

Feasibility study project to realize the merits of 10 MW- class superconducting wind turbine generators

National Institute of Advanced Industrial Science
& Technology (AIST), Tsukuba, Japan



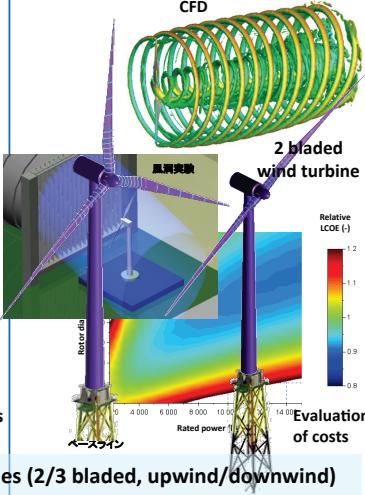
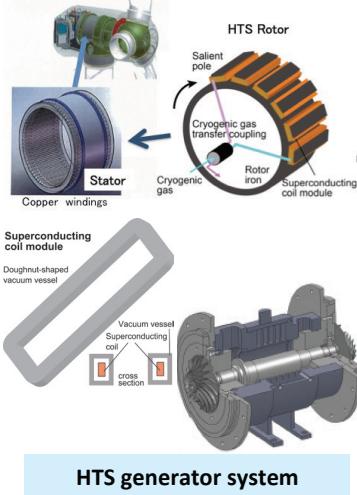
H. Yamasaki and M. Furuse

This presentation is based on the results obtained in the project commissioned by New Energy and Industrial Technology Development Organization (NEDO).

Research on Over 10 MW Class Wind Turbine (NEDO Feasibility Studies, 2013–14)

1. Total design (Hitachi, Ltd.)
Design of a 10 MW downwind wind turbine (3 bladed)
2. Elemental technologies (Adv. Industrial Sci. & Tech. (AIST), U. Tokyo, Mie U. and Wind Energy Institute of Tokyo, Inc.)
Survey of advanced elemental technologies, such as high rotational speed, 2 bladed wind turbine
3. Generator (AIST, Furukawa Electric Co. Ltd., Mayekawa Manufacturing Co. Ltd., Niigata U., Sophia U., U. Tokyo)
General design of a 10 MW-class high- T_c superconducting (HTS) wind turbine, and R & D of its key components
Target: Appealing the advantages of a salient-pole type HTS wind turbine generator → light-weight (<200 t), low cost, high reliability, high efficiency, etc.

Contents of NEDO feasibility studies

	Total design group	Elemental technologies group	Generator group
Players	Hitachi, Ltd.	AIST University of Tokyo Mie University Wind Energy Institute of Tokyo, Inc.	Furukawa Electric Co. Ltd. Mayekawa Manufacturing Co. Ltd. AIST
Theme	Detailed investigations of a 10 MW downwind wind turbine (3 bladed)	Detailed investigations on COE (cost of energy) and high rotational speed, 2 bladed wind turbines	R&D of key components for 10 MW HTS wind turbine generator/verification of the validity of general design
Major topics	 <p>Drivetrain (2-stage, Medium speed) Rotor blade for 10 MW wind turbine Airfoil DU4-A-00-050 100 DU9-W-300 40 DU9-W-250 30 DU9-W-220 25 DU8-W-210 21 NACA6418 18</p> <p>Downwind wind turbine Towing experiments in water</p> <p>NEDO 10 MW reference wind turbines (2/3 bladed, upwind/downwind)</p>	 <p>CFD 2 bladed wind turbine Relative LCOE (-) Evaluation of costs Rated power (kW)</p>	 <p>HTS Rotor Salient pole Cryogenic gas transfer coupling Copper windings Stator Superconducting coil module Doughnut-shaped vacuum vessel Vacuum vessel Superconducting coil cross section</p> <p>HTS generator system</p>

The project was commissioned by New Energy & Industrial Technology Development Organization (NEDO).

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Collaborators (Generator group)

1. National Institute of Advanced Industrial Science & Technology (AIST) — Total management, cryogenic gas transfer coupling
S. Fuchino, M. Okano, N. Natori

2. Furukawa Electric Co. Ltd. — Superconducting coil module
S. Mukoyama, T. Matsuoka, T. Amano, M. Furukawa

1. Niigata University (Prof. S. Fukui)
Design study of over 10 MW superconducting wind turbine generator



2. Sophia University (Profs. O. Tsukamoto & T. Takao)
Co-winding method to detect coil quench



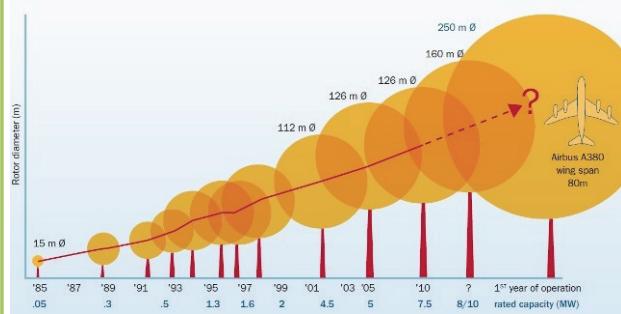
3. Mayekawa Manufacturing Co. Ltd. — Highly reliable refrigerator
A. Machida, M. Kudoh, M. Ikeuchi, N. Tamada

1. University of Tokyo (Prof. H. Ohsaki)
Inverter system suitable for ultra-high-speed motor drive



Recent trends in wind generation

Larger wind turbine

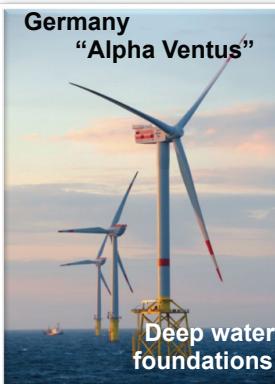


- Development of >5 MW wind turbines
current major systems are 2–3 MW

Why larger turbines?

- Larger electricity generation
 $(\text{Power generation}) \propto (\text{Rotor diameter})^2$
while $(\text{Interval of turbine}) \propto (\text{Rotor diameter})$
- Improvement of capacity factor
Higher altitude, higher wind speed

Offshore



Why?

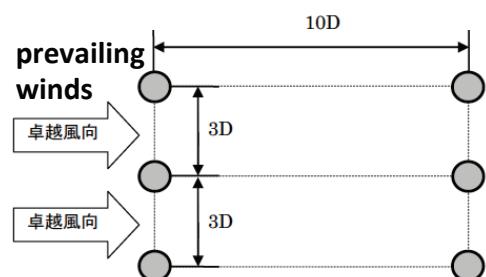
- Better wind speeds
- Space scarcity for installation of onshore (opposition to construction is much weaker)

Japan's Exclusive Economic Zone (EEZ) is the 6th largest in the world.

Impact of using large turbines

- Calculations assuming replacement of 1.5 MW wind turbines with larger capacity turbines. (Bay area with **prevailing winds**)

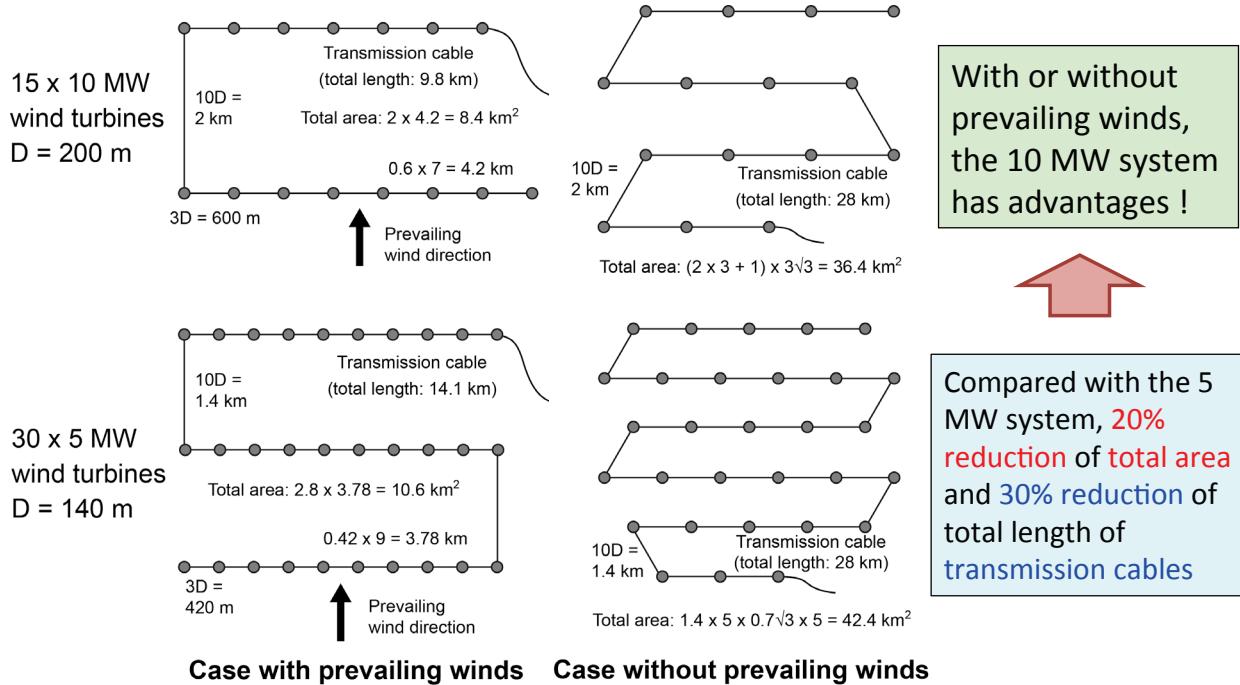
	1.5 MW (datums)	2.5 MW	5 MW	10 MW
Rotor diameter (D)	70 m	90 m	129 m	180 m
Interval of turbines (3D)	~ 210 m	~ 270 m	~ 387 m	~ 540 m
Number of turbines	17	12	9	6
Total output	25.5 MW	30 MW	45 MW	60 MW
Initial costs (by 0.2B¥/MW)	5.1 billion Yen	6.0 billion Yen	9.0 billion Yen	12.0 billion Yen
Capacity factor	28.7%	29.8%	34.8%	40.2%
Annual generation	64.1GWh	78.4 GWh	$\times 1.7$ 137 GWh	$\times 1.5$ 211 GWh
Annual income (by 10¥/kWh)	0.6 billion Yen	0.8 billion Yen	1.4 billion Yen	2.1 billion Yen
Profits for 20 years	7.7 billion Yen	9.7 billion Yen	18.4 billion Yen	30.2 billion Yen



Hachiryu wind farm (Akita, Japan)
17 wind turbines along 2.9 km coast

Advantages at offshore wind farms

- Comparison of using 10 MW wind turbines (rotor diameter D = 200 M) and using 5 MW wind turbines (D = 140 m) to construct a 150 MW offshore wind farm



Various drivetrains for wind turbines

Vestas, REpower

Conventional multistage gear

o: field-proven
o: low cost
o: rare earth free

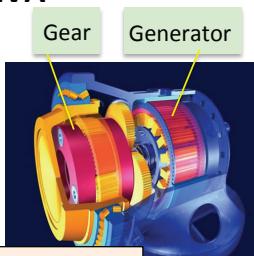
x: robustness
x: gear loss
x: failure rate
x: fixed speed ratio

High speed

Beyond 6 MW ?
→
Limitations of gear technologies

Yasukawa Electric, AREVA

1-stage gear and middle size generator



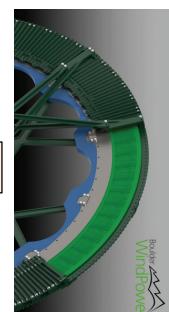
o: smaller gear loss
o: relatively smaller generator
x: less field-proven

Siemens

Direct-drive (conventional generator)

o: gearless
x: huge generator
x: rare earth problems
x: less field-proven

Low speed

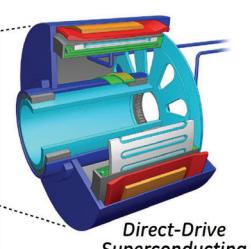
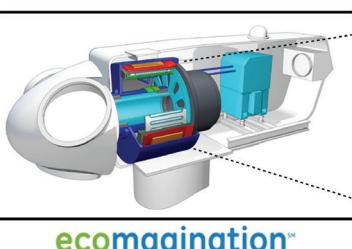


GE (USA), Suprapower (EU FP7)

Direct-drive, Superconducting generator

o: gearless
o: light-weight, compact
o: rare earth free
o: high efficiency, low cost (R&D target)
x: under development

Low speed



Based on low-Tc superconducting wires (GE)

Comparison of reference wind turbines

		Total design G (NEDO)	Elemental technologies G (NEDO)		Reference wind turbine		
					DTU (Light Rotor)	Siemens (SWT-6.0-154)	MHI-Vestas (V164-8.0)
Rated power		10 MW	10 MW		10 MW	6 MW	8 MW
Blade num.		3	3	2	3	3	3
Rotor position		Downwind	Upwind		Upwind	Upwind	Upwind
Rotor diameter		204 m	200 m		178.3 m	154 m	164 m
Hub height		130 m	130 m		119 m	Site dependent	Site dependent
Rotor speed		4.0–8.5 rpm	8.6 rpm	10.8 rpm	6–9.6 rpm	5.0–11.0 rpm	4.8–12.1 rpm
TSR		10	10	12.2	7.5	n/a	n/a
Gear box		2-stage Medium speed	2-stage Medium speed		2-stage Medium speed	Direct drive	Medium speed
Generator		PMG or RCG	PMG			PMG	PMG
Weight	Rotor	880 ton	326 ton	318 ton	229 ton (41 ton/blade)	26 ton/blade	35 ton/blade
	Nacelle		472 ton	437 ton	446 ton	360 ton	390 ton
	Tower	800 ton	887 ton	850 ton	605 ton	Site dependent	Site dependent
Substructure		Jacket	Jacket		Onshore	Site dependent	Site dependent
Wind turbine class*		IEC IC,T	IEC IC,T		IEC IA	IEC IA	IEC S

*The wind turbine class "T" for typhoon will be approved in the next version of the IEC standard 61400-1.

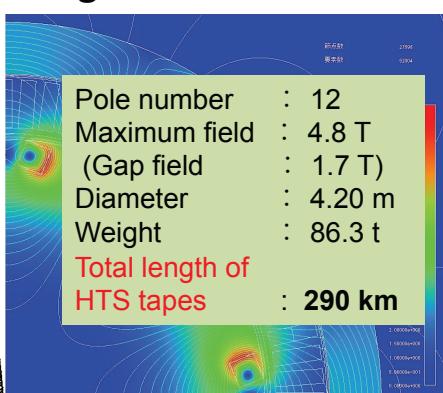
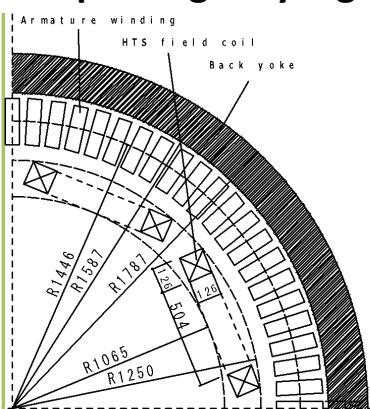
The project was commissioned by New Energy & Industrial Technology Development Organization (NEDO).

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Trial design of 10 MW HTS generators

★Case 1: An extremely light-weight and compact design
exploiting very high magnetic field of air-core HTS coils

Assumed rotation
speed: 10 rpm



Pole number : 8
Maximum field : 9.6 T
(Gap field : 2.5–4 T)
Diameter : 3.67 m
Weight : 60.6 t

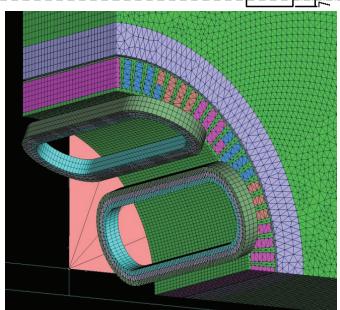
Comparable weight with
conventional 2–3 MW
synchronous generators

[S. Fukui, Teion Kogaku (J. Cryo. Supercond. Soc. Jpn.), 47, 362 (2012).]

Total length of superconducting tapes (~4 mmW): 570 km

- Assuming future cost of 1,000 yen/m (~8 US\$/m)
→ 0.6 billion yen for superconductor
- Desired price for a 10 MW generator → 0.3–0.4 billion yen

Cost of the extremely compact design, air-core
HTS generator is unacceptably high !



Desired price for a 10 MW generator

0.3–0.4 billion yen

(300–400 m¥ ≈ 2.4–3.2 m\$)

(Power generation) \propto (Rotor diameter: D)², while
 (Weight (cost) of turbine) \propto D³ → (Cost) \propto (Power)^{3/2}

1. Private communication with an wind turbine supplier

2. (cost of 5 MW generator + gear box) × (from 2 to 2^{3/2})

$$= 0.16 \text{ billion yen} \times 2\text{--}2.8 = 0.32\text{--}0.45 \text{ billion yen}$$

T1.4. Gearbox

Function	The gearbox converts rotor torque at a speed of 5-15 rpm to a speed of up to around 1500rpm for efficient conversion to electrical energy by the generator.
Cost	A 5MW gearbox costs £700k to £1m. ~ 0.13 billion yen

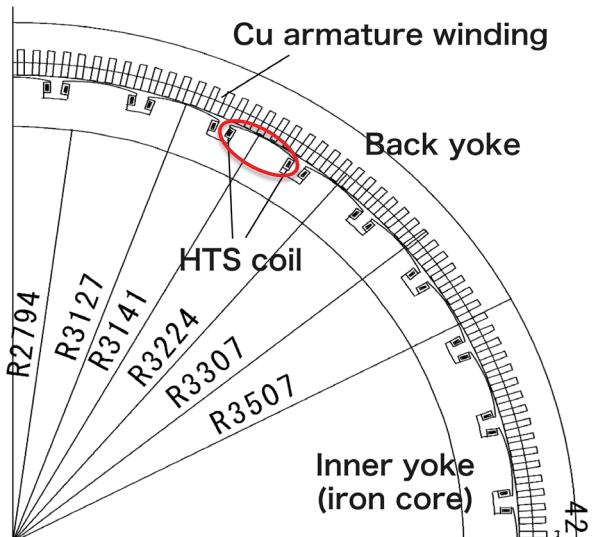
T1.5. Generator

Function	The generator converts mechanical energy to electrical energy.
Cost	Depending on generator type, a 5MW generator costs of the order of £200-£250k.

~ 0.03 billion yen

[BVG Associates, "A Guide to an Offshore Wind Farm", *THE CROWN ESTATE*, pp. 9–68 (2010)]

★ Case 2: a cost-effective design saving superconducting wires by the use of iron core



Cold iron core or warm iron core?
 → Warm iron core (only HTS coils are cooled)
 → Superconducting coil-module system

[H. Yamasaki, M. Furuse and N. Natori: IEEE Trans. Appl. Supercond. **25**, 5201405 (2015)]

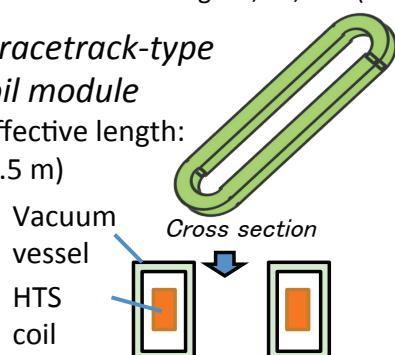
Pole number : 36
 Maximum field : —
 (Gap field : 1.0 T)
 Diameter : 7.0 m
 Weight : ~160 t

1/2 of conventional direct-drive 10 MW generator

Total HTS wire length : 45 km

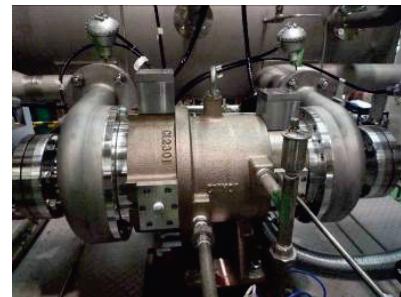
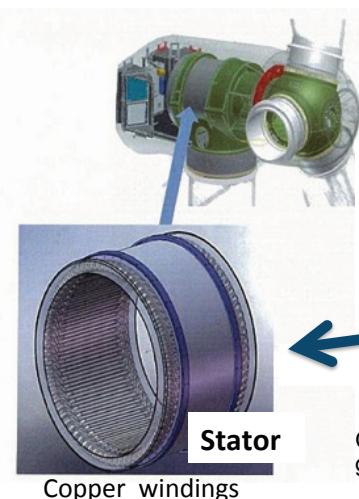
[S. Fukui: Teion Kogaku, **47**, 362 (2012)]

A racetrack-type coil module
 (effective length:
 1.5 m)

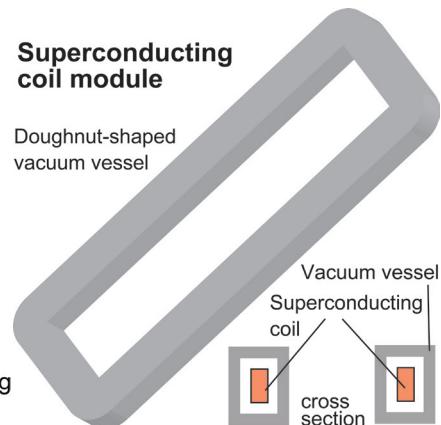


Key components of HTS generator to be developed

- HTS racetrack coil module
- Highly reliable refrigerator
- Cryogenic gas transfer coupling



Compressor for cryogenic gas
(turbo-Brayton refrigerator)



Modified design of an iron-cored generator FURUKAWA ELECTRIC

HTS wire : SuperPower (RE)BCO tape
Operating temperature : 40 K
Operating current : 160 A
Magnetic loading : 0.84 Wb
Gap magnetic field : 1.0 T



Dimensions

Rated output power : 10 MW
Pole number : 48 (\leftarrow 36)
Rated voltage (phase-to-phase): 5 kV
Rated current : 1,155 A
Rotation speed : 10 rpm
Outer diameter : ~10.5 m (\leftarrow 7 m)

Weight

Rotor + stator : ~142 t
HTS coil module : ~1.8 t
Total weight : ~144 t (\leftarrow ~160 t)

Length of HTS wire

1 pole of racetrack coil : ~546 m
(Coil effective length : 1 m (\leftarrow 1.5 m))
48 poles of coils : ~26.2 km (\leftarrow ~45 km)

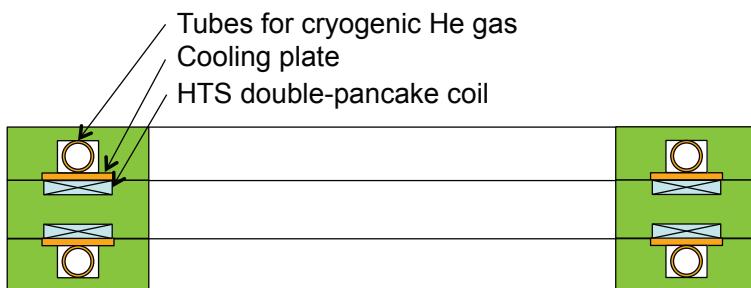
**Cost of HTS wires no longer matters much,
thinking of future wire price (2,000 ¥/m)**

Design of an HTS coil module

FURUKAWA
ELECTRIC

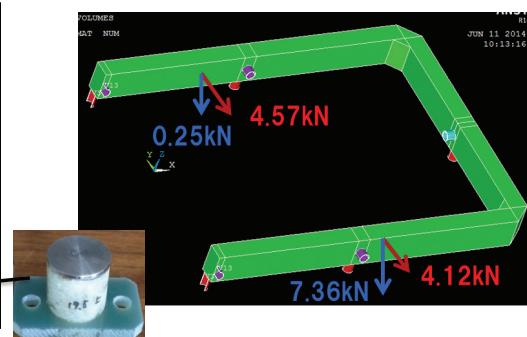
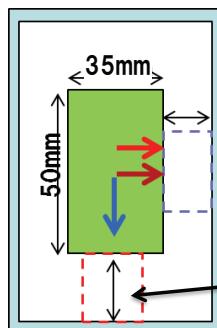
Coil structure

Structural design of an HTS coil, iron core and cooling pipes



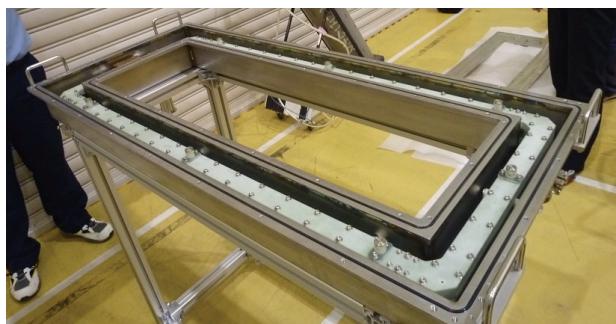
Cryostat (vacuum vessel)

Supporting materials (FRP tubes) are placed between the cryostat and the racetrack coil, for which thermal compressive pressure and Lorentz forces are exerted.

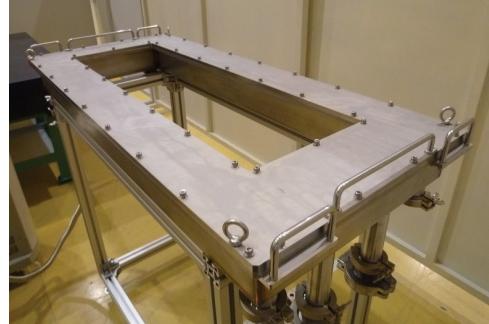


Fabrication of an HTS coil module

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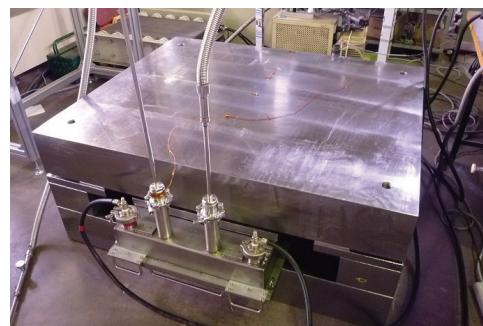
Racetrack coil placed inside of a cryostat



Appearance of a cryostat



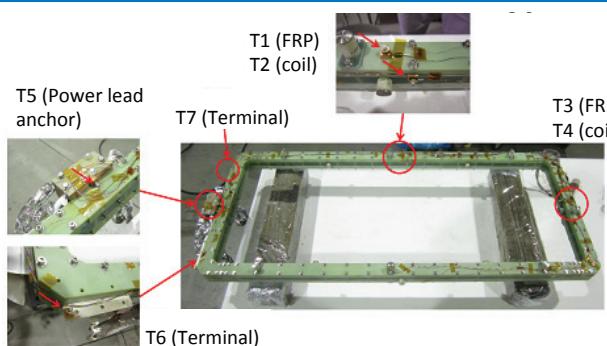
Cryostat stored in an iron core



Appearance of a cryostat and iron core

Test of a coil module: heat inleak

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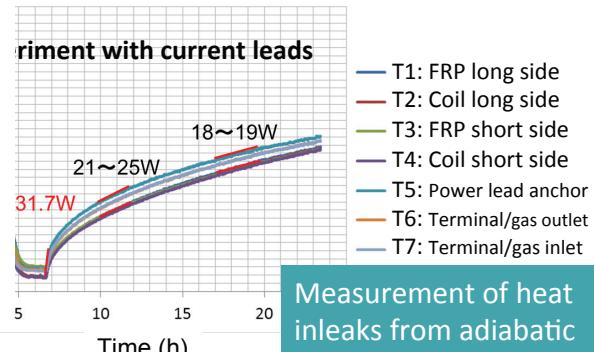


1. Measurement of time dependent temperature (T) increase at various points by Cernox T sensors.

2. Calculation of heat inleaks at ~150 K from measured T increase rates and reported specific heats (heat capacity).
 3. Calculation of heat inleak at 30 K from the 150 K result through heat conductivity.

$$Q_{30K} = Q_{FRP@150K} \times \frac{\int_{150K}^{300K} \lambda_{FRP}(T) dT}{\int_{150K}^{300K} \lambda_{FRP}(T) dT} + Q_{SUS@150K} \times \frac{\int_{150K}^{300K} \lambda_{SUS}(T) dT}{\int_{150K}^{300K} \lambda_{SUS}(T) dT} \\ + Q_{Cu@150K} \times \frac{\int_{150K}^{300K} \lambda_{Cu}(T) dT}{\int_{150K}^{300K} \lambda_{Cu}(T) dT} + Q_{Radiation}$$

temperatures at various points in the coil

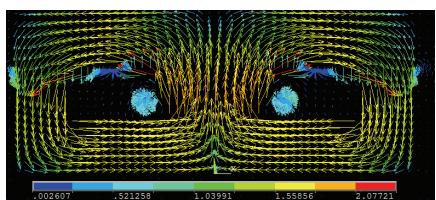


Measurement of heat inleaks from adiabatic temperature increase

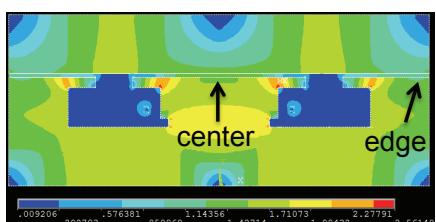
	30 K	100 K	150 K (Ref.)
Supporting materials	6.2	5.2	4.2 (calc.)
Transfer tubes (SS)	12.3	10.4	8.2 (differential)
Radiation	0.6	0.6	0.6 (calc.)
Cu current leads	12.6	8.1	6 (differential)
Calculated heat inleak	31.7	24.3	(19)
Measured heat inleak	—	21–25	18–19

Generated & calculated magnetic fields

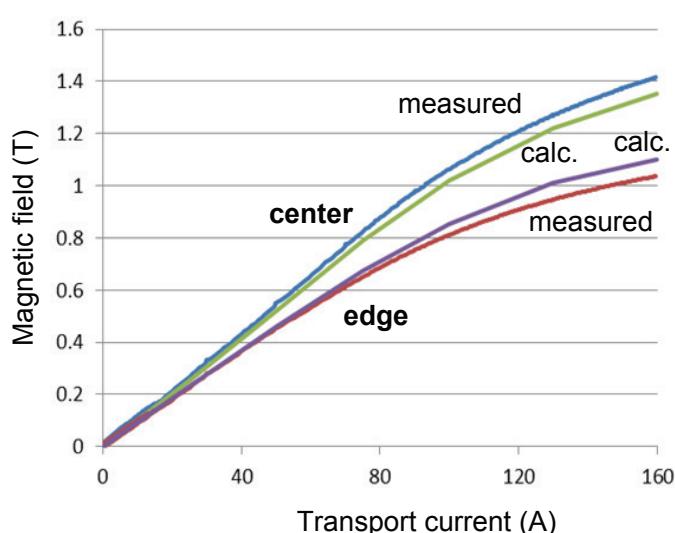
FURUKAWA
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Vector figure of calculated magnetic fields



Distribution of magnetic flux density



Analysis results
 gap magnetic field (center) 1.35 T
 gap magnetic field (edge) 1.1 T

Measured magnetic field values nearly coincided with the calculated values

Calculation of total heat inleaks

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ELECTRIC

Calculation of heat inleaks for 48 poles (6 series-connected modules × 8 units)

(1) Measure heat inleaks: supporting materials + He transfer tubes (TT) + radiation
(total: 19.1 W@30 K) measured without current leads (Cf. TT: 12.3 W@30 K)

(2) Measure heat inleaks: supporting materials + TT + radiation + current leads
(31.7 W@30 K) measured with current leads connected
→ (2) – (1) : (current leads: 12.6 W@30 K)

(3) Current transport test: Joule heating at current leads with 160 A transport current
(10.7 W@30 K)

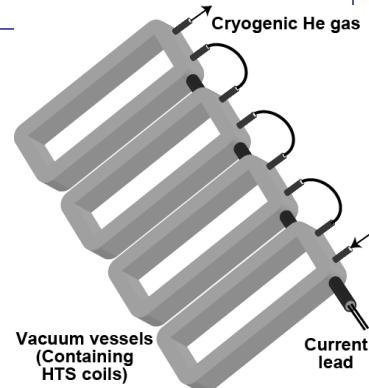
Calculation of total heat inleaks (48 poles)

Heat inleaks to 6 series-connected modules

$$= 6 \times (1) + (12.6 + (3)) - 5 \times \text{TT} = 76.4 \text{ W}$$

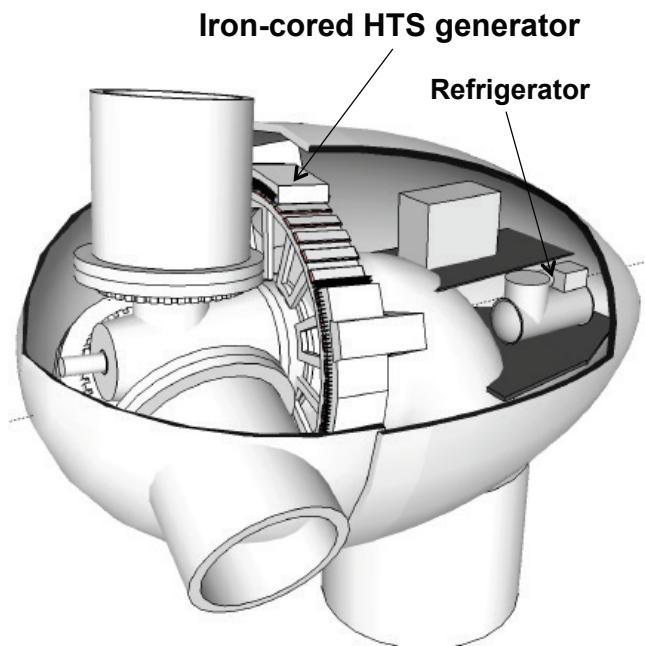
Total heat inleaks (8 units) = $8 \times 76.4 = 611.2 \text{ W}$

This value is sufficiently lower than the capacity of the refrigerator (1 kW)



F.S. of 10 MW-class HTS generator

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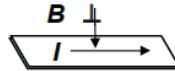
Electromagnetic design of ultra-light, air-cored HTS generator

Total length of HTS wires: $\geq 290 \text{ km}$

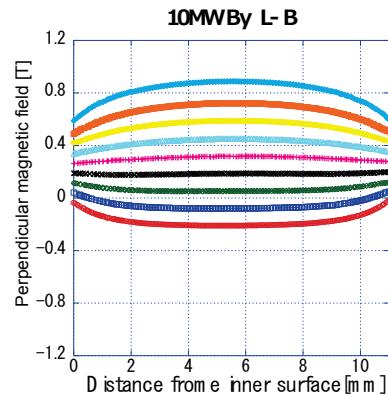
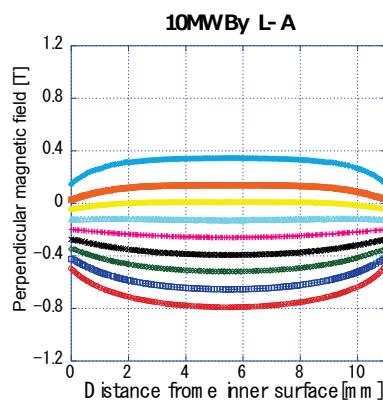
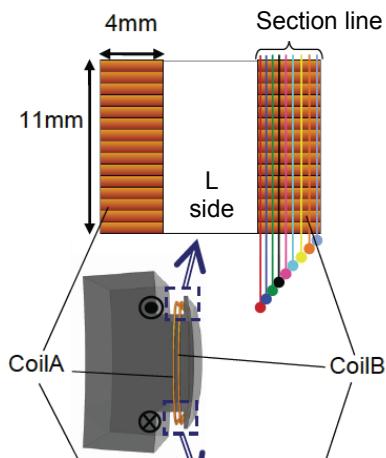
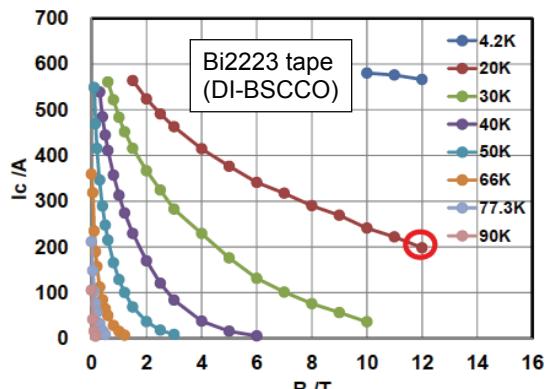
Proposal of low-cost, iron-cored HTS generator (HTS length: 26 km)

Demonstrated the validity of the HTS coil-module system with warm iron cores

Selection of HTS wires



- Highest **perpendicular** magnetic field component applied to the tape was calculated as **about 1 T**
- YBCO: operation current $I_{op} = 160$ A is possible at 40–50 K.
- Bi2223: $I_{op} = 160$ A only at ~40 K.



Refrigerator for superconducting machines

Refrigerator type	Capacity	Reliability	Operating principle
Regenerator type Stirling refrigerators	Features: Compact size 1 kW (77 K)	Many Mechanical contact Continuous operation about 8,000 hr	Compressor Expander Regenerator
Heat exchanger type Brayton cycle refrigerator	Features: Easy to get large capacity 2–20 kW (77 K)	Mechanically non-contact More than 10 years	Compressor Heat exchanger Expander

Brayton refrigerator is advantageous, in terms of high-efficiency, large-capacity, high reliability

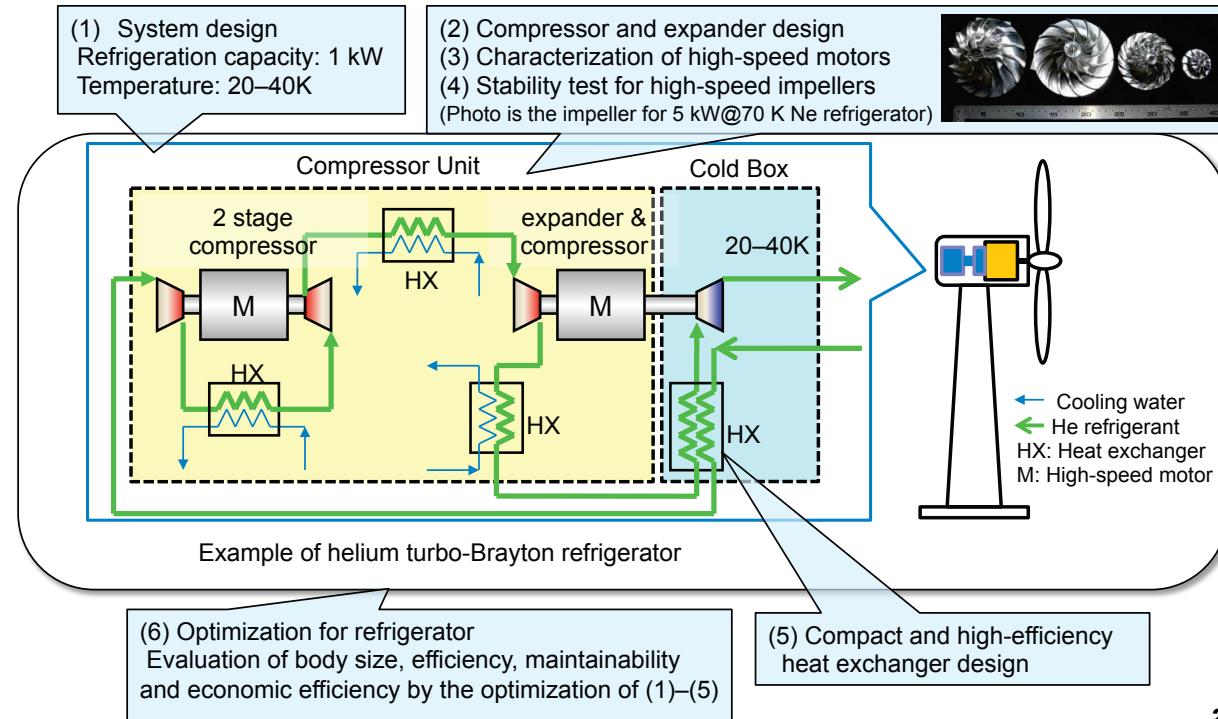
GM type refrigerator in Suprapower project

Turbo-Brayton Refrigerator
In Superconducting cable demonstration project (NEDO)

Working gas: **Neon**
Efficiency: COP = 0.1 @5 kW (77 K)
Reliability: >30,000 hr (MTBF)

Refrigerator for superconducting wind turbine generator
Working gas: **He (high speed turbine)**
Temperature: 20–40 K (Low Temperature)
Maintenance interval: >30,000 hr
Compact size and high efficiency

Development of a refrigerator for superconducting wind turbine generators

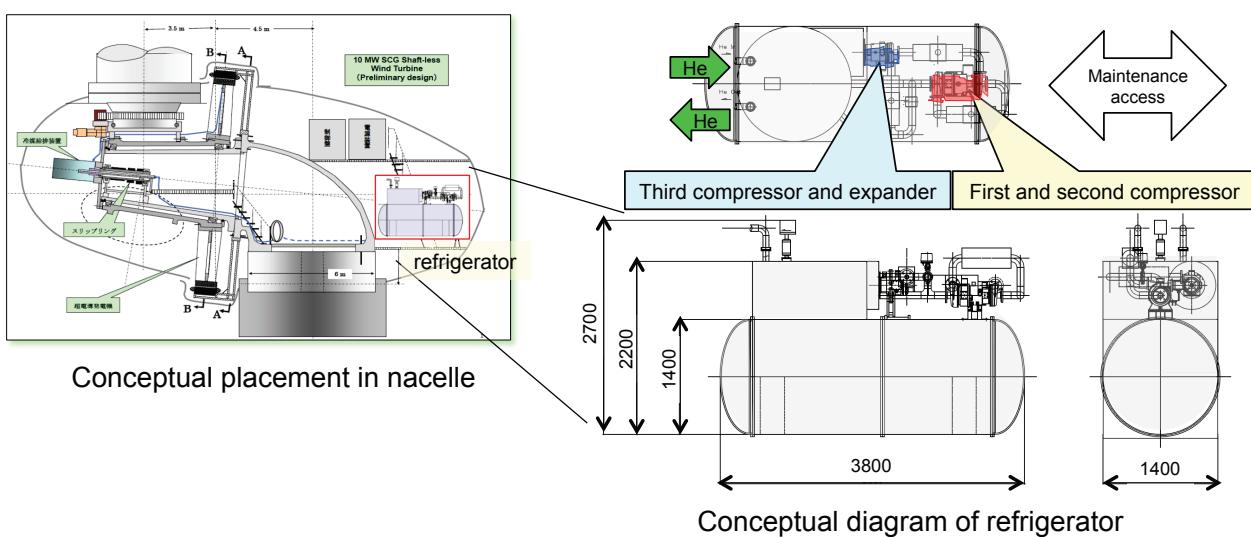


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Design of a refrigerator for wind turbines

Conceptual design for refrigerator

- Horizontal placement of rotating machines makes the refrigerator system compact and enables easy maintenance
- Independent maintenance operations for the rotating heat exchanger (cryogenic gas transfer coupling) and stationary refrigerator by the installation of shut-off valve
- Optimization for heat exchanger for helium gas
- Confirmation of the refrigerator installation on the outside of the elbow structure



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Test of rotating machines for compressor and expander units in a Brayton refrigerator

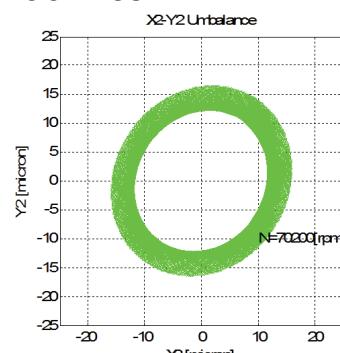
Test of rotating machines to verify the stability during **high-speed operation** for using **helium** as a refrigerant.

- 2 stage compressor unit (1st & 2nd compressor)
- Expander & compressor unit (3rd & expander)

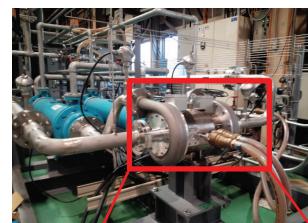
We have checked the status at the time of high-speed operation of rotating machines

	1 st & 2 nd compressor	3 rd comp. & expander
Poles	2	2
Rated speed (rpm)	85,000	100,000
Rated power (kW)	42	20
Voltage (V)	340	340

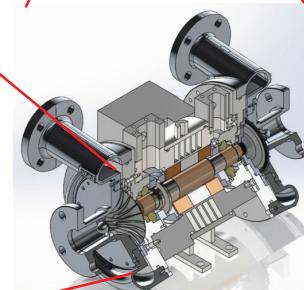
Specifications of ultra-high-speed built-in motors (permanent magnet synchronous motors)



Locus of the shaft (radial) in high-speed operation (70,000 rpm) of 2 stage compressor unit



Test facility for the rotation test



3D model of 2 stage compressor unit

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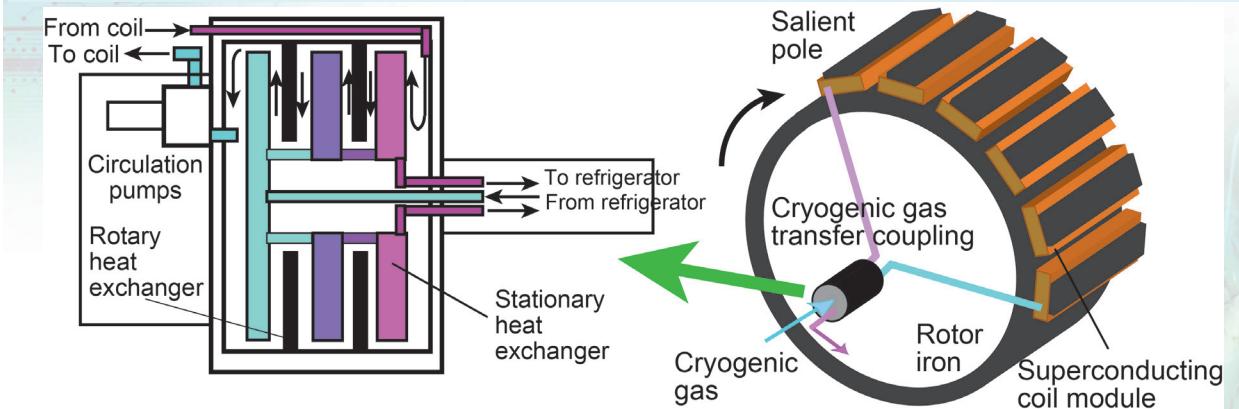


Cryogenic gas transfer coupling using circulation pumps

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High-pressure cryogenic He gas (20–40 K) is used to cool HTS coil modules

- ➔ Conventional cooling system may be difficult to use or not be reliable enough
- We have proposed a method of **supplying a coolant by circulation pumps built in the rotor** and by **rotational-stationary heat exchangers**. It is possible to separate the high-pressure refrigerant in the stationary system from the rotational system (left fig.)
- ➔ Another advantage: easy to control the flow rate in several parallel units

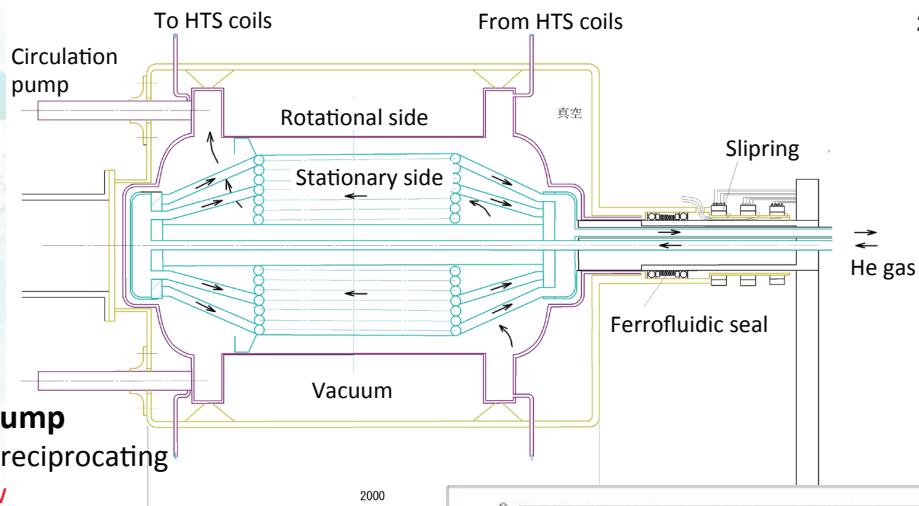


Rotor side: **nearly ambient pressure He gas** circulated ➔ easy to use rotational **ferrofluidic seal**
Refrigerator side: **high-pressure refrigerant** circulated only in the stationary system

Heat exchangers and circulation pumps

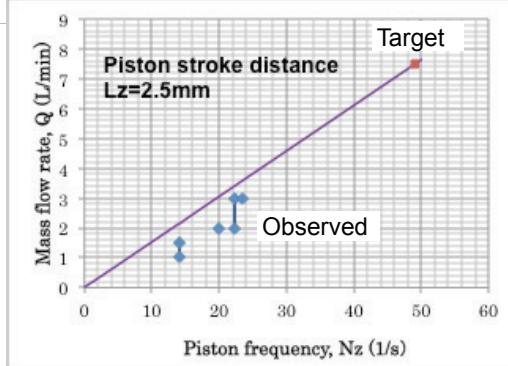
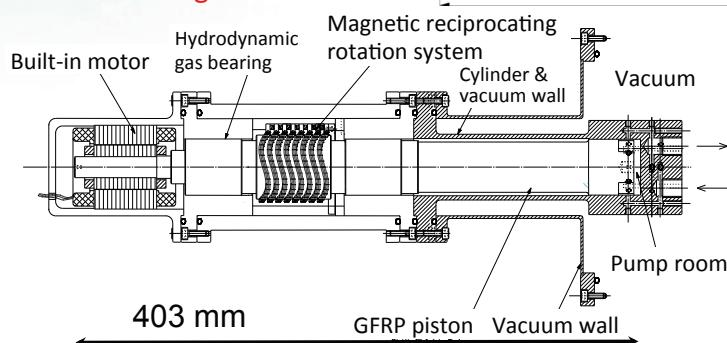
27

Concept design of a rotational-stationary heat exchanger



Tested circulation pump

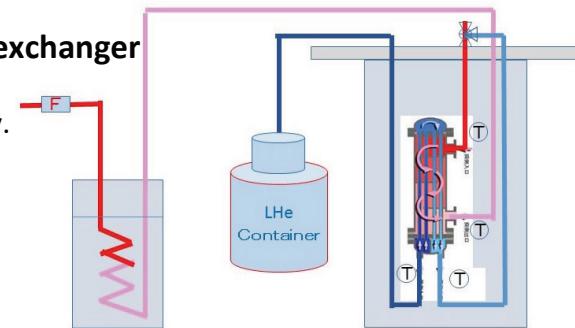
rotation → rotation + reciprocating movement → gas flow



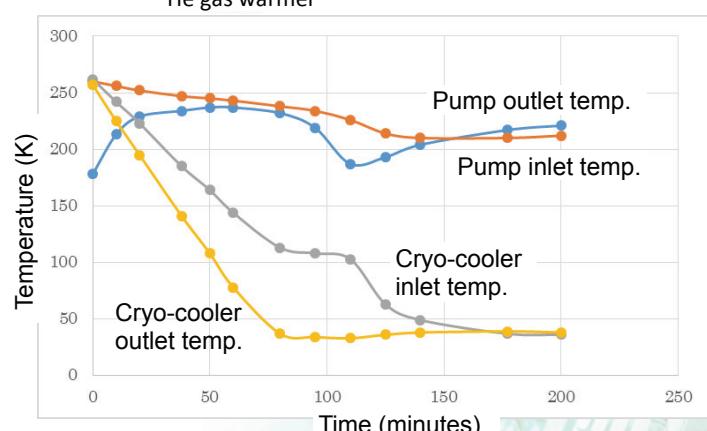
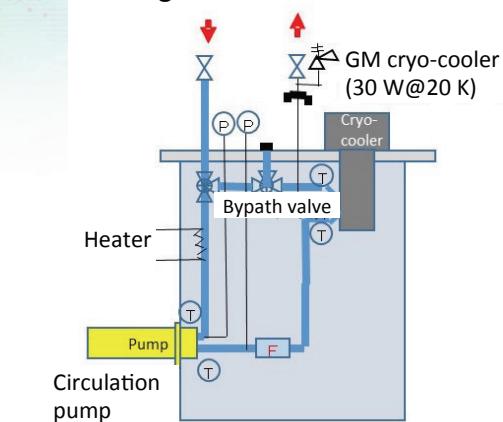
Low temperature tests of a heat exchanger and a circulation pump

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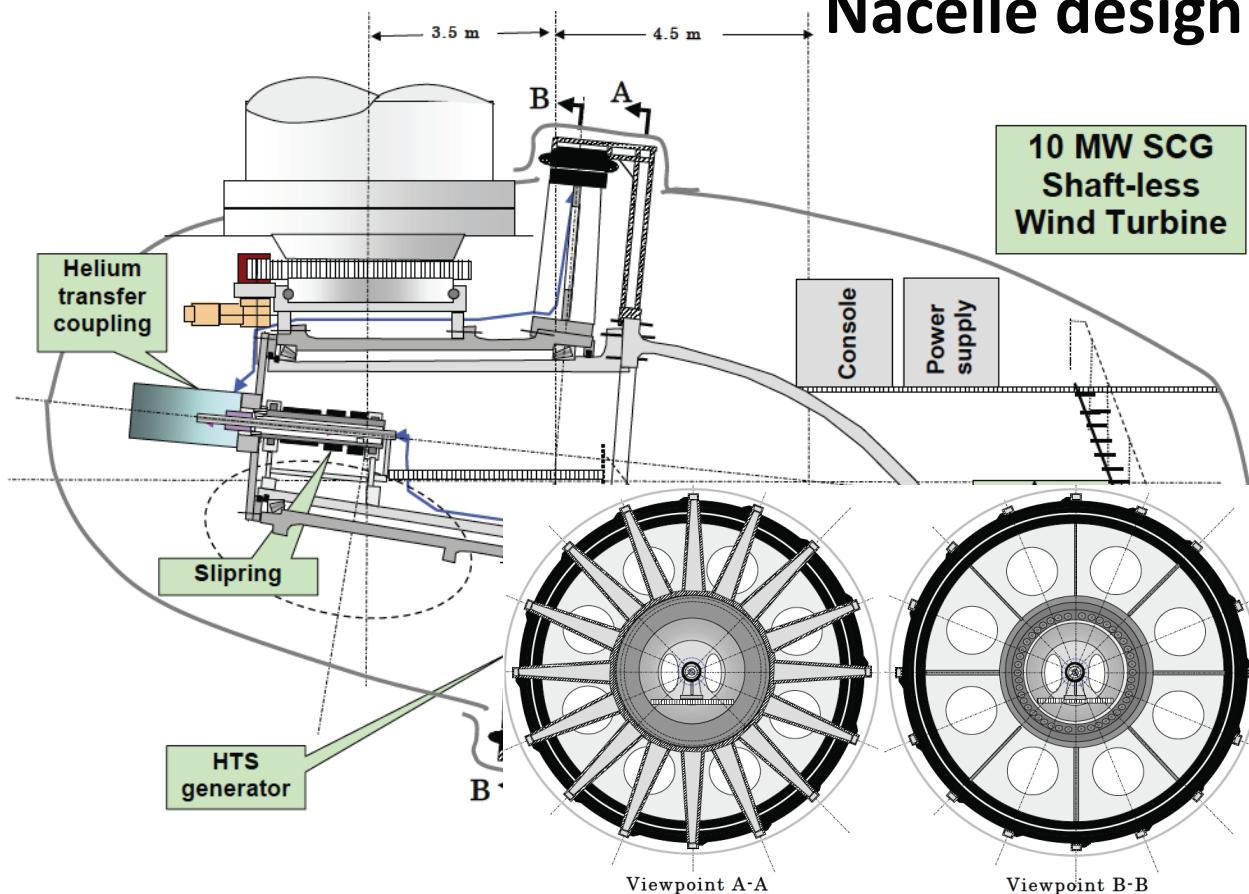
Cooling test of a modified shell & tube heat exchanger (model of a rotational-stationary heat exchanger)
→ Confirmed highly efficient heat exchange ability.



Low temperature test of a circulation pump
→ Confirmed the gas flow at ~210 K, but the temperature did not decrease further due to the insufficient gas flow rate.

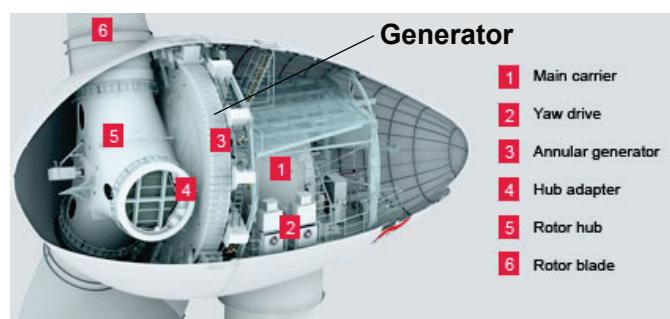


Nacelle design

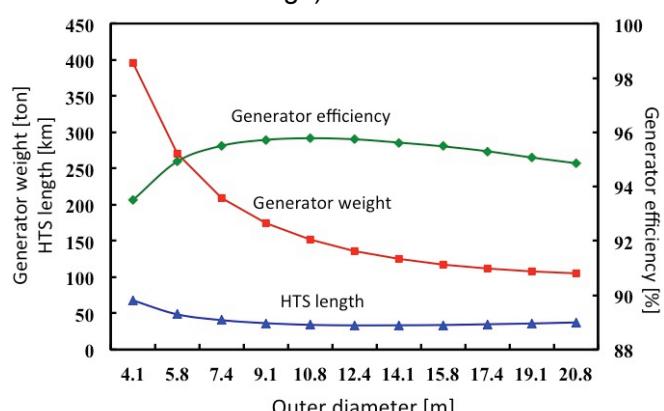
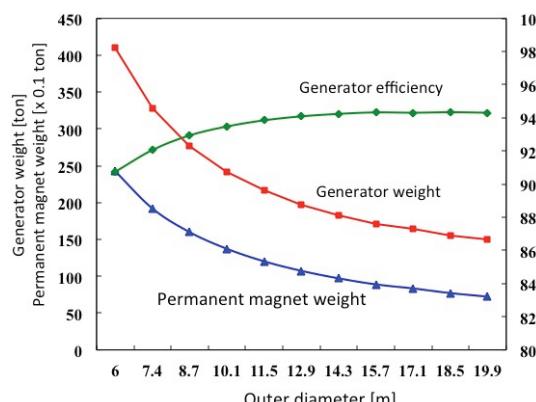


Design of large direct-drive wind turbine generators

- General trend for the structure of the large annular generator directly connected to the rotor hub
- Generator voltage is proportional to the rotational speed of the field magnet → total weight becomes smaller when outer diameter of the generator becomes larger



Enercon E-126 (7.5 MW synchronous generator with Cu field windings)



Effect of outer diameter on the weight of wind turbine generator [Maki, Xu & Izumi, the 90th CSSJ Conference, Japan (2014)]

Direct-drive 10 MW generator: comparison between HTS and conventional machines

Generator (rotation speed: 8 rpm)	(A) Cu field winding machine	(B) Permanent magnet machine	(C) HTS machine	(D) Compact HTS machine (another design, 10 rpm)
Pole numbers	120	200	96	48
Outer diameter [m]	13.9	14.3	14.1	10.5
Gap magnetic field [T]	0.82	0.41	1.1	1.0
Weight of field windings (or permanent magnet) [t]	12.8	9.7	0.42	1.8 (including vacuum vessel)
Generator weight [t]	224	183	126	~150
Generator efficiency [%]	94.8	94.2	95.5	97.6 (including refrigerator power)

Designer: N. Maki (A, B, C), Furukawa Electric Co. Ltd. (D), generator weight includes spider weight

- Cu field winding machine → very heavy; large power supply needed for magnetic generation (e.g., 6 sets of 300 V, 150 A apparatuses, total cost ~40 million yen)
- Permanent magnet machine → rare-earth magnets still expensive (raw material (Nd: 30%, Dy 4%) costs ~60 million yen/10 ton); difficult to treat large and strong magnets

NEDO **Conclusions** AIST

- From a cost standpoint we adopted the salient-pole iron-core rotor design, and focused on three key components: (1) superconducting coil module, (2) highly reliable Brayton refrigerator and (3) cryogenic gas transfer coupling. We also made a general design of the whole nacelle and realized the advantages of SC-WTGs over conventional generators.
- An iron-cored 10 MW SC-WTG was designed, and one of the 48-pole coil modules (including iron core) was produced for demonstration. Cooling and electrical transport tests to measure heat inleaks and generated magnetic fields were successfully performed, which has demonstrated the validity of the design and verified the feasibility of the HTS coil.
- For the highly reliable turbo Brayton refrigerator ($\geq 30,000$ h maintenance free), we designed the refrigerator and confirmed that the refrigerator can be installed in a nacelle. We have proposed a unique He transfer coupling, which supplies a coolant by circulation pumps built in the rotor. We have confirmed their validity, but still need to increase the flow rate.
- In the next stage we need to confirm the validity of the coil at rotation, and extensive R & D efforts are necessary on the cooling system.