IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017.
Invited presentation Tu-Mo-Or11-01 given at MT25, 27 August - 01 September 2017, Amsterdam, The Netherlands.

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창원대학교 CHANGWON NATIONAL UNIVERSITY

[Invited] Recent Progress of Superconducting Induction Heater with HTS magnets in Korea

2017. 08.29 (Tue.), 08:45 ~ 09:15, in **MT25**

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Supercoil Co., Ltd. in Korea

Co-authors; Prof. Minwon Park, and Sangho Cho

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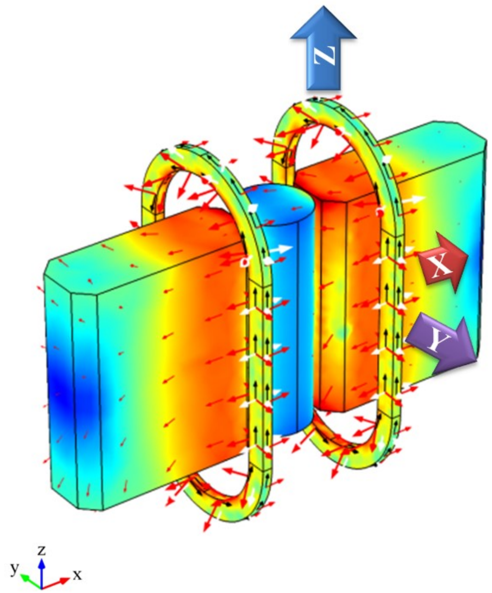
Super coil



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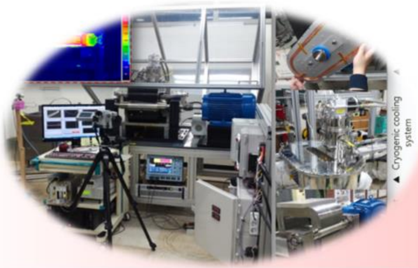
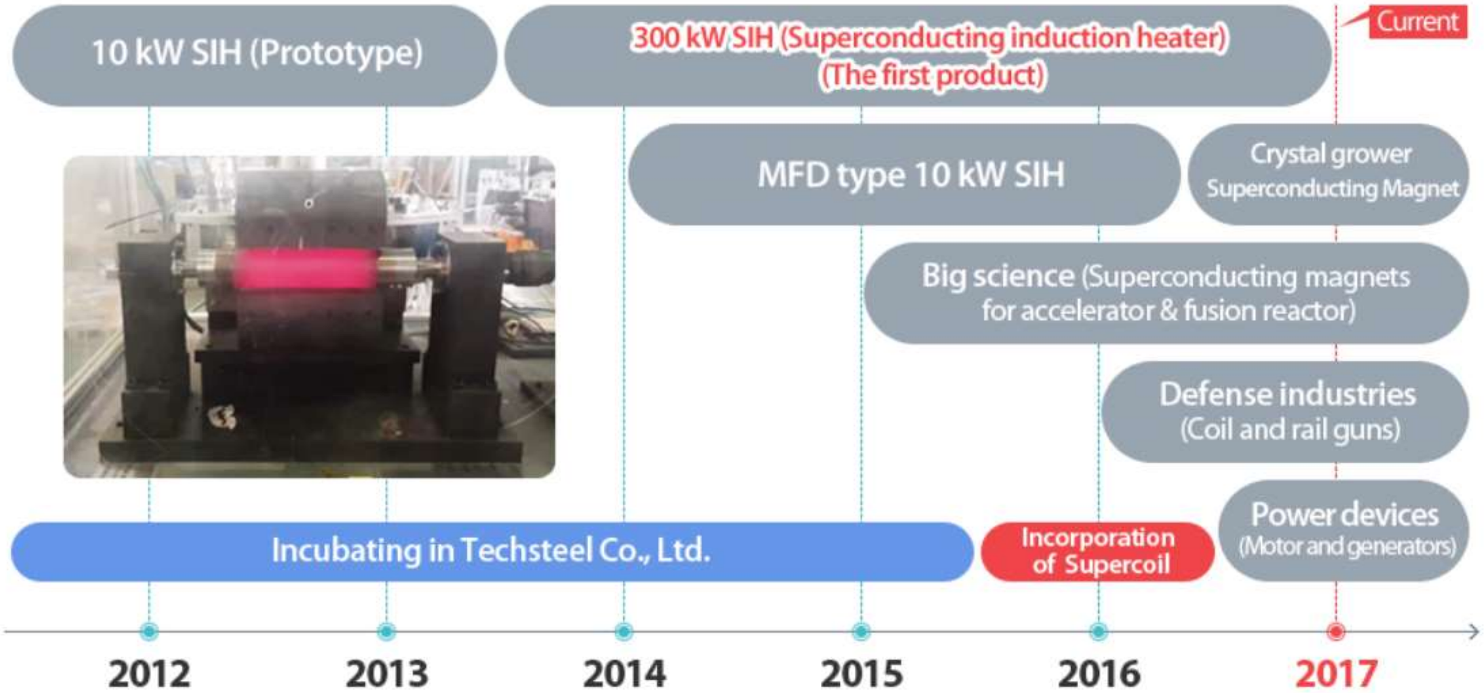
Development history of Superconducting induction heater

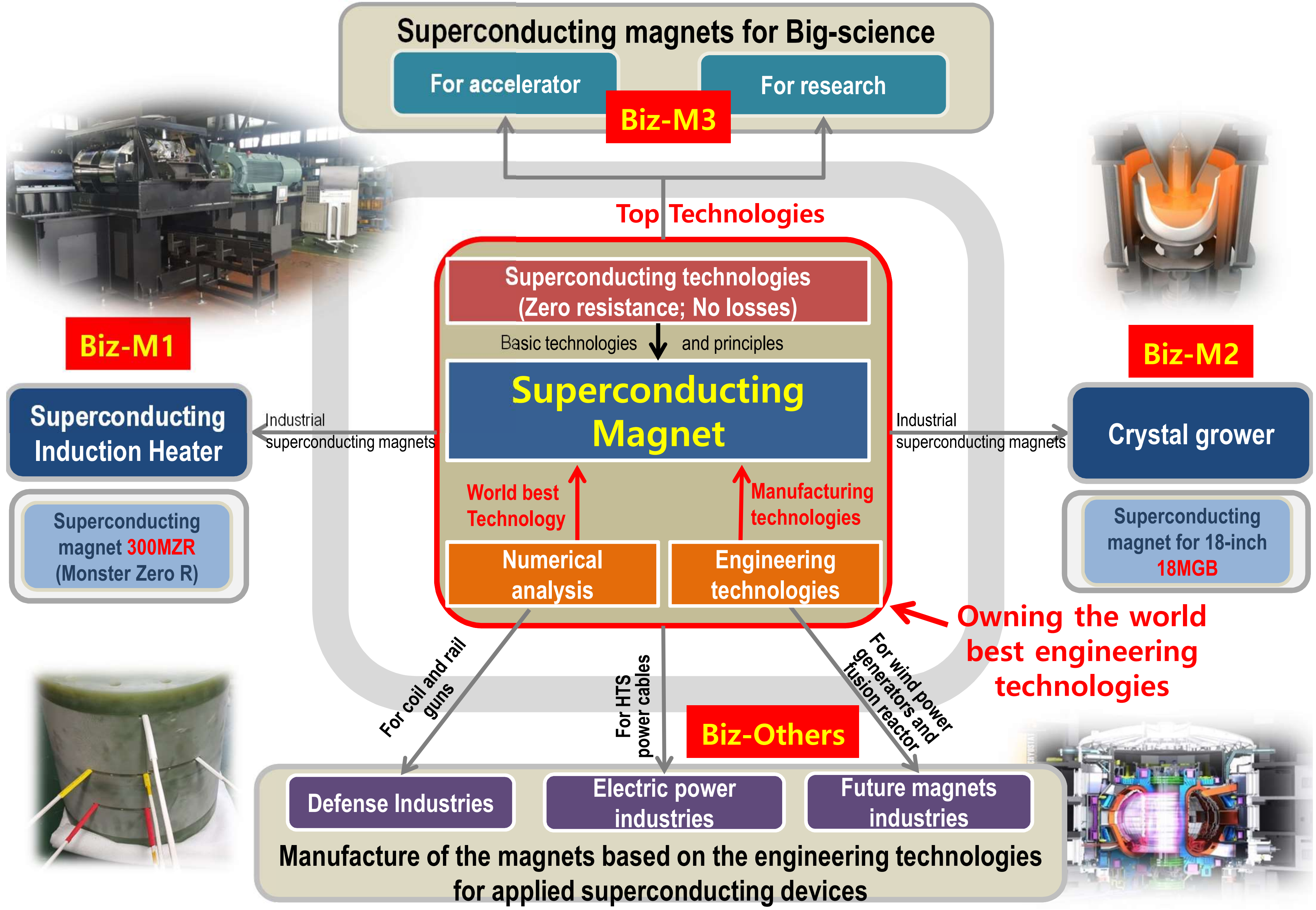
Super coil




Company History



Supercoil Technologies & Business model



About the superconducting induction heater (SIH)

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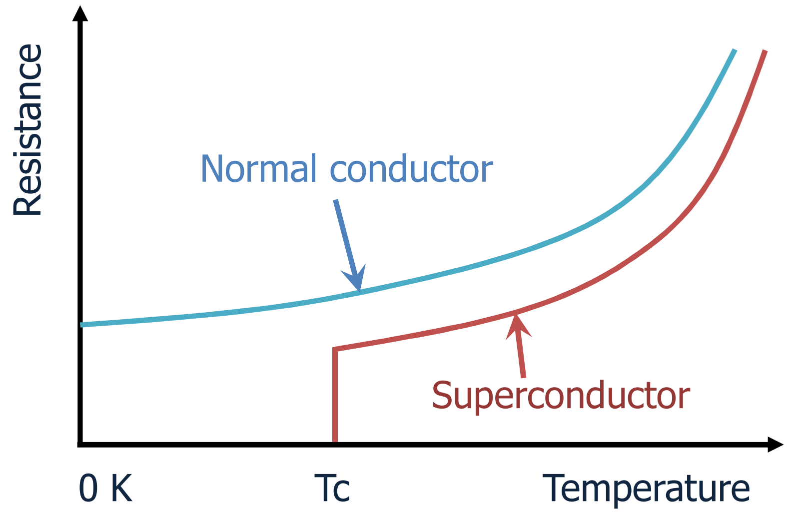
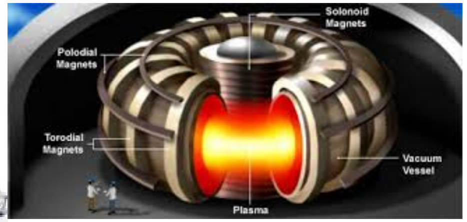
Current Status of Superconducting Application Industries

Super coil



- Superconductor has 'Zero' resistance → **Energy loss is 'Zero.'**
- Superconducting wire has 100 times of the current density than a copper wire → **Lightening devices and raising market competitiveness**

▲ Medical business: MRI



▲ Big sciences: Fusion reactor, High field magnet

▲ Transportation business: Large-sized magnets

▲ Power transmission, and network: cables

Ref. by google images

- **Industrial fields?**
- **It is not any more future technology!!**

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Conventional Furnaces in industries

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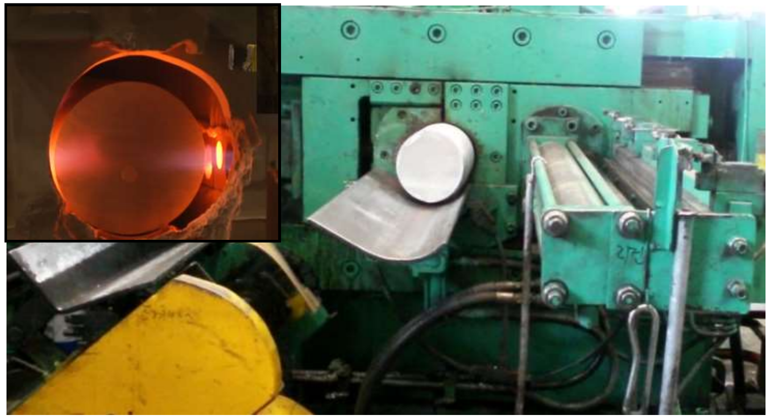
❖ **These are available for the preheating process of the metal billets, in order to producing parts for the airplanes, automobiles, and electric power machineries.**



▲ Aluminum extrusion plant

▲ Forging company with iron metals using Gas furnace and electric furnace

➢ Major products

▲ Lightening frame structures of airplanes, ships and automobiles

▲ Forging parts for automobiles

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Necessities of the development on SIH

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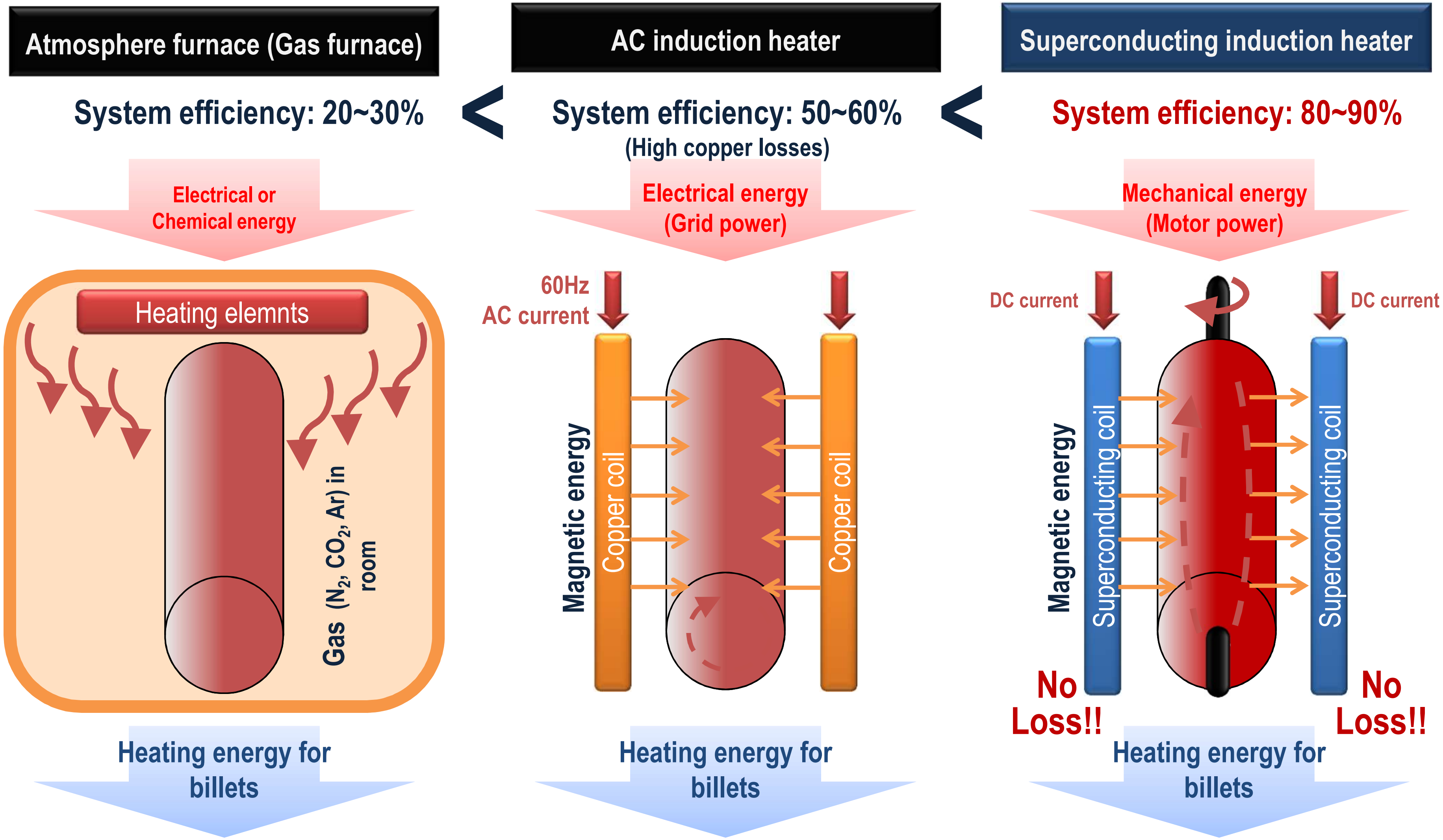
- Superconducting Induction Heater: It is expected as **30~70% Energy efficiency improvement than conventional furnaces**



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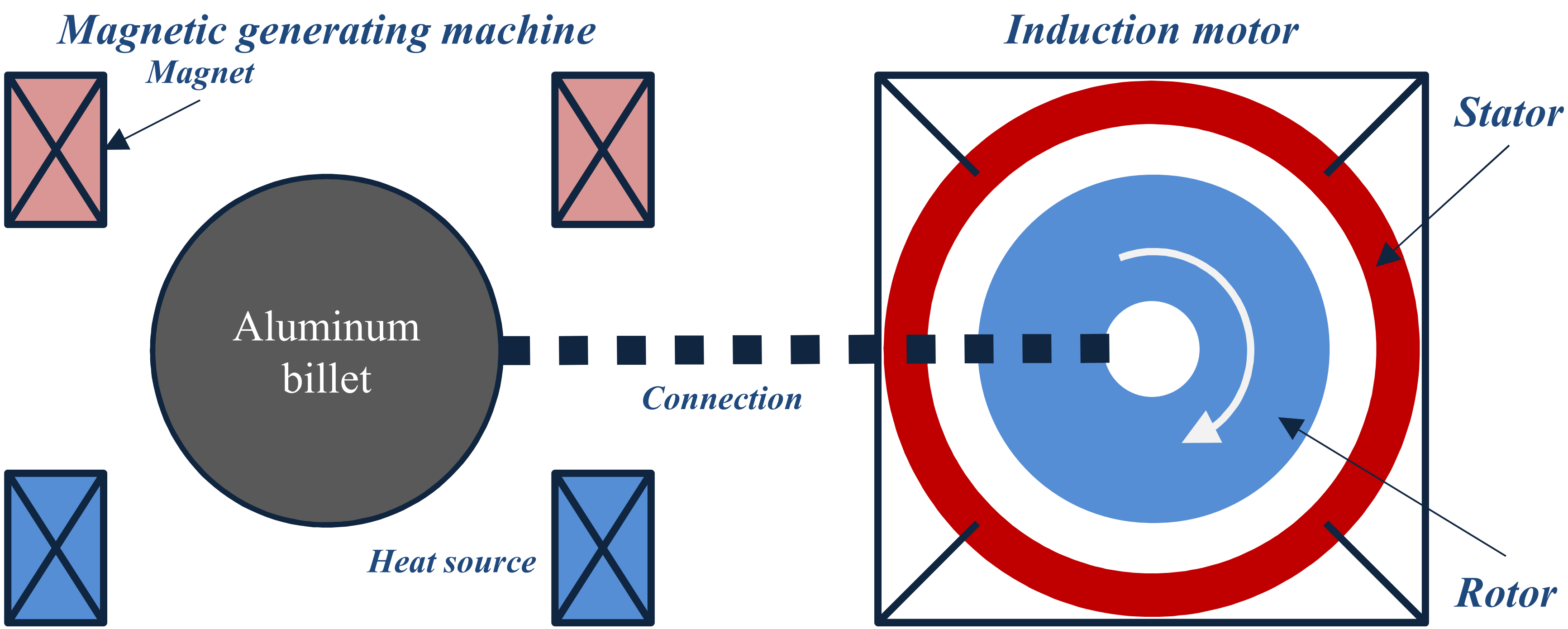
Energy transfer relations of SIH



DC Induction heating

Heat energy — *Temperature increment* — *Induced current in the billet* — *Torque* — *Angular velocity*

$$Q = M \cdot C_p \cdot \frac{dT}{dt} = R_{Al} \cdot I_{ind}^2 \cdot t = k \cdot T \cdot \omega \cdot t$$

Heat transfer energy from the aluminum billet	Electrical energy in the aluminum billet	Mechanical energy by induction motor

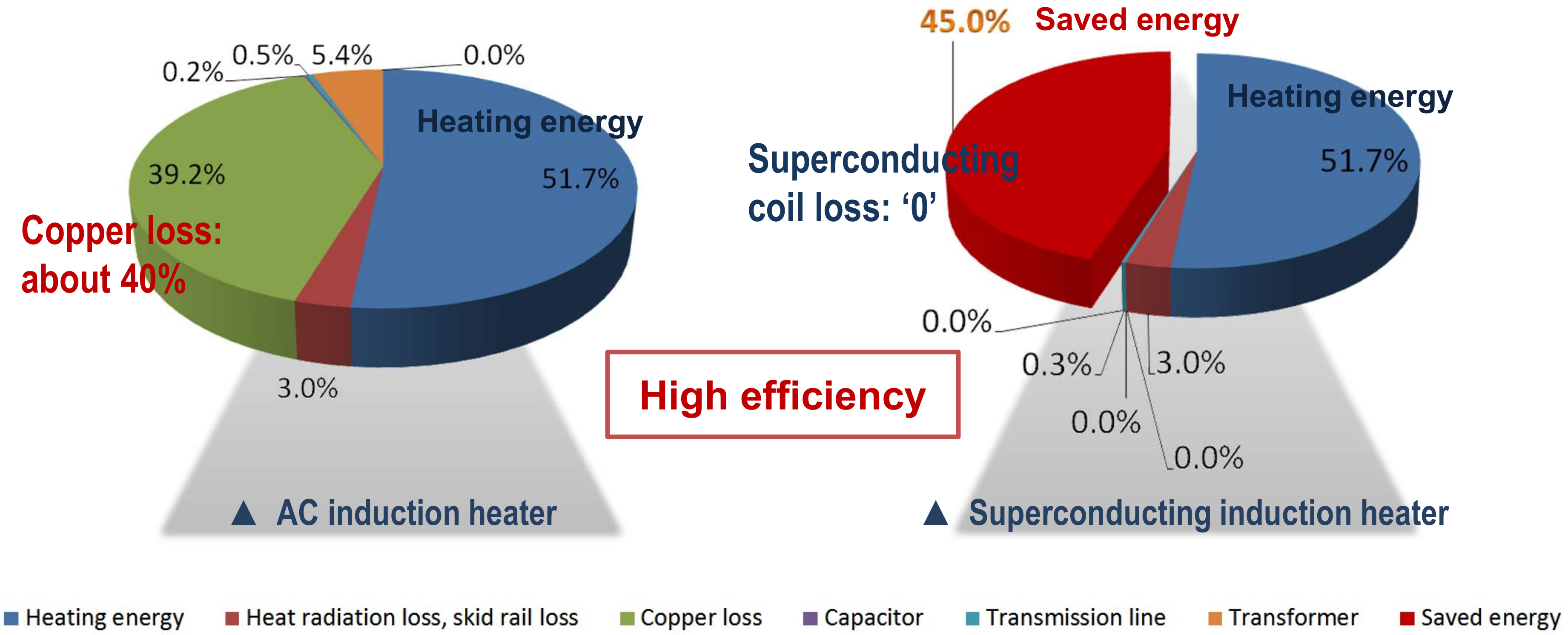
Advantages 1: Energy efficiency improvement!

- AC induction heater has a copper heat loss of about 40 %.
- We can save the energy by using superconducting magnet to generate the magnetic field.

❖ Energy-saving effect

Ref. by data of the catalog of Fuji Electric Systems Co., Lt

	AC induction heating types	HTS DC induction heating
	Single-layer	
Input Power (kW)	1,588	913
Overall efficiency[%]	51.7	90 (Expected)



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Advantages 2: Heating quality improvement!

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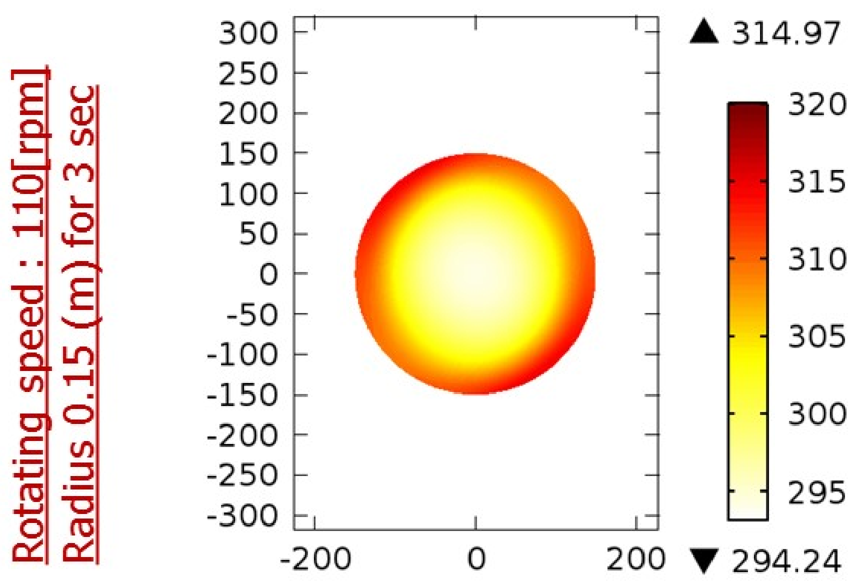
- The quality of the metal billet is depended on the penetration depth of heating power.
- The penetration depth is related to the frequency of the induced current inside of the metal billet.
- SIH makes the quality better by controlling the rotating speed.

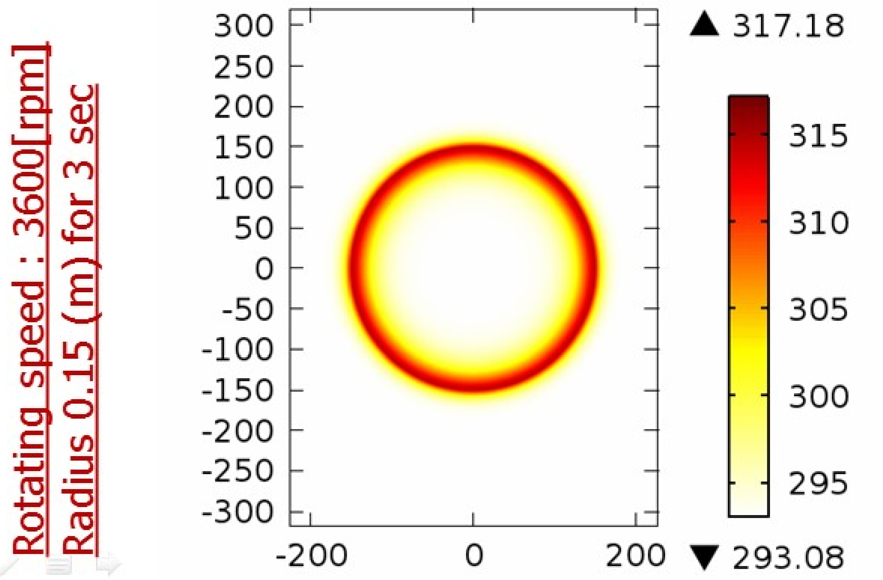


- Superconducting induction heater

$$\therefore \delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

ρ: *Relative resistivity*
ω: Angular frequency
μ: permeability

- 60 Hz AC induction heater



- Frequency (Aluminum billet) in SIH: 1.83 Hz,

  Penetration depth: 100 mm

- Frequency (Aluminum billet) in AC induction heater: 60 Hz, Penetration depth: 19 mm

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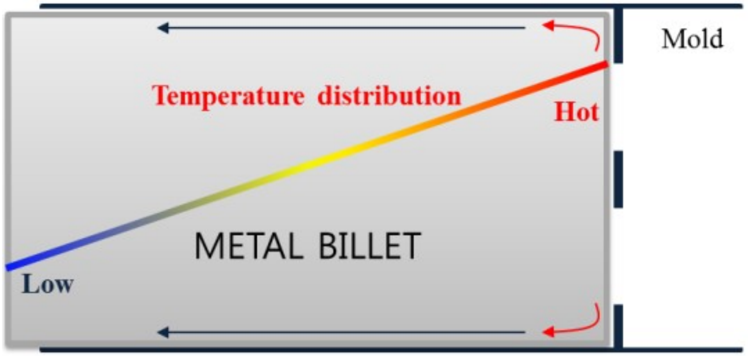
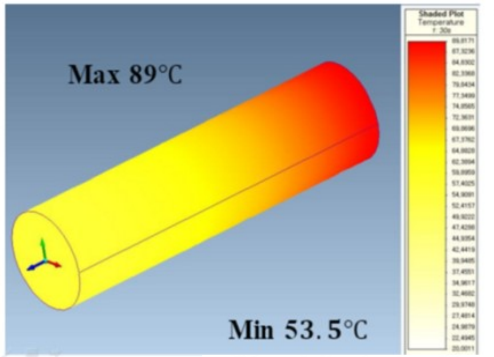
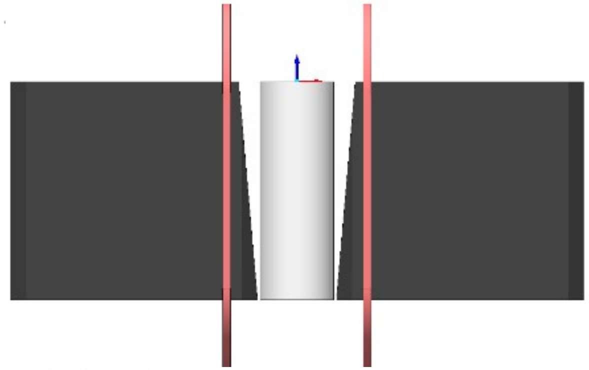
Advantages 2: Product quality improvement!

Super coil

- Applying new magnetic displacement control unit ➔ Control the billet temperature along the length direction ➔ Higher extrusion performance ➔ The product quality improvement
  - When it extrudes, the deviation along the longitudinal temp. is controlled by the angle of iron yoke shape to get the best product quality

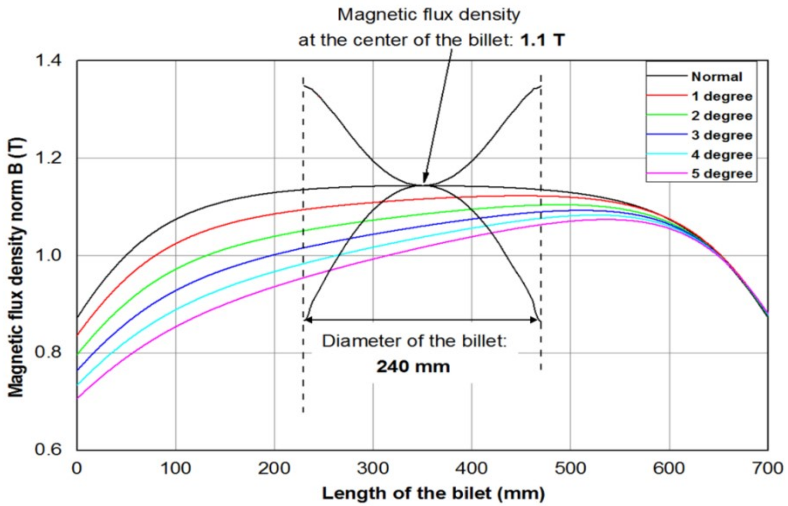






- Magnetic flux density with various beveled angles

- 10 kW SIH operation test for the new magnetic displacement control



- Development of the simulation model of the 300 kW SIH operation for the new magnetic displacement control

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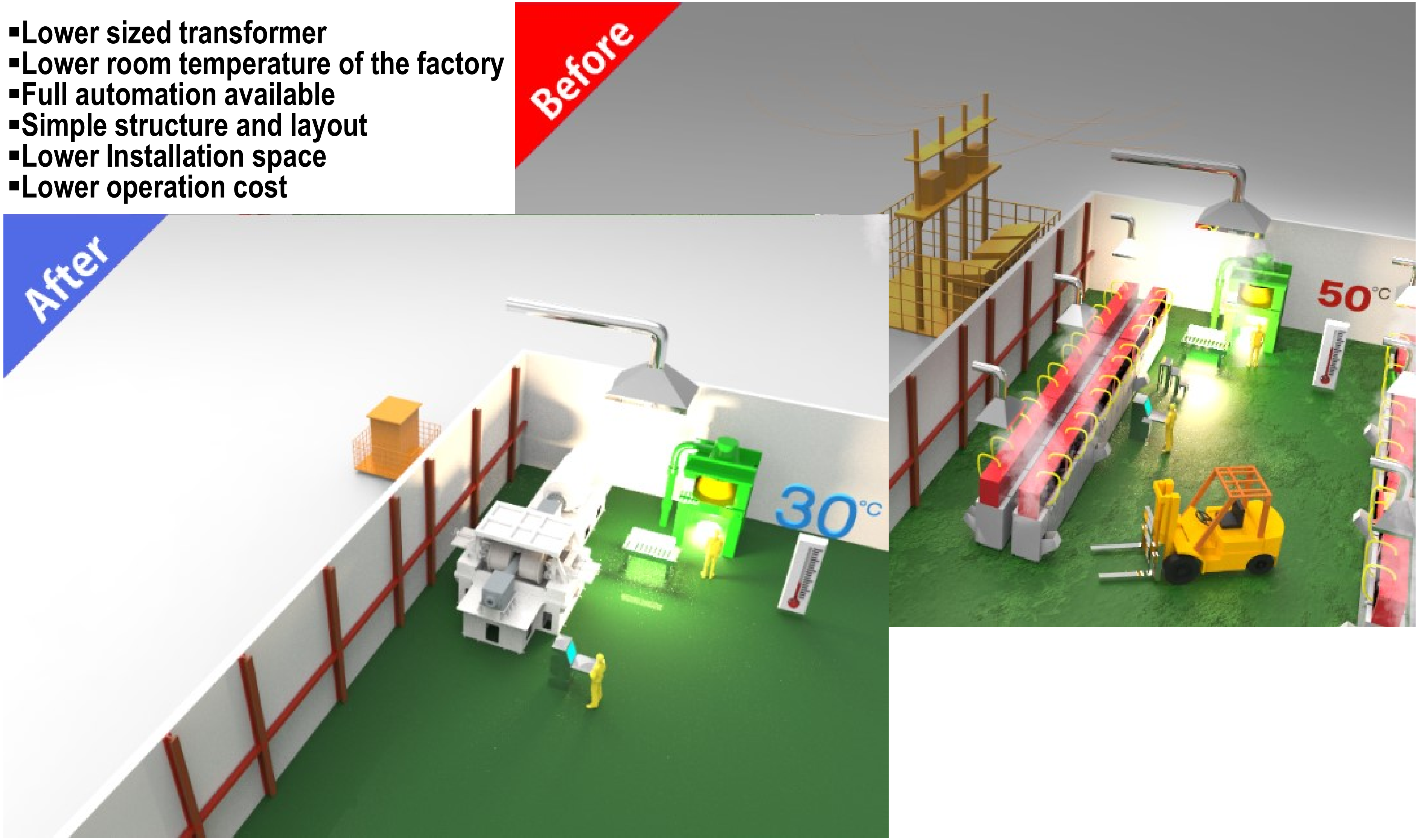
Change of the factory conditions after the installation

Super coil

These pictures show the change of the factory environments through the comparison between the before and after the installation of the superconducting induction heater.

- **Lower sized transformer**
- **Lower room temperature of the factory**
- **Full automation available**
- **Simple structure and layout**
- **Lower Installation space**
- **Lower operation cost**



About the design process of the SIH

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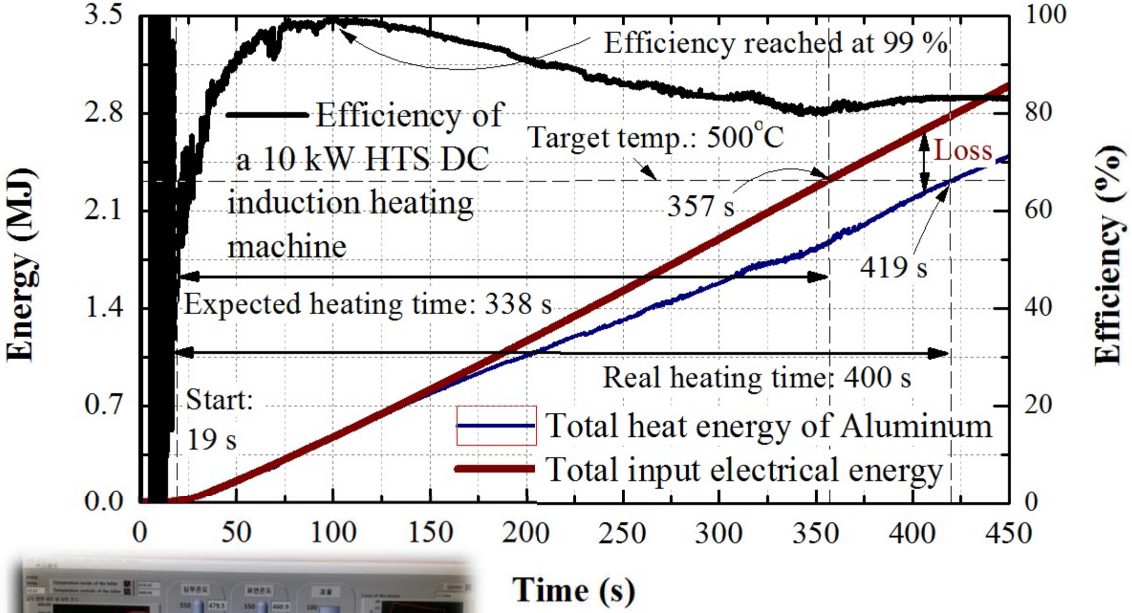
Results of the 10 kW-class superconducting induction heater developed

Super coil

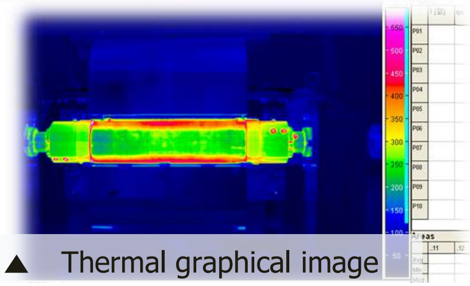
❖ **We are convinced about the commercialization possibility through this results.**

You tube link: Operation of a 10 kW HTS DC induction heating machine



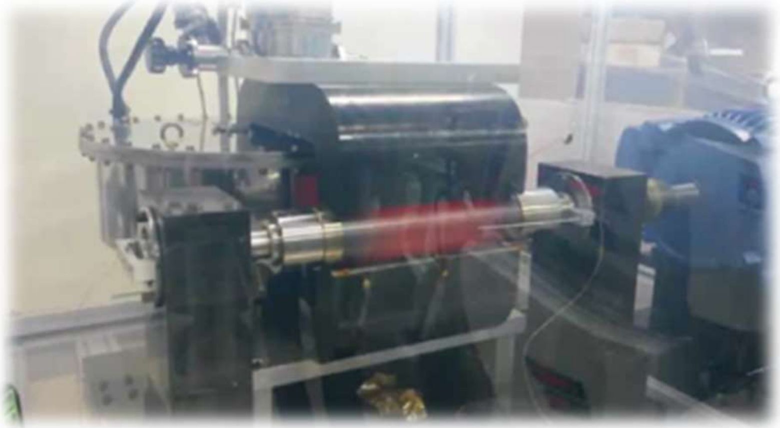
▲ Experimental view

▲ Real-time monitoring system



▲ Thermal graphical image

▲ Trial performance



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Design process for 300 kW superconducting induction heater

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❖ **We finally adapted the candidate 2, racetrack and iron cored type, because of the highest magnetic field we could get at the center of the billet.**

Target : 300kW class SIH
- Metal billet type : Aluminum Billet
- Average temperature : 540 (°C)
- Temperature deviation : below ±5 (°C))
- Magnetic flux density at the center of the billet : 1 (T)

↓

Determination of the size
- Decide radius (mm), length (mm), weight (kg)

↓

Determine the resistive heating and operating range for heating with FEM tool
- Rotating speed (rpm)
- Mechanical torque (N·m)

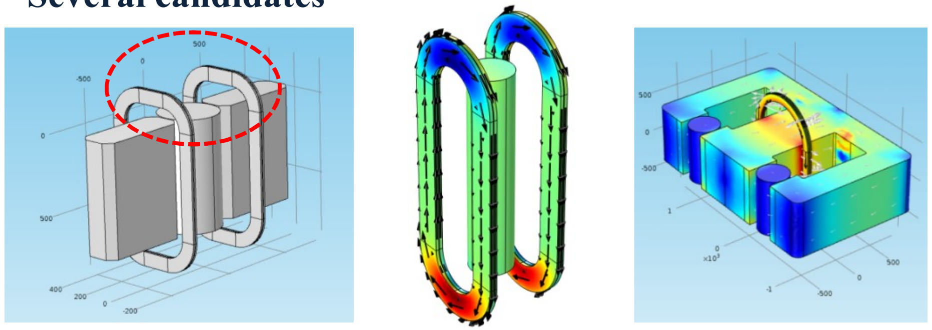
↓

Determine the specification of the magnet to generate the uniform magnetic field
- Maximum magnetic field
- Type of HTS wire
- Shape of HTS magnet
- Considering the perpendicular magnetic flux density

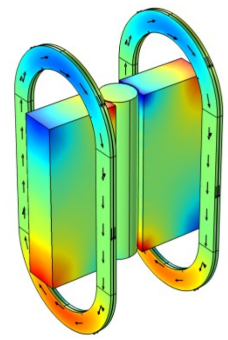
↓

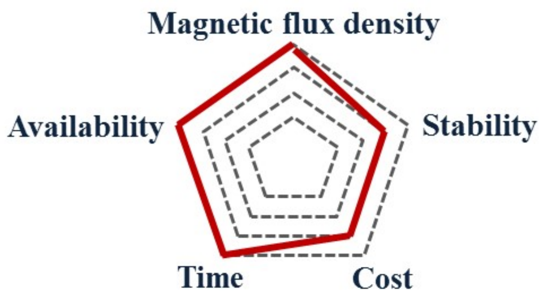
Design completion of an 300 kW-class SIH

Several candidates



Candidate 2



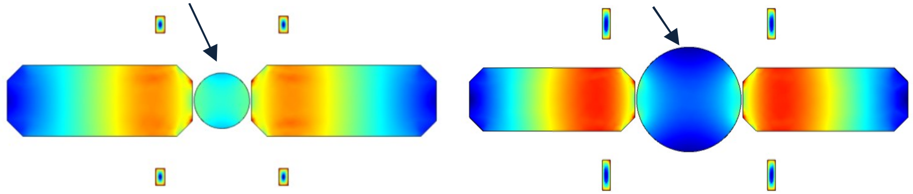


1.1 T, 3.4 km, 1 ea

Considering metal billet sizes

▪D180mm billet **No. 1**

▪D380mm billet **No. 2**



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Specifications of the HTS magnets and the 300kW SIH

Super coil

❖ **We set the billet size of the diameter, 9 inch, and the length, 700mm. It requires the magnetic flux density of 0.83 T at the rotating speed of 300 rpm. Total heating time would be 193 s.**

Parameter	Value
HTS tape maker	**SuNam, Korea**
HTS tape (Width×Thickness)	**W12.1 (±0.1) mm×T150 (±15) μm**
Minimum Critical current (77 K)	≥600 A (copper laminated)
HTS magnet type	**MI, racetrack, a double pancake, iron cored type, metal tape co-wound**
Size(Radius×Length)	**H622 mm×L1247 mm**
Number of turns	300 turns
Total length of the HTS tape	**3,407 m**
Inductance of a DPC magnet	**560 mH without an iron core**
Estimated critical current at 30K (I_c)	520 A calculated by only perpendicular magnetic flux density
Operating current (I_{op})	440 A (I_{op}/I_c =0.85)
B_{norm} at the center of the magnet	2.755E-3 (T/A)
Position of the magnetic field sensor	(x,y,z) = (0,0,0) ; (unit: mm)
B_{norm} at the center of the magnet	**1.08E-3 (T/A)**

Candidates	Billet diameter (mm)	Billet length (mm)	Billet weight (kg)	Target Magnetic field for 300 kW (T)	AC induction furnace (kW)	Atmosphere furnace (kW)	Heating time (s)	Operating temp. (K)	Critical current (A)	Operating current (A)	I_{op}/I_c	No. of Turns	**Total length (km)**
No. 1	180 (7")	700	48.1	0.858	650	550	108.2	30	530	440	0.83	250	**2,810**
No. 2	240 (9")		85.5	0.828		700	193.1		520	440	0.85	300	**3,410**
No. 3	290 (11")		124.8	0.813	▲	1,050	282.5		498	410	0.82	400	**4,660**
No. 4	380 (15")		214.3	0.797			486		490	383	0.78	500	**6,000**

Choi, J., et al. "Characteristic Analysis of a Sample HTS Magnet for Design of a 300 kW HTS DC Induction Furnace." *IEEE Transactions on Applied Superconductivity* 26.3 (2016): 1-5.

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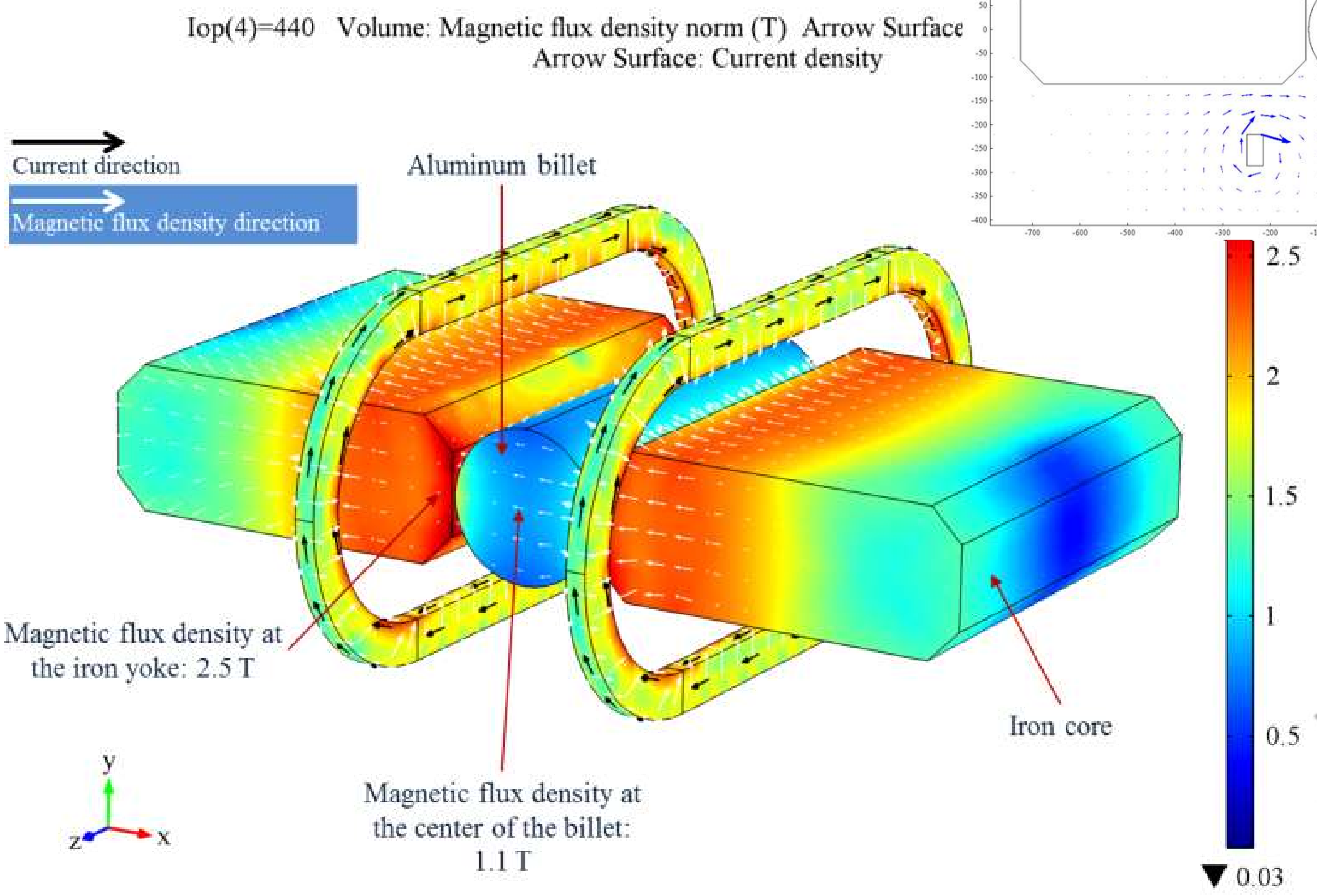
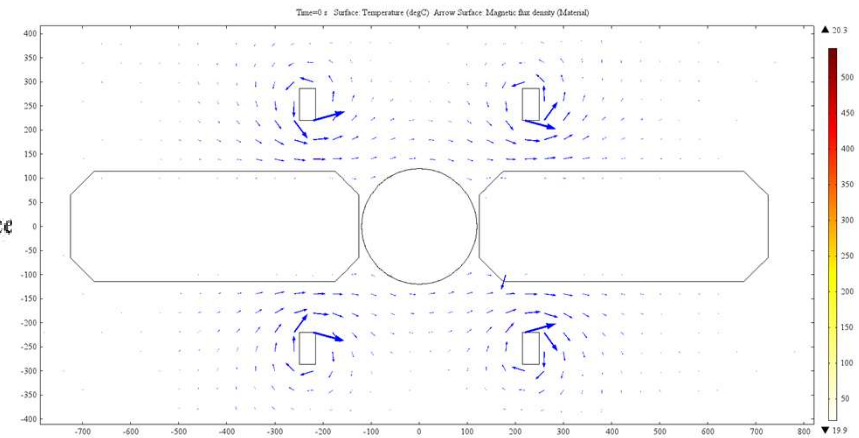
Development of the electromagnetic FEM analysis model

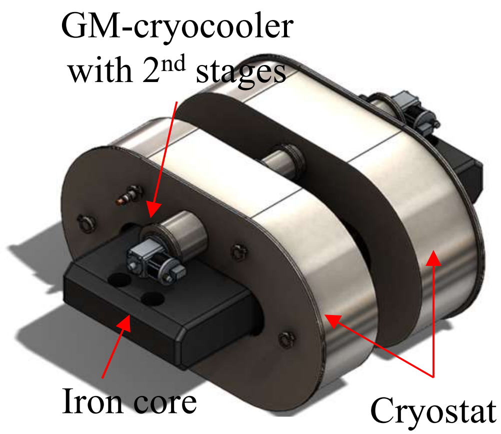
- **We developed the electromagnetic FEM model of 300kW-class HTS DC IF.**
- **We designed the HTS magnet with the magnetic flux density of 1.1 T at the center of the billet.**



- FEM results of a 300 kW HTS DC IF



- Design of the magnet system



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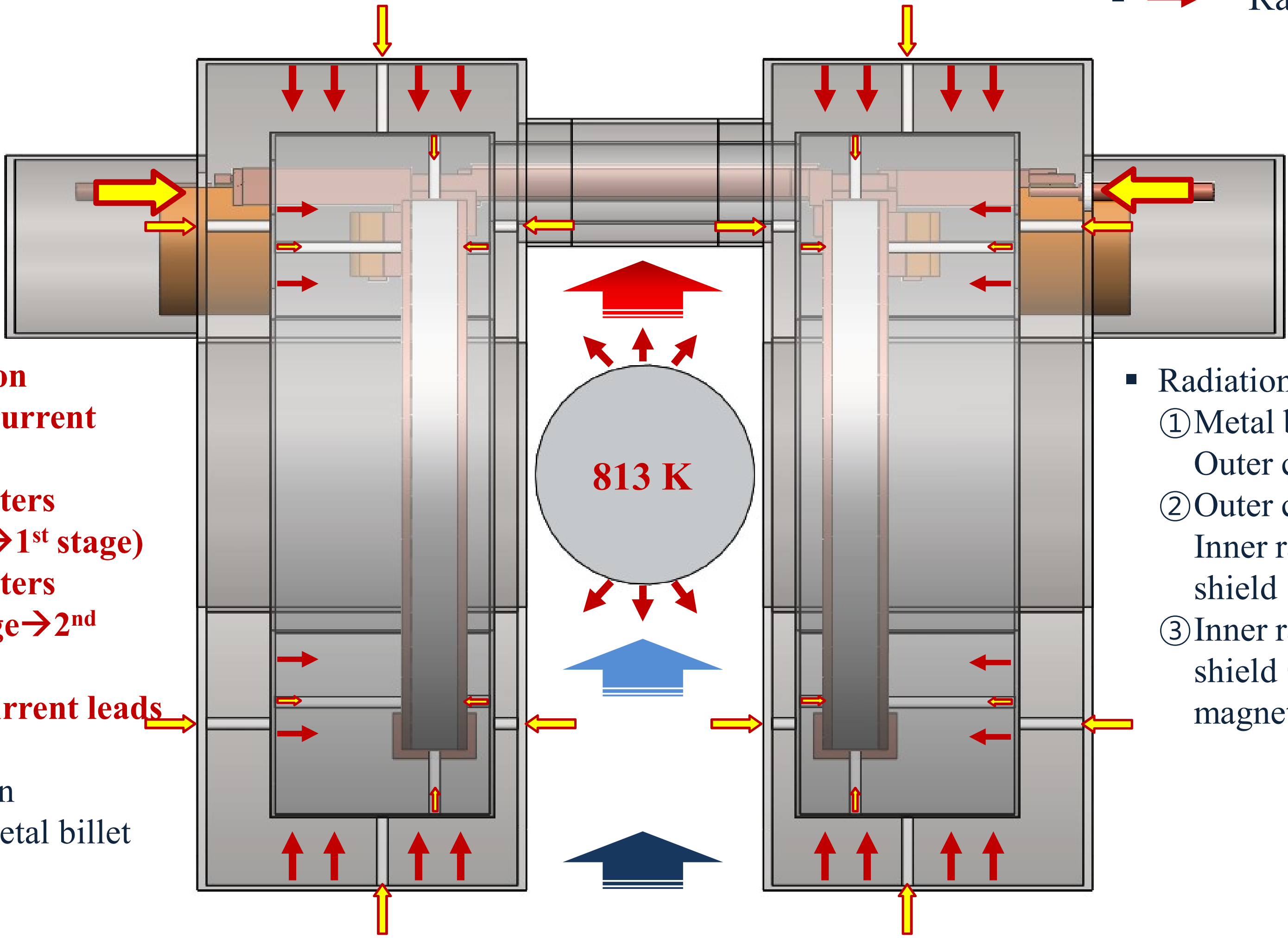
Heat invasion loads analysis

Super coil

❖ **We need to analyze heat loads of the conduction cooling system for HTS magnet operation. There are three conditions, such as conduction, convection and radiation.**

- Conduction
- Convection
- Radiation

❖ Heat invasion loads



- **Conduction**
  ①Metal current leads
  ②Supporters (300K→1st stage)
  ③Supporters (1st stage→2nd stage)
  ④HTS current leads

- Convection
  ①From metal billet

- Radiation
  ①Metal billet → Outer cryostat
  ②Outer cryostat → Inner radiation shield
  ③Inner radiation shield → HTS magnets

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Lorentz forces and their directions

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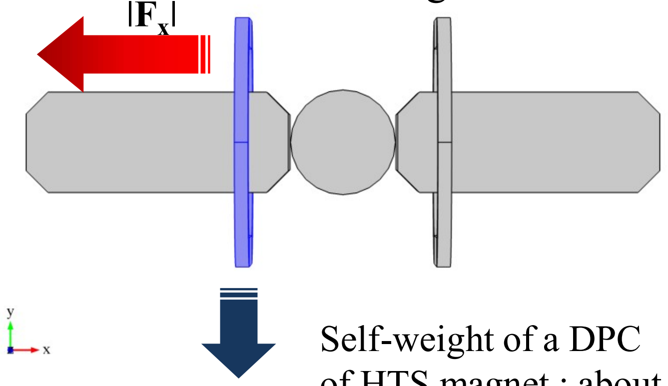
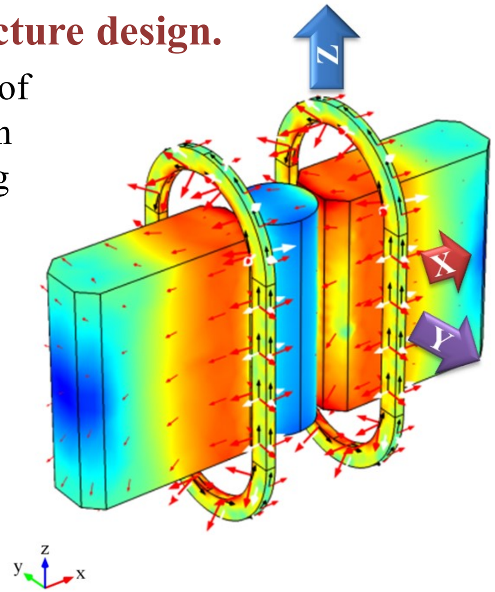
❖ **We calculated Lorentz forces of the HTS magnets for mechanical structure design.**

- F_x is caused by the attracting force between iron core and HTS magnet

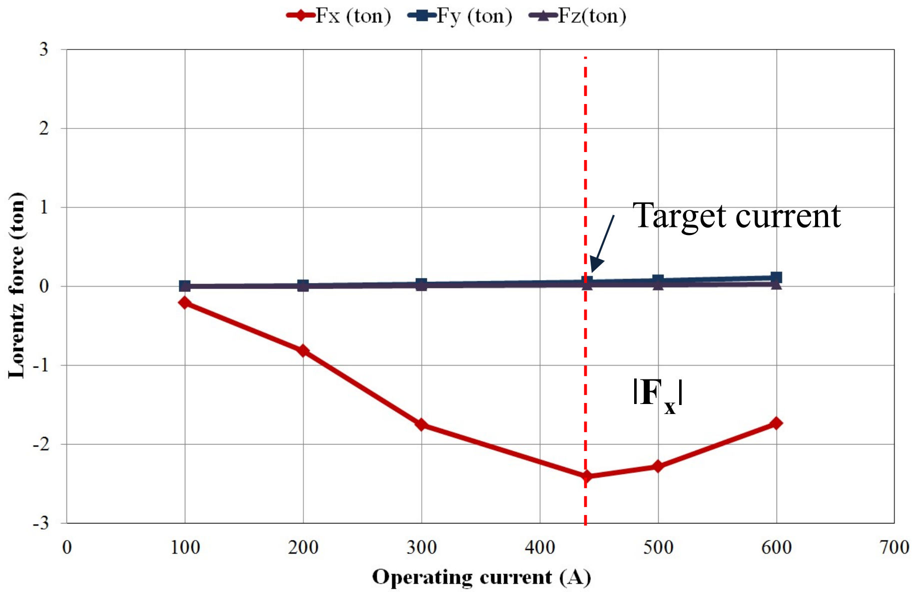


Self-weight of a DPC of HTS magnet : about 150 kg

- The volume integral of Lorentz force by each component according to the operating current



I_{op} (A)	F_x (ton)	F_y (ton)	F_z(ton)
100	-0.20	0.0030	0.00075
200	-0.82	0.012	0.0030
300	-1.76	0.027	0.0068
440	**-2.40**	**0.057**	**0.015**
500	-2.28	0.073	0.019
600	-1.73	0.106	0.027



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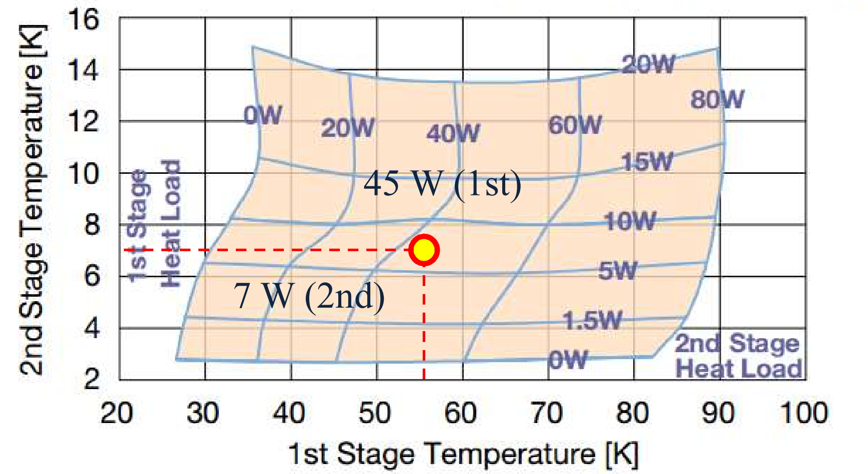
Results of the heat transfer and mechanical analysis

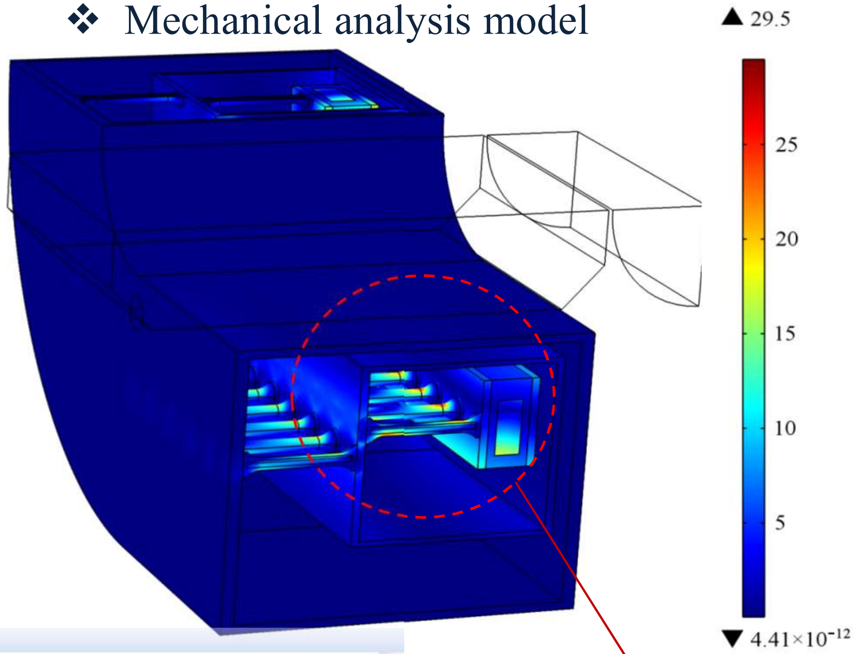
Super coil

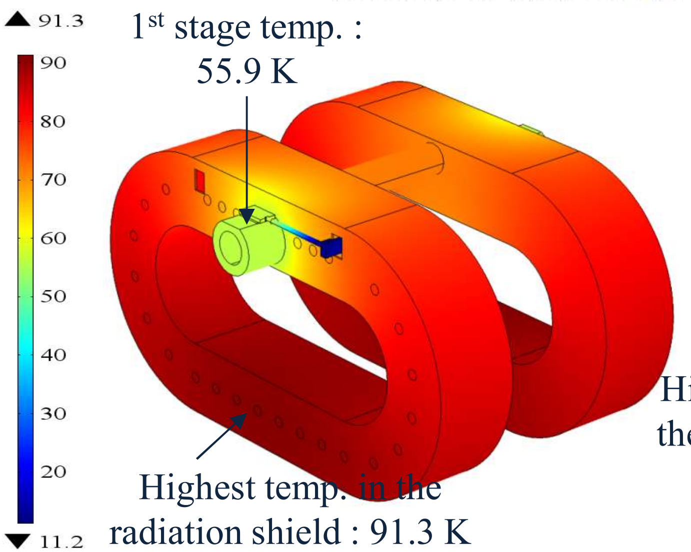
- ➢ **Total heat load was expected to 45 W at the 1st stage.**
- ➢ **7 W was expected for the 2nd stage and HTS magnet.**
- ❖ Expected heat loads of the 2nd stage cryo-cooler

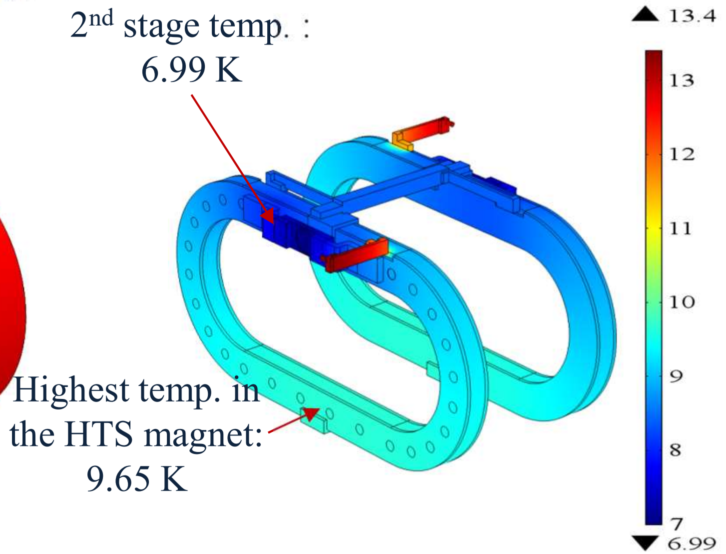
SRDK-415D Cold Head Capacity Map (60 Hz)

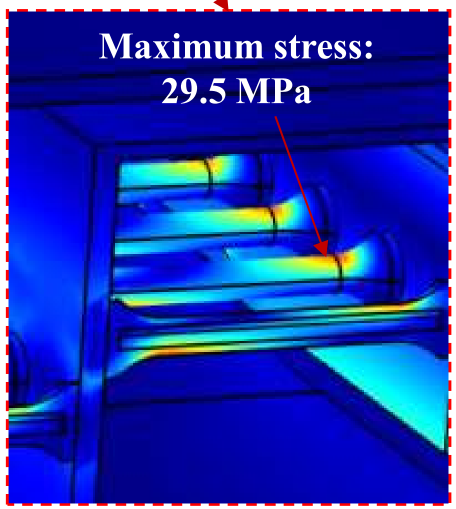


❖ Mechanical analysis model









About the fabrication process and test results of the HTS magnets

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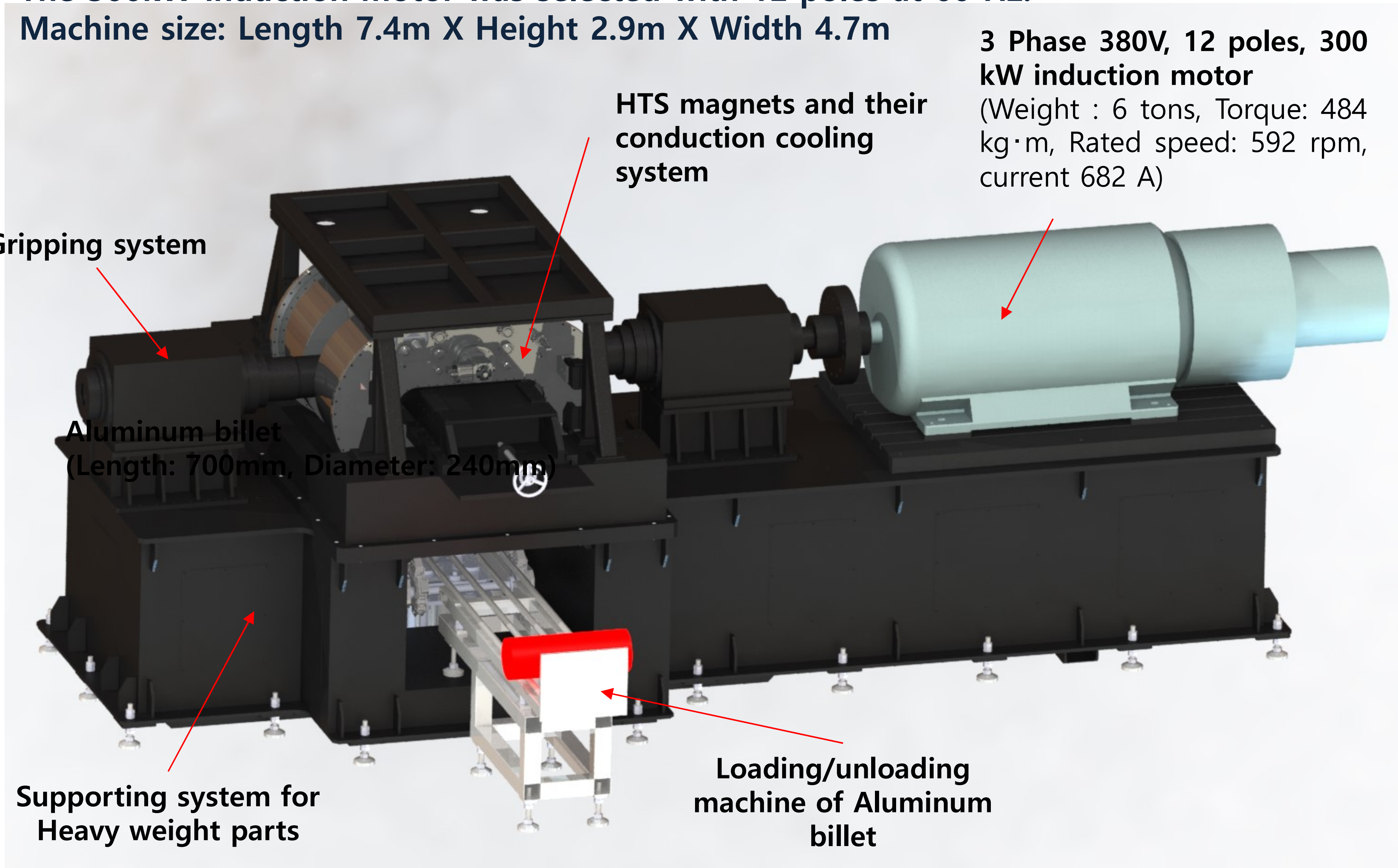
Real 3D design of the 300 kW superconducting induction heater

Super coil

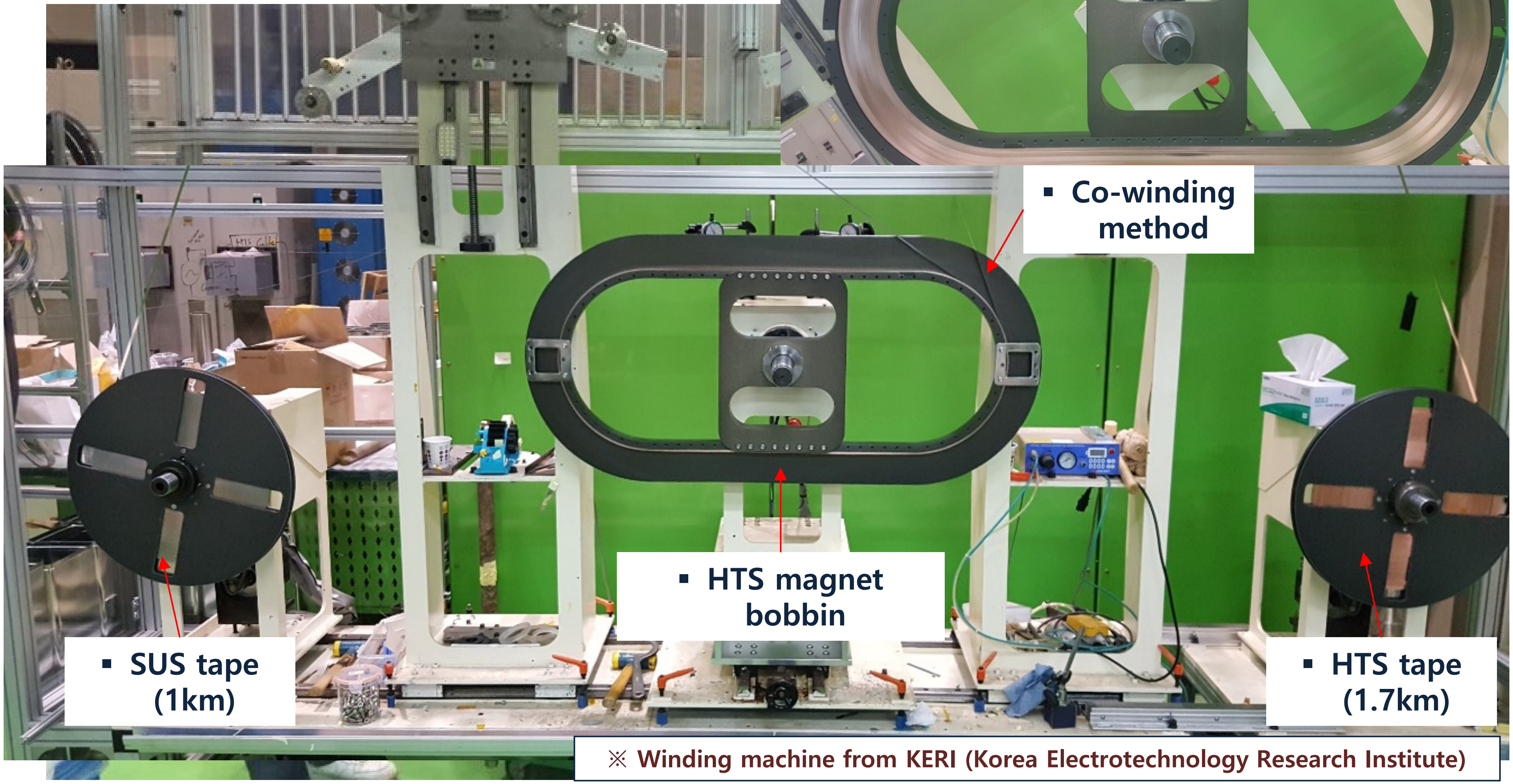
- The 300kW induction motor was selected with 12 poles at 60 Hz.
- Machine size: Length 7.4m X Height 2.9m X Width 4.7m



Winding composition of HTS magnet

Super coil

- **We fabricated the large-sized two HTS magnets for induction furnace in the world.**
- **The HTS magnet size: length 1.25m X height 0.62 m**



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Experiment preparation of the magnet under LN_2 and cryogenic state

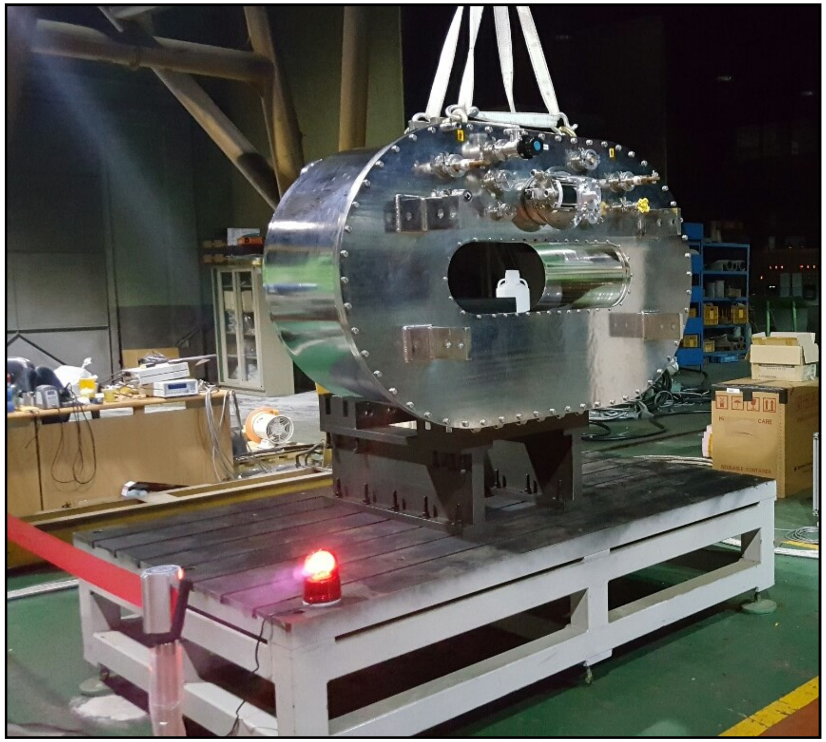
Super coil

- We performed the critical current test and measured magnetic flux density.
- The critical currents were measured as the magnet A : 145 A@77K, magnet B : 165 A@77K
- We fabricated the conduction cooling system including cryostat and radiation shield.

▲ Cooling HTS magnet in liquid nitrogen, 77.4 K

▲ Fabrication process of the HTS magnets with conduction cooling system

- Total cryostat weight: 3.1 ton
- Module coil weight: 83 kg/1ea
- Iron cores: 1.72 ton
- Cryostat weight: 630 kg/1ea
- Inner radiation shield weight: 31 kg/1ea



▲ We completed the experimental set-up.

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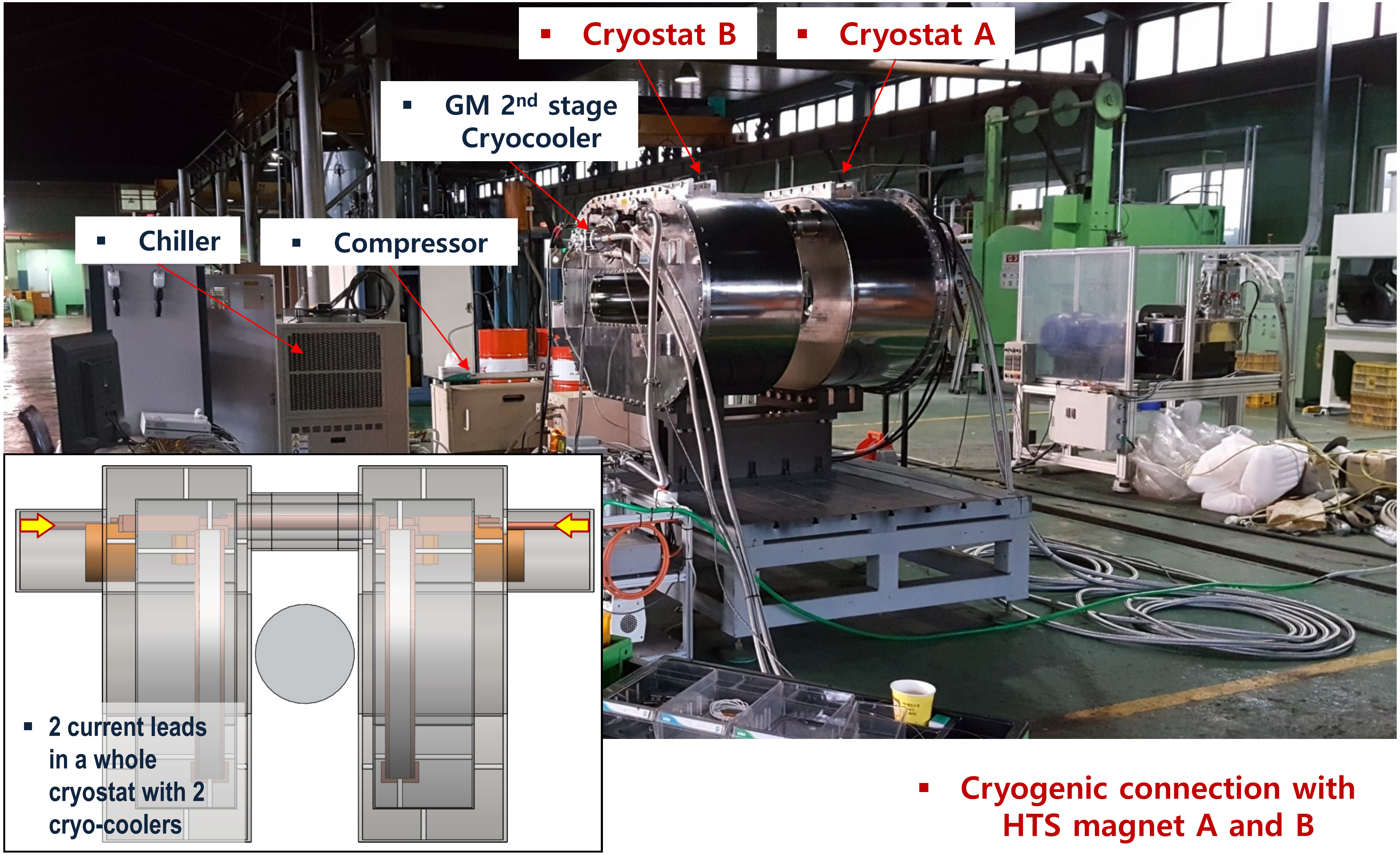
System composition of the cooling down test

Super coil



- Cryogenic connection with HTS magnet A and B

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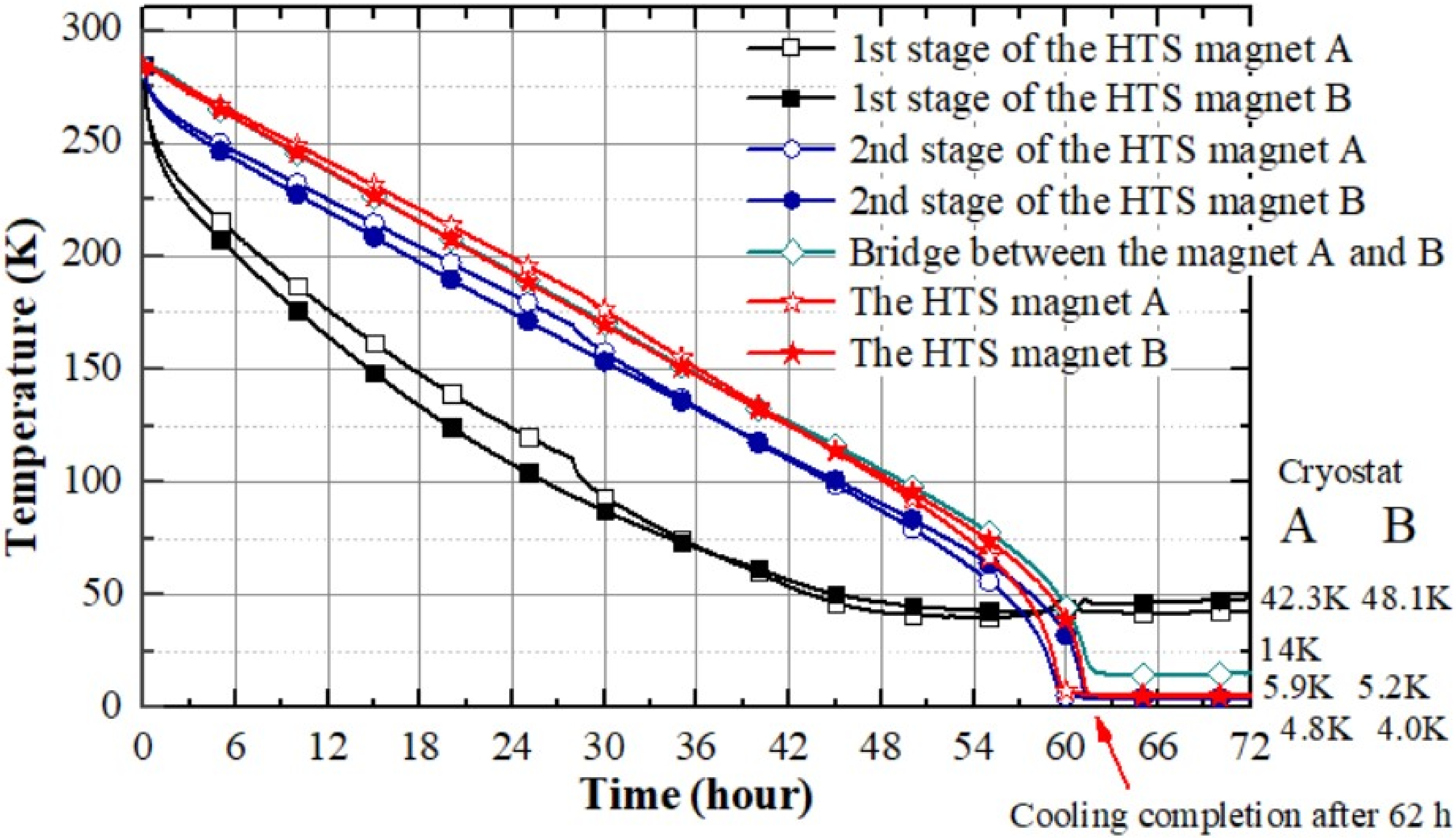
Cooling down test results of Cryostat A and B in the test B

Super coil

- The total cooling time took 2 days and 14 hours. It was 10 hours shorter than the results of Test A.
- The temperature at the 1st stage of cryo-cooler was saturated at 42.3K.
- Temperatures of the 2nd stage was cooled down and saturated at 5.2 K.



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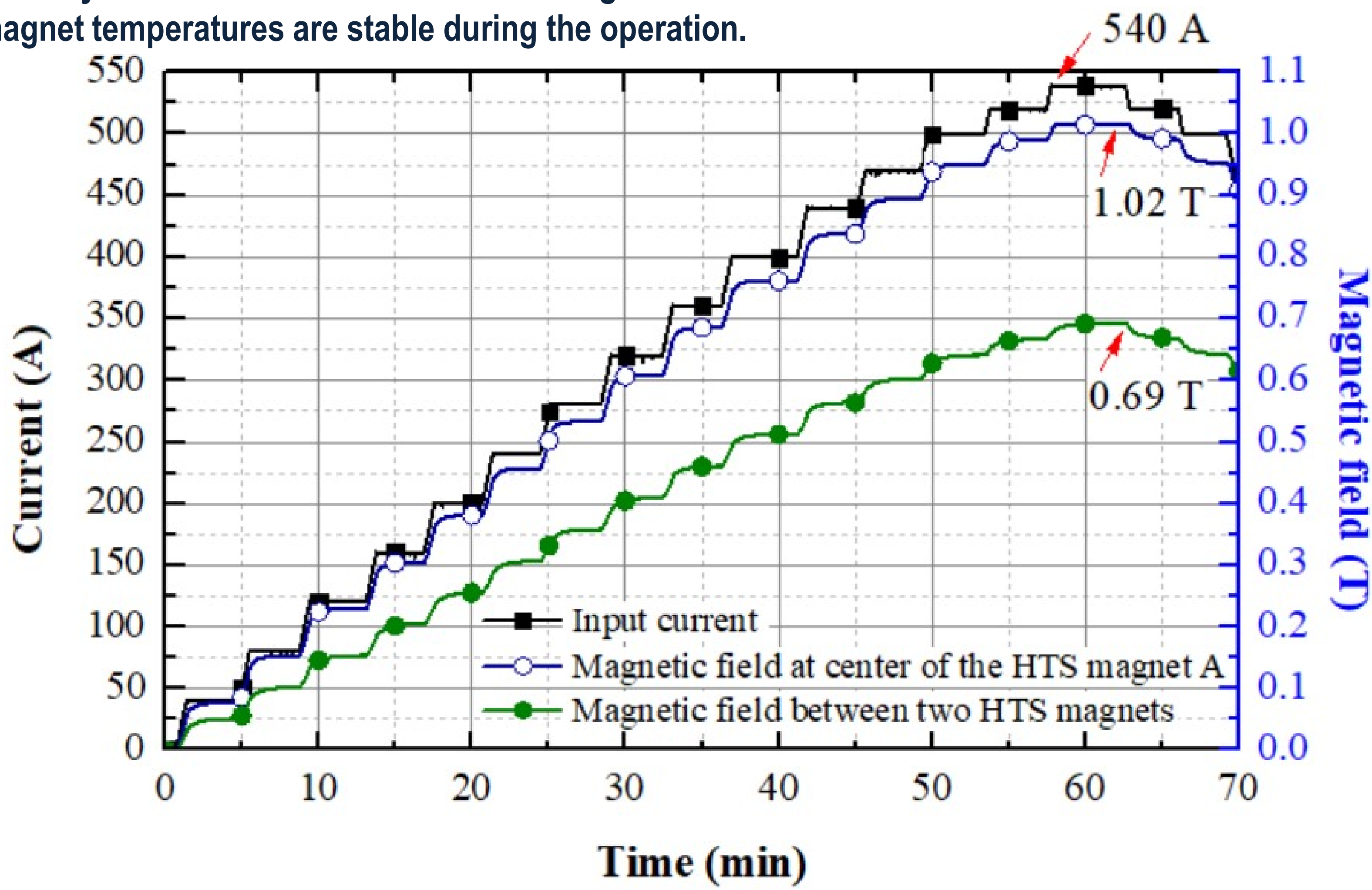
Current flowing test results in the test B

Super coil

- **When the current with 0.5 A/s ramping rate was supplied into the magnets up to 540A, the magnetic field increased as the current, proportionally.**
- **The magnetic flux density at the center of the magnet A was measured as maximum 1.02 T. And the magnetic flux density at the center between two HTS magnets was measured as maximum 0.69 T.**
- **All magnet temperatures are stable during the operation.**



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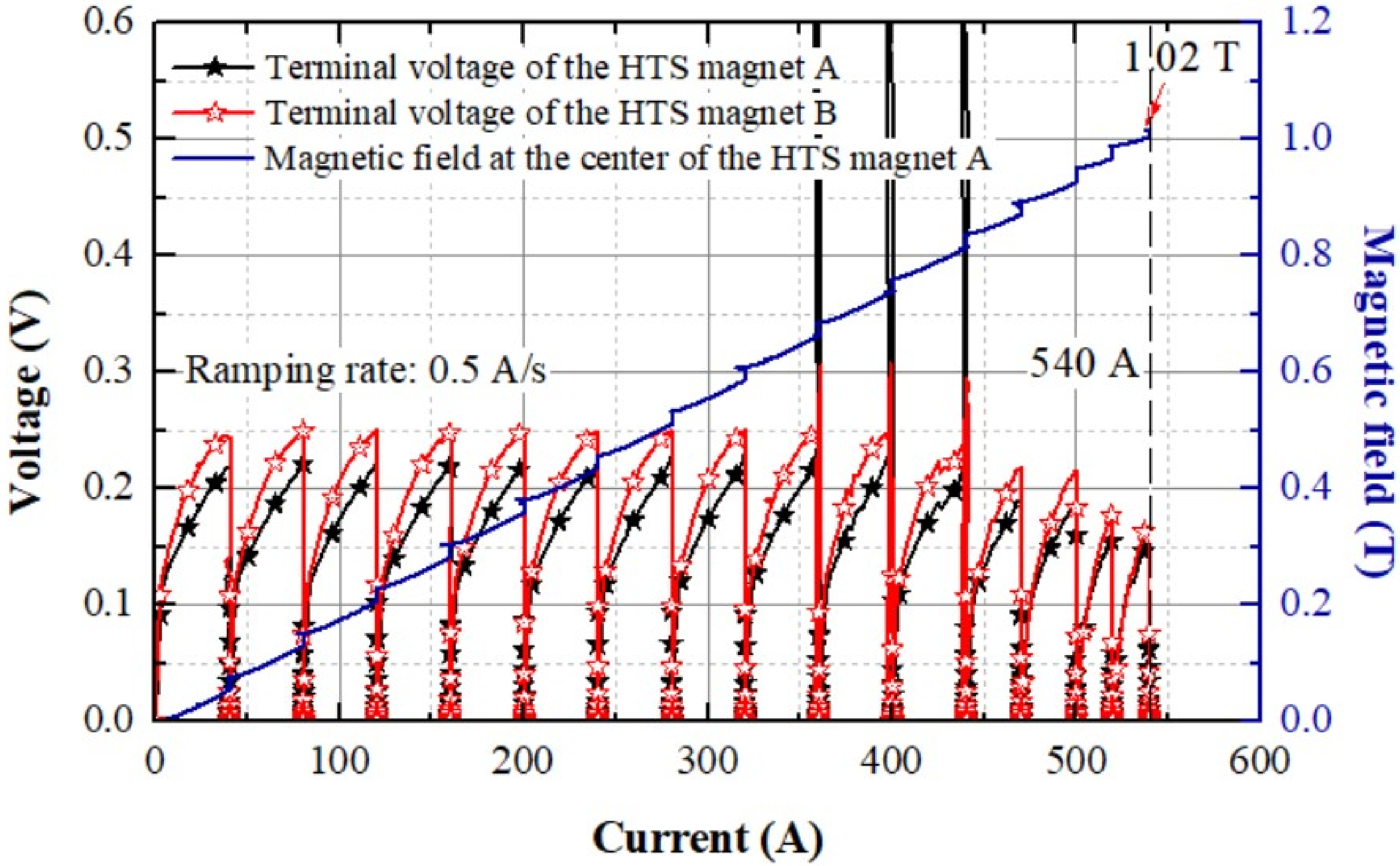
Current flowing test results in the test B

Super coil

- When the current with 0.5 A/s ramping rate was supplied into the magnets as 40 A step, the terminal voltages increased with inductive voltage and the magnetic field at the center of the magnet A was saturated every ramps.
- The total inductance 560 mH without iron cores. Charging time was about 3 minutes. The characteristic resistance was 23.6 mohms of the HTS magnet A.



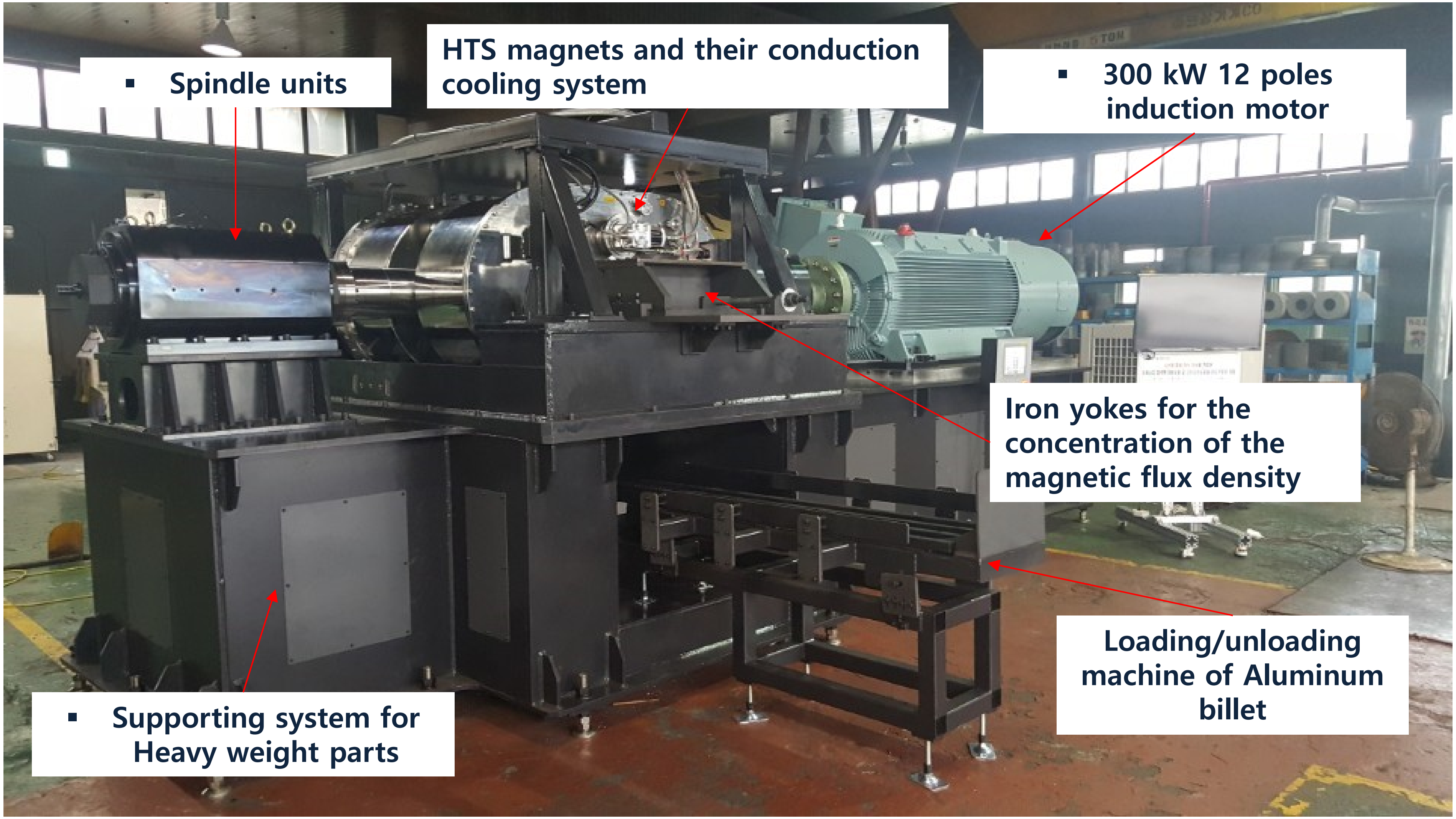
About the manufacturing process and operation test results of the SIH

SUPERCOIL®

Manufacturing Process of SIH (Sep. 2016 ~ Jul. 2017)

Super coil

➢ The first superconducting induction heater was manufactured in Korea.

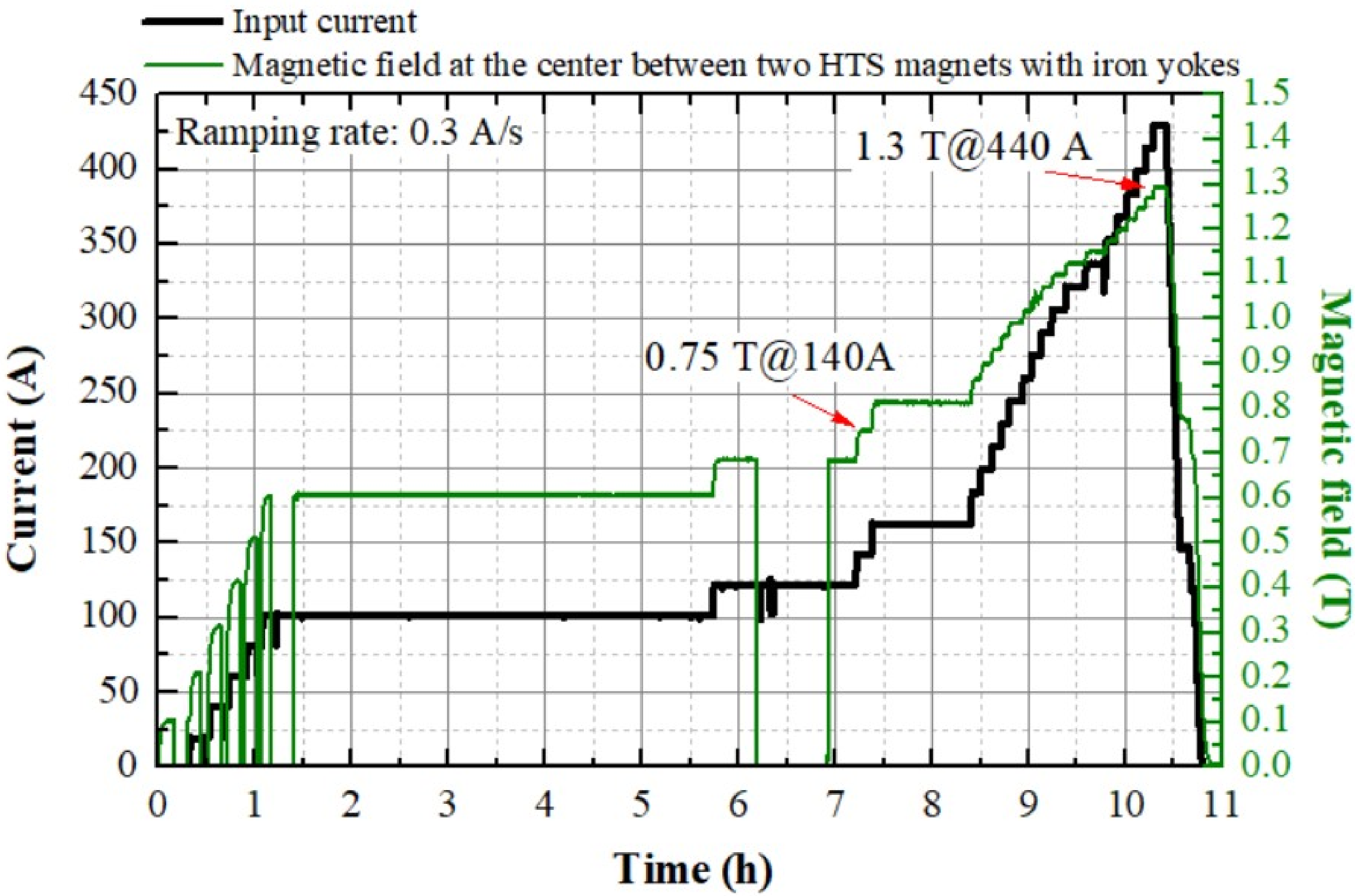


SUPERCOIL®

Current flowing test results in HTS magnets with iron cores

Super coil

- When the current with 0.3 A/s ramping rate was supplied into the magnets up to 440A, the magnetic field increased as the magnetization characteristics of the iron yokes.
- The magnetic flux density at the center between two HTS magnets was measured as 0.75 T at the input current 140 A. And the maximum magnetic flux density was measured as 1.3 T.
- All magnet temperatures are stable during the operation.

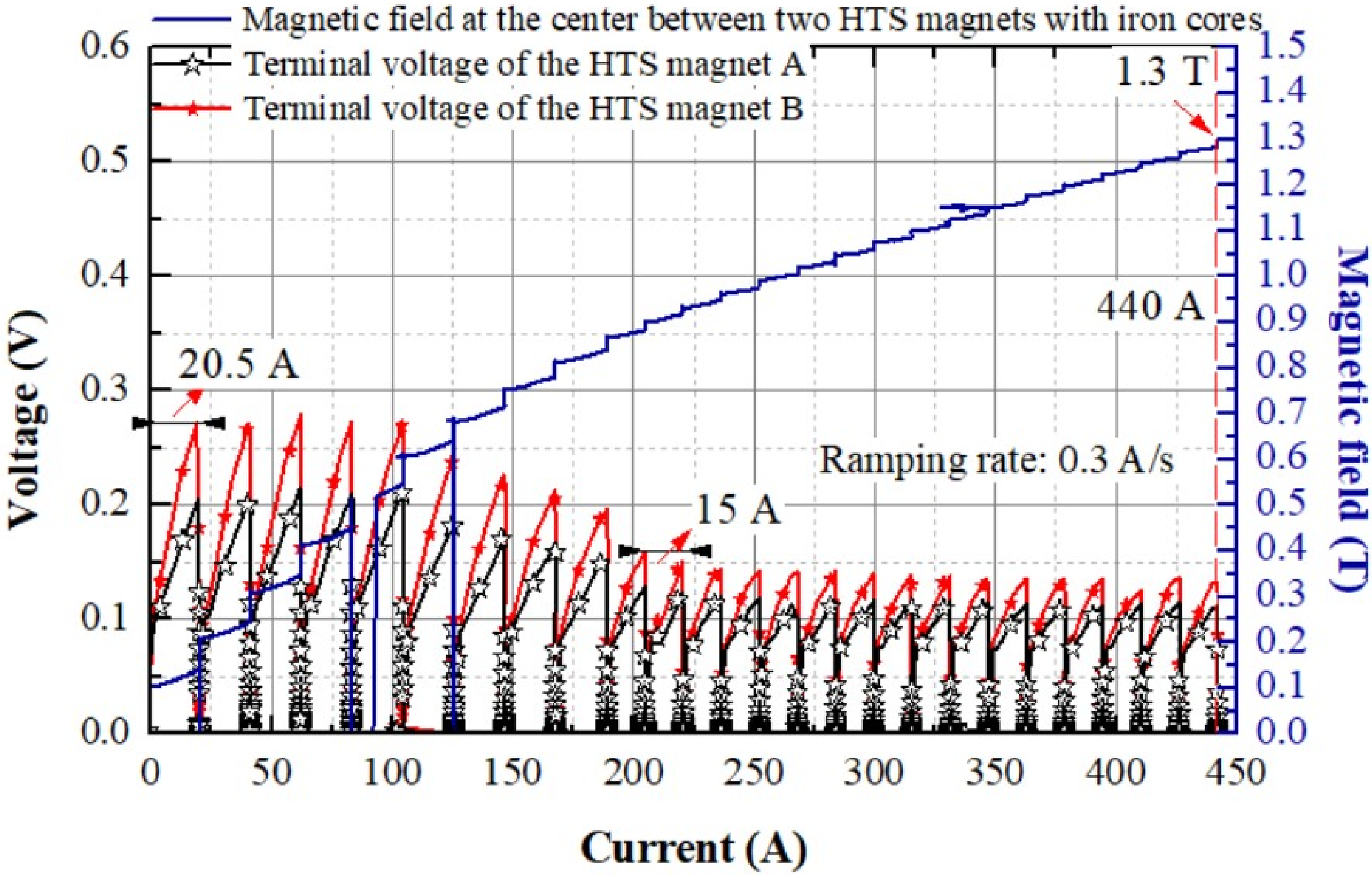


SUPERCOIL

Current flowing test results in HTS magnets with iron cores

Super coil

- When the current with 0.3 A/s ramping rate was supplied into the magnets as 20 A step, the terminal voltages increased with inductive voltage and the magnetic field at the center between two HTS magnets was saturated every ramps. From the operating current of 200 A, the current step was reduced to 15 A. So, the terminal voltage was reduced.
- The total inductance 1.8 H with iron cores. Charging time was about 10 minutes.



Manufacturing Process and test movies of SIH

Manufacturing Process of SIH (Sep. 2016 ~ Jul. 2017)

Youtube ➔ https://youtu.be/SQ9z_Jcq_rg

Test completion for aluminum billet with 300 kW SIH (Jul. 31, 2017)

Youtube ➔ https://youtu.be/rWKLf8ECrak

Test completion for iron billet with 300 kW SIH (Aug. 19, 2017)

Youtube ➔ https://youtu.be/6sHqKhX2pb4

SUPERCOIL

The first industrial superconducting induction heater

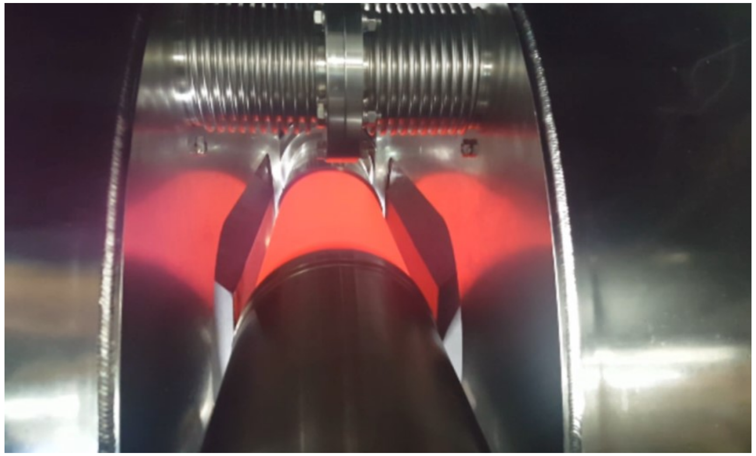
Super coil

- The first superconducting induction heater was open to public in Korea on the 28th of Sep. in 2017.

SUPERCOIL

Conclusion and discussion

- We developed the HTS magnet with the conduction cooling system for superconducting induction heater. The excitation test was successful.
- We developed the rotating system for the superconducting induction heater. The performance of the spindle unit was demonstrated through the design parameters and real test results.
- The first superconducting induction heater was manufactured. The aluminum and iron billet heating tests were successful .
- Supercoil has a target to realize these superconducting induction heater technologies for industries.



Thank you for your attention.