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AP1-2-INV

Development status of DC induction heating device for aluminum billets using high temperature superconducting magnet

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OUTLINE

- ***Background***
- ***Status of Projects***
  - ***- Germany, China, Korea, Japan***
- ***Comparison of features***
- ***Future Technical Issues***

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Niigata University
Applied Superconductivity Lab.

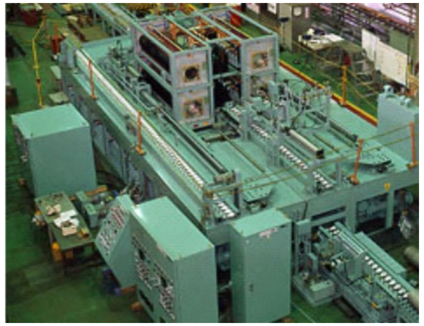
Aluminum hot extrusion process

Material

Aluminum billet

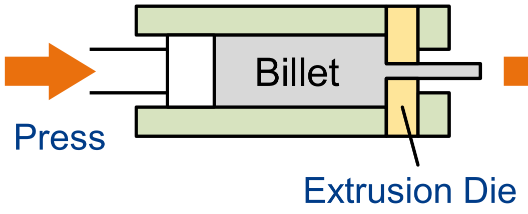
Heating process

High Frequency AC Induction Heater



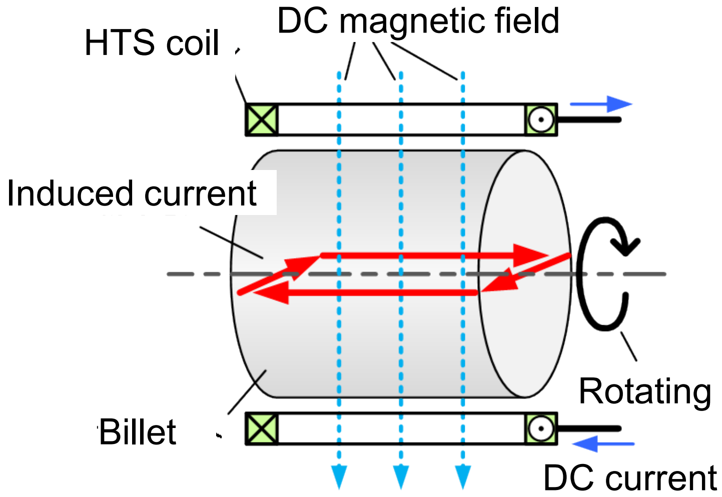
Extrusion process

Extrusion Machine



Final products

- *In various industrial productions such as building materials and automotive parts, aluminum hot extrusion processes are commonly used.*
- *Energy efficiency of conventional high frequency AC induction heating of aluminum billets using water-cooled Cu coils is generally low (～50 %).*
- *Highly efficient and fast heating methods of aluminum billets are strongly required.*
- *Induction heating by rotating aluminum billet in strong DC magnetic field using HTS coils (HTS DC induction heating) is a promising solution to achieve large heating capacity together with higher energy efficiency and faster heating.*



HTS DC induction heating

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BACKGROUND

Heating power

$$P \propto B^2 \cdot f^2$$

Magnetic field (B)   Frequency (f)

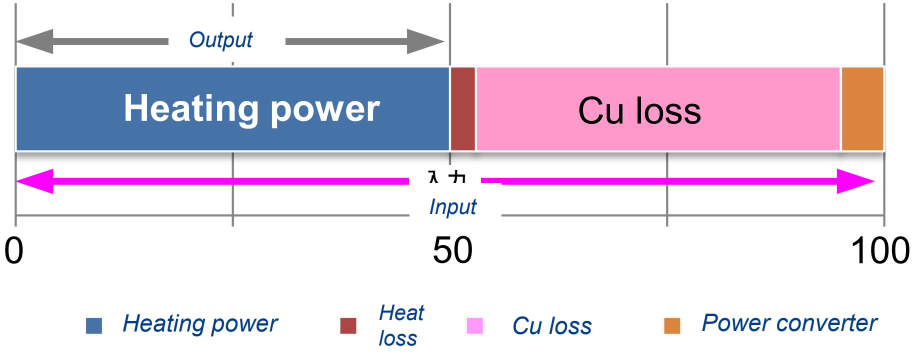
Key aspects

① High power : High magnetic field and frequency
② Uniform heating : Low frequency
③ High efficiency : Low Joule loss

High Frequency AC Induction Heater

- Low magnetic field due to low current density in Cu coils
- Non-uniform heating due to severe skin effect
- Slow temperature rise in central part
- Large Joule loss in Cu coils

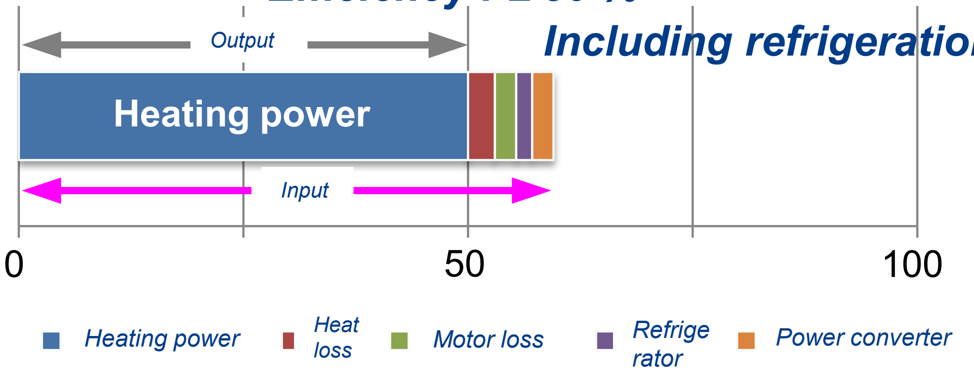
Efficiency : ～50 %



HTS DC Induction Heater

- High magnetic field by using HTS coils
- Uniform heating by suppressing skin effect due to low rotation speed (= low frequency)
- Fast temperature rise in central part
- No Joule loss

Efficiency : ≥ 80 %
Including refrigeration power



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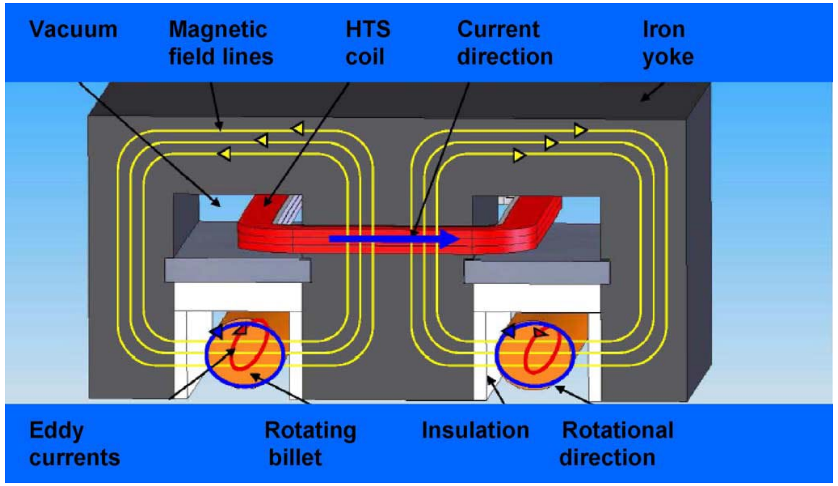
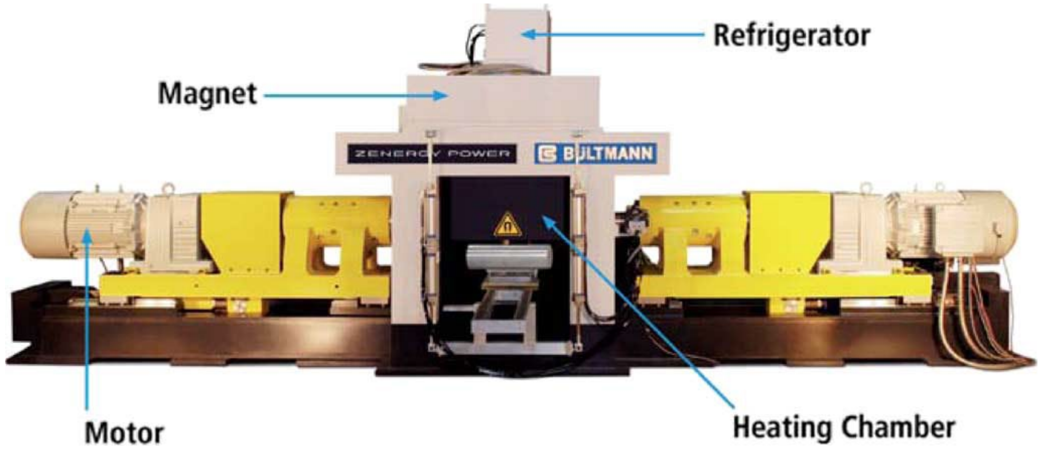
PROJECTS IN GERMANY

Zenergy power, Bültman

M. Runde, N. Magnusson, C. Fülbier and C. Bührer, "Commercial Induction Heaters with High-Temperature Superconductor Coils," IEEE Trans. Appl. Supercond., vol. 21, no. 3, pp.1379-1382, 2011.





HTS coil :
- *BSCCO/Ag (SEI), W 4.2 mm – t 0.27 mm*
- *Ic : 125 A @ 40 K, 1 T (perpendicular)*
- *Warm bore : 750 mm × 400 mm.*
- *Operated temperatures : 22 - 24 K*
- *Rated current : 100 A*

Billet size : Φ 152 – 177 mm × 690 mm
2 billets parallel
Revolution : 240 – 750 rpm
Output : 360 kW
Heating time : 140 s
Efficiency : 80 %

https://www.weseralu.de/en/company

Installation in Weseralu aluminum extrusion plant in Germany
2008 – 2010 : Heated 10,000 tons ≈ 350,000 billets, 2.2 tons / hr

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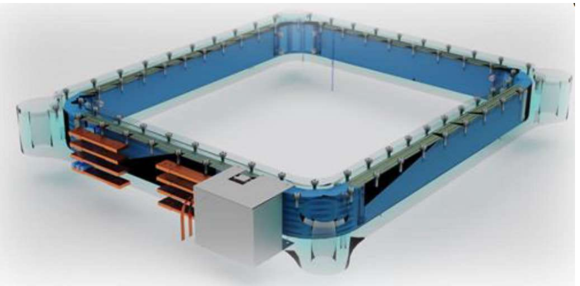
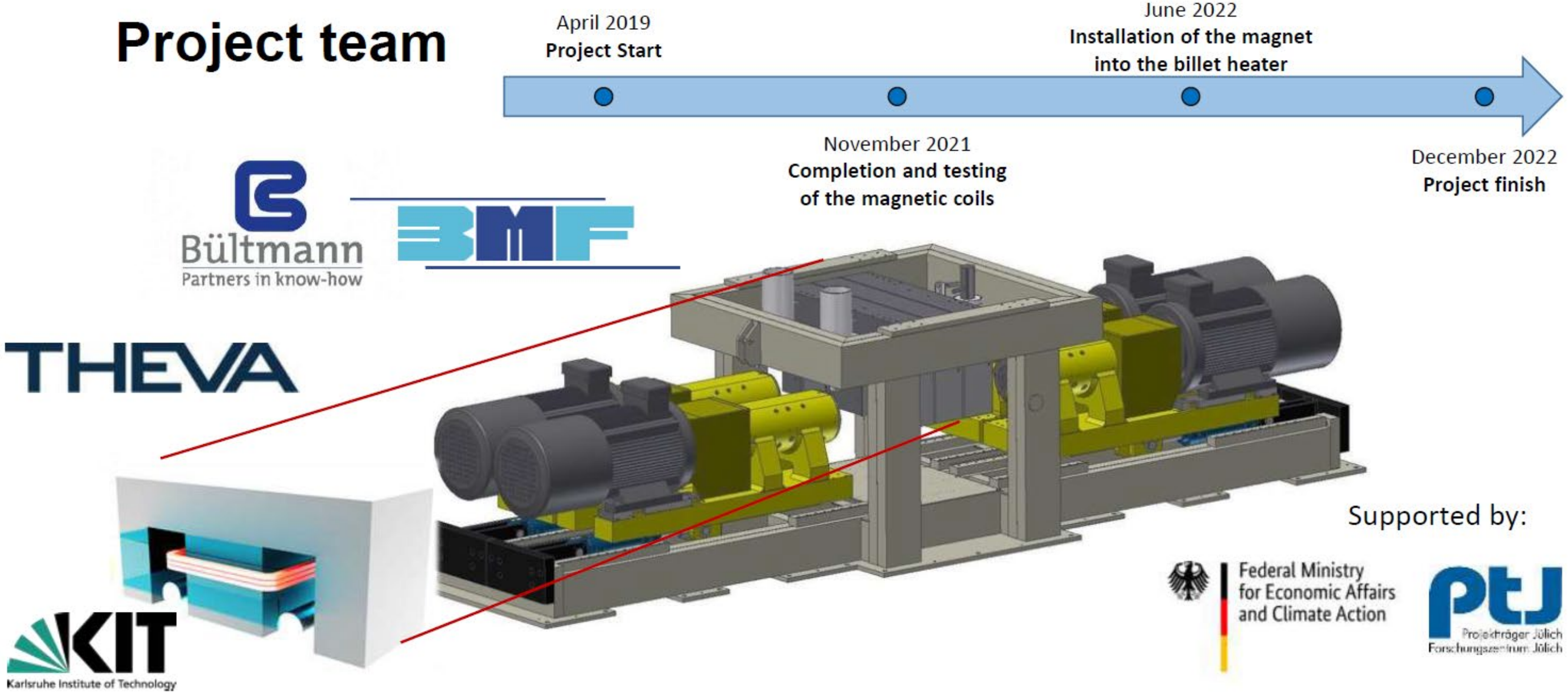
PROJECTS IN GERMANY

Bültman, KIT, THEVA

"RoWaMag" (Robuster und Wartungsarmer Magnetheizer mit Hochtemperatursupraleiter-Spulen für Warmumformprozesse)





- 3 double pancakes
- 127 turns per coil
- Operating current : 505 A
- HTS tape length : 3110 m

https://ivsupra.de/viii-ziehl-vortraege/

Magnetfeld am Billet	600…700 mT
Magnetfeld am Ende des Billets	500…550 mT
Billet-Länge	220…750 mm
Billet-Durchmesser	<225 mm
Max. Drehzahl	<16 Hz
Heizleistung	2×300 kW
Zwei-Schacht-Betrieb	✓

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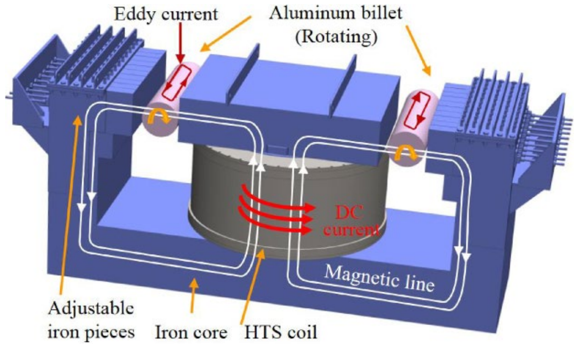
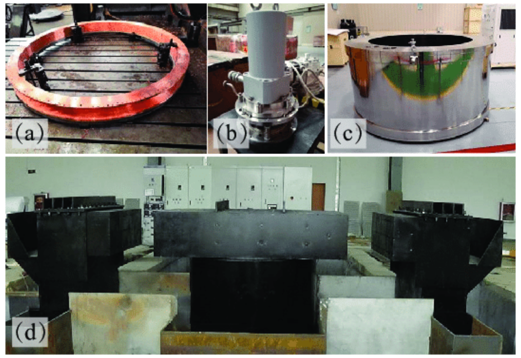
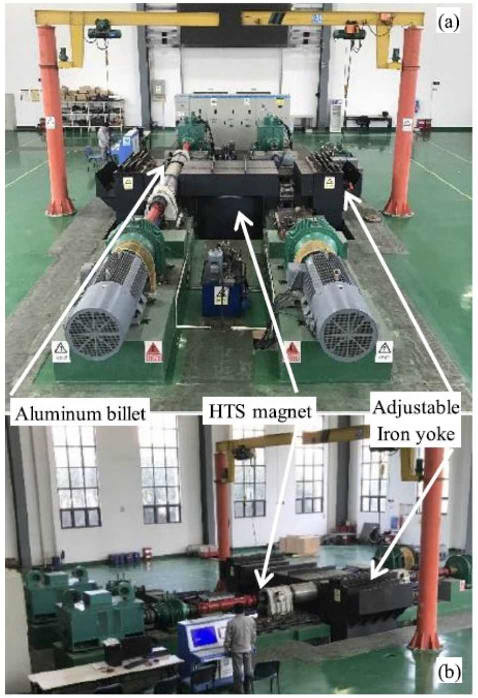
PROJECTS IN CHINA

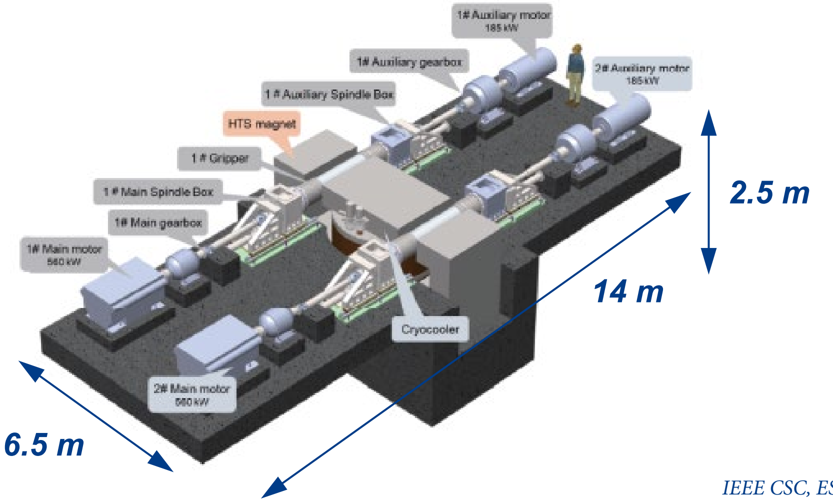
Beijing Jiaotong Uni., Shanghai ST, Jiangxi Lianchuang Optoelectronic Tech. etc.







Weight of iron core : 130 t



Parameters	Quantity
Maximum size of billets	Max.diameter 446 mm × Max.length 1500 mm
Work mode	Two billets synchronously
Operated heating power capacity	1.1 MW
Maximum system power capacity	1.2 MW
System energy efficiency	85 - 90%
Maximum excitation current	130 A @ 25 K
Magnetic field at air gap	> 0.45 T
Inductance of the HTS magnet with iron core	189 H
HTS tape maker	Shanghai Superconductor Technology Company Ltd, China
HTS tape	W4.8±0.1 mm × T0.43±0.02 μm
Motor type	3 phase induction motor
Rotation speed range of billets	240 - 720 rpm (4 - 12 Hz)
Heating period (from 20 to 500 °C)	12 minutes

Main parts	Parameters	Quantity
Heating method	Former material	Oxygen-free Copper
	Width/Thickness of ReBCO tape	4.8/0.43 mm
	Inner diameter	1900 mm
	Coil height	124 mm
	Coil turns	936
	Tape length per coil	5937 m
	Number of coils	3
HTS magnet	Number of turns in series	2808
	Inner / outer diameter	1942/2200 mm
	Height	622 mm
	Maximum operation current	130 A
	Total length of tape	18024 m
Cooling system	Rated temperature	25 K
	Refrigeration capacity	200 W
	Refrigerator	AL325
	Refrigerator quantity	2
Cryogenic vessel	Cryogenic vessel Inner diameter	1776 mm
	Outer diameter	2420 mm
	Height	1220 mm

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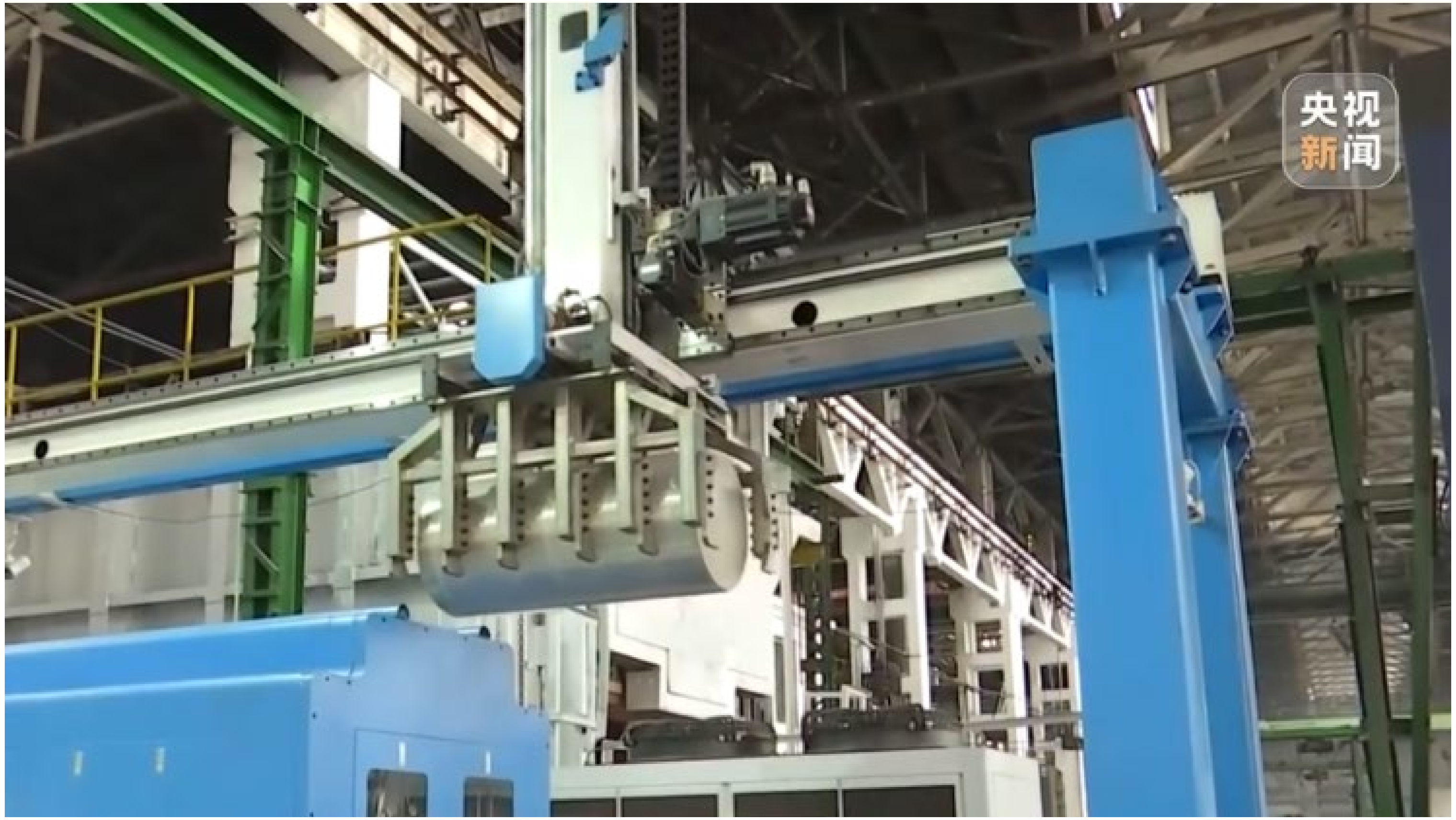
- *Installed and operated in Northeast Light Alloy Co., Ltd., Heilongjiang Aluminum Corporation of China*



Chinese Academy of Sciences, Press release April 24, 2023

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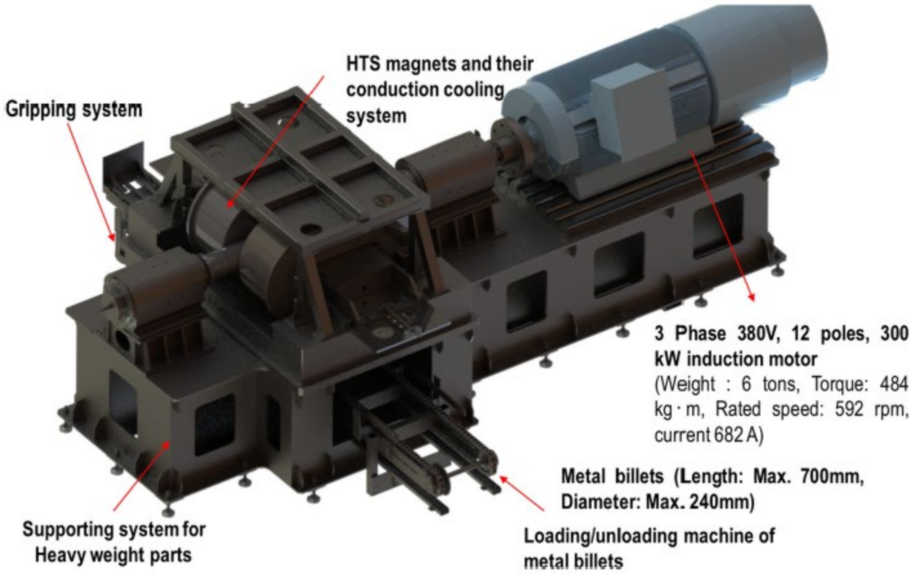
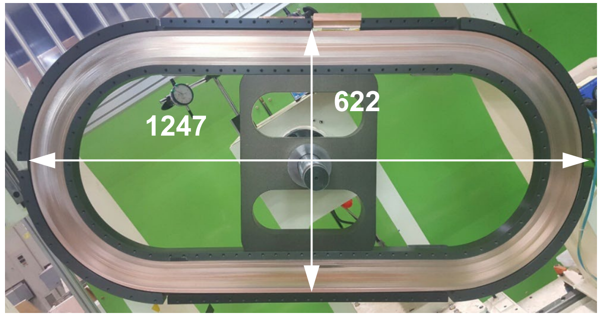
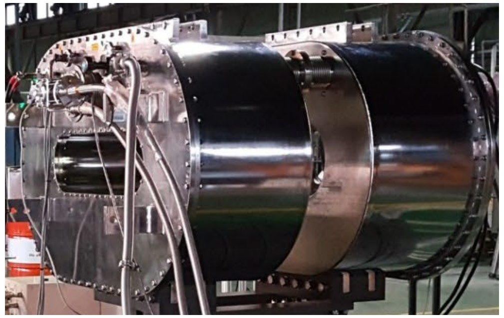
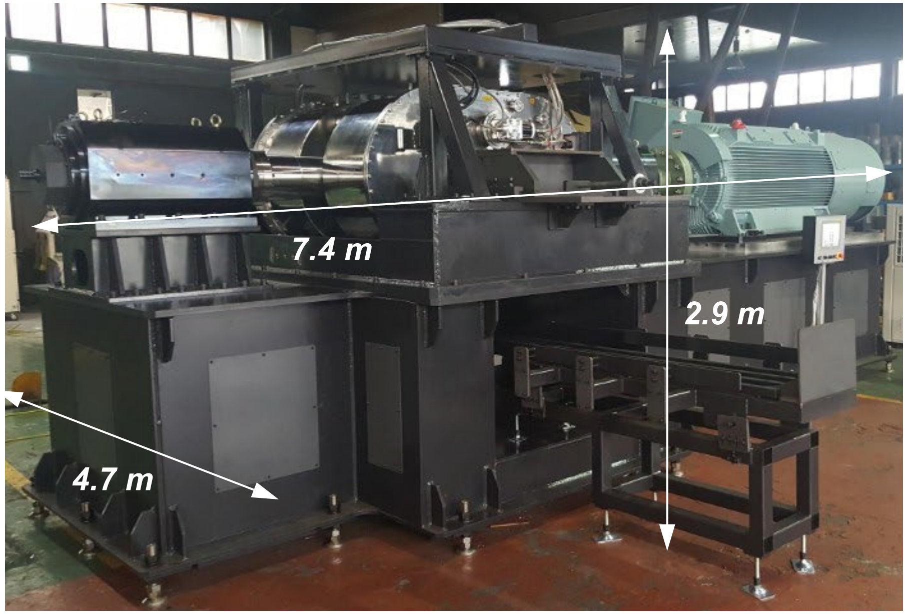
Supercoil









Item	Value
Heating capacity	~ 300 kW
System efficiency	~ 90%
Excitation current	≤650 A@10 K
Heating metal available	Stainless steel, copper, brass, aluminum billet
Billet size	Max. diameter 240 mm x Max. length 700 mm
Magnetic field range	≤1.5 T@10 K at the center of two magnets
Max. inductance	1.6 H with iron cores
Magnet type	HTS magnet, metal insulation, racetrack, a double pancake, iron cored type, stainless steel tape co-wound
HTS tape maker	SuNam, Korea
HTS tape	W12.1 (±0.1) mm × T100 (±15) μm
Motor type	3 phase induction motor by HYOSUNG, Korea
Rotational speed range	Max. 592 rpm (rated speed)
Machine size	Length 7.4 m x height 2.9 m x width 4.7 m
Machine weight	45 tons
Heating temperature	Dependent on the heating metal billet

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Supercoil

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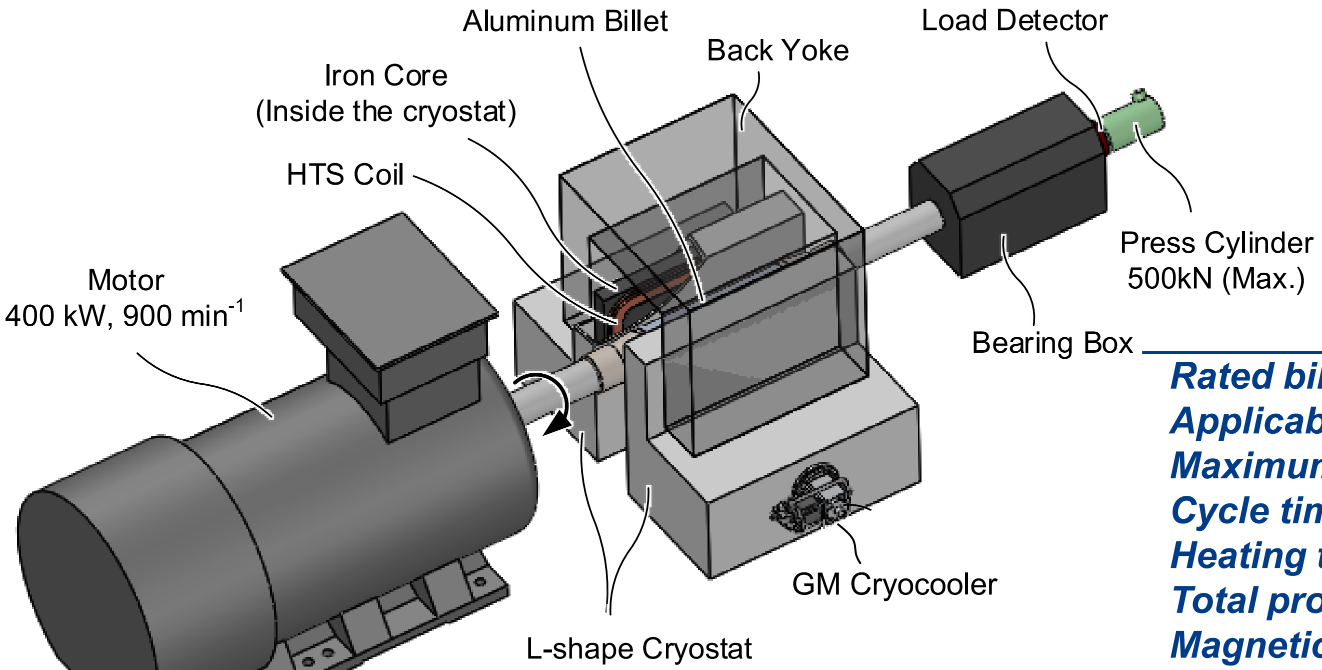

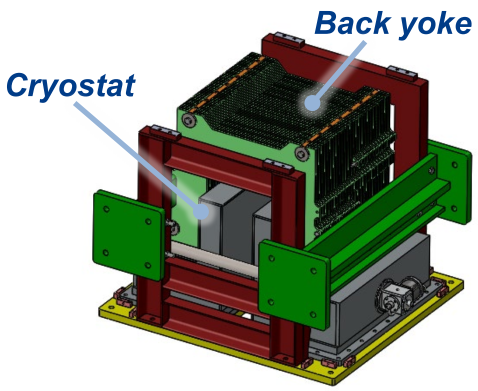

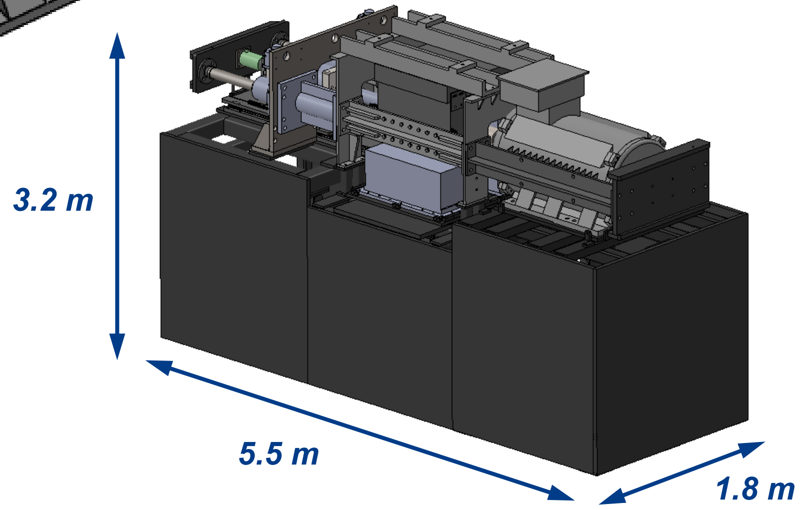

Rated billet size	*155 mm in diameter, 500 mm long*
Applicable billet length	*250 mm to 600 mm*
Maximum heating power	*400 kW*
Cycle time of heating process	*90 s (including billet change time)*
Heating time	*< 60 s*
Total process time	*90 s (insertion and ejection : 30 s)*
Magnetic field generator	*HTS magnet (NI winding)*
Type of HTS wire	*REBCO tape (12 mm x 110 μm)*
Rated HTS coil current	*200 A*
Magnetic flux density at the center of the heating region	*1.06 T*
Cooling system of HTS coil	*10 K two-stage GM cryocooler*
Driving system	*3- ph. induction motor + inverter*
Revolution speed	*0 ~ 900 min^{-1}*
Approx. external dimensions	*W 5.5 m, D 1.8 m, H 3.2 m*
Approx. mass	*10 t*

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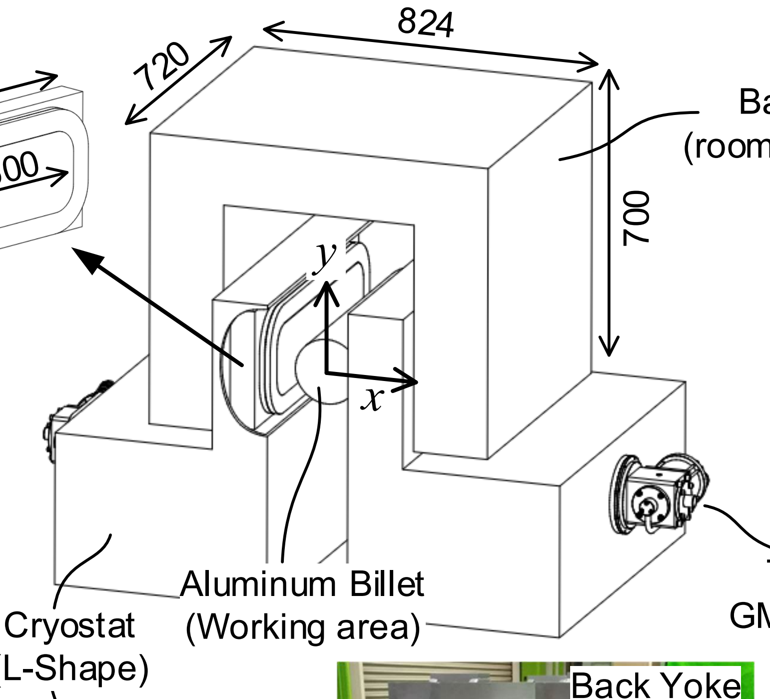
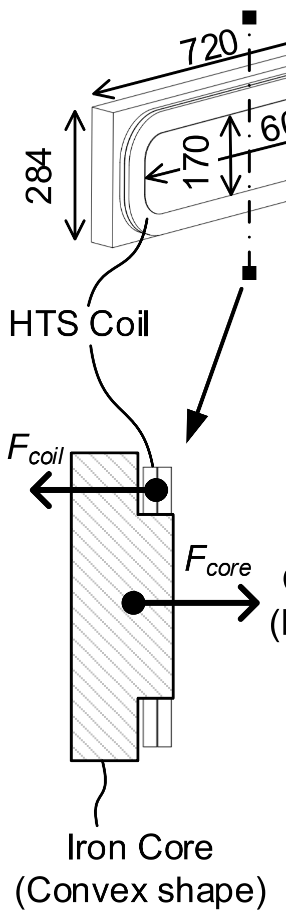
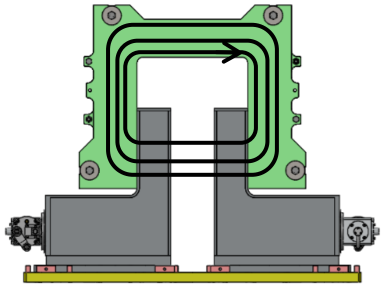
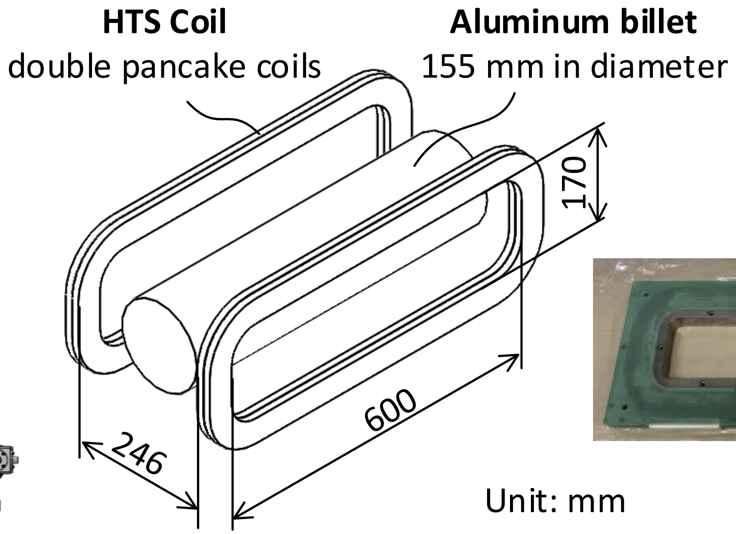
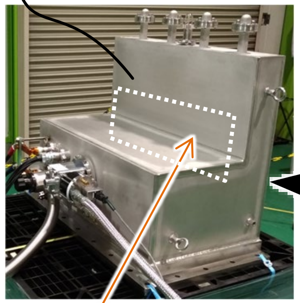
PROJECT IN JAPAN



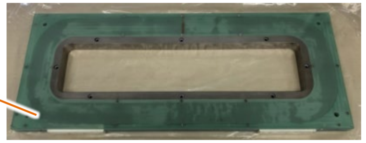








HTS coil with iron pole



SPECIFICATIONS OF HTS COIL

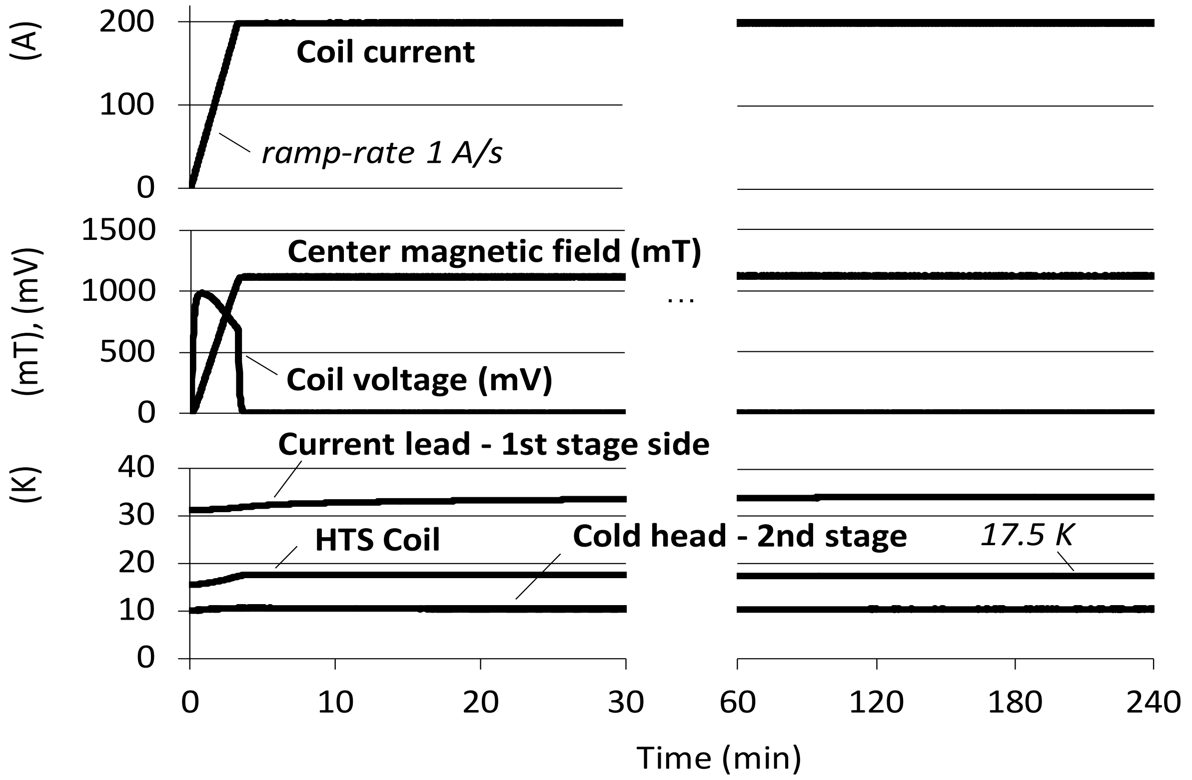
HTS tape	*REBCO tape (ʷ12 mm, ᵗ110 μm) (SuperOx)*
Rated current	*200 A*
Number of turns	*1400 turns (700 turns / DP × 2 DP coils)*
Number of coils	*4 SP coils (series connection)*
Total tape length	*around 2.3 km*
Structure	*no-insulation, SUS-tape co-wound*
Coil cooling method	*Conduction-cooling by cryocooler*
Coil temperature	*below 20 K*

T. Ito, S. Fukui, H. Kawashima, Y. Ogata, M. Furuse, T. Watanabe, S. Nagaya, and J. Ogawa, "Fabrication and Test of HTS Magnet for Induction Heating Device in Aluminum Extrusion Processing," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 4, 2022, Art. no. 4600205.

PROJECT IN JAPAN

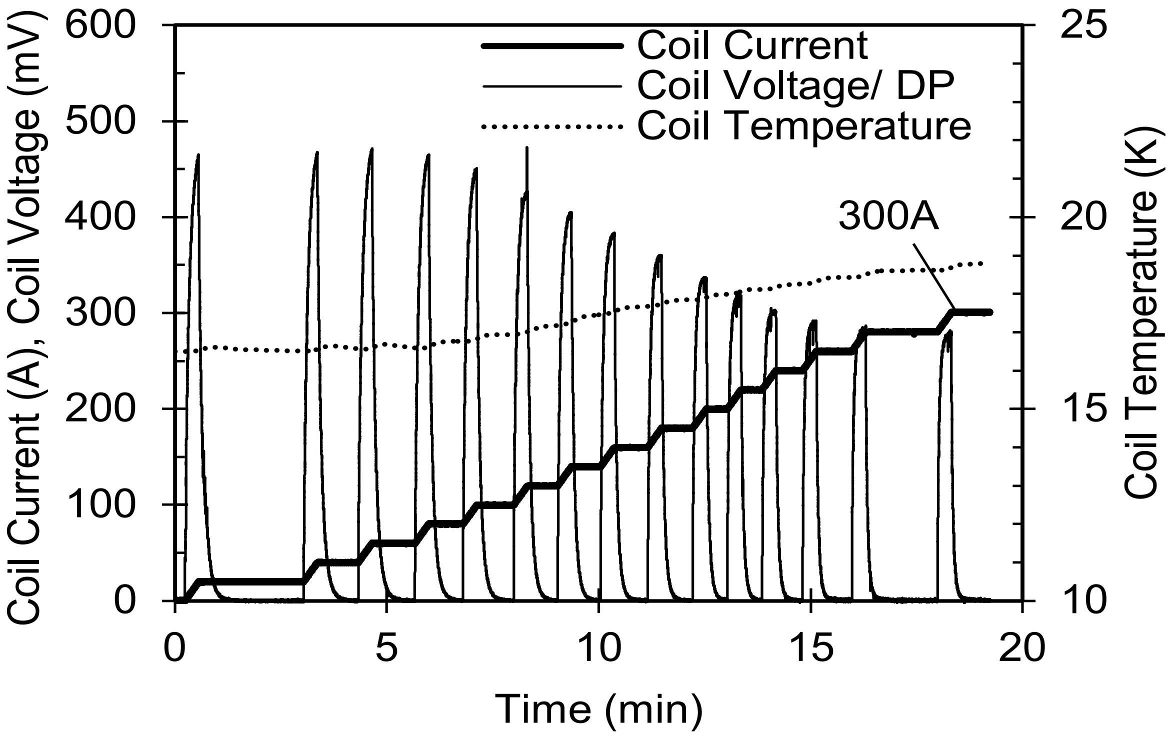
Continuous charging test

- 200 A continuous current test was conducted for 4 hours.
- There were no signal of normal transition in coil voltage and temperature of each part.
- Coil temperature was kept around 17.5 K.



Over rated current excitation test

- HTS magnet can be stably charged without normal transition
- Coil temperature is kept within about 18 K.



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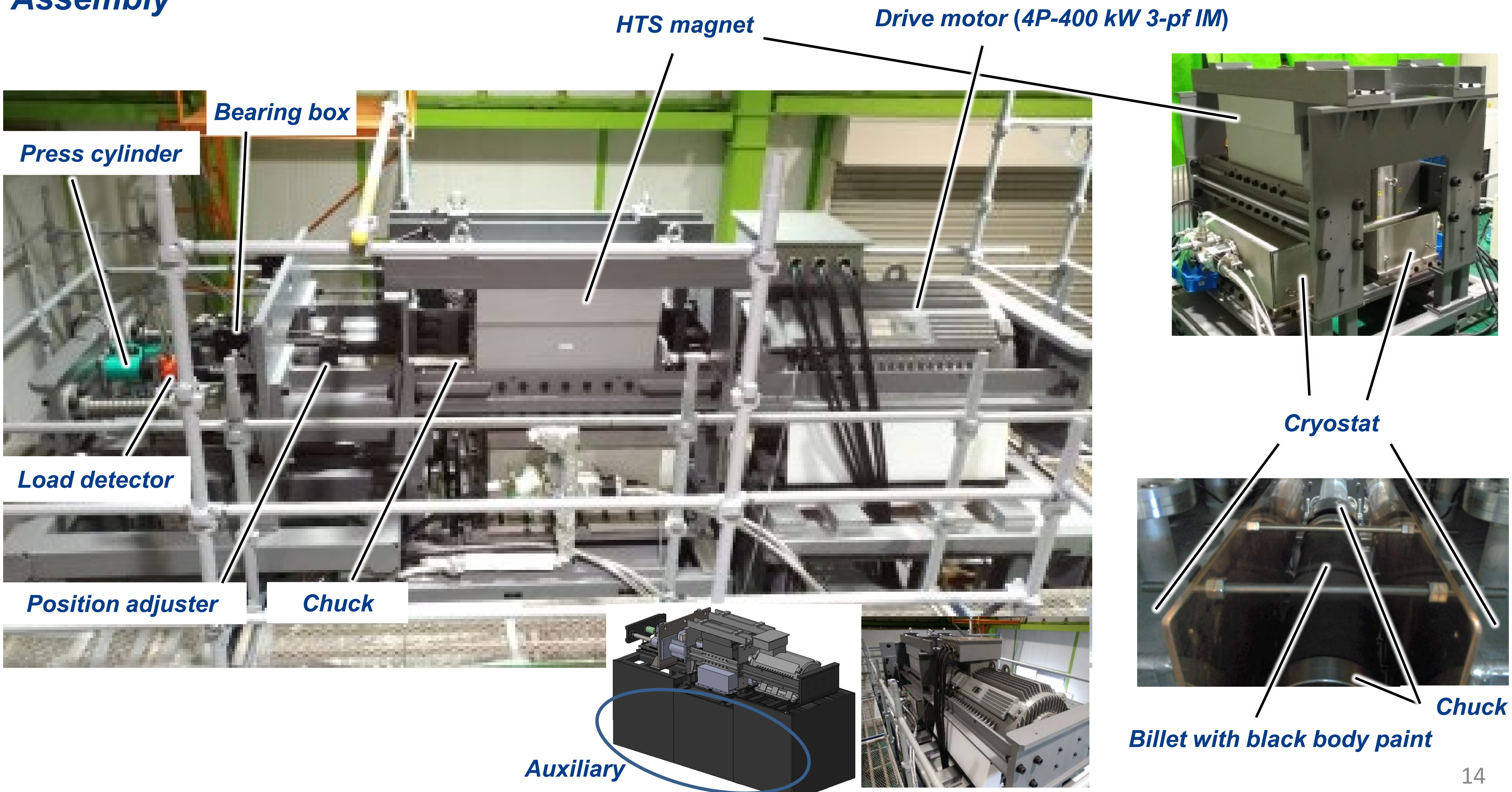
Assembly

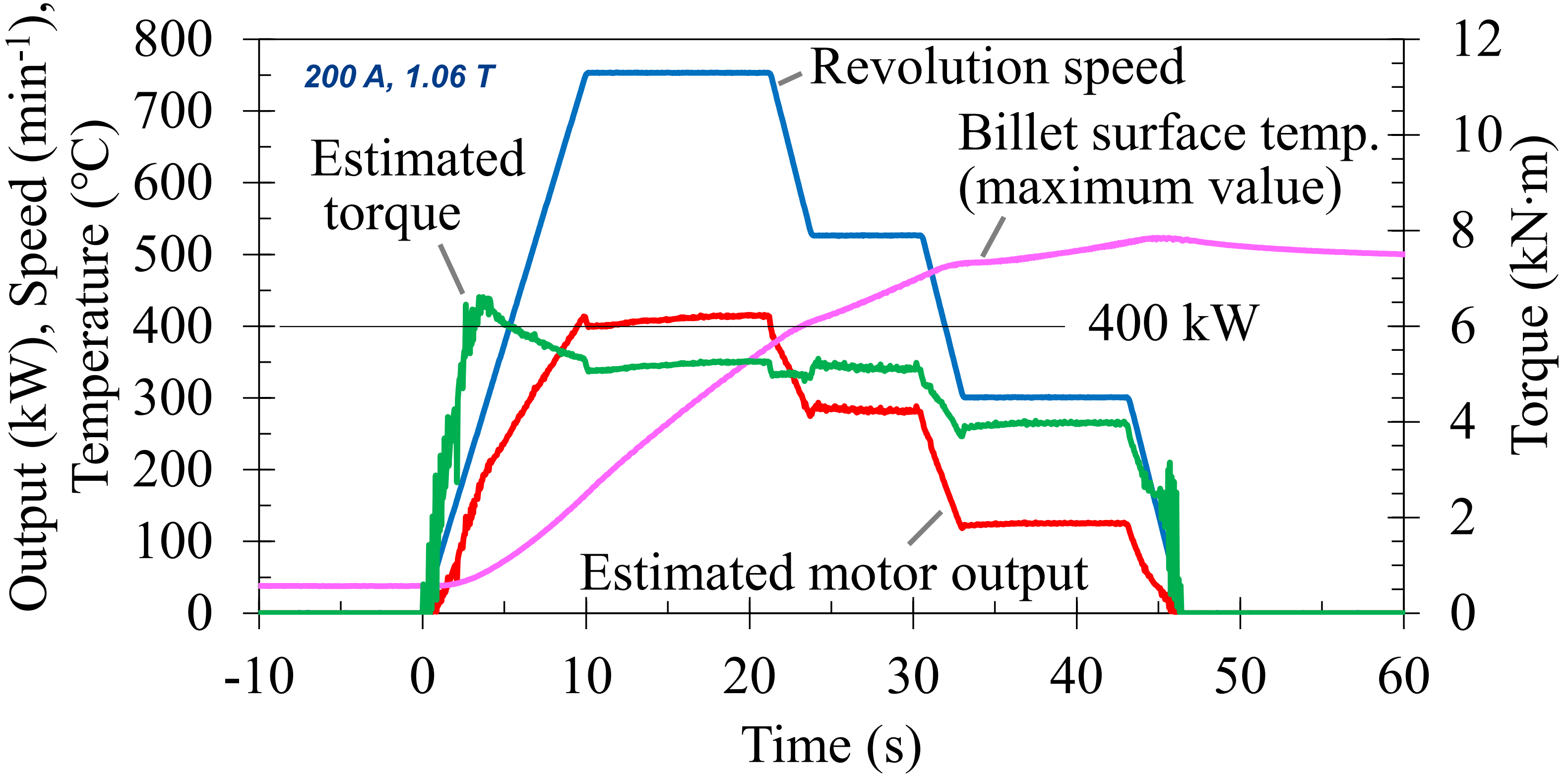


HTS magnet
Drive motor (4P-400 kW 3-pf IM)
Bearing box
Press cylinder
Load detector
Position adjuster
Chuck
Auxiliary
Cryostat
Chuck
Billet with black body paint

PROJECT IN JAPAN

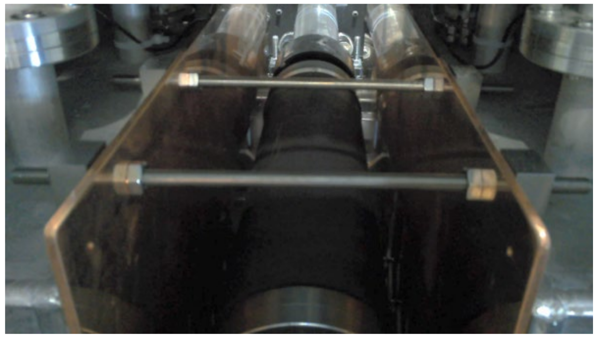
Heating test

- Heating test to demonstrate 400 kW heating power input to the aluminum billet.
- Output power of derive motor was estimated from motor input supposing that motor efficiency = 0.95.
- Torque was estimated from estimated motor output and revolution speed.
- Billet surface temperature was monitored by using the thermography camera.
- Maximum motor output (i.e. input heating power) exceeded 400 kW.



TEST CONDITIONS

Billet size	ϕ 155 mm, l 500 mm
Coil current	200 A
Magnetic field	1.06 T at center
Revolution	0 ~ 750 min^{-1}



T. Ito, S. Fukui, H. Kawashima, Y. Ogata, T. Sho, M. Furuse, T. Watanabe, S. Nagaya, J. Ogawa, Y. Morishita, N. Fuyama, T. Nagaoka, N. Nawachi, "Development of 400 kW Class Aluminum Billet Heater using HTS Magnet", IEEE Trans. Appl. Supercond., vol. 33, no. 5, 4600505 2023

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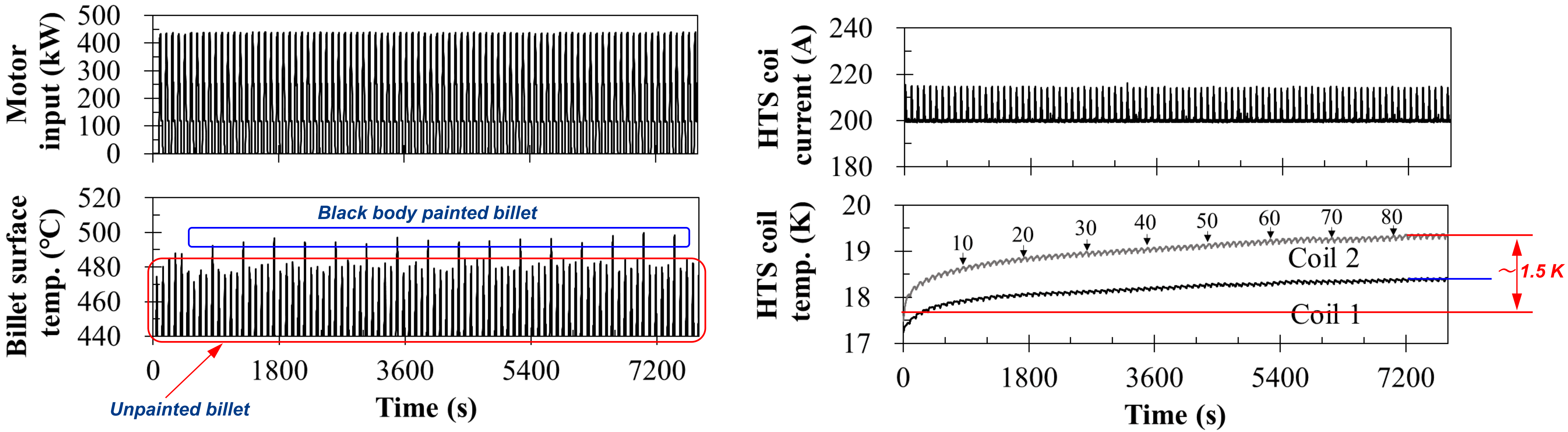
- Continuous repetitive heating test (90 billets, 2.25 hour) to confirm :

Stable heating at rated power of 400 kW

Effect on temperature rise of HTS coils

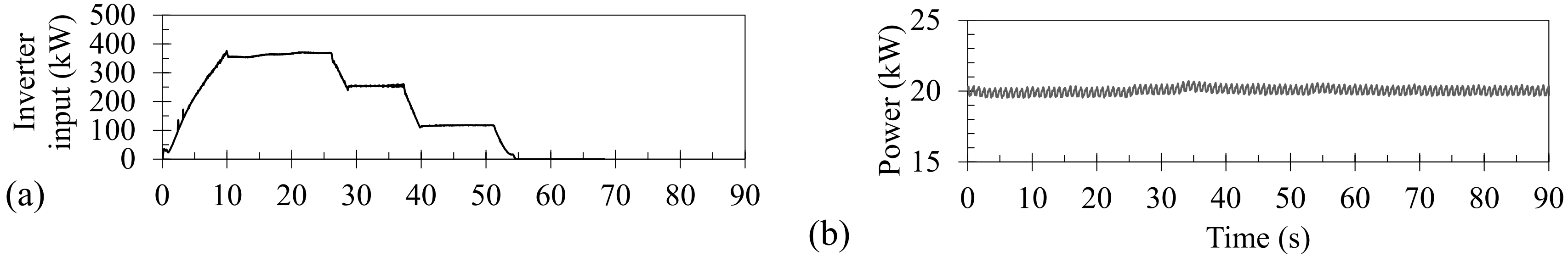


IEEE CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 58, Feb. 2025. Presentation given at ISS 2024, Kanazawa, Japan, Dec. 3-5, 2024.

PROJECT IN JAPAN

Energy efficiency

- Radial heat diffusion was achieved to be equilibrium in 10 s after stopping of rotation (i.e. 65 s).
  → Average temperature of billet : 455 ℃ using the data at 65 s
- Theoretical energy used for temperature rise : 25 kg × 1.002 kJ/kg·K × (455 ℃ - 20 ℃) = **10.9 MJ**
  25 kg : mass of the billet 1.002 kJ/kg·K : average specific heat between 20 – 455 ℃.
- Total input energy to demonstration device : **14.6 MJ**
  (integration of input electric power to inverter and auxiliary over 90 s)

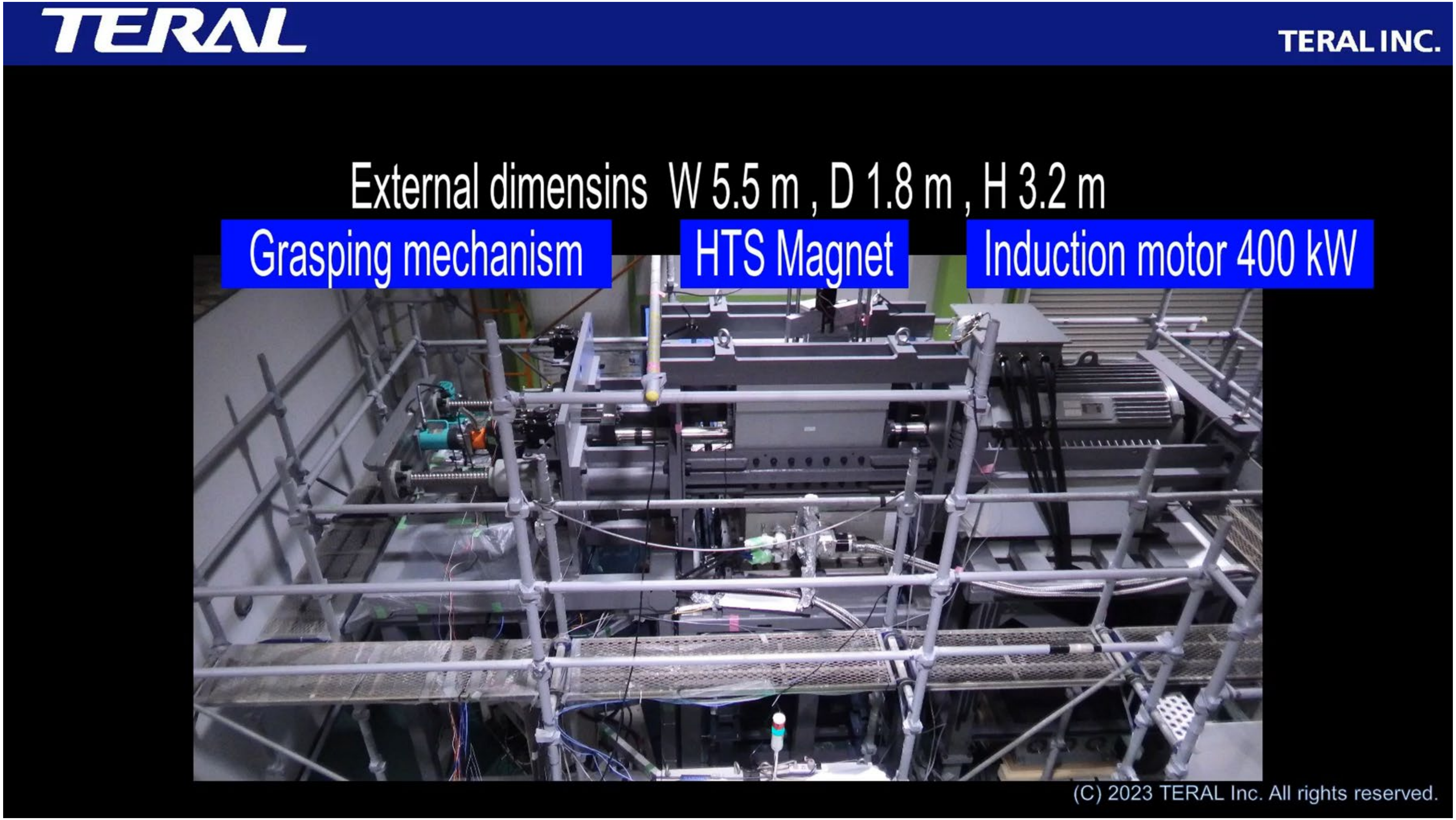


→ Energy efficiency : **74.5 %**.

Cycle time of heating process	90	s
Average billet temperature 10 seconds after heating	455	℃
Theoretical energy required for billet heating	10.9	MJ
Energy input of the drive system	12.75	MJ
Energy input of auxiliaries	1.85	MJ
Total energy consumption	14.6	MJ
Energy efficiency	74.5	%

T. Ito, S. Fukui, H. Kawashima, Y. Ogata, T. Sho, M. Furuse, T. Watanabe, S. Nagaya, J. Ogawa, Y. Morishita, N. Fuyama, T. Nagaoka, N. Nawachi, "Development of 400 kW Class Aluminum Billet Heater using HTS Magnet", IEEE Trans. Appl. Supercond., vol. 33, no. 5, 4600505 2023

HEATING DEMO



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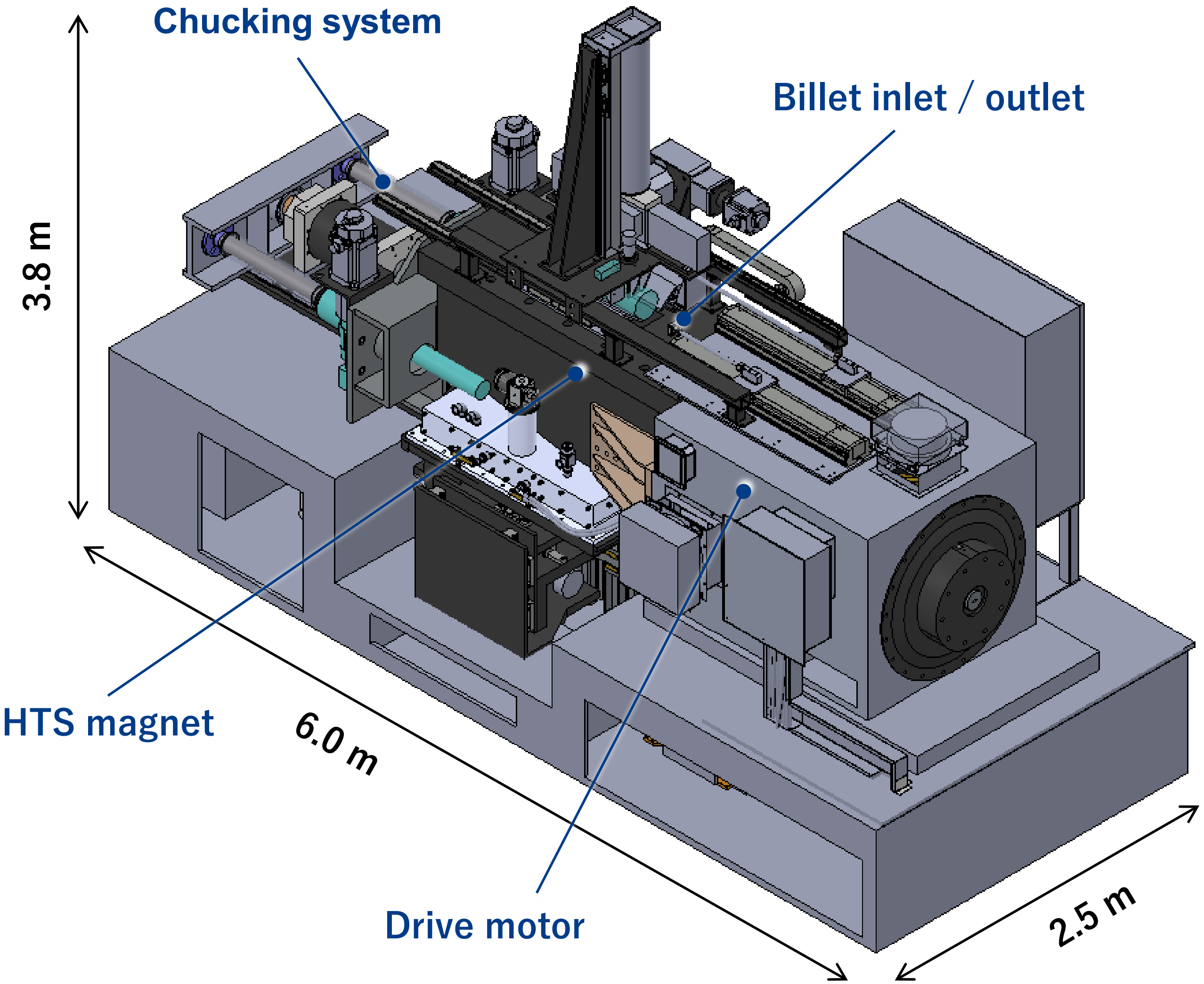
- 750 kW device for commercialization



Billet size	7-inch × 800 mm
Output	750 kW
Processing time	90 s
Magnetic field	1 T @ 330 A
Revolution	900 rpm
Size	L 6 m, H 2.5 m, W 2.5 m
Weight	30 t

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COMPARISON OF FEATURES

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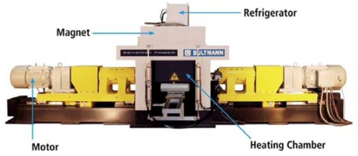
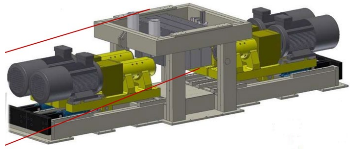
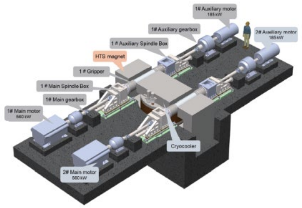
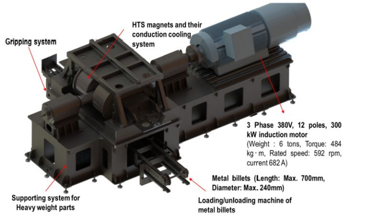
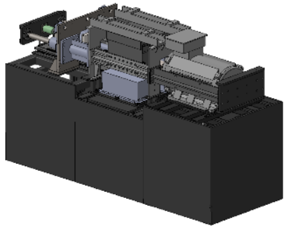
	Germany	Germany RoWaMag	China	Korea	Japan
Output	360 kW	2× 300 kW	1.1 MW	300 kW	400 kW
Billet size	5 – 7 inch× 690 mm	5 – 7 inch× 750 mm	Φ 446× 1500 mm	Φ 230× 700 mm	5 inch× 500 mm
HTS coil	BSCCO (Sumitomo) W 4.2 mm× t 2.7 mm Racetrack, Pancake --- Ic : 125 A @ 40 K, 1 T Iop : 100 A @ 22 – 24 K Tape length : --- GM cryo-cooler× 1	RECO (THEVA) Rectangular, Pancake 127 turns/coil ×3 coils Ic : --- Iop : 505 A Tape length : 3110 m	REBCO (Shanghai ST) W 4.8 mm× t 0.43 mm Circular, Pancake 936 turns/coil ×3 coils Ic : 170 A @ 30 K (coil) Iop : 130 A @ 25 K Tape length : 18024 m GM cryo-cooler× 2	REBCO (SuNAM) W 12.1 mm× t 0.1 mm Racetrack, Pancake 300 turns/coil ×2 coils Ic : --- Iop : 440 A @ 10 K Tape length : 3407 m GM cryo-cooler× 2	REBCO (SuperOX) W 12 mm× t 0.11 mm Racetrack, Pancake 700 turns/coil ×2 coils Ic : 600 A @ 40 K, 2.5 T Iop : 200 A @ 20 K Tape length : 2300 m GM cryo-cooler× 2
Magnetic field	---	0.6 - 0.7 T	0.46 T (@ 130 A)	1.3 T (@ 440 A)	1.06 T (@ 200 A)
Drive motor	2 motors 240 – 750 rpm	2 motors 96 rpm	Main : 560 kW× 2 motors Sub : 185 kW× 2 motors 240 – 720 rpm	300 kW× 1 motor 300 – 600 rpm	400 kW× 1 motor 250 – 750 rpm
Heating time	140 s (Φ 155× 690 mm)	---	12 min (Φ 446× 1500 mm)	200 s (Φ 230× 700 mm)	60 s (5 inch× 500 mm)
Efficiency	80 %	---	80.6 %	89.7 %	74.5 %
Size Weight	--- ---	--- ---	L 14 m× H 2.5 m× W 6.5 m > 130 t (iron cores)	L 7.4 m× H 2.9 m× W 4.7 m 45 t	L 5.5 m× H 3.2 m× W 1.8 m 10 t
					

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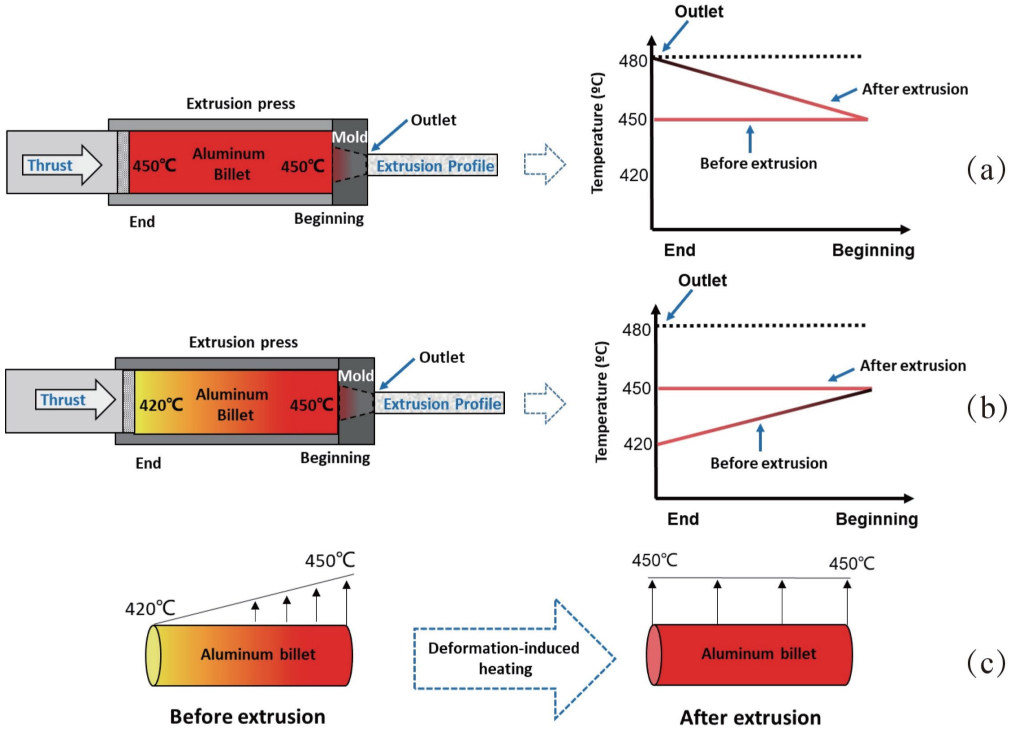
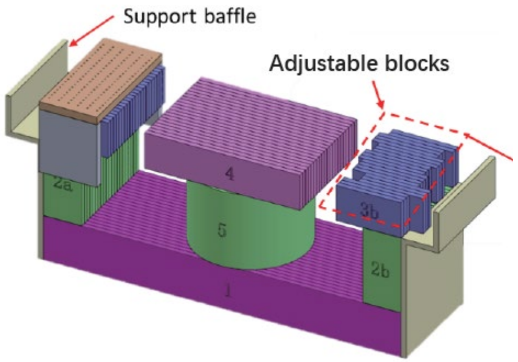
FUTURE TECHNICAL ISSUES

- Taper heating : Temperature gradient along billet axis





During the extrusion process, friction and deformation will generate heat on aluminum billet.

⇒ Temperature at pressing end should be lower.

S. Dai et al., IEEE Access, vol. 9, pp. 3301-3314, 2021.

- Use of 'offcut' billets

How to rotate combination of different length offcut billets ?

- Total energy efficiency

Refrigeration power at night and on holidays

5 - 10 kW / GM refrigerator, 3 – 5 kW / chiller

- High price of HTS wire

Payback period

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Thank you for attention.

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