Acoustic MEMS Sensor Array for Quench Detection of CICC Superconducting Cables

Makoto Takayasu

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA  02139

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Abstract—A novel quench detection method using micro-electro-mechanical system (MEMS) sensor technology has been investigated in use for high temperature superconducting (HTS) conductors such REBCO tape cables. The sensor array along a superconducting cable, such as a cable-in-conduit-conductor (CICC), is installed in a cooling channel. It will allow sensitive and quick detection for a local quench of a superconducting cable. This work has confirmed that a quench of a single REBCO tape can be detected in liquid nitrogen by a MEMS piezoelectric microphone sensor. The quench detection design utilizing a MEMS sensor array method is discussed for the case of a toroidal field (TF) magnets of a fusion Tokamak device.

Index Terms—Quench detection, MEMS sensor, acoustic sensor, MEMS microphone, MEMS speaker, superconducting magnet, cable-in-conduit-conductor (CICC), superconducting power cable, HTS, REBCO.

I. INTRODUCTION

HTS (High Temperature Superconductor) tapes such as REBCO (Rare Earth Barium Copper Oxide) are very attractive for various industrial applications of magnets and power-cables, especially for high field, high current superconducting magnets. An implementation of a sensitive quench detection for HTS devices is urgently needed for safe operation, since normal zone propagations of an HTS conductor are very slow, and the quench zone is confined to a very small area [1]-[5]. Therefore, the quench detection of a conventional electric voltage method which has been used for NbTi and Nb3Sn devices is difficult in application using HTS.

Recently we have been proposing a unique quench detection method using very small MEMS (Micro-Electro-Mechanical System) sensors distributed in a cooling channel along a superconducting conductor [6]. For example, a linear array of MEMS microphone chips could be installed along the coolant space of a CICC (Cable In-Conduit Conductor) superconducting cable to detect a quench and abnormal behavior by monitoring the coolant condition. The sensor array allows for a fast and sensitive quench detection.

In this paper, the characteristics of MEMS acoustic sensors of a microphone and a speaker will be experimentally examined for a quench detection in a cryogenic condition, and the quench detection characteristic of a single REBCO tape will be demonstrated using a MEMS microphone sensor. Additionally, a quench detection system using the MEMS sensor array method will be discussed for toroidal field (TF) magnets of a Fusion Tokamak.

II. QUENCH DETECTION TECHNIQUE

Various quench detection methods have been developed. The quench detection methods are classified into three categories: (a) Line sensing, (b) Scanning and (c) Point sensing. Their detection characteristics are shown in Fig. 1.

(1) Voltage detection (Line sensing): Voltage tap method is widely used for low-temperature superconductor applications [7], however, may not provide enough sensitivity for HTS application where the quench propagation zone is short [1]-[5].

(2) Optical fiber temperature detection (Scanning): Detect temperature rise of a superconducting cable by scanning reflection light through an optical fiber along a cable. Recently this method has been successfully demonstrated for REBCO tape quench detections [8]-[10].


(4) Hydraulic pressure and flow detections (Point sensing): Coolant pressure and mass-flow rise detection at an inlet and an outlet of a CICC [7], [12].

(5) Acoustic emission (AE) detection (Point sensing): Detect acoustic signals generated by cracking, delamination and rapid temperature changes due to a quench [13]-[17].

Fig. 1 A view of quench detection methods of superconducting magnets.
(6) Magnetic flux change detection (Point sensing): Antenna electric coil detects flux changes due to a quench [18]-[20].

The quench detection method discussed in this work, using an array of small MEMS chips in a cooling channel is a new method within the point sensing technology. The sensors in a coolant channel detects acoustic sound pressure wave generated by a quench. In this method, an acoustic wave propagates in a fluid media of liquid or gas, although acoustic signal propagates in a solid for the existing conventional quench detection techniques of Acoustic Emission (AE) type [13]-[17].

The speed of sound of an acoustic wave in a fluid is much slower than that in a solid. Therefore, a linear sensor array of many MEMS sensors is installed in a cooling channel of a superconductor device to shorten the distance between a sensor and a possible quench point. The MEMS sensor array method provides a fast and sensitive quench detection.

When a quench occurs, the superconductor generates heat in a coolant. It vaporizes the liquid coolant or expands the coolant gas where the superconductor is immersed. Those temperature and hydraulic condition changes of the coolant generate an acoustic pressure wave in the coolant which can be detected by the MEMS sensors.

The MEMS sensors are small enough to be installed in a cooling channel, and they are arranged to form an array along the cooling channel. The acoustic sensors are wired and externally connected to electrical devices such as a voltmeter to detect the sensor output signal. A sensor array allows identifying the location of temperature changes in a superconducting cable with the minimum number of electric wires [6]. The sensors are widely distributed in the coolant channel so that it is possible to sensitively detect the location of a quench even if small.

Fig. 2 shows a schematic drawing of MEMS sensor arrays in a CICC conductor. The sensor arrays are inserted in a cooling channel from both ends of a conductor such a power transmission cable and a magnet conductor.

![Fig. 2](image_url)

**Superconducting Conductor**

<table>
<thead>
<tr>
<th>Coolant inlet</th>
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<th>Coolant outlet</th>
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<td>Sensor array #1</td>
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Fig. 2. A schematic drawing of a linear array of MEMS acoustic sensors in a CICC cable. Sensor array is inserted from both ends of a cable.

Any kinds of sensors can be used for this quench detection method. It is not limited to acoustic sensors, and does not need to have a linear output response to the quench. The sensors should be robust and reliable to high-pressure and vacuum environments for a long operation in liquid and gas coolants. The sensors must be small in size, low power consumption, low cost, and non-magnetic. We have tested acoustic MEMS sensors of a microphone and a speaker shown in Fig. 3.

III. EXPERIMENTAL

To investigate a concept of the proposed quench detection technique, commercially available MEMS microphone chips of piezoelectric type acoustic transducers were used. Fig. 3 shows the used sensors of Vesper Microphone (VM1000\textsuperscript{®}) and U-Sound Speaker (UT-P2016\textsuperscript{®}). Those sensors are generally used at room temperature in air. For the superconductor applications, they were tested in liquid nitrogen with a pulsed injection flow of helium gas at 77 K. Experimental tests have been carried out in the same way as described in our previous paper [6].

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(a) MEMS Microphone Vesper VM1000\textsuperscript{®} (3.76 mm x 2.95 mm x 1.1 mm), (b) MEMS Speaker U-Sound UT-P2016\textsuperscript{®} (6.7 mm x 4.7 mm x 1.56 mm).

A. MEMS Acoustic Sensor Operation Test

The simulation of a quench was performed with the injection of a gas bubble (77 K helium gas) of 0.1 MPa (1 atm). The MEMS piezoelectric sensors were used to detect the signal of the pressure wave generated. The pressure is much higher than the expected pressure for the commercial sensors. At the high pressure, the sensor (VM1000\textsuperscript{®} at 77 K) signal output voltages were about ~4 times those of low pressure (~14 kPa) responses. The output voltages of the sensor were not proportional to the pulse pressure amplitudes. After the high-pressure pulse test, the sensor was tested with a low-pressure pulse of 14 kPa (2 psi). It was confirmed that operating the sensor at 0.1 MPa did not damage it.

MEMS speaker of UT-P2016\textsuperscript{®} seems to be less sensitive than the VM1000\textsuperscript{®} for an acoustic response, but it is much more robust than a MEMS microphone. The tested U-Sound Speaker (UT-P2016\textsuperscript{®}) did barely respond to a 14 kPa pulse, but showed a good response to 0.1 MPa at room temperature.

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A quench test of a single REBCO tape was carried out using a MEMS piezoelectric sensor of Vesper VM1000\textsuperscript{®} in a stagnant liquid of nitrogen. The sensor and a pair of a current leads were mounted on a thin G10 plate with a 4 mm width, 150 mm long REBCO tape (SuperPower, the critical current 113 A at 77 K) as seen in Fig. 4. The DC applied voltage for the VM1000\textsuperscript{®} sensor was \(V_{\text{dd}} = 2.0\) V. The test results are shown in Fig. 5. The voltages of the REBCO tape (in red) and the MEMS sensor signal (in blue) are shown in Fig. 5(a) as a function of the current. The voltages were recorded while increasing the current of the REBCO tape until quench. When the REBCO Tape voltage measured over a 50 mm length reached 400 µV during the transition to a normal state, the first large voltage spike of the MEMS acoustic sensor was observed, followed by a few more spike voltages as seen in Fig.
5(a). The sample voltage of 400 µV for the 50 mm voltage-tap corresponds to 8 times of the upper criterion of \(E_{c2}=10 \mu V/cm\). The MEMS acoustic sensor could sensitively detect the superconducting-to-resistive transition of the REBCO tape.

Besides the heat of the REBCO tape, there was an additional heat generated by the copper current lead. Fig. 5(b) shows a semi-logarithmic graph of the heats of both the copper lead and the REBCO tape while the current was increased. In this figure the sample and the MEMS signal voltages from Fig. 5(a) are also shown. The heat of the copper lead was evaluated from its measured resistance. The first MEMS spike voltage occurred at 134 A. Until the REBCO tape quenched at ~138 A, the copper lead heat was more substantial, but the sharp rise of the heat due to the REBCO tape triggered the MEMS sensor. The copper resistive heat increased very slowly, and the MEMS acoustic sensor did not generate an output signal as the sensor did not respond to a DC or slow ramp phenomenon [6].

![Fig. 4](image1.png)

**Fig. 4.** A single REBCO tape quench test setup. A MEMS sensor and a REBCO tape on a test holder.

![Fig. 5](image2.png)

**Fig. 5.** (a) Test results of the voltages of the REBCO tape (in red) and the MEMS sensor signal (in blue) as a function of the current. MEMS Sensor: Vesper VM1000. REBCO Tape: SuperPower 4 mm width (\(I_c=113\) A). (b) A Semi-log plot of the dissipated powers of the REBCO tape and the copper lead, the voltages of the REBCO tape and the MEMS signal as a function of the current.

IV. DISCUSSION

A. Single Tape Quench Detection

The transition from the superconducting to normal state for the REBCO single tape was detected with a voltage that is 8 times the upper criterion of 10 µV/cm at 134 A (Fig. 5). In the test, heat power was generated by the REBCO tape and the copper lead. The latter heat increased very slowly, while the heat of the REBCO tape sharply increased much faster and more dominantly than that of the copper lead during the quenching process, as seen in Fig. 5(b). The MEMS microphone detected the quenching phenomenon of the REBCO single tape.

The quench experiment was performed in a stagnant fluid of liquid nitrogen without any flow noises. In the real operation condition of a quench detection for a magnet, the flow noise would be a concern. The quench detection for a cable carrying a much higher current (~10 kA) will be possible even under a flow-noise environment since the heat dissipation of the high current cable is much large. However, further investigations are necessary.

B. Quench Detection Delay Time

In solids, sound waves propagate with both transverse shear waves and longitudinal compression waves, and the speed in solids is a few thousand meters per sec, which is much faster than that in fluids. Fluids do not transmit shear stresses. Therefore, a quench signal in coolant fluids of liquid and gas in our quench detection method propagates only with compression waves. The speed of sound, \(v\) in fluids is well known to be given by

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v = \left[\left(\frac{c_p}{c_v}\right) \left(\frac{p}{\rho}\right)\right]^{1/2}
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where \(c_p\) is the specific heat capacity for constant pressure, \(c_v\) is the specific heat capacity for constant volume, \(p\) is the pressure, and \(\rho\) is the density.

Fig. 6 shows the speed of sound in helium [21]. As seen in this figure, the speed of sound varies significantly with temperature but is less affected by pressure changes, since in (1) the density \(\rho\) is proportional to the pressure \(p\), and the ratio \(c_p/c_v\) is relatively constant over the pressure range in the superconductor applications.

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**Fig. 6.** The speed of sound in helium gas: (a) Gas at various temperatures and liquid helium at Temperature \(T=4.2\) K at the pressure \(P=1\) atm. (b) Gas at various pressures at Temperature \(T=100\) K.

The speeds of sound of other coolants are, for example, liquid hydrogen: 1199 m/s at 20 K, and liquid nitrogen: 880 m/s at 77 K, 940 m/s at 71 K and 1005 m/s at 65 K [22].
To evaluate the quench detection delay time of the MEMS sensor array method, let us assume, for simplicity, the speed of sound to be 1000 m/s. If the separation distance of the sensors is \( L_x = 2 \) m in Fig. 7(a), the acoustic signal can be detected in less than about 1 ms (= 2 m/2/1000 m/s). If we distribute more sensors along a superconducting cable in the cooling channel, the delay time can additionally be shortened, and the MEMS sensor array method can improve the quench detection sensitivity and spatial resolution.

Fig. 7(b) illustrates a sub-group of the MEMS sensors separated by a distance \( L_a \). The sub-group is spread over a distance \( L_x \). If the sensor separation length of the sub-group is \( L_a = 20 \) cm, the delay time can be reduced to 0.1 ms. The speed of sound will be typically slower than 1000 m/s, as seen in Fig. 6. If the speed is 250 m/s, the delay time could be 4 times bigger than the one at 1000 m/s.

When the number of the sensors increases, the number of signal detection wires to identify the active sensor for a quench also increase. For a number of sensors of \( 2^n - 1 \), \( n \) wires can be utilized using a binary code analogy [6]. For example, 63 sensors can be uniquely identified with 6 wires (\( n = 6 \) for 63 sensors).

The sensors in the sub-group can be wired in parallel to reduce the instrumentation wires, as discussed in [6]. It can be made as a unit element, and one signal conditioner such as an amplifier can be installed for the sensors in the unit element, as shown in Fig. 7(c). A series connection of the units will make a long-length sensor array.

**C. Conceptual Design for Fusion Magnets**

If each TF coil is 1 km in length and has 5 double pancakes and the length of one double pancake is 200 m, one sensor array length of 100 m will be used and be mounted from each end of a double pancake. The 100 m long sensor array will have 50 MEMS sensors if the sensor major separation \( L_x = 2 \) m. In this case 6 signal wires \( 2^n - 1 = 63 > 50 \) are required in order to identify an active sensor among 50. For one TF magnet of 5 double pancakes, 500 sensors will be needed. For the TF magnets of 18 coils shown in Fig. 8, we need 9,000 MEMS sensors for the sensor major separation \( L_x = 2 \) m. If we install more sensors with the sub-group with \( L_a = 20 \) cm to improve the quench detection speed 10 times as shown in Fig. 7(b), 90,000 sensors will be used for one fusion TF reactor. However the amplifiers can be 9,000 if one is installed in each sub-group unit as seen in Fig. 7(c). The cost associated with developing a new MEMS sensor is high, but the investment will be recuperated quickly if 90,000 sensors are needed. Current MEMS sensor are less than one dollar each for 1000.

**V. CONCLUSION**

A MEMS sensor array in the cooling space of a superconducting cable will provide a unique quench detection method. It will allow sensitive and quick detection for a local quench of a superconducting cable. In this work we demonstrated that even the quench of a single REBCO tape can be detected in liquid nitrogen by a MEMS piezoelectric microphone sensor.

The ultimate goal of this work was to evaluate the proposed MEMS sensor array for a quench detection using existing sensor MEMS chips in a cryogenic environment and to provide necessary information for the development of optimized MEMS sensors for a quench detection of superconducting cables and magnets, especially for a REBCO CICC magnet.

The sensor for this application should be small, low energy consumption, low cost and non-magnetic. Furthermore, the sensors will be operated in liquid and/or gas environments, and it might be exposed to vacuum during preparation before introducing a coolant. Consequently, the MEMS sensors for the quench detection of a superconductor have very different operational requirements from conventional commercial sensors such as microphone and speaker acoustic sensors. Further development of MEMS sensors is required to obtain appropriate sensitivity and optimized frequency range for the superconducting applications.
REFERENCES


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Fig. 1 A view of quench detection methods of superconducting magnets.

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M. Takayasu is with the MIT Plasma Science and Fusion Center, Cambridge, MA 02139, U.S.A. (e-mail: takayasu@psfc.mit.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.
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![Fig. 2](image)

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The sensors in the sub-group can be wired in parallel to reduce the instrumentation wires, as discussed in [6]. It can be made as a unit element, and one signal conditioner such as an amplifier can be installed for the sensors in the unit element, as shown in Fig. 7(c). A series connection of the units will make a long-length sensor array.

C. Conceptual Design for Fusion Magnets

If each TF coil is 1 km in length and has 5 double pancakes and the length of one double pancake is 200 m, one sensor array length of 100 m will be used and be mounted from each end of a double pancake. The 100 m long sensor array will have 50 MEMS sensors if the sensor major separation $L_x = 2$ m. In this case 6 signal wires ($2^6 - 1 = 63 > 50$) are required in order to identify an active sensor among 50. For one TF magnet of 5 double pancakes, 500 sensors will be needed. For the TF magnets of 18 coils shown in Fig. 8, we need 9,000 MEMS sensors for the sensor major separation $L_x = 2$ m. If we install more sensors with the sub-group with $L_a = 20$ cm to improve the quench detection speed 10 times as shown in Fig. 7(b), 90,000 sensors will be used for one fusion TF reactor. However the amplifiers can be 9,000 if one is installed in each sub-group unit as seen in Fig. 7(c). The cost associated with developing a new MEMS sensor is high, but the investment will be recuperated quickly if 90,000 sensors are needed. Current MEMS sensor are less than one dollar each for 1000.

V. CONCLUSION

A MEMS sensor array in the cooling space of a superconducting cable will provide a unique quench detection method. It will allow sensitive and quick detection for a local quench of a superconducting cable. In this work we demonstrated that even the quench of a single REBCO tape can be detected in liquid nitrogen by a MEMS piezoelectric microphone sensor.

The ultimate goal of this work was to evaluate the proposed MEMS sensor array for a quench detection using existing sensor MEMS chips in a cryogenic environment and to provide necessary information for the development of optimized MEMS sensors for a quench detection of superconducting cables and magnets, especially for a REBCO CICC magnet.

The sensor for this application should be small, low energy consumption, low cost and non-magnetic. Furthermore, the sensors will be operated in liquid and/or gas environments, and it might be exposed to vacuum during preparation before introducing a coolant. Consequently, the MEMS sensors for the quench detection of a superconductor have very different operational requirements from conventional commercial sensors such as microphone and speaker acoustic sensors. Further development of MEMS sensors is required to obtain appropriate sensitivity and optimized frequency range for the superconducting applications.
REFERENCES


