Cryogenic Engineering Conference/International Cryogenic Materials Conference 2015
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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

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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)

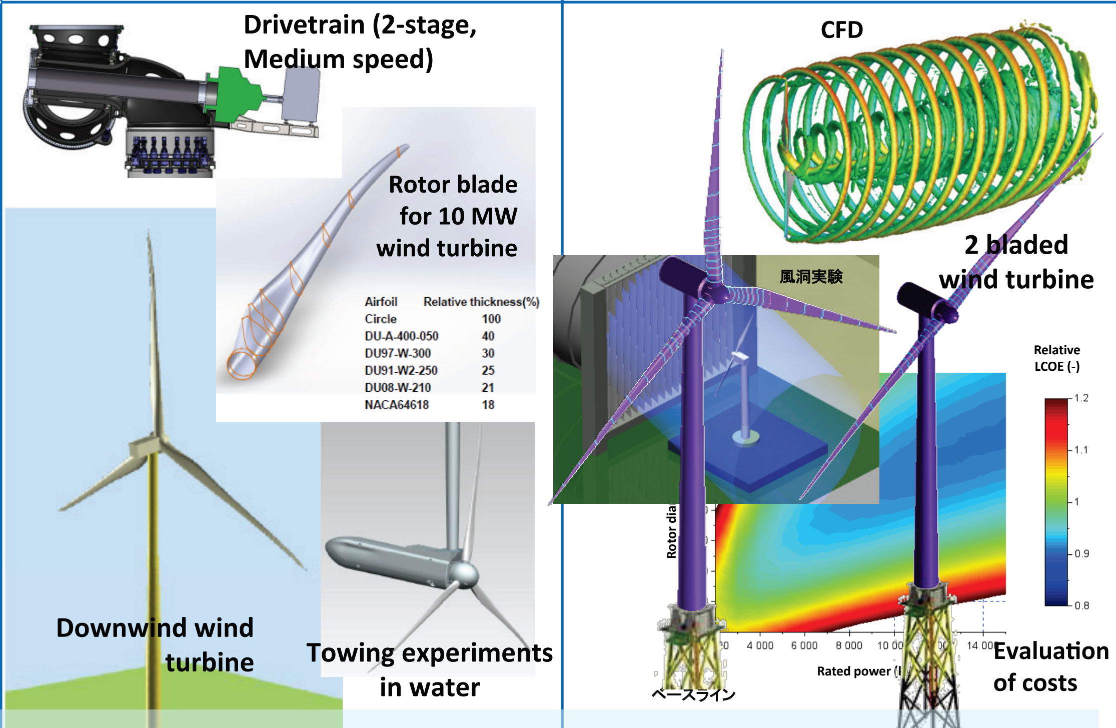
1. Total design (Hitachi, Ltd.)
   Design of a 10 MW downwind wind turbine (3 bladed)
2. Elemental technologies (Adv. Industrial Sci. & Tech. (AIST), U. Tokyo, Mie U. and Wind Energy Institute of Tokyo, Inc.)
   Survey of advanced elemental technologies, such as high rotational speed, 2 bladed wind turbine
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

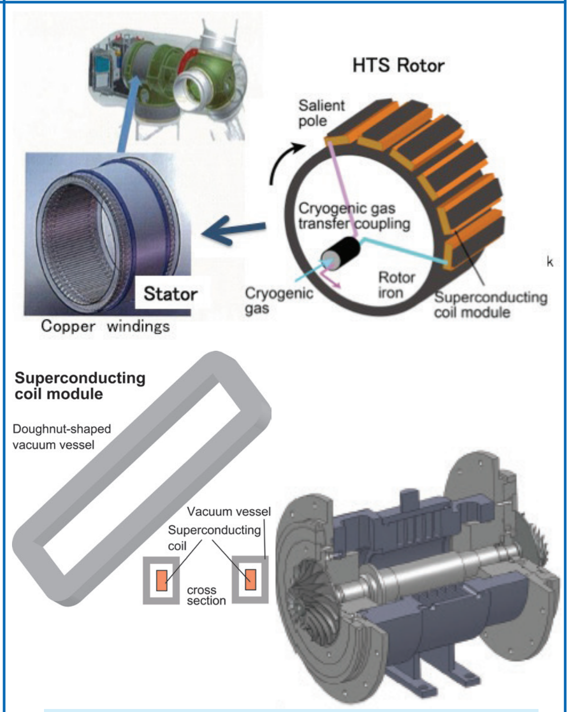
WIND ENERGY INSTITUTE OF TOKYO INC.

	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



NEDO 10 MW reference wind turbines (2/3 bladed, upwind/downwind)



HTS generator system

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

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

新潟大學

上智大学
SOPHIA UNIVERSITY

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

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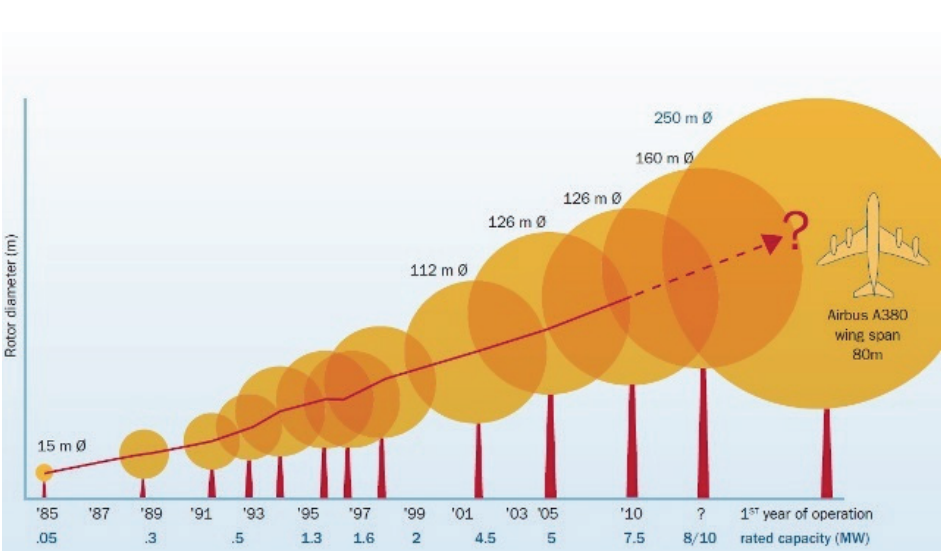
AIST　FURUKAWA ELECTRIC GROUP　MAYEKAWA MYCOM

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
  (Power generation) ∝ (Rotor diameter)^2
  while (Interval of turbine) ∝ (Rotor diameter)
- ➢ Improvement of capacity factor
  Higher altitude, higher wind speed

Offshore

Why?

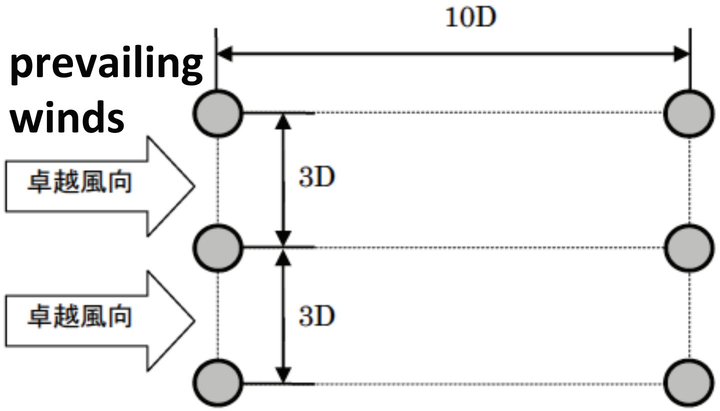
- ➢ Better wind speeds
- ➢ Space scarcity for installation of onshore (opposition to construction is much weaker)

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	× 1.7 137 GWh	× 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

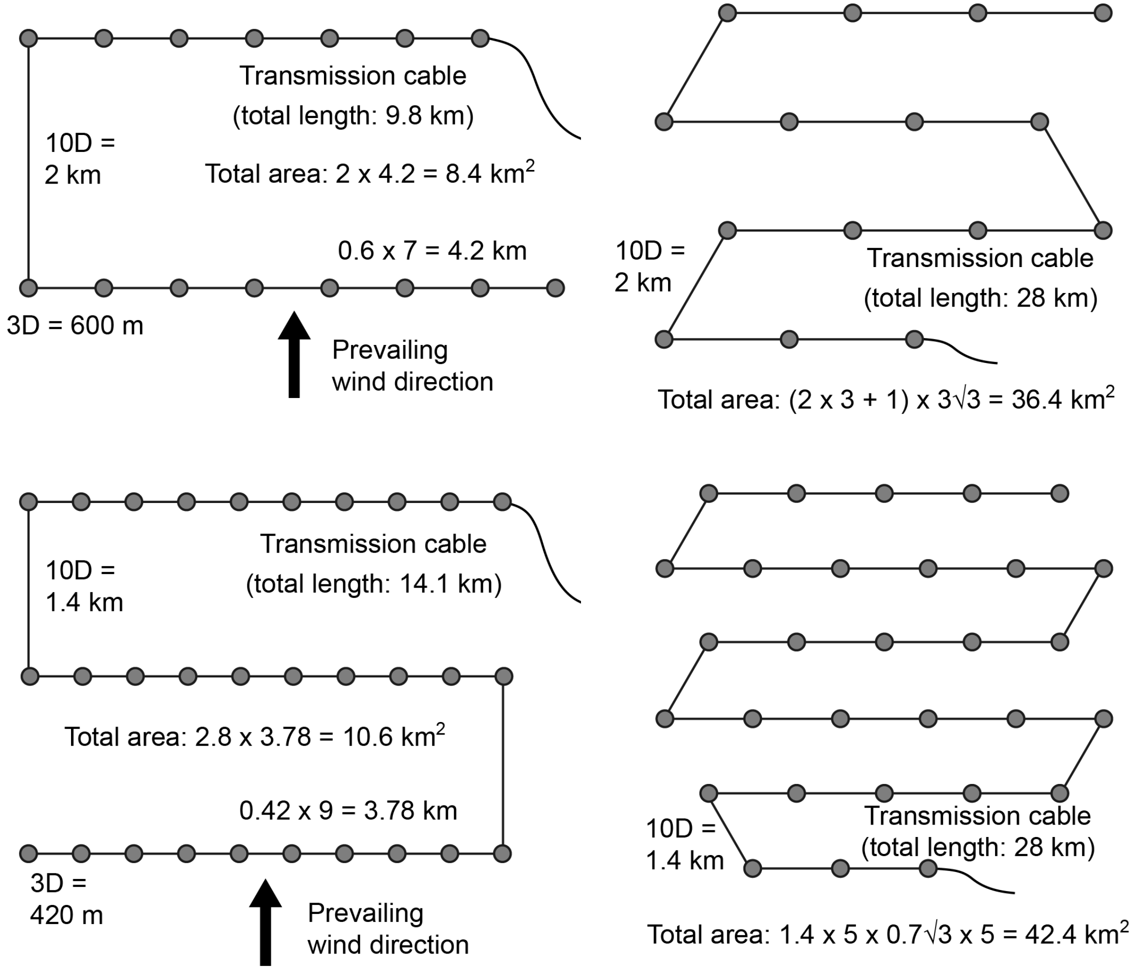
[Tsukamoto et al., report of the technical meeting of the institute of electrical engineers of Japan, ASC-10-028 (2010)]

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

15 x 10 MW wind turbines D = 200 m

30 x 5 MW wind turbines D = 140 m



Case with prevailing winds **Case without prevailing winds**

With or without prevailing winds, the 10 MW system has advantages !

Compared with the 5 MW system, 20% reduction of total area and 30% reduction of total length of transmission cables

Various drivetrains for wind turbines

Vestas, REpower

Conventional multistage gear

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

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

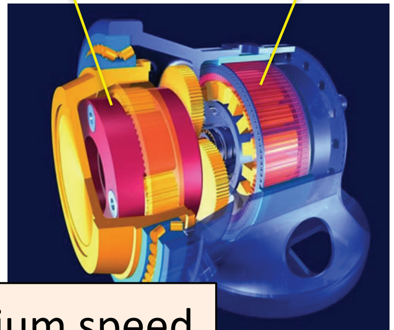
High speed

Beyond 6 MW ?
➔
Limitations of gear technologies

Yasukawa Electric, AREVA

1-stage gear and middle size generator

○: smaller gear loss
○: relatively smaller generator
×: less field-proven



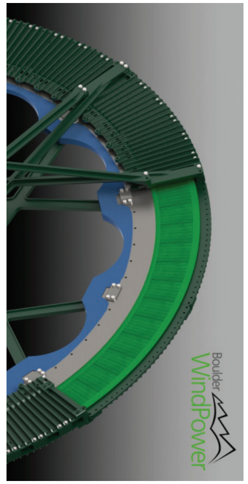
Medium speed

Siemens

Direct-drive (conventional generator)

Low speed

○: gearless
×: huge generator
×: rare earth problems
×: less field-proven

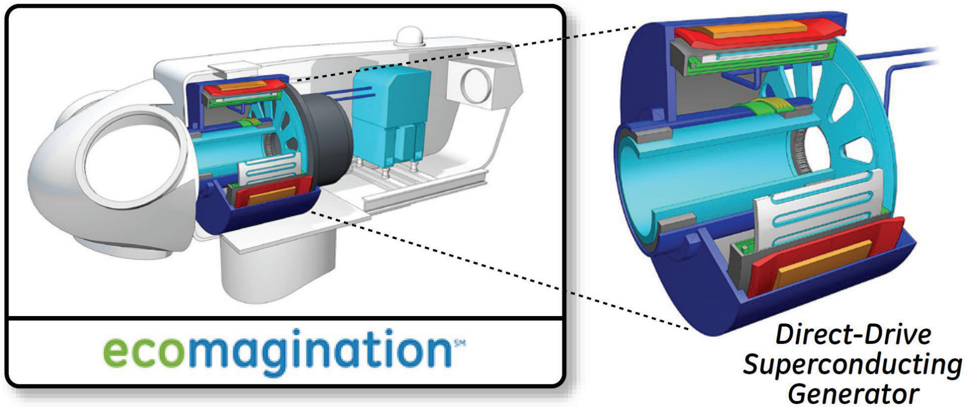


GE (USA), Suprapower (EU FP7)

Direct-drive, Superconducting generator

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

Low speed



Based on low-Tc superconducting wires (GE)

Comparison of reference wind turbines

weit WIND ENERGY INSTITUTE OF TOKYO INC.

		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

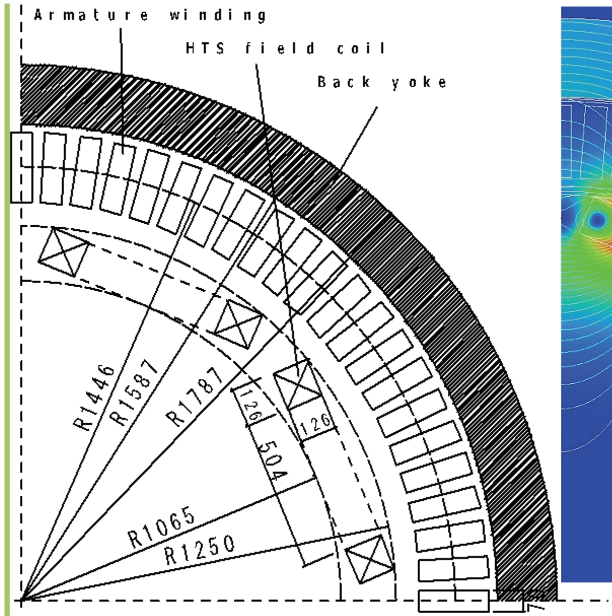
*The wind turbine class "T" for typhoon will be approved in the next version of the IEC standard 61400-1.

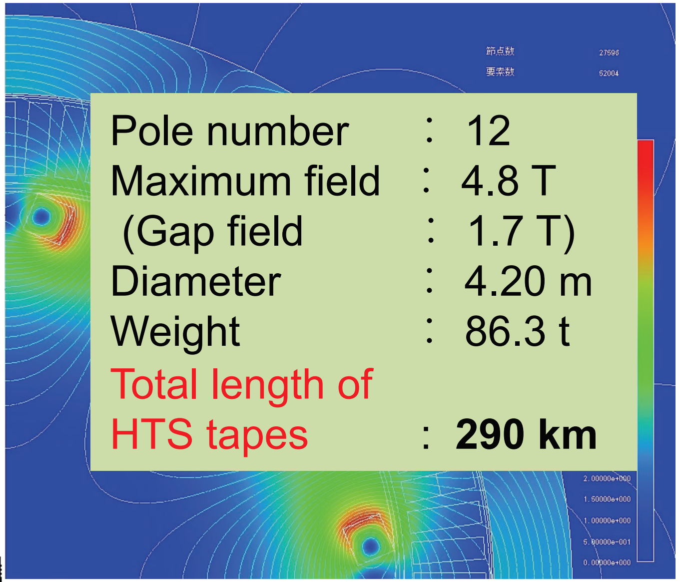
The project was commissioned by New Energy & Industrial Technology Development Organization (NEDO).

Trial design of 10 MW HTS generators

Assumed rotation speed: 10 rpm

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

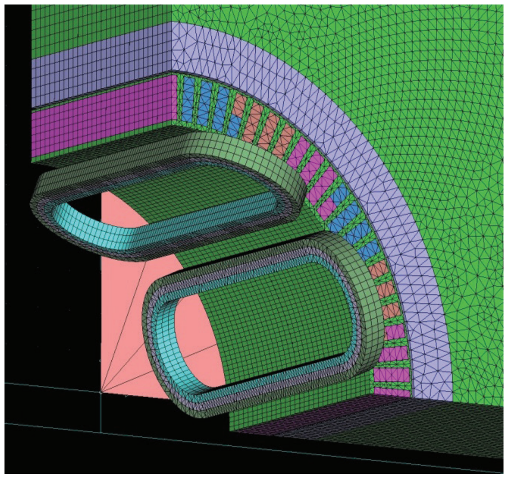




Pole number	12
Maximum field	4.8 T
(Gap field	1.7 T)
Diameter	4.20 m
Weight	86.3 t
Total length of HTS tapes	**290 km**

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) ∝ (Rotor diameter: D)^2, while
(Weight (cost) of turbine) ∝ D^3 ➔ (Cost) ∝ (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 billion yen × 2–2.8 = 0.32–0.45 billion yen

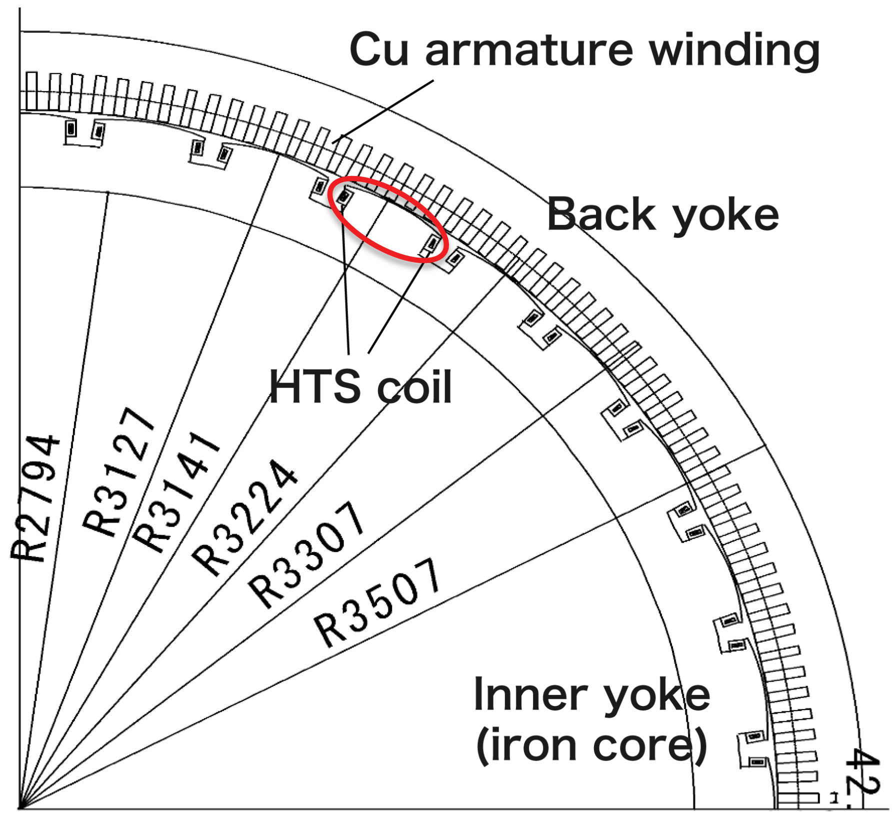
T1.4. Gearbox	
Function	The gearbox converts rotor torque at a speed of 5-15 rpm to a speed of up to around 1500rpm for efficient conversion to electrical energy by the generator.
Cost	A 5MW gearbox costs £700k to £1m. ~ 0.13 billion yen

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



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

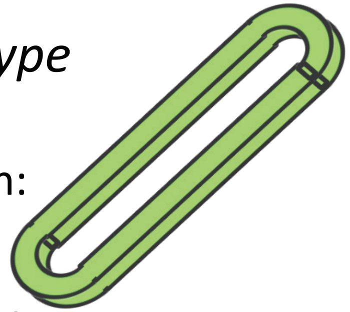
Total HTS wire length : 45 km

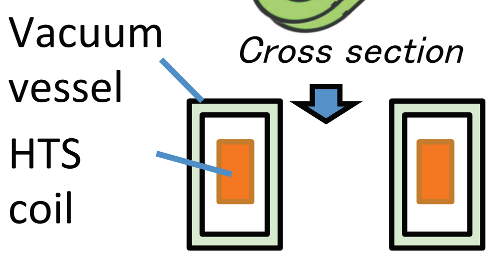
[S. Fukui: Teion Kogaku, **47**, 362 (2012)]

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)]

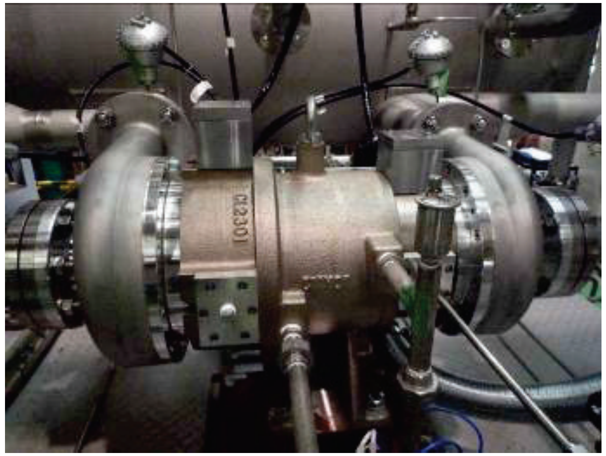
A racetrack-type coil module
(effective length: 1.5 m)



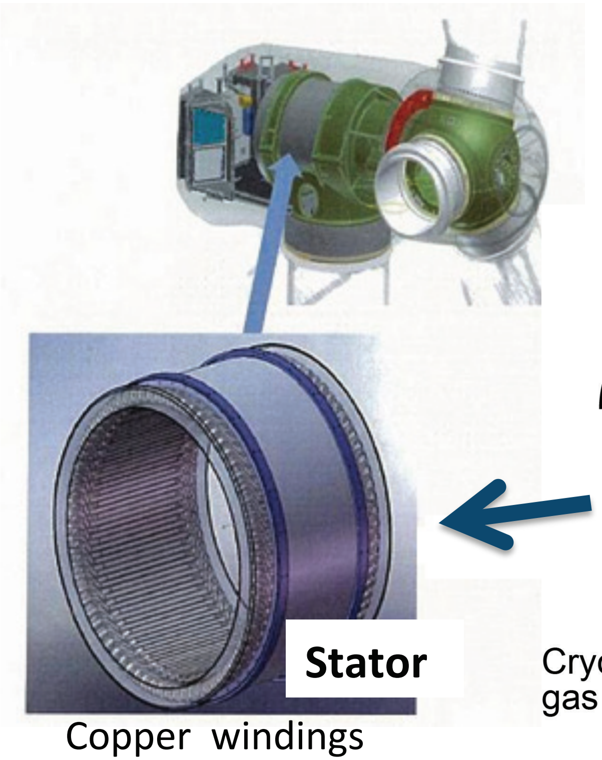


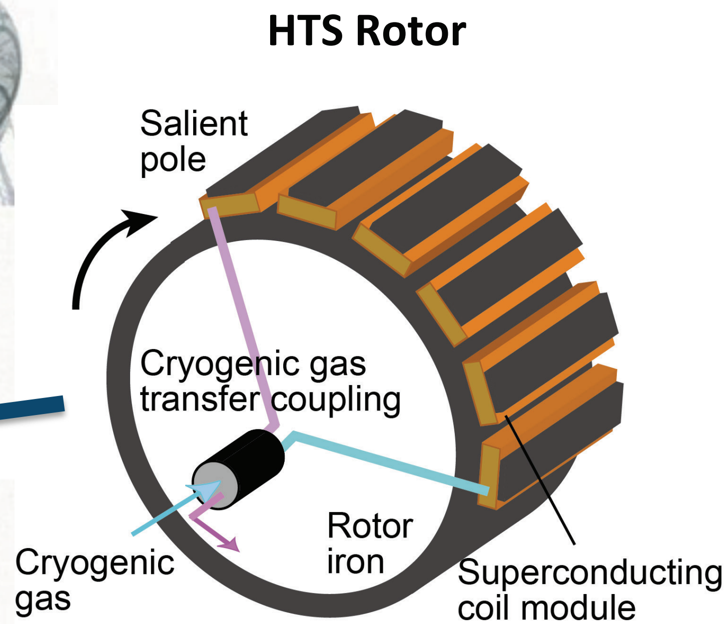
Key components of HTS generator to be developed

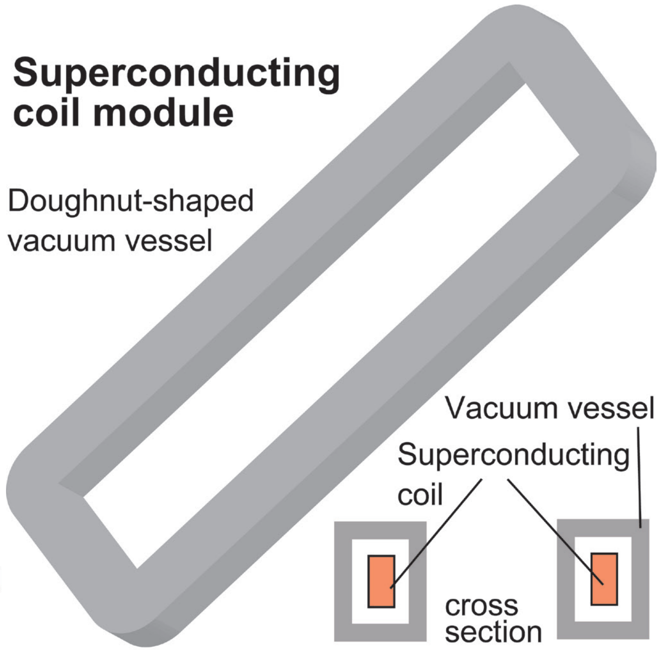
- HTS racetrack coil module
- Highly reliable refrigerator
- Cryogenic gas transfer coupling



Compressor for cryogenic gas
(turbo-Brayton refrigerator)







Modified design of an iron-cored generator

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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 (←36)
Rated voltage (phase-to-phase): 5 kV
Rated current : 1,155 A
Rotation speed : 10 rpm

Outer diameter : ~10.5 m (←7 m)

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

Length of HTS wire
1 pole of racetrack coil : ~546 m
(Coil effective length : 1 m (←1.5 m)
48 poles of coils : ~26.2 km (←~45 km)

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

Design of an HTS coil module

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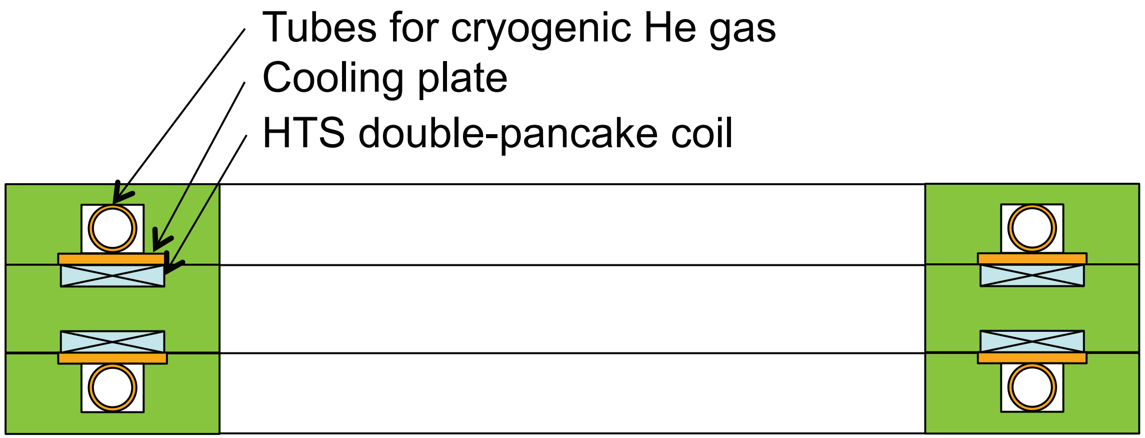
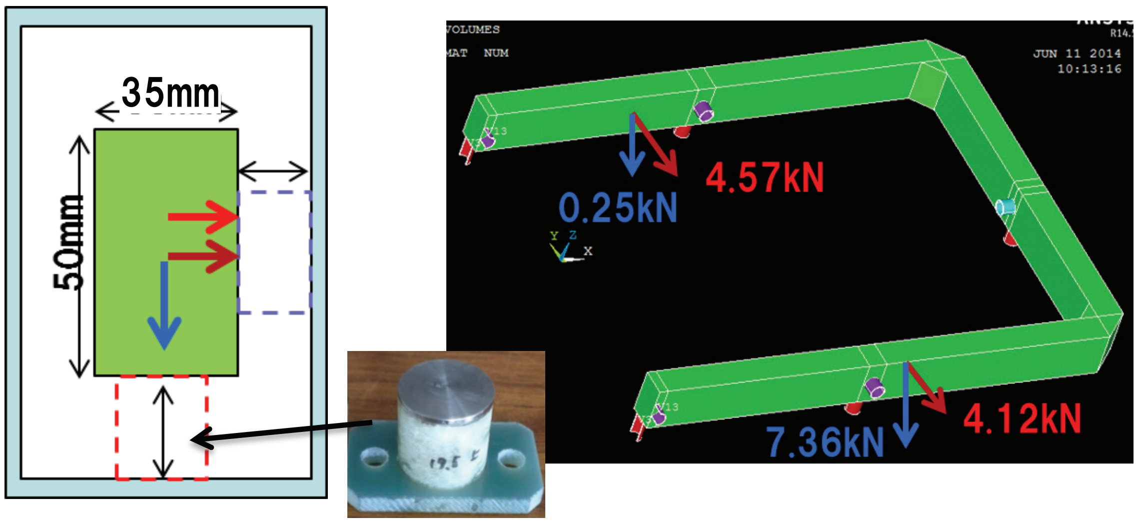
Coil structure

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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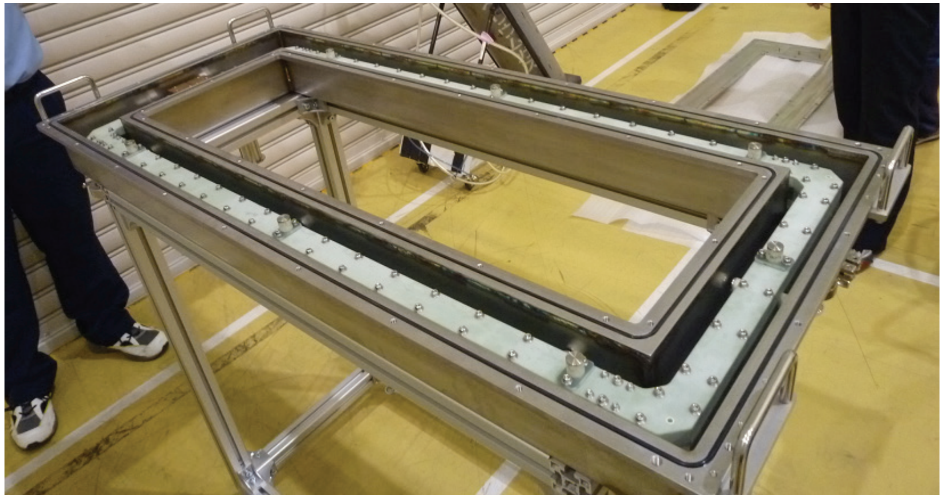
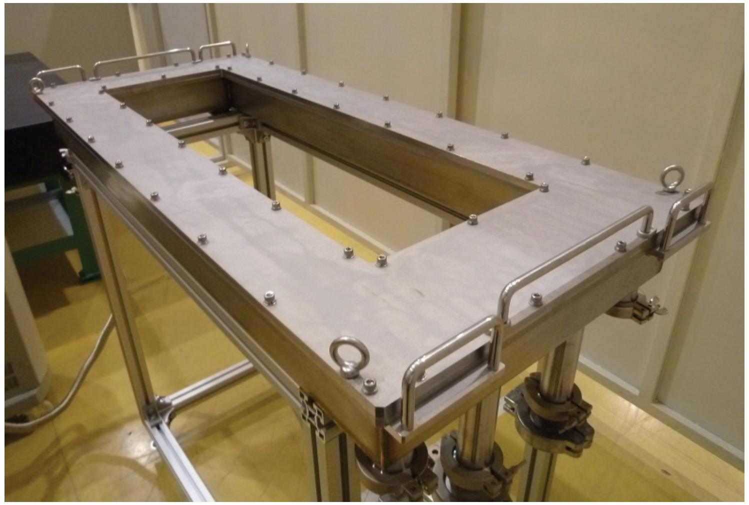
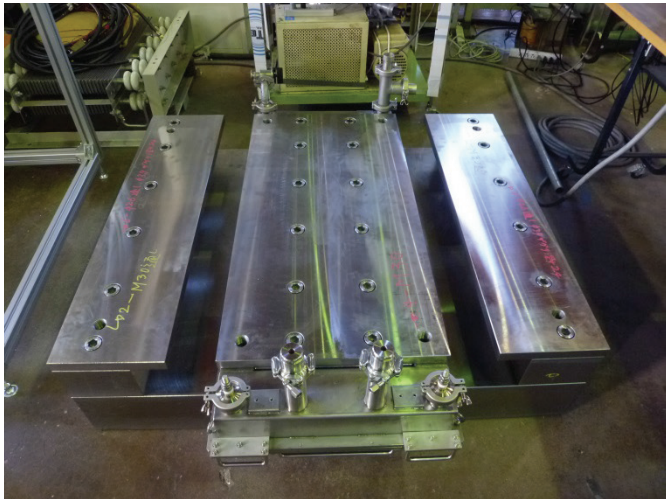


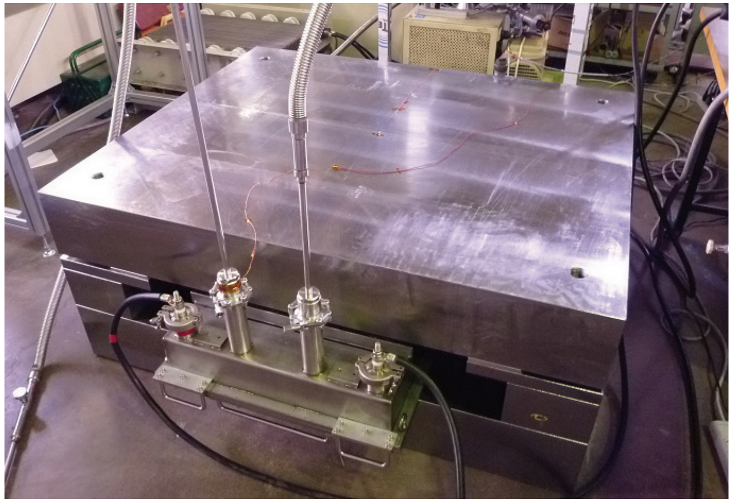
Racetrack coil placed inside of a cryostat



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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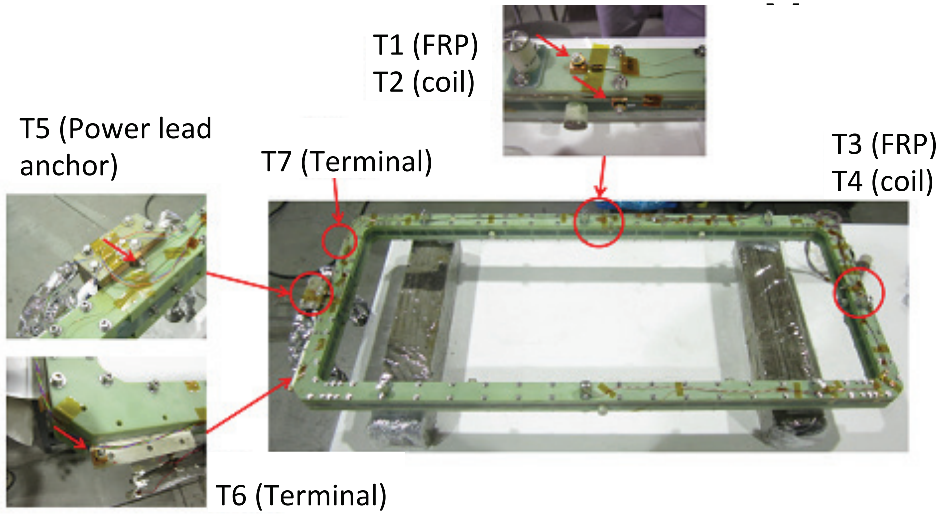
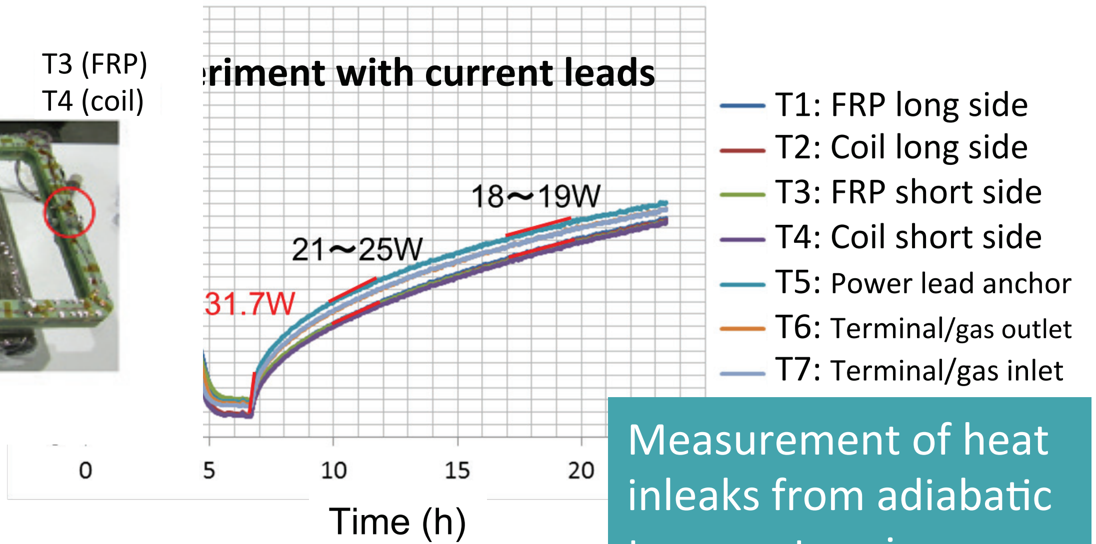


temperatures at various points in the coil



Measurement of heat inleaks from adiabatic temperature increase

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.

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

	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

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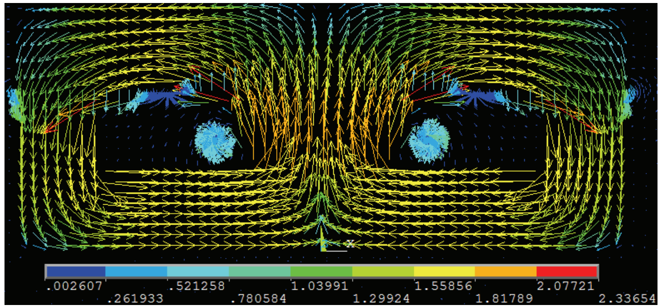
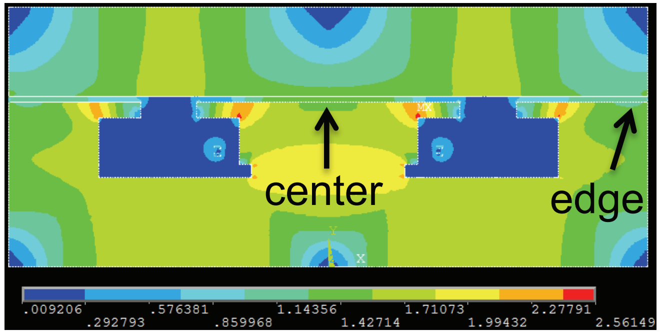
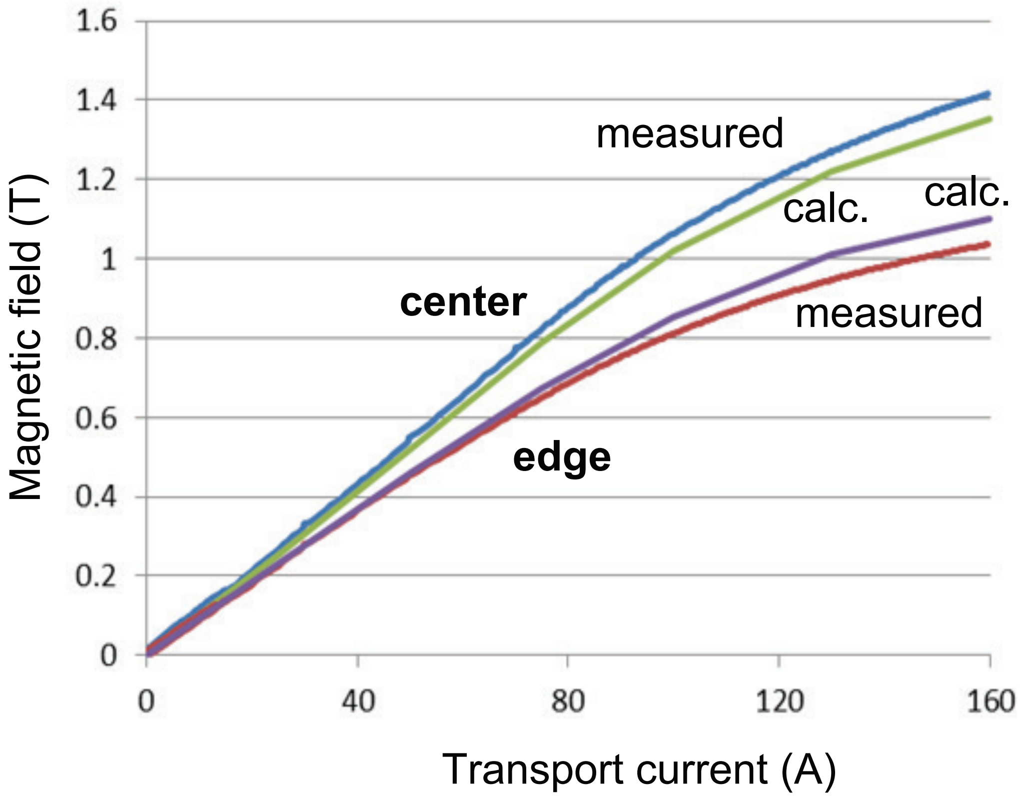


Vector figure of calculated magnetic fields



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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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)

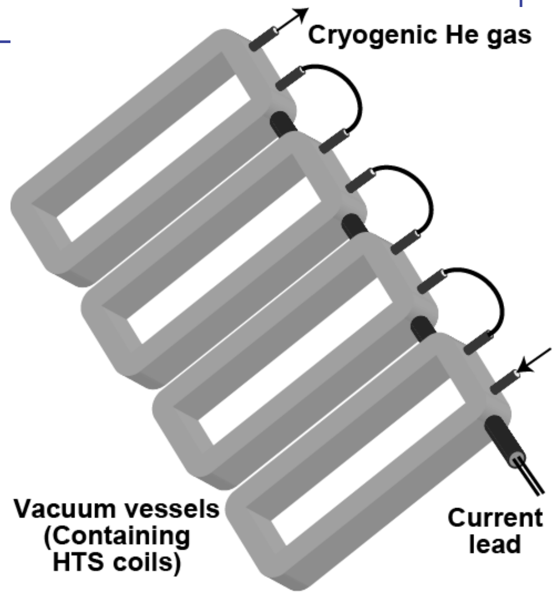
(2) Measure heat inleaks: supporting materials + TT + radiation + current leads
(31.7 W@30 K) measured with current leads connected
➔ (2) – (1) : (current leads: 12.6 W@30 K)

(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 × (1) + (12.6 + (3)) – 5 × TT = 76.4 W
Total heat inleaks (8 units) = 8 × 76.4 = 611.2 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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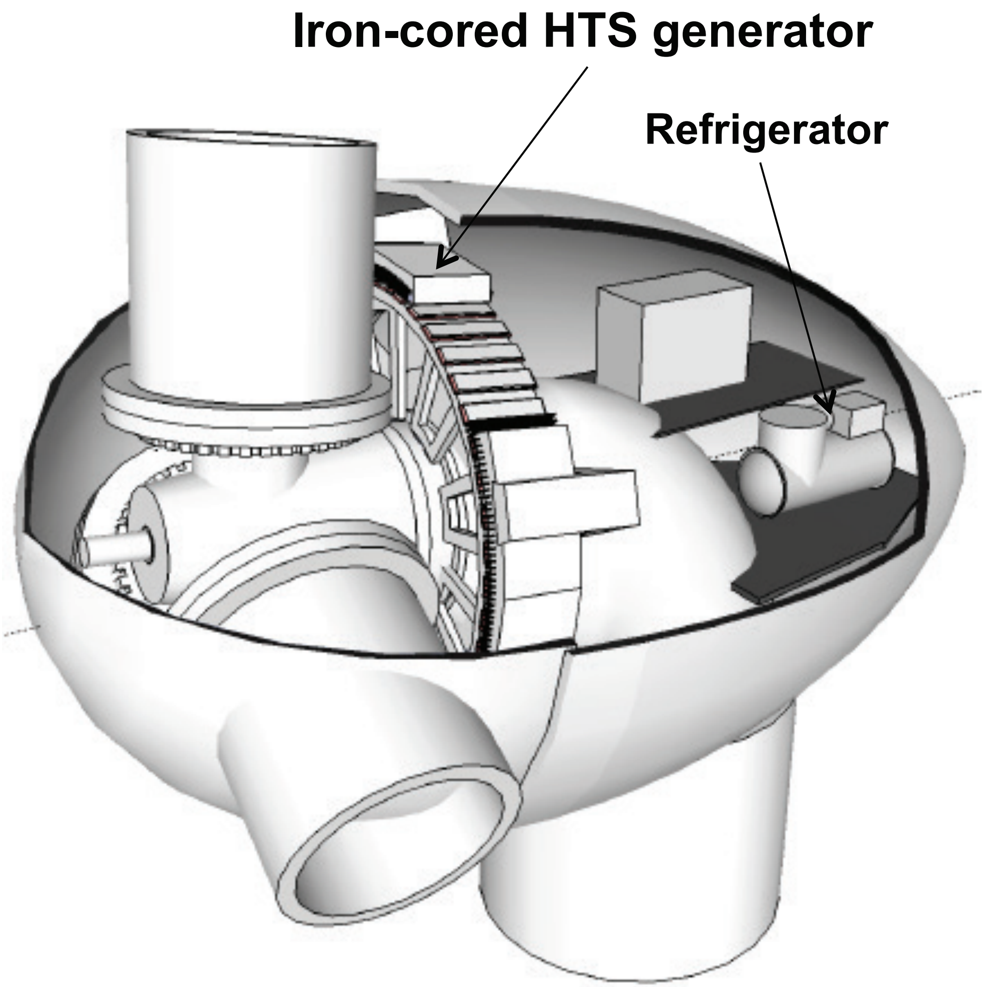


Electromagnetic design of ultra-light, air-cored HTS generator

↓

Total length of HTS wires: ≥290 km

↓

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

↓

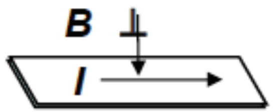
Demonstrated the validity of the HTS coil-module system with warm iron cores

[S. Mukoyama et al., "Development of HTS magnet on feasibility study for 10 MW class wind power generator", the 90th CSSJ Conference, Fukushima, Japan (2014)]

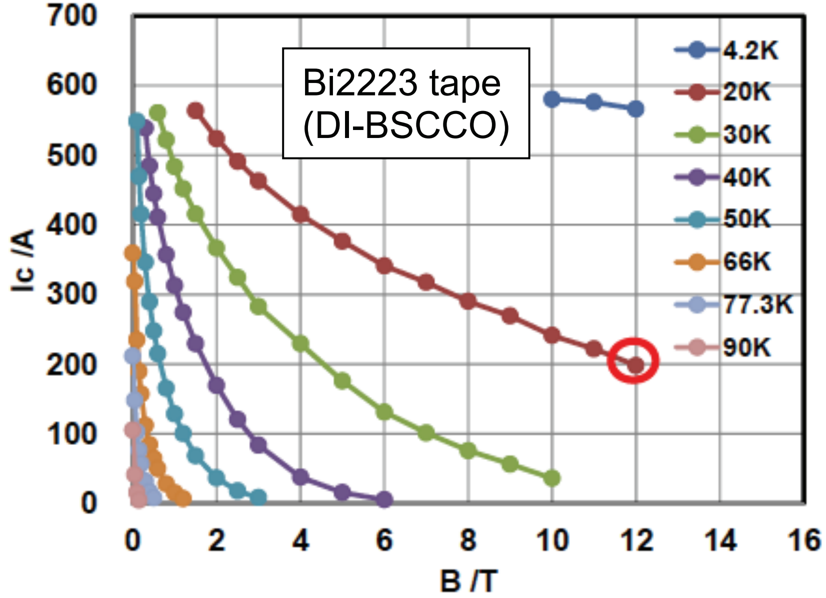
NEDO

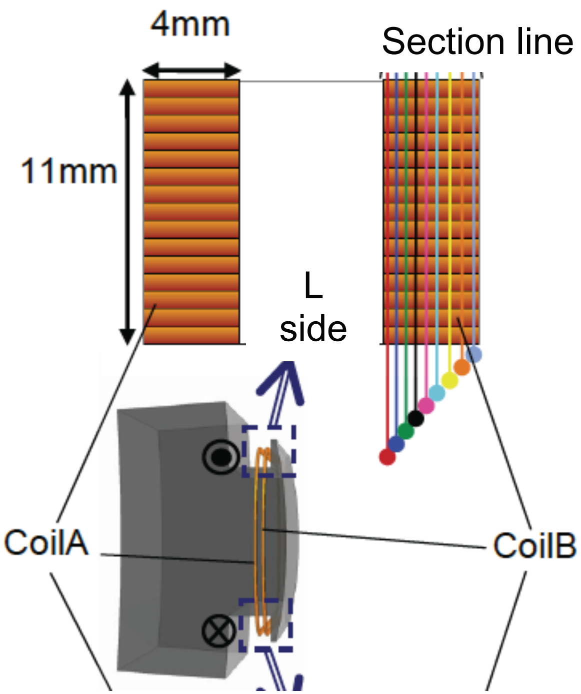
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2015.
Invited presentation M3OrD-02 given at CEC-ICMC 2015, Tucson, USA, June 28 – July 2, 2015.

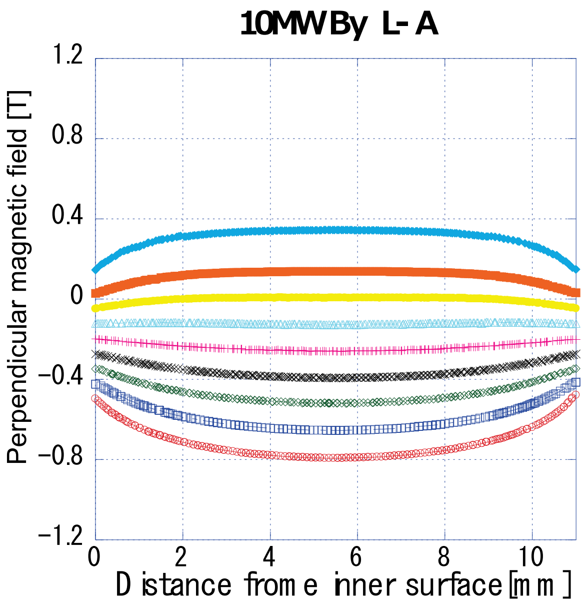
Selection of HTS wires

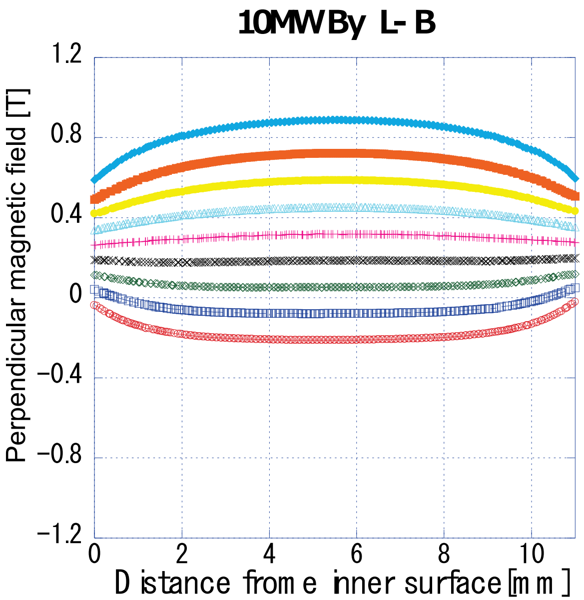


- Highest perpendicular magnetic field component applied to the tape was calculated as about 1 T
- YBCO: operation current I_{op} = 160 A is possible at 40–50 K.
- Bi2223: I_{op} = 160 A only at ~40 K.









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Invited presentation M3OrD-02 given at CEC-ICMC 2015, Tucson, USA, June 28 – July 2, 2015.

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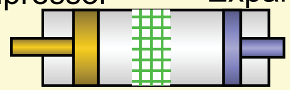
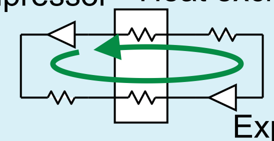
Refrigerator for superconducting machines

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 n-contact More than 10 r	 Compressor Heat exchanger Expander

GM type refrigerator in Suprapower project

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

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

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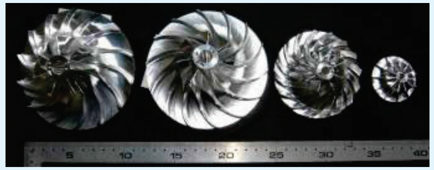
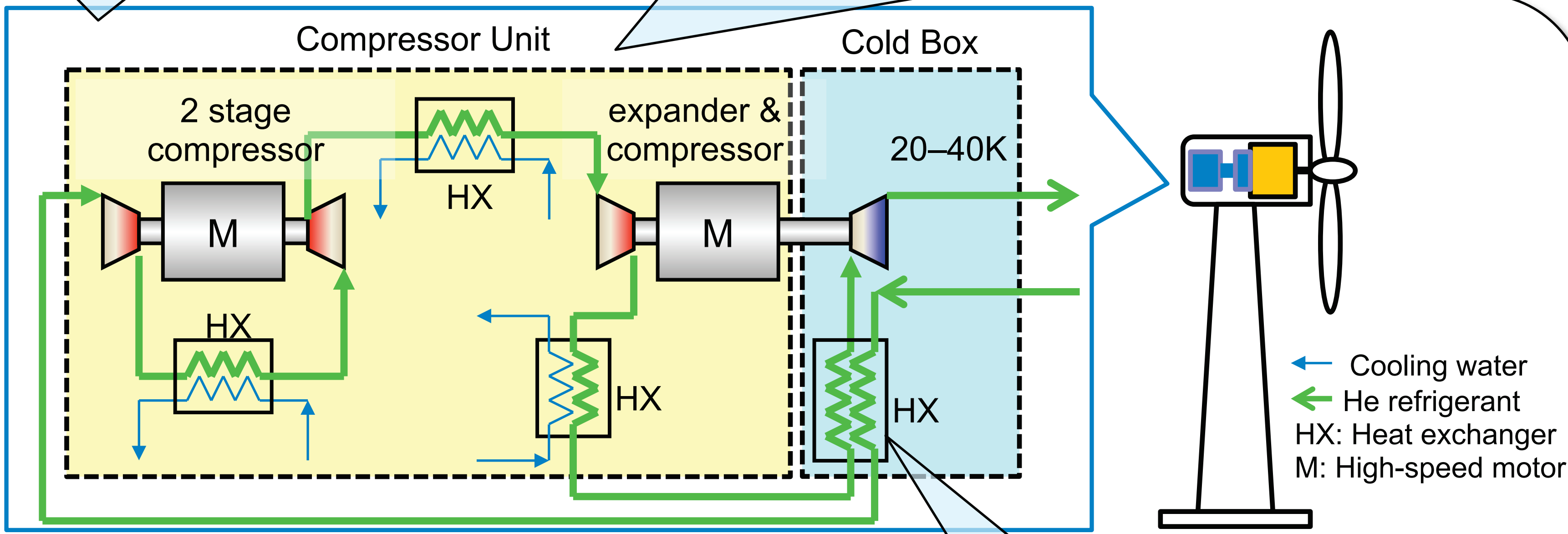
Development of a refrigerator for superconducting wind turbine generators

(1) System design
Refrigeration capacity: 1 kW
Temperature: 20–40K

(2) Compressor and expander design
(3) Characterization of high-speed motors
(4) Stability test for high-speed impellers
(Photo is the impeller for 5 kW@70 K Ne refrigerator)





Example of helium turbo-Brayton refrigerator

(6) Optimization for refrigerator
Evaluation of body size, efficiency, maintainability and economic efficiency by the optimization of (1)–(5)

(5) Compact and high-efficiency heat exchanger design

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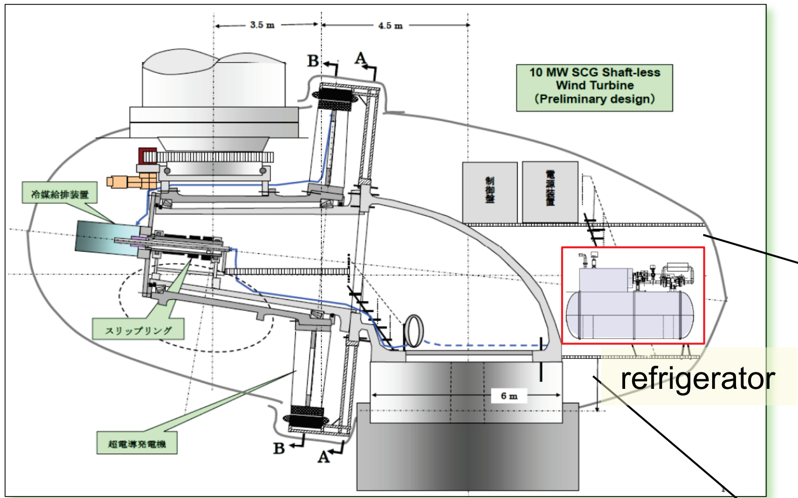
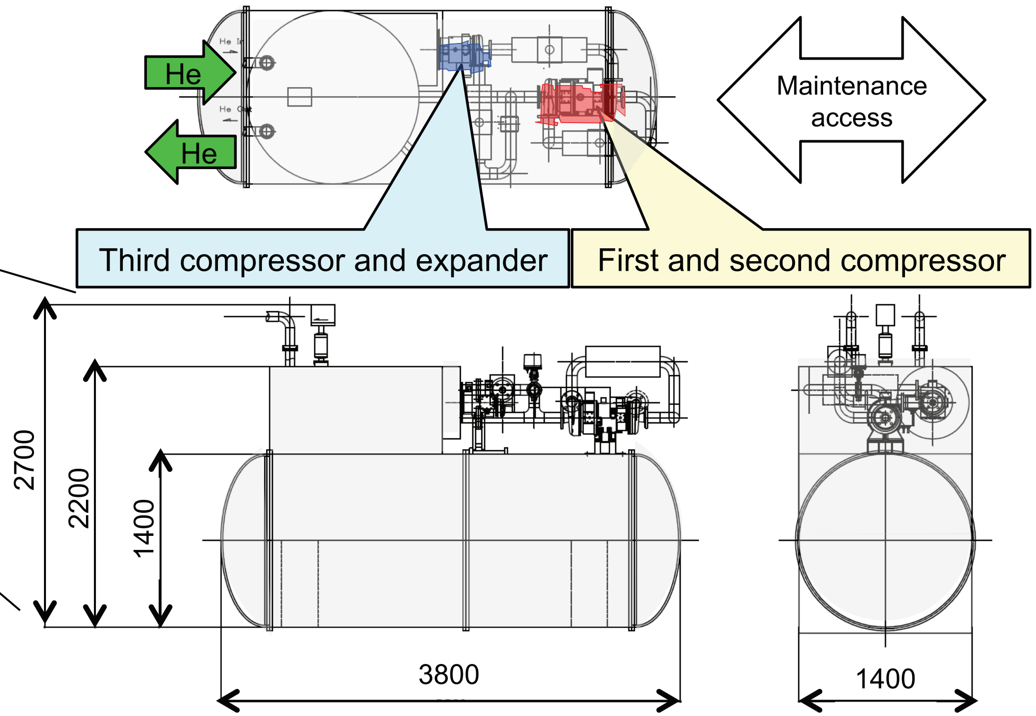
Design of a refrigerator for wind turbines

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



Conceptual placement in nacelle



Conceptual diagram of refrigerator

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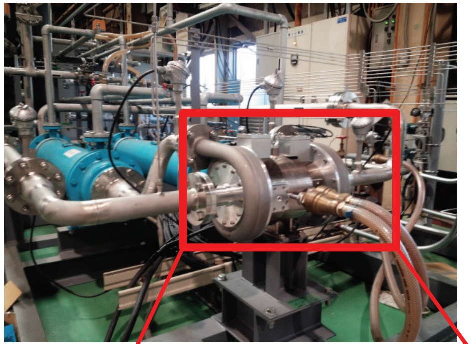
Test of rotating machines for compressor and expander units in a Brayton refrigerator

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)

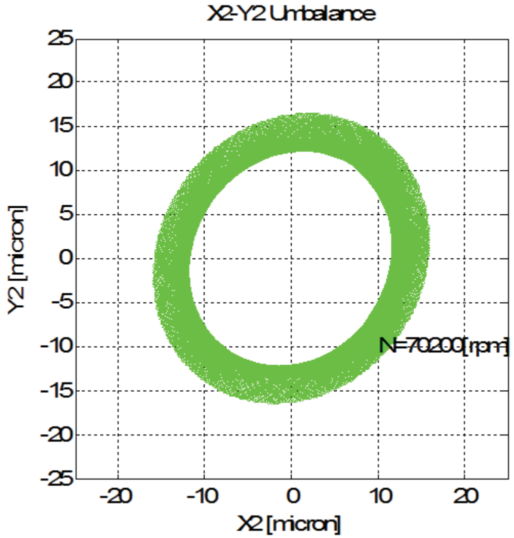
We have checked the status at the time of high-speed operation of rotating machines



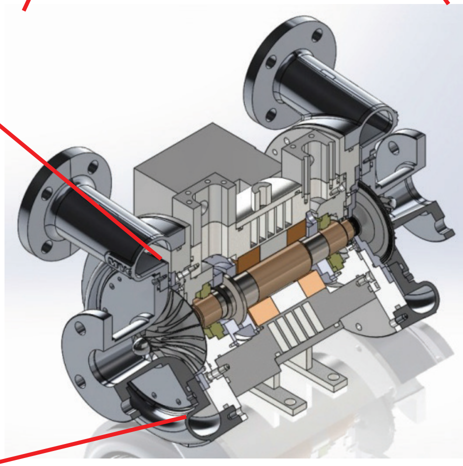
Test facility for the rotation test

	1st & 2nd compressor	3rd 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



3D model of 2 stage compressor unit

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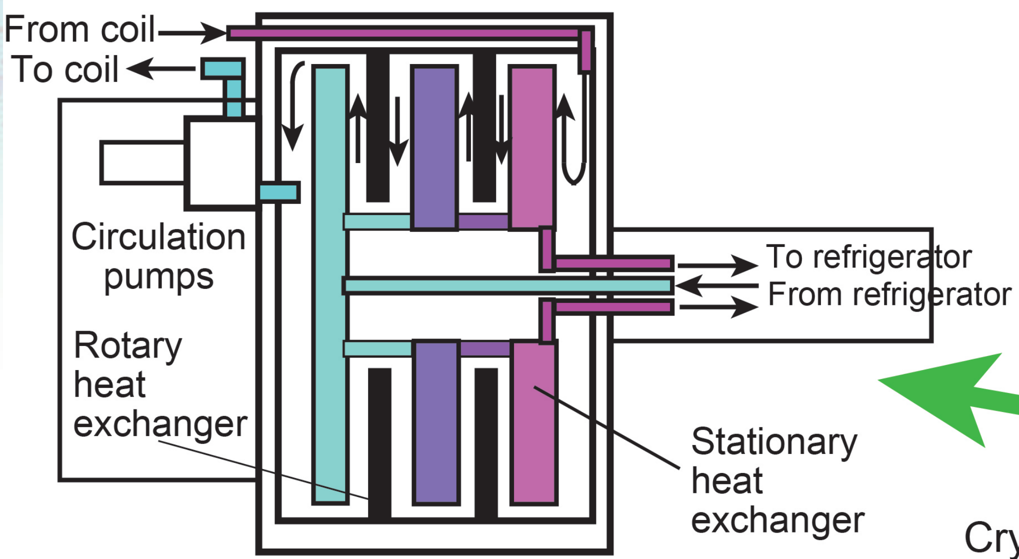
Cryogenic gas transfer coupling using circulation pumps

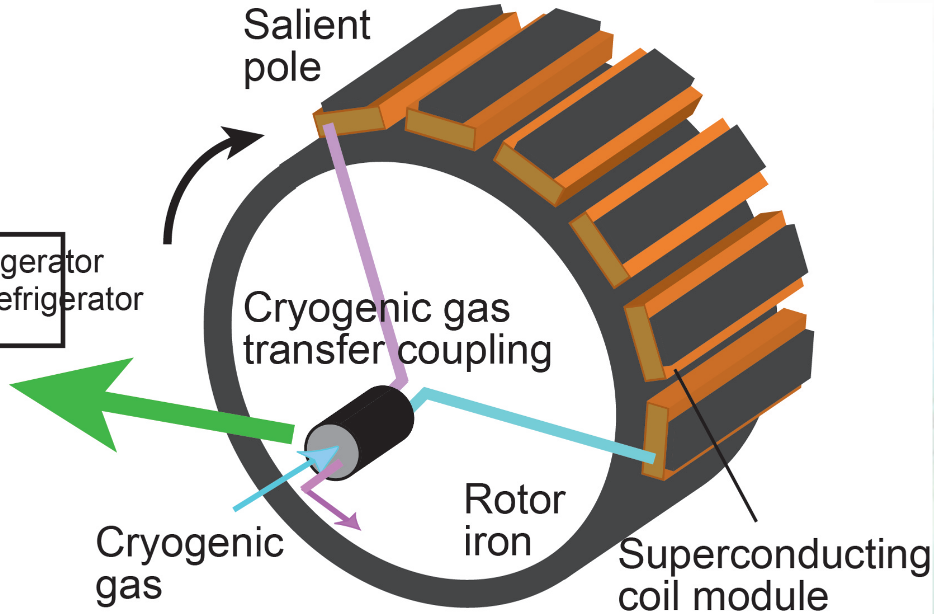
High-pressure cryogenic He gas (20–40 K) is used to cool HTS coil modules

➔ 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

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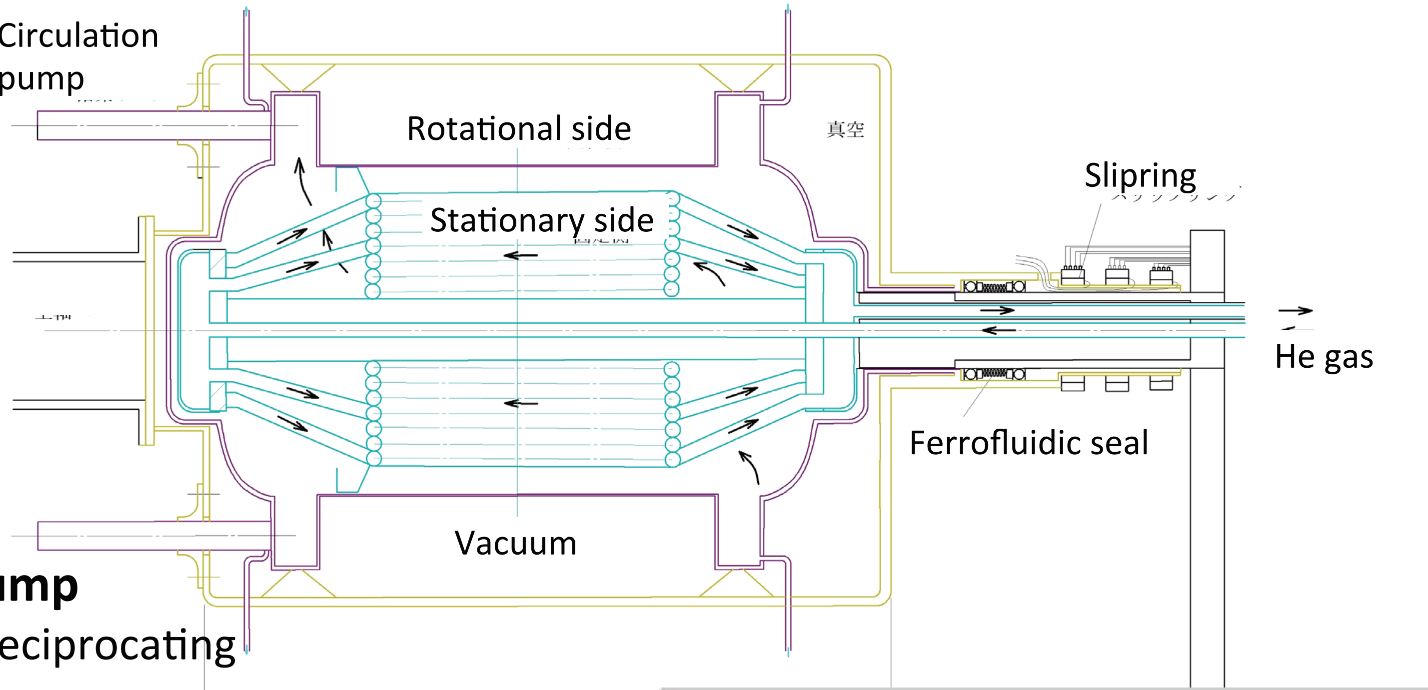
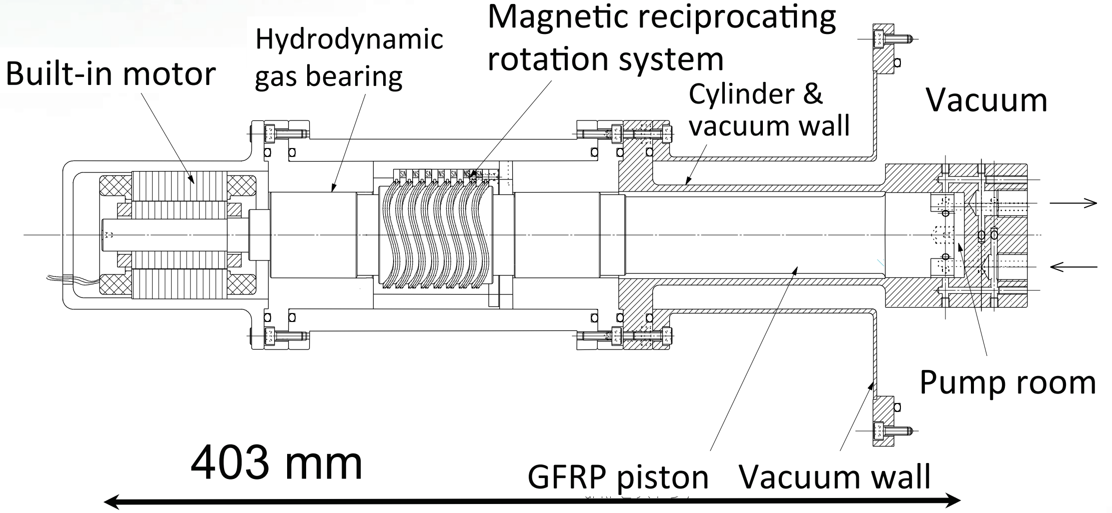
Heat exchangers and circulation pumps

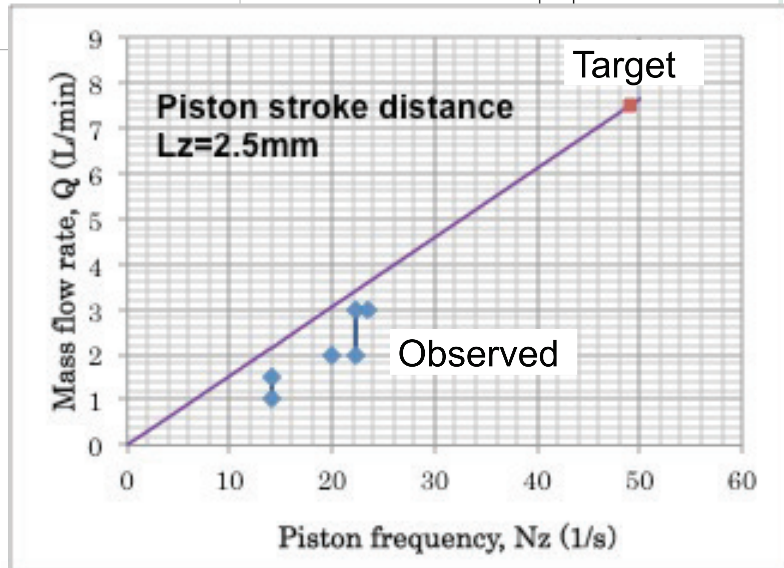
Concept design of a rotational-stationary heat exchanger



Tested circulation pump

rotation ➔ rotation + reciprocating movement ➔ gas flow





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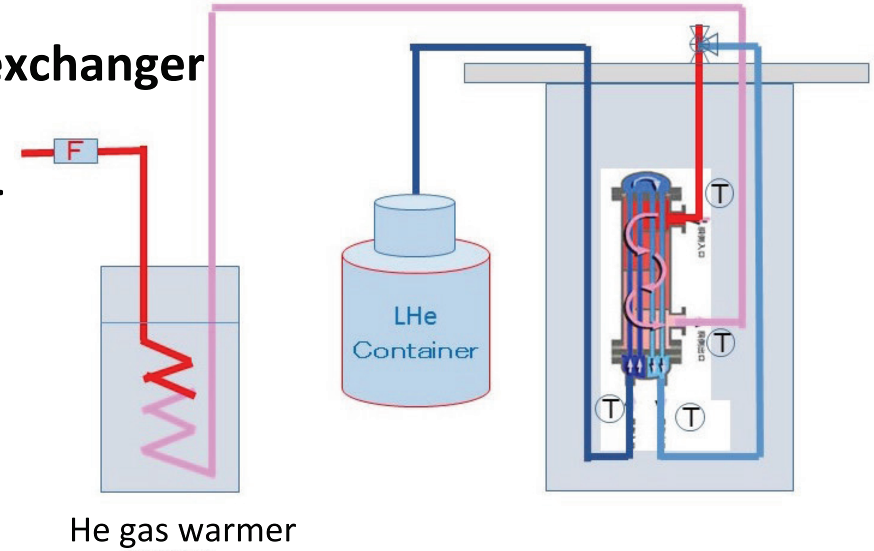
Low temperature tests of a heat exchanger and a circulation pump

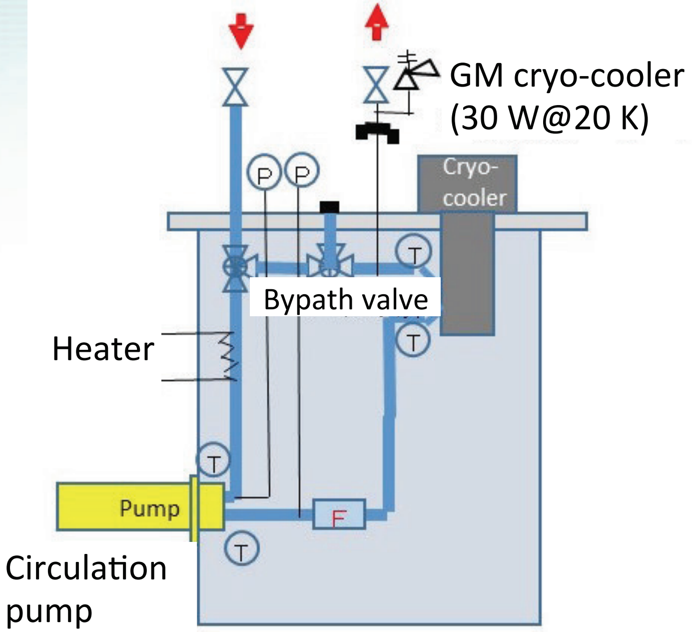
Cooling test of a modified shell & tube heat exchanger (model of a rotational-stationary heat exchanger)

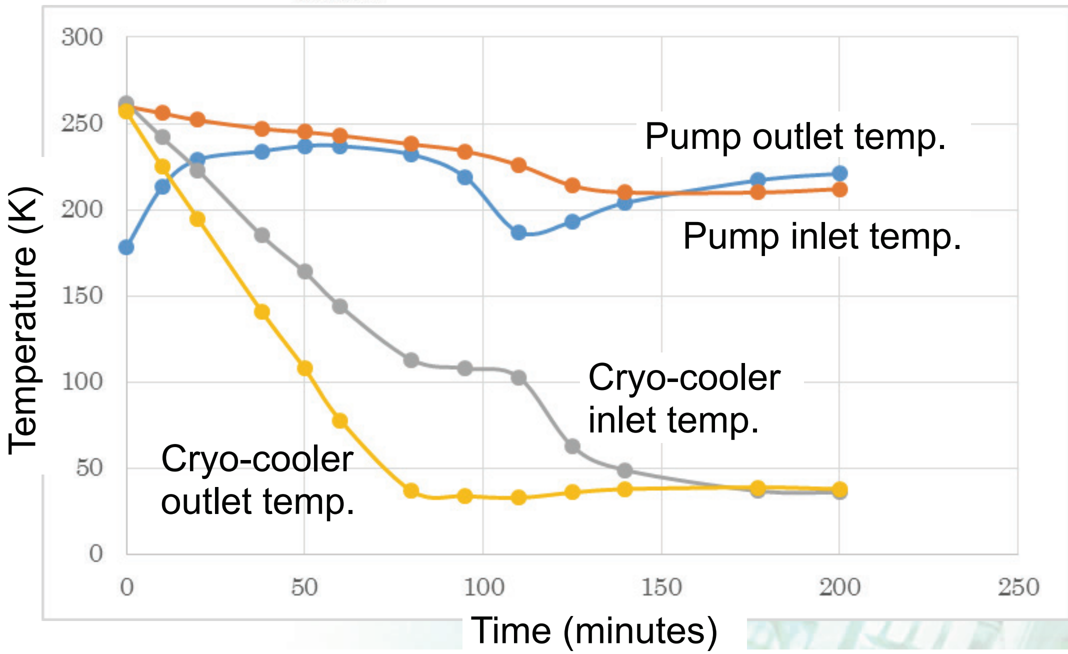
➔ Confirmed highly efficient heat exchange ability.



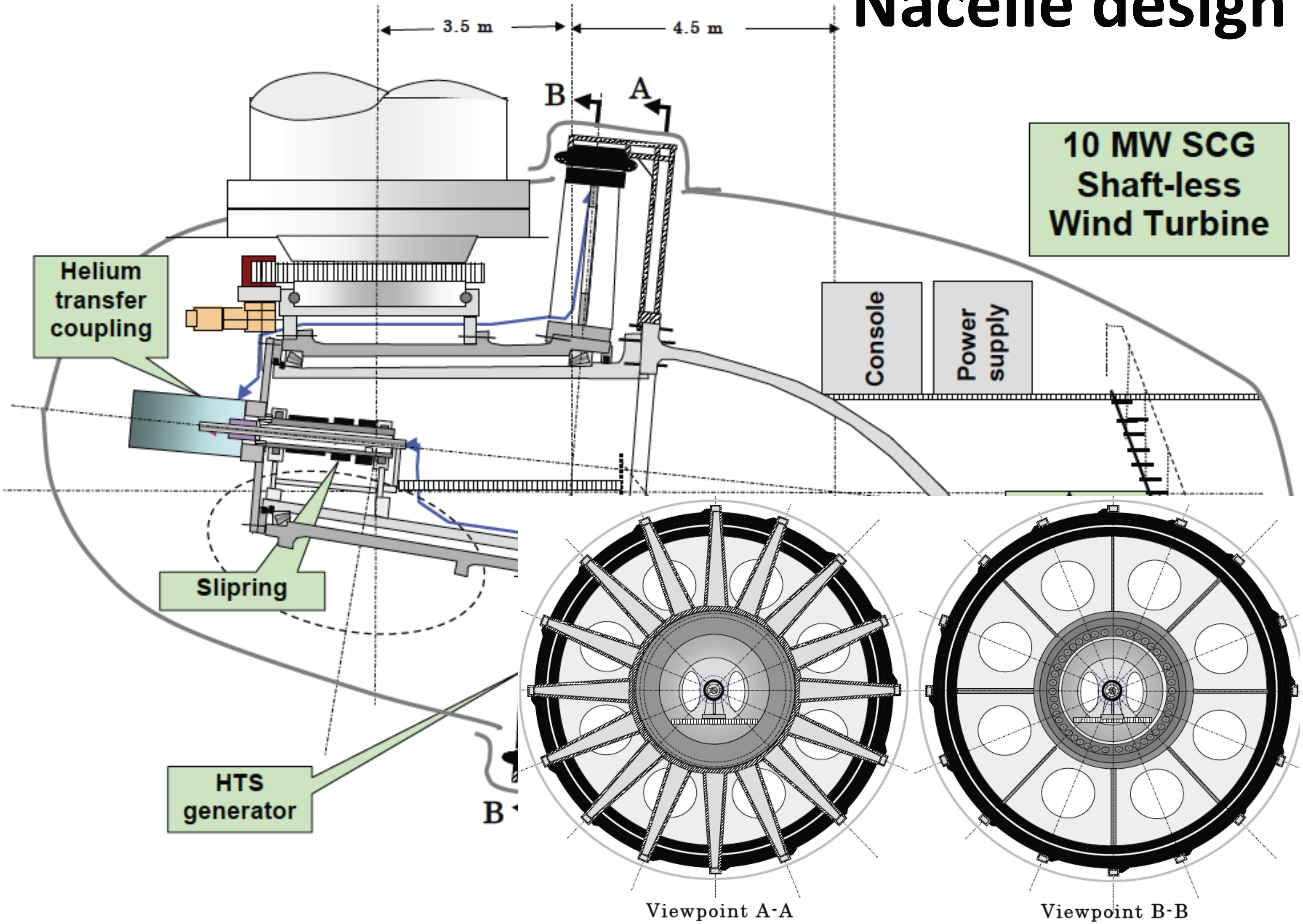
Low temperature test of a circulation pump

➔ Confirmed the gas flow at ~210 K, but the temperature did not decrease further due to the insufficient gas flow rate.



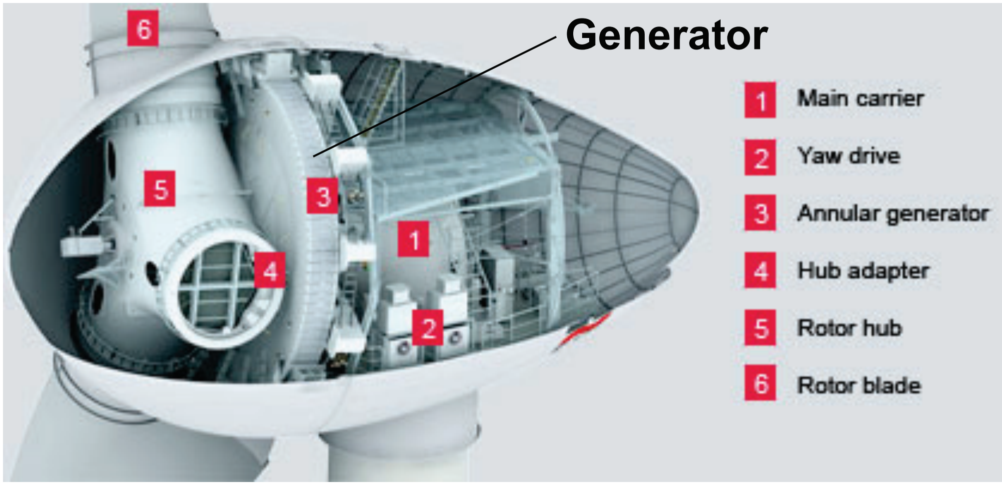


Nacelle design

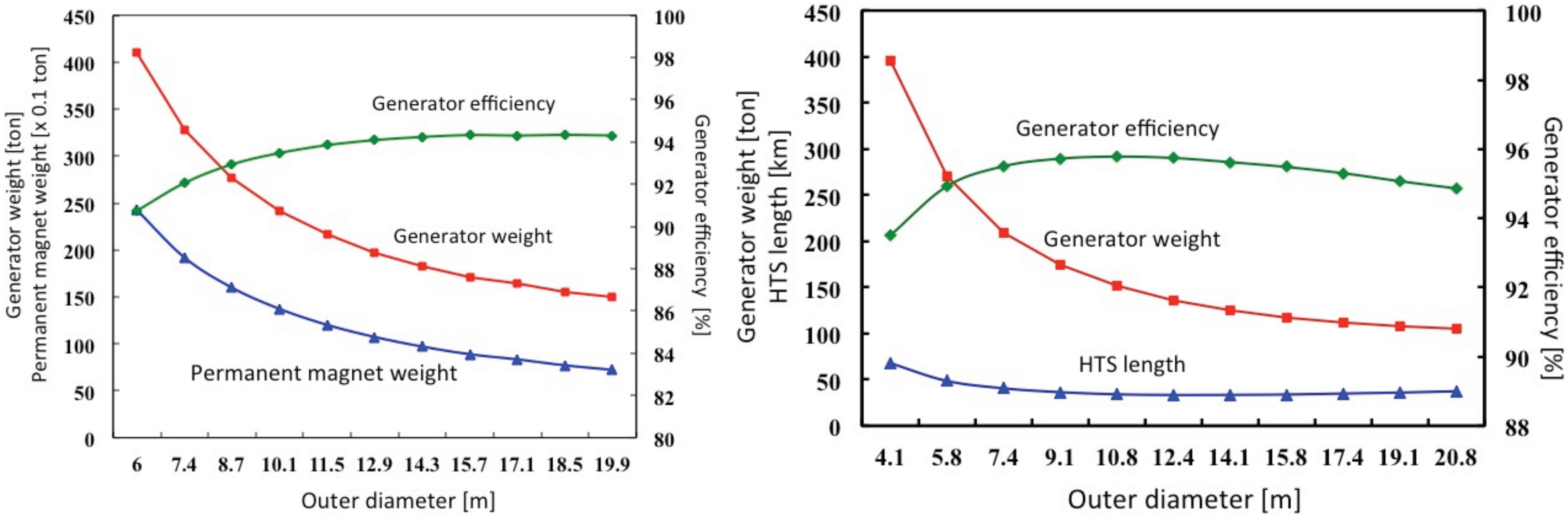


Design of large direct-drive wind turbine generators

- 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

Conclusions

- 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 (≥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.