AP2-2-INV

Development of 400 kW class induction heating device for aluminum billets using HTS magnet

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T. Watanabe, S. Nagaya : Chubu Electric Power Co. Inc.
Y. Morishita, N. Fuyama, T. Nagaoka, N. Nawachi : Hiroshima Prefectural Technology Research Institute

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R & D CONSORTIUM

TERAL Inc. (PL)

Total design & development, Grasping and rotating system

Niigata University (SL)

Total design, Numerical analysis, HTS magnet

AIST (National Institute of Advanced Industrial Science and Technology)

Cooling system

Chubu Electric Power Co., Ltd.

HTS Coil

HiTRI (Hiroshima Prefectural Technology Research Institute)

Measurement of physical properties of materials

Yasuda Metal Industries, Ltd. (Advisor)

Advice for the project

OUTLINE

- ***Introduction and Objectives***
- ***400 kW - class Demonstration Device***
  - ***Specification and structure***
  - ***HTS magnet, rotation system of aluminum billet***
- ***Heating Test Results***
  - ***Demonstration of 400 kW heating power input***
  - ***Investigation of heating uniformity***
- ***Energy Efficiency***
- ***Summary***

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Aluminum hot extrusion process

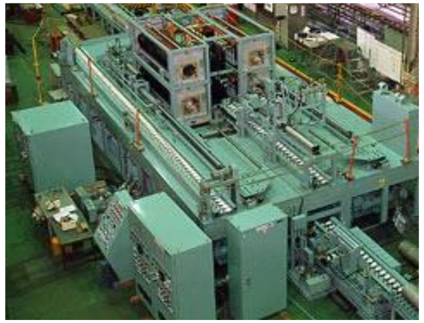
Material

https://www.nikkeikin.co.jp/billet/

Aluminum billet

Heating process

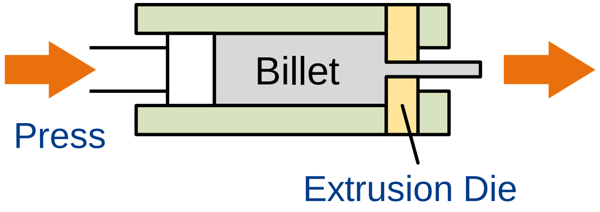
High Frequency AC Induction Heater



https://www.fujielectric.co.jp/products/ihsys/products/heat/heat_02.html

Extrusion process

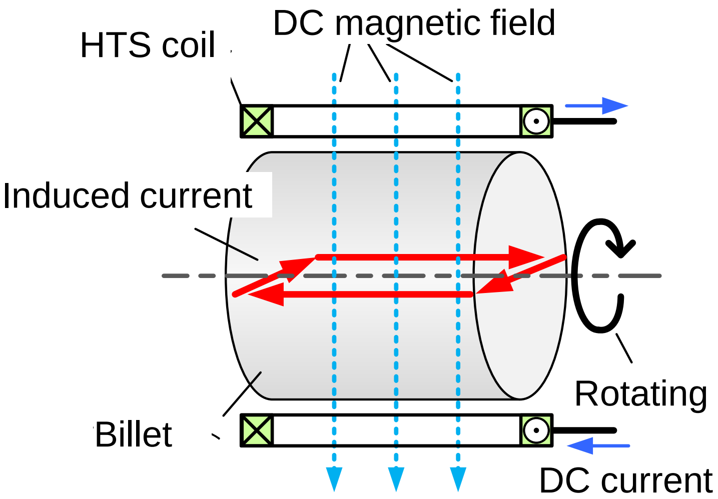
Extrusion Machine



Final products

https://uexo.uacj-group.com/products.html

- ***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 realize large heating capacity together with higher energy efficiency and faster heating.***



HTS DC induction heating

INTRODUCTION AND OBJECTIVES

Heating power

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

Magnetic field — Frequency

Key aspects

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

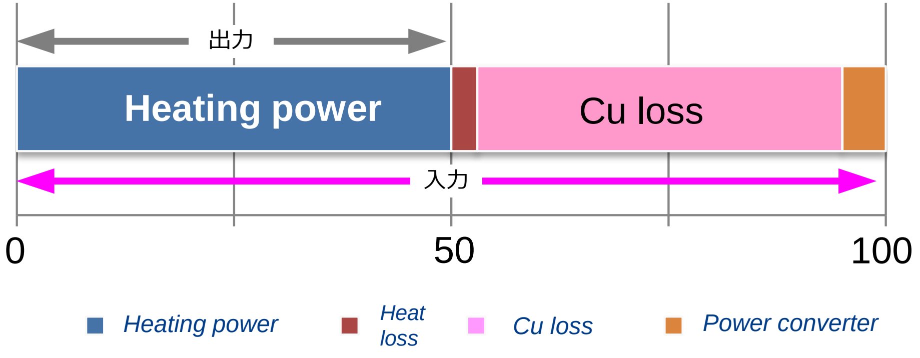
High Frequency AC Induction Heater

- 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

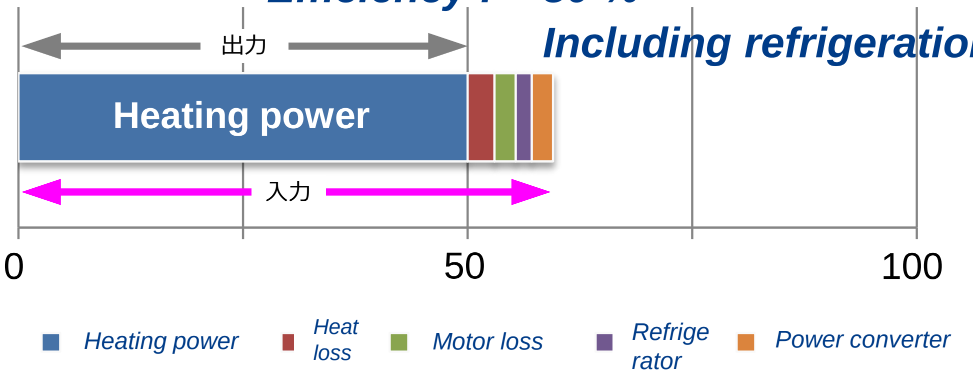
HTS DC Induction Heater

- 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

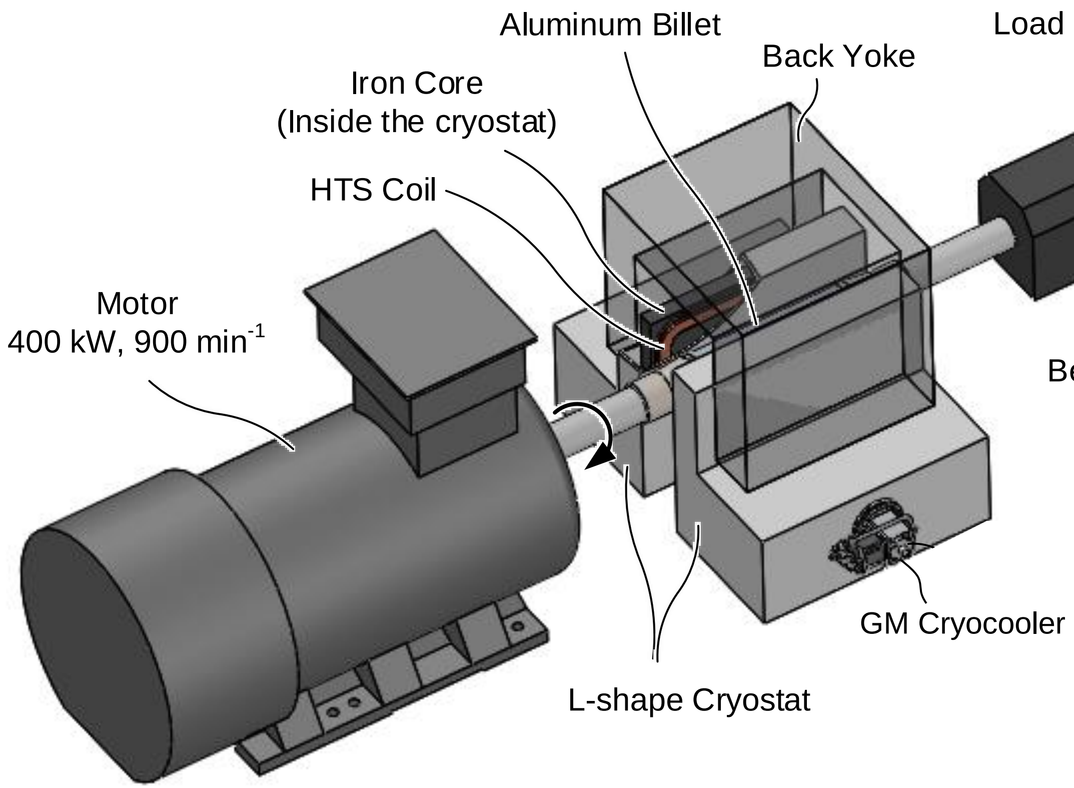
Efficiency : ～ 50 %

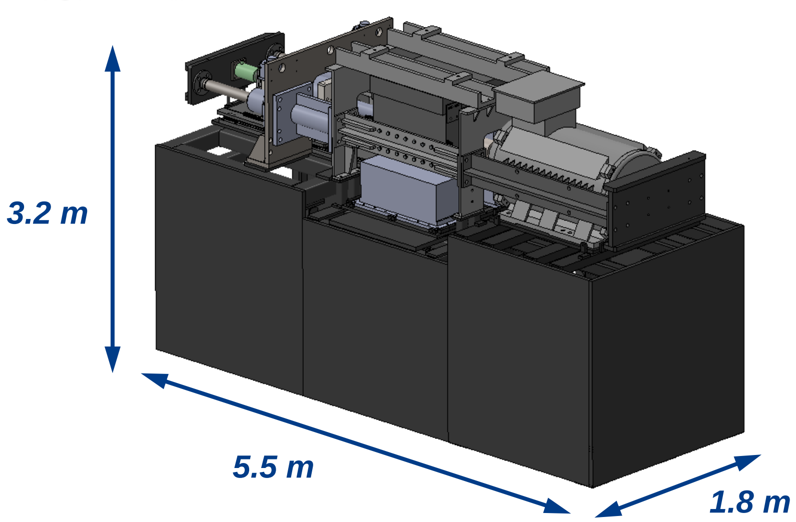


Efficiency : > 80 %
Including refrigeration power



400 kW-CLASS DEMONSTRATION DEVICE





Specification of Demonstration Device

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 processing time	< 60 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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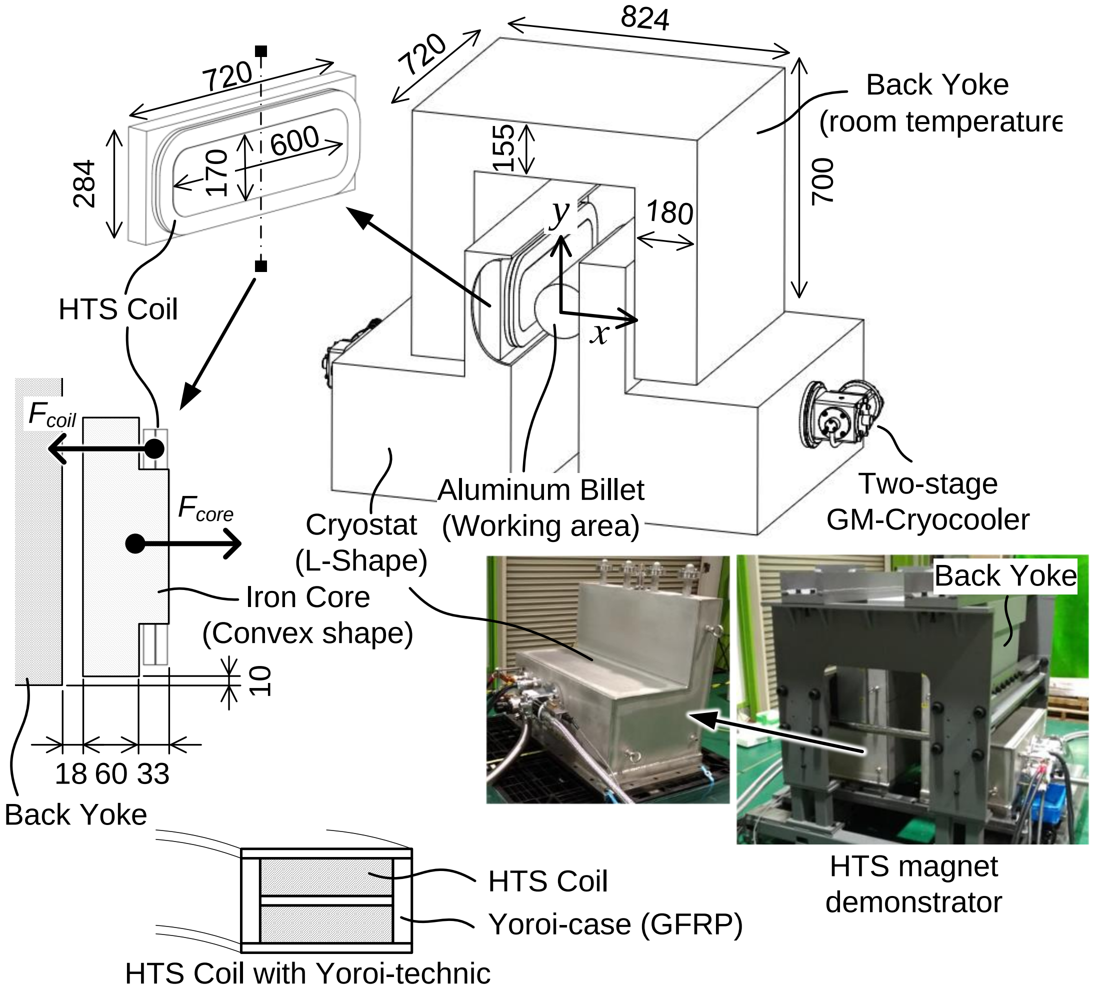
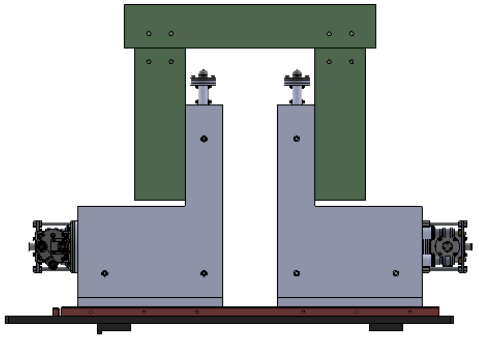
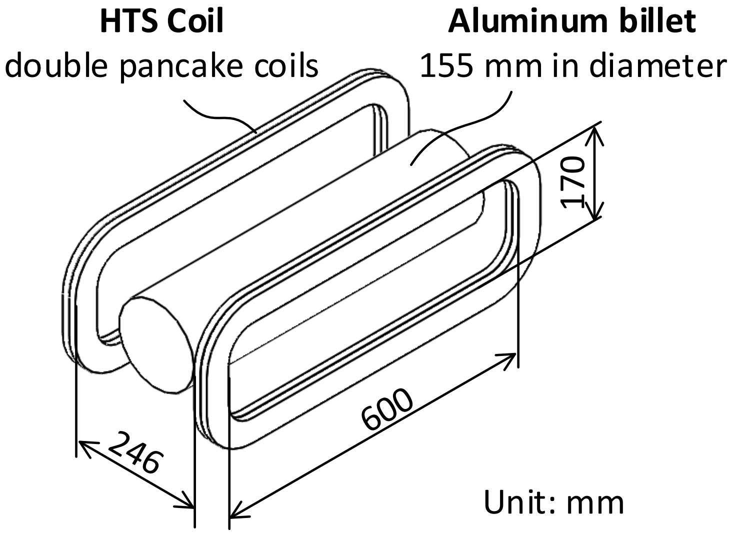
HTS magnet







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, Jun. 2022, Art. no. 4600205.

SPECIFICATIONS OF HTS COIL

HTS tape	*REBCO tape (^{w}12 mm, ^{t}110 μm) (SuperOx)*
Rated current	*200 A*
Number of turns	*1400 turns (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*

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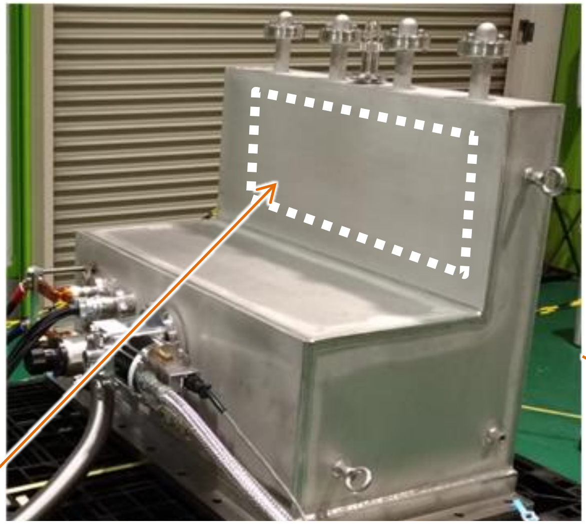
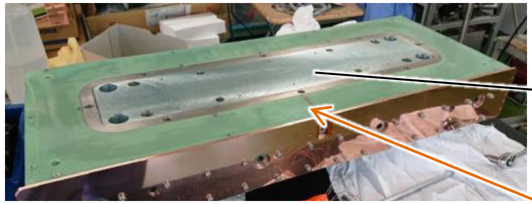
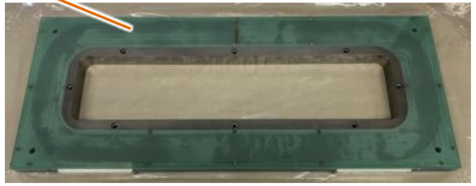
HTS magnet



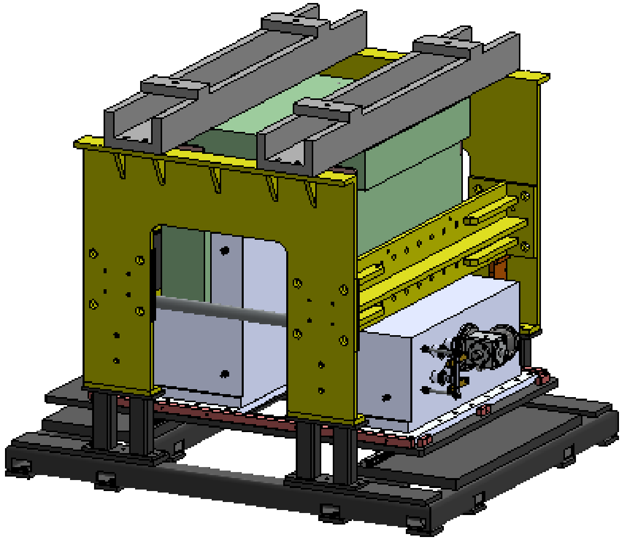
L-shape cryostat

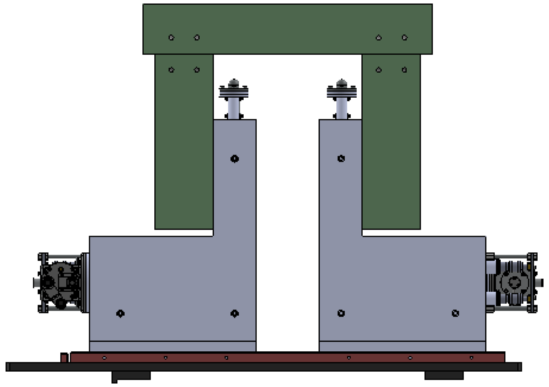


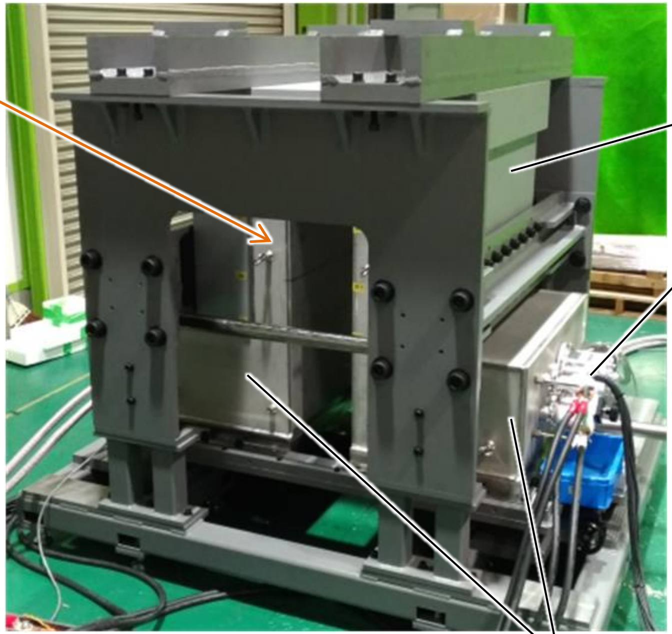


Iron pole

HTS coil with iron pole







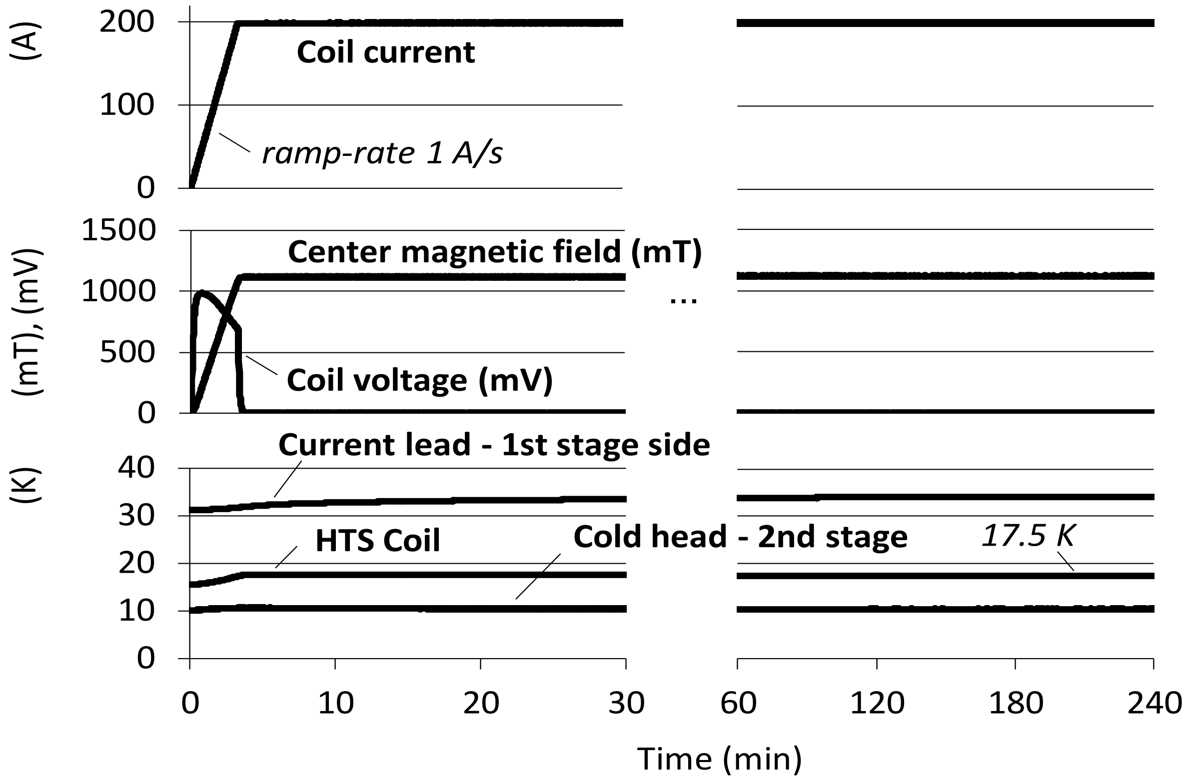
Back yoke

GM cryocooler

L-shape cryostat

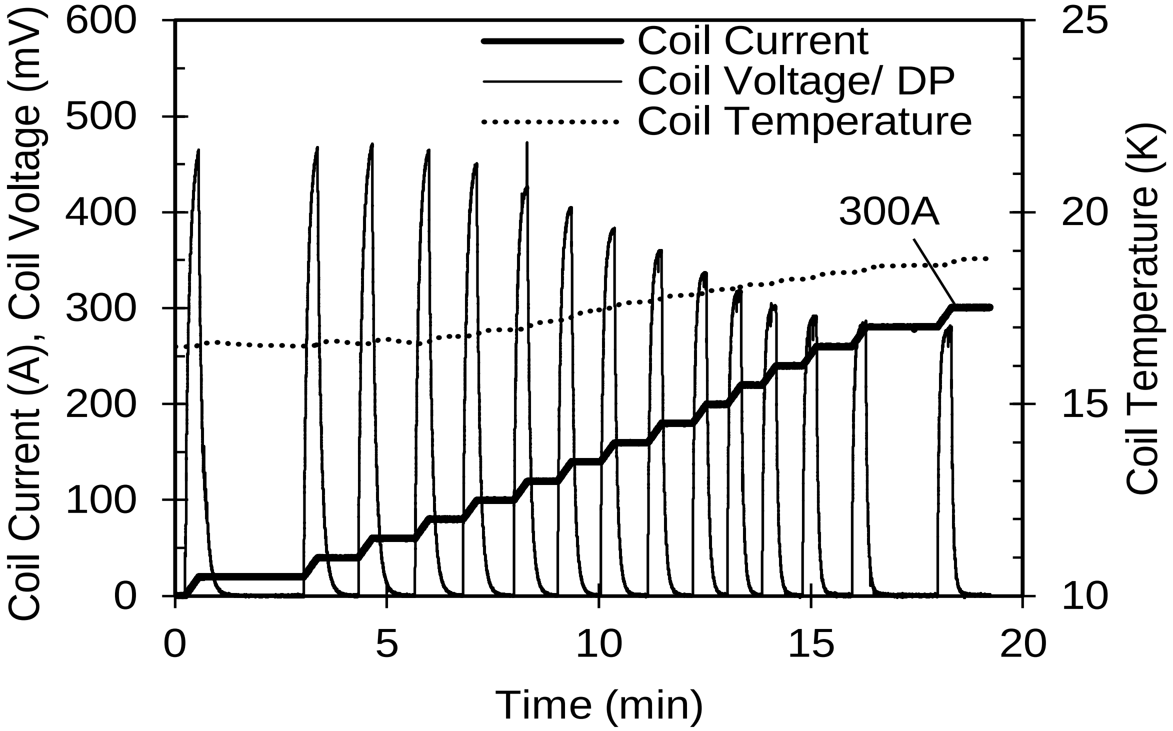
Continuous charging test

- ***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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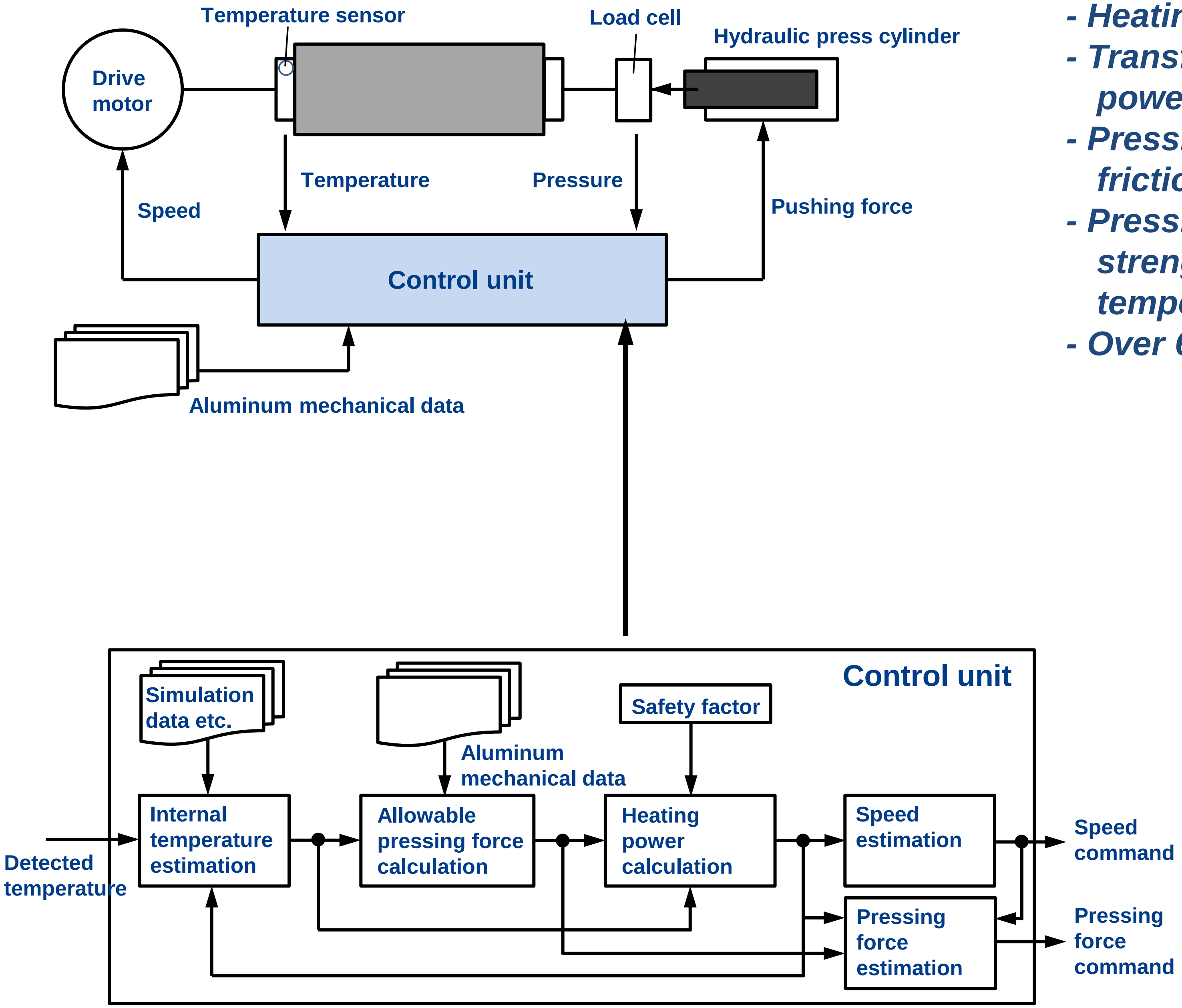
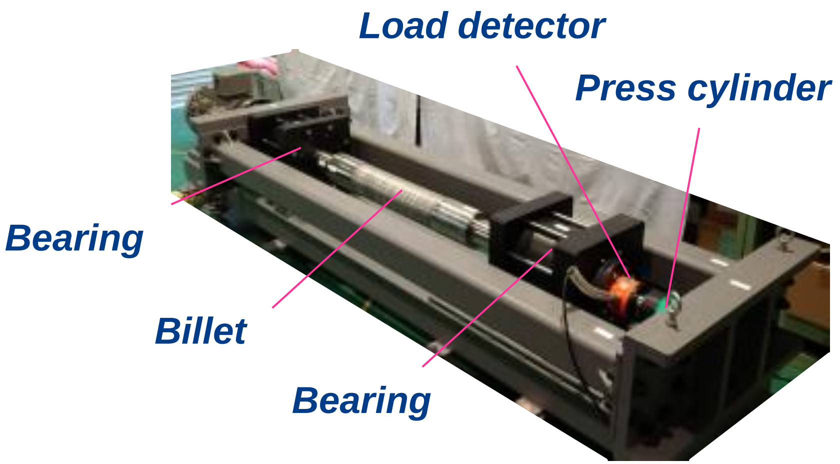
Grasping mechanism



- *Heating power is decided from revolution.*
- *Transfer torque to billet is decided from heating power.*
- *Pressing force is decided from transfer torque and frictional coefficient.*
- *Pressing force must be lower than mechanical strength of aluminum billet depending on its temperature.*
- *Over 6000 Nm torque can be transmitted.*



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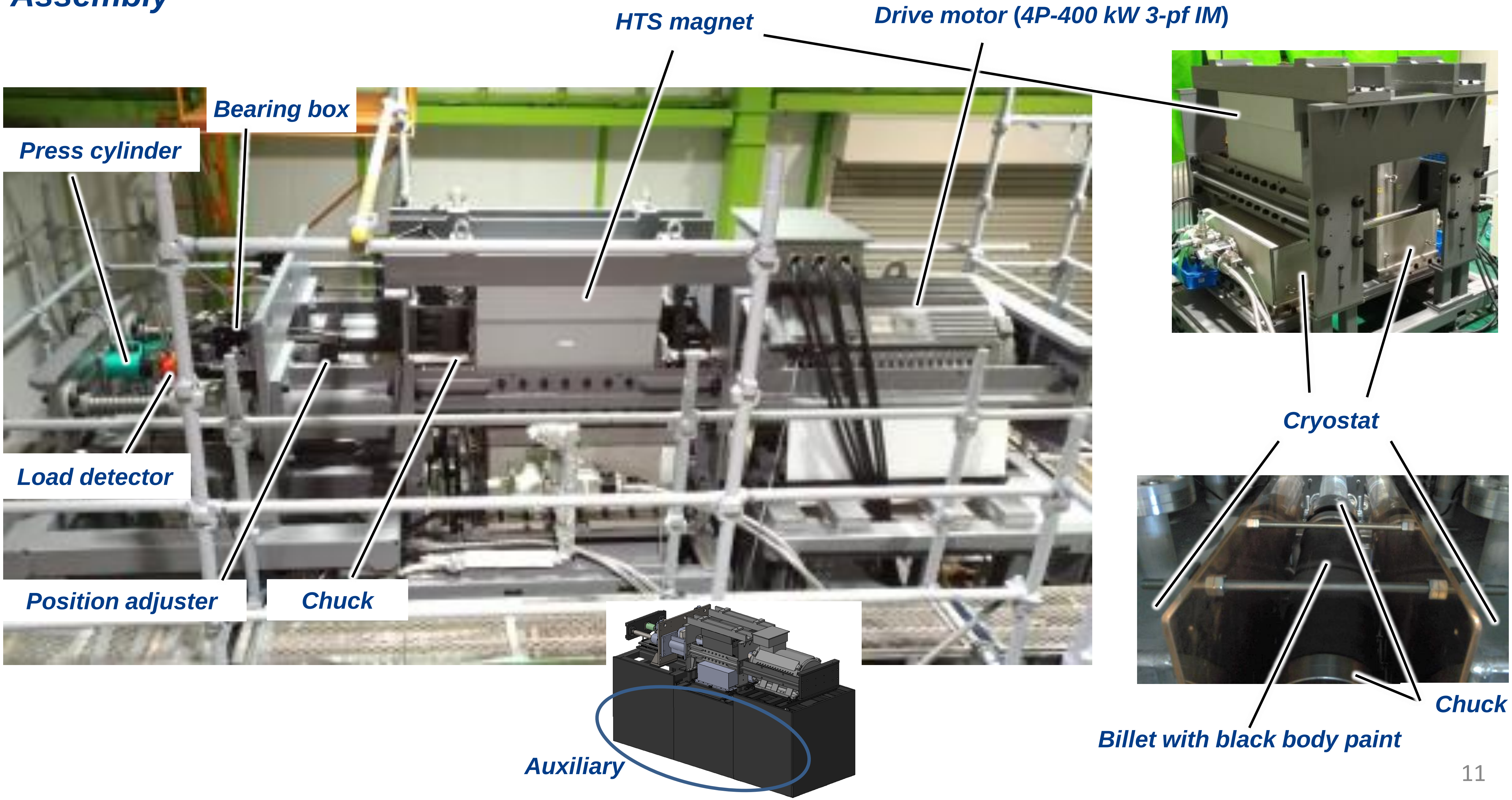
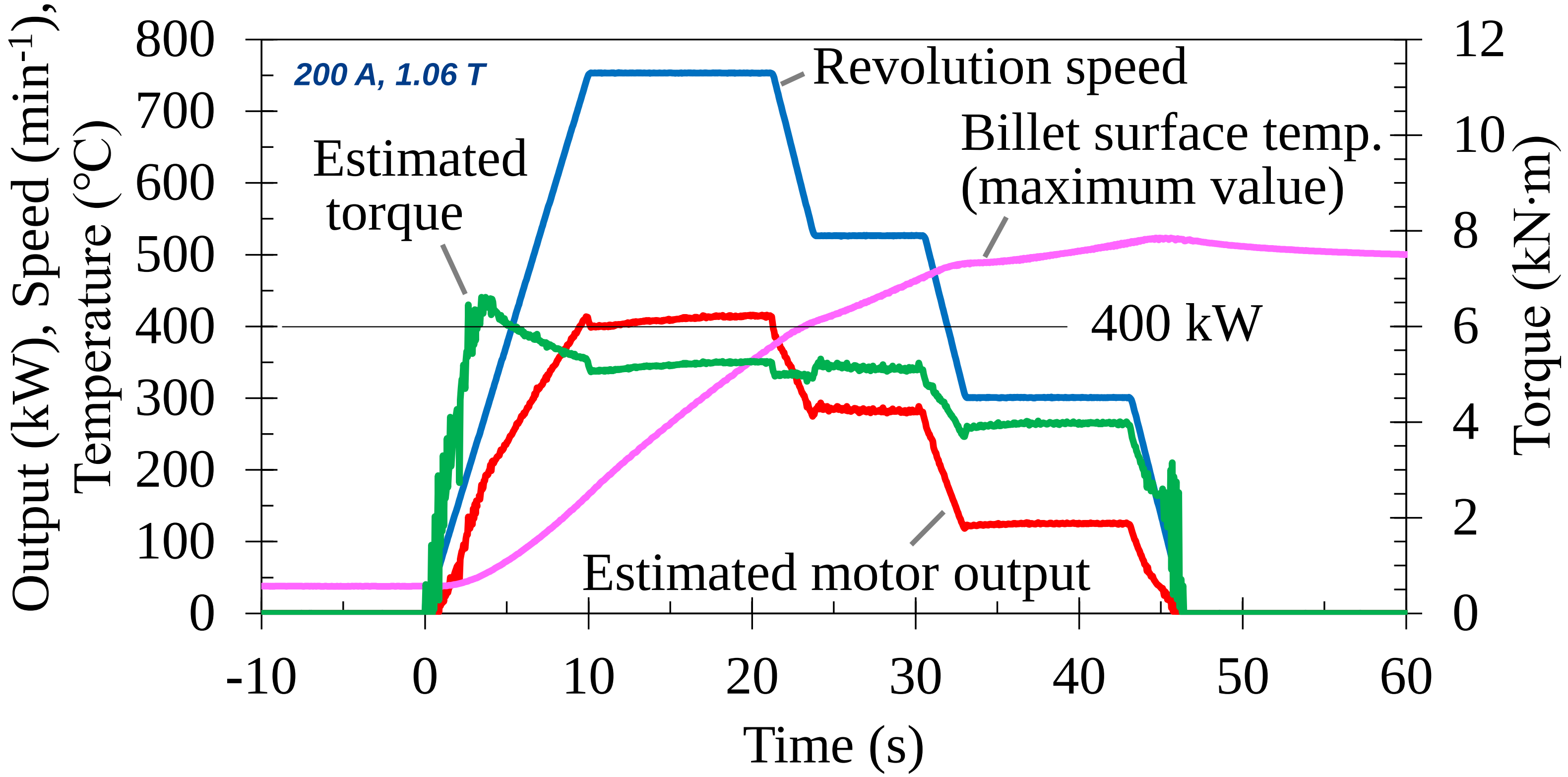
Assembly

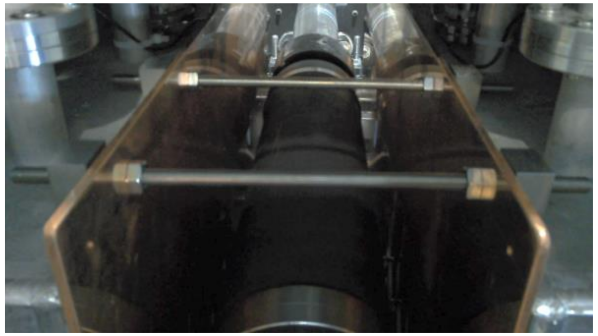


- ***Heating test to demonstrate 400 kW heating power input to the aluminum billet.***
- ***Output power of derive motor was estimated from motor input supposing that motor efficiency = 0.95.***
- ***Torque was estimated from estimated motor output and revolution speed.***
- ***Billet surface temperature 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}*



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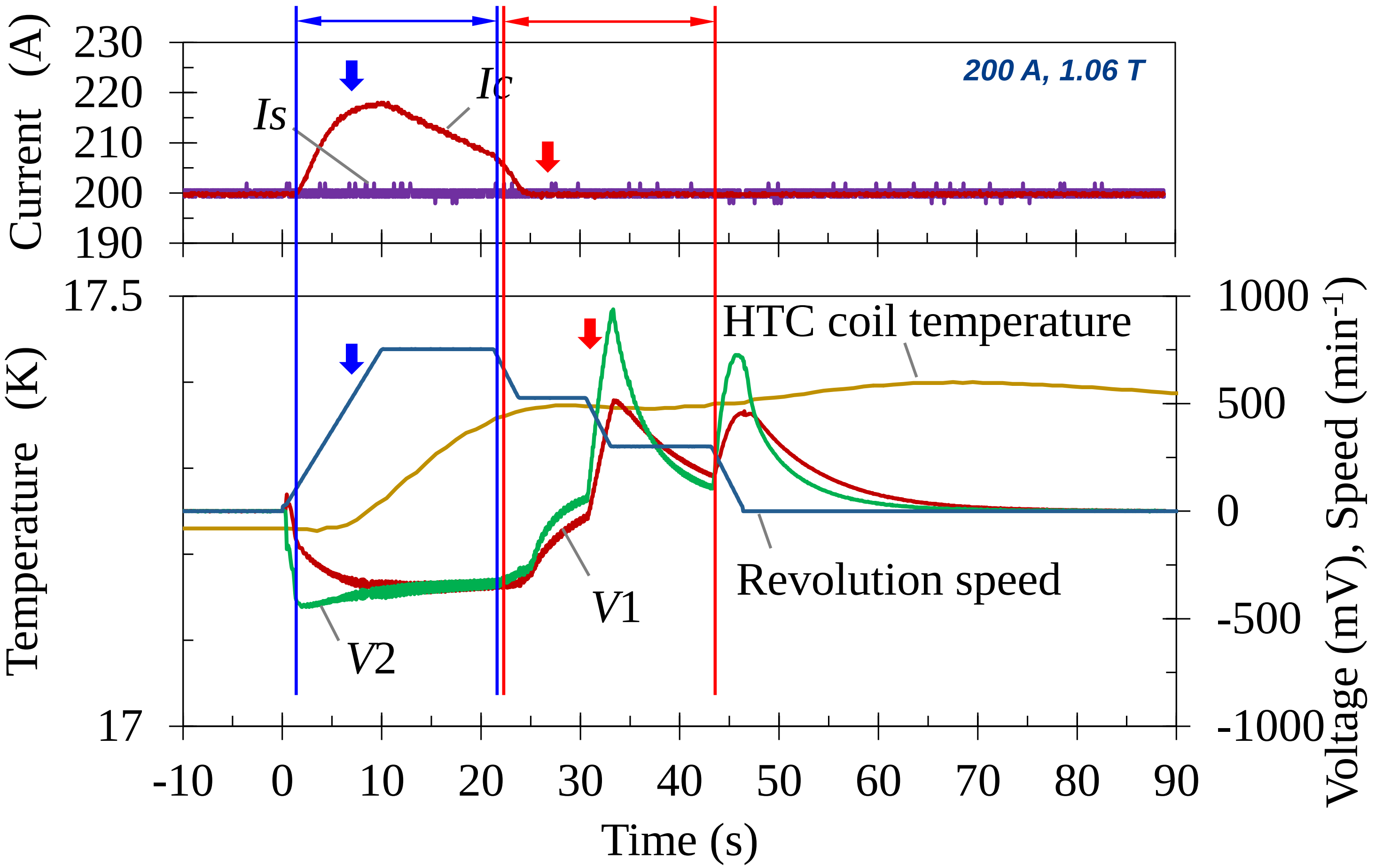
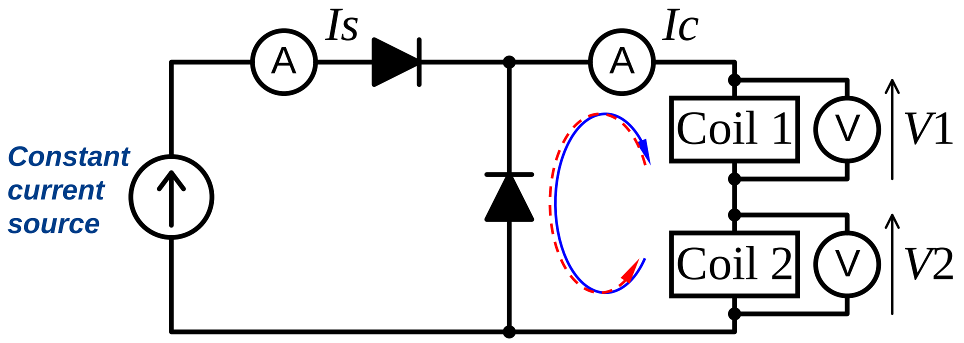
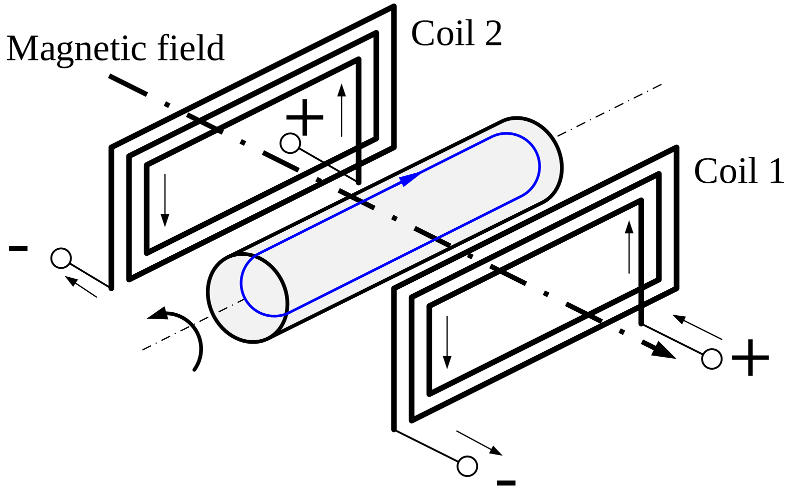
HEATING TEST - 1

- ***Coil current increased as billet accelerated.***
- ***Induction of eddy current in billet shielded magnetic flux***
- ***Induced current flowed through the freewheeling diode to compensate the decrease in magnetic flux.***
- ***In the deceleration of billet, induced current was blocked by the diode.***
- ***Maximum increase (～17 A) was enough lower than current margin.***







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HEATING TEST - 1

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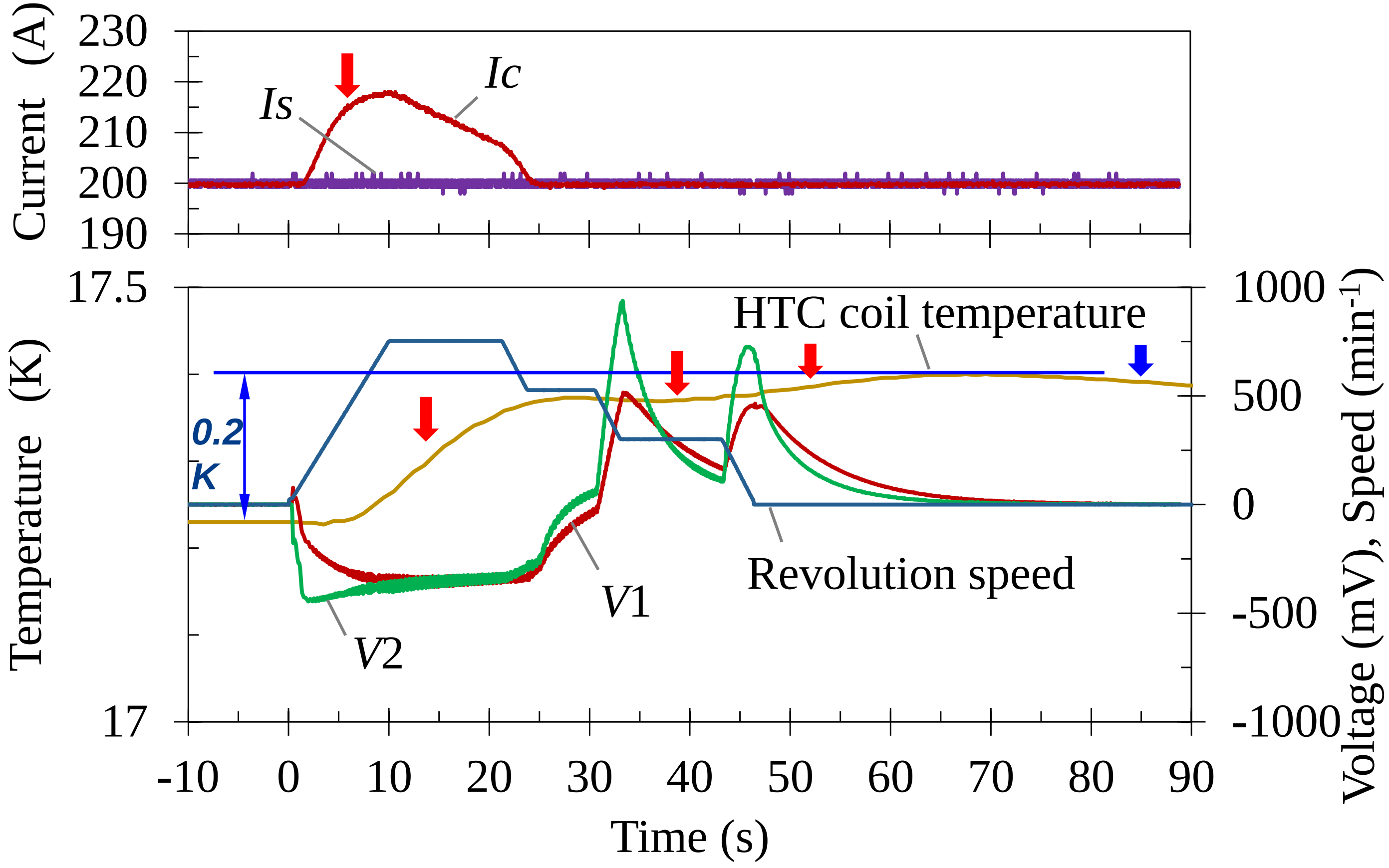
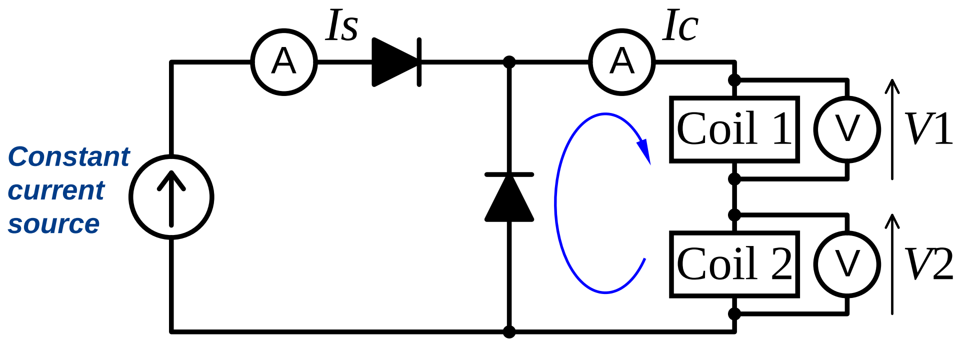
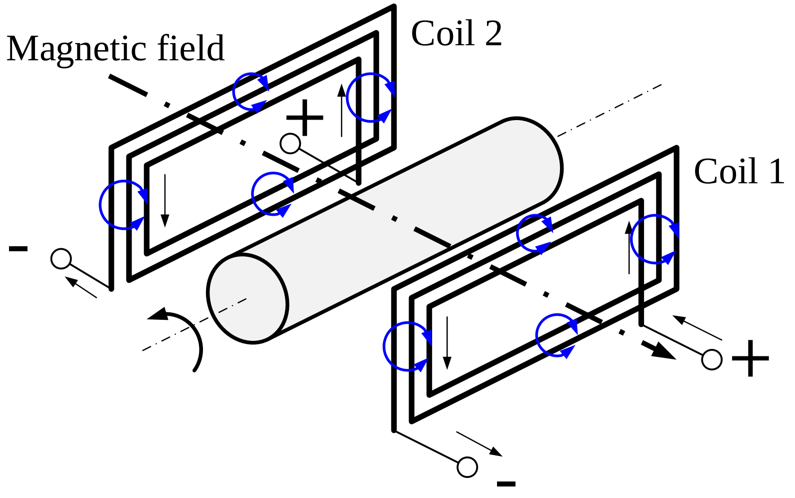
- ***Coil temperature increased by about 0.2 K.***
- ***Possible causes :***
  Increase in coil current increased Joule heat in current leads.
  Turn-to-turn transverse currents in no-insulation winding of HTS coils induced losses.
- ***Coil temperature turned to drop and gradually decreased.***
  Transverse current was decayed and losses was extinguished.







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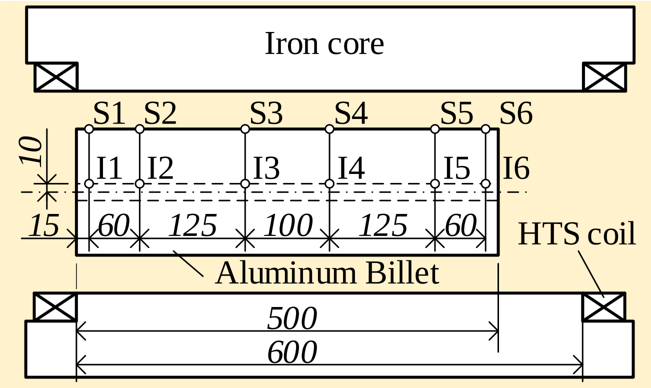
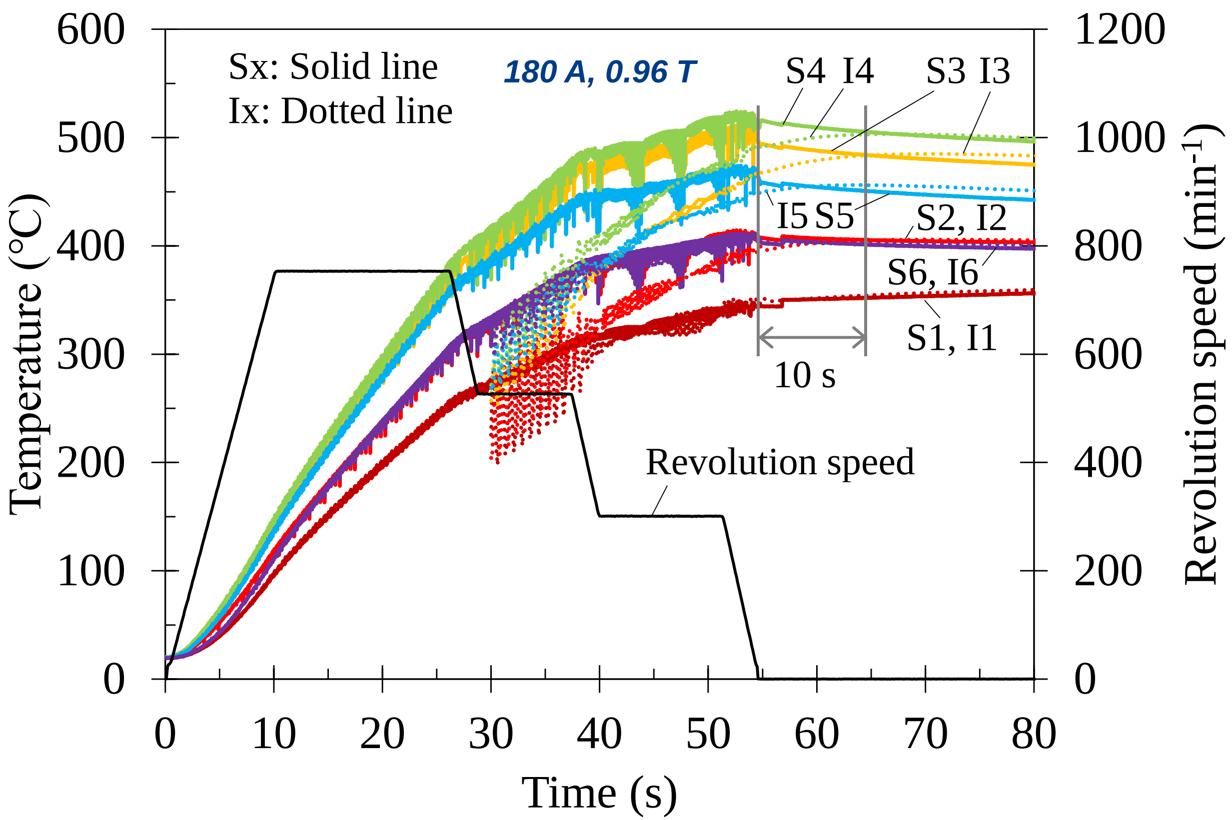
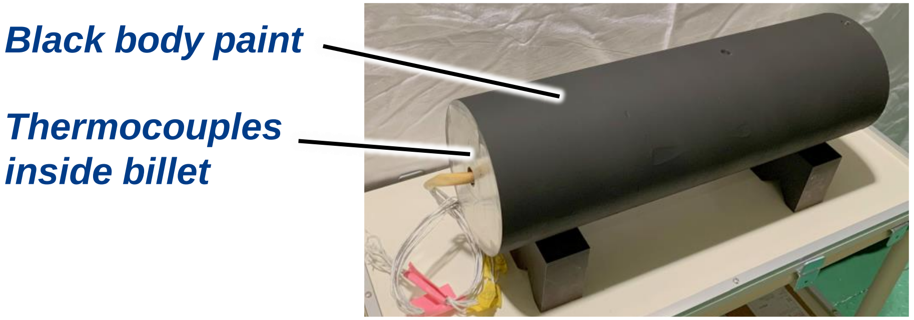
HEATING TEST -2

- ***Heating test to investigate :***
  - ***Temperature distribution inside billet***
  - ***Time delay until achieving radial uniformity due to heat diffusion***
- ***Temperature measurement positions :***
  - ***S1-S6 : Surface temperature measured using thermo-camera***
  - ***I1-I6 : Temperature inside billet measured by thermocouples***







- ***Temperatures at I1-I6 coincided with temperatures at S1-S6 at around 65 s.***
- ***Radial temperature uniformity was achieved 10 s after stopping of rotation.***

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- 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	%

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SUMMARY

- ***Demonstration device for 400 kW-class aluminum billet heater using HTS magnet was fabricated and tested.***

- ***Heating power of over 400 kW to raise billet temperature to about 500 ℃ within 60 s were demonstrated.***

- ***In heating tests, induction of additional current in HTS coils by rotation of billet was observed. However, this increase in coil current was within designed current margin. Coil temperature increased by about 0.2 K after one heating cycle. This temperature increase did not deteriorate thermal stability of HTS coils. However, we could not make sure whether coil temperature increased continuously by repeated heating operation. This point should be investigated in next study.***

- ***By temperature distribution measurement, it was found that radial temperature uniformity was achieved in 10 s after stopping of rotation. This data gives a useful information for determination of heating sequence in commercial device.***

- ***Energy efficiency obtained in heating test was 74.5 %.***

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Thank you for attention.