High Temperature Superconductors and Medical Devices: Ultra-compact MRI and LFEIT

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Outline

1. Ultra-compact MRI

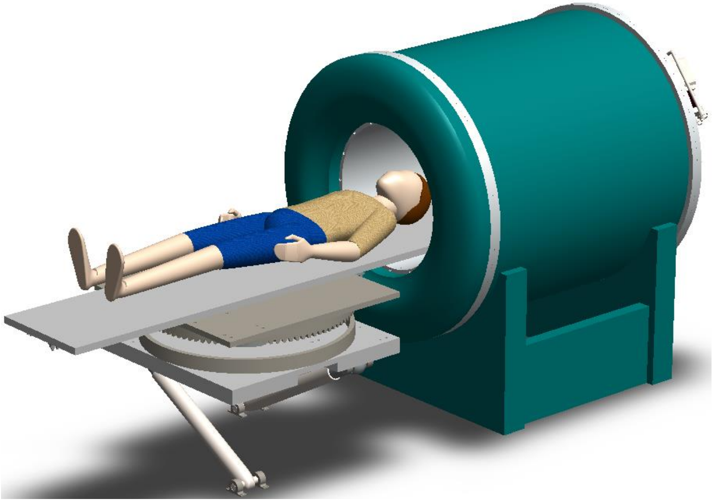
2. Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)

1. Ultra-compact MRI

Ultra-compact MRI

Mobile MRI

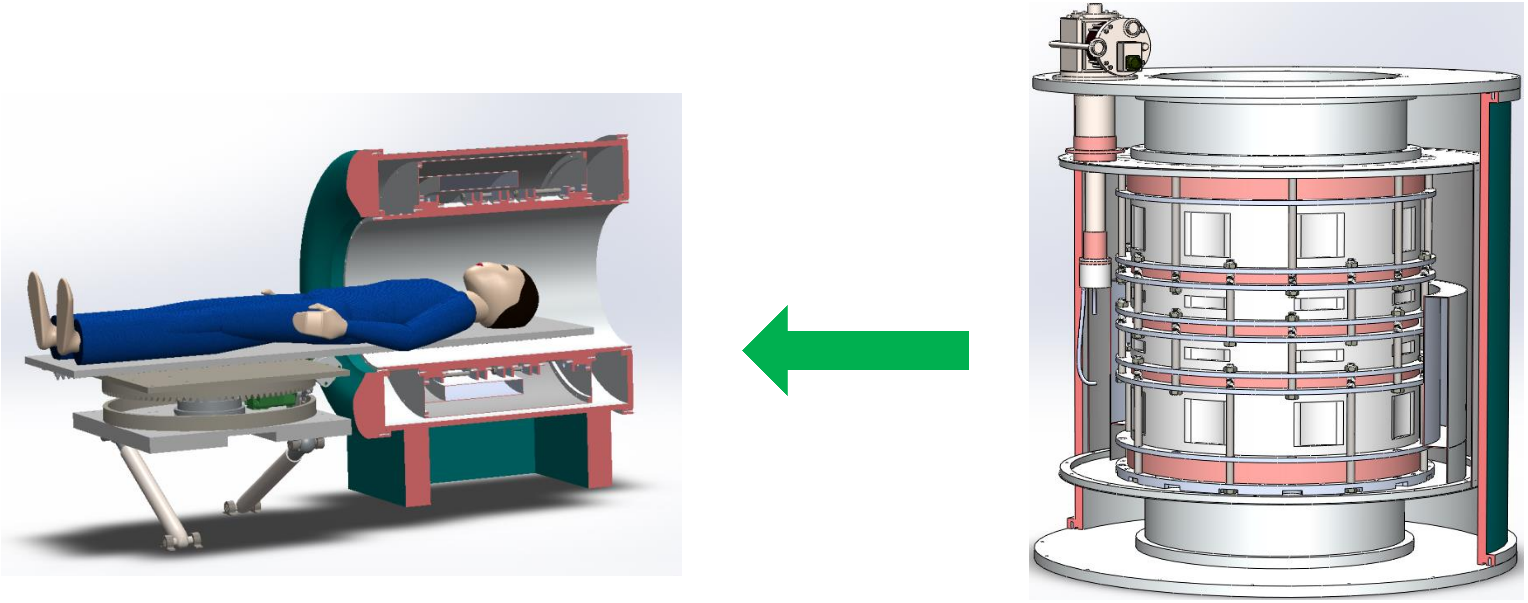
Pre-surgery Room



Ultra-small MRI

→Ultra-compact MRI system is for the rapid diagnosis of the brain syndrome and some other urgent diseases, which can be potentially equipped into the pre-surgery room and ambulance.

HTS magnet for Ultra-compact MRI



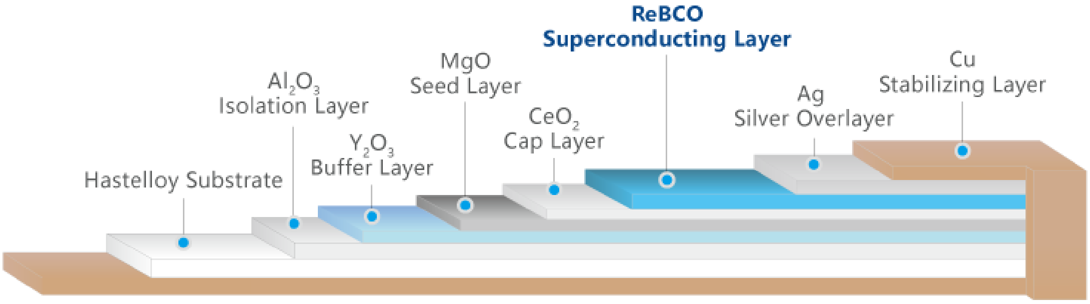
Key component: HTS magnet

Compact Geometry

Strong Magnetic Field

High Uniformity

Strong and Uniform HTS Magnet



Shanghai Superconductor Technology®

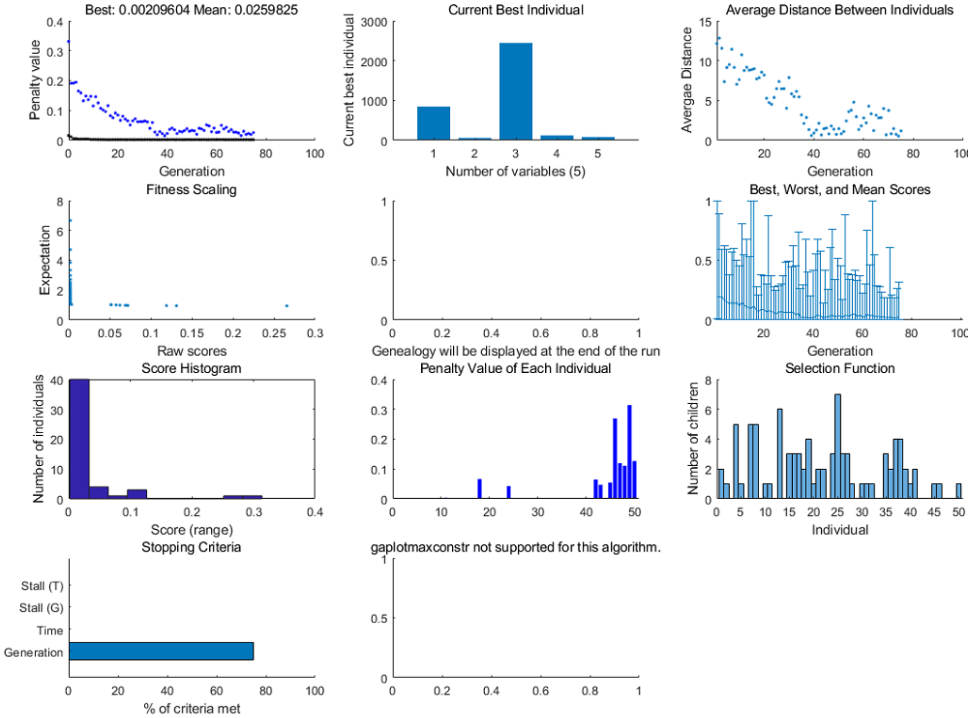
Second Generation (2G) HTS
e.g. ReBCO HTS tape

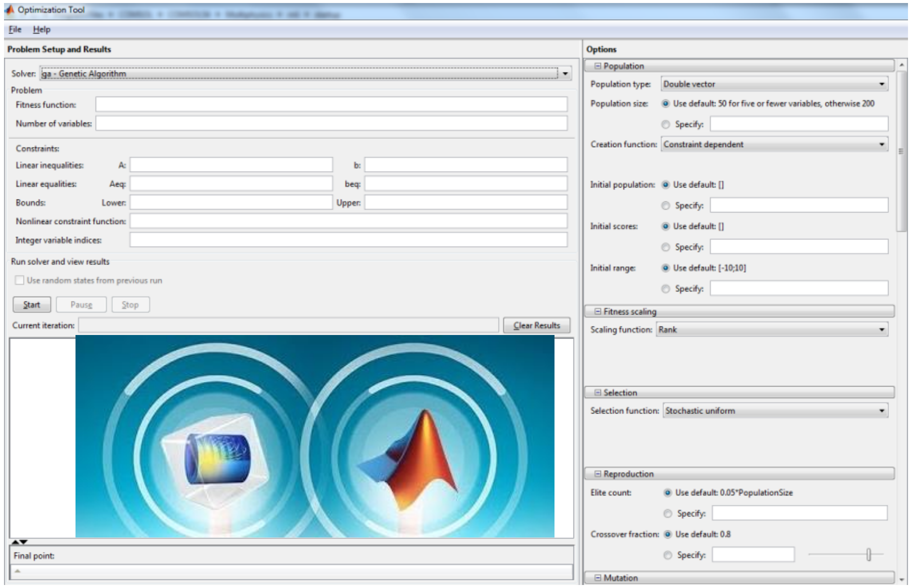
High aspect-ratio dimension

Challenges:

uniformity optimization

Powerful optimization tool needed





Problem Setup and Results

Solver: ga - Genetic Algorithm

Problem

Fitness function:

Number of variables:

Constraints:

Linear inequalities: A: b:

Linear equalities: Aeq: beq:

Bounds: Lower: Upper:

Nonlinear constraint function:

Integer variable indices:

Run solver and view results

☐ Use random states from previous run

Current iteration:

Final point:

Options

Population

Population type: Double vector

Population size: ● Use default: 50 for five or fewer variables, otherwise 200

○ Specify:

Creation function: Constraint dependent

Initial population: ● Use default: []

○ Specify:

Initial scores: ● Use default: []

○ Specify:

Initial range: ● Use default: [-10;10]

○ Specify:

Fitness scaling

Scaling function: Rank

Selection

Selection function: Stochastic uniform

Reproduction

Elite count: ● Use default: 0.05*PopulationSize

○ Specify:

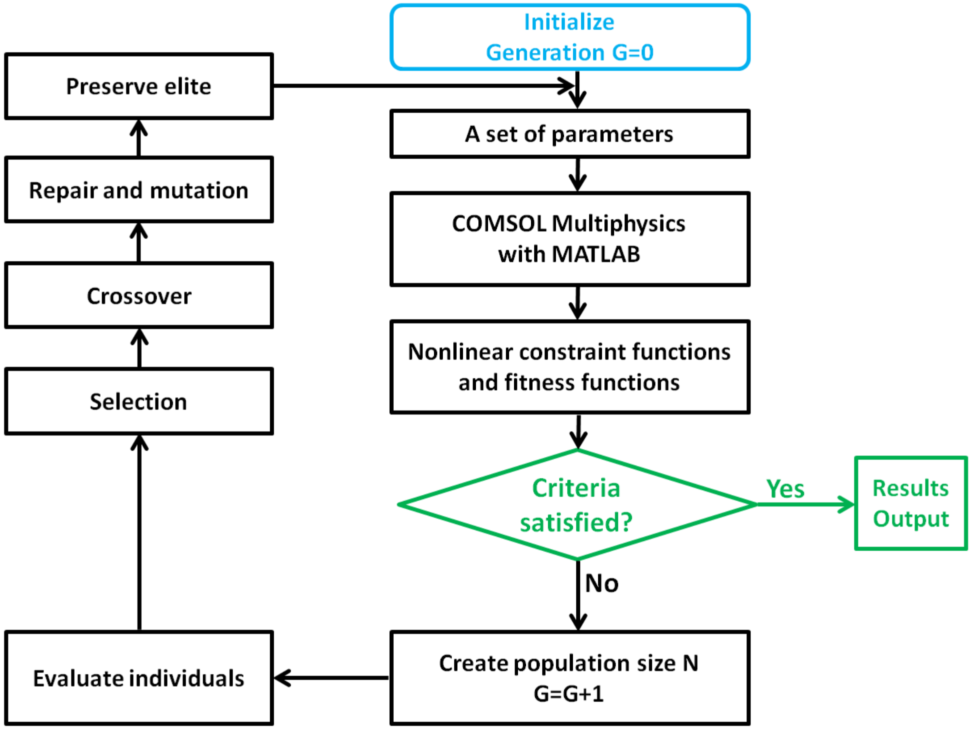
Crossover fraction: ● Use default: 0.8

○ Specify:

Mutation

➔Genetic Algorithm (GA) optimization were based on the FEM package COMSOL Multiphysics with the LiveLink for MATLAB.

Optimisation Strategy



Initialize
Generation G=0

A set of parameters

COMSOL Multiphysics
with MATLAB

Nonlinear constraint functions
and fitness functions

Criteria
satisfied?

Yes

Results
Output

No

Create population size N
G=G+1

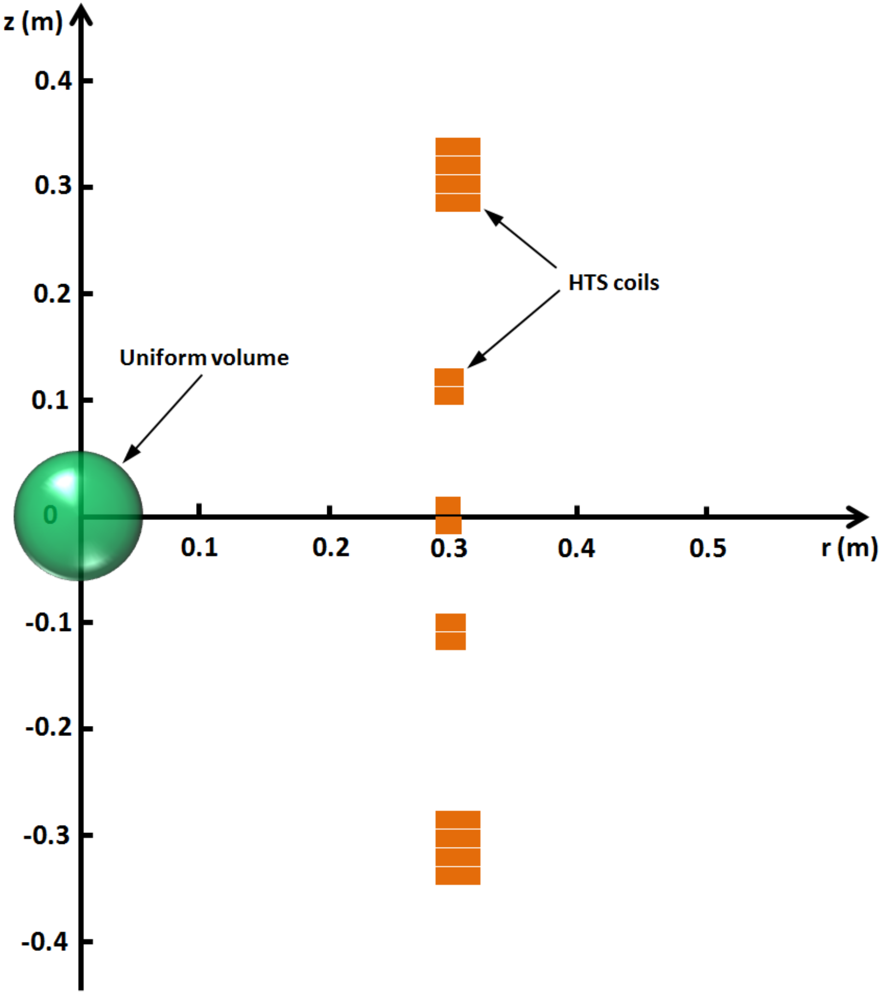
Evaluate individuals

Selection

Crossover

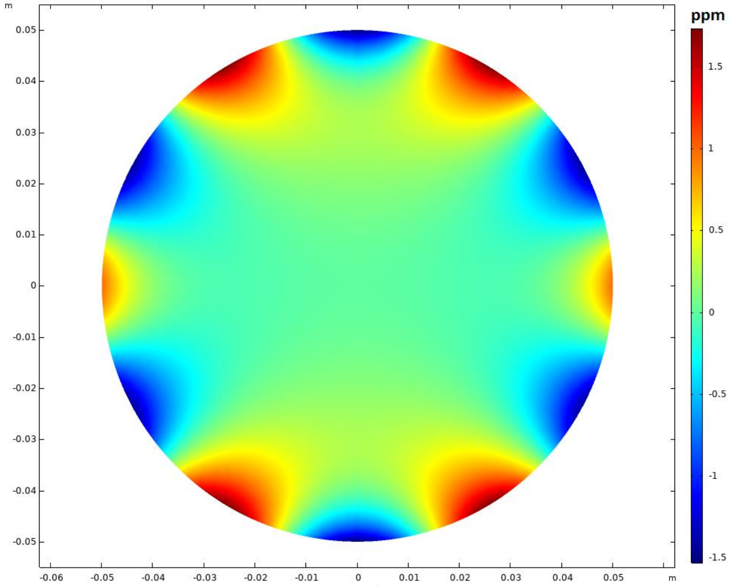
Repair and mutation

Preserve elite

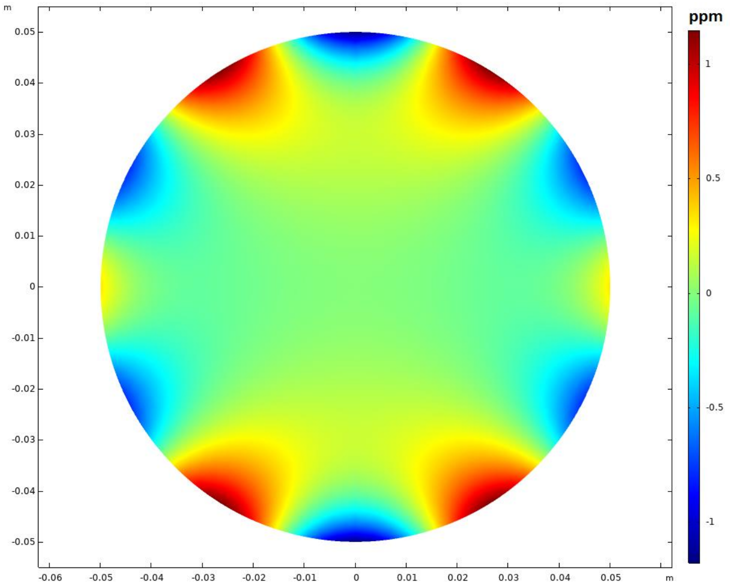


➔5-set of double-pancake HTS coils. If the criteria achieved, the optimization iterations stopped; otherwise, the iterations continued to reach the targets through repetitive selection, crossover, mutation, and elite preservation, until targets achieved.

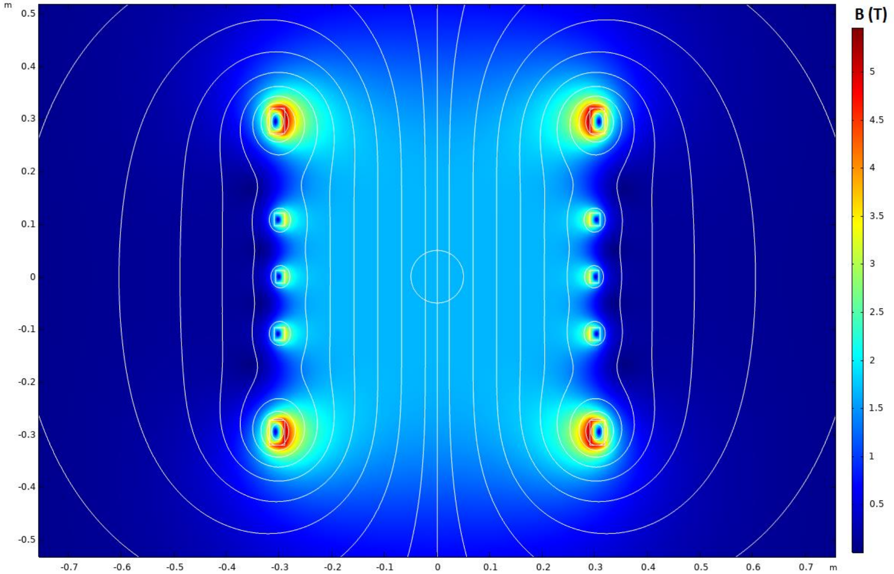
Magnetic Profile

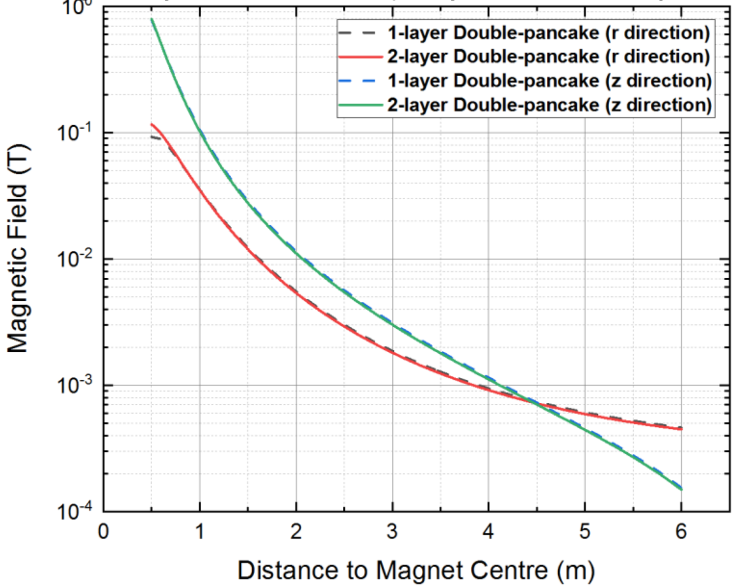


Inhomogeneity in a 10 cm DSV (1-layer end double-pancake case)

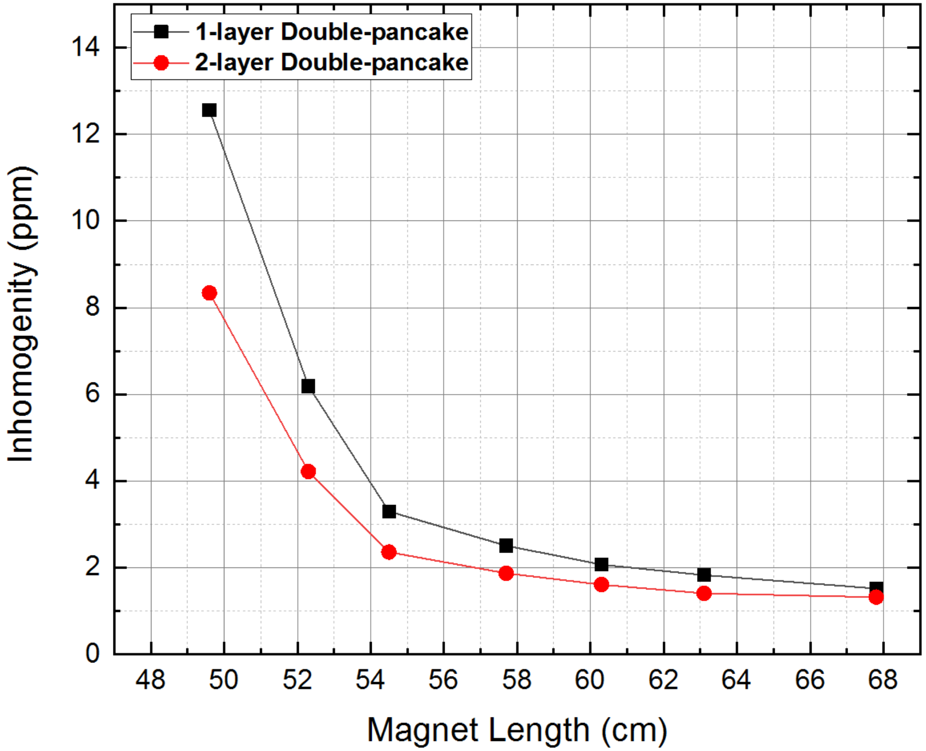


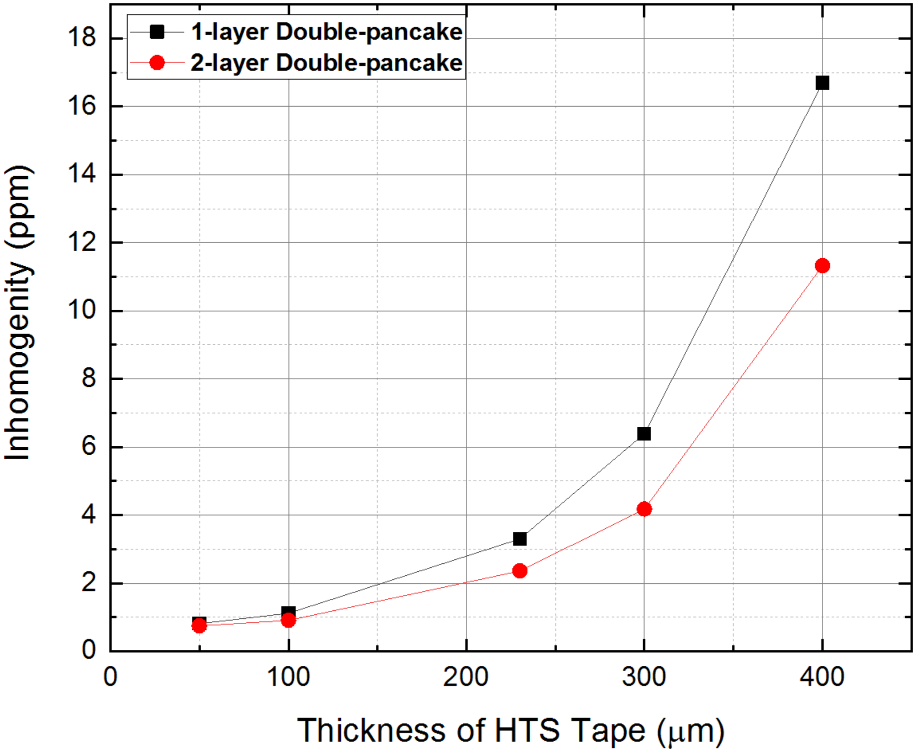
Inhomogeneity in a 10 cm DSV (2-layer end double-pancake case)





Sensitivity Study

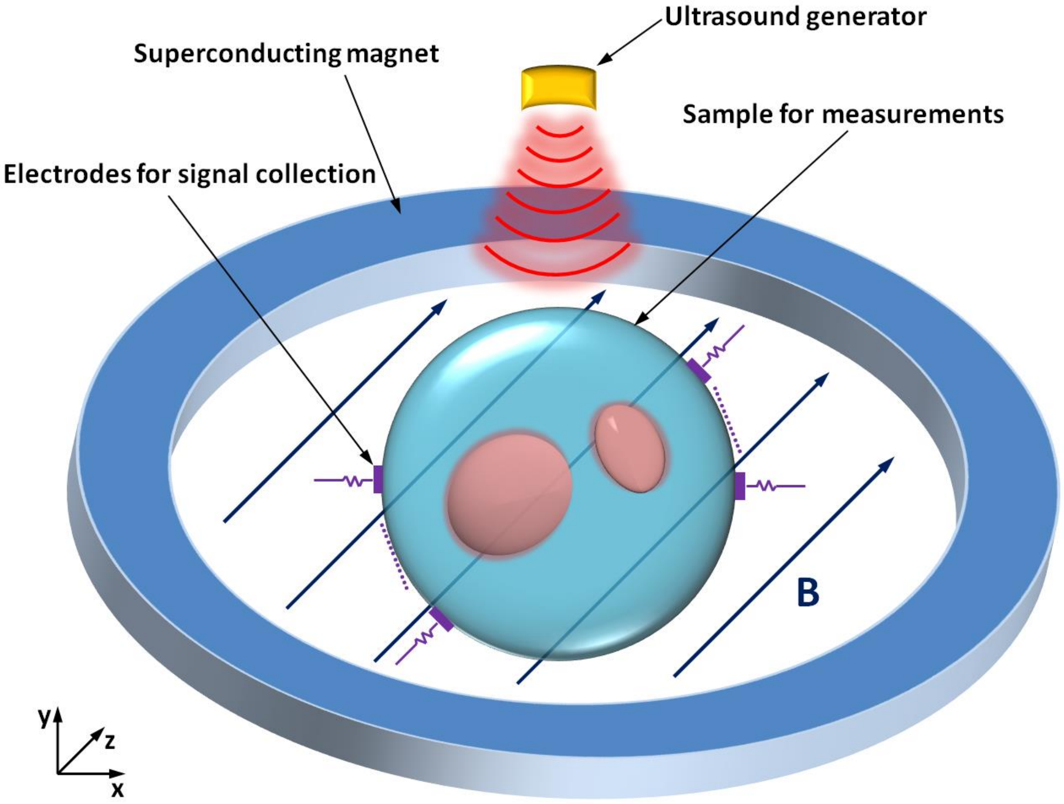




➔The sensitivity studies were carried out, for the relationship between the homogeneity in a 10 cm DSV and (1) magnet length, and (2) thickness of HTS tape.

2. Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)

Design of Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)



Superconducting LFEIT

Conventional Electrical Impedance Tomography (EIT)

➔LFEIT is a novel diagnostic scanner which is able to achieve the 3D high resolution imaging of tissue impedance based on ultrasonically induced Lorentz force

Advantages of LFEIT

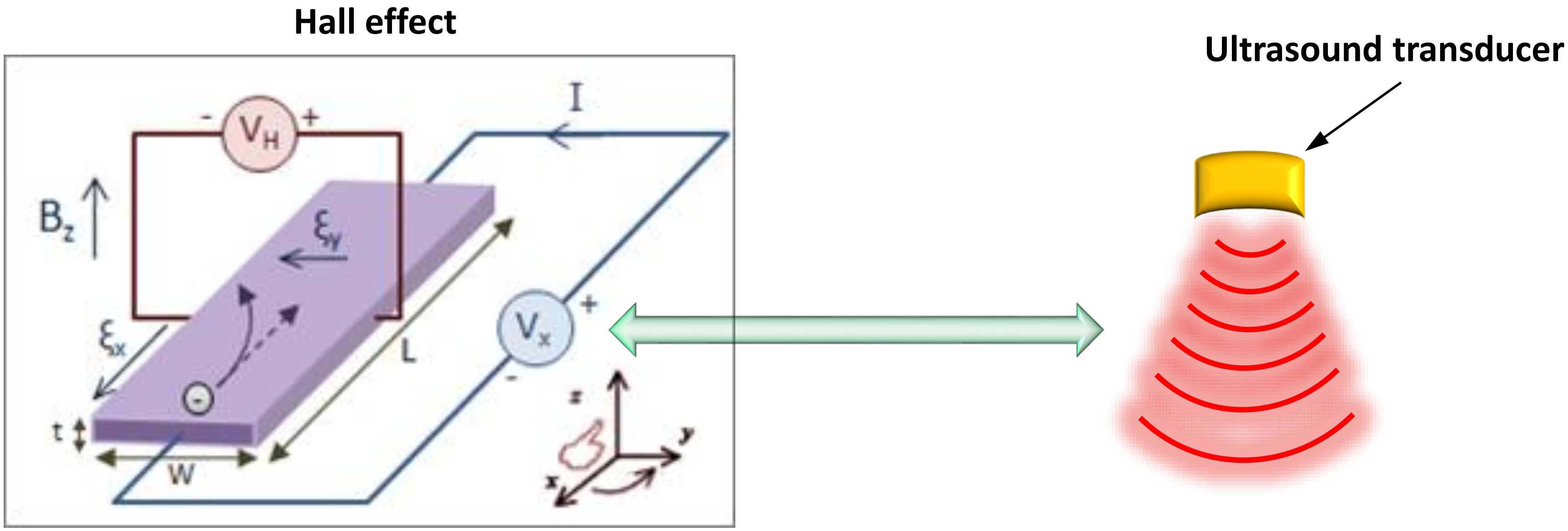
1. Excellent bio-detection

2. High resolution

3. Portability

4. Low cost

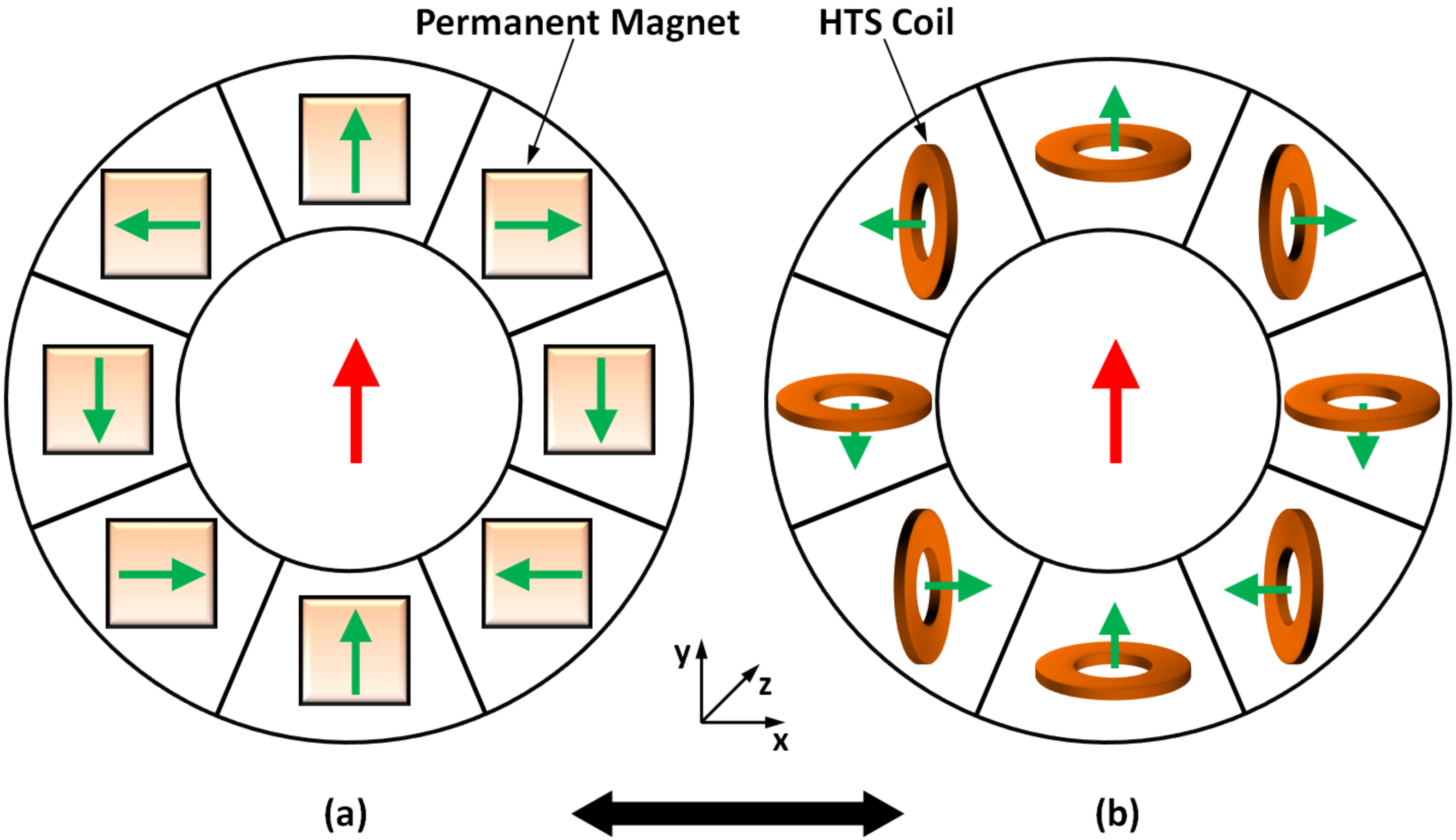
Working Principle



$$V_{measured} = \alpha W R_e B_a \int\limits_{U-path} M(z,t) \frac{\partial}{\partial z}\left[\frac{\sigma(z)}{\rho(z)}\right] dz \qquad \textbf{(1.1)}$$

➔The measured signal is proportional to the magnitude of magnetic field, the momentum of ultrasound and the gradient of electrical conductivity.

Superconducting Magnet Design



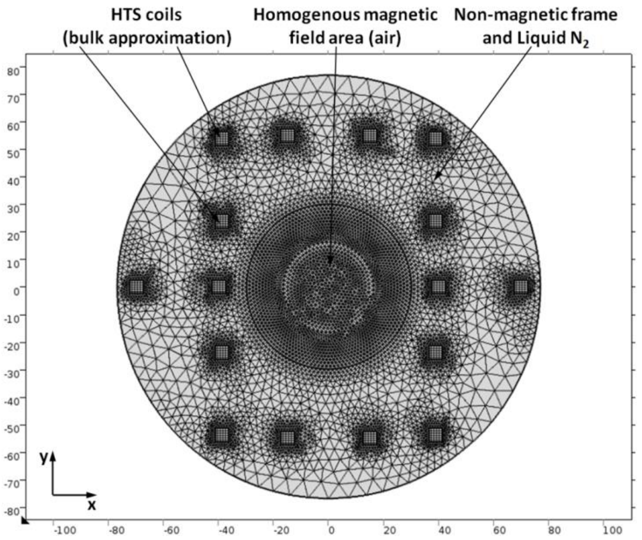
(a) Configuration of permanent magnet (PM) based Halbach Array magnet.

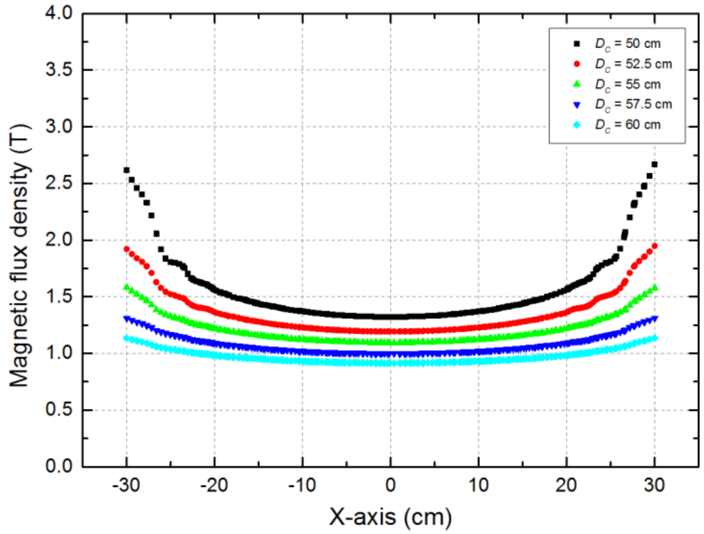
(b) Configuration of high temperature superconducting (HTS) coils based Halbach Array magnet.

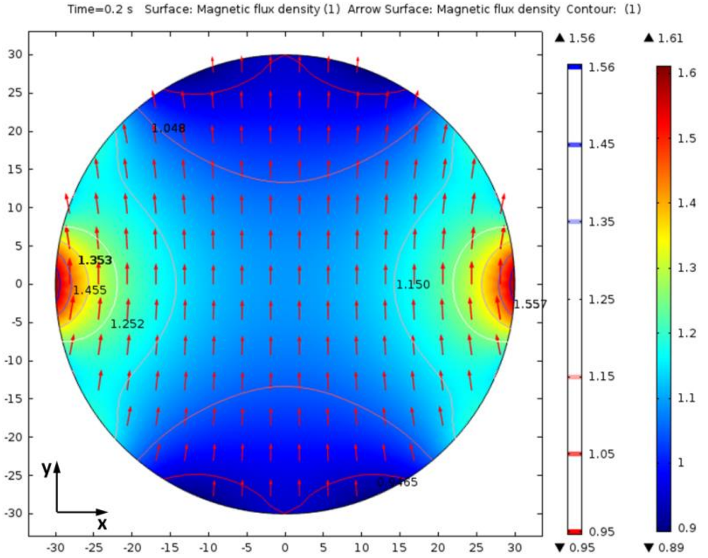
→Halbach Array is an effective arrangement of magnets that is able to generate a homogenous magnetic field, whose geometry has thin depth in z direction.

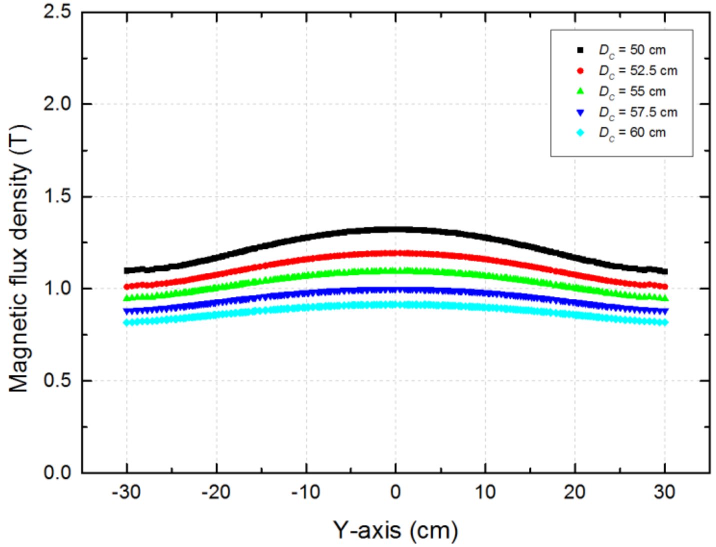
B. Shen *et al*, “Design of a Superconducting Magnet for Lorentz Force Electrical Impedance Tomography”, *IEEE Trans. Appl. Supercond.*, 2016.

Superconducting Magnet Design



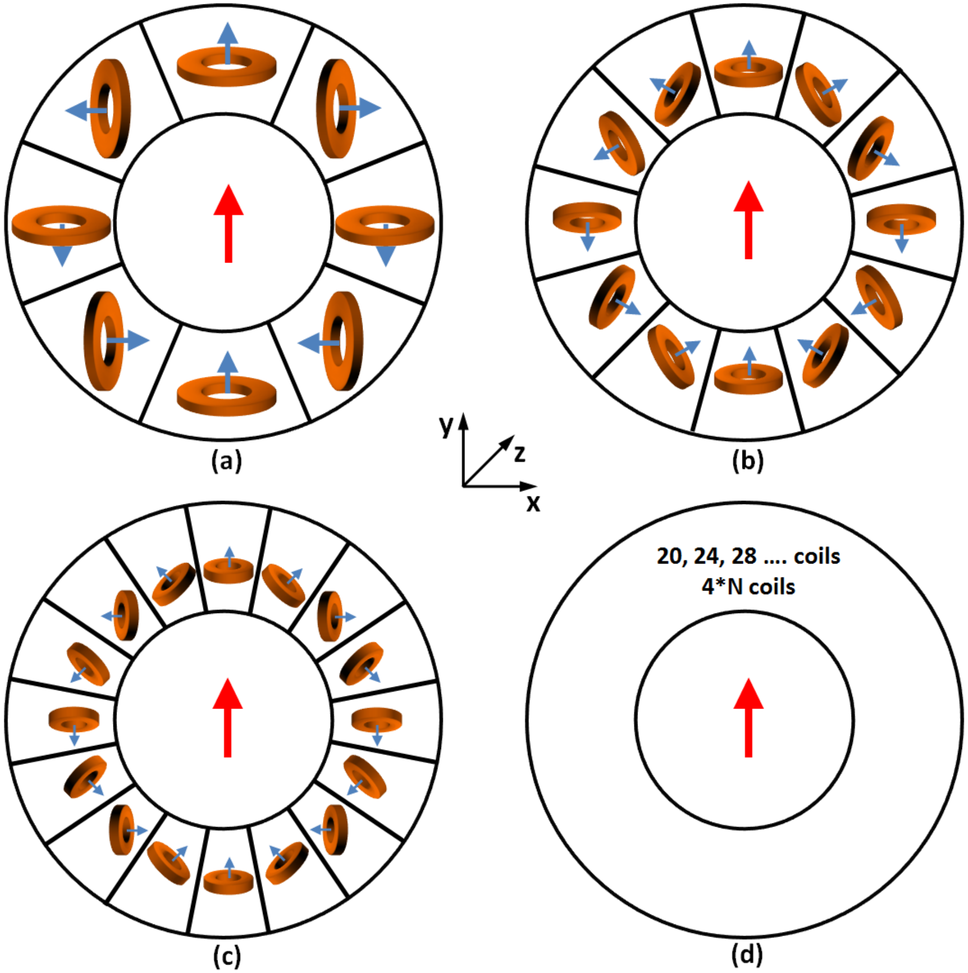


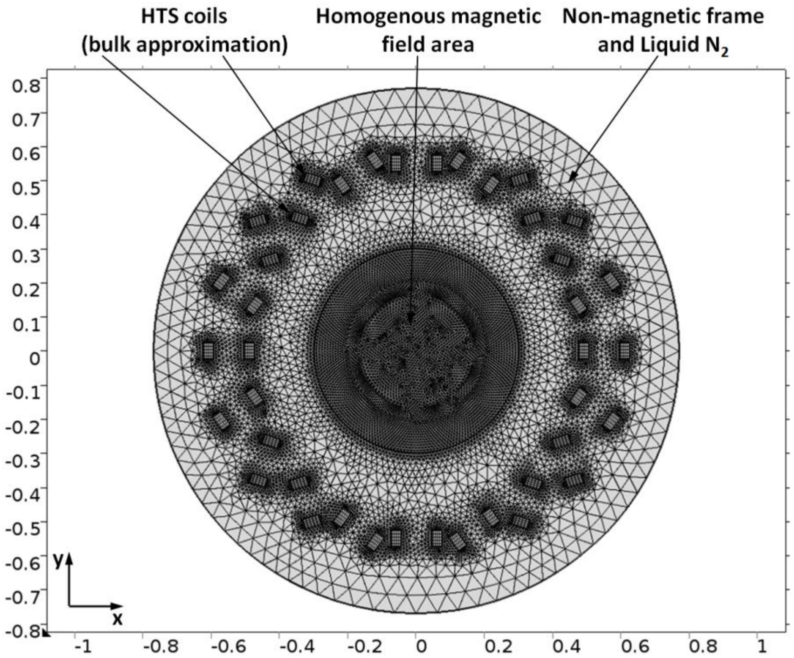




B. Shen *et al*, "Design of a Superconducting Magnet for Lorentz Force Electrical Impedance Tomography", *IEEE Trans. Appl. Supercond.*, 2016.

Superconducting Magnet Optimisation

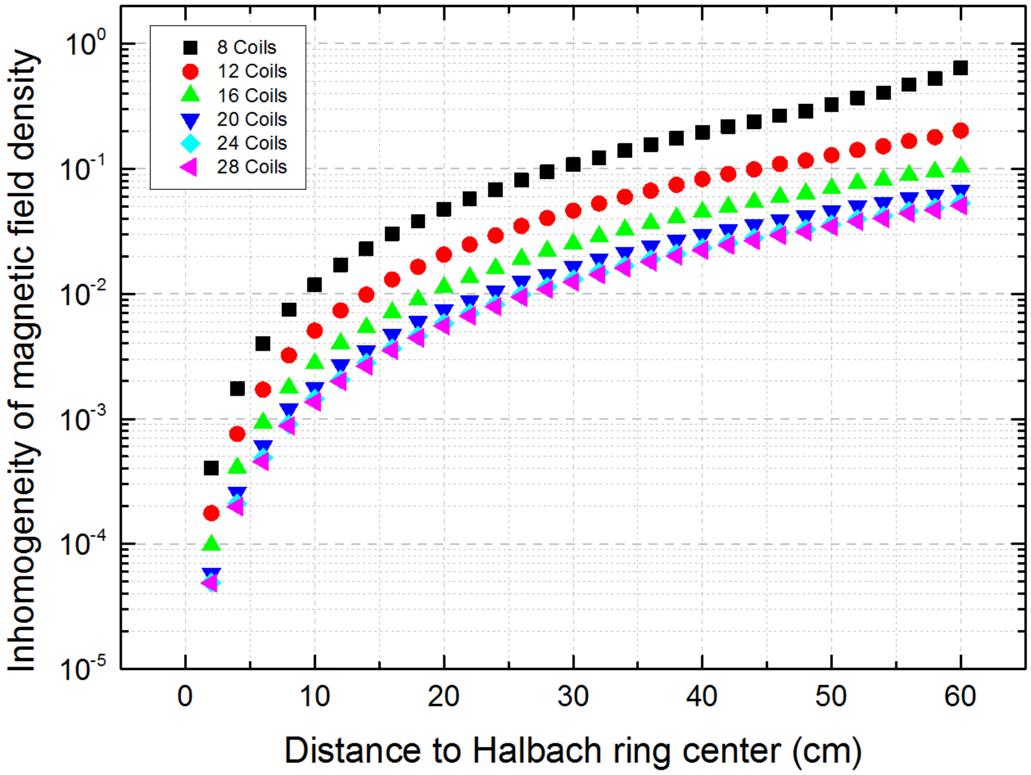




➔Without changing the total amount of superconductor, optimisation on using increasing numbers of coils can be done by shrinking each coil's size with increasing number of coils.

B. Shen *et al*, "Optimization Study on the Magnetic Field of Superconducting Halbach Array Magnet", *Physica C*, 2017.

Superconducting Magnet Optimisation



$$Inhomogeneity = \alpha \cdot D^{\beta} \qquad \textbf{(2.1)}$$

$$\alpha = a \cdot \exp(b \cdot n) + c \qquad \textbf{(2.2)}$$

$$\beta = e \cdot \exp(f \cdot n) + g \qquad \textbf{(2.3)}$$

➔Some equations have been derived from this investigation. α and β are the variables for power law which is related to the n (numbers of coils) in equation (2.2) and (2.3). Both α and β have exponential relation with n and adding a constant, where a = 1.408E-4, b = -0.1556, c = 1.188E-05, e = 43.32, f = -0.5279, g = 2.022.

B. Shen *et al*, "Optimization Study on the Magnetic Field of Superconducting Halbach Array Magnet", *Physica C*, 2017.

LFEIT System simulation

According to the formula of Lorentz force:

$$F = qv \times B \tag{2.4}$$

Where q is charge of particle move with velocity v, and B is magnetic flux density. This Lorentz force is also equivalent to the force caused by the induced electric field :

$$F = qE \tag{2.5}$$

Meanwhile, the relation of electrical conductivity is :

$$J = \sigma E \tag{2.6}$$

Combining Equation (2.4), (2.5) and (2.6), the equation for transient current density can be derived:

$$J = \sigma v \times B \tag{2.7}$$

Assuming the ultrasound wave propagating along z direction, the ultrasound bean width is W and ultrasound path is L, the voltage measurement can be described as:

$$V_h(t) = \alpha RWB_0 \int_L \sigma(z) v(z,t) dx \tag{2.8}$$

Where a is a percentage constant representing the efficiency current collected by the electrodes, B_0 is the static magnetic field and R is the total impedance of measurement circuit. According the formula for relation of sound pressure and particle movement velocity, z direction term can be:

$$v_z = -\frac{1}{\rho_0} \int \frac{\partial p}{\partial z} dt \tag{2.9}$$

The ultrasound momentum M can be expressed by using the time integration of ultrasound pressure with regard to time t:

$$M(z,t) = \int_{-\infty}^{t} p(z,\tau) d\tau \tag{2.10}$$

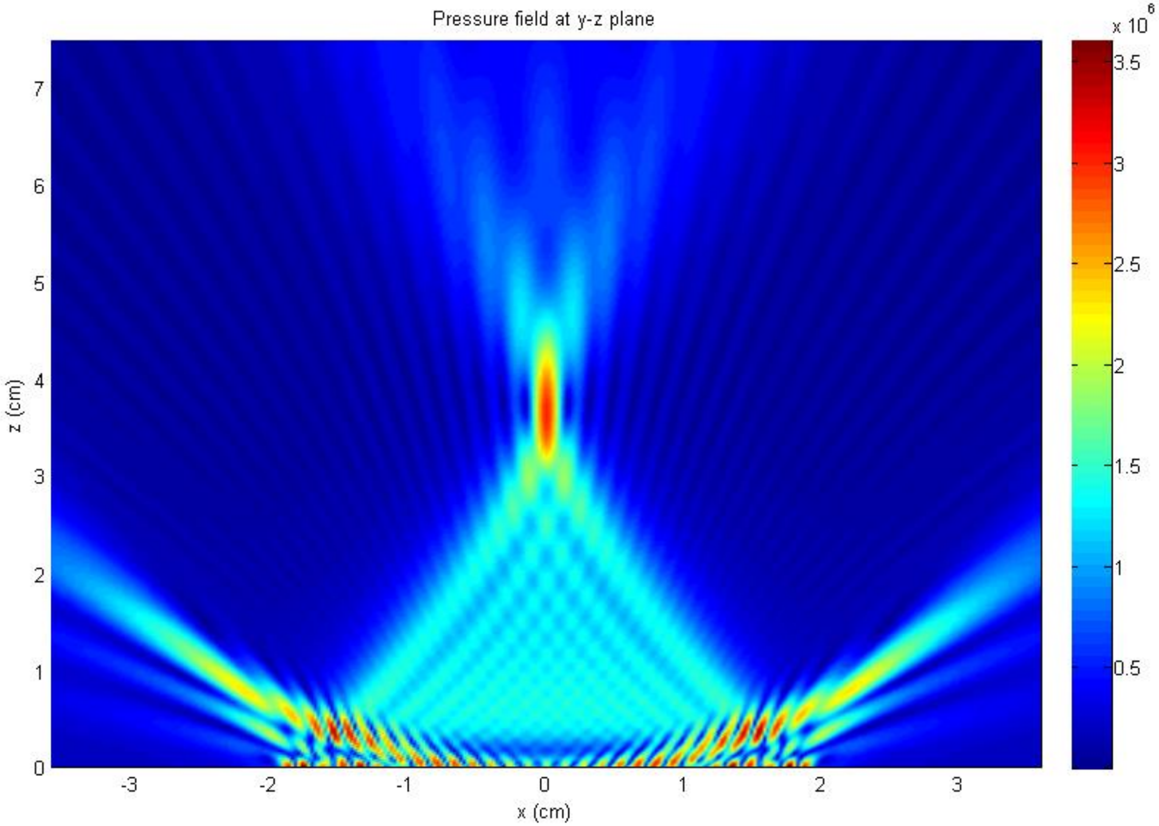
Therefore, that the governing equation for final output signal of LFEIT can be determined by combining Equation (4.5), (4.6) and (2.10):

$$V_h(t) = \alpha RWB_0 \int_L M(z,t) \frac{\partial}{\partial z}\left[\frac{\sigma(z)}{\rho(z)}\right] dx \tag{2.11}$$

Equation (2.11) reveals that magnitude of final output signal is proportional to the strength of magnetic field and the ultrasound pressure. More importantly, output signal is nonzero only at the interface where the gradient of electrical conductivity over mass density $\nabla(\sigma/r)$ is not zero. The mathematical MATLAB model of LFEIT system was built based on governing equations (2.11).

B. Shen *et al*, "Design and Simulation of Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)", *Physica C*, 2016.

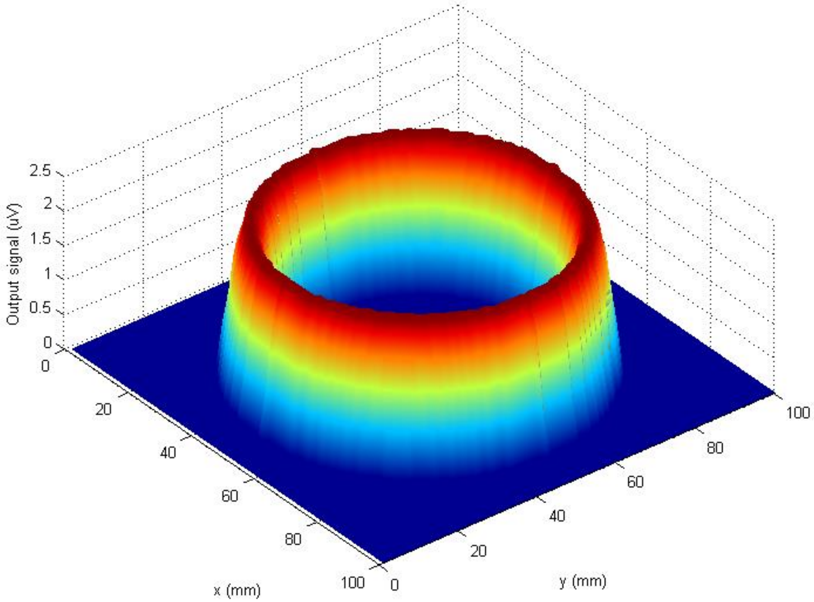
Ultrasound Module Design



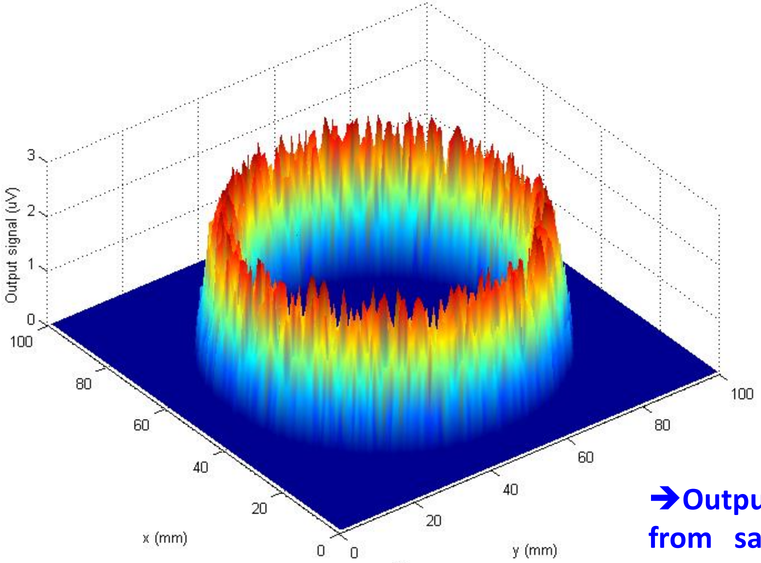
➔This acoustic module used ultrasound phase array structure, which consisted of 32 transducer elements with each generating 1 MHz ultrasound signal.

B. Shen *et al*, "Design and Simulation of Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)", *Physica C*, 2016.

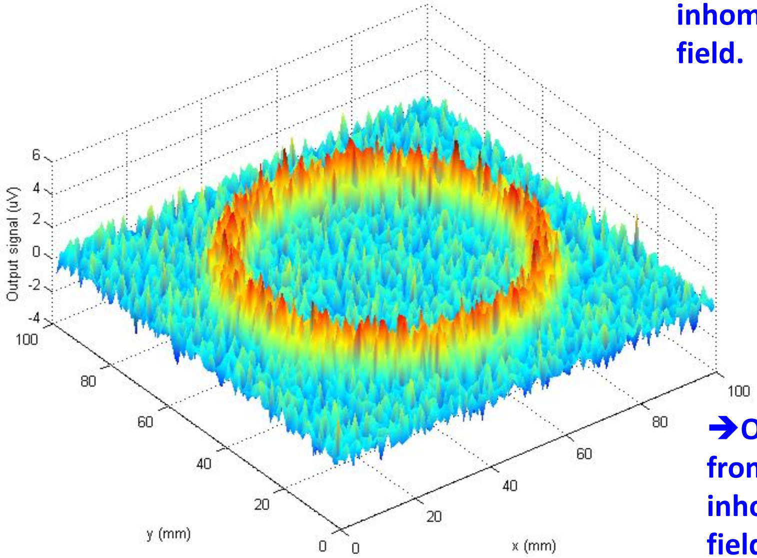
Modelling of Electrical Signal



➔Ideal output signal (absolute value) detected from sample with absolute uniform magnetic field and zero noise.



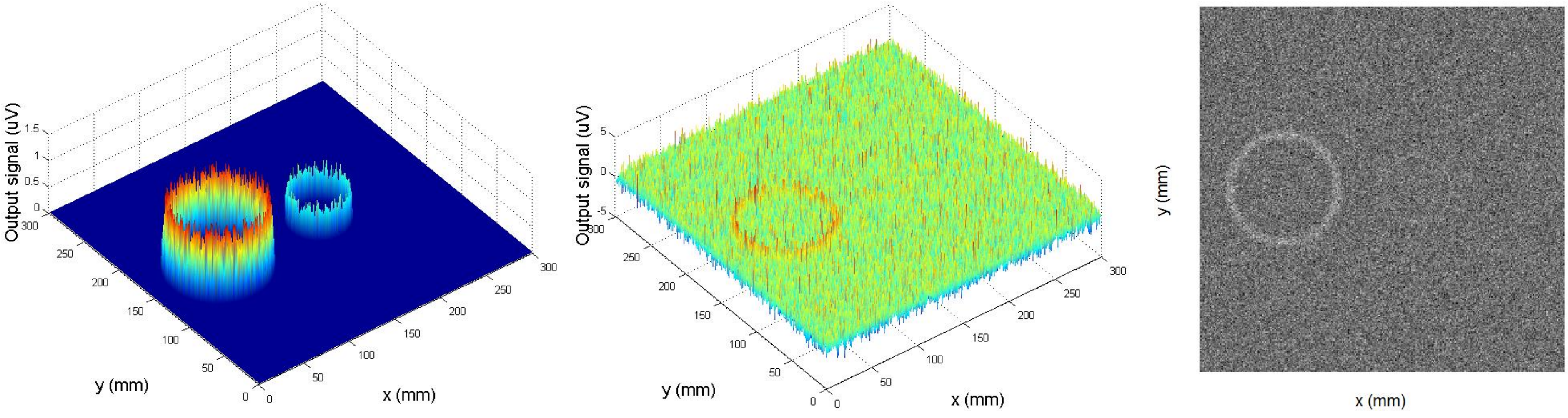
➔Output signal detected from sample located in inhomogeneous magnetic field.



➔Output signal detected from sample located in inhomogeneous magnetic field with noise condition.

B. Shen *et al*, "Design and Simulation of Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)", *Physica C*, 2016.

Final Signals and Basic Imaging – Normal Iron Magnet



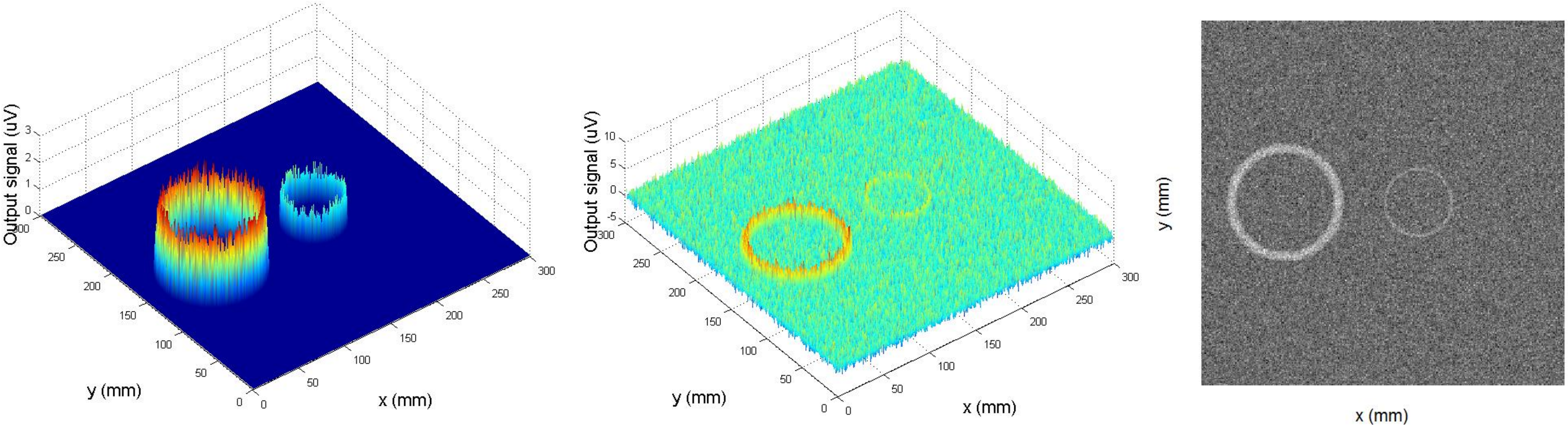
(a) **(b)** **(c)**

(a) voltage output (absolute value) without noise, (b) with noise, (c) electrical signal imaging: from the sample.

➔The imaging of electrical signal is faint and it is very difficult to find the edge and location of second sample.

B. Shen *et al*, “Design and Simulation of Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)”, *Physica C*, 2016.

Final Signals and Basic Imaging – Superconducting Magnet



(a)

(b)

(c)

(a) voltage output (absolute value) without noise, (b) with noise, (c) electrical signal imaging: from the sample.

➔The edge and shape of both samples can be discovered

B. Shen *et al*, "Design and Simulation of Superconducting Lorentz Force Electrical Impedance Tomography (LFEIT)", *Physica C*, 2016.

Thank you! Questions?

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