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Design and Development of a High-Frequency Magnet

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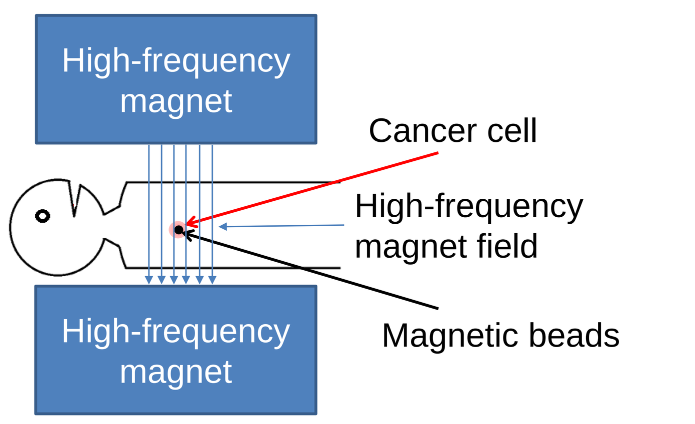
Introduction

Research objective:
Examine the design method of high frequency magnet systems for the magnetic hyperthermia cancer therapy.

magnetic hyperthermia cancer therapy



Target specifications[1]

- 0.06 T and 200 kHz of the AC peak magnetic flux density, and
- The operating time of the system is required to be 300 s

In order to examine the design method, we design and development a small-scale high-frequency magnet prototype including:

- Wire design
- Capacitor banks
- Magnet design
- Cooling method

REFERENCES :[1] S. Nomura, T. Isobe, IEEE Trans. Appl. Superconduct. vol. 28, NO.3, 2018, Art. NO. 441807

Wire Configuration for the High –Frequency Magnet

Resistance of coils

DC

- Law of resistance

$$R = \rho \frac{l}{NS} \quad (1)$$

R: Resistance
ρ: Resistivity
l: Length
S: Cross sectional area
N: Number of conductors

AC

- Skin effect

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \quad (2)$$

δ: Skin depth
μ: Magnetic permeability
ρ: Resistivity
ω: Angular frequency

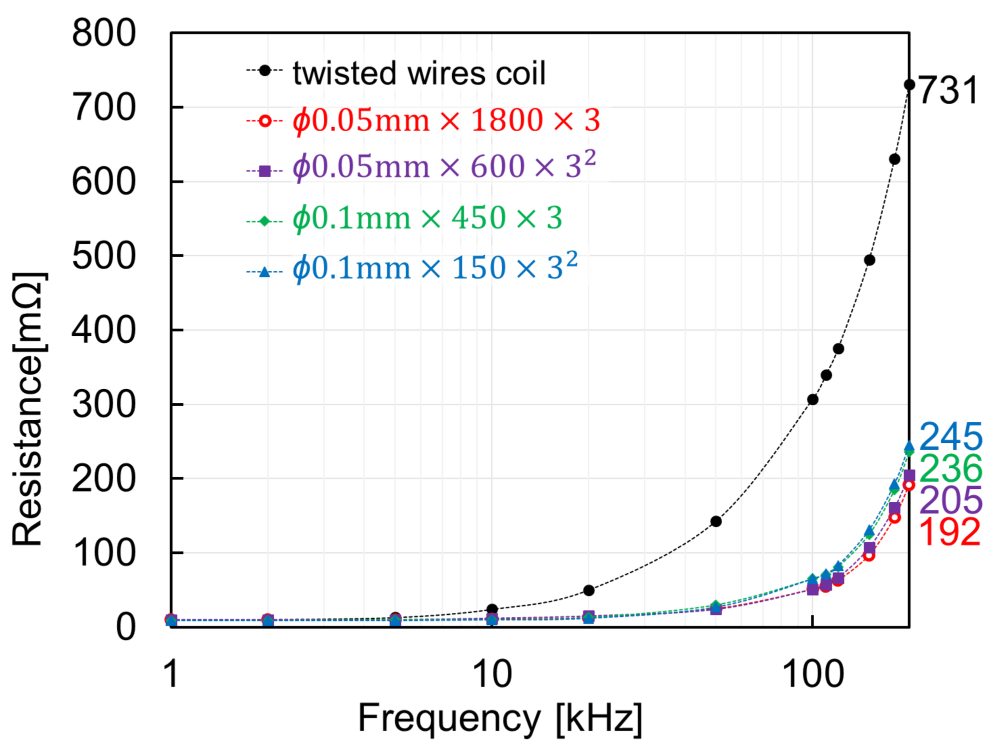
200 kHz ➡ $\delta = 0.148$ mm
➡Using the wires that have radii of their strands lower than 0.148 mm

- Proximity effect
- Current sharing problem

Five experimental coils

Wire type	Stranded wire	Litz wire	Litz wire	Litz wire	Litz wire
Diameter of strands	0.32 mm	0.05 mm	0.05 mm	0.10 mm	0.10 mm
No. of strands	70	1800	600	450	150
No. of bundles	2	3	9	3	9

The resistance of each coil



*The inductance of all coils was kept at 70 μH by adjusting the ferrite core placement.

- Twisted wire pitch of all coils is 14.3 mm.
- All the experiment coils are 10-turns double-pancake coils with an equal total cross-sectional area.

- The resistance of Litz wire is less than stranded wires.
- The resistance of coil consists of 3 bundles of ϕ 0.05mm × 1800 Litz wire was the lowest at 200 kHz

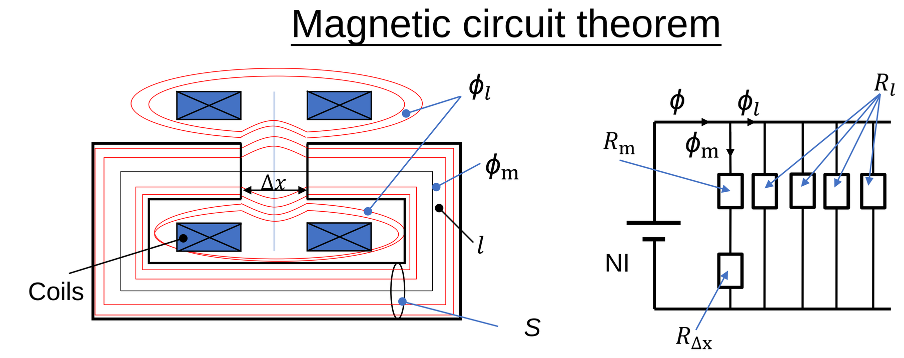
Final design copper Litz wires of coil windings

- Made by Ishizue Magnet Wire
- $\phi 0.05\text{mm} \times 1800 \times 3$

Investigation of Self-Inductance and Coil Arrangements of Magnet

Estimation of the Magnetic Flux Base on Magnetic Circuit Theorem

Magnetic circuit theorem



Total magnetic flux:

$$\phi = \phi_m + \phi_l \quad (3)$$

Magnetic circuit theorem:

$$\phi_m = \frac{NI}{R_m} = \frac{NI}{\frac{\Delta x}{\mu_0 S} + \frac{l}{\mu_s \mu_0 S}} \quad (4)$$

Assumption:

$$\phi_l = \eta \phi_m \quad (5)$$

$$\phi = \phi_m + \phi_l = (1+\eta)\phi_m \quad (6)$$

$$L = \frac{N\phi}{I} = (1+\eta)\frac{N^2}{R_m} \quad (7)$$

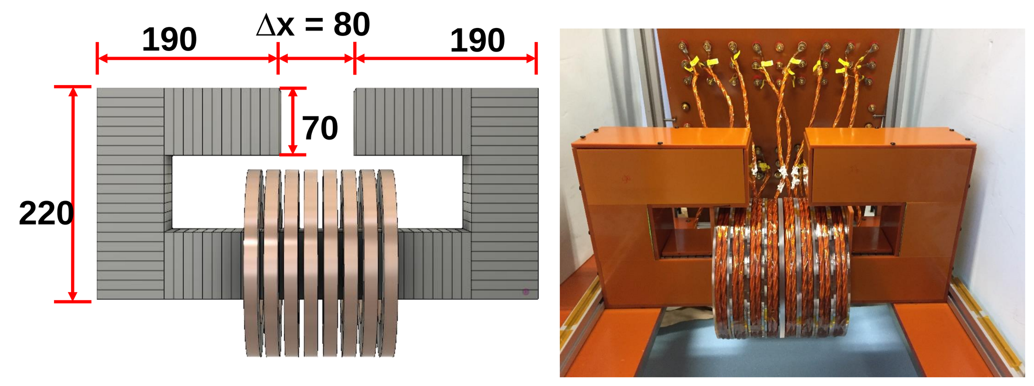
Self-inductance of magnet should be reduced to lower the applied voltage between both ends of coil.
In order to optimize the design of magnet
➡ High-frequency magnet prototype
- Ferrite core length is 1 m
- 8 sets of 10-turns coils

Ferrite

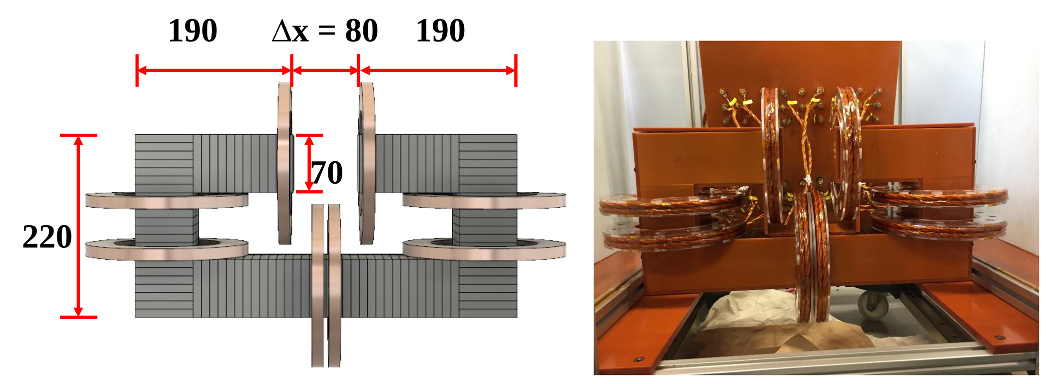
- Made by TDK
- μ_s: 2300 (at 200 kHz)
- ρ: 6.5 Ω・m (resistivity)
- $79 \times 70 \times 10$ mm^3 × 100 sheet

Optimization of the Coil arrangements on the Ferrite Core

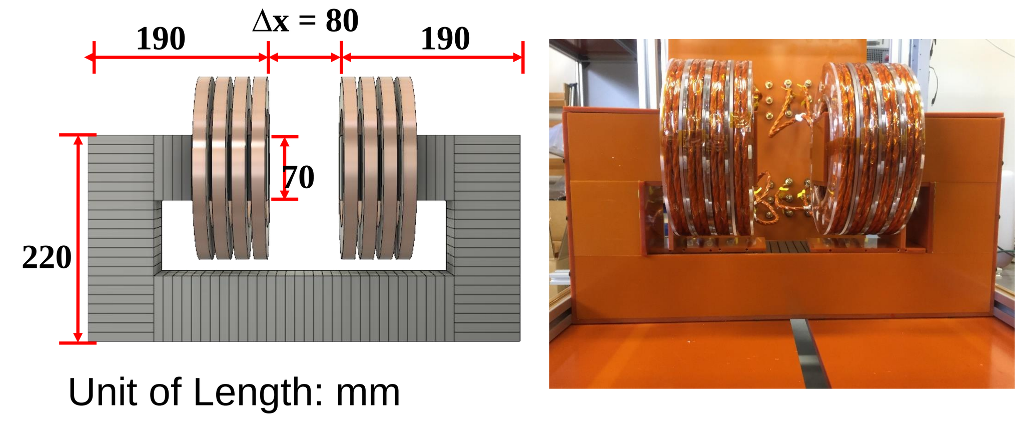
Core centralized-type



Distributed-type

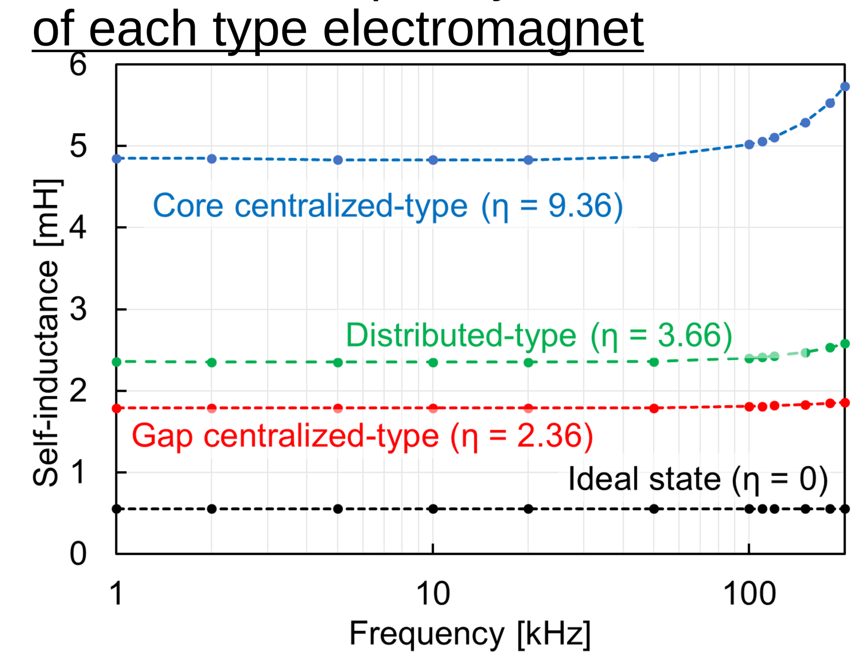


Gap centralized-type

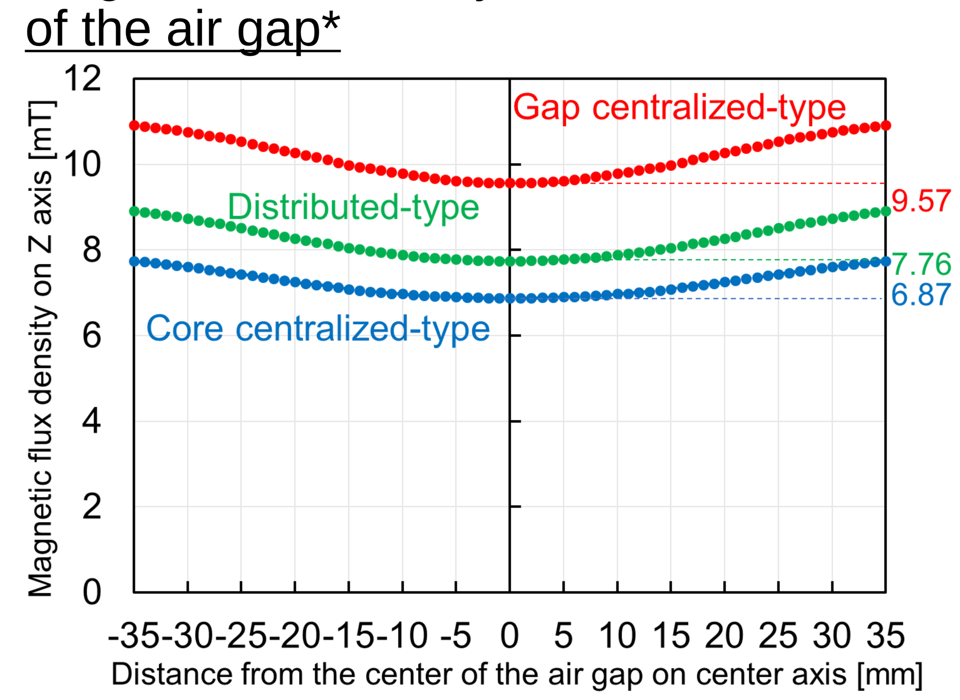


Unit of Length: mm

Inductance frequency characteristics of each type electromagnet



Magnetic flux density on the center axis of the air gap*



*Excitation current is 7.07 A (10 Ap), 50 Hz

The specifications of each type magnet

	Core centralized	Distributed	Gap centralized
Self-inductance	5.73 mH	2.58 mH	1.86 mH
$\eta = \frac{\phi_l}{\phi_m}$	9.36	3.66	2.36
Peak Current	87.2 A	77.56 A	62.67 A
Peak Voltage	628.62 kV	251.48 kV	146.48 kV

"Target peak magnetic flux density: 600 G

Therefore, the authors carry out the final design of the magnet prototype is the gap centralized-type high-frequency electromagnet.

The basic specifications of the final design high-frequency magnet prototype

Peak magnetic field	0.06 T
Frequency	200 kHz
Operating time	300 s
Air gap (therapy area)	0.08 m
Magnetic core length	1.0 m
Peak / effective value current	65 Ap / 46 A
Total number of turns	80 turns
Litz wires	Φ0.05 mm×1800× 3
Resistance	10 Ω (200 kHz)
Self inductance	1.86 mH(200 kHz)
Copper losses power	21.2 kW
Peak Voltage	146.48 kV

Prototype for Magnetic Hyperthermia Applications

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University of Tsukuba

Series Resonance Circuit for the Power Supply of The Magnet Prototype

Design of the Series Resonance Circuit

In order to reduce required inverter capacity
➡ Compose a series resonance circuit by using capacitor banks [1]

Capacitance of capacitor banks:

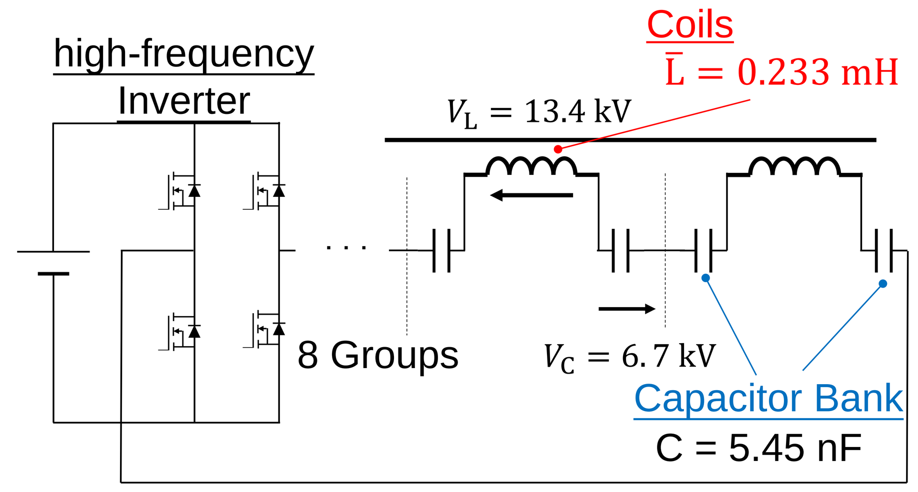
$$C = \frac{n}{\omega^2 L} \quad (8)$$

Voltage between Both ends of capacitor banks:

$$V = \frac{I}{\omega C} \quad (9)$$

n: Number of capacitor banks

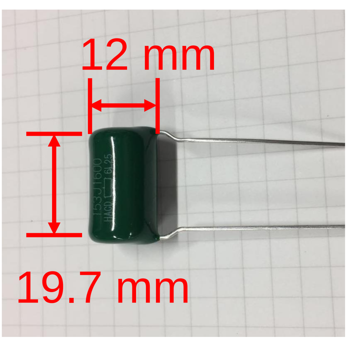
Schematic circuit diagram of the system



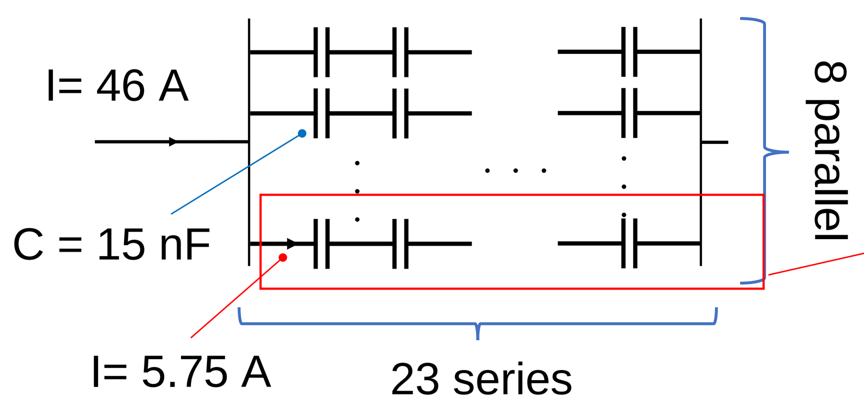
* L = 1.86 mH,
I= 46 A,
f= 200 kHz,
n= 16

Test Results and Comparison of the capacitor banks

HACD series high frequency capacitor



Made by NIPPON CHEMI-CON
HACD135J16006L25
Capacitance：15 nF
Rated ripple voltage：Vac = 350 V
Rated ripple current：I = 2.56 A

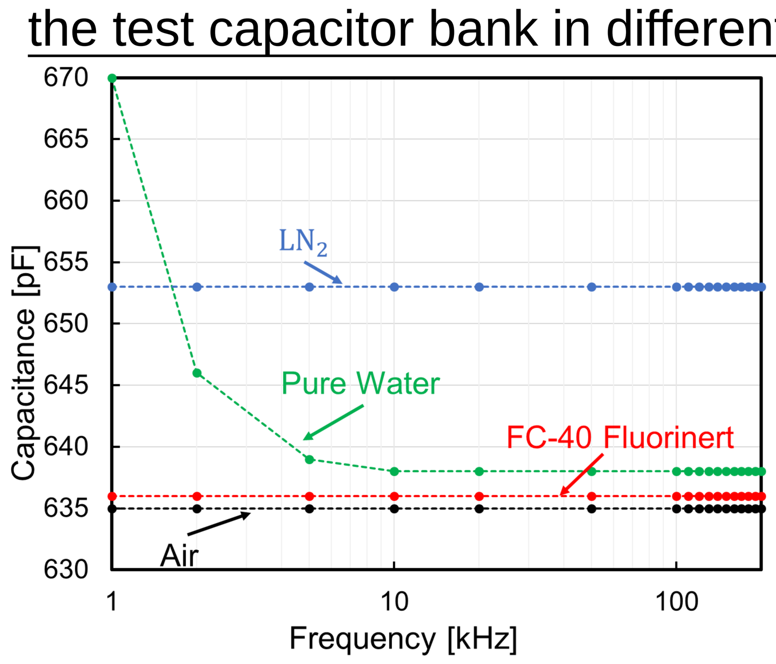


Capacitance is 5.21 nF
➡Resonate frequency is 204 kHz

A 23 series × 1 parallel test capacitor bank

Capacitance：15 nF / 23 = 652 pF
Rated ripple voltage： 8 kV
Rated ripple current：2.56 A

Capacitance frequency characteristics of the test capacitor bank in different coolant

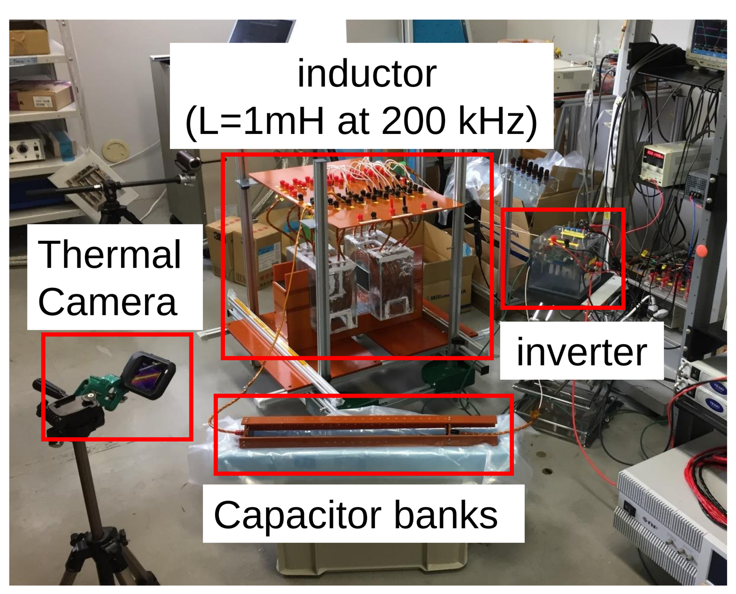


Capacitance of the test capacitor bank is 0.636 nF when the coolant is fluorinert at 200 kHz.
➡Can resonate with a 1.0 mH inductor at 199 kHz.

Verification experiment of cooling method

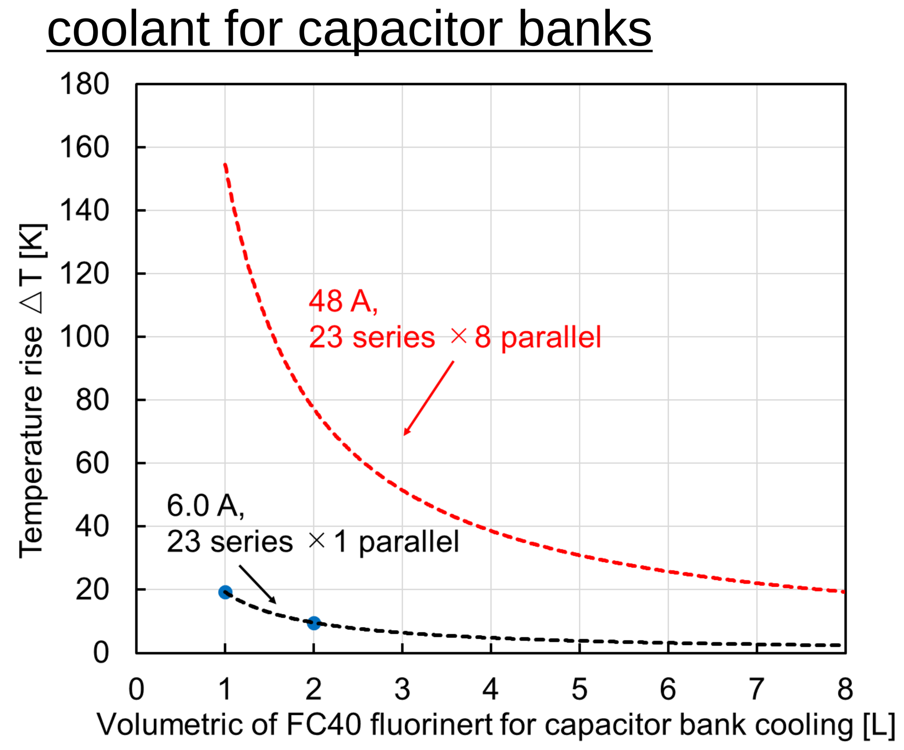
Coolant	FC-40 Fluorinert	Pure water
Boiling point	165 ℃	100 ℃
Liquid density	1870 kg/m^3	1000 kg/m^3
Liquid specific heat	1050 J/kg·K	4217 J/kg·K
Dielectric constant	1.9	80

Compose a series resonance circuit using the test capacitor bank and a 1.00 mH inductor.



- Cooling the test capacitor bank by 1L~2L fluorinert.

Test results of the temperature rise of coolant for capacitor banks



- Resonate with inductor in 199 kHz.
- 6 A , 1 L➡ 20 K

23 series ×8 parallel capacitor bank
48 A, 8L➡20 K (target current is 46 A)

Thermal Conditions and Cooling Method of Coil Windings

Calculation of the Temperature Rise of the Coil Windings

$$U_j = U_c + U_r \quad (10)$$

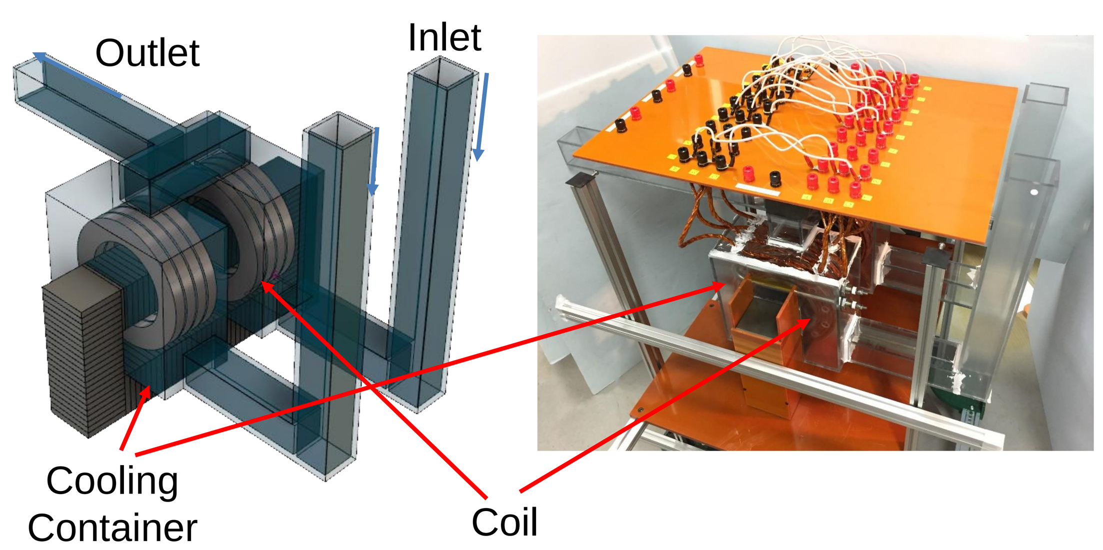
$$\int_0^{t_{op}} I_{rms}^2 R dt = \int_{T_0}^{T_c} m_c C_c dT + \int_{T_0}^{T_r} Q t_{op} \rho_r C_r dT \quad (11)$$

$$Q = \frac{I_{rms}^2 R t_{op} - m_c C_c (T_c - T_0)}{\rho t_{op} C_r (T_r - T_0)} \quad (12)$$

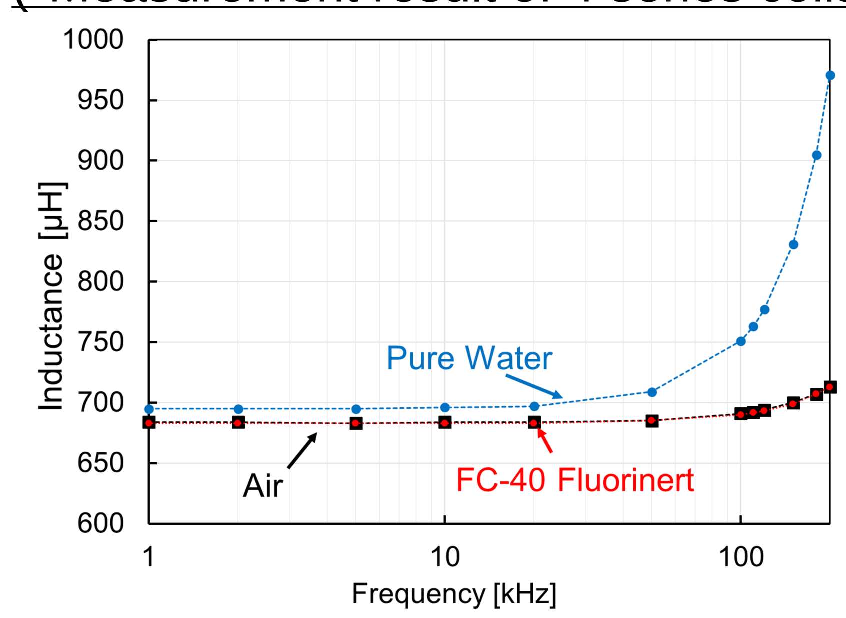
U_j: Copper losses (Joule heat)
U_c: Heat capacity of the coil winding
U_r: Endothermic energy
Q: Volumetric flow rate of refrigerant
m_c/C_c: Mass / Heat capacity of coils
ρ_r/C_r: Mass density/ Heat capacity of refrigerant
T_c: Maximum coil temperature
T_r: Maximum refrigerant temperature
T_0: Initial temperature

Test Results and Comparison of the Cooling Method for the Coil Windings

Cooling Container of Coil

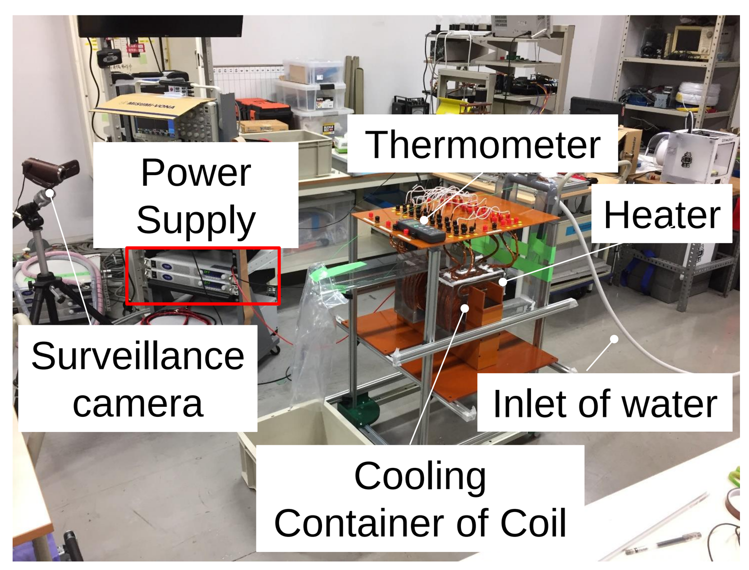


Self-inductance of coil in different coolant (*Measurement result of 4 series coils)



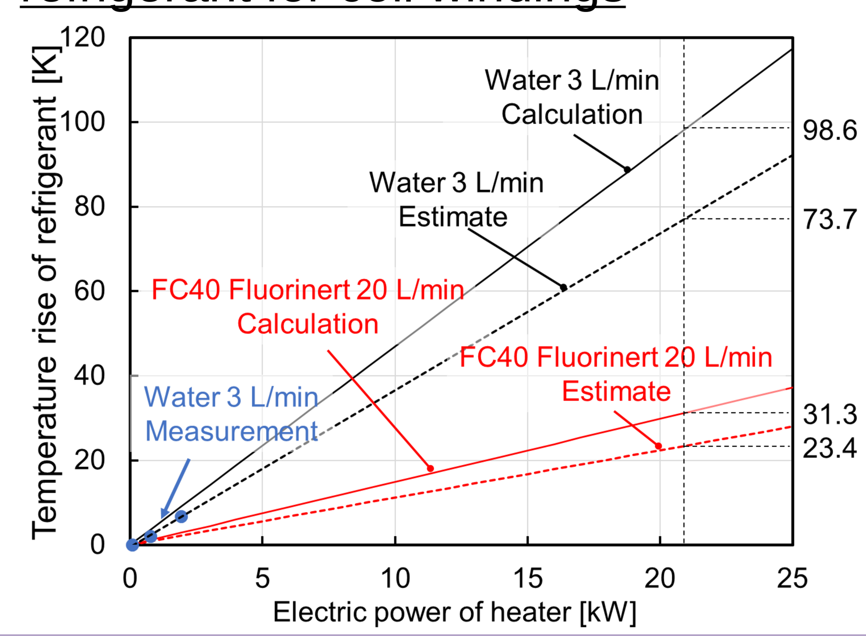
Water can not be use as coolant because the inductance will become higher at high-frequency

Verification experiment of cooling method



Experiment method
- Set the Q of water to 3 L/min.
- Control the power cost of Heater form 0 kw to 2 kW.
- Measure the 5 minutes temperature rise of water.
- Estimate the temperature rise when power cost is 2 kW~25 kW.
- Estimate the temperature rise when refrigerant is FC40-fluorinert.

The results of the temperature rise of refrigerant for coil windings



The temperature rises of coolant is 23 K (Calculation is 31 K) when using the fluorinert that volumetric flow rate Q is 20 L/min. (*Initial temperature is 24 ℃ (297.2 K))

Conclusions

The authors design and developed a small-scale high-frequency magnet prototype.
From the results of test experiments:

- The resistance of high-frequency magnet coils is higher than calculation by “law of resistance” even the wires of the coils that have the radii of their strands lower than the skin depth, and
- The gap centralized-type is the best arrangements to reduce self-inductance, and
- The capacitor bank for series resonance circuit can be prepared by commercially available HACD series high frequency capacitors. And it can be operated continuously in 300 s by using coolant as fluorinert, and
- The copper loss problem of high-frequency magnet coil windings can be resolved by using a fluorinert cooling system.

These results is verified by this high-frequency magnet prototype and test experiments. These results can use as references to design a high-frequency magnet real machine.

Next step of this work is to establish a design method for high-frequency magnet, and design a high-frequency magnet real machine.