HTS-WISE conductor and magnet impregnated with low-melting point metal

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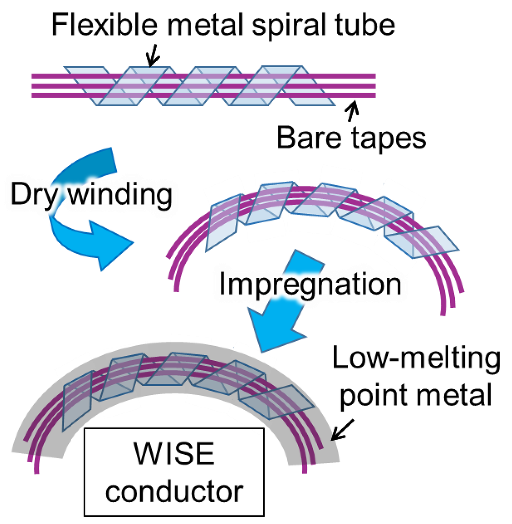
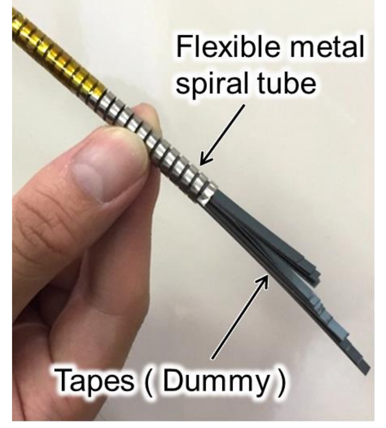
Abstract –
The several types of High-Temperature Superconducting (HTS) large-current capacity conductors to be applied to the LHD-type helical heliotron fusion reactor have been investigated in NIFS. Recently, J. Miyazawa *et al.* invented an unique winding technique, called "Wound and Impregnated Staked Elastic tapes (WISE)". The HTS-WISE conductor has been considered as one of the candidate conductors for the next generation helical fusion device. This poster reports the results on the first trial making of the HTS-WISE conductor/magnet and its testing.

Introduction

HTS-WISE concept

Stacked HTS tapes are inserted into a flexible metal tube to form an assembled conductor, and wound onto a coil frame. In the flexible metal tube, each tape naturally deforms so as to minimize strain. Flexibility of this type of conductor allows easy coil winding even if a coil has a complex shape like helical coils. Then a coil is impregnated using low-melting point metal in liquid state, as it eliminates voids between tapes.
(J. Miyazawa *et al*, Japanese Patent, Application No. 2017-232731, 2017)





Sample Fabrication and Experimental Setup

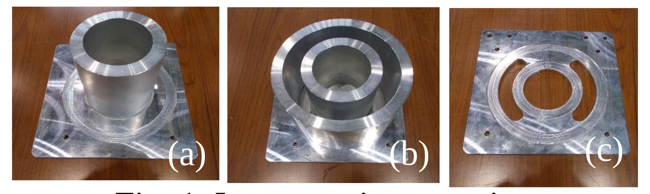


Fig. 1 Impregnation container

Fig. 2 Impregnation using low-melting point metal U-78 (Sn-type alloy, produced by Asahi Metal Co., Ltd., m. p. ~78 ℃)

ST-4-100-Cu (SuperOx Japan Inc., I_c > 100 A@77 K, s. f., 4-mm wide)

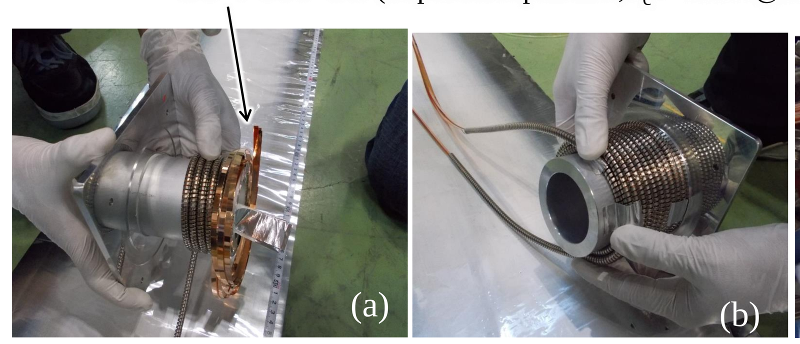


Fig. 3 Coil winding

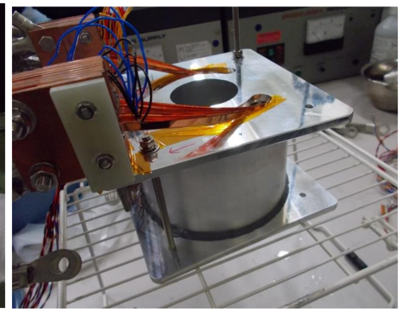


Fig. 4 Picture of the sample

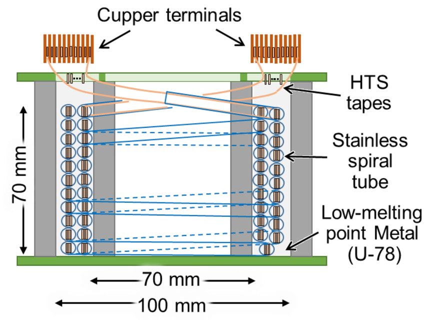


Fig. 5 Schematic drawing of the sample

Tab. 1 Specification of the sample

Number of stack	10
Conductor length	6 m
Coil shape	Double solenoid
Total turn number	21.5
Non-insulation	Yes

The sample was considered to be a **Metal-as-Insulation** (MI) coil [1]

Measurement setup

- Terminal voltages of all tapes
- Operation current (shunt resistor)
- Magnetic field at the center in the bore of the coil (Hall probe)
- All the tests were performed in liquid nitrogen bath at the temperature of 77 K.

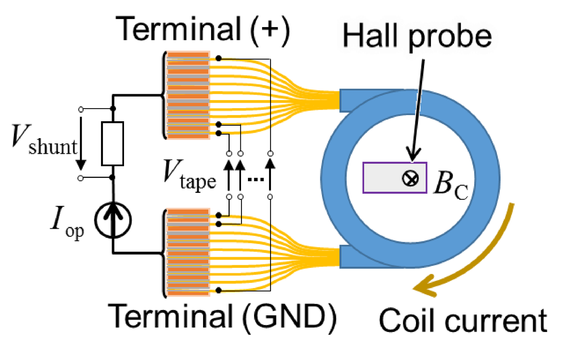


Fig. 6 Measurement Setup

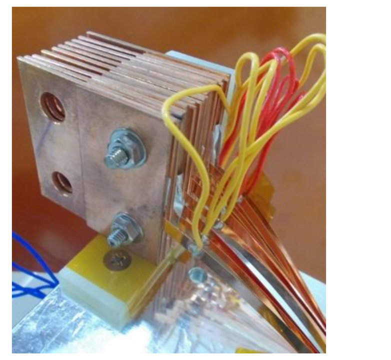


Fig. 7 Separate-type terminal

Experiment

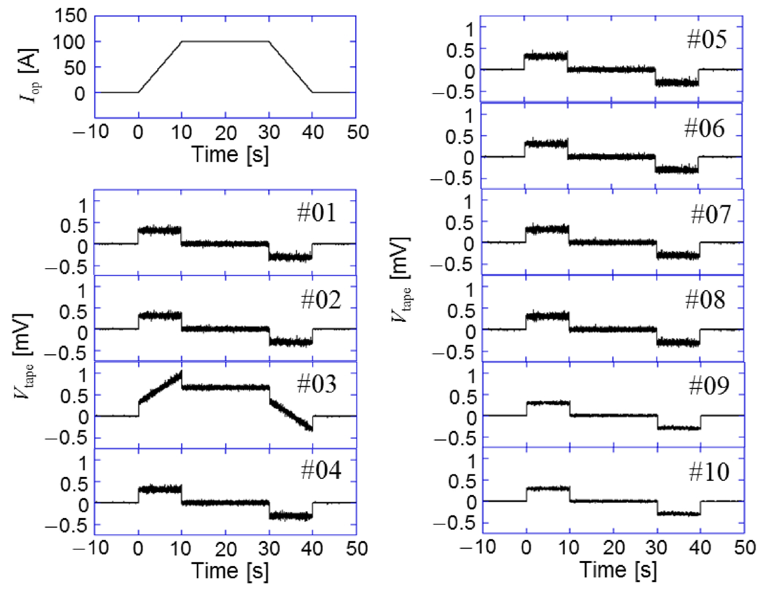


Fig. 8 Tape terminal voltage signals on the charging test before impregnation. #01 indicates the tape along most outer side by a coil curve

Charging test before impregnation

- As most of induced voltages are evaluated to be 0.3 mV with the ramp rate of 10 A/s, the inductance of the sample coil can be estimated to be **~30 μH**.

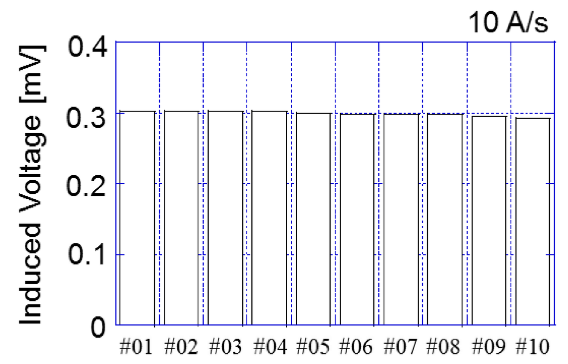


Fig. 9 Induced voltage levels for ramping of 10 A/s

Charging test after impregnation

- Both the magnetic field and voltages behaved like those observed in Non-Insulation (NI) coils [2].
- Time constant of the delay with the magnetic field was found to be **~7.5 s** and the characteristic resistance is calculated to be **~4 μΩ** at first cooling.
- Thermal cycles made the damage in tapes from the second cooling.
- Achieved a central magnetic field of 0.16 T @ 800 A (15 A/mm²) in steady-state
- Thermal runaway occurred at a current of 850 A in the steady-state operation.

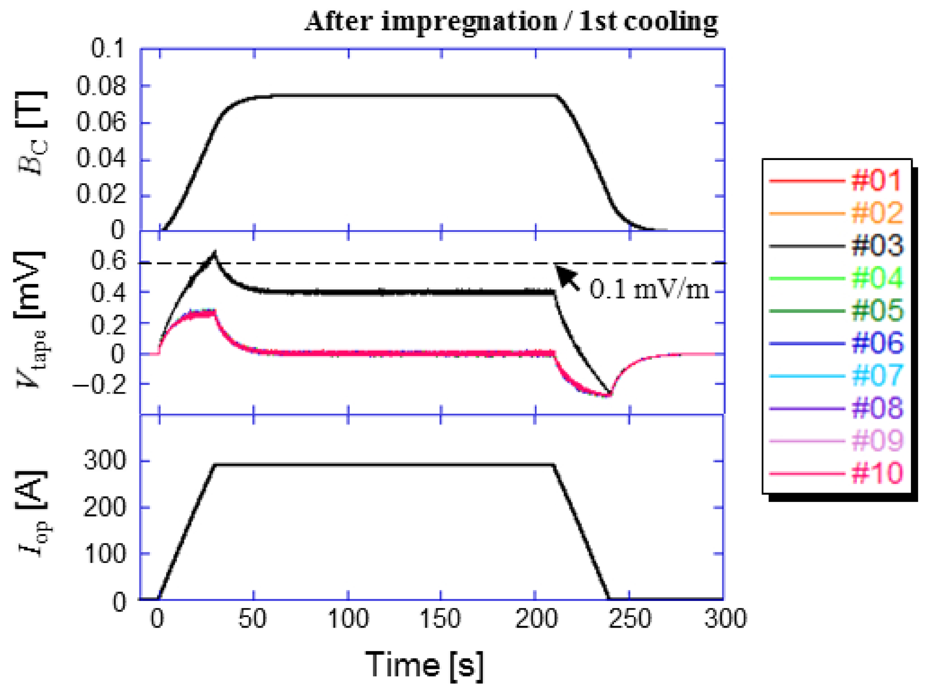


Fig. 10 Results on the charging test after impregnation

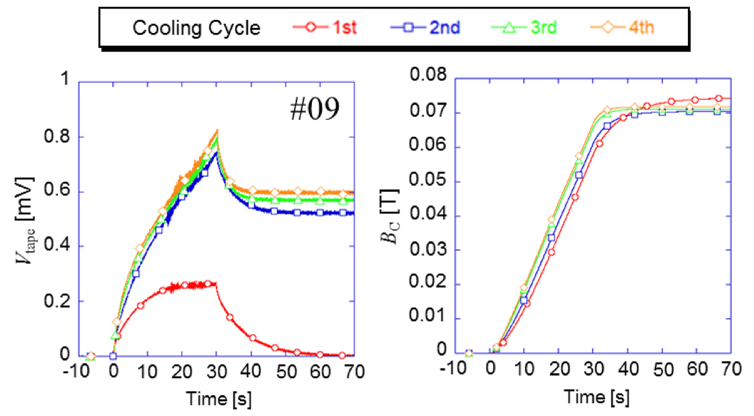


Fig. 11 Results on thermal cycle test

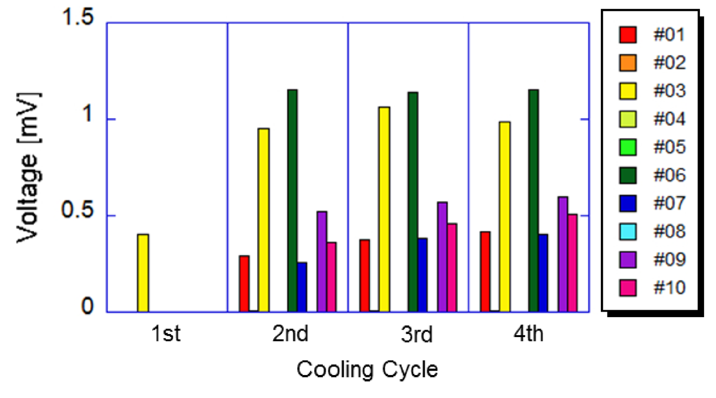


Fig. 12 Voltage levels at 291 A steady-state

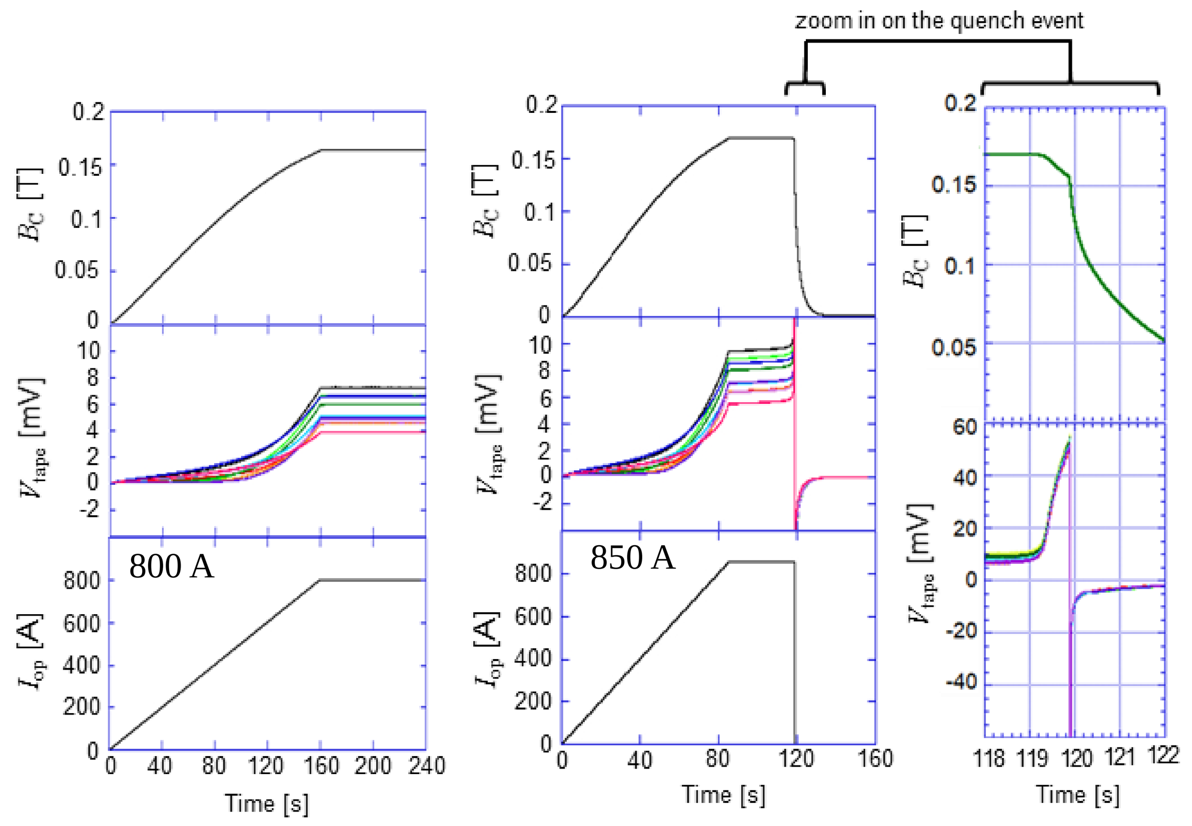


Fig. 13 Quench Behavior of the sample

Analysis

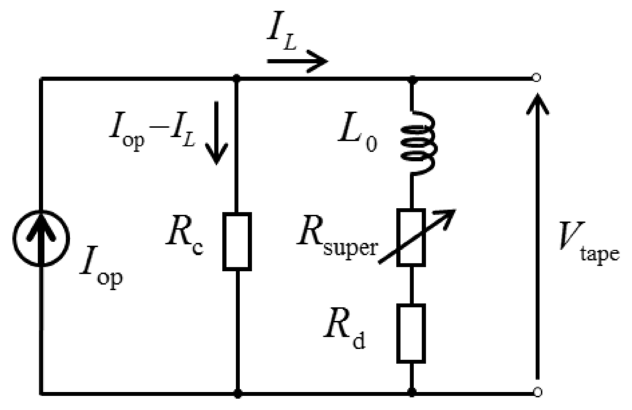


Fig. 14 SPEC model taking degradation into account

Circuit equation $$(R_d + R_{super})I_L + L_0 \frac{dI_L}{dt} = R_c (I_{op} - I_L)$$

n-value model $$R_{super} = \frac{V_c}{I_{c,\,multi}} \left(\frac{I_{sample}}{I_{c,\,multi}}\right)^n$$

Used in fitting $$B_C = gI_L \qquad V_{tape}\big|_{R_d=0} = L_0 \frac{dI_L}{dt}$$

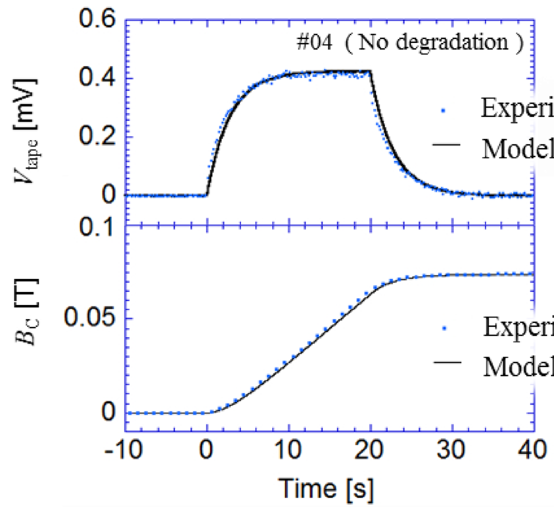


Fig. 15 Fitting result

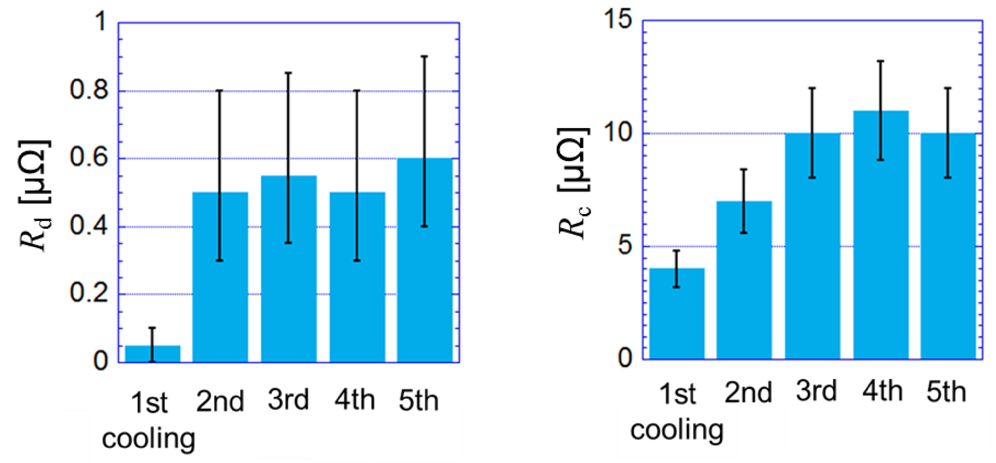


Fig. 16 R_d and R_c depending on thermal cycle

- SPEC model in [3] can express the behavior of the HTS-WISE solenoid coil sample.
- Contacting conditions between tape surface and low-melting point metal seems influence R_d and R_c.

Discussion and Conclusion

- By fabricating a WISE solenoid coil sample, it was shown that WISE is a smart winding method to make a MI coil having even complex 3D shapes.
- In this first test, thermal cycles damaged the 2G HTS tapes impregnated with U-78. To solve this problem, optimizations of the impregnation process, the investigations of the mechanism, and the usage of some other HTS tapes and low-melting point metal are desirable to be examined.
- Even with some degradation, the WISE coil sample demonstrated an outstanding thermal stability; it allowed about ten times the typical voltage criterion of critical current (0.1 mV/m) for stable operation. In order to apply the WISE conductor/magnet in some applications having complex shapes like heliotron fusion reactors, the optimizations are expected.
- After the experiment, the sample was examined by water jet cutting. Fig. 17 shows the cross sectional view of the cut surface. Some voids are observed at some locations in a flexible metal tube. In order to improve the impregnation, we had better consider the vacuum pressure impregnation (VPI) process to completely fill up the coil case.

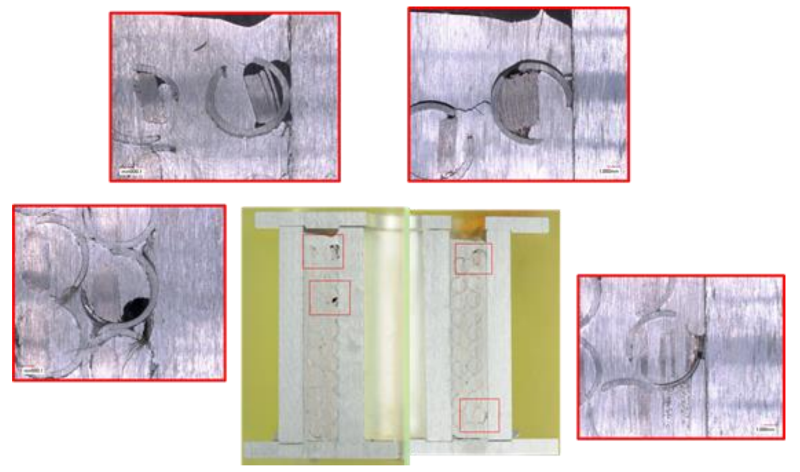


Fig. 17 cross sectional view of the cut surface of the sample

[1] T. Lécrevisse and Y. Iwasa, "A (RE)BCO Pancake Winding With Metal-as-Insulation," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, Apr. 2016, Art. no. 4700405.
[2] S. Hahn *et al.*, "HTS Pancake Coils Without Turn-to-Turn Insula-tion," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, Dec. 2010, pp. 1592 – 1595.
[3] X. Wang *et al.*, "Charging Behavior in No-Insulation REBCO Pancake Coils ," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Oct. 2014, Art. no. 4601805