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Feasibility Study on a Real-Scale High-Frequency Electromagnets for Magnetic Hyperthermia Base on a Magnetic Scaling law

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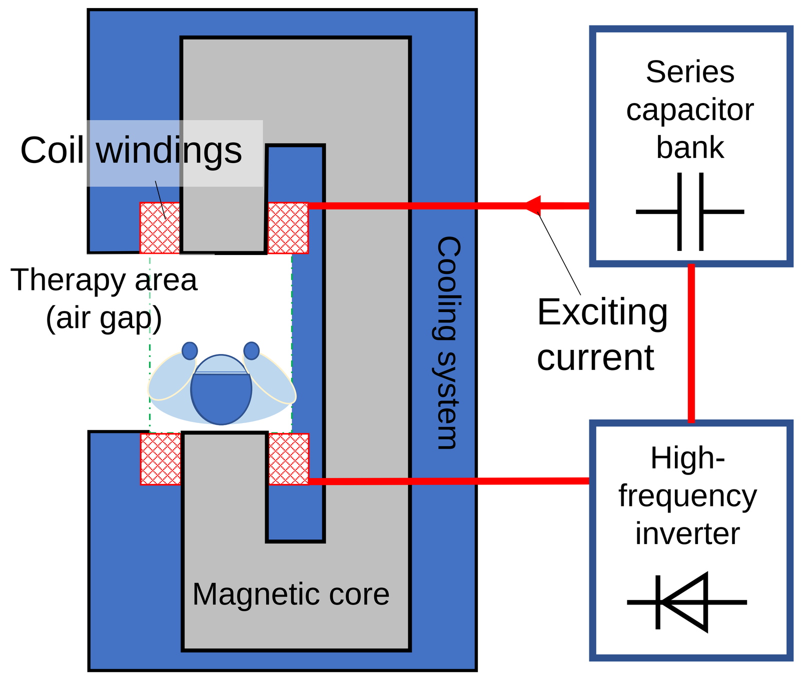
Introduction

High-frequency electromagnet system for magnetic hyperthermia



Target specifications of the high-frequency magnet[1]

- 64 mT and 114 kHz of the peak magnetic flux density
- 360 s of the operating time

Electromagnet with a wide air gap

- Wide air gap ➡ For enter a body
- Magnetic core ➡ To focus the magnetic flux

However: high-frequency ➡ core losses

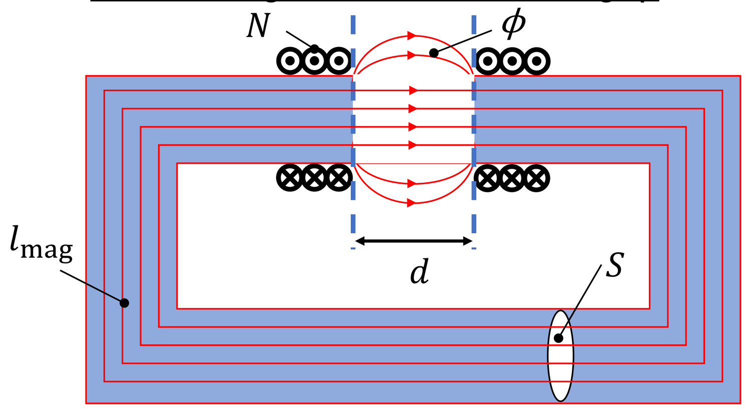
Research objective of this work:

1. Establish a design method for high-frequency electromagnet include:
   - Self-inductance calculation
   - Center magnetic flux density estimation
   - Power losses analysis
2. Verify the feasibility of a real-scale high-frequency electromagnet for magnetic hyperthermia

REFERENCES ：[1] E. Kita *et al*., Int. J. Hyperthermia, vol. 53, NO.11, 2017, Nov. NO. 5100905

Self-inductance calculation

Electromagnet with a wide air gap



$$L = \frac{N^2}{\mathcal{R}_{\mathrm{core}} + \mathcal{R}_{\mathrm{air}}} \quad (1)$$

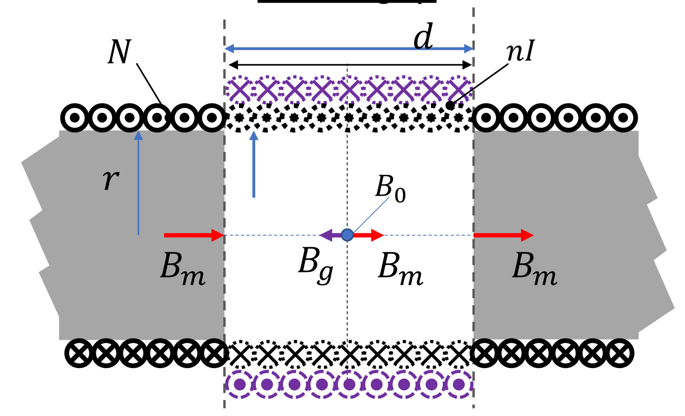
$$\mathcal{R}_{\mathrm{core}} = \frac{l_{\mathrm{mag}}}{\mu_0 \mu_r S} \quad (2)$$

$$\mathcal{R}_{\mathrm{air}} = (1 - K_n)\frac{d}{\mu_0 S} \quad (3)$$

K_n is the Nagaoka coefficient.
The formulation of (3) can be found in appendix.

Center magnetic flux density estimation

Calculation model for center magnetic flux density of the air gap



$$B_0 = B_m - B_g \quad (4)$$

$$B_m = \frac{LI}{NS} = \mu_0 nI \quad (5)$$

$$B_g = \frac{\mu_0 nId}{\sqrt{4r^2 + d^2}} \quad (6)$$

nI is the magnetomotive per unit length of the equivalent infinite length solenoid.

Power losses analysis [2]

Skin effect losses of the Litz wires P_{sL}

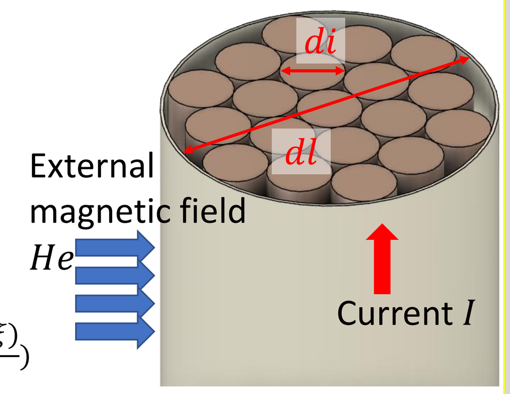
$$P_{\mathrm{sL}} = n\, R_{\mathrm{DC}} F(\xi) \cdot \left(\frac{I_{\mathrm{peak}}^2}{n}\right) \quad (7)$$

$$F(\xi) = \frac{\xi}{4\sqrt{2}}\left(\frac{\mathrm{ber}_0(\xi)\mathrm{bei}_1(\xi) - \mathrm{ber}_0(\xi)\mathrm{ber}_1(\xi)}{\mathrm{ber}_1^2(\xi) + \mathrm{bei}_1^2(\xi)} - \frac{bei_0(\xi)ber_1(\xi) + bei_0(\xi)bei_1(\xi)}{ber_1^2(\xi) + bei_1^2(\xi)}\right)$$

Proximity effect losses of the Litz wires P_{pL}

$$P_{\mathrm{pL}} = n\, R_{\mathrm{DC}} G(\xi) \cdot \left(H_e^2 + \frac{I_{\mathrm{peak}}^2}{2\pi^2 d_l^2}\right) \quad (8)$$

$$G(\xi) = -\frac{\xi \pi^2 d_l^2}{2\sqrt{2}}\left(\frac{\mathrm{ber}_2(\xi)\mathrm{ber}_1(\xi) + \mathrm{ber}_2(\xi)\mathrm{bei}_1(\xi)}{\mathrm{ber}_0^2(\xi) + \mathrm{bei}_0^2(\xi)} + \frac{\mathrm{bei}_2(\xi)\mathrm{bei}_1(\xi) - \mathrm{bei}_2(\xi)\mathrm{ber}_1(\xi)}{\mathrm{ber}_0^2(\xi) + \mathrm{bei}_0^2(\xi)}\right)$$



$R_{\mathrm{DC}} = 4\rho l/d_i$ is the Litz wire's DC resistance.
$\xi = d_i/\sqrt{2}\delta$ and $\delta = \sqrt{\rho/\pi\mu_0 f}$ is the skin depth.

Core losses P_m

$$P_m = k f^{\alpha} B_m^{\beta} \cdot V \quad (9)$$

k, α, β are the material parameters.
V is the volume of the magnetic core.

Equivalent losses

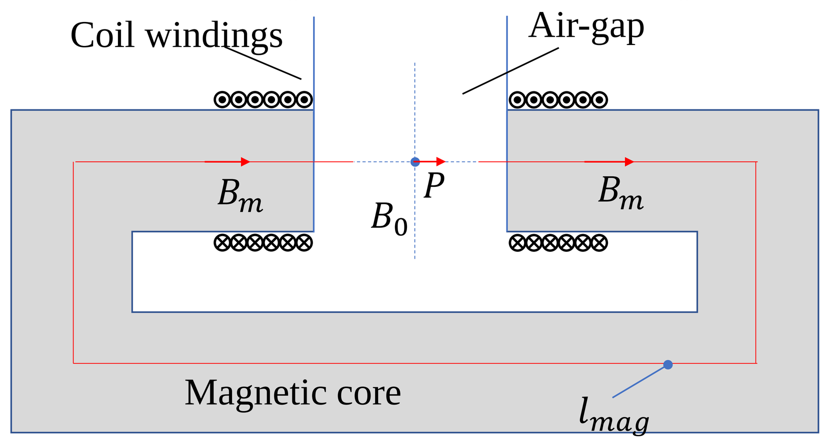
$$R_e = \frac{2(P_{\mathrm{sL}} + P_{\mathrm{pL}} + P_m)}{I_{\mathrm{peak}}^2}$$

Equivalent resistance Re is changing with the exciting current.

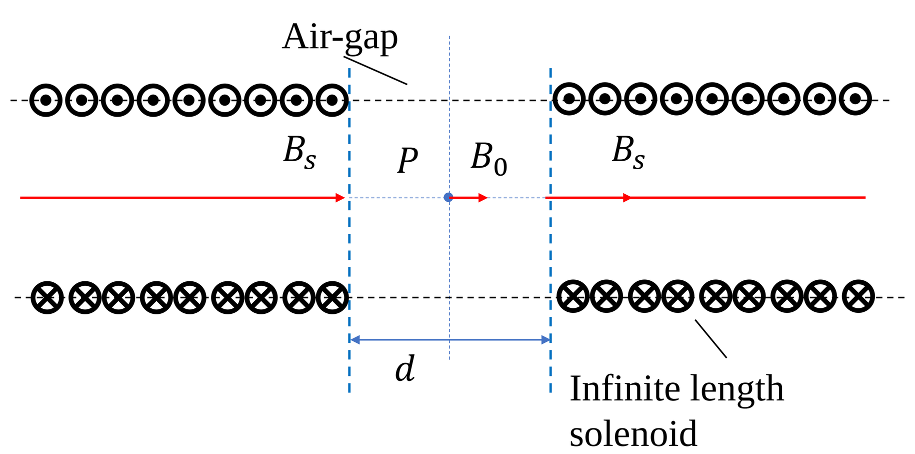
REFERENCES ：[2] S. Nomura *et al*., IEEE Trans. Appl. Superconduct, vol. 28, NO. 3, 2018, Art. NO. 441807

A simple equivalent model of the electromagnet with a wide air gap

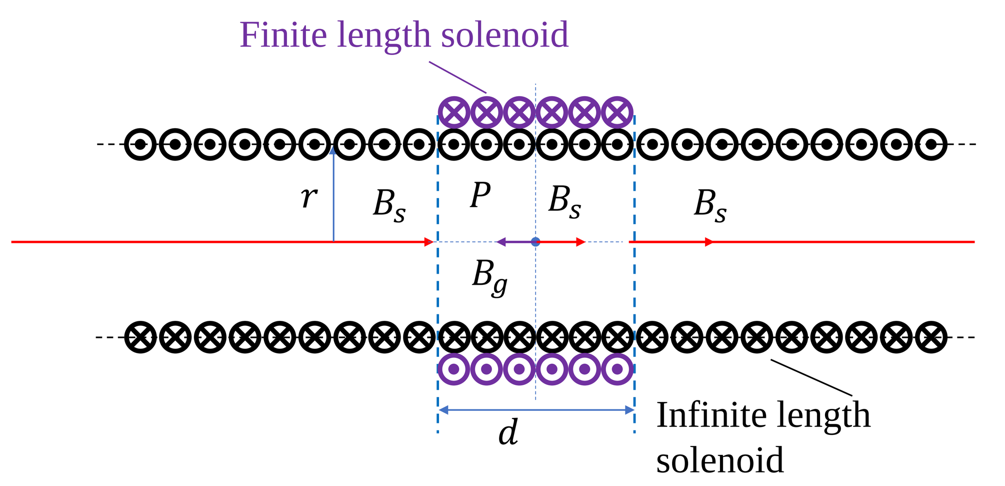
Electromagnet with a wide air gap



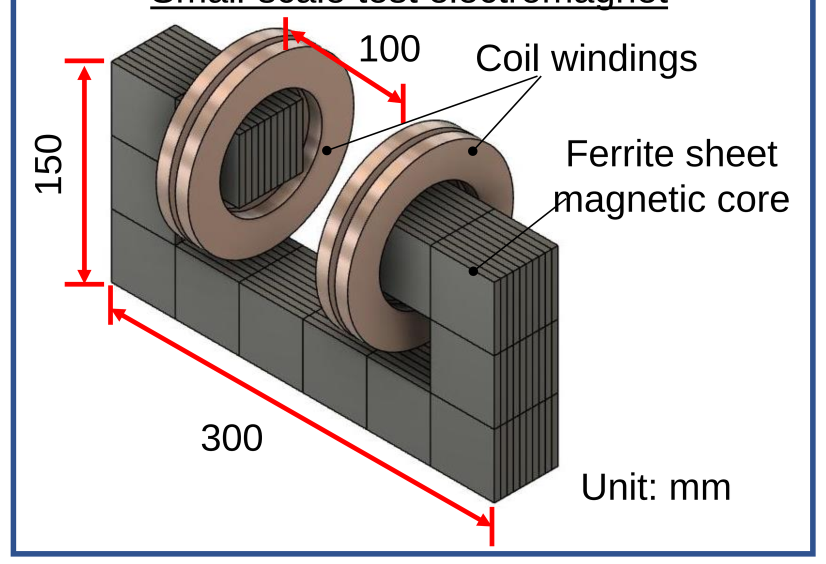
A infinite length solenoid with a wide air gap

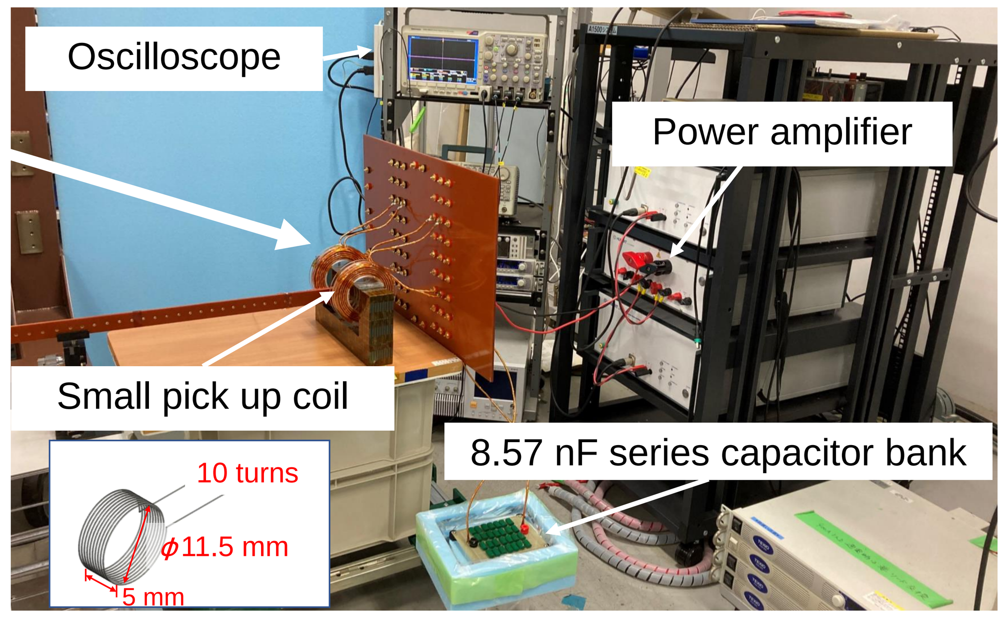


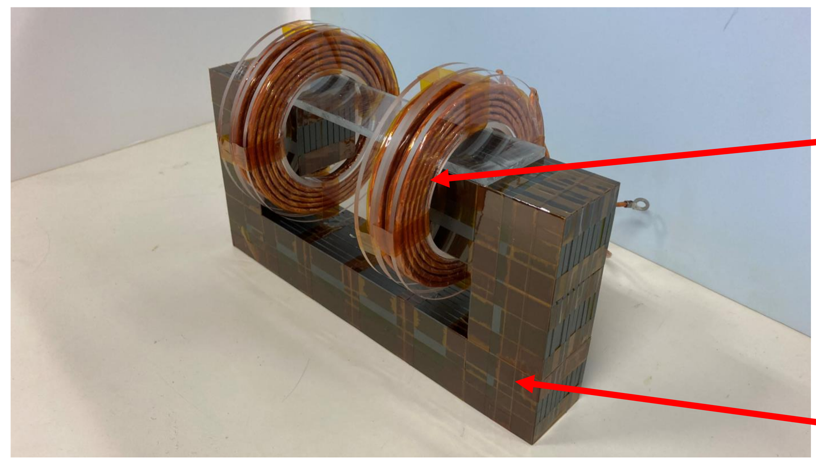
A infinite length solenoid with a reverse direction finite length solenoid

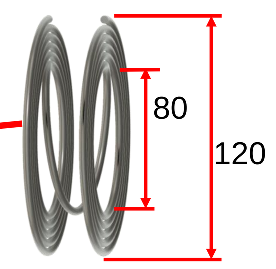


Small-scale high-frequency electromagnet and test exciting experiment









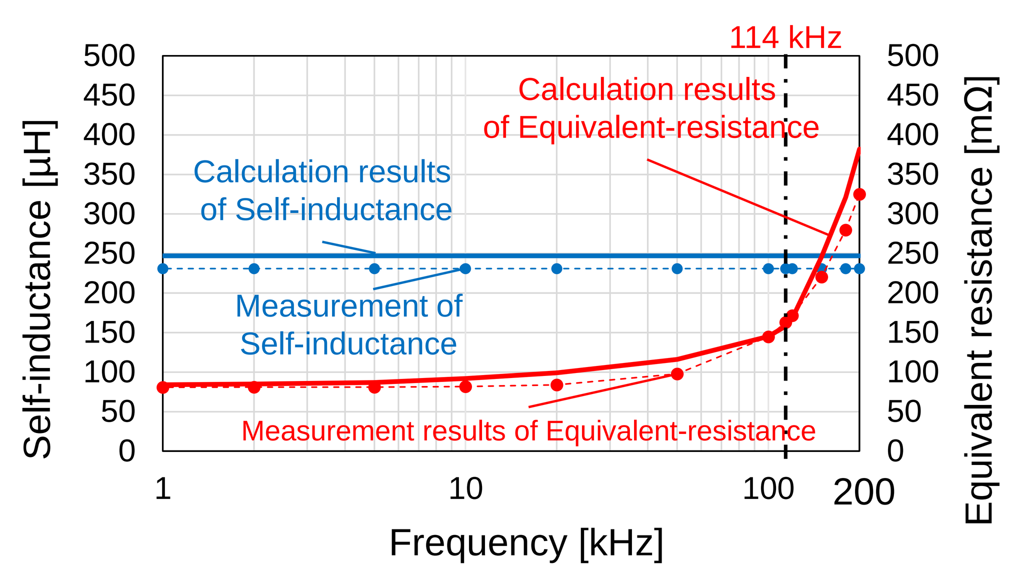
Double pancake coil
10 turns × 4 sets
= 40 turns

Litz wires
ϕ 0.05 mm × 1800

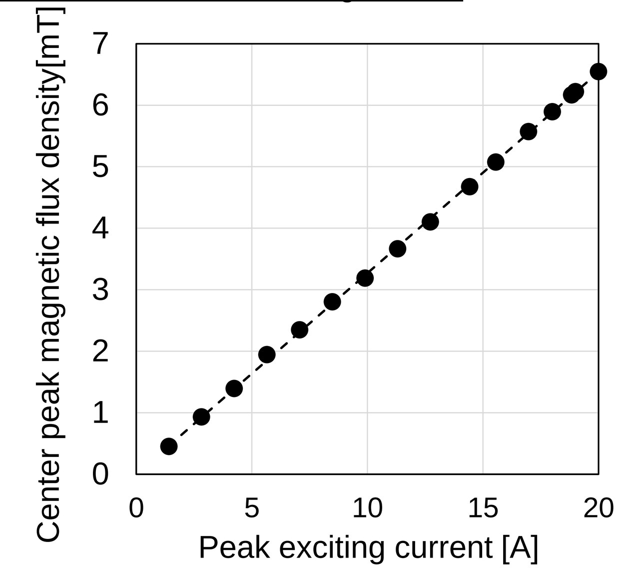
TDK PC40

- μ_s: 2300 (at 200 kHz)
- 50 × 50 × 5 mm × 120 sheet
- $k = 2.09, \alpha = 1.43, \beta = 2.41$ [3]

Calculation results and measurement results of self-inductance and equivalent resistance of test electromagnet (in 20 mA)



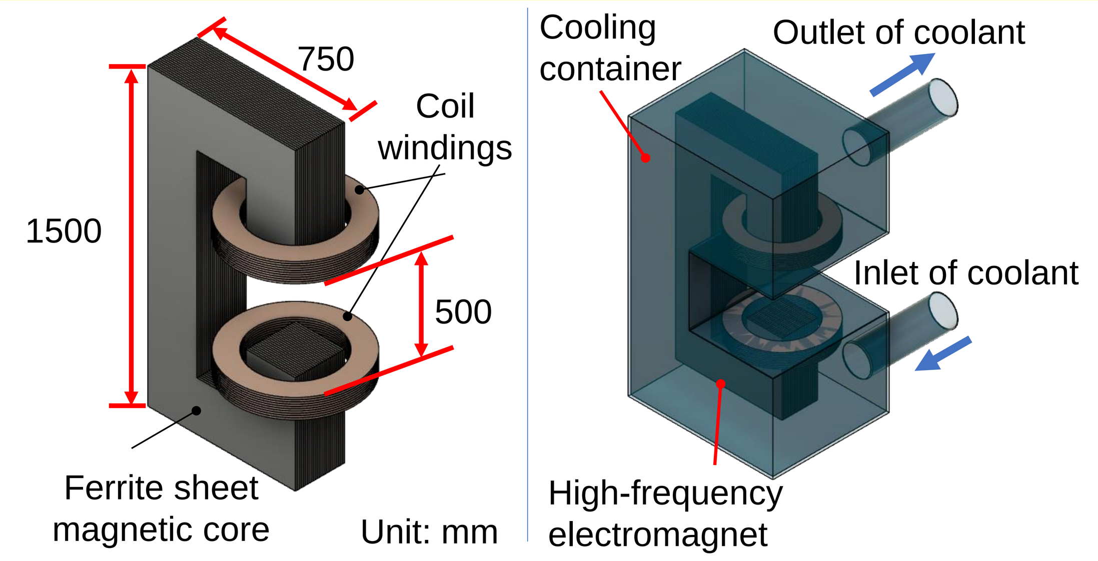
The peak magnetic flux density of the air gap center in different exciting current



COMPARISON OF DESIGN RESULTS AND MEASUREMENT RESULT

		Design results	Measurement results
Self-inductance	L	247 μH	247 μH in 114 kHz
Center peak magnetic flux density in unit current	B_0/I_{peak}	0.32 mT	0.33 mT in 114 kHz
Peak exciting current for target magnetic flux density (64 mT)	I_{peak}	201 A	195 A
Equivalent resistance in 20 mA, 114 kHz	R_e	164 mΩ	158 mΩ

Design results of the real-scale high-frequency electromagnet for magnetic hyperthermia



Peak magnetic field	64 mT in 114kHz
Operating time	360 s
Air gap (therapy area)	0.5 m
Magnetic core length	3.0 m
Peak exciting current	201 A
Total number of turns	200 turns
Litz wires	Φ0.05 mm×1800
Self inductance	30.8 mH
Total power losses ($P_m + P_c$)	1.1 MW+0.1 MW=1.2 MW
Peak Voltage of one-turn coil	22.2 kV

Conclusion

From the results of the small-scale high-frequency electromagnet exciting experiment,

- The high-precision design for high-frequency electromagnet is applicable.

From the design results of the real-scale high-frequency electromagnet,

- A 201-A peak exciting current is necessary when the electromagnet is excited up to 64 mT of peak magnetic flux density at the center of the 0.5 m air gap with 114 kHz of operating frequency,
- The total power losses of the electromagnet is 1.2 MW. It means that an electromagnet cooling system is necessary.
- It maybe difficult to manufacture the real-scale electromagnet due to the high core loss.
- The next step of this work is to improve the real-scale high-frequency electromagnet design to reduce the high power losses.