Unbalanced Torque in High Magnetic Field No-Insulation REBCO Pancake Magnet after Quench

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1. Introduction

This paper presents the risk of the unbalanced torque generated in No-Insulation (NI) $REBa_2Cu_3O_{7-x}$ (REBCO, RE = Rare Earth) pancake coils.

- The coil-radial current in the magnetic field generates the Lorentz force in the coil-circumferential direction *i.e.* torque.
- We present the numerical-simulation of the behaviors of the torque generated in the NI REBCO double pancake coil after quench.

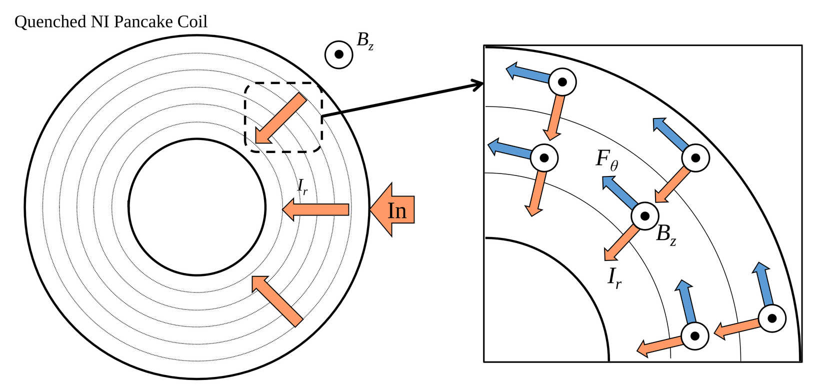

Fig. 1. Torque generated by turn-to-turn radial current in NI pancake coil.

2. Simulation Method

In the circuit analysis, the current is computed with the PEEC method [], [], and then the Joule heating inside the pancake is obtained as an input of thermal analysis. The thermal analysis is performed to obtain the temperature distribution, and it determines the properties of REBCO tape, such as the critical current.

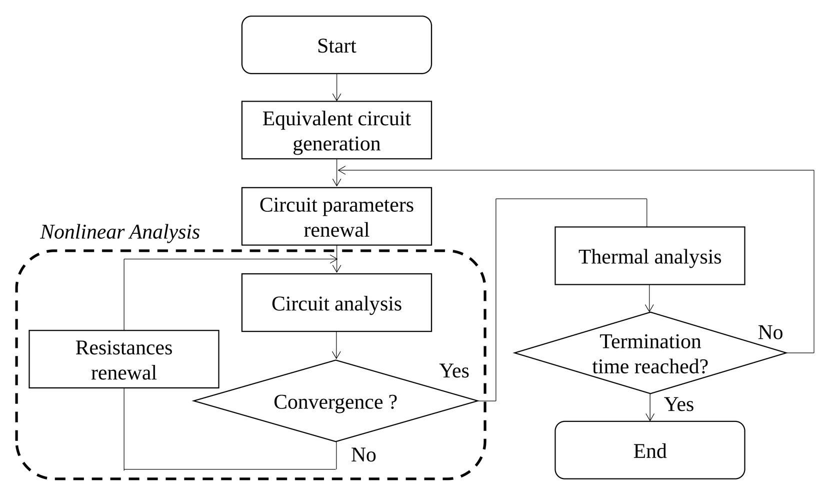

Fig. 1. Flowchart of simulation

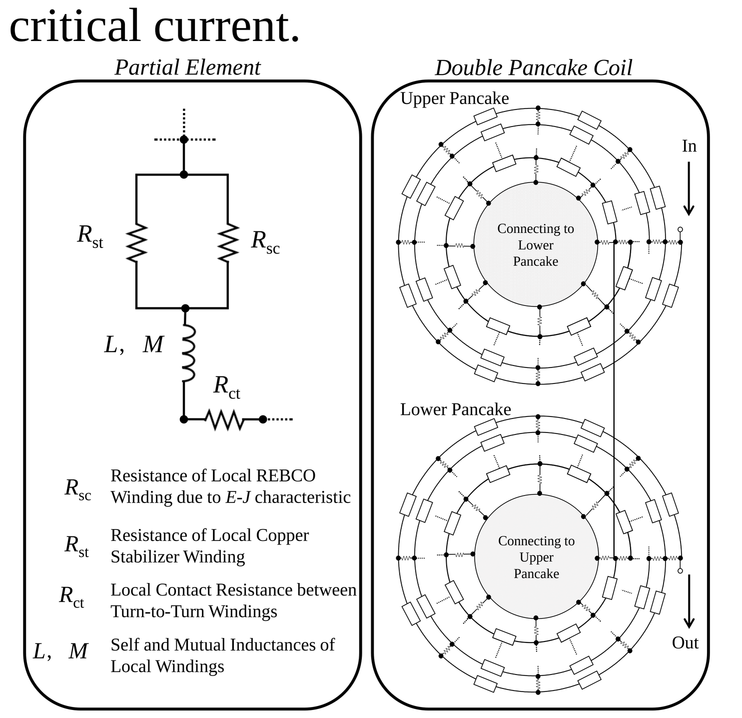

Fig. 2. The PEEC model extended to a double pancake and a multiple-stacked double pancake.

The PEEC model is constructed on the basis of Kirchhoff's first and second laws, which are expressed as follows:

$$I_{L\_i} - I_{L\_i-1} + I_{ct\_i} - I_{ct\_i-d} = 0 \quad (1)$$

$$\sum_{j=i}^{i-d-1}\left(\sum_{k=0}^{n} M_{jk}\frac{I_{L,k}-I_{L,k}^{-1}}{\Delta t} + I_{L,j}\frac{R_{sc,j}R_{st,j}}{R_{sc,j}+R_{st,j}}\right) - I_{ct,i}R_{ct,i} = 0 \quad (2)$$

where, i, d and n are the element number, the number of the circumferential division, the number of the element, respectively. I_L and I_{ct} are the currents flowing in the circumferential and radial directions, respectively. R_{sc}, R_{st} and R_{ct} are the supposititious resistance of REBCO layer, the resistance of the copper stabilizer and the contact resistance between turn-to-turn windings, respectively. M is the matrix that includes the self and mutual inductances of the partial elements.

Thermal Analysis (Finite Element Method)

Governing Equation:

$$\rho c\frac{\partial T}{\partial t} = \lambda \Delta T + Q \quad (3)$$

where, ρ, c, T, t, λ, and Q are the specific heat, the mass density, the temperature, the time, the thermal conductivity, and the heating per volume, respectively.

3. Simulation Model

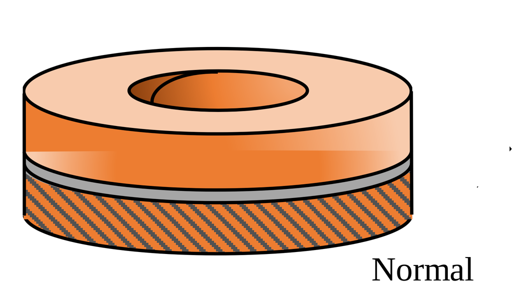

Fig. 3. Schematic drawings of simulation model.

TABLE I
PARAMETERS OF SIMULATED MODEL

Parameters	Values
REBCO tape	
REBCO tape width [mm]	4.0
REBCO tape Thickness [mm]	0.096
Copper stabilizer thickness [mm]	20.0
REBCO layer thickness [µm]	1.0
I_c @ 77 K, self-field [A]	115.0
Double pancake coil	
Coil inner radius [mm]	50,100, 500,1000
Number of turns (each pancake)	100
Coil thickness [mm]	9.6
Flange (insulator) width [mm]	1.0
Contact resistivity [µΩcm²]	70.0

TABLE II
SIMULATION CONDITIONS

Parameters	Values
Time step [s]	0.1
Simulation time [s]	50.0
Operating current [A]	500
External magnetic field, axial ,radial [T]	10.0, 0.0
Operating temperature [K]	20

4. Simulation Results

Torque Transition

Small Radius

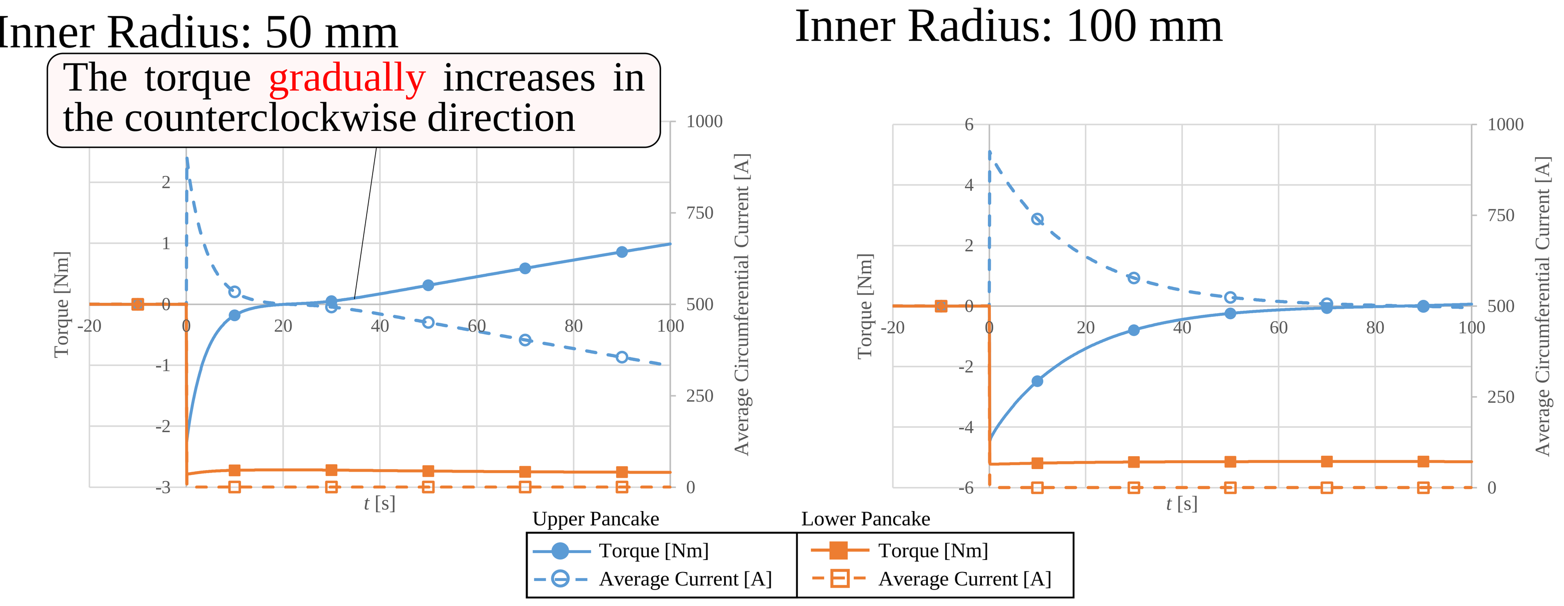

Fig. 4. Torque and average circumferential current transition when inner radius is (a) 50, (b) 100 mm. In graph, a counterclockwise direction is positive.

Large Radius

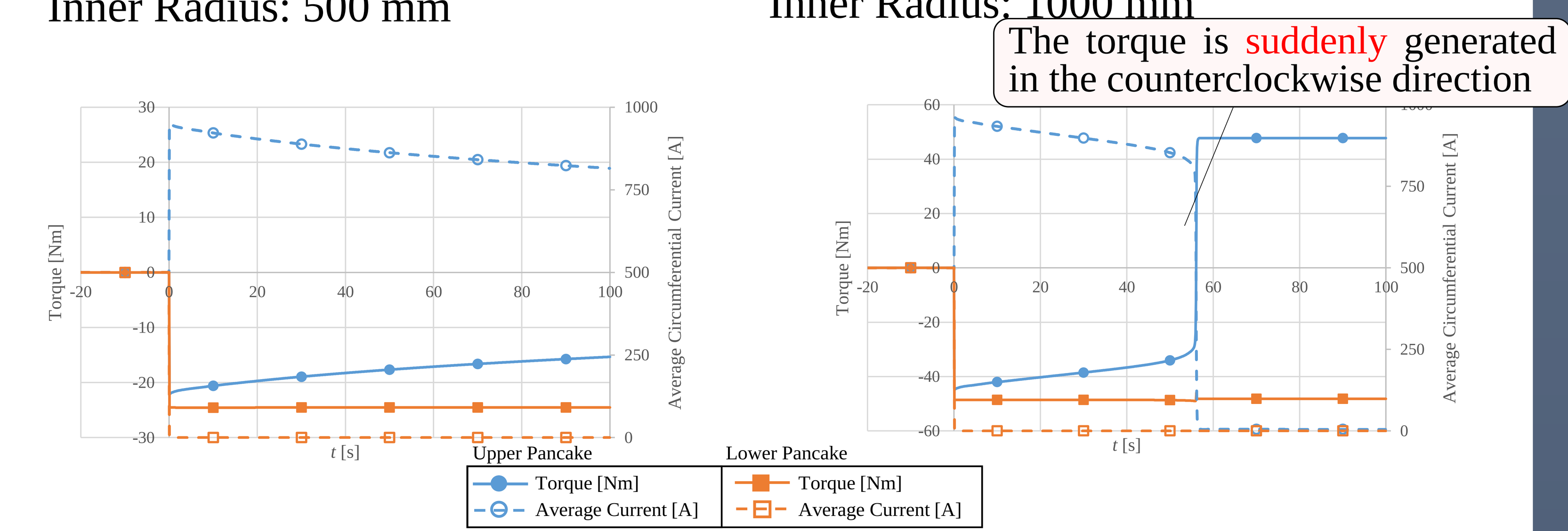

Fig. 5. Torque and average circumferential current transition when inner radius is (a) 500, (b) 1000 mm. In graph, a counterclockwise direction is positive.

In the upper pancake coil, the torque is generated due to the induced current.
The faster the decay speed of torque, the smaller the coil radius is, because the contact resistance is larger.

Distribution

Inner Radius: 50 mm

Radial Lorenz Force Distribution

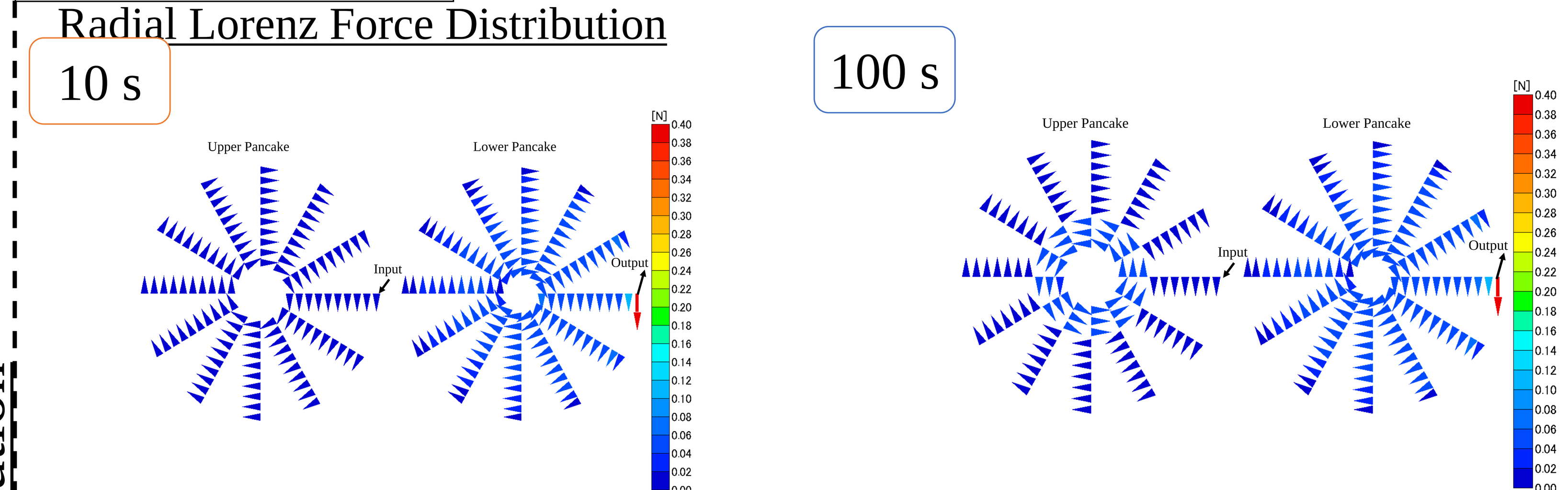

Fig. 6. Distribution of circumferential Lorenz force applied in NI pancake coils when inner radius is 50 mm at (a) 10 s and (b) 100 s after appearance of normal-state transition (not to scale).

Radial Current Density Distribution

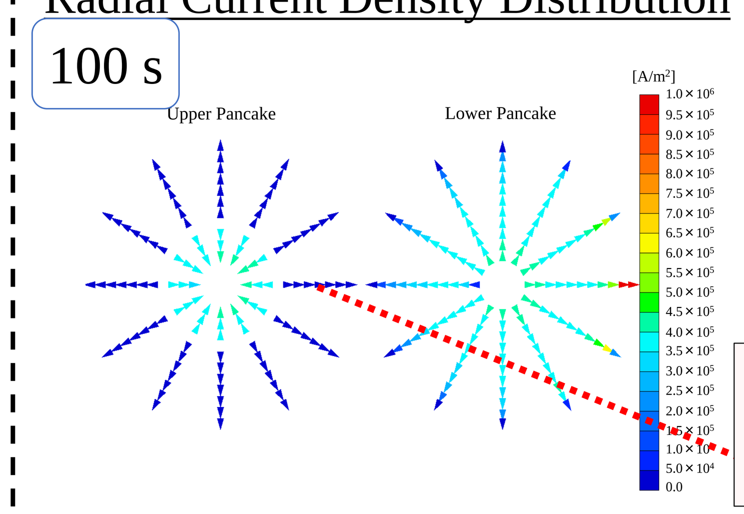

Fig. 7. Distribution of radial current density when inner radius is 50 mm at 100 s after appearance of normal-state transition (not to scale).

Temperature Distribution

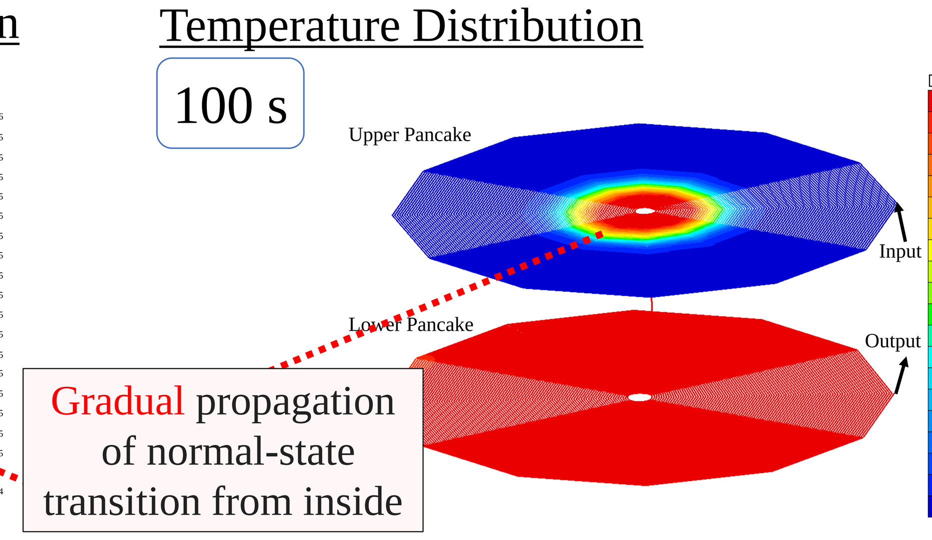

Fig. 8. Distribution of temperature when inner radius is 50 mm at 100 s after appearance of normal-state transition (not to scale).

Inner Radius: 1000 mm

Radial Lorenz Force Distribution

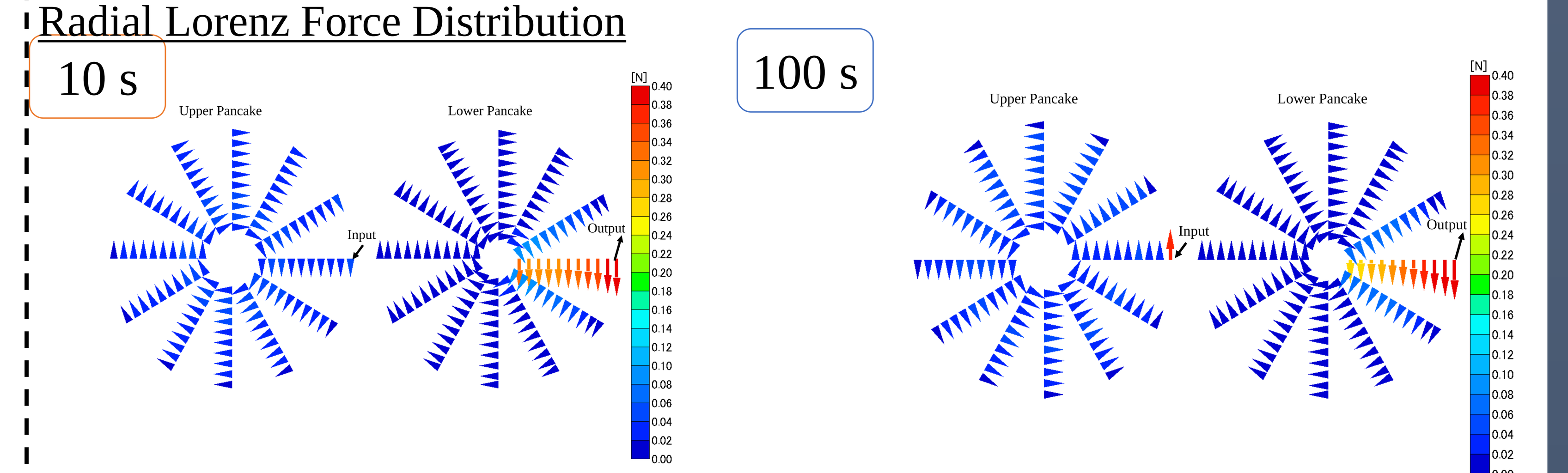

Fig. 9. Distribution of circumferential Lorenz force applied in NI pancake coils when inner radius is 1000 mm at (a) 10 s and (b) 100 s after appearance of normal-state transition (not to scale).

Radial Current Density Distribution

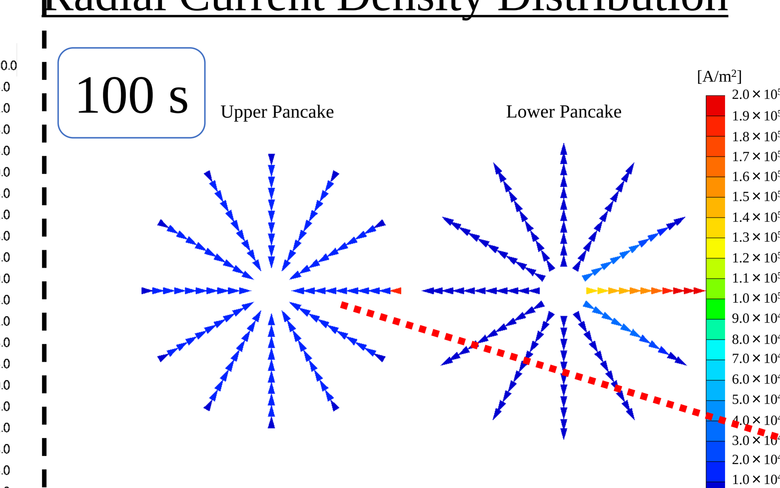

Fig. 10. Distribution of radial current density when inner radius is 1000 mm at 100 s after appearance of normal-state transition (not to scale).

Temperature Distribution

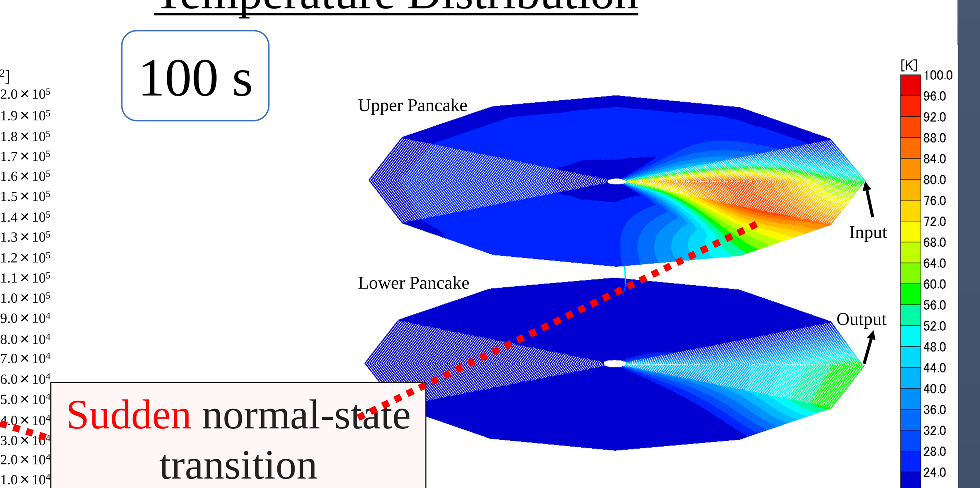

Fig. 11. Distribution of temperature when inner radius is 1000 mm at 100 s after appearance of normal-state transition (not to scale).

Behavior of Torque when Sudden Shutdown

Inner Radius: 1000 mm

When a local normal zone occurs, the operating current should shortly shut down in seconds. It is necessary to investigate the safety from the view point of torque after shutting off the operating current.

Immediately after the shutdown, the torque generated in the quenched lower pancake decays to zero, and the strength of upper pancake torque increases.

However, The total strength of them does not change at that time

A sudden shutdown is hardly caused to break a coil.

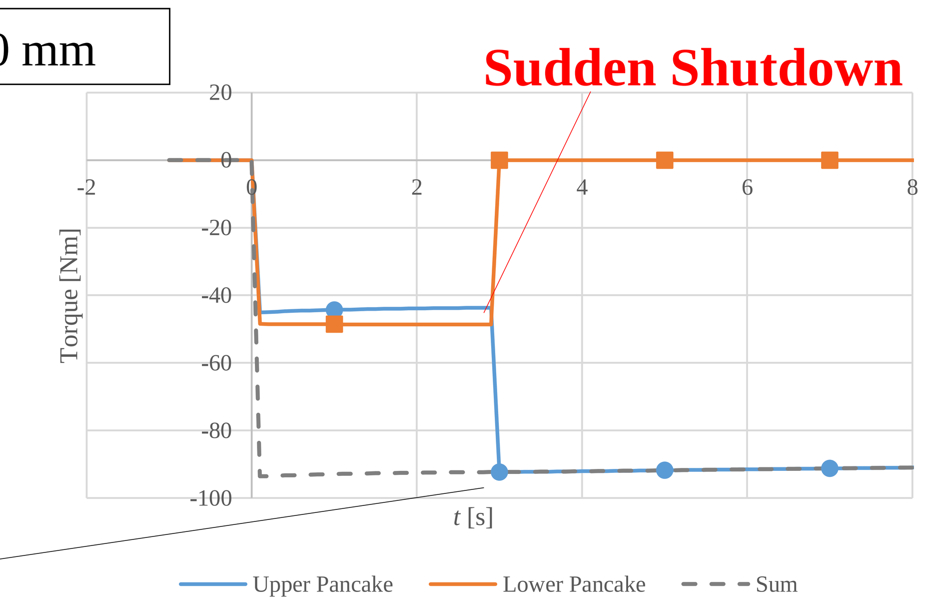

Fig. 12. Transition of torque when current is cut off at 3 s after appearance of normal-state transition. Coil inner radius is 1000 mm.

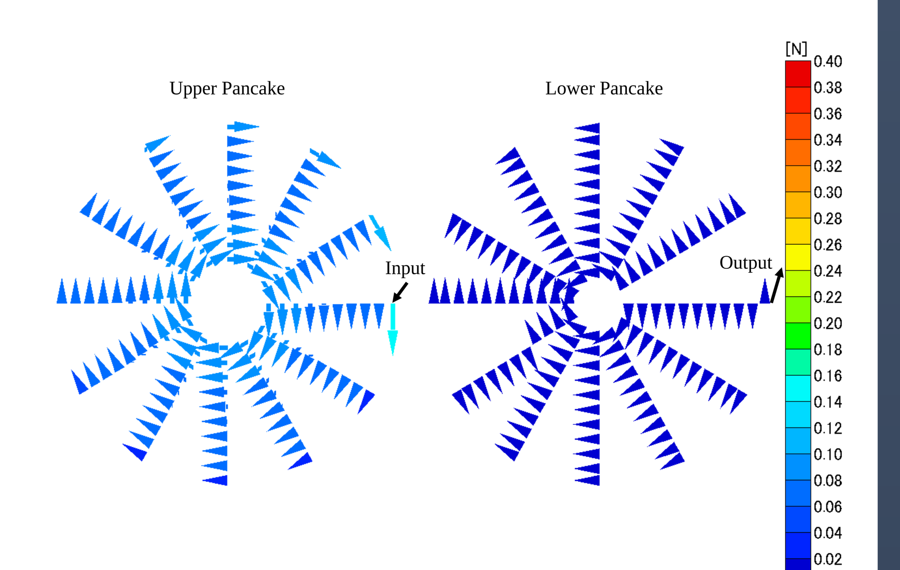

Fig. 13. Distribution of circumferential Lorenz force at 3 s from current interruption. Coil inner radius is 1000 mm (not to scale).

5. Conclusion

When an NI REBCO pancake coil has a large bore radius and is operated in large magnetic field, it is possible that a torque large enough to cause damage to magnet is generated. When a quench occurs, a torque is generated in coils not quenched too, due to induced current. It gradually decreases with the decrease of induced current. The faster the decay speed of torque, the smaller the coil radius is. Here, a normal-state transition occurs due to heating by the induced current. When a very small-size coil, the torque in the direction opposite to the torque initially generated is gradually generated. When the very large-size coil, the sudden inversion of torque is generated.