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Design Study on High Frequency Magnets for Magnetic Hyperthermia Applications

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Introduction

Research objective

Discussion of the engineering feasibility of high frequency magnet systems for the magnetic hyperthermia cancer therapy.

Target specifications for a short time cancer therapy

- 0.06 T and 200 kHz of the AC peak magnetic field
- 300 s (5 minutes) of the continuous or intermittent operation time

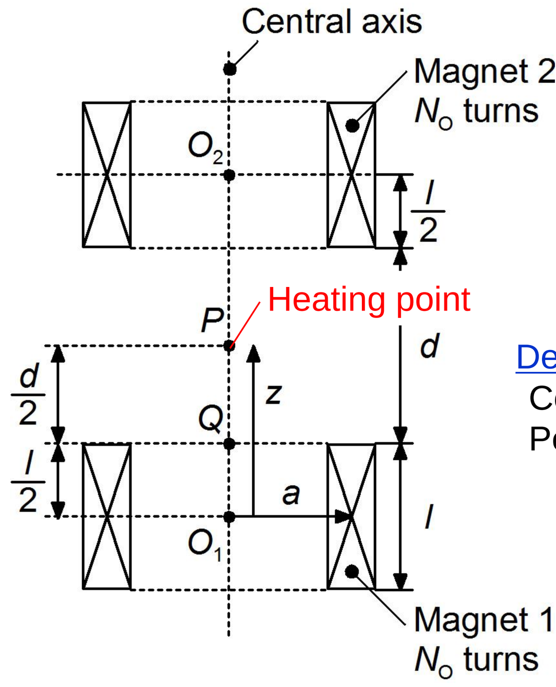
Current status: 0.02 T (18 kA/m) and 100 kHz
MFH 300 F (MagForce Nanotechnologies AG, Berlin, Germany)

Technical challenges and Feasible solutions

- Dielectric breakdown in magnet windings (should be less than 10 kV)
  - ⇨ Reduction of the ampere-turns based on a iron core coil design
- Skin effects and magnet losses due to the high frequency operation
  - ⇨ Use of Litz wires and the feasibility of water cooling magnets
- Required capacity of high frequency power converter system
  - ⇨ Compensation of the magnet reactance using series capacitors

Estimation of the Required Magnetic Flux Density

The required magnetic flux density in the iron core is estimated from a Helmholtz coil arrangement.



The magnetic field on the central axis:

$$B_z = \frac{\mu_0 N_0 I_{peak}}{2l}(\cos\theta_2 - \cos\theta_1)$$

$$\cos\theta_1 = \frac{z - l/2}{\sqrt{a^2 + (z - l/2)^2}} \quad \cos\theta_2 = \frac{z + l/2}{\sqrt{a^2 + (z + l/2)^2}}$$

The required peak magnetic field at the heating point B_P: 0.06 T

Design conditions

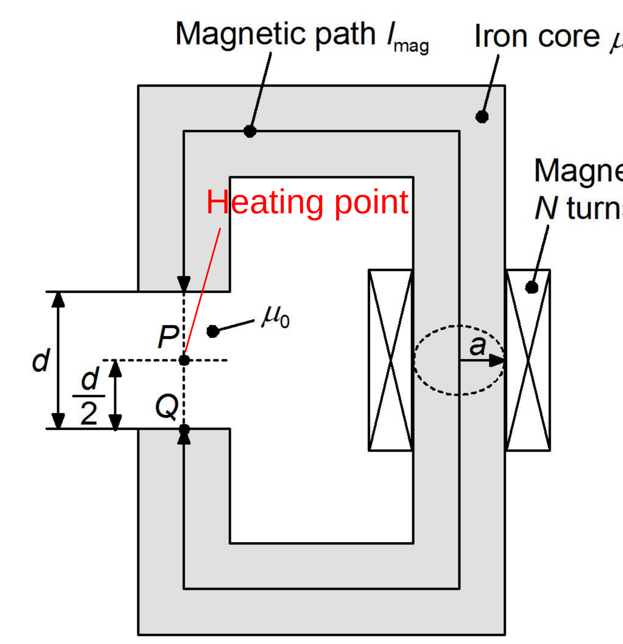
Coil radius a: 0.10 m, Coil length l: 0.20 m
Peak current I_{peak}: 200 A, Coil distance d: 0.30 m

Number of turns of each solenoid N_0: 369 turns

Required magnetic flux density in the iron core B_Q: 0.21 T

Iron Core Magnet Design

The magnetic path length should be designed while taking into account the wavelength of electromagnetic waves propagated through the iron core.



Design conditions

Frequency: 200 kHz
Relative permeability: 1000
Air gap length d: 0.30 m
Peak current I_{peak}: 200 A
Magnetic flux density B_Q: 0.21 T

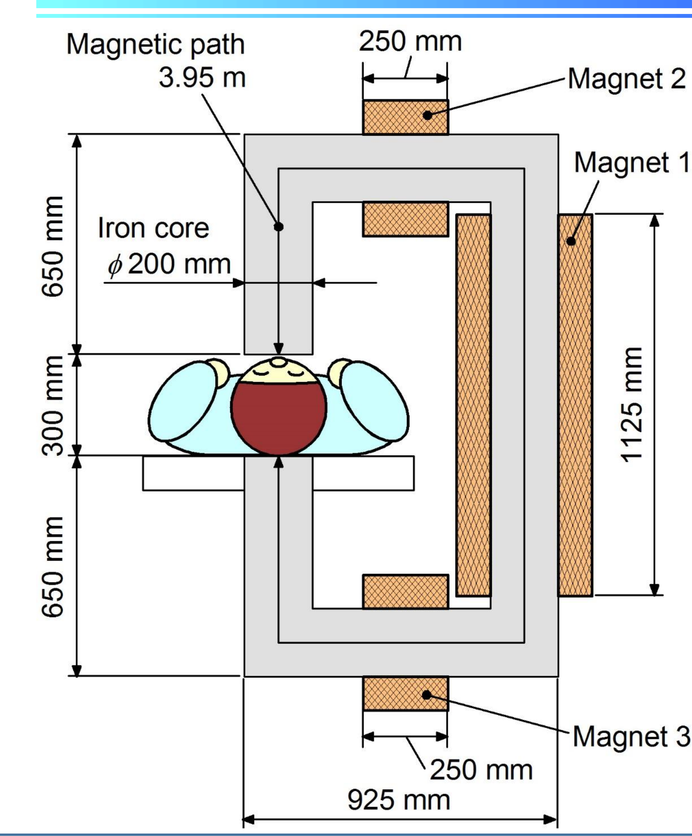
Magnetic path l_{mag}: 3.95 m
1/12 wavelength (47.4 m at 200 kHz)

Ampere-turns of the magnet

$$NI_{peak} = \left(\frac{l_{mag}}{\mu} + \frac{d}{\mu_0}\right)B_Q$$

Number of turns N: 260 turns
35% of the Helmholtz coil case

Overview of the Hyperthermia Magnet System



Key Parameters

Peak magnetic field	0.06 T
Frequency	200 kHz
Operating time	300 s
Air gap (Treatment space)	0.30 m
Magnet outer diameter	0.40 m
Magnet inner diameter	0.20 m
Peak magnet current	200 A
Total number of turns	260 turns
(Magnet 1: 45 turns x 4 layers)	
(Magnet 2 & 3: 10 turns x 4 layers)	
Self inductance	8.75 mH
Peak voltage	2.20 MV
1-turn peak voltage	8.47 kV

Thermal Design Analysis

Joule heat loss distribution of high frequency magnets

$$U_{Joule} = (1-\eta)U_{Cu} + \eta U_{water}$$

Heat capacity / Water cooling

η: Water cooling ratio

$$U_{Joule} = \int_0^{t_{op}} R I_{rms}^2 dt$$

$$U_{Cu} = \int_{T_0}^{T_{max}} M C_{pCu} dT$$

$$U_{water} = \int_0^{t_{op}} \dot{m} C_{pH2O} \Delta T dt$$

Function of a current density J_{op}

Max. magnet temperature

$$T_{max} = \frac{(1-\eta)\rho_e t_{op}}{2\rho_m C_{pCu}} J_{op}^2 + T_0$$

Water flow rate

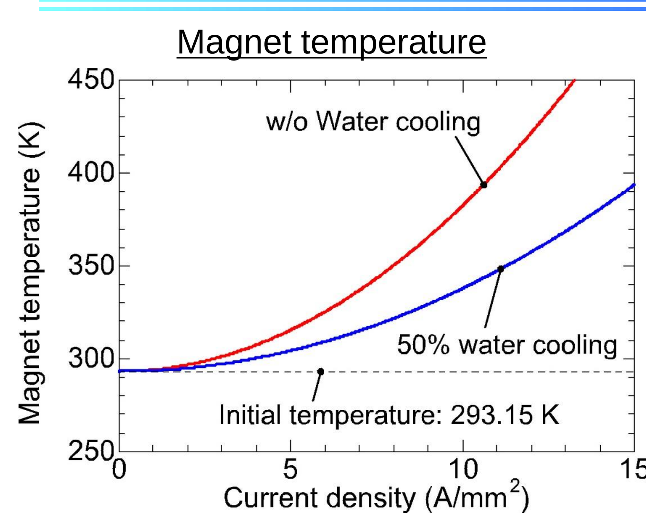
$$\dot{m} = \frac{\eta \pi \rho_e a N t_{op} I_{peak}}{C_{pH2O}\Delta T} J_{op}$$

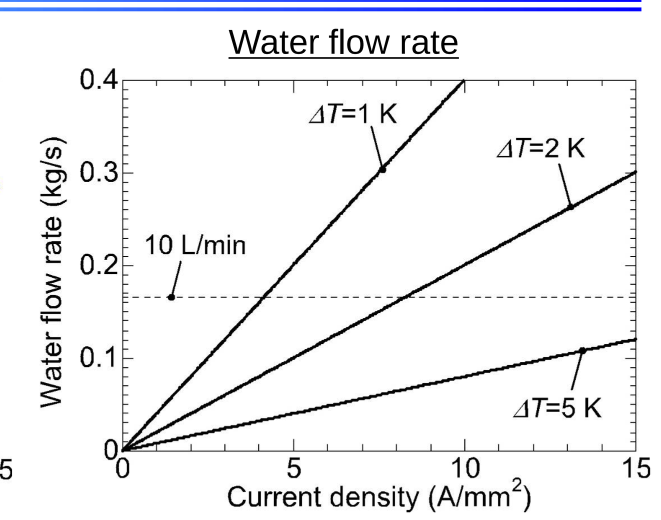
Design conditions

Operating time t_{op}: 300 s
Coil radius a: 0.10 m
Peak current I_{peak}: 200 A
($I_{rms} = I_{peak}/\sqrt{2}$ =141 A)
Number of turns N: 260 turns

Initial temperature T_0: 293.15 K (20 ℃)
Resistivity of conductors ρ_e: 2.06×10^-8 Ωm
Mass density of conductors ρ_m: 8.96×10³ kg/m³
Heat capacity of copper C_{pCu}: 3.86×10² J/kg·K
Heat capacity of water C_{pH2O}: 4.18×10³ J/kg·K

Thermal Properties vs. Current Density

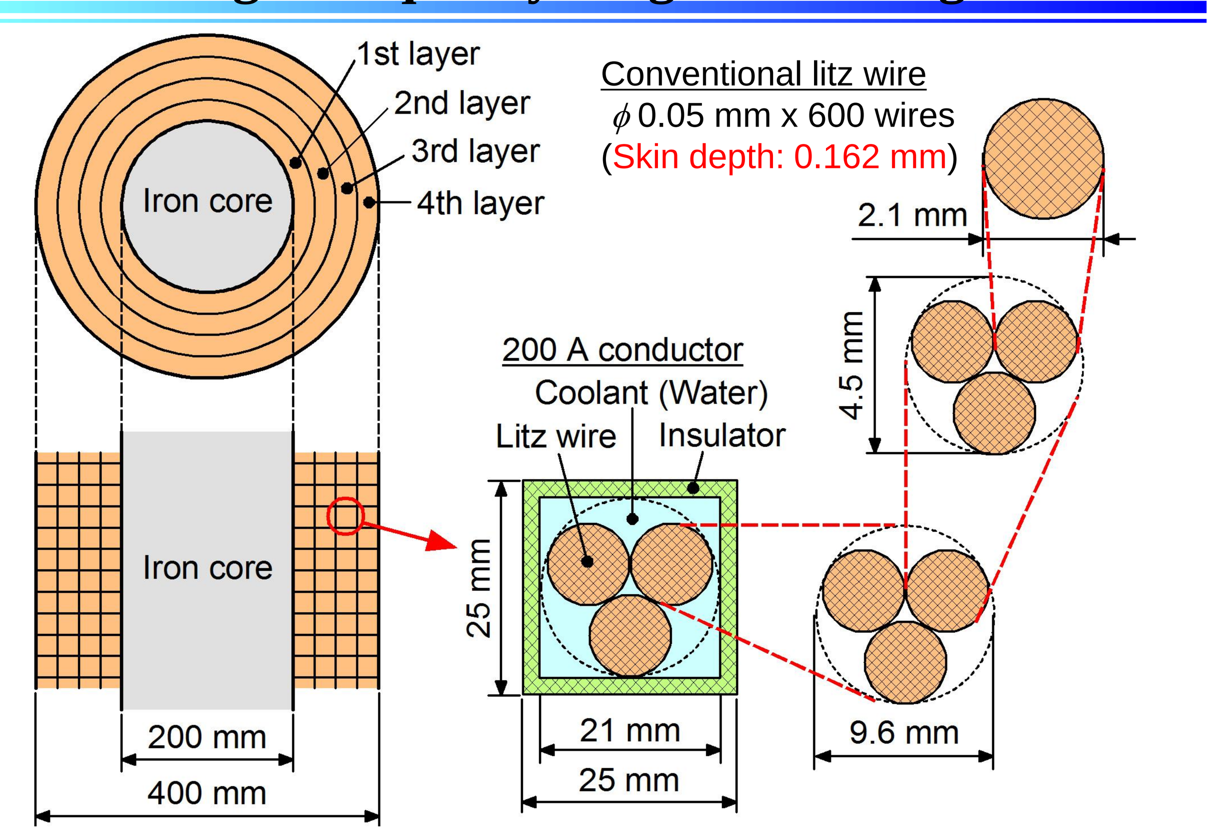




Magnet design parameters

Operating current density: 6.3 A/mm², Joule loss: 2.1 kW
Magnet temperature
w/o Water cooling: 329 K (55 ℃), 50% water cooling: 311 K (38 ℃)
Water flow rate: 15 L/min. (ΔT = 1 K), 7.6 L/min. (ΔT = 2 K)
Conventional chillers are available for the water cooling magnet.

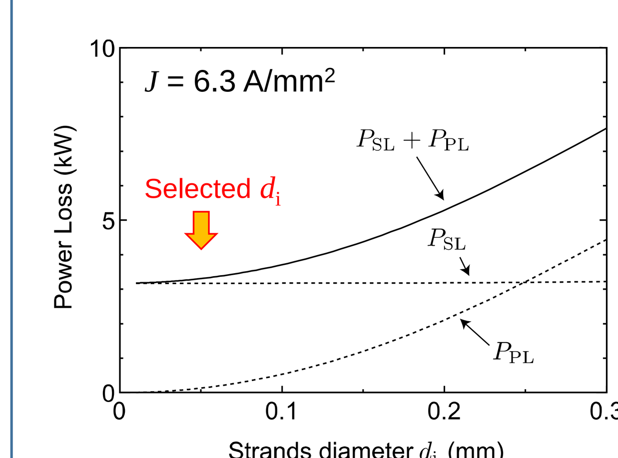
High Frequency Magnet Windings



Loss Calculation

Winding Loss

P_{SL}: Loss by dc resistance + skin effect
P_{PL}: Loss by proximity effect



Winding Loss $P_{loss.w}$: 3.31 kW

Core Loss

Empirical Steinmetz equation

$$P_{core} = k_C \cdot f^{\alpha} \cdot B_{peak}{}^{\beta} \cdot A_C \cdot l_C$$

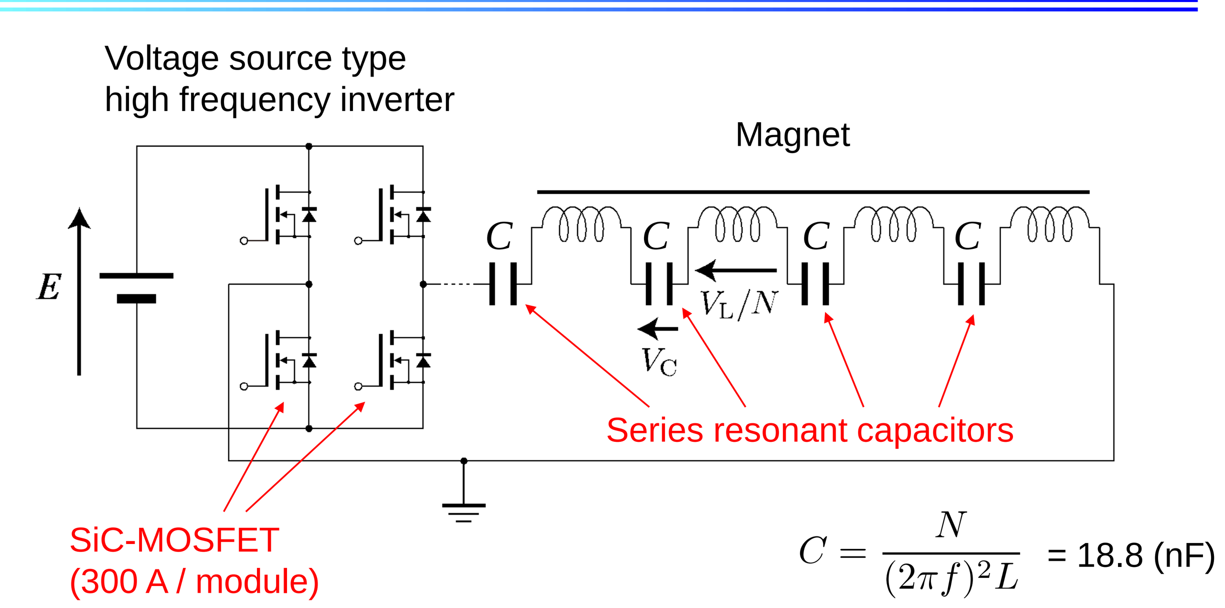
A_C: Effective core cross-sectional area
l_C: Effective core length

Selected Core

Core material: TPW33 (Soft Ferrite)
Saturation flux density: 0.52 T
Parameter k_C: 0.0682 W/m³
Parameter α: 1.74
Parameter β: 2.81

Core Loss P_{core}: 1.33 kW

Power Supply System

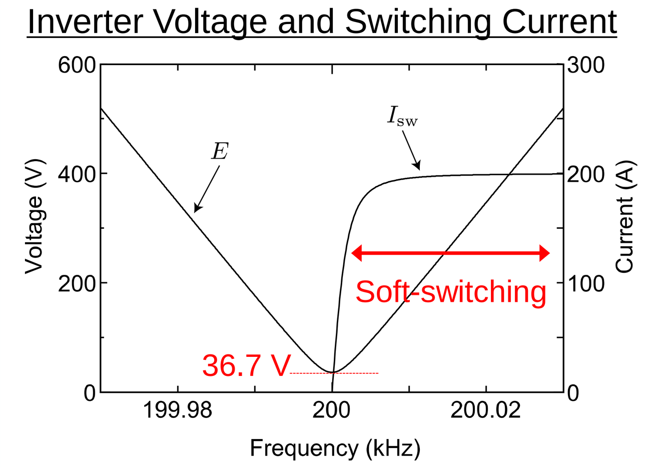


$$C = \frac{N}{(2\pi f)^2 L} = 18.8 \text{ (nF)}$$

- A separated-by-turn configuration to make voltages to ground low as possible
  - ⇨ Maximum voltage to ground can be 1-turn peak voltage 8.47 kV.
- SiC-MOSFET can be operated with soft-switching, 200 kHz operation is feasible.

Design and Control

Inverter Voltage and Switching Current

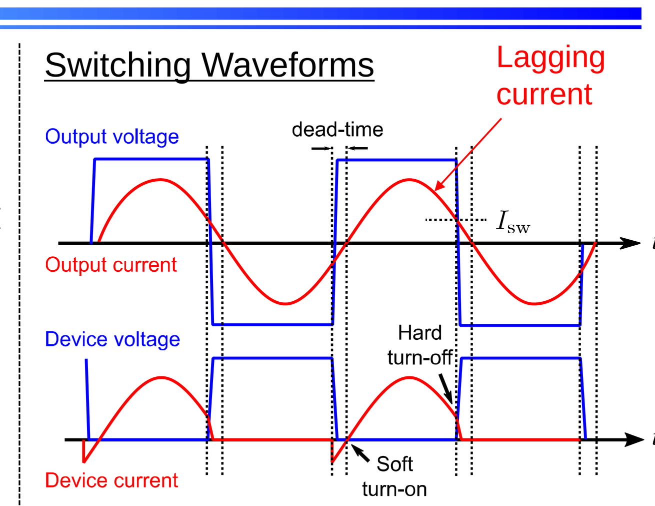


Inductance L: 8.75 mH
Equivalent resistance $R_{loss.all}$: 0.232 Ω

$$Z = \sqrt{\left(\omega' L - \frac{1}{\omega' C_{total}}\right)^2 + R_{loss.all}{}^2}, \quad I = \frac{V_{inv}}{Z}$$

- Highly frequency sensitive system
  - ⇨ Inverter voltage control is applied.

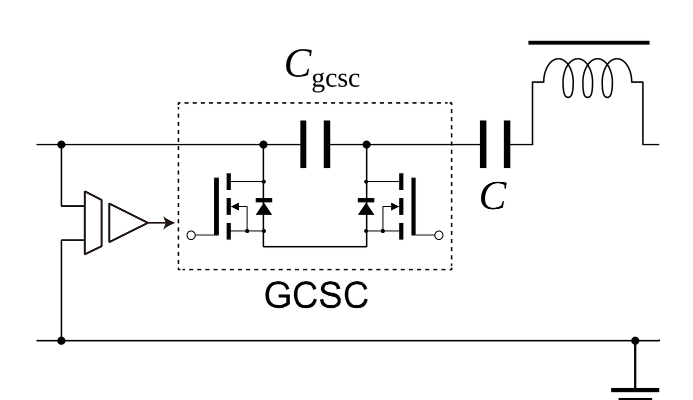
Switching Waveforms



- Firstly, free-wheeling diode conducts.
  - ⇨ Zero voltage turn-on of MOSFET
  - ⇨ No parasitic capacitor shorting
- MOSFET turns off.
  - ⇨ *dv/dt* is mitigated by parasitic cap.
  - ⇨ No free-wheeling diode recovery

Voltage Balancer

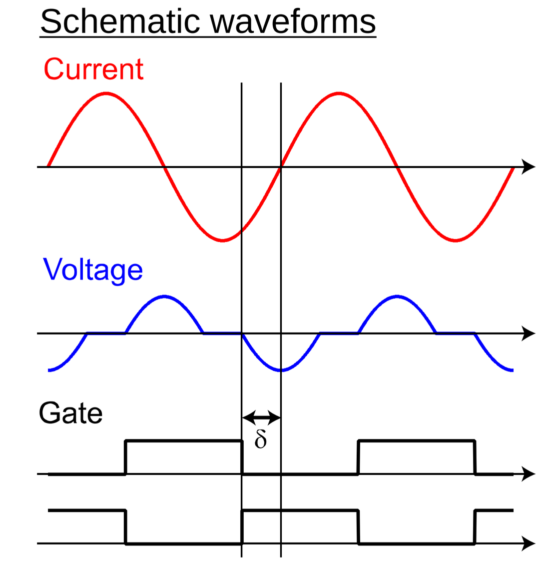
Voltage balancer circuit



GCSC: gate controlled series capacitor

- GCSC works as variable capacitor.
- Total compensation voltage for 1-turn coil can be partially controlled.
- ⇨ Controlling voltage to ground not to be high

Schematic waveforms



Equivalent reactance

$$X_{GCSC} = X_c\left(\frac{2\delta}{\pi} - \frac{\sin 2\delta}{\pi}\right)$$

X_C: Reactance of equipped capacitor

Conclusions

Results of the Design Study

- One turn voltage of the winding can be reduced to 8.47 kV even when the magnet is excited up to 0.06 T of the peak magnetic field with 200 kHz of the operating frequency.
- The winding loss is 3.3 kW, which result suggests that the magnet can be operated without a water cooling system. Even if the magnet cooled by water, conventional chillers are available.
- Single voltage source high frequency inverter using commercially available SiC-MOSFET (< 1.2 kV) can drive the magnet with balancer circuits.

Engineering feasibility of a 0.06-T, 200-kHz Hyperthermia magnet

Future works

- Developing laboratory proto-type for particles and medical investigations
  - ⇨ Experimental verifications of the proposed design principles of the system