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An Experimental Study on "Defect-Irrelevant" Behavior of No-Insulation REBCO Pancake Coil in Conduction-Cooling Operation

Uijong Bong[1], Jaemin Kim[1], Jeseok Bang[1], Jeonghwan Park[1], Kyle Radcliff[2], Kwang Lok Kim[2], Kwangmin Kim[2], and Seungyong Hahn[1]
[1]Department of Electrical and Computer Engineering, Seoul National University, Seoul 08826, South Korea.
[2]National High Magnetic Field Laboratory, Tallahassee, FL 32310 USA.

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(Corresponding Author: S. Hahn)

Abstract - The "defect-irrelevant" behavior of a no-insulation (NI) high temperature superconductor (HTS) pancake coil was firstly reported in 2016. The test coil was wound with REBCO tapes having multiple "defects" and tested in a bath of liquid nitrogen at 77 K. Coil terminal voltage and magnet constant of the test coil are essentially identical to those of its "healthy (defect-free)" counterpart in steady-state operation below the critical current (I_c), which demonstrated a potential of the defect-irrelevant-winding (DIW) approach to build an NI magnet with a substantially reduced cost. Here we report, as a continuation to the previous study, test results of a "DIW" REBCO pancake coil operated in a conduction-cooling environment below 77 K. Charging tests were performed and the results were compared in terms of voltages, magnet constants and maximum operating currents without thermal runaway in accordance with each operating temperature. Also, by the use of an equivalent lumped parameter circuit model, the test results were numerically analyzed to evaluate the performance of our DIW coil compared to its healthy counterpart.

◆ Introduction

- **"Defect-irrelevant" winding (DIW)** approach suggested in 2016 [1]

  Approach: **No-insulation (NI)** coil wound with REBCO conductor containing **defects**
  Proved: (DIW coil) = (healthy counterpart) in steady-state operation
  Benefit: Substantial **cost reduction** on magnet construction
  Problem: Only demonstrated at 77 K in a LN2 bath

- Experimental Study with **conduction-cooled** DIW single pancake coil (SPC)

  Goal: To demonstrate DIW at temperatures under 77 K in conduction cooling operation.

◆ Coil Construction and Experimental Setup

- NI SPC construction with SuNAM's tin plated REBCO tapes containing defects

Defect definition: the local spot whose I_c is <80 % of the whole tape's average I_c

Lengthwise I_c measurement: **two major defects** were identified. (measured in SuNAM Co.)

Parameters		Values
REBCO tape width	[mm]	4.1
Average REBCO tape thickness	[mm]	0.148
REBCO tape length	[m]	22.6
Copper stabilizer thickness	[μm]	30
Inner diameter	[mm]	57.8
Outer diameter	[mm]	87.3
Total turns		100
Field constant at center	[mT A^{-1}]	1.64
Inductance	[mH]	1.02
Characteristic resistance @ 20; 40 K	[$\mu\Omega$]	5.82; 9.85
Charging time constant @ 20; 40 K	[s]	175; 104

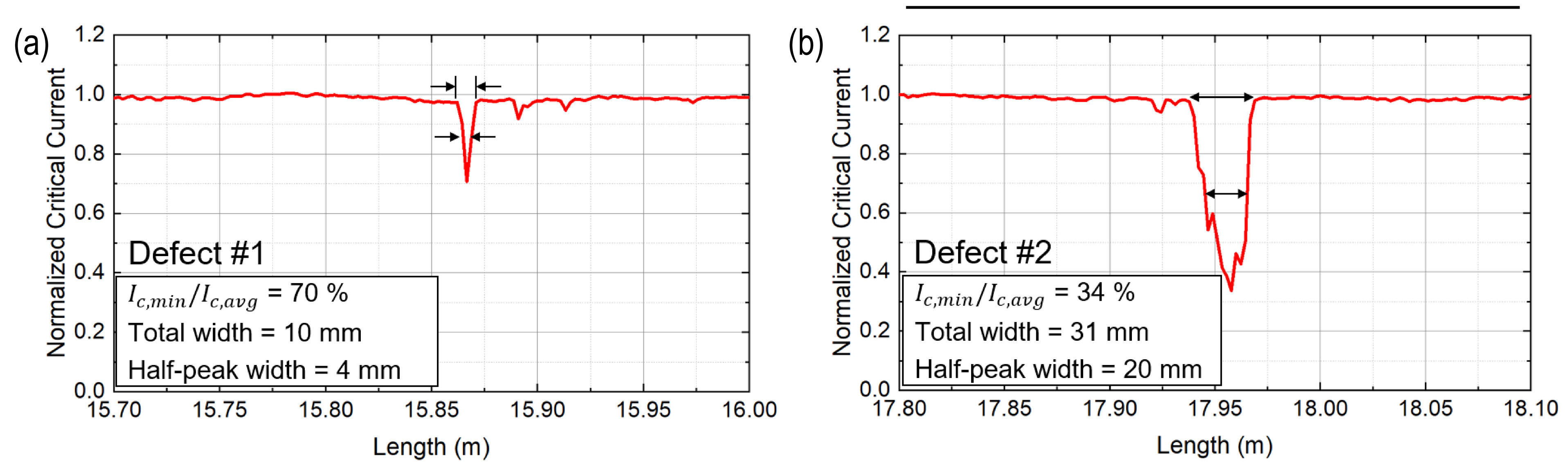
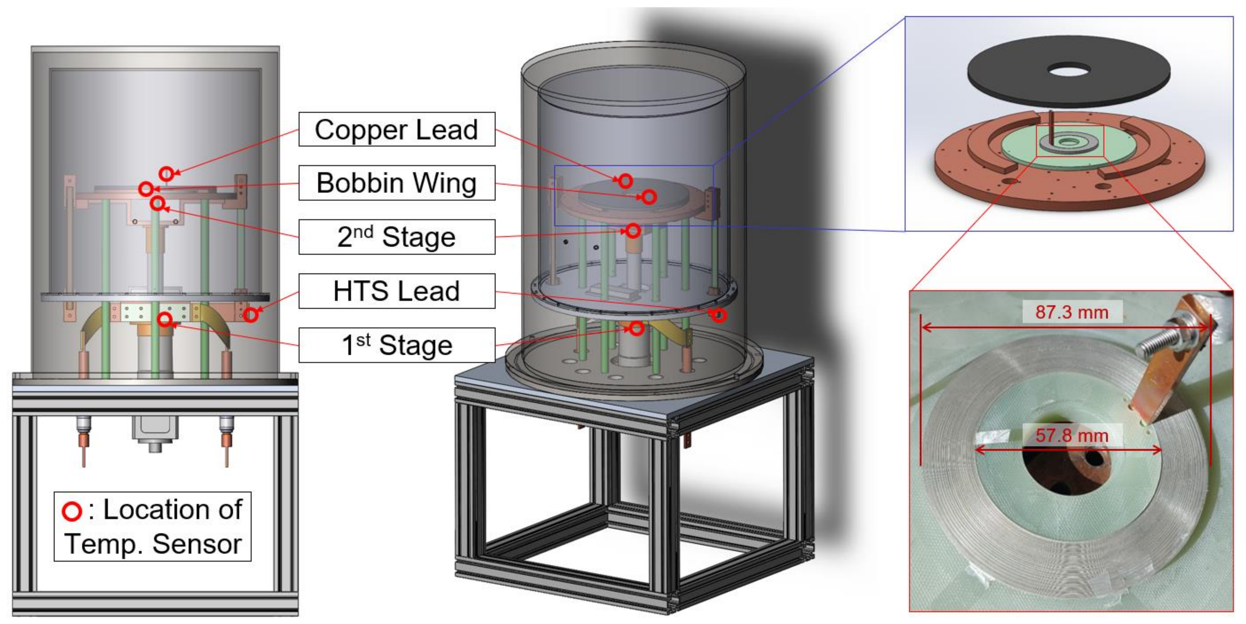


Figure 1. (a) **the defect #1** with the minimum normalized I_c of 0.7 and the 4 mm wide half-peak width, and (b) **the defect #2** with the minimum normalized I_c of 0.34 and the 20 mm wide half-peak width



- Conduction cooling system with constructed NI DIW SPC

Figure 2. Overview of conduction cooling system for the test and picture of the NI DIW test coil. Red circles indicate the location of installed temperature sensors

◆ Charging Tests Performed in a Range of 20 K – 65 K

- Charging test procedure

  Current control: 1) With ramping rate of 0.2 A/s
  2) Hold the current with regular interval to check steady-state behavior

  Temperature control: Control the temp. of the 2nd stage in a range of 20-65 K at every 5 K

- Selected charging test result conducted at 20 K

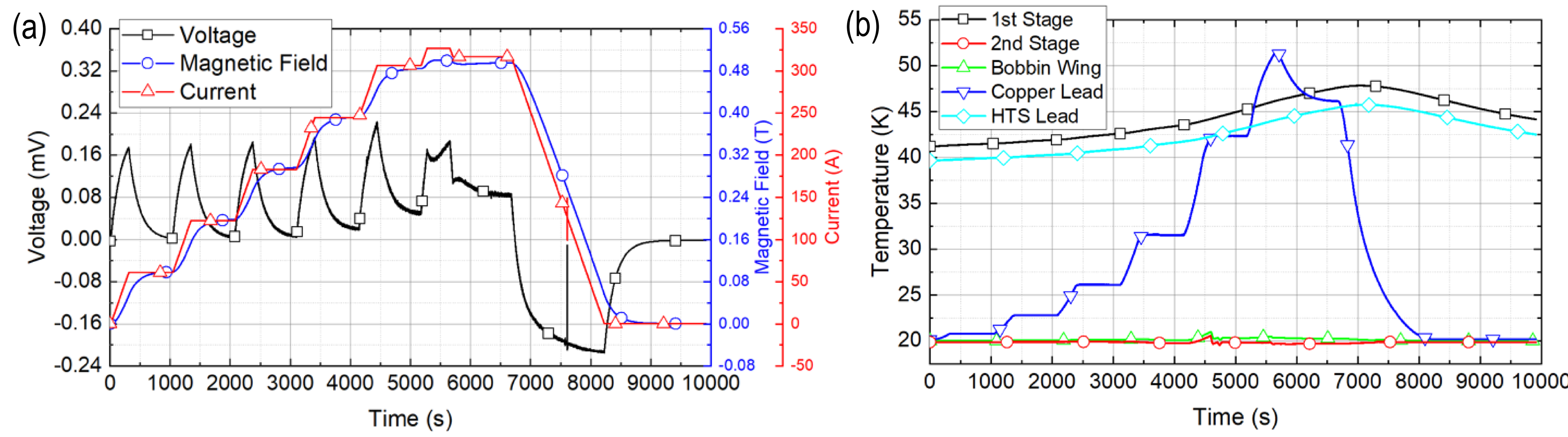


Figure 3. Result of the charging test conducted at 20 K: (a) profiles of **coil terminal voltage**, **center field of the coil** and **power supply current**; (b) **temperatures** measured by each temperature sensors

◆ Discussion 1: Steady-state Behavior & Maximum Operation Current

- Steady-state behaviors in accordance with operating current and temperature

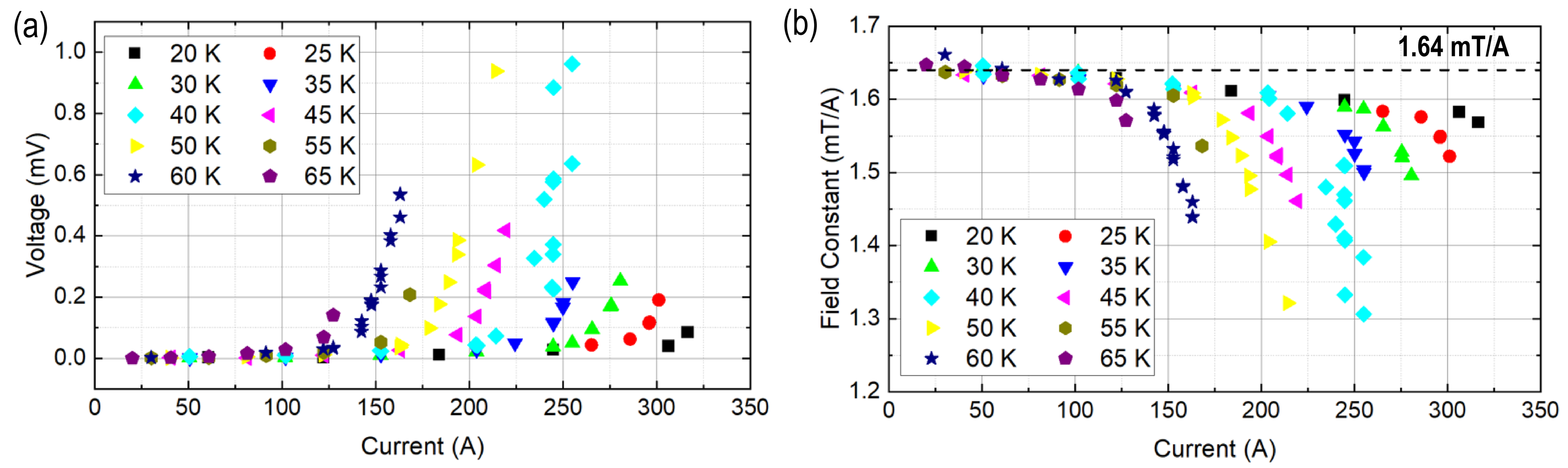
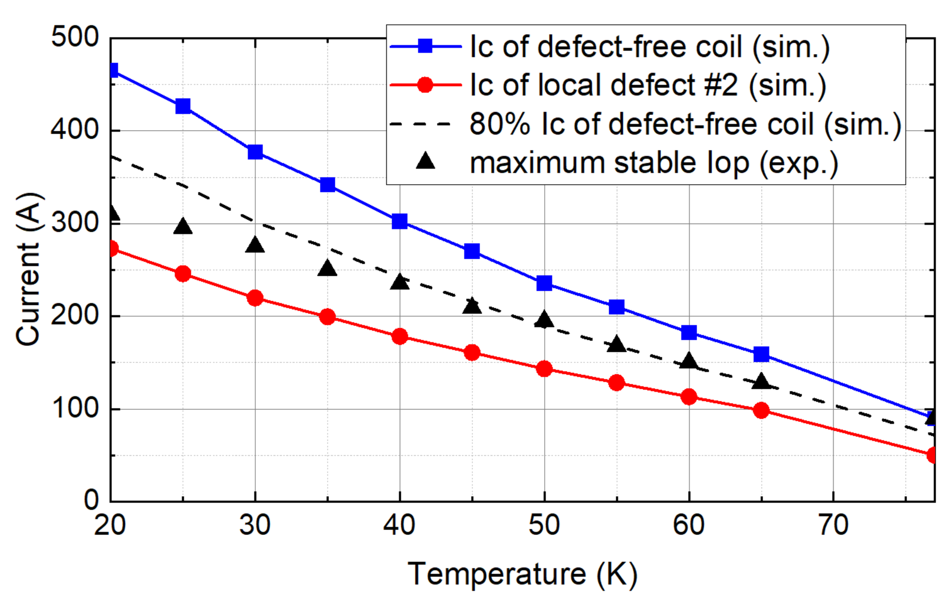


Figure 4. Steady-state behaviors of DIW coil at each temperature ranged from 20 K to 65 K: (a) **coil terminal voltage**; (b) **magnet constant** calculated as the center field of the coil divided by the operating current.



- Comparison between $I_c(B,\theta)$ and maximum operation current

Based on practical fit-function $I_c(B,\theta)$ [2, 3]

Figure 5. **Blue line** represents calculated I_c of same-sized healthy coil, while **red line** shows I_c of the local defect #2 of the test coil. **Dotted line** is the 80 % of estimated I_c of the healthy coil. **Black** triangle markers indicate the measured maximum steady-state operating current

◆ Discussion 2: Effect of Local "Defect" on Entire Coil Performance

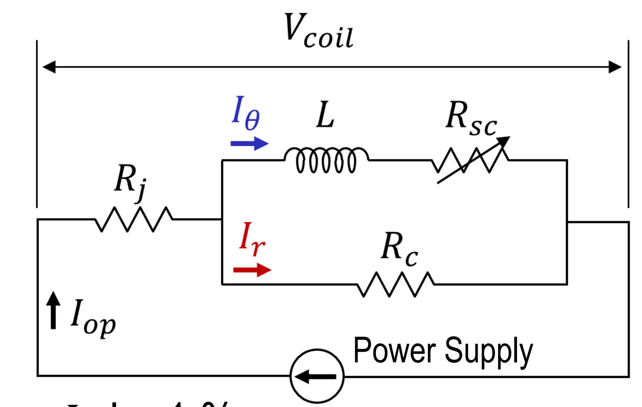
- (DIW experiment) vs. (same-sized coil simulation with overall I_c degradation)

Assumptions:

1) Index resistance (E_c = 1 μV/cm, n = 40 [4])
2) Temperature dependency of resistances [5]

$$R_{sc}(T) = \frac{E_{cl}}{I_\theta}\left(\frac{I_\theta}{I_c(T)}\right)^n,\ R_c(T) = R_c(T_0)\frac{\rho_{cu}(T)}{\rho_{cu}(T_0)}$$

$$T = 0.8\,T_{wing} + 0.2\,T_{lead}$$



Finding best-fitted result: Iterative simulation by decreasing I_c by 1 %

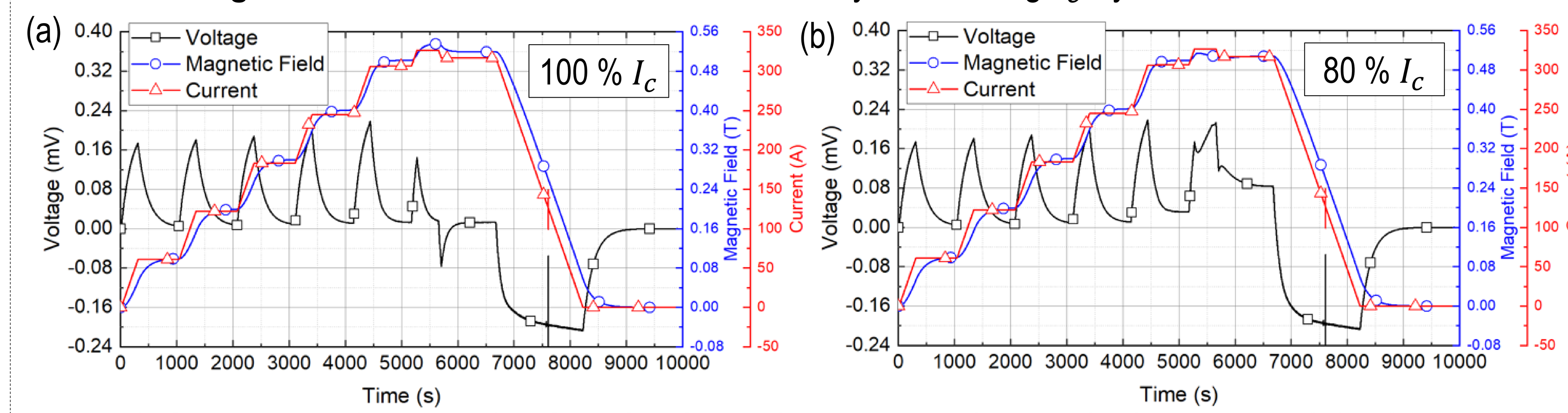


Figure 6. Charging simulation results of a defect-free coil containing coil terminal voltage, center field of magnet, and power supply current: (a) **with no I_c degradation** at 20 K; (b) **with 80 % I_c (best-fitted)** at 20 K.

Comparison between the "local" and "overall" degradation

$$A = \frac{\text{(Estimated } I_c \text{ of local defect \#2)}}{\text{(Estimated } I_c \text{ of same-sized healthy coil)}}$$

B = (best-fitted % of I_c of circuit simulation)

T (K)	20	25	30	35	40	45	50	55	60	65
A (%)	59	58	58	58	59	60	61	61	62	62
B (%)	80	82	82	83	86	85	87	87	88	90

◆ Conclusion

- The defect-irrelevant behavior was demonstrated in conduction cooling conditions below 77 K, but is not as effective as in a bath of liquid nitrogen.
- For a further application employing the defect-irrelevant winding approach in conduction cooling system, additional care on defects would be needed to diminish the effect of defects.

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