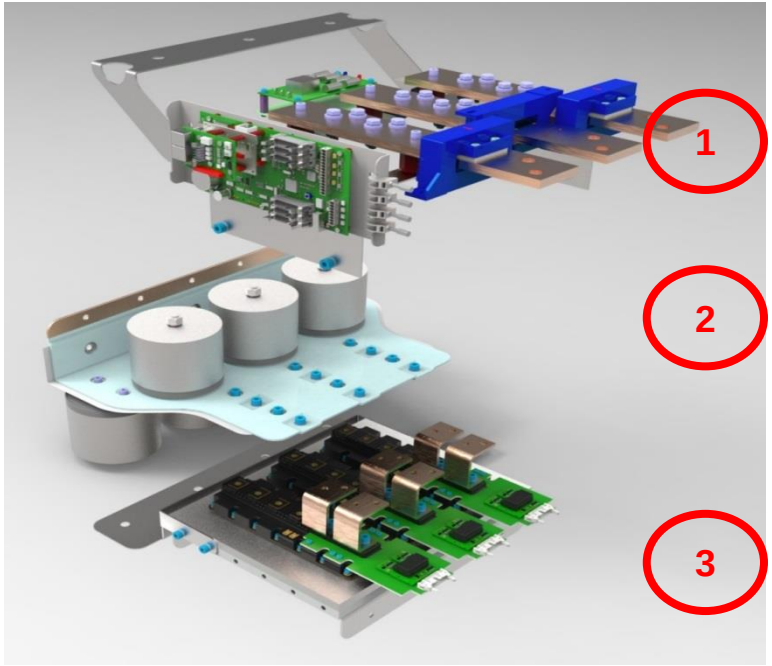
DELTA ENERGY SYSTEMS

Power conversion
Stack Detail



- Metallic holder with mounted electronics, such as current and voltage transducer and the Control Board (1)
- DC link bus with DC link capacitors (2)
- Cooling plate with IGBT modules (3).

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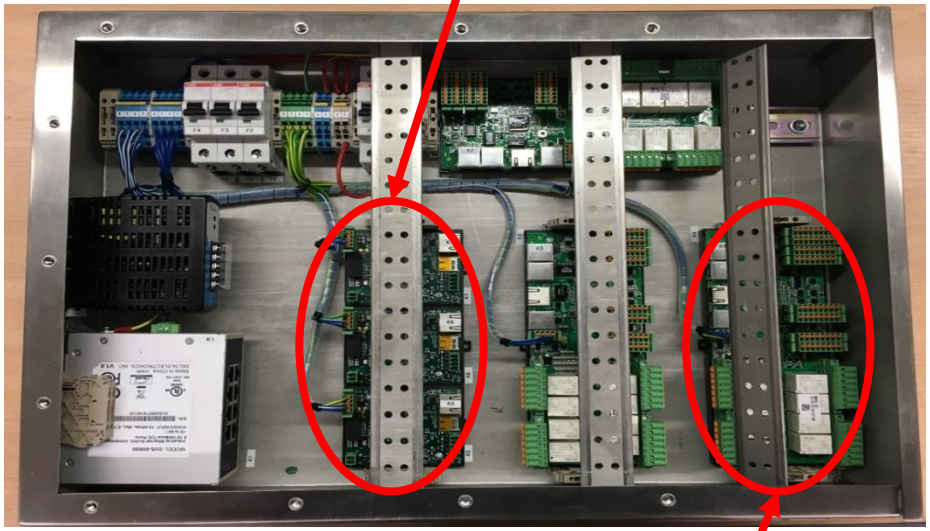
DELTA ENERGY SYSTEMS

Quench protection / DAQ



- Quench protection / DAQ system
  - Contains voltage and temperature measurement cards
  - Voltage drop increase will immediately be recognized and excitation will be stopped
  - Sensor data will be stored in data acquisition system.

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DELTA ENERGY SYSTEMS

Exciter

- Powering the superconducting rotor coils
- Mounted in rotating frame
- Steady state voltage drop only determined because of voltage drop over copper connections
- Exciter control by microcontroller
- Communication via Ethernet
- Error detection:
  - Ground fault
  - Overcurrent
  - Communication fault
  - Over temperature
  - Quench.

Parameter	Requirement
Supply voltage	400 V
Slip ring current	50 A
Frequency	50 Hz
Rotor inductance	4 – 16 H
Rotor resistance	0.2 mΩ
Output Current	0 – 600 A
Output Voltage	0 – 15 V
Maximum charging rate	1 A/s
Maximum discharging rate	10 A/s
Maximum induced voltage	200 V
Ground fault detection	DC output
Lightning protection	AC input
Safety Chain	
Shielded signal wires	-
Communication	Ethernet

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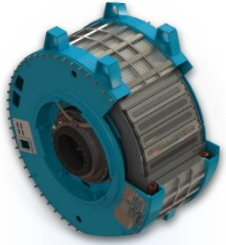
DELTA ENERGY SYSTEMS

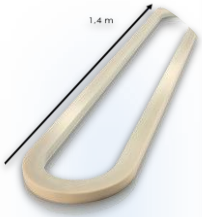
Assembly

Specs



Design

Materials



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Assembly

Testing

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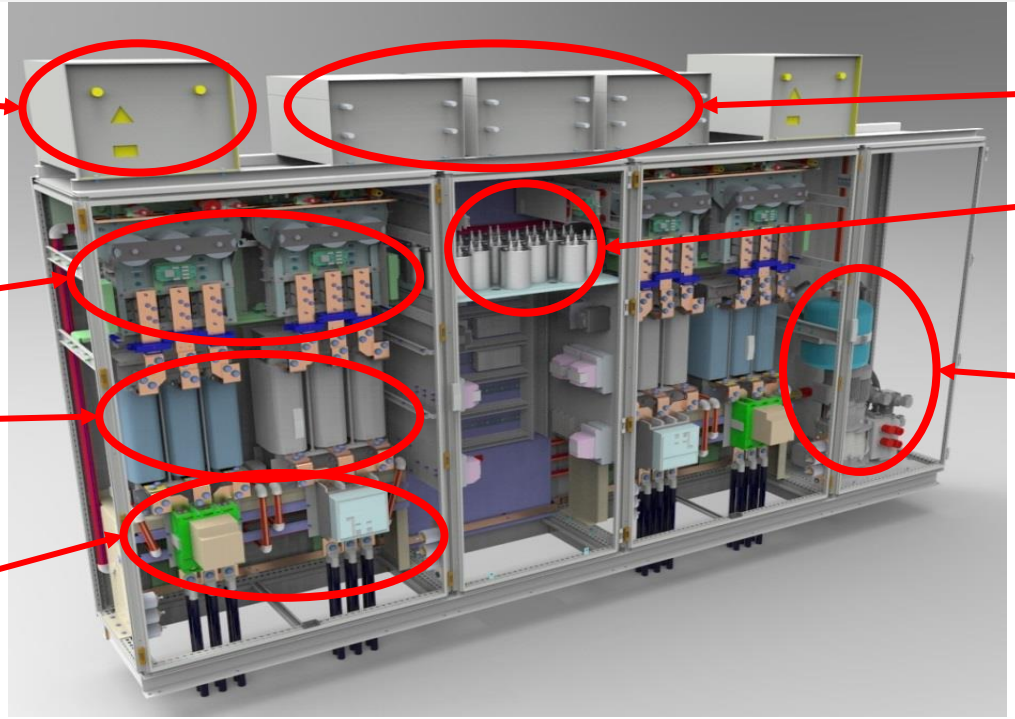
Power converter

DC – Brake resistor

Back-to-Back Powerstacks

Filter inductor

Generator and grid circuit breaker



Damping resistor for C-Filter

Filter capacitor bank

Cooling system pump

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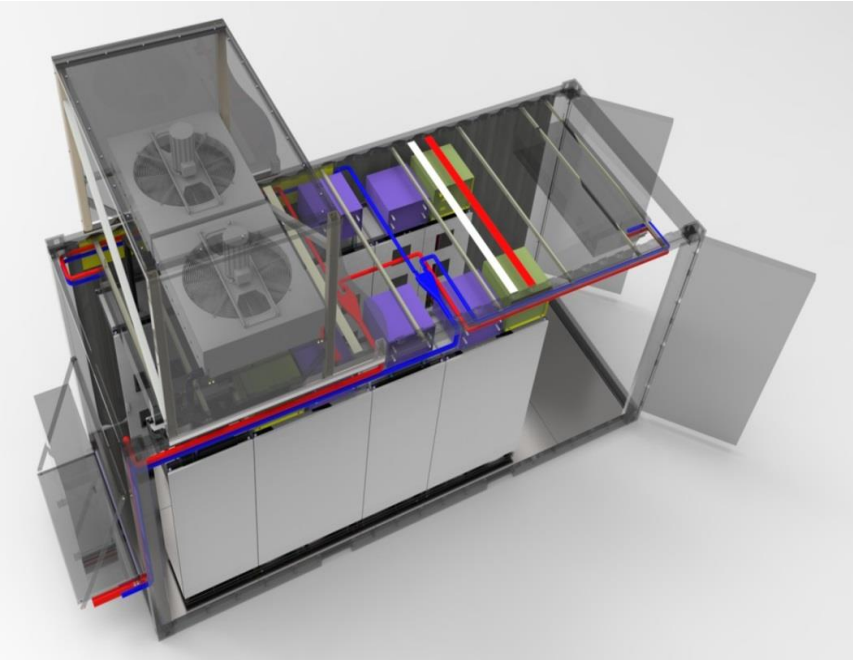
DELTA ENERGY SYSTEMS

Converter container



- Converter mounted into standard 20’ container
- Main water cooling system for converter with 2 heat exchanger
- Air conditioning for container
- Cooling systems can handle losses of 120 kW.

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DELTA ENERGY SYSTEMS

Stator coils

Form wound copper, mica insulation, VPI, class F

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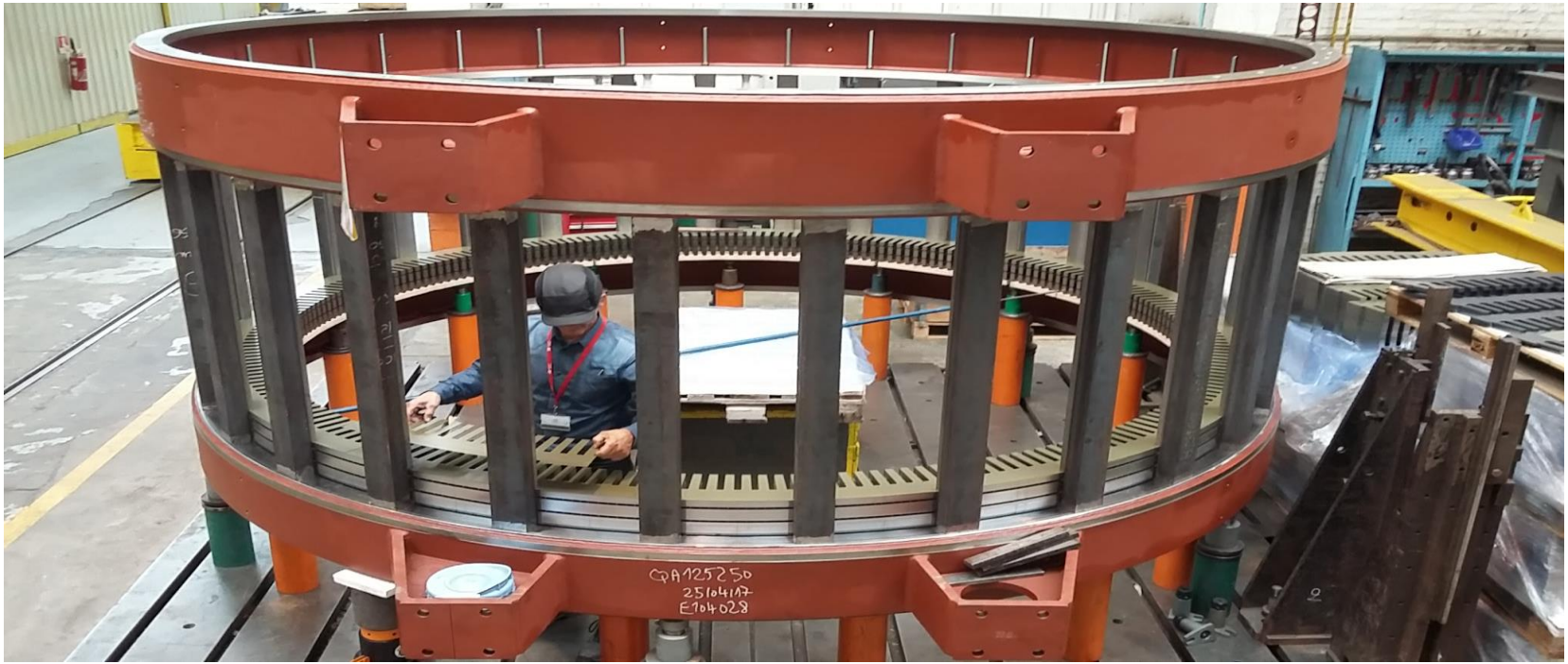
JEUMONT Electric

Stator assembly

Conventional with iron core sheets



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JEUMONT Electric

Rotor yoke
With coils ready for mounting

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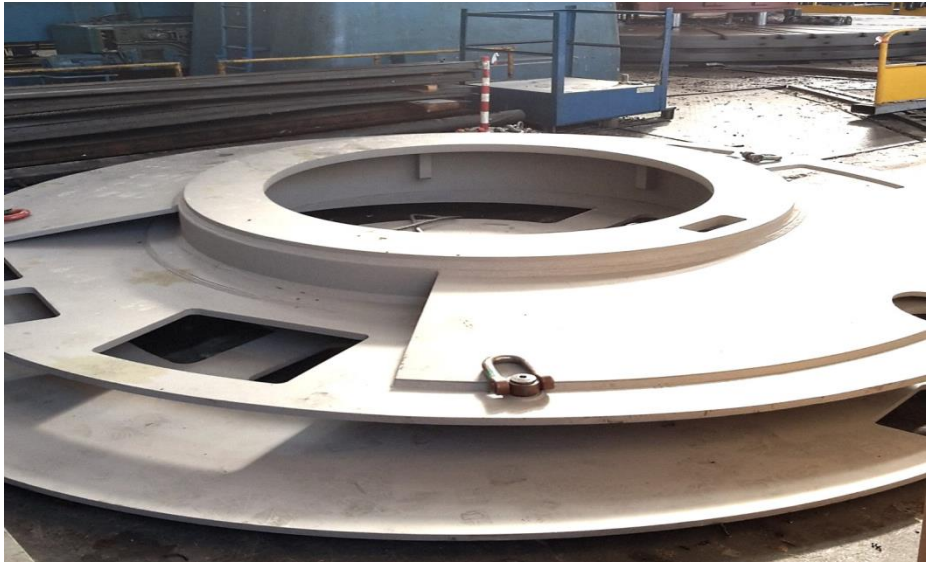
JEUMONT Electric

UNIVERSITY OF TWENTE.

Stator flanges

Drive end side and non-drive end side



Stator air ducts

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Main shaft
Raw cast at foundry

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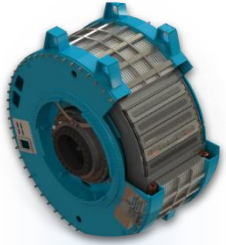
Testing

Specs



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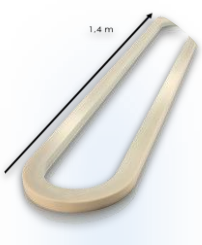

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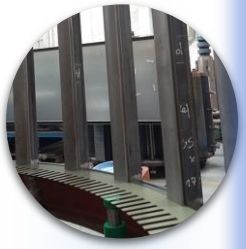

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Testing

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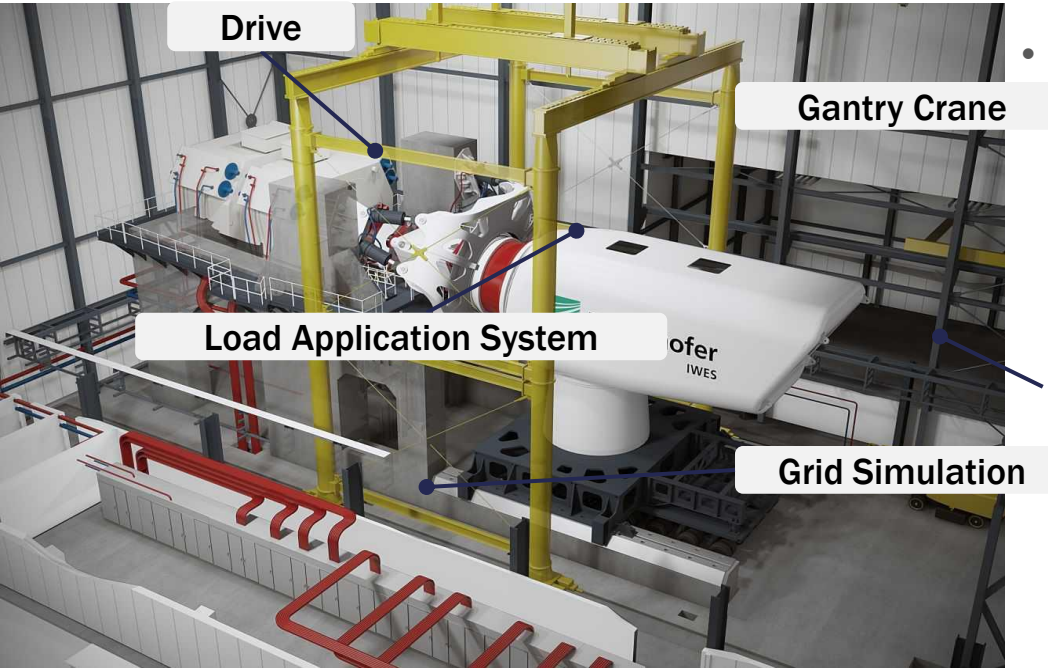
Ground based test at Dynamic Nacelle Laboratory



- Fraunhofer IWES will execute tests in its DyNaLab facility
  - Nacelle testing lab
  - Max torque 13 MNm
  - Max power 15 MW.

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Key features of nacelle test rig

Hydraulic load application system

- Simulation of wind loads
- 1.2 MW ~2,1m^3/min @315bar
- Thrust: ± 1900 kN, Radial : ± 2000 kN
- Bending: ± 20000 kNm (rotating y-, z-axis)
- Dynamic: 0-2 Hz (30% of max. load)
- 0-g unit for weight compensation (150 to)

Drive

- 5° inclined drive train
- 10/15 MW (nominal/peak) - Twin Synchronous Direct Drive
- 8.6/13 MNm (nominal/peak)
- Flexible coupling
- Hydraulic safety coupling (adjustable 8-15 MNm)

Grid simulation

- 10/20/36 kV tappings
- 44 MVA installed converter capacity
- LVRT & HVRT simulation
- < 2% THD @ 50 Hz

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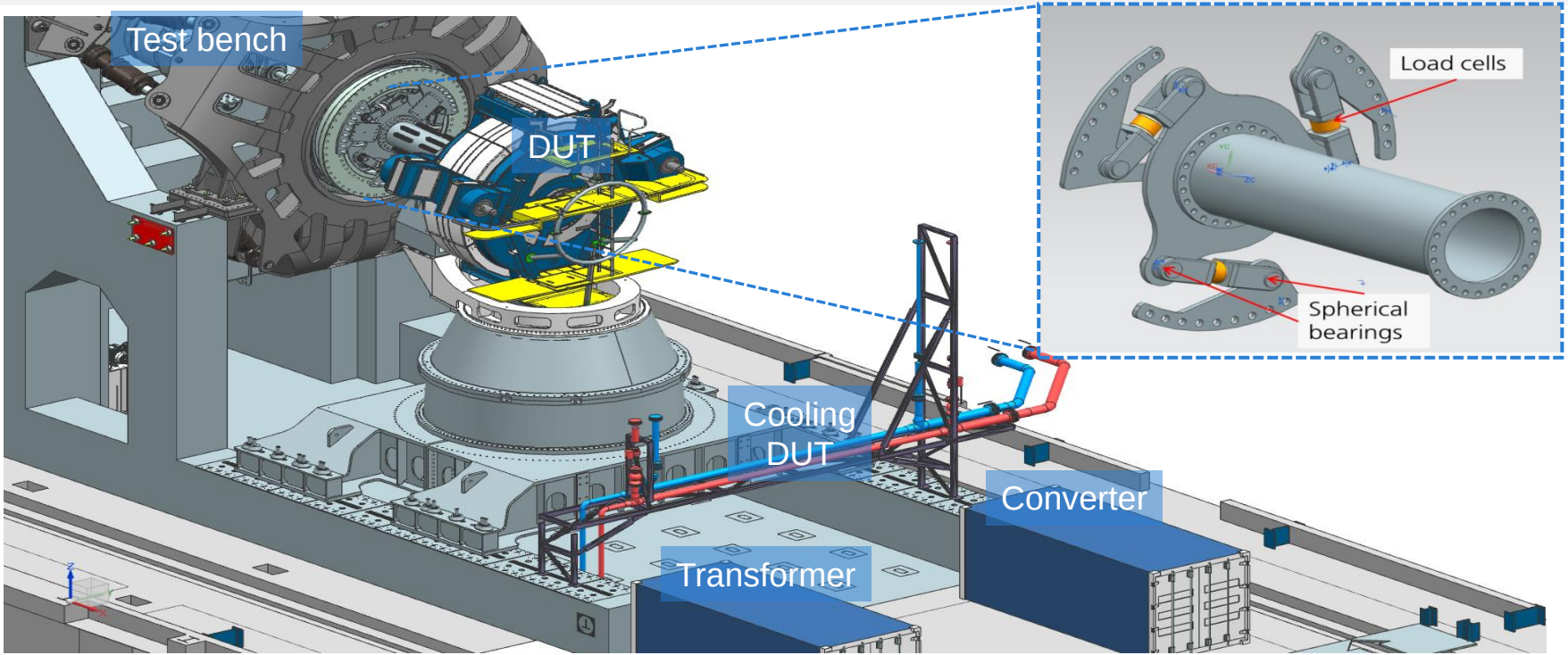
Fraunhofer

Ecoswing test setup



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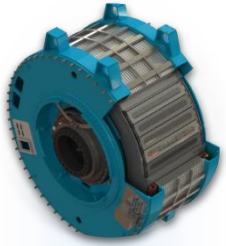
Specs



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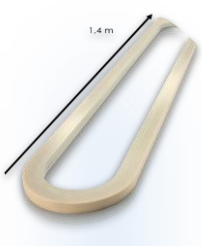

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Assembly

Testing

Installati
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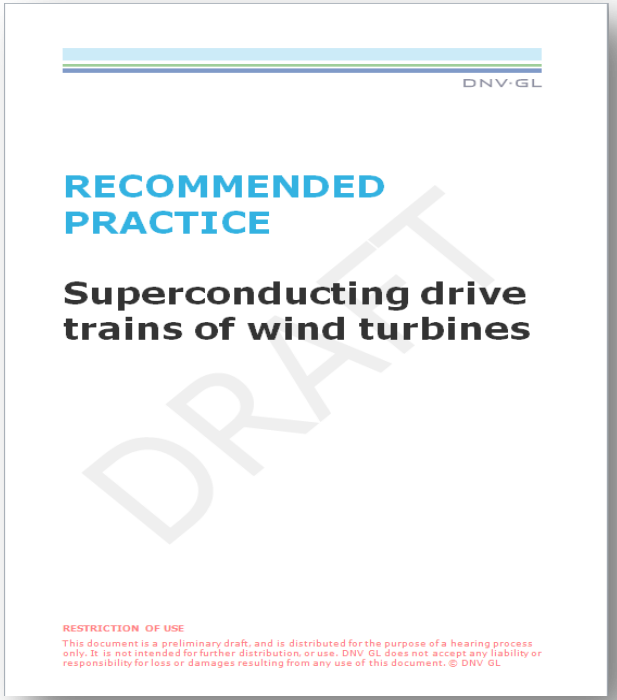
Future accreditation considered from the start

- DNV GL Renewables Certification is accredited Certification Body according to DIN EN ISO/IEC 17065:2013
- DNV GL has long history – developing guidelines for wind turbines (1986 1st guideline for certification of onshore wind turbines published).

Tasks of DNV GL in EcoSwing


DNV·GL

RECOMMENDED PRACTICE

Superconducting drive trains of wind turbines

DRAFT

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- Monitoring of development and tests
- Focus on critical aspects as well as certification aspects
- Participation in type testing at Fraunhofer IWES in Bremerhaven and on-site tests in Thyborøn
- Development of “DNV GL Recommended Practice for superconducting drive trains of wind turbines”
  - Currently there are no relevant standards or guidelines covering critical aspects of superconductors inside generators for wind turbines
  - DNV GL wants to change this.

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DNV·GL

Certification of superconductive wind generators

- There are no superconductor requirements in relevant standards
  - IEC 61400-1 for wind turbines
  - IEC 60034 for generators
  - IEC 62477 for converter
- This will be considered in the new Recommended Practice as well as additional requirements for cryogenic cooling equipment
  - Provides principles, technical requirements and guidance for design of superconducting drive trains for wind turbines
  - Will be the technical basis for future DNV GL certification processes of superconductive drive trains.

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Commercialization Necessities
Observations during execution of the project

- Superconducting drive trains in wind turbines are “development projects”
  - **Suppliers need to meet industrial market standards**
- For commercialization, the following aspects need to be accomplished
  - **Sufficient availability of superconductor** wire and coils in good quality at low costs
  - **Operational safety** in normal or faulted operation
  - **Demonstration of expected lifetimes**
  - **High reliability under extremely challenging environmental conditions** of wind turbines installed onshore as well as offshore (e.g. temperature range incl. minimum and maximum temperature, vibration, shock, marine environment, etc.)
  - **“Simple” and “easy” maintenance** of the superconductor components.

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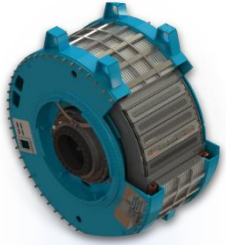
Installation

Specs



Design

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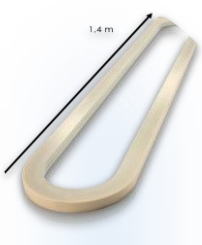

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Assembly

Testing

Installati
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The GC-1 wind turbine

- Two bladed turbine with partial pitch
  - Innovative design
  - Typhoon safe
  - In operation since 2013
- More info www.project-gc1.com
- Ideally suited for generator exchange.

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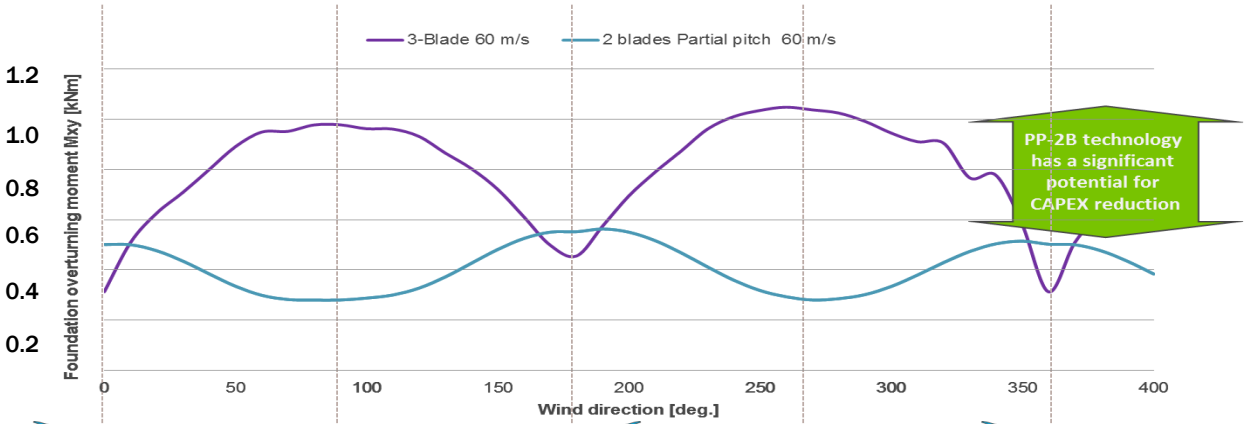
The GC-1 wind turbine

ecoswing

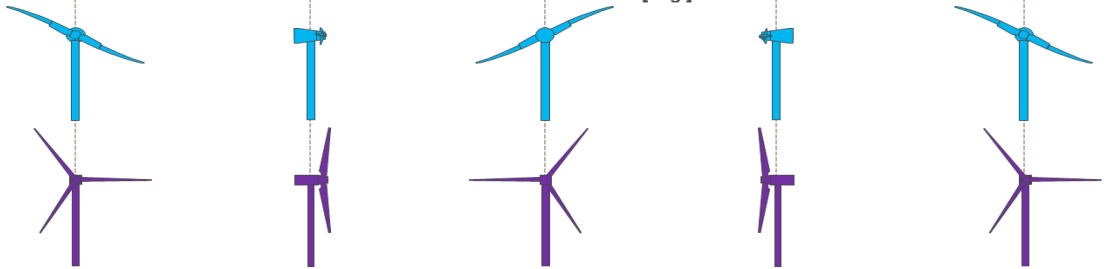
Foundation Loads during a 360 degree change in wind direction

Moment caused by wind



Two bladed profile

Three bladed profile



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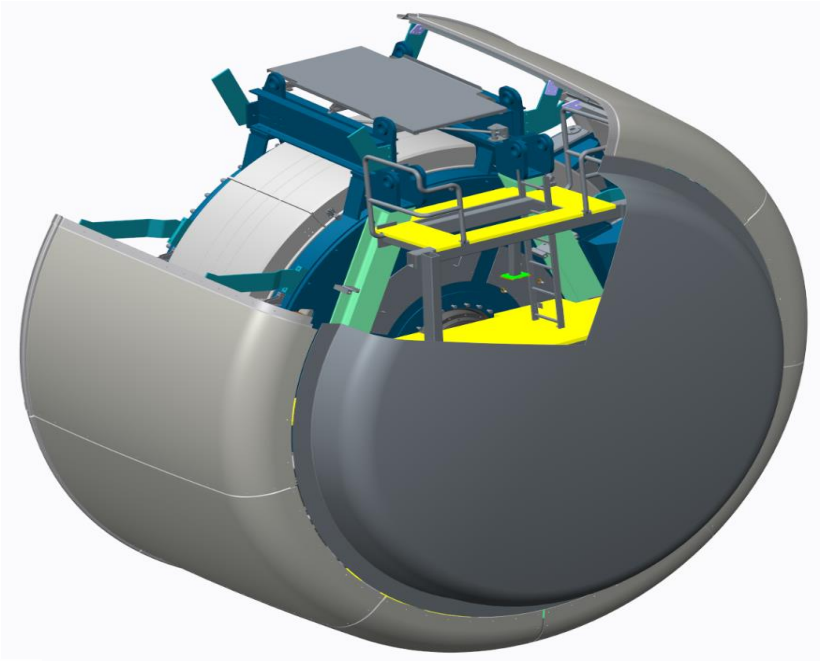
ENVISION

Turbine integration

- Generator in rear module

- Rear module with existing Permanent Magnet Generator is replaced by more compact HTS Generator.
- Outer diameter is reduced from 5.4m down to 4m and torque capability is unchanged.



Placement of power conversion container

- Location at bottom of tower
- Replaces existing power conversion container
- Grid connection container on the other side of the tower.

EcoSwing Mission

“EcoSwing aims at nothing less than world's first superconducting low-cost, lightweight drive-train demonstrated on a large-scale modern wind turbine”

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Acknowledgements to the Team

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