Highly Time-Resolved Measurement of Quench Inception and Propagation in ac Superconducting Wires

N.Hayakawa, *Member, IEEE*, F.Iwahana, S.Chigusa and H.Okubo, *Member, IEEE*

Department of Electrical Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, JAPAN

***Abstract*—In this paper, highly time-resolved and highly sensitive measurements of quench phenomena in ac superconducting wires enabled us to investigate the propagation characteristics of normal zone at the quench inception. Experimental results revealed that the transient propagation velocity of normal zone reached 90km/sec at 6μsec after the quench-onset of the non-insulated NbTi/CuNi superconducting wires. Furthermore, there could exist an intrinsic length of about 100μm at quench inception and propagation under the criterion of 3.3μV/cm for ac superconducting wires.**

***Index terms*—quench inception, normal zone propagation**

I. INTRODUCTION

Quench phenomena are peculiar to superconducting wires and may affect thermal and dielectric performances of superconducting power apparatus [1][2]. Quench characteristics of superconducting wires play an important role not only to protect the apparatus such as superconducting magnets and transmission cables, but also to exhibit the function of superconducting fault current limiters (FCL) and persistent current switches (PCS). Especially, for the development and reliable operation of FCL and PCS utilizing quench phenomena, quench inception and propagation characteristics in ac superconducting wires with CuNi matrix should be understood. Many studies have so far discussed on the propagation velocity of normal zone in ac superconducting wires [3][4]. However, it is necessary to investigate in more detail the propagation characteristics of normal zone at the quench inception.

We have been investigating the quench characteristics of ac superconducting wires and coils [5][6]. This paper aims at investigating the propagation characteristics of normal zone at the quench inception of NbTi/CuNi composite superconducting wires through highly time-resolved and highly sensitive measurements.

II. EXPERIMENTAL

TABLE I Specifications of ac superconducting wires

Sample		#1	#2	#3
Cu/CuNi/NbTi		0/1.8/1	0/4.0/1	0.6/2.3/1
NbTi filament	Diameter	0.75μm	0.065μm	0.135μm
	Number	23,749	1,051,896	1,269,400
Strand	Diameter	0.19mm	0.25mm	0.30mm
	Twist pitch	1.8mm	1.9mm	2.2mm
	Insulation	No	Yes	Yes
	Critical current	55A at 1T	93A at 0.5T	106A at 0.5T 62A at 1T
Cable	Diameter	0.58 mm	0.90mm	0.99 mm
	Strand number	6	6	6
	Strand pitch	5.8mm	8.0mm	13mm
	Length	3m	3m	3m
	Normal resistance at 77K	2.53Ω	1.97Ω	0.134Ω

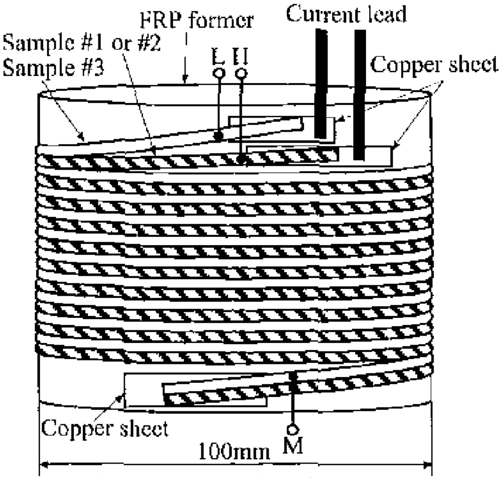


Fig.1 Configuration of test coil

TABLE I summarizes the specifications of ac superconducting wires used in the experiments. Samples #1 and #2 are 6-stranded, NbTi/CuNi composite cables to be discussed. Sample #3 is a reference wire with much larger ac quench current level than those of #1 and #2, which will be described in the next section. Fig.1 shows the configuration of test coil to be immersed in liquid helium. The samples #1 and #3 (or #2 and #3) with each length of 3m were bifilarly wound and partially impregnated with epoxy resin around the FRP former with the diameter of 100mm. Voltage taps were arranged at both terminals H and L to current leads, and also at the intermediate terminal M for the measurement of quench inception and propagation in the test coil.

Fig.2 shows the experimental setup. Quench of the test coil was induced by a large ac current of 60Hz during 1cycle without heater and external magnetic field. The peak

Manuscript received September 27, 1999

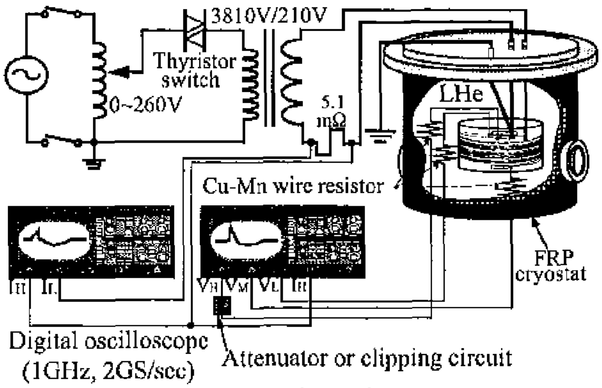


Fig.2 Experimental setup

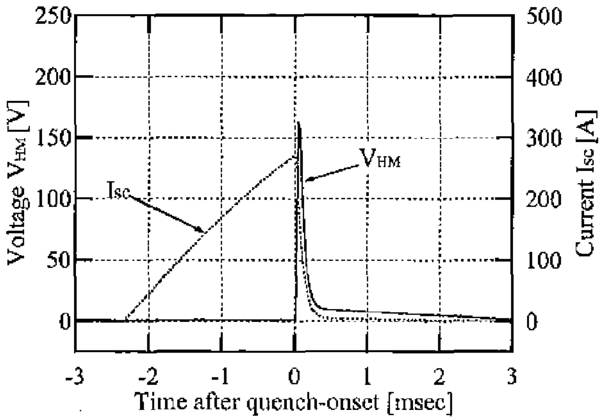


Fig.3 Waveforms of resistive voltage V_{HM} and current Isc (Sample #1, I_{PRO}=350A)

value of prospective current I_{PRO} was parametrically changed at 300A, 350A, 400A for the test coil composed of #1 and #3, and at 450A, 500A, 550A for the test coil composed of #2 and #3, respectively. The current Isc flowing in the test coil and the terminal voltages V_H, V_M, V_L were recorded with digital oscilloscopes (1GHz, 2GS/sec).

The impedance matching system was constructed for the highly time-resolved measurement. A Cu-Mn wire resistor of 50Ω was immersed in liquid helium together with the test coils and attached at each voltage tap for the impedance matching with the coaxial cables. The coaxial cables were also terminated with 50Ω at the digital oscilloscopes.

Quench would induce a large magnitude of terminal voltage due to normal resistance of the test coils after the quench-onset. Thus, an attenuator or a clipping circuit was arranged in front of the digital oscilloscopes. The attenuator was used to measure the fully developed terminal voltage signal for the evaluation of final propagation length of normal zone in the test coils. On the other hand, the clipping circuit enabled us to focus on the minute level of terminal voltage signal and improve the criterion of quench inception in ac superconducting wires.

I. RESULTS AND DISCUSSION

A. Statistical scattering in quench current

We derived the resistive voltage signal of sample #1 at the quench inception of the test coil composed of #1 and #3 in the following procedure: The prospective current I_{PRO} between quench currents of #1 and #3 caused the quench only in #1, while #3 remained in the superconducting state. Thus, we can write the following equations:

$$V_H - V_M = R_{HM} I_{sc} + (L_H - L_{HM})\frac{dI_{sc}}{dt} \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

$$V_M - V_L = (L_L - L_{HM})\frac{dI_{sc}}{dt} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where R_{HM} is the resistance of #1 in the normal state, L_H and L_L are the self inductance of #1 and #3, respectively, and L_{HM} is the mutual inductance between #1 and #3. The resistive voltage signal V_{HM} of sample #1 is calculated as

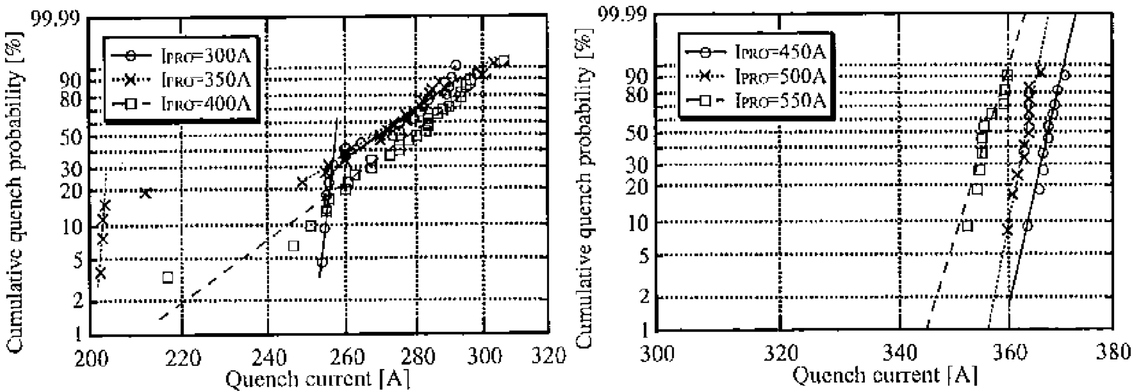
$$V_{HM} = R_{HM} I_{sc} = (V_H - V_M) - (V_M - V_L)\frac{L_H - L_{HM}}{L_L - L_{HM}} \cdots\cdots (3)$$

The values of $L_H - L_{HM}$ and $L_L - L_{HM}$ can be preliminarily obtained in Eqs. (1) and (2) from the current and voltage waveforms for the smaller I_{PRO} than quench current of #1, where R_{HM}=0.

Fig.3 shows thus derived typical waveforms of the resistive voltage signal V_{HM} for the sample #1 at I_{PRO}=350A. V_{HM} emerged together with the drastic reduction of Isc. The quench current of #1 was measured to be 270A as the instantaneous value at the appearance of V_{HM}. Fig.4(a) shows the statistical scattering in quench current of #1 for different I_{PRO}. The vertical axis designates the cumulative quench probability of Weibull distribution; a probability function based on the weakest link theory [5]. In the case of larger I_{PRO} such as 400A, the Weibull plots result in a regression line, which means that quench was induced by an intrinsic weak point with a high quench probability in #1. On the other hand, in the case of smaller I_{PRO} such as 300A and 350A, the Weibull plots result in two regression lines, respectively. This is understood by the interpretation that an another kind of weak point with lower quench probability would be occasionally activated. Fig.4(b) shows the Weibull plots for quench current of the sample #2. The scattering in quench current of #2 is found to be negligible and irrespective of I_{PRO}. This may be attributed to the existence of an intrinsic weak point with much higher quench probability in #2.

B. Propagation of normal zone at the quench inception

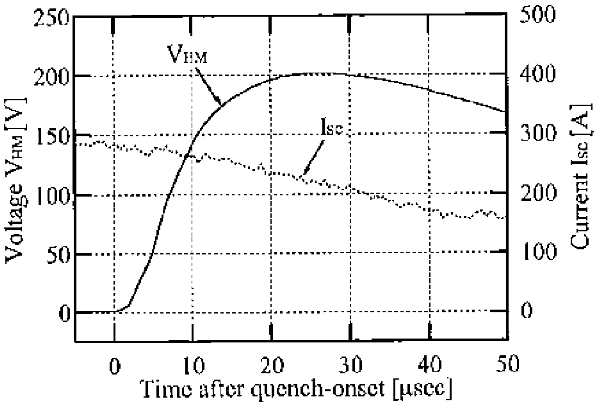
The waveforms of V_{HM} and Isc are shown in Fig.5(a) in the enlarged time scale with the impedance matching system and the attenuator for the sample #1 at I_{PRO}=350A. Fig.5(b) shows waveforms of the resistance R_{HM} derived as V_{HM}/Isc in Eq. (3) and the propagation velocity U_{HM} of



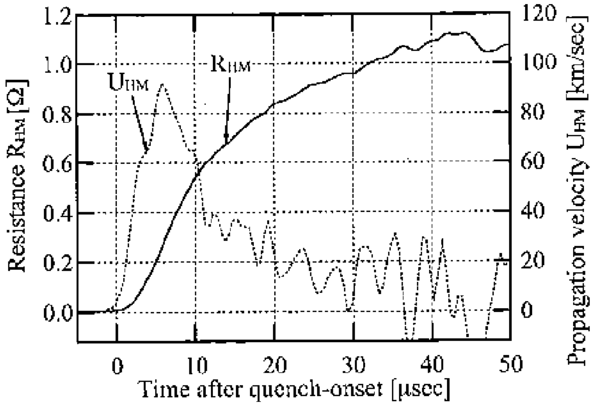
(a) Sample #1

(b) Sample #2

Fig.4 Statistical scattering in quench current (Weibull plots)

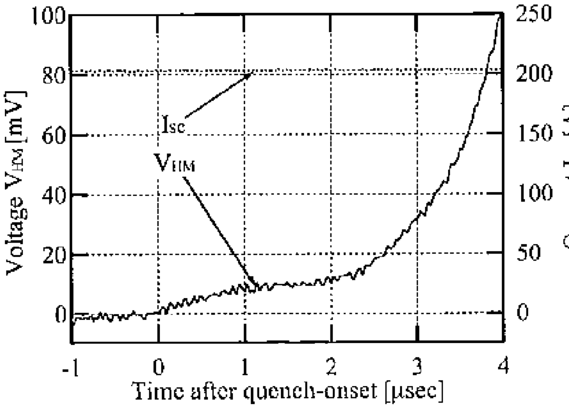


(a) V_{HM} and I_{SC}

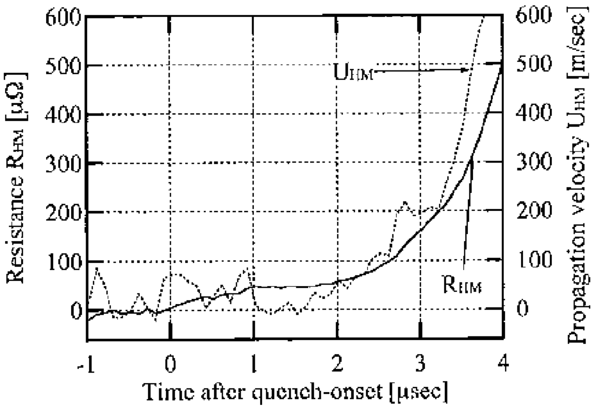


(b) R_{HM} and U_{HM}

Fig.5 Waveforms of V_{HM}, I_{SC}, R_{HM}, U_{HM} (Sample #1, I_{PRO}=350A, Quench-onset : V_{HM}=1.5V)



(a) Voltage V_{HM} and current I_{SC}

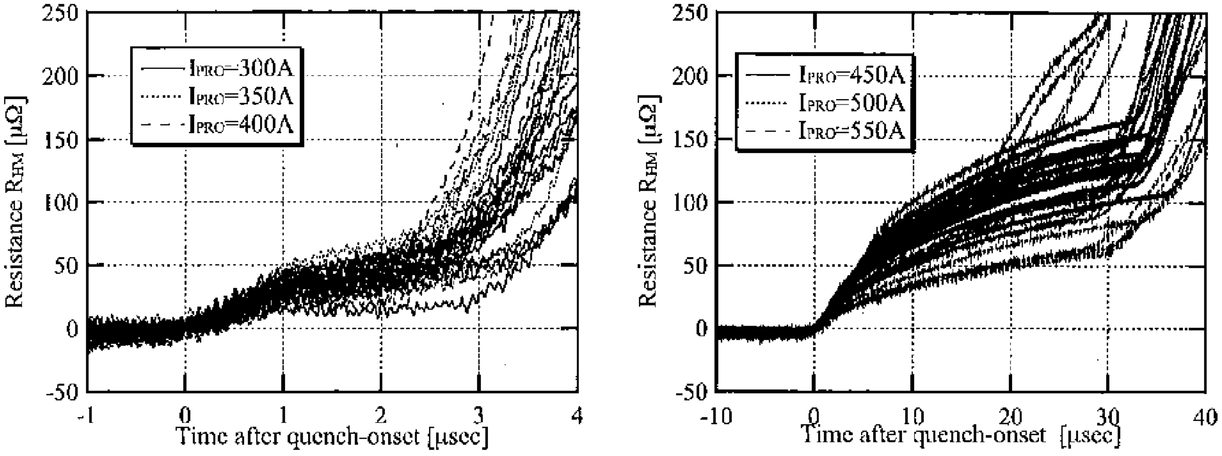


(b) Resistance R_{HM} and velocity U_{HM}

Fig.6 Waveforms of V_{HM}, I_{SC}, R_{HM} and U_{HM} (Sample #1, I_{PRO}=350A, Quench-onset : V_{HM}=1.0mV)

normal zone. U_{HM} is obtained by differentiating R_{HM}, since the resistivity of NbTi/CuNi composites in the samples #1and #2 is independent of temperature [3][4]. Note that in Fig.5 the time of quench-onset is defined as the instant when V_{HM} exceeded 1.5V; the detection sensitivity of V_{HM} in the voltage scale in Fig.5(a). Fig.5(b) reveals that R_{HM} is saturated at about 1.1Ω after the quench-onset, which corresponds to 43% of the normal resistance of #1 in TABLE I, i.e. the final propagation length of normal zone was 1.3m. Furthermore, the transient propagation velocity of normal zone reached 90km/sec at 6μsec after the quench-onset. Such an extremely high propagation velocity of normal zone has been reported as the fast quench for an insulated, stranded cable with CuNi matrix [7]. Thus, the normal zone could also propagate in the non-insulated cable of #1 as quickly as the fast quench.

Figs.6(a) and (b) show waveforms of V_{HM}, I_{SC}, R_{HM} and U_{HM} for #1 at I_{PRO}=350A through highly time-resolved and highly sensitive measurement with the clipping circuit. The detection sensitivity of V_{HM} is improved at



(a) Sample #1

(b) Sample #2

Fig.7 Waveforms of R_{HM} for different I_{PRO} (Quench-onset : V_{HM}=1.0mV)

1.0mV in the enlarged voltage scale in Fig.6(a). This sensitivity corresponds to the criterion of quench inception at 3.3µV/cm for ac superconducting wires. We found in Fig.6(b) that the increase in R_{HM}, i.e. the propagation of normal zone, was accelerated after a short propagation at the quench inception. We obtained R_{HM} of #1 repetitively at the same experimental condition and for different I_{PRO}. The waveforms of R_{HM} are superposed in Fig.7(a) and are reproducible for different I_{PRO}. Furthermore, the reproducibility of R_{HM} is confirmed even under statistical scattering in quench current as was shown in Fig.4(a). These results suggest the existence of a specific propagation length of normal zone at the quench inception. Supposing that R_{HM} would be proportional to the propagation length of normal zone even at the quench inception, the specific length for #1 can be evaluated as 25~85µm from the values of R_{HM} (20~70µΩ), where the propagation of normal zone was accelerated in Fig.7(a).

In the same way, Fig.7(b) shows waveforms of R_{HM} for the sample #2. Note that the time scale in Fig.7(b) is 10times longer than that in Fig.7(a). Fig.7(b) reveals that the specific length also exists for #2 and can be evaluated as 90~260µm (60~170µΩ). Consequently, the specific propagation length of normal zone in the samples #1 and #2 was found to be about 100µm and independent of I_{PRO}, quench current and sample specifications. Thus, the specific propagation length may be regarded as an intrinsic length at the quench inception and propagation in NbTi/CuNi composite wires.

I. CONCLUSIONS

We focused on the propagation characteristics of normal zone at the quench inception in NbTi/CuNi composite superconducting wires. Highly time-resolved and highly sensitive measurements brought about the following experimental results:

1. Quench current of test coils exhibited a statistical scattering on Weibull distribution. There could exist weak points with different quench probability.
2. Transient propagation velocity of normal zone could reach 90km/sec at 6µsec after the quench-onset in the non-insulated, stranded cable with CuNi matrix.
3. Criterion of quench inception was improved at 3.3µV/cm for ac superconducting wires.
4. Existence of an intrinsic length of about 100µm was suggested for the propagation of normal zone at the quench inception.

REFERENCES

[1] B.H.Oh, K.Ishikawa, N.Hayakawa, H.Okubo, Y.Kito, M.Yamamoto, "Temperature Rise in a Superconducting Transformer Winding Overheated by Quenching", *Advances in Superconductivity IV*, pp.1043-1046, 1992

[2] S.Chigusa, H.Maeda, Y.Taniguchi, N.Hayakawa, H.Okubo, "Insulation Performance of Pressurized Liquid Helium under Quench-induced Thermal Bubble Disturbance for Superconducting Power Apparatus", *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol.6, No.2, pp.385-395, 1999

[3] A.Ishiyama, Y.Sato, M.Tsuda, "Normal-Zone Propagation Velocity in Superconducting Wires Having a CuNi Matrix", *IEEE Trans. on Magnetics*, Vol.27, No.2, pp.2076-2079, 1991

[4] V.S.Vysotsky, V.N.Tsikhon, Yu.A.Ilyin, "Normal Zone Propagation Velocity In High Current NbTi/CuNi Superconductor With Fast Changing Current", *Cryogenics*, Vol.34, pp.517-520, 1994

[5] N.Hayakawa, M.Wakita, M.Hikita, H.Okubo, "Weibull statistical analysis of quench current of ac superconducting wires and coils", *Cryogenics*, Vol.37, No.2, pp.91-95, 1997

[6] N.Hayakawa, Y.Taniguchi, S.Chigusa, H.Okubo, "Highly Time-Resolved Observation of Local Disturbance in Liquid Helium Induced by Quench of Superconducting Wires", *Proc. of Int. Conf. on Magnet Technology*, pp.981-984, 1998

[7] H.H.J. ten Kate, S.L.Wipf, B. ten Haken, L.J.M. van de Klundert, "Development of a Superconducting Protection Switch for the HERA P-Ring. Design Study and Demonstration Models", *IEEE Trans. on Magnetics*, Vol.24, No.2, pp.1178-1181, 1988