Hardware integration and performance analysis of a 10 kW HTS wind power generator

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25th International Conference on Magnet Technology

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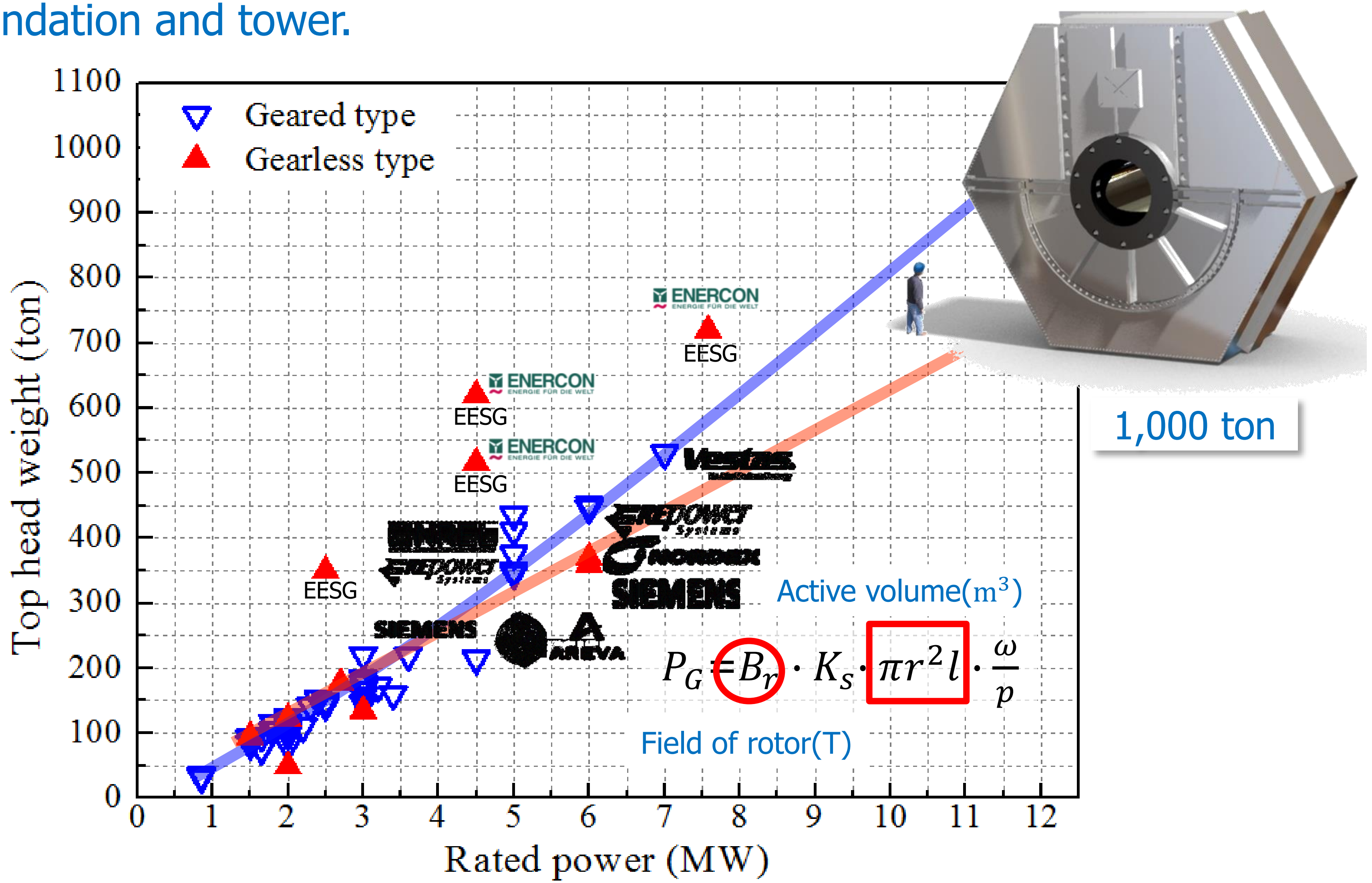
But, problem is the top head weight.

The heavy top head causes the high mechanical stress and high cost of foundation and tower.



The large-scale wind turbine using **HTS**

➢ Scale-up properties of WT

A scale factor, α, is defined as the ratio of the scaled blade length (L_1) to the nominal blade length (L_2):

$$\alpha = \frac{Scaled\ length}{Nominal\ length} = \frac{L_1}{L_2}$$

The total blade mass follows this relationship:

$$m_{up} = \alpha^3 m_{blade}$$

The rotor power:

$$P_{up} = \alpha^2 P$$

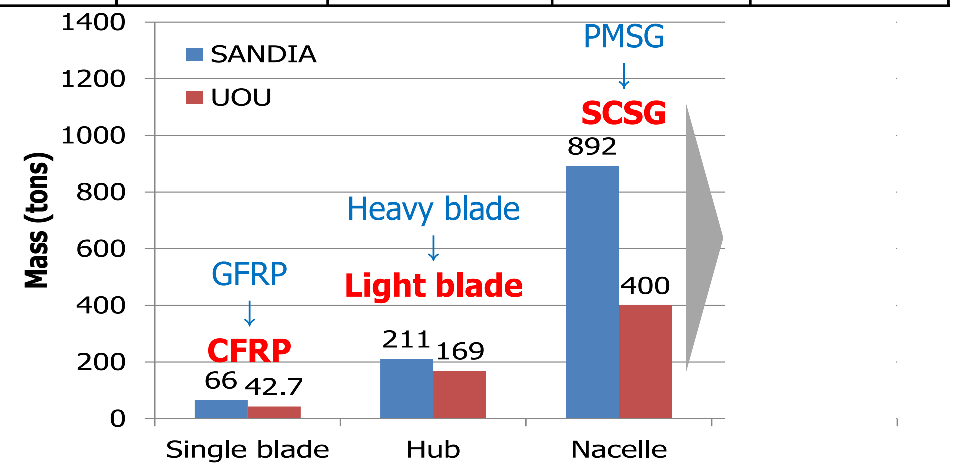
Cap.	Conventional scaling	HTS generator scaling			
	Top tower (tons)	Nacelle (tons)	Hub (tons)	Blade-CFRP (tons)	**Top tower (tons)**
12 MW	1,301	400	169	42.7	**697**

Ref. UOU, Development of 12MW FOWT core technology for commercialization

<Conventional WT> *Ref. SANDIA REPORT, June 2011* *(Criterion: 5MW)*

Capacity	Scale ratio (α)	Rotor diameter (m)	Blade length (m)	Blade mass (tons)
5 MW	1	126	61.5	18
10 MW	1.414	178.2	87.0	50
12 MW	**1.549**	**195.2**	**95.3**	**66**
13.2 MW	1.625	204.7	99.9	76
15 MW	1.732	218.2	106.5	92

Capacity	Scale ratio (α)	Top tower mass (tons)	Nacelle mass (tons)	Hub mass (tons)
5 MW	1	350	240	56.8
10 MW	1.414	990	679	161
12 MW	1.549	**1,301**	892	211
13.2 MW	1.625	1,501	1030	244
15 MW	1.732	1,819	1250	295



Project about 12 MW Floating Offshore Wind Turbine

➢ 12MW Superconducting generator

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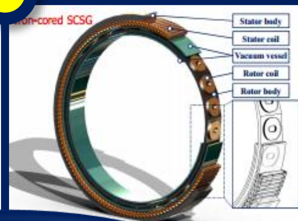
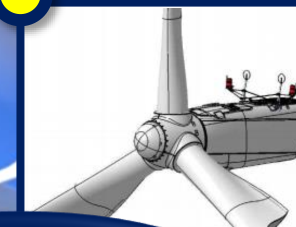
1st year — **2nd year** — **3rd year**





Design of a 12 MW wind turbine

- Conceptual design of a 12 MW HTS generator
- 12 MW wind turbine output power considering efficiency

10 kW HTS generator manufacturing & testing

- HTS coil inductance
- HTS coil magnetic field
- HTS generator performance

Detail design of a 12 MW wind turbine with cooling system

- Magnetic and mechanical design of the generator
- Cooling system design in detail
- Standard regulation for wind turbine

Year	Appraisal
1st yr. Design of a 12 MW wind turbine	Confirm 12 MW wind turbine output power with the HTS generator
2nd yr. An HTS pole manufacturing for the HTS generator	HTS one pole coil test in liquid nitrogen based on design results of the 12 MW HTS generator (<10% error of simulation result)
3rd yr. Detail design of a 12 MW wind turbine with cooling system	Validity and review of the 12 MW wind turbine detail design using 3D CATIA program from related experts

Contents

Fundamental design of the 10 kW HTS generator

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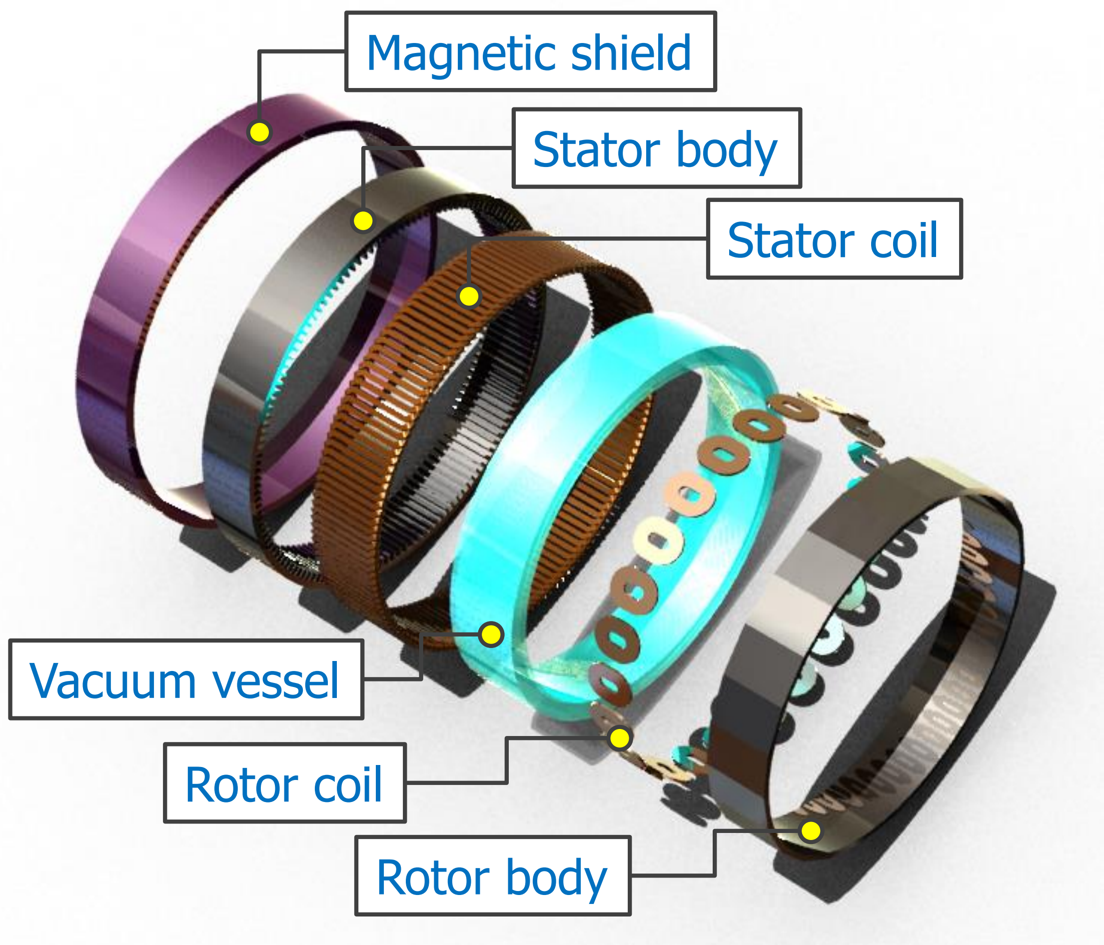
➢Fundamental specifications of the SCSG

Items	Value
Rated power	10.3 kW
Rated L-L voltage	380 V
Rated armature current	15.65 A
Rated rotating speed	400 RPM
Rated torque	246 N·m
The length of air gap	20 mm
Thickness of vacuum vessel	7 mm
Current density of copper wire	3 A/mm^2
Safety margin of operating current	40%
Width of the SC wire	4 mm
Thickness of the SC wire	0.16 mm

- Double Pancake Coil (DPC)

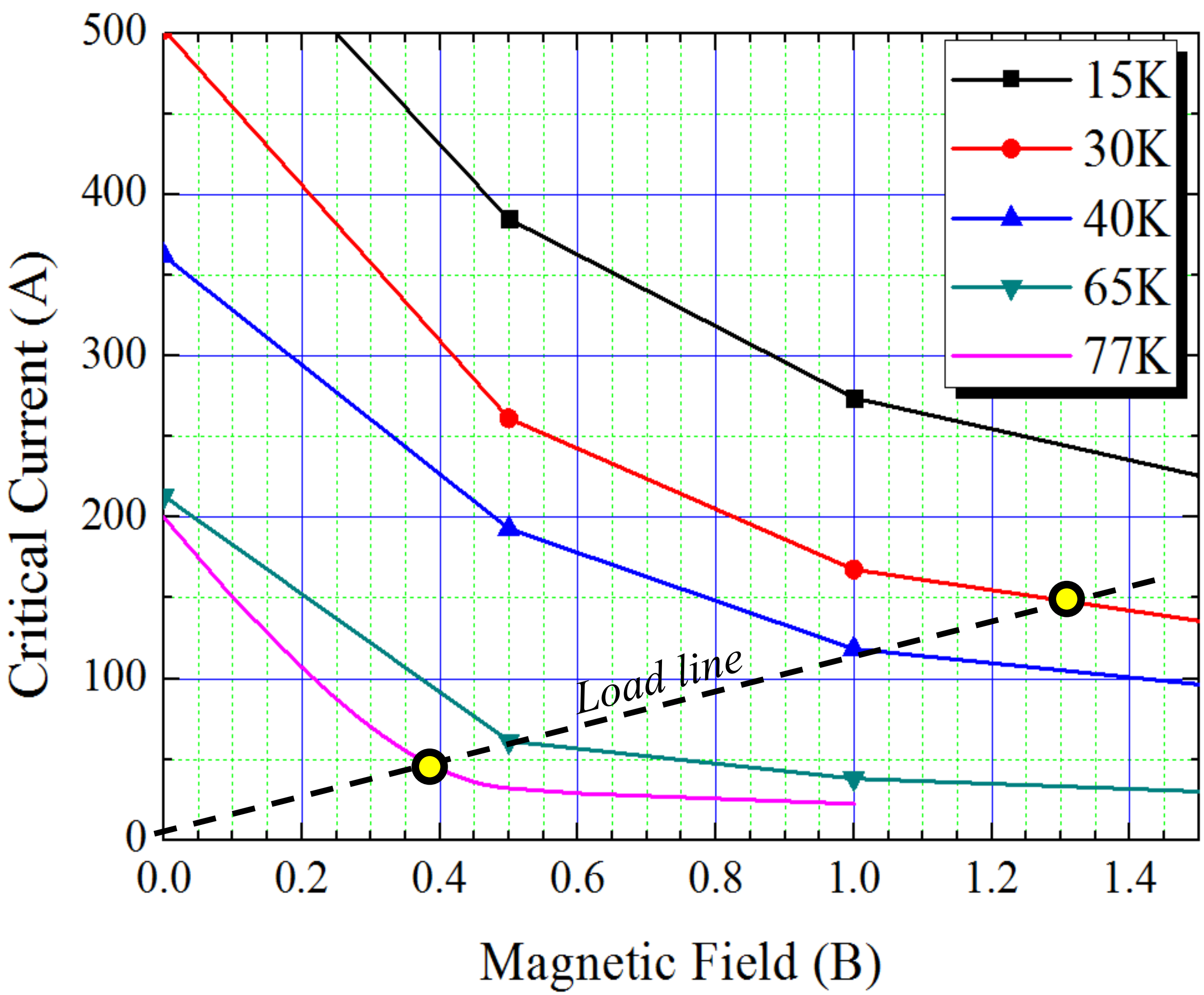


< Configuration of the superconducting generator>

Fundamental design of the 10 kW HTS generator

➢Properties of the superconducting wire

Property	Ref.
Type	(Gd/Y)BCO
Thickness	0.16 mm
Width	4 mm
Min. RT bend diameter	11 mm
Max. RT rated tensile stress	550 Mpa
Critical current (self field, 77 K)	200 A
Operating temperature	30 K



Specifications of 10 kW HTS generator

Parts		Value
HTS coil	Rotational speed	400 rpm
	Temperature	30 K
	Insulation thickness of coil layers	1 mm
	Width of coil bobbin	28 mm
	Total width of HTS coil	98.5 mm
	Effective length of HTS coil	174 mm
	Turns of HTS coil/layer/pole	225
	Operating current	90 A
	Margin of field current	40%
	Num. of poles	6
	No. of HTS coil layers/pole	4
	Total length of HTS wire	3.1 km
Results	Inductance	0.88 H
	Total diameter	476 mm
	Frequency	15 Hz
	Maximum magnetic field	2.6 T
	Perpendicular magnetic field	1.1 T

◀ Detail specifications of the generator

▼ Materials of the generator

Parts		Value
Rotor part	Bobbin of HTS field coil	Aluminum
	Rotor body	Aluminum
	Cryostat	Stainless steel
Stator part	Stator coil	Copper
	Bobbin stator coil	GFRP
	Magnetic shield	M-27 24 Ga

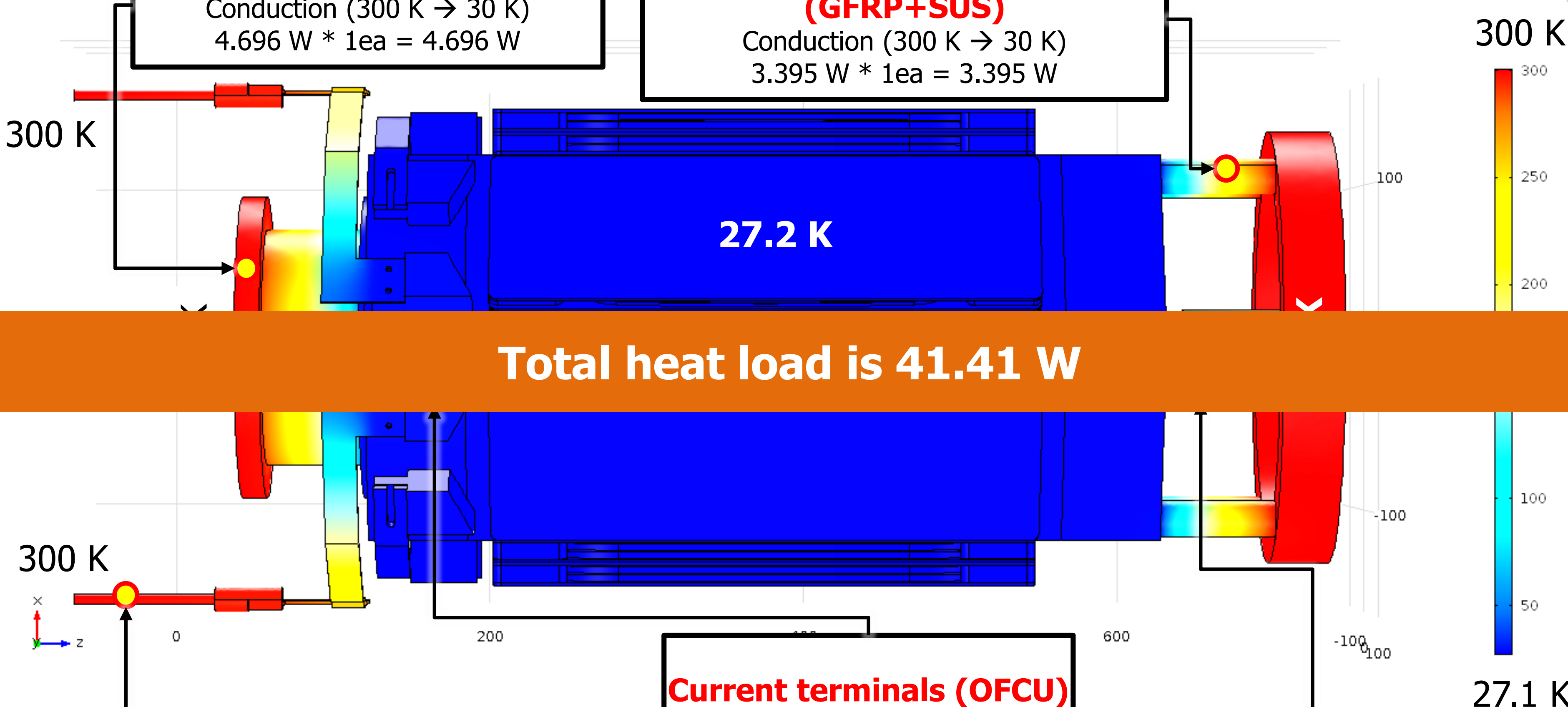
Thermal analysis results

➢Thermal distribution result of the rotor part

Radiation heat load
7.3 W

Torque tube (GFRP)
Conduction (300 K → 30 K)
4.696 W * 1ea = 4.696 W

Torque sticks & supporter (GFRP+SUS)
Conduction (300 K → 30 K)
3.395 W * 1ea = 3.395 W



Total heat load is 41.41 W

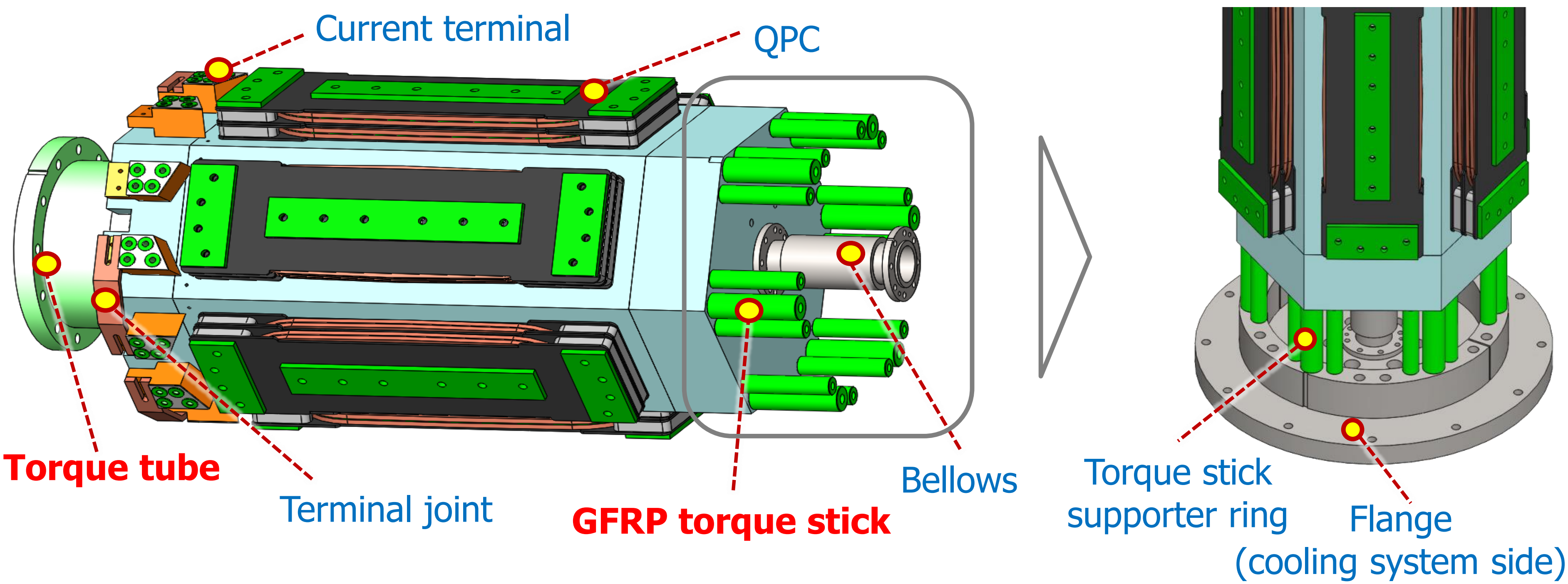
Current lead (Brass)
Joule' heat & Conduction
(300 K → 30 K)
9.9 W

Current terminals (OFCU)
Joule' heat (95 A)
0.01 W * 12ea = 0.12 W
Field coil joint
0.1 W * 12 = 1.2 W

Neon gas bellows (SUS)
Conduction (300 K → 30 K)
14.81 W * 1ea = 14.81 W

Mechanical analysis results

➢Torque tube and torque sticks



❖ Thermal insulation and Torque transmission

- Shaft generates a very large thermal gradient.
- GFRP torque tube and sticks are required to transfer torque to the shaft at room temperature.

➔ When designing the torque tube or sticks there is always a trade off between structural and thermal.

Mechanical analysis results

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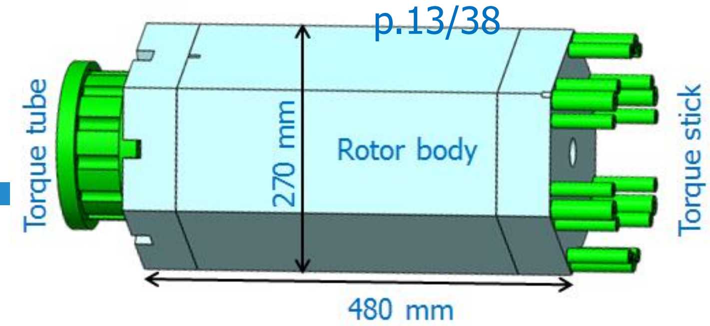


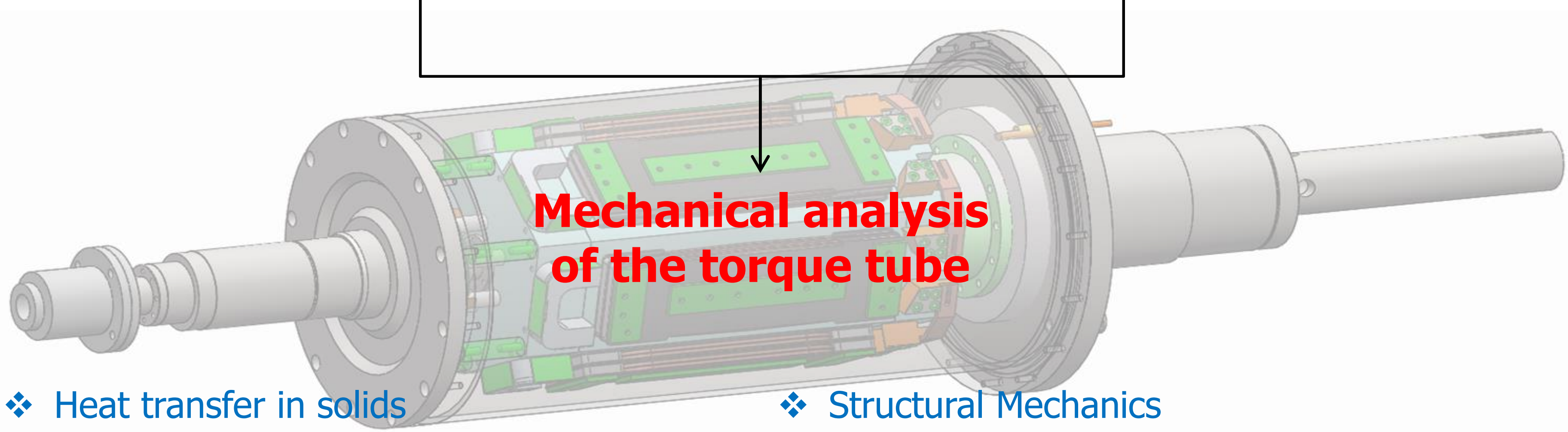
➢ Simulation model

Thermal contraction

Heat transfer in solids

Torque of the generator

Structural Mechanics



❖ Heat transfer in solids

- Temperature conditions
  : The superconducting part is 30 K.
  Two ends of the rotor is room temperature.

- Temperature gradient
  : *GFRP & Al*

❖ Structural Mechanics

- Thermal stress
  : Induced by thermal expansion of structures

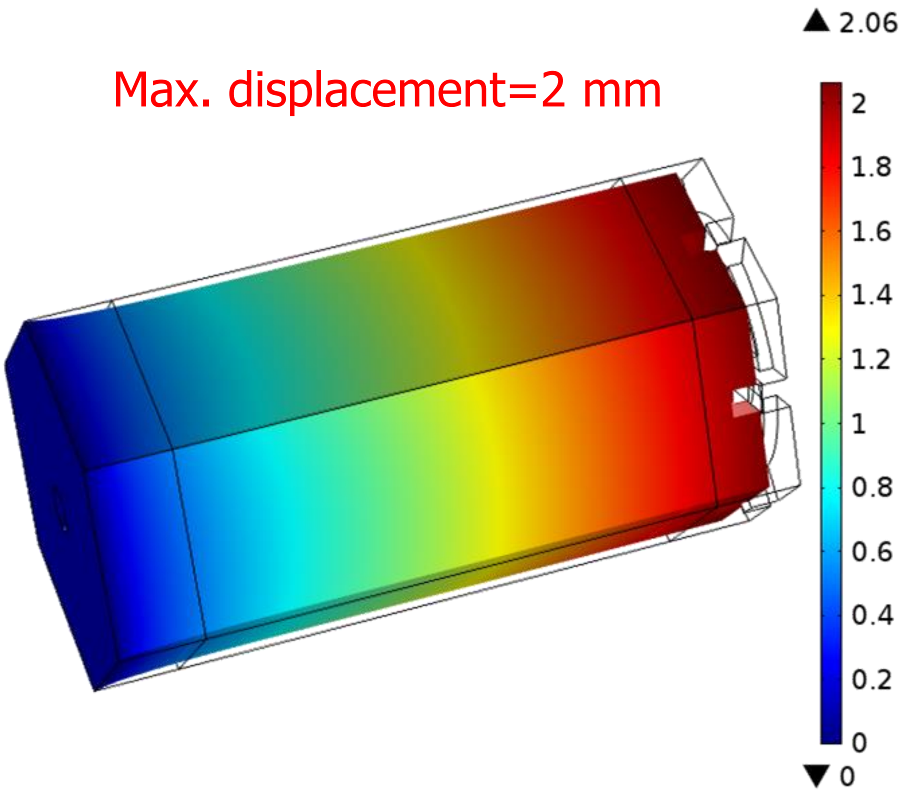
- Torque
  : Induced by the applied torque (shear stress)

Mechanical analysis results –Thermal contraction

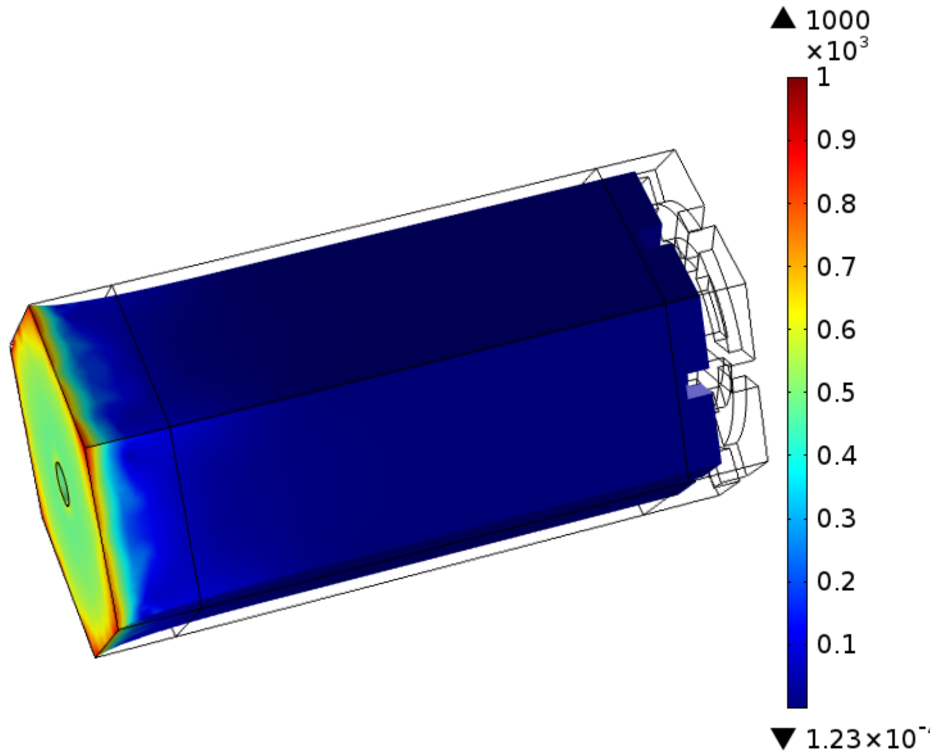
- Simulation model-*Al* rotor body

✓ Displacement (mm)

Max. displacement=2 mm



✓ Von mass stress (MPa)



The effective displacement of the rotor body to the torque tube and stick is 2 mm.

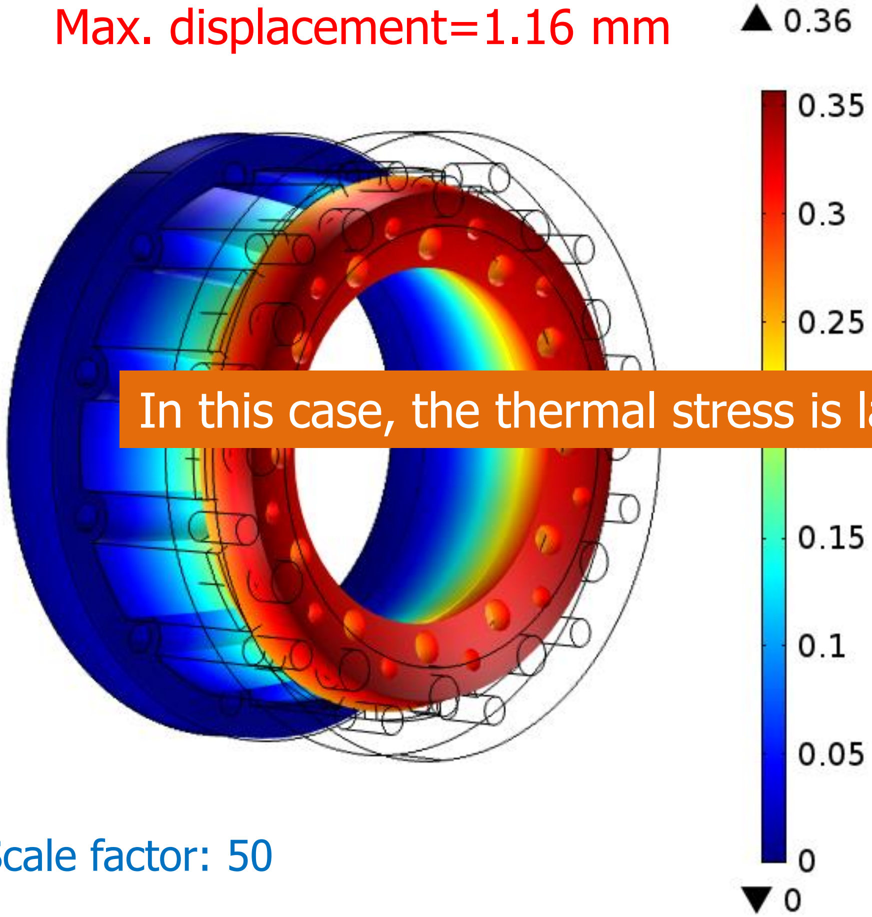
Mechanical analysis results - Thermal contraction & Torque

➢Simulation model- Torque tube

Force=Torque/Tube length=246 Nm/0.09 m=2,733N)

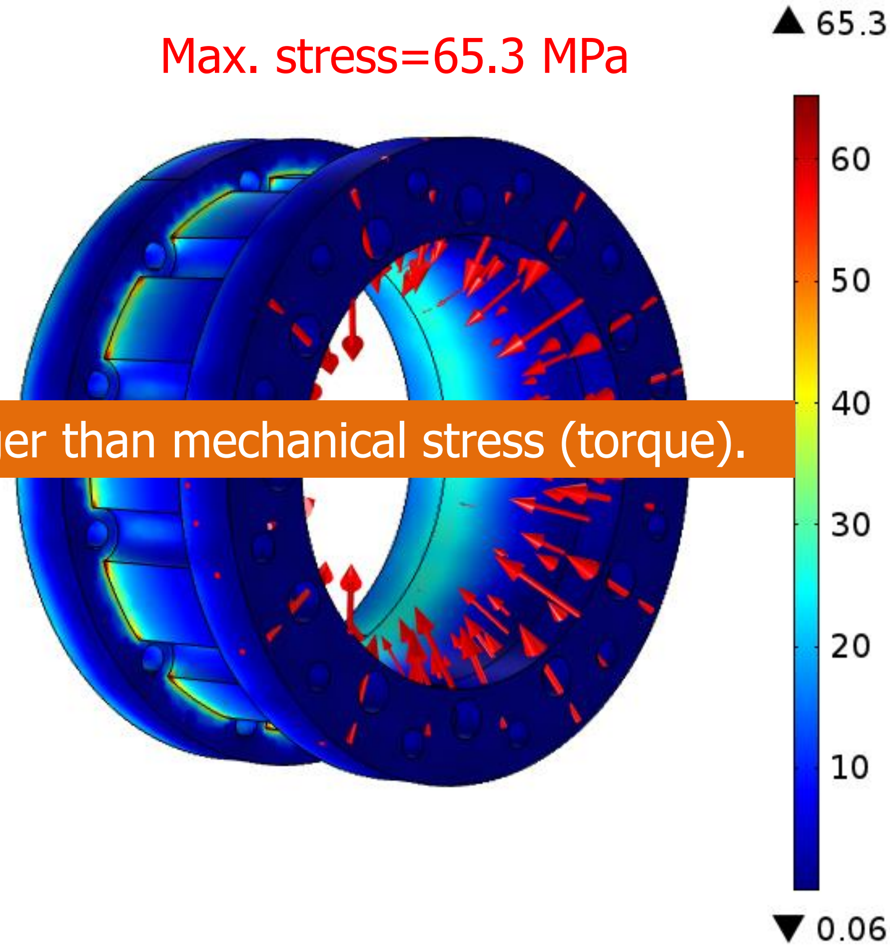
- ✓ Displacement (mm)
- ✓ Von mises stress (MPa)

Max. displacement=1.16 mm



In this case, the thermal stress is larger than mechanical stress (torque).

Max. stress=65.3 MPa



*Scale factor: 50

Mechanical analysis results - Thermal contraction & Torque

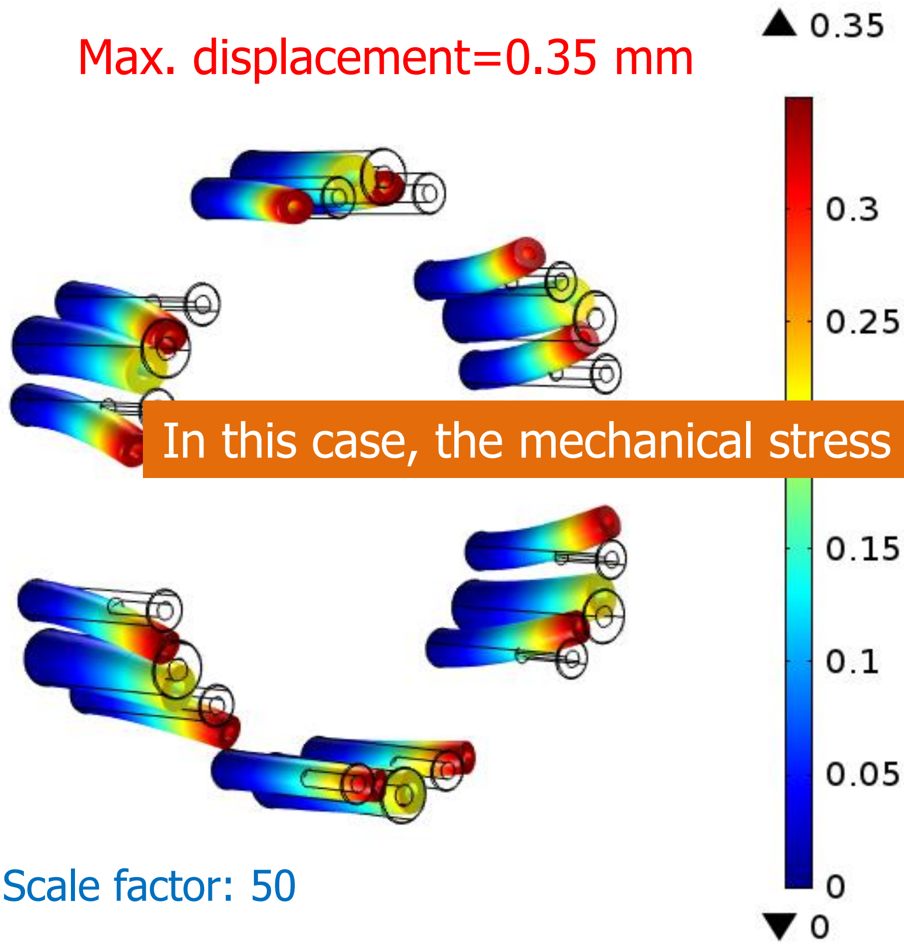
➢Simulation model- Torque stick

Force=Torque/Tube length=246 Nm/0.07 m=3,514N)

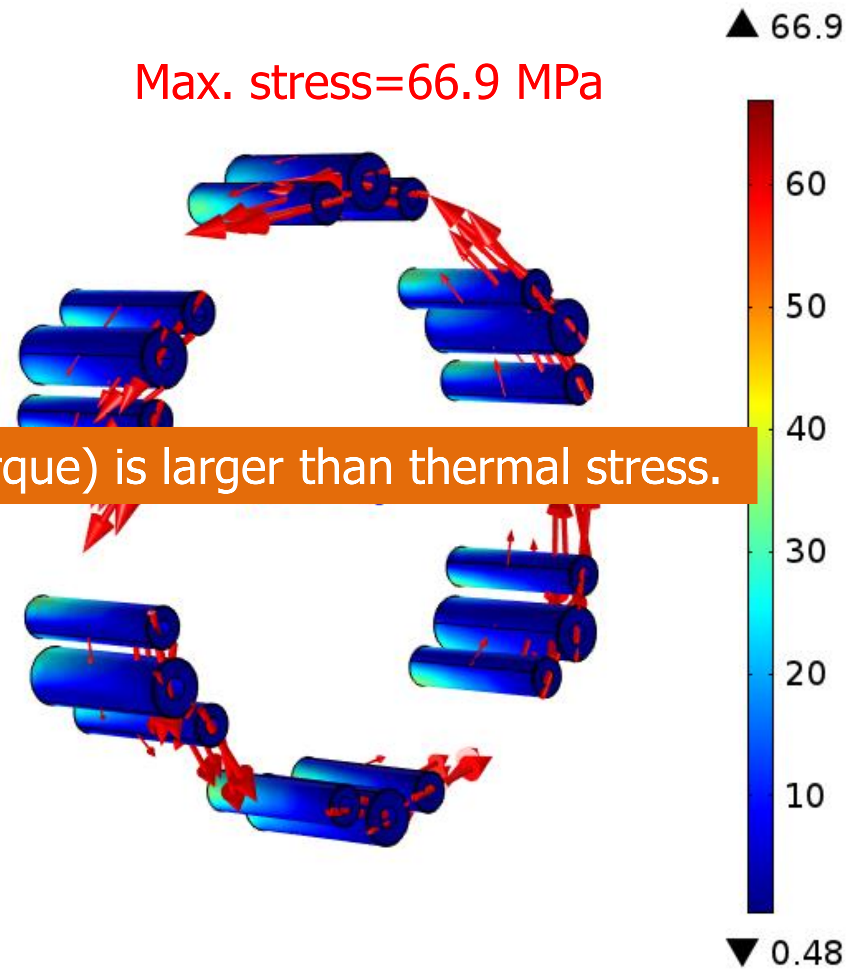
✓ Displacement (mm)

✓ Von mises stress (MPa)

Max. displacement=0.35 mm



Max. stress=66.9 MPa



In this case, the mechanical stress (torque) is larger than thermal stress.

*Scale factor: 50

Mechanical analysis results - Thermal contraction & Torque

Ref. Case Studies in Superconducting Magnets, Yukikazu Iwasa

Material	σ_U [MPa]	
T [K]	295	77
Aluminum 6061 (T6)	315	415
Copper (annealed)	160	310
Copper (1/4 hard)	250	350
Copper (1/2 hard)	300	
Nickel	345→2000	
Silver	190	295
Stainless steel 304	550→ 1030	1450→ 1860
Stainless steel 316LN	1290	1790
Epoxy	40	100
G-10 (warp/normal)	280/240	—
Mylar	145	215
Teflon	14	105

- The sum of the thermal stress and mechanical stress
    - Toque tube: 65.3 MPa
    - Toque sticks: 66.9 MPa

Therefore, the stresses of the torque tube and sticks are within acceptable value (72 MPa @ 70% margin).

Contents

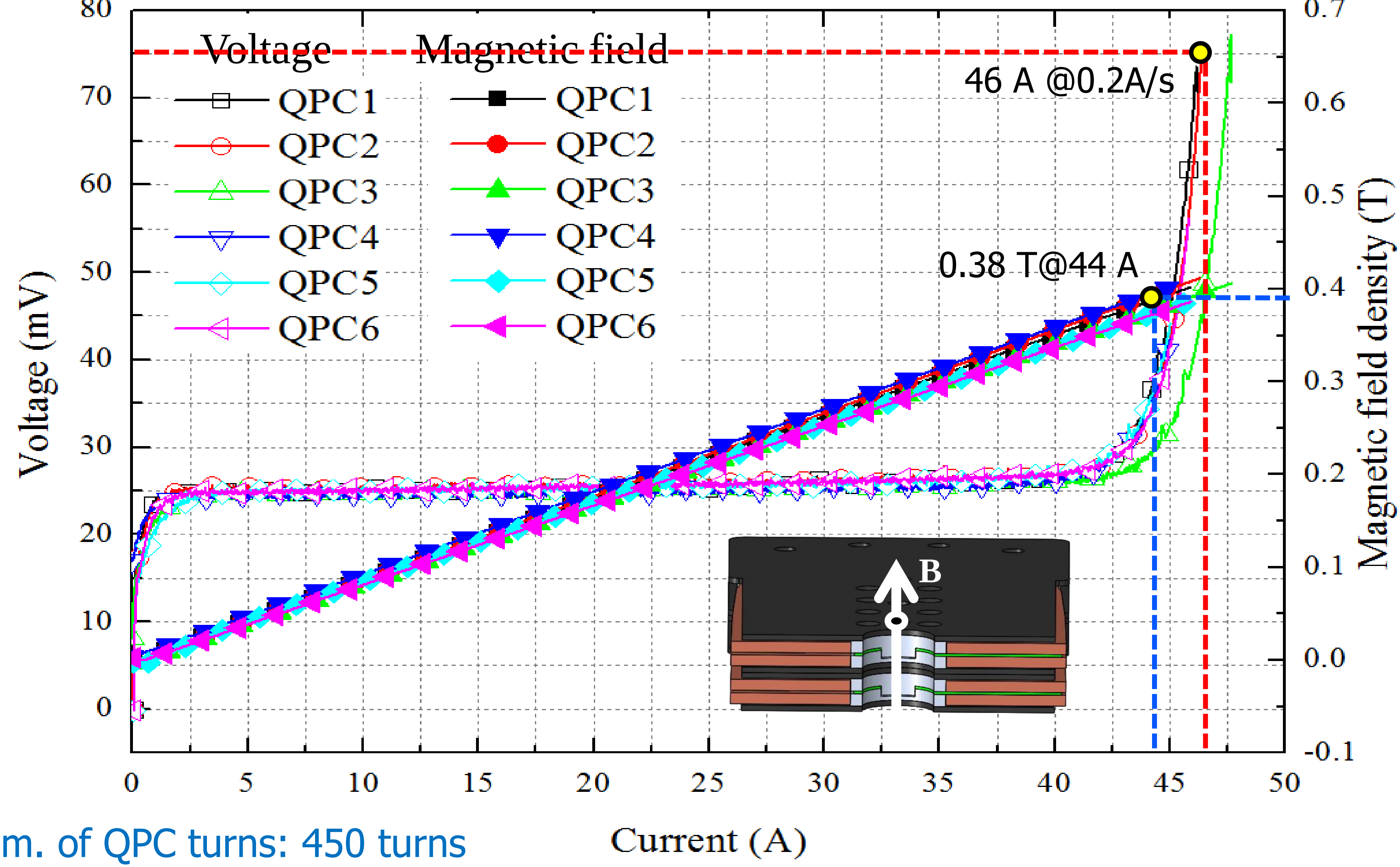
Winding of HTS field coil (QPC)

- Assembly of the DPC

- Assembly of the QPC

Measured results of QPC (I_c & B)

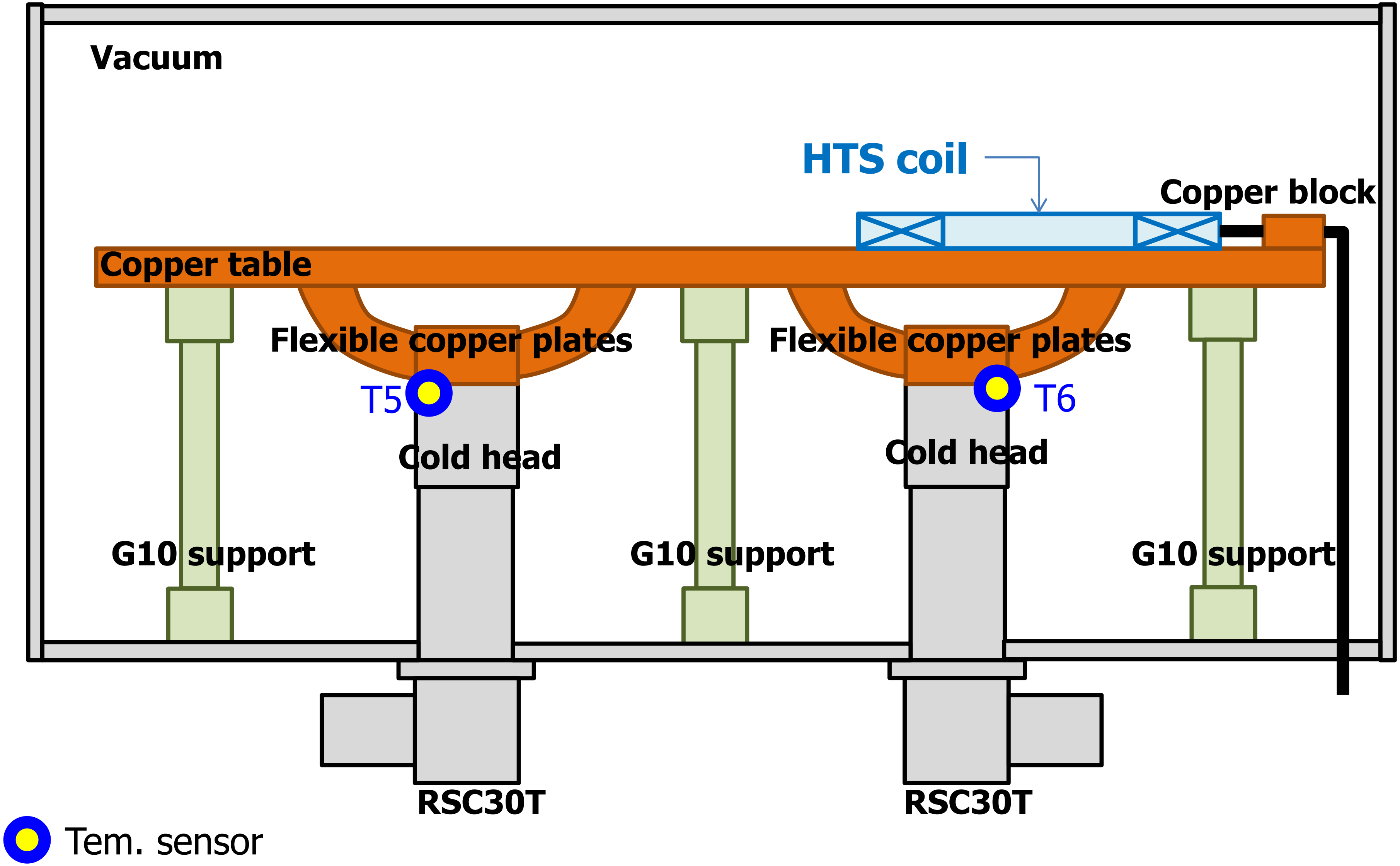
➢ Ic@77 K test results



- Num. of QPC turns: 450 turns
- Total HTS length: 500 m
- Inductance: 125 mH

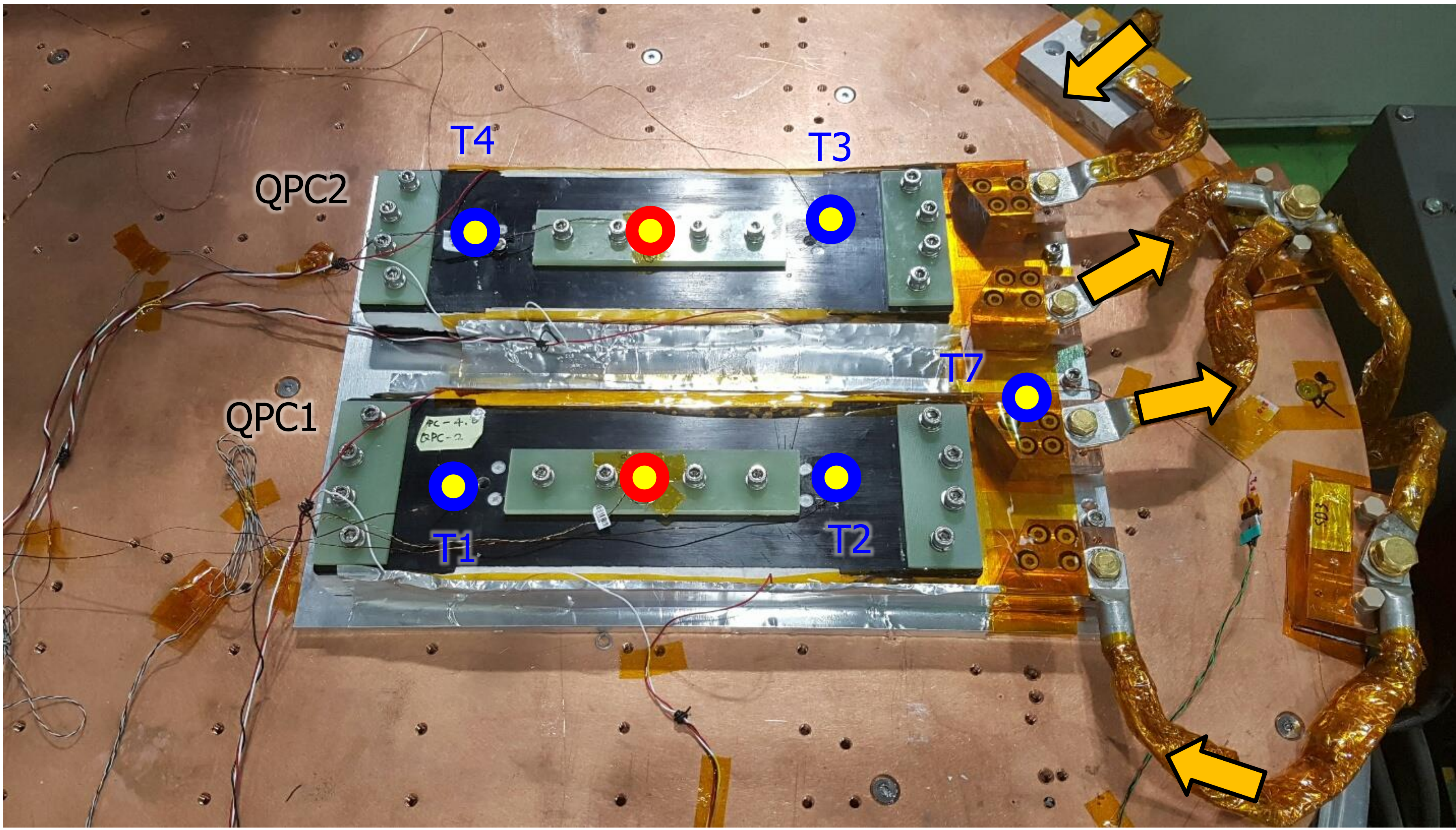
Conduction cooling test set-up

➢ Configuration of test chamber



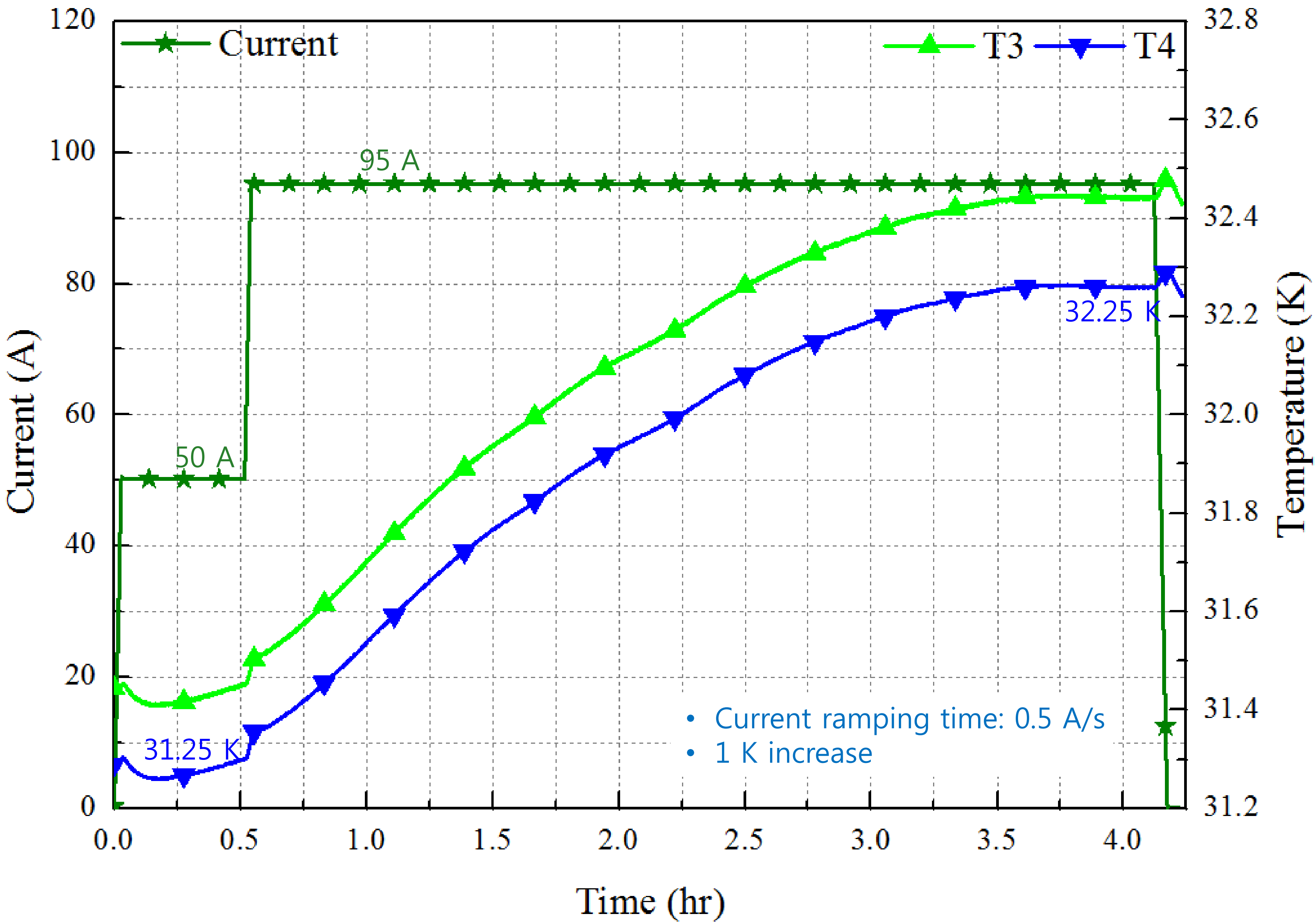
Conduction cooling test set-up

✓ Two coils are one set for the conduction cooling test

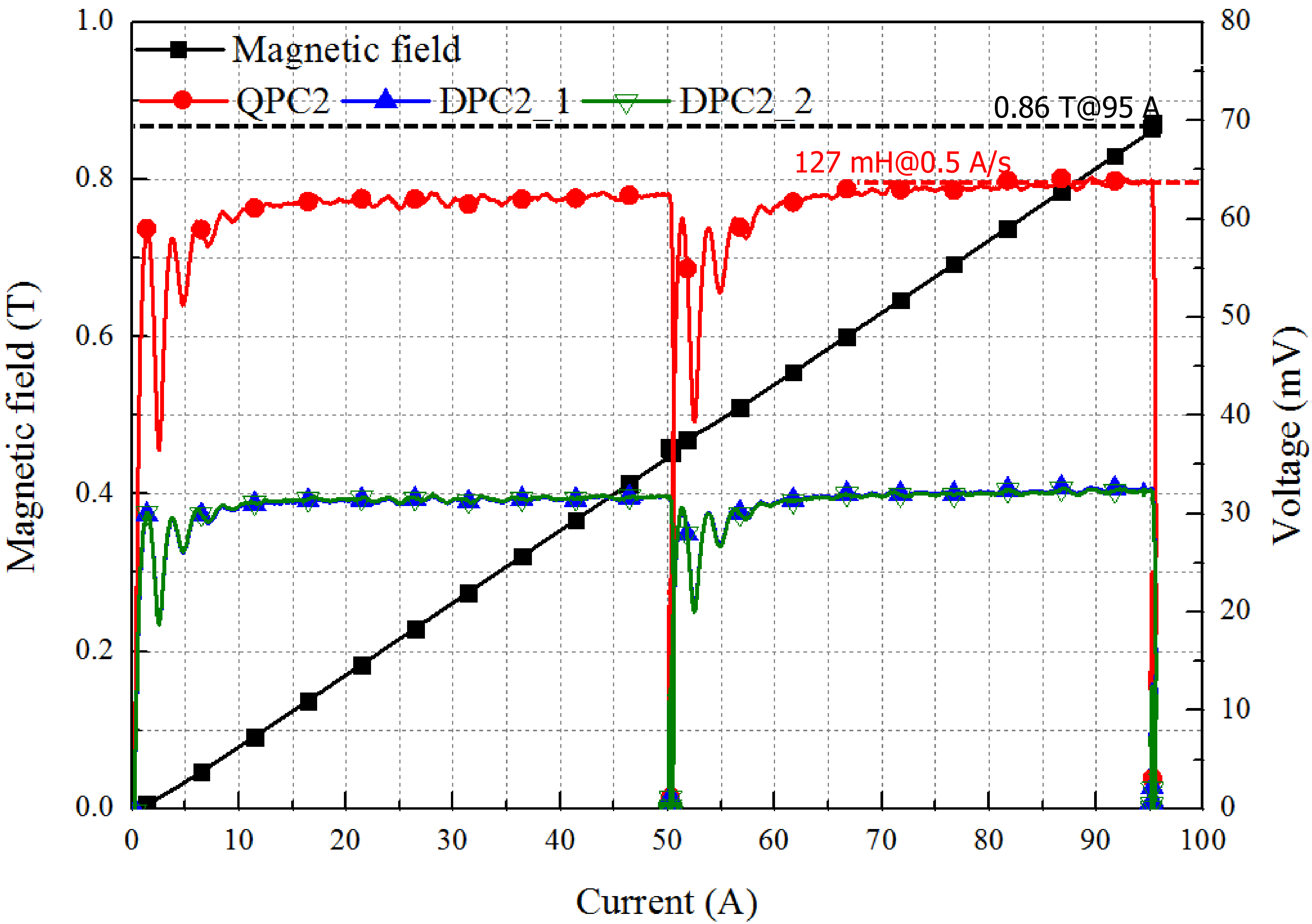


Hall sensor Tem. sensor Current direction

Conduction cooling test – Current & Temperature



Conduction cooling test – Current & Voltage & Magnetic field

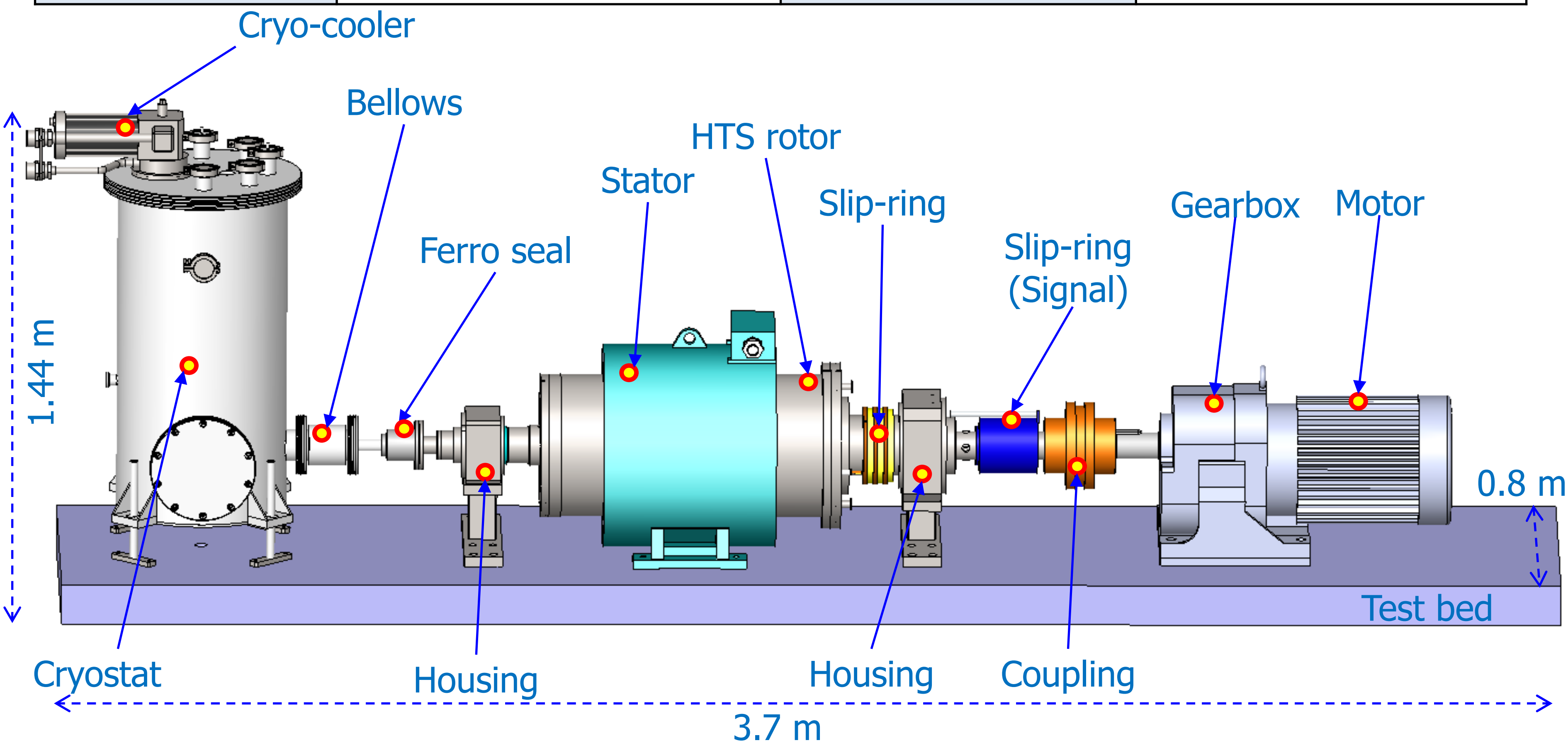


Conduction cooling test – Measurement results of QPCs

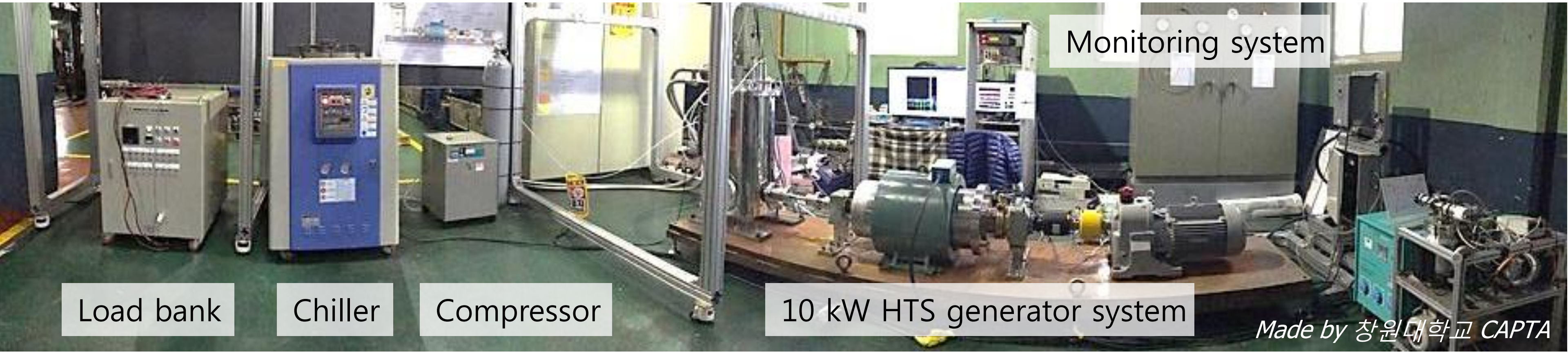
Fabrication of the HTS field coils for 10 kW SCSG (Target = QPC 6 ea)						
Coil	Winding	Impregnation	Inductance (mH)	Operating current (A)	Magnetic field (T)	Test
QPC1	Done	Done	127 mH	95 A	0.85 T	Success
QPC2	Done	Done	127 mH	95 A	0.86 T	Success
QPC3	Done	Done	130 mH	95 A	0.85 T	Success
QPC4	Done	Done	130 mH	95 A	0.86 T	Success
QPC5	Done	Done	130 mH	95 A	0.87 T	Success
QPC6	Done	Done	127 mH	95 A	0.85 T	Success

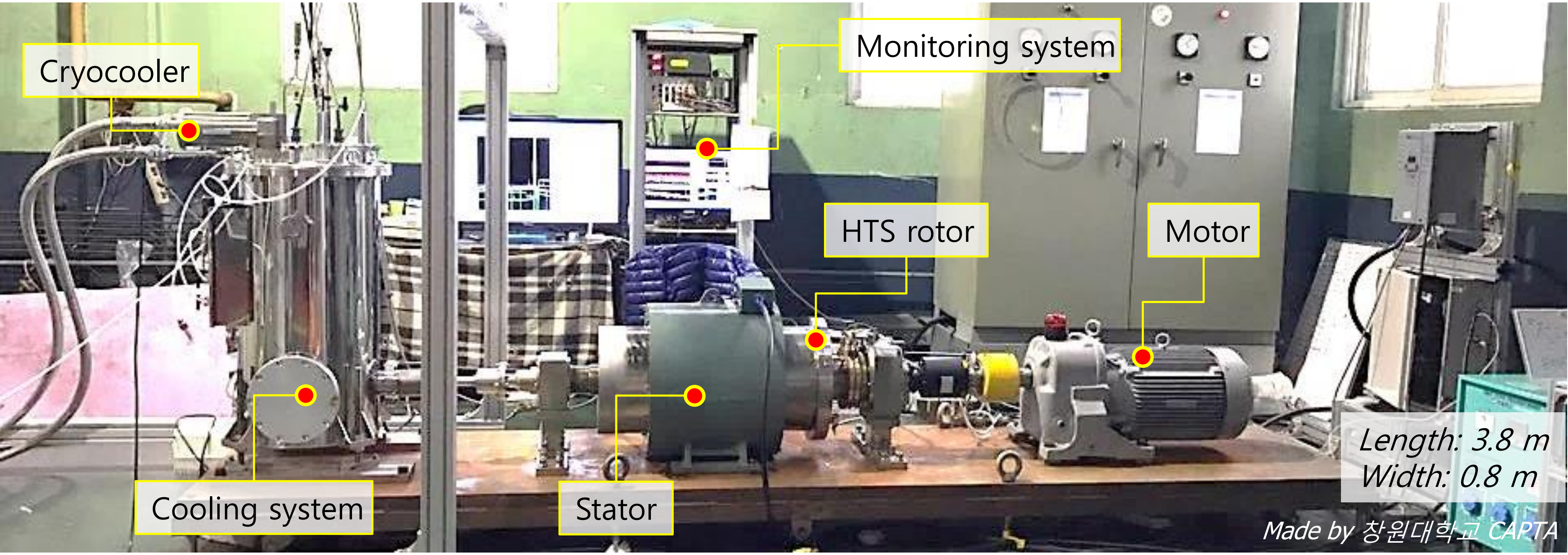
Configuration of the 10 kW HTS generator system

Wire type	2G GdBCO wire (SuNAM Corp.)	Refrigerant	Liquid Neon
Target I_{op}	95 A	Number of pole	6 pole
Target temp.	<30 K	Rotating speed	400 rpm
Cooling method	Thermosyphon + Conduction cooling	Target capacity	10 kW



10 kW HTS generator system





Video of the 10 kW HTS generator

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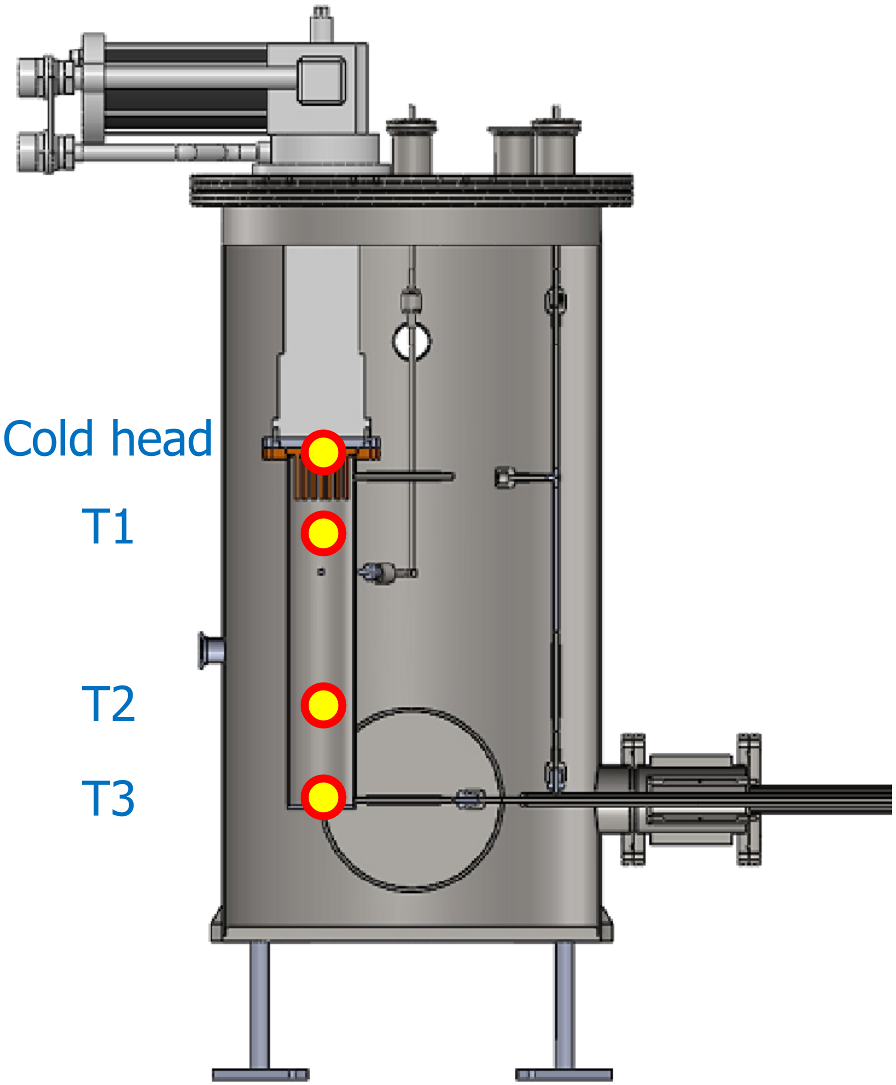
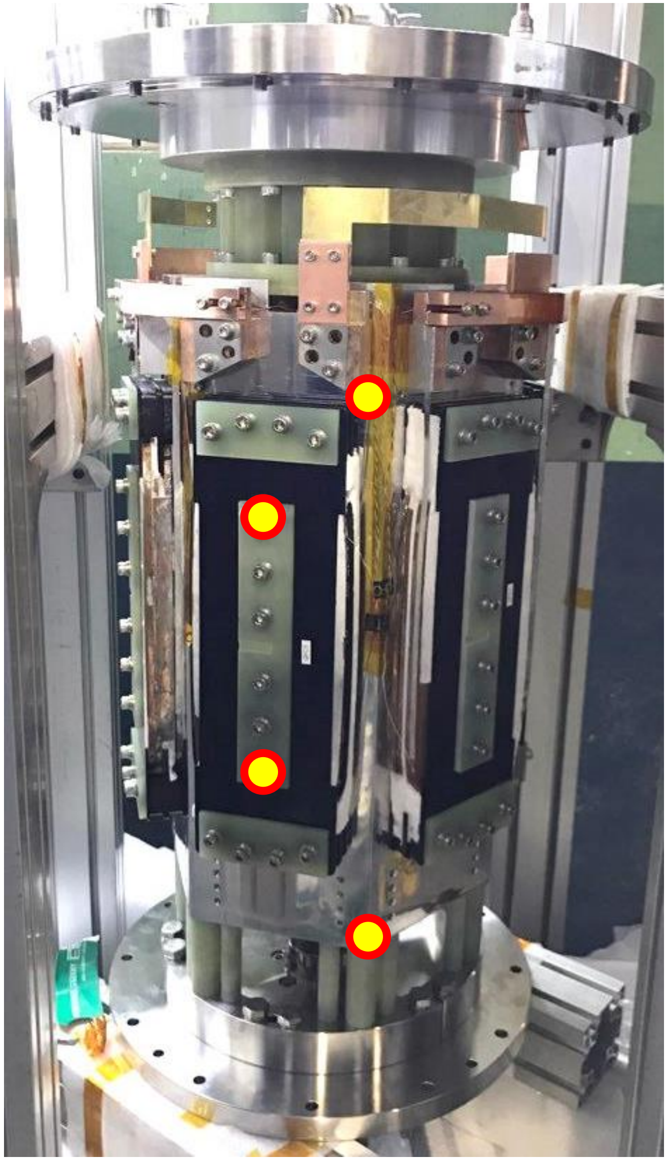
Cooling test of the generator

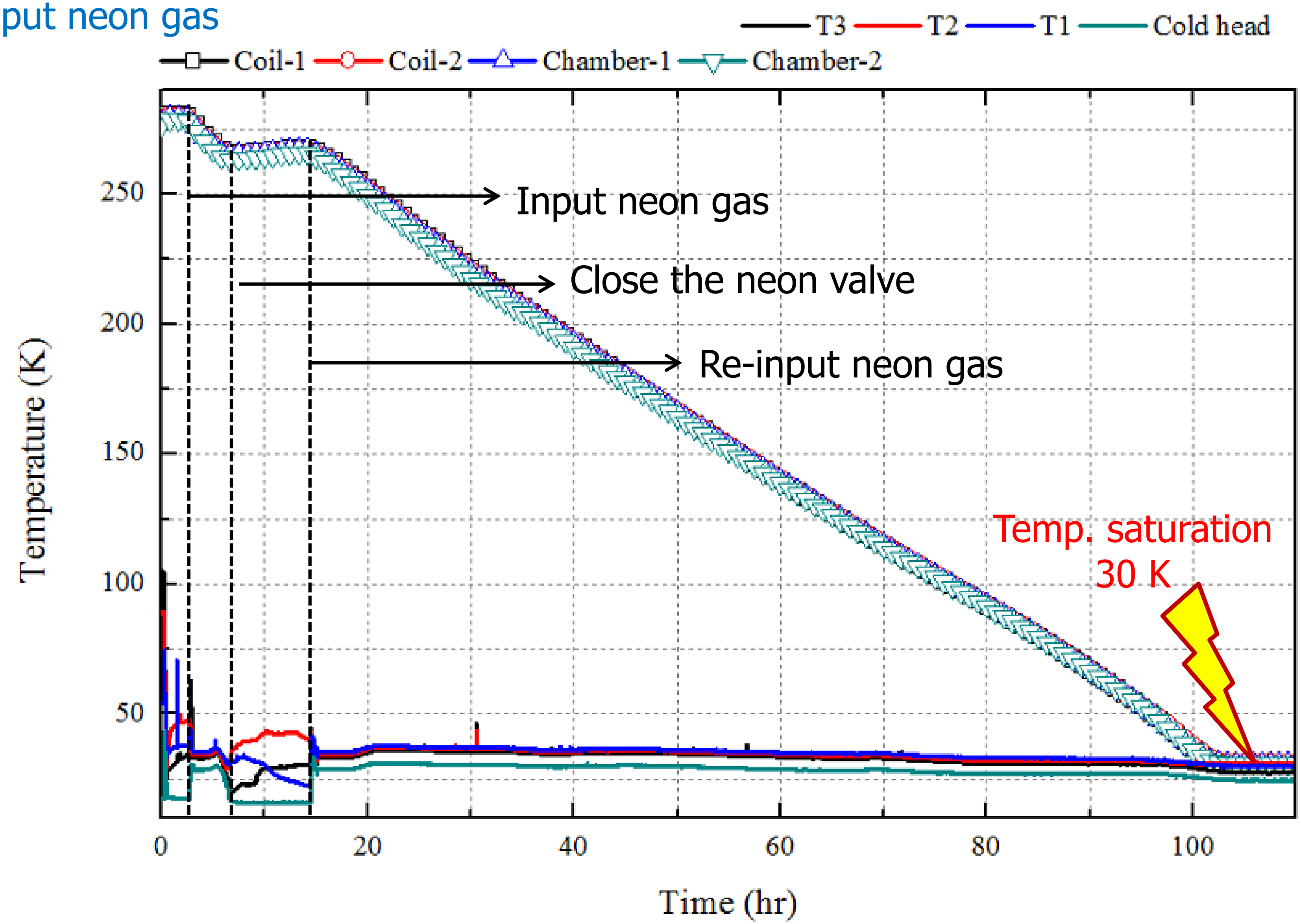
- Temp. sensor positions





Cooling test of the generator

➢ Input neon gas



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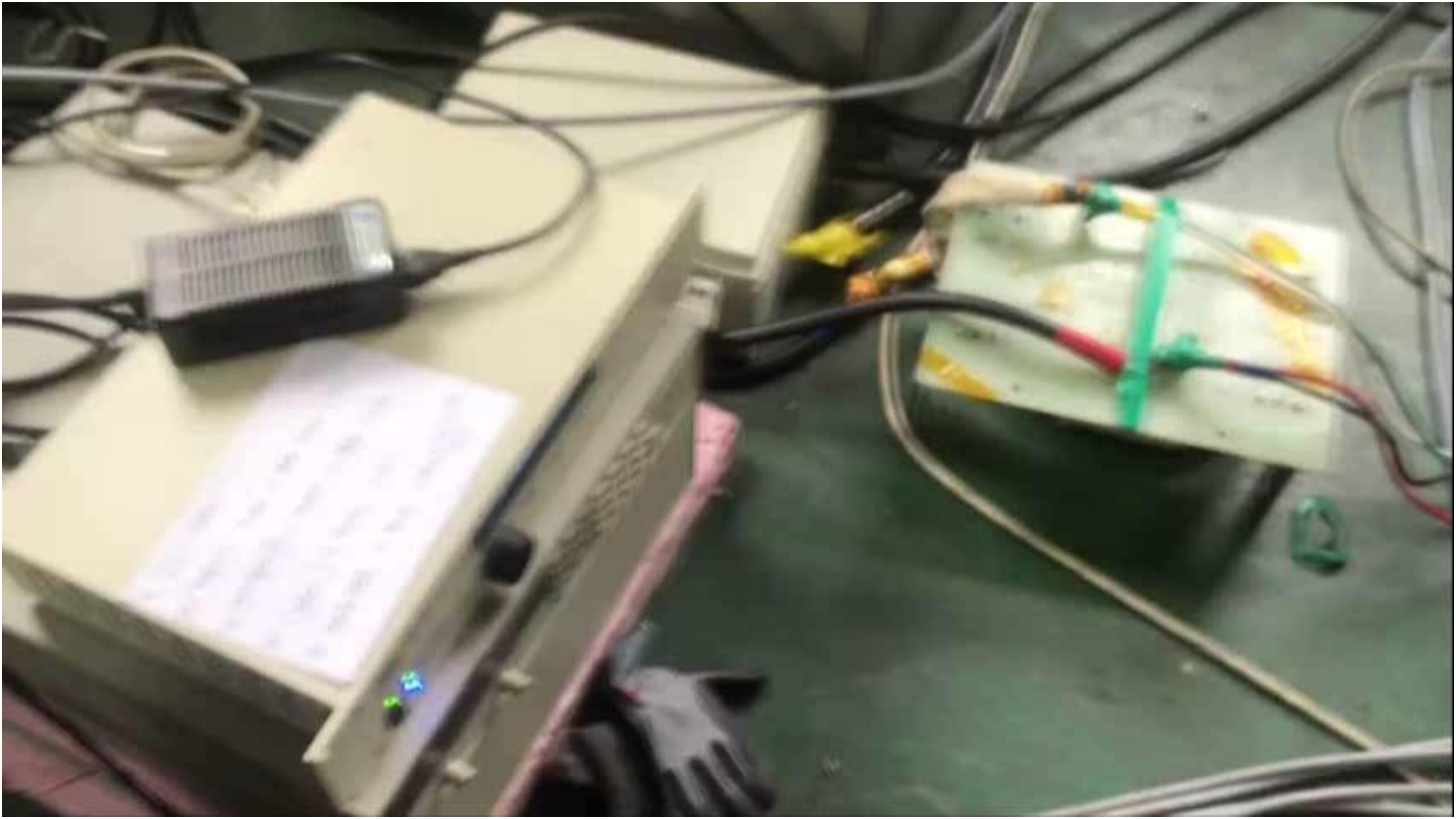
Performance results



Performance results

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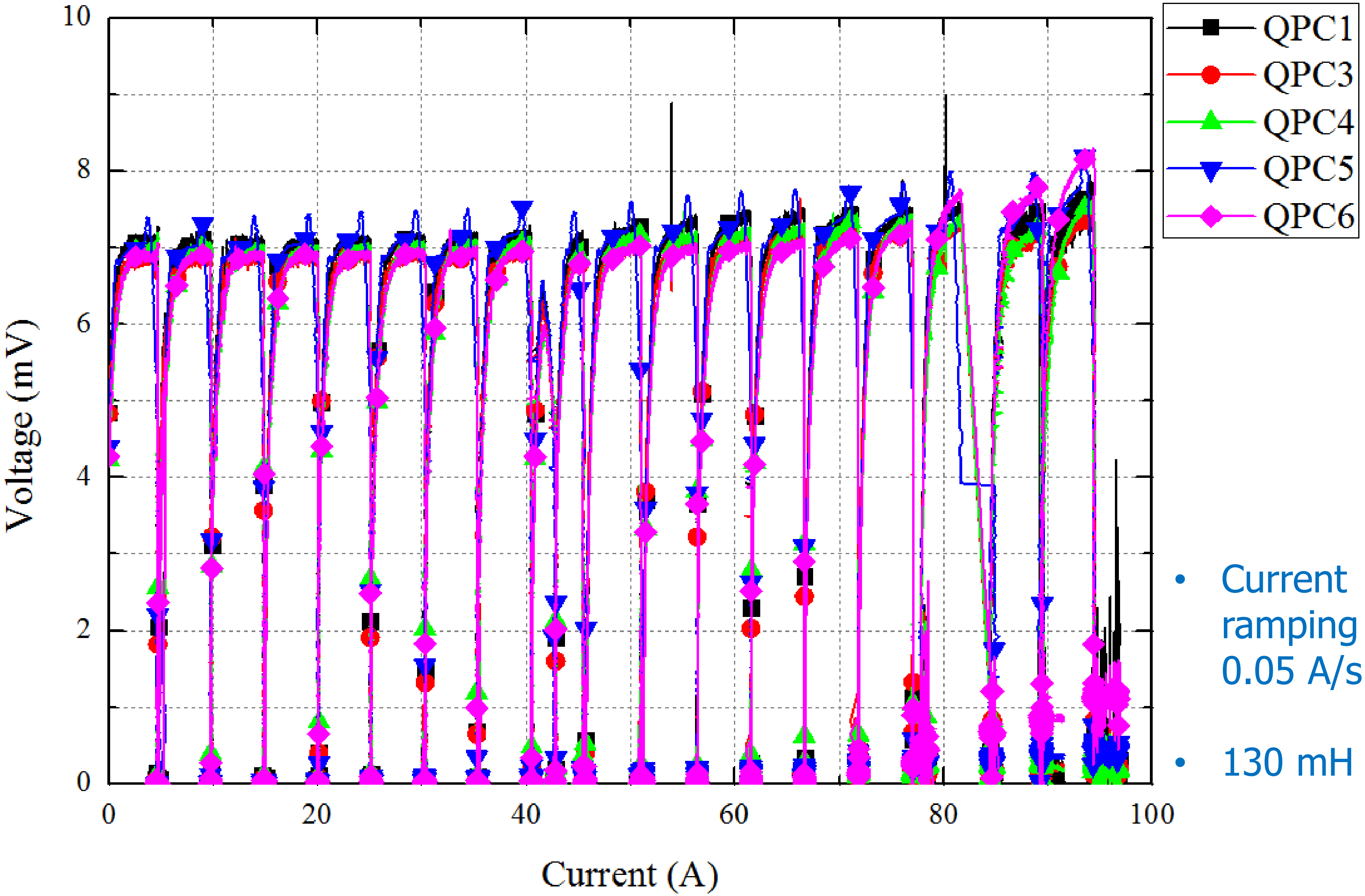
➢ QPC voltage & Current

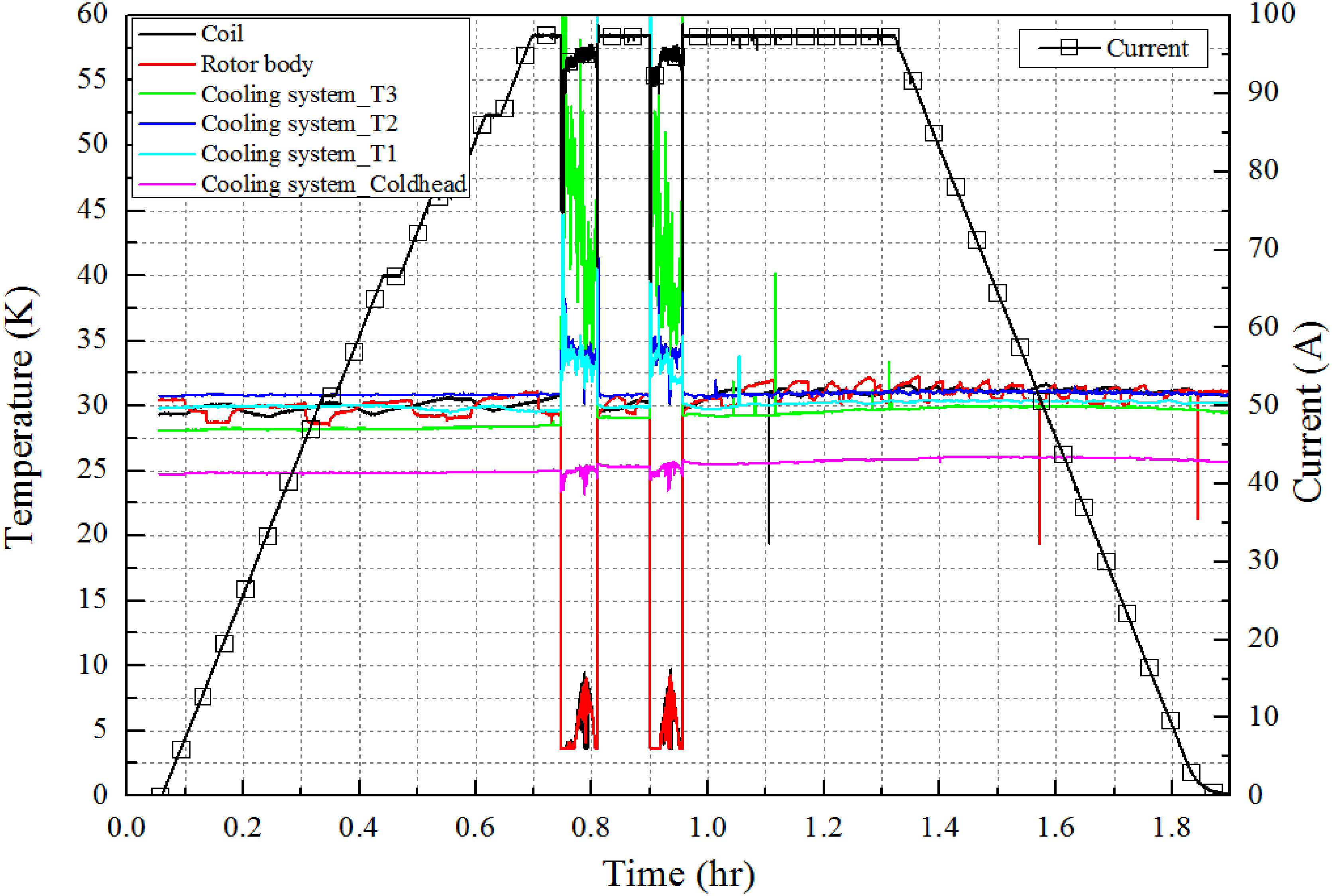


- Current ramping time: 0.05 A/s
- 130 mH

Performance results

➢ Temperature & Current

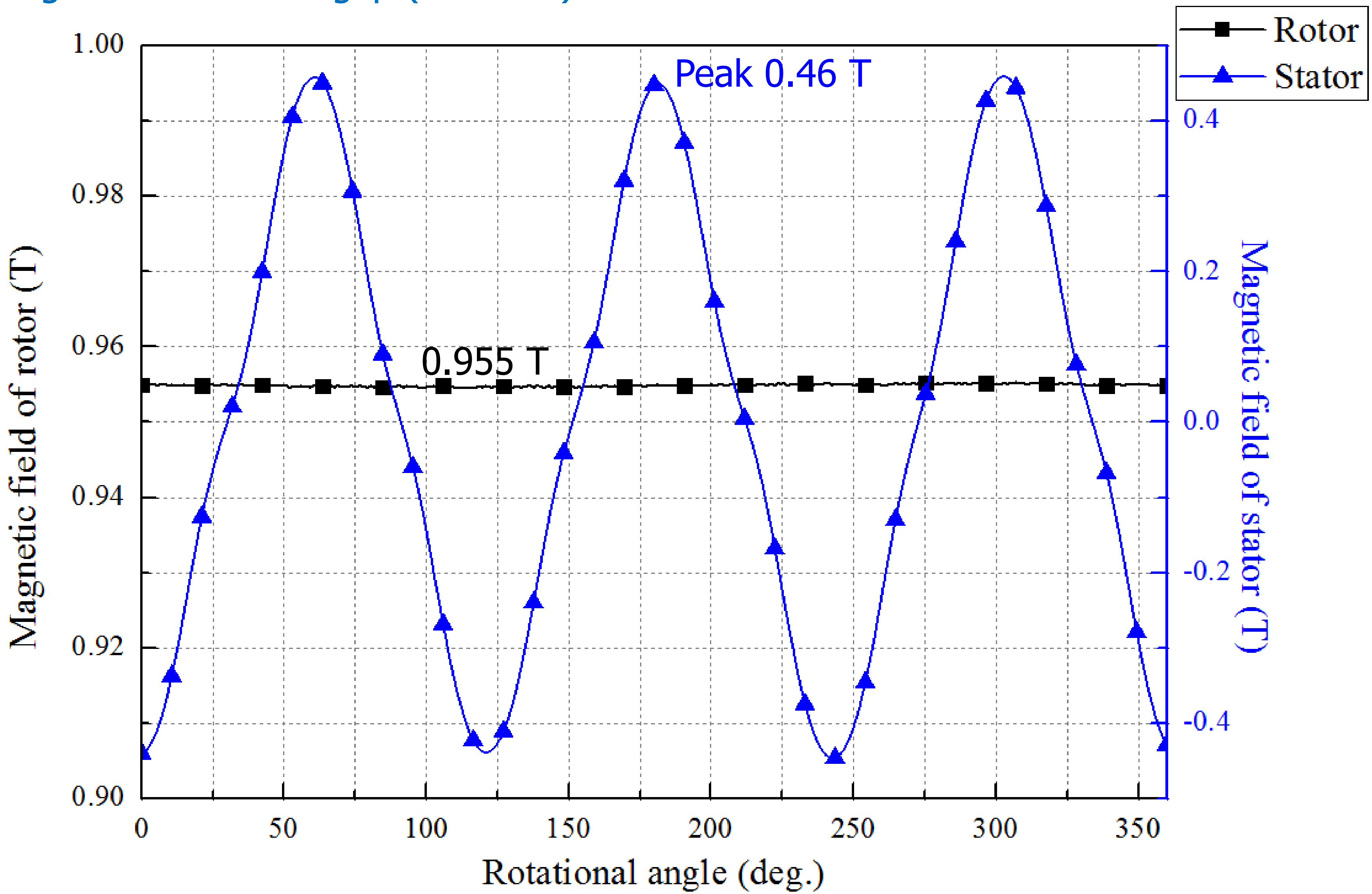
- From 29 K to 31 K



Performance results

- At 400 rpm

➢ Magnetic field of air-gap (or stator)



Performance results

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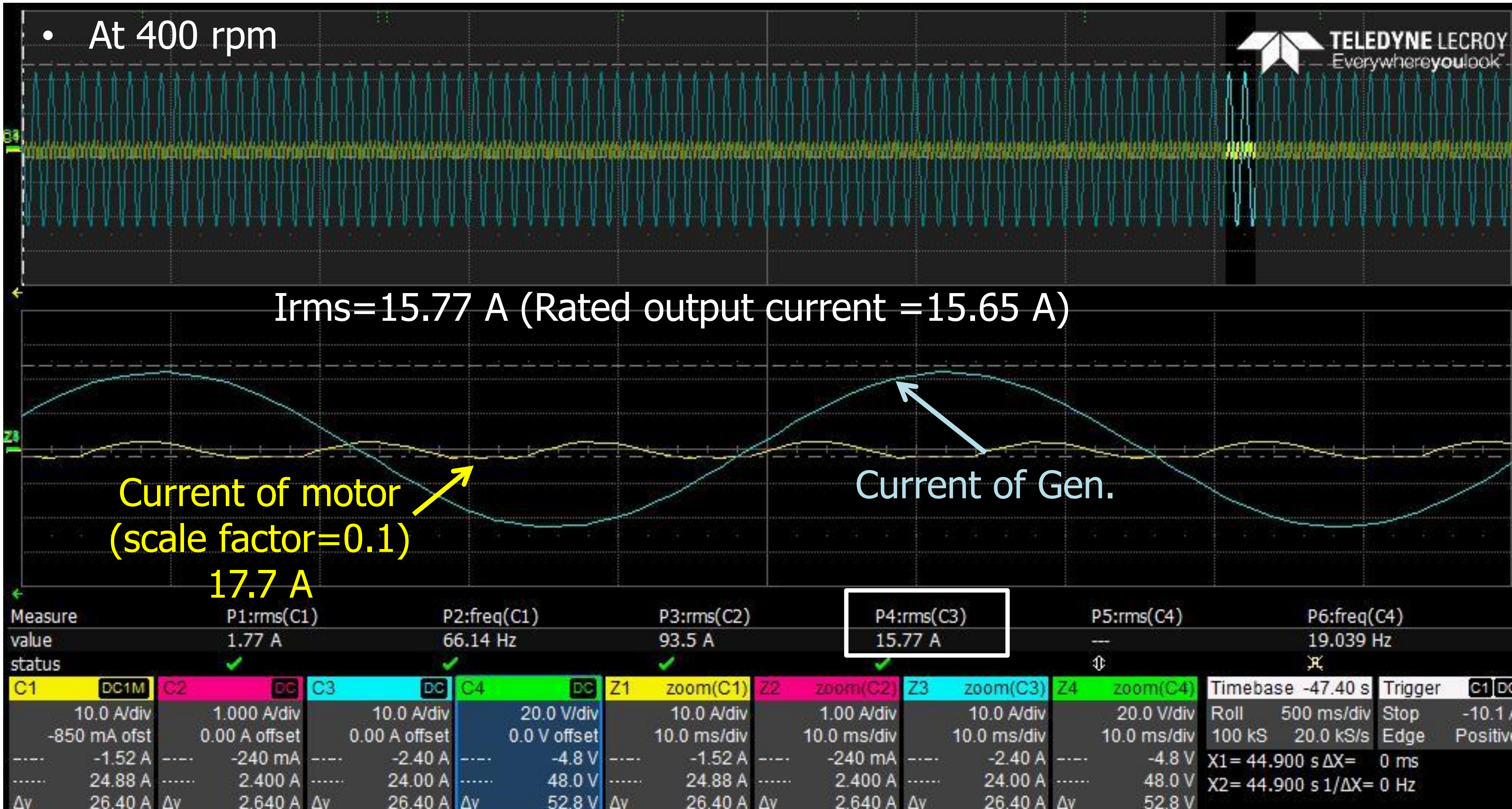
➢ Generator current & Motor current

- At 400 rpm

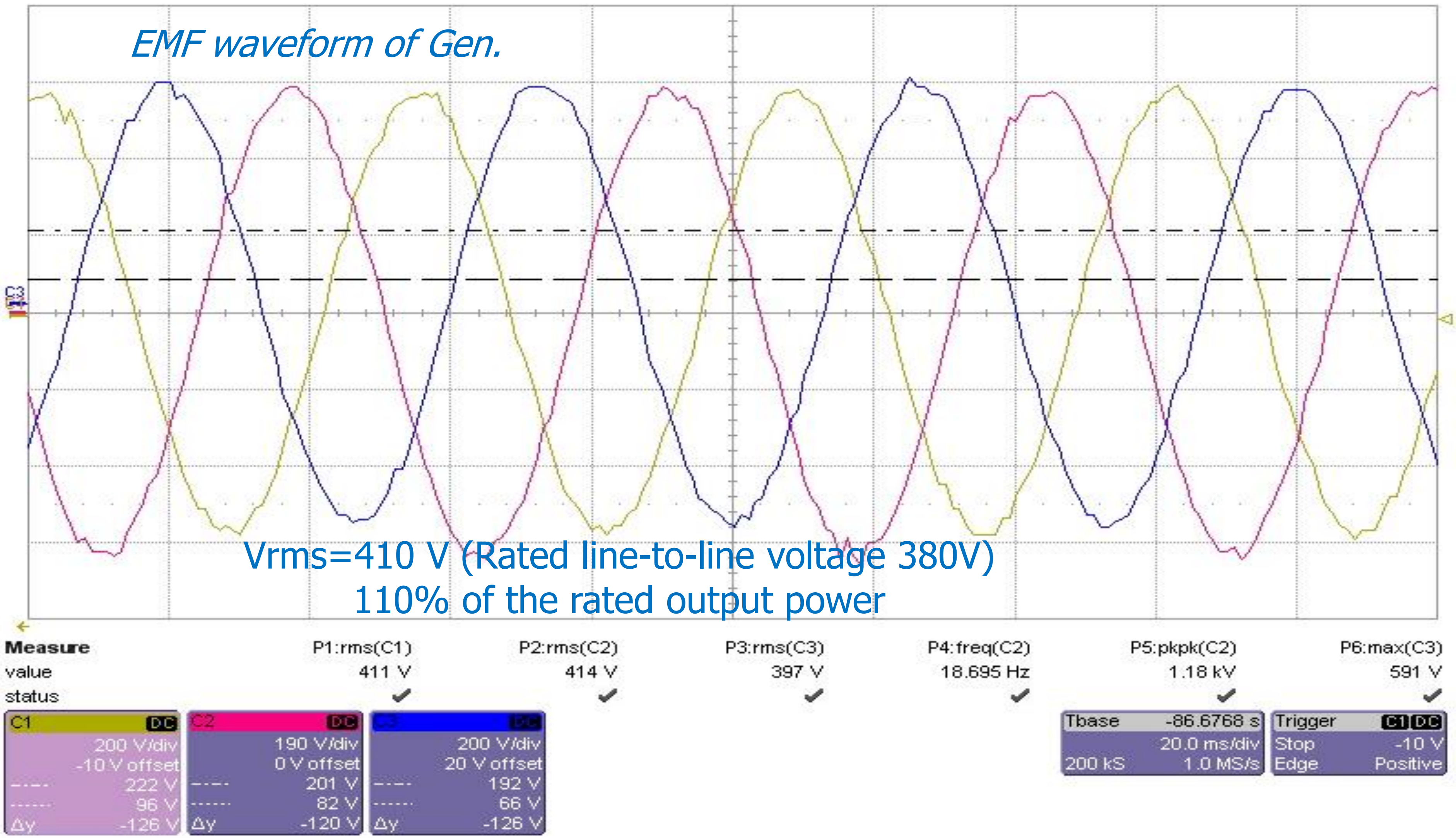


Performance results

- EMF at load test

- At 400 rpm
- Full output power= 11 kW

EMF waveform of Gen.

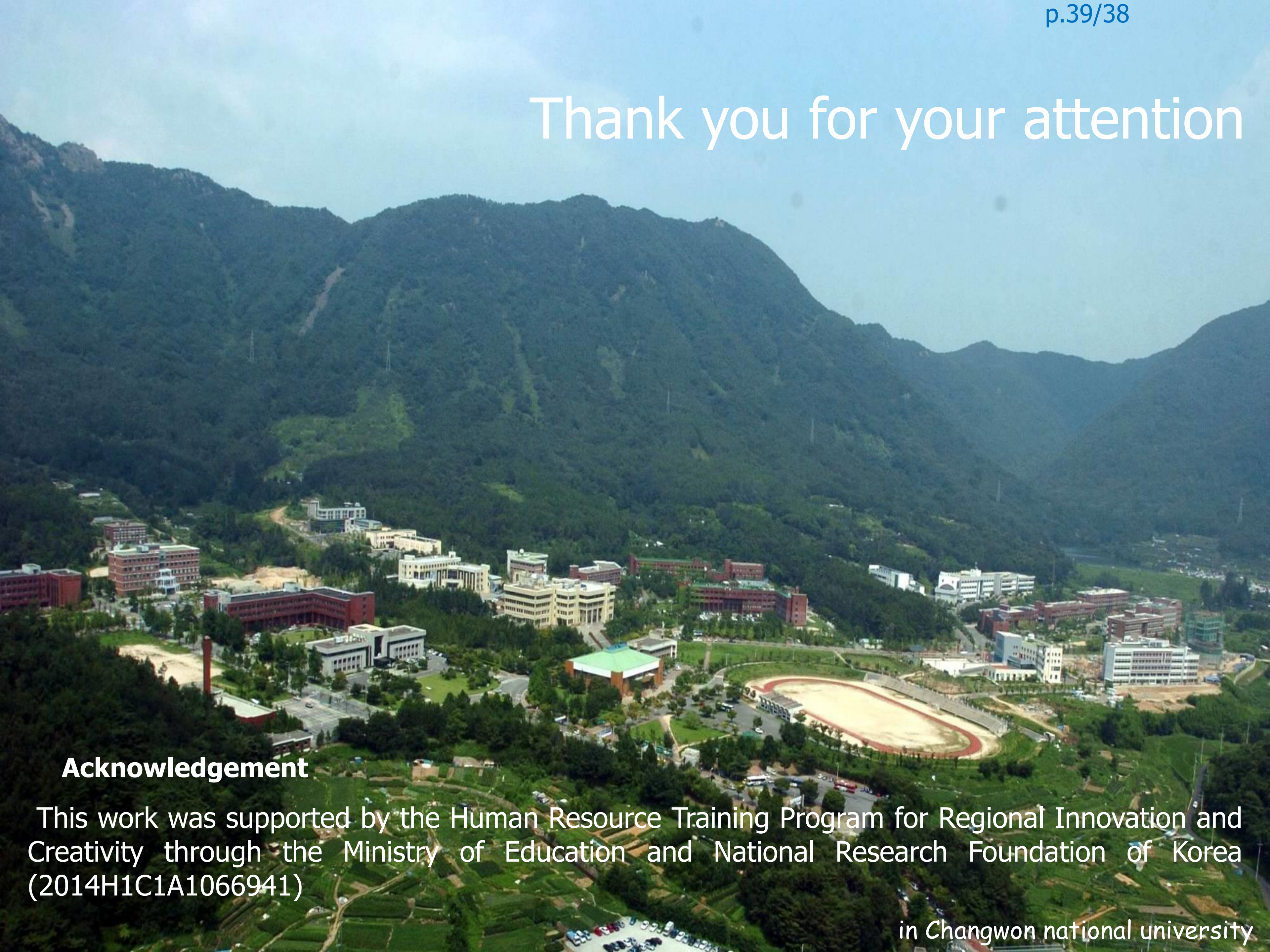


Vrms=410 V (Rated line-to-line voltage 380V)
110% of the rated output power

Conclusions

- A high temperature superconducting (HTS) generator for a large-scale wind power generation system draws much attention as a contemporary research item.
- This presentation deals with the hardware integration and performance analysis of a 10 kW HTS wind power generator.
- The HTS generator, which consists of 6 pole racetrack type HTS coils for rotor and 36 slots copper windings for stator, was designed.
- The generator was designed by considering electromagnetic, thermal, and mechanical analyses.
- Conduction cooling test for HTS field coils wound by 2G GdBCO wire was performed in a cryogenic test chamber using two GM cryocoolers at 30 K, and then the whole generator system was fabricated and assembled.
- The generator was cooled down by thermosyphon cooling method with a GM cryocooler using liquid neon, and achieved at 30 K.
- As a result, full output power of the generator was 11 kW. Therefore, rated output power of 10 kW was achieved.
- The results will be applied to comparative analysis with the generator having the HTS brushless exciter and the development of the large-scale wind power generator core technology.

Thank you for your attention



Acknowledgement

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