# Investigation into Quench Detection for a Multi-Stacked Pancake Coil Wound with $Nb_3Sn$ CIC Conductors*)

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(Received 20 November 2019 / Accepted 25 March 2020)

For a multi-stacked (MS) pancake coil wound with $Nb_3Sn$ CIC conductors, quench detection methods using voltage measurements were investigated. In this study, we utilized two methods: the balanced voltage between two coil windings and the balanced voltage between one coil winding and a disk-shaped pickup coil. During the energization of the MS pancake coil, voltage measurements of the coil were conducted to compare the measurement results of the two quench detection methods. The measurement results indicate that the quench detection based on the balanced voltage between two coil windings is more reliable than the other. In the measurements, spike voltages were observed when there was a rapid change of a coil current. Magnetization of the MS pancake coil is considered one cause of the spikes. When determining criteria of quench detection, spike voltages should be taken into account to prevent malfunction of a quench detection system.



Keywords: $Nb_3Sn$, cable-in-conduit conductor, multi-stacked pancake coil, quench detection, pick-up coil

DOI: 10.1585/pfr.15.2405028

## 1. Introduction

To operate superconducting magnets stably and safely, quench protection for the magnets must be conducted properly, otherwise superconducting magnets will cause burnout due to quench in the worst case. In quench protection, accurate detection of quench occurrence in superconducting magnets is demanded. There are two types of the quench detection method utilized in the magnets for fusion devices. One is quench detection based on the balanced voltage between either two coil windings or two segments into which one coil winding is divided. This method has been adopted in the following fusion devices: TORE SUPRA [1], LHD [2], KSTAR [3, 4], SST-1 [5], and W7-X [6]. In not only fusion devices but also in other applications using superconducting magnets, this quench detection has commonly been used.

The other method is quench detection by using a pickup coil whose configuration is either a co-wound coil [7] or a disk-shaped coil [8]. In this method, the balanced voltage between a superconducting coil and a pickup coil is utilized to detect a quench. The fusion devices EAST [9] and KSTAR have used this quench detection method with a co-wound coil, which is wound with a superconducting coil. In the KSTAR poloidal field coils 1-5 using the two quench detection methods simultaneously, the quench detection method with a pickup coil is given priority [3, 4]. The quench detection with a disk-shaped coil has been adopted for the JT-60SA central solenoid (CS) [8], which is currently under construction.

In this study, these two methods of quench detection are investigated experimentally by using a multi-stacked (MS) pancake coil wound with $Nb_3Sn$ cable-in-conduit (CIC) conductors. The experiment with the MS pancake coil was conducted in the coil test facility at the National Institute for Fusion Science (NIFS) [10–13]. This paper describes the measurements of the balanced voltage for the MS pancake coil by the two quench detection methods. And the quench detection methods are discussed based on the measurement results. In this paper, the balanced voltage is defined as the voltage difference between two coils.

## 2. MS Pancake Coil and $Nb_3Sn$ CIC Conductor

The MS pancake coil, which is the JT-60SA CS1 module, is composed of six octa-pancake (OP) coils and one quad-pancake (QP) coil [10, 14, 15]. The QP coil is sandwiched between the six OP coils. All coils are wound with $Nb_3Sn$ CIC conductors. Each pancake coil is connected through butt joints [15–17] of the conductor. The number of coil winding layers is 52. The inner and outer diameters of the coil windings are 1.3 m and 2.0 m, respectively. The height of the coil winding is 1.6 m, and the coil weight is 18 tons. The layout of the MS pancake coil installed in the coil test facility of NIFS is shown in Fig. 1. The details of the MS pancake coil and the coil test facility are described in Ref. [10].

Regarding the CIC conductor, the cable is composed of 216 $Nb_3Sn$ strands plated with chromium and 108 cop-

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*) This article is based on the presentation at the 28th International Toki Conference on Plasma and Fusion Research (ITC28).

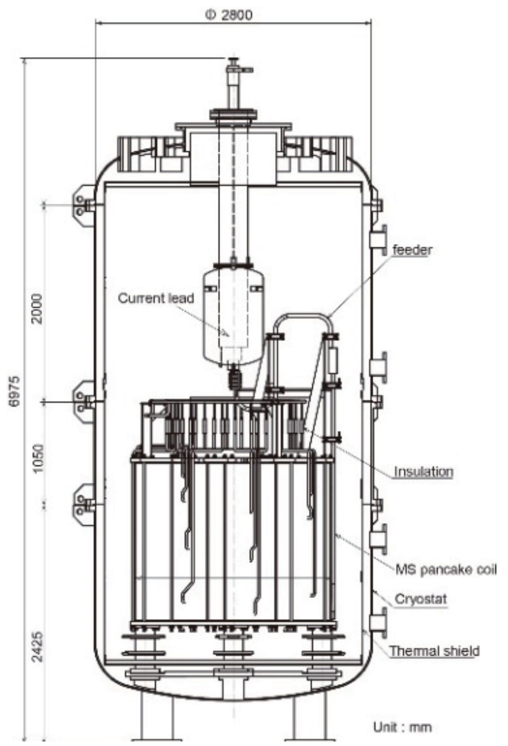


Fig. 1 Layout of the MS pancake coil installed in the coil test facility.

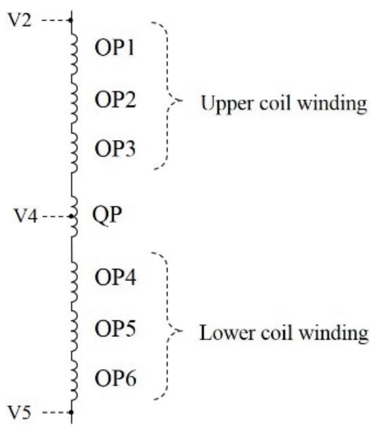


Fig. 2 The position of the voltage taps in the multi-stacked pancake coil.

per strands. The diameter of the strands is 0.82 mm. The CIC conductor is equipped with a central spiral. The details of the CIC conductor are described in Ref. [18].

## 3. Measurement Equipment

Figure 2 shows the position of the voltage taps in the MS pancake coil. To measure the balanced voltage between two coil windings of the MS pancake coil for quench detection, the voltage tap V4 is set at the middle of the QP coil. And the voltage taps V2 and V5 are set at the terminals of the MS pancake coil. Voltages of the upper coil winding and the lower coil winding can be measured by using these voltage taps. The upper coil winding is composed of the OP1 coil, the OP2 coil, the OP3 coil, and the upper half of the OP coil. The lower coil winding is composed of the OP4 coil, the OP5 coil, the OP6 coil, and the lower half of the OP coil.

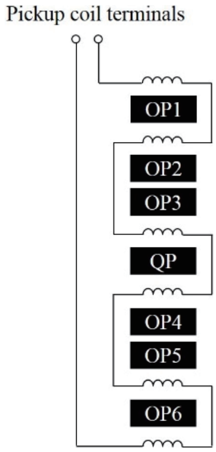


Fig. 3 The position of the disk-shaped pickup coil in the multi-stacked pancake coil.

In addition, a pickup coil is inserted into the MS pancake coil for quench detection. Figure 3 shows the position of the pickup coil in the MS pancake coil. The configuration of the pickup coil is disk-shaped. The disk-shaped coil can reduce the risk of wire breakage, which is a problem in a co-wound pickup coil [4] due to the conduit shape of CIC conductors and high compressive stress when energizing a superconducting coil [8]. The pickup coil is composed of six coil windings wound with wires which are made of stainless steel insulated with glass epoxy (G10) and Kapton. Details of the disk-shaped pickup coil are described in Ref. [8].

In this experiment, the balanced voltage between the upper and the lower coil windings in the MS pancake coil was used for quench detection. The criterion of quench is set as the balanced voltage of 0.1 V for more than 0.1 s.

## 4. Energization Tests of the MS Pancake Coil

Using the coil test facility of NIFS, energization tests of the MS pancake coil were conducted. The voltages of two coil windings in the MS pancake coil, the entire voltage of the coil, and the voltage of the disk-shaped pickup coil were measured in the tests. During the tests, a supercritical helium (SHe) was supplied to the MS pancake coil. The MS pancake coil was excited to 5 kA at a ramp rate of 20 A/s, and then was kept at 5 kA for 300 s. Then the coil was degaussed to 0 A at a ramp rate of 20 A/s. In this test, the temperature and the mass flow rate of SHe were 6 K and approximately 20 g/s, respectively.

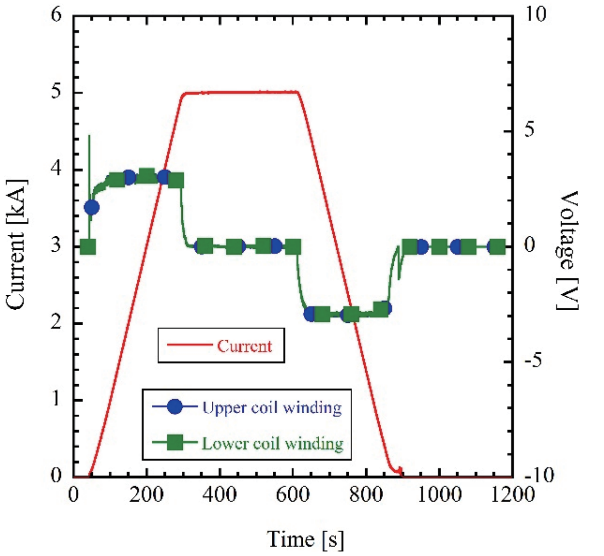


Fig. 4 The measured voltages of the upper and the lower coil windings at the energization test.

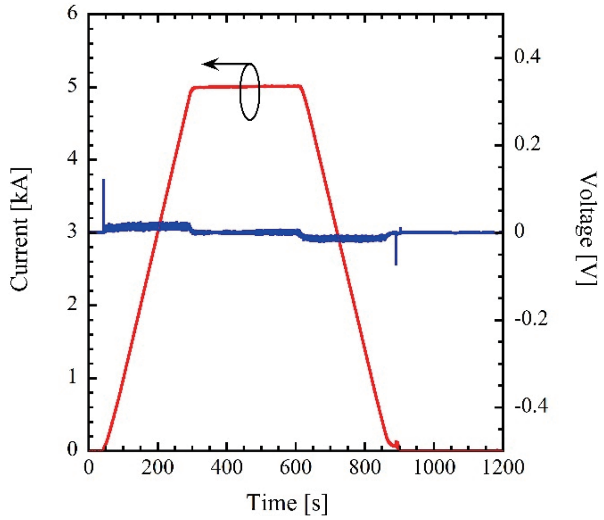


Fig. 5 The balanced voltage signal derived from the voltages of the upper and the lower coil windings.

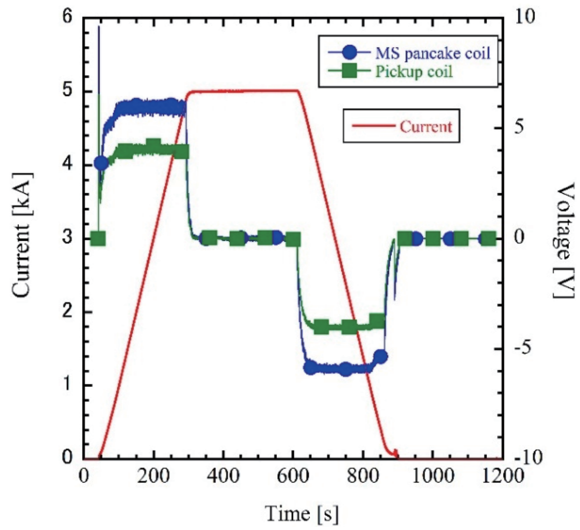


Fig. 6 The voltages of the MS pancake coil and the disk-shaped pickup coil at the energization test.

# 5. Measurement Results and Discussion

## 5.1 Quench detection using two coil windings

Figure 4 shows the voltages of the upper and the lower coil windings in the MS pancake coil in the energization test of the MS pancake coil. The voltages of the coil windings occurred during the coil excitation and degauss. Spike voltages were observed in both coil windings at the start of the exaction and the end of the degauss. The balanced voltage derived from the voltages of the coil windings is shown in Fig. 5. Compared with the voltage of each coil winding in Fig. 4, the balanced voltage is slightly influenced by coil excitation and degauss. The spikes were observed in the balanced voltage as well. In the case that quench occurs locally in the MS pancake coil, the balanced voltage can be detected between the two coil windings.

## 5.2 Quench detection using a disk-shaped pickup coil

Figure 6 shows the entire voltage of the MS pancake coil and the voltage of the disk-shaped pickup coil. The entire voltage and the pickup coil voltage occurred during the excitation and the degauss. The entire voltage was about one-and-a-half times as large as the pickup coil voltage because of the difference of inductance. At the start of the exaction and the end of the degauss, spikes occurred in both voltages, similar to the voltages of the coil winding. In terms of quench detection, the voltages induced at the coil excitation and degauss, which is shown in Fig. 6, must be eliminated. Therefore, the balanced voltage was obtained by compensating the entire voltage of the MS pancake coil with the pickup coil voltage multiplied by the coefficient 1.47. As shown in Fig. 7, the induced voltage can be almost eliminated. However, the spike and noise voltages remain in the balanced voltage. The configuration of the pickup coil is considered a cause of these voltages. Unlike a co-wound pickup coil, the disk-shaped pickup coil is some distance from the coil winding [8] and the inductance of the disk-shaped pickup is not consistent with that of the coil winding. Hence, it would be difficult to detect completely voltages induced by magnetization in the coil winding and by a ripple in the coil current.

The spike voltage cannot be eliminated by using the disk-shaped pickup coil inserted in the MS pancake coil, similar to the balanced voltage between the upper and the lower coil windings. Therefore, the spike voltage should be considered in determining criteria for quench detection of the MS pancake coil. Otherwise the system of quench

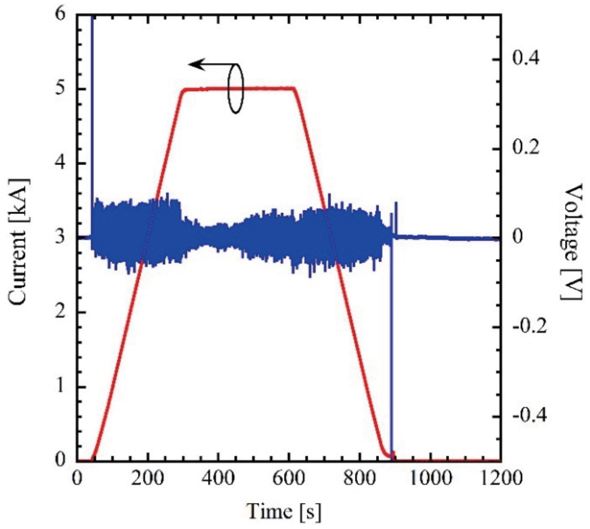


Fig. 7 The balanced voltage signal derived from the voltages of the MS pancake coil and the disk-shaped pickup coil.

detection will malfunction at the coil excitation and degauss. Regarding the duration of the spike voltage over 0.1 V, the duration in the two coil windings was 0.05 sec at the coil excitation. And the duration in the MS pancake coil with the pickup coil was 0.1 sec at the coil excitation and 0.05 sec at the coil degauss. As a result, the criterion of quench in this test is appropriate for the quench detection using the two coil windings. In the case of the quench detection using the pickup coil, on the other hand, the criterion of the quench must be tighter.

### 5.3 Comparison between two quench detections

The two quench detection methods mentioned above were compared in order to evaluate the reliability of quench detection for the MS pancake coil. Comparing the balanced voltages for the quench detection shown in Figs. 5 and 7, voltage noises differ substantially between the voltage measurements during the coil energization. The DC power supply used in the energization test seems to relate to the voltage noise. The noise in the balanced voltage between the upper and the lower coil windings is much smaller than that in the balanced voltage using the disk-shaped pickup coil. Consequently, in the case of the MS pancake coil, the balanced voltage between the coil windings can realize reliable quench detection with high accuracy, compared with the quench detection using the disk-shaped pickup coil.

## 6. Conclusion

The quench detection based on voltage measurements has been investigated for the MS pancake coil wound with $Nb_3Sn$ CIC conductors. In this study, as the quench detection, the balanced voltages were derived from the measurements in the DC energization test of the MS pancake coil. The noise in the balanced voltage between two coil windings is much smaller than that in the balanced voltage between a coil winding and a disk-shaped pickup coil. The result indicates that the quench detection based on the balanced voltage between two coil windings is more reliable than that based on the voltage using a disk-shaped pickup coil in the case of the MS pancake coil.

At the coil energization and degauss, spike voltages occurred due to magnetization of the MS pancake coil. The spikes are not compensated by the voltages of two coil windings, nor by the voltages of the coil winding and the disk-shaped pickup coil. Hence, the spikes should be considered in determining criteria for quench detection.

## Acknowledgments

The authors would like to thank the JT-60SA CS module test team of NIFS and QST for their technical support. This work was supported by JSPS KAKENHI Grant Number JP15K05974.

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