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Characterization of In-field Critical Currents in REBCO Tapes over Wide Temperature Range by Pulsed Current Source with Supercapacitor

Y. Tsuchiya, K. Mizuno, Y. Kohama, A. Zampa, T. Okada, and S. Awaji

Abstract—The field and temperature dependence of the critical current I_c is a vital factor in designing the superconducting magnets. The standard method of measuring I_c involves applying a DC current and measuring voltage. However, when assessing the field dependence of I_c , the high magnetic field's space constraints and cooling power limit the injection of DC current into the sample. To address this, we have developed a method using pulsed current to significantly reduce heat generation. Our previous research reported an I_c measurement system capable of handling up to 19 T and variable temperatures with a pulse current up to 500 A. In this study, we have enhanced the system with electric double layer capacitors, known as supercapacitors, allowing currents up to 2 kA. This upgrade enables the measurement of I_c in the high-temperature superconducting REBCO tapes, which are 4 mm wide, at cryogenic temperatures as low as 4.2 K in magnetic fields or 20 K even under a self-field. We have verified the system's reliability by comparing measurements of DC and pulsed currents. Additionally, we contrasted the I_c values of full width samples with those of samples containing micro-bridges.

Index Terms—Critical current, High magnetic field, Pulsed current, REBCO coated conductor, Supercapacitor

I. INTRODUCTION

High temperature superconductors (HTS) have critical temperatures T_c above that of liquid nitrogen, and recent attention has been drawn to enhance their performance at low temperatures even under high magnetic field. The main materials in commercial use are $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ (BSCCO) or $\text{REBa}_2\text{Cu}_3\text{O}_y$ (RE: rare-earth elements, REBCO). At high field laboratory for superconducting materials (HFLSM), we are involved in the development of a cryogen-free superconducting magnet (CSM) without liquid He [1]–[3]. To date, we have developed and operated a 25 T cryogen-free superconducting magnet, employing the innermost coil with highly strengthened BSCCO tapes. Currently, a 33T-CSM is under development using the REBCO tapes for the innermost coil [4], [5]. The high intrinsic performance at low temperatures leads to the emergence of the numerous attractive applications such as compact nuclear fusion power plants using bundled REBCO conductors operated below 20 K [6], [7] compared with the international project ITER [8], or rotating machines for electric airplanes operating in liquid hydrogen or sub-cooled liquid nitrogen [9].

The critical current I_c of REBCO depends on temperature, angle and magnitude of magnetic field, strain, etc. In magnet

design, it is important to investigate such critical surface parameters. Due to the intrinsic properties of the material, I_c has a magnetic field angle dependence, and in most cases I_c is higher when the magnetic field is applied parallel to the plane. In the practical REBCO tapes, which is called as coated conductors, REBCO is biaxially oriented and thus inherits the material-specific properties. It is necessary to measure I_c for a wide region of the parameters to scale I_c in coated conductors [10]–[13]. The I_c is obtained from a nonlinear current-voltage characteristic. This is usually done by measuring it using a DC current. Measurement of the very high I_c in a constrained environment such as a high field magnet and variable temperature insert is difficult mainly limited by excessive losses throughout the system occurring over the current leads or at the termination at the sample location. Such measurement is available so far only at few sites [14]–[19]. To reduce heat generation, pulsed current is a suitable method. Several critical current measurements using pulsed current have been reported, especially in zero magnetic field [20], [21]. There is also a very state-of-the-art method that uses pulsed current to measure critical currents in pulsed magnetic fields above 60 T [22]. However, critical current measurements for commercial HTS tapes using pulsed high currents in high magnetic fields have not been developed. To measure the I_c of REBCO coated conductors, the issue is a very larger currents over 2 kA at 20 K and over 4 kA at 4.2 K are required [14]–[19].

In recent years, electric double layer capacitors, so called supercapacitors, with low internal resistance and high energy density have become inexpensive, and long-pulse high current generation has attracted attention. These advantages led to the development of technologies to generate long pulse high magnetic fields with metal coils [23], [24]. We have focused on pulsed current generation and I_c measurement using those supercapacitors.

In this study, we upgraded our pulse current generation system using supercapacitors, enhancing it to a current capacity from 500 A [25] to 2 kA, and investigated whether I_c can be measured using the pulse current. Furthermore, we compared the results for DC and pulsed currents to confirm the reliability of this system. We also compared I_c for the sample with micro-bridges or full width.

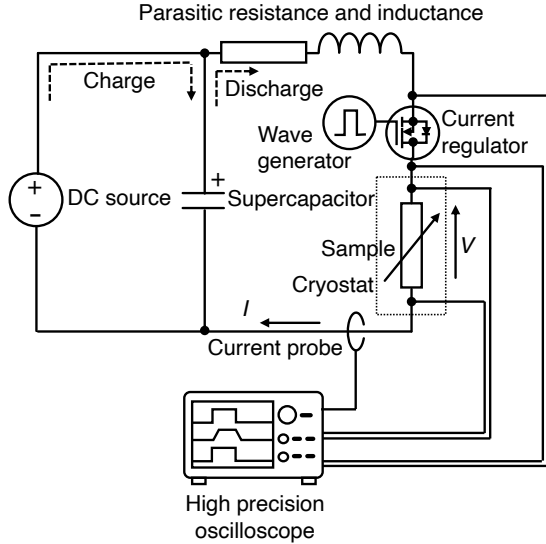


Fig. 1. Circuit diagram for the I_c measurements system with pulsed current measurement using the supercapacitor.

II. EXPERIMENTAL METHOD

A. Circuit for pulsed current measurement with supercapacitor

This section presents a probe and pulse power supply circuits are described. We manufactured a probe with low impedance with opposing copper bars. The structure of the probe was previously described elsewhere [25]. The probe had a built-in thermometer and heater for temperature control. When installing the REBCO tape, the tapes were electrically connected by the easy clamping. The voltage signal lead was changed from the twisted pair cable to a semi-flexible coaxial cable, and a stainless-steel weight was attached to the end of the probe to suppress the vibration of the probe caused by Lorentz force when applying pulse current.

Fig. 1 shows the schematic circuit of the pulse current measurement system. In this circuit, the supercapacitor was charged from a DC voltage source, and a pulse current was discharged through the sample connected in series with the current regulator. The supercapacitor (LICAP Technologies, Inc.) has a capacitance of 500 F and 2 units are connected in parallel. The internal resistance and the regulated voltage of the supercapacitor was about 2 m Ω and 16 V, respectively. Its maximum peak current was 1.9 kA for 1 unit. DC voltage source with 16 V output was used to charge the supercapacitors, and the current flowing through the sample was controlled by a current regulator. The slew rate of current during increase or decrease was varied from 0.5 to 2 MA/s depending on the input waveform of the current regulator. The voltage over the sample, located inside the cryostat, and the voltage across the current regulator were measured with a high-precision oscilloscope (Yokogawa, DL950). The current flowing through the sample was measured using a current probe. The circuit has parasitic resistance and inductance in the μH and m Ω range. To estimate the parasitic parameters, current waveforms were generated without the probe and the sample. Since the DC power supply was a

switching power supply, there are spikes of switching noise in the range of 10 to 20 kHz, making μV measurements difficult. However, the supercapacitor and the 4 kHz filter in the high-precision oscilloscope effectively eliminates the spike noise, enabling precise measurements. Earlier [20], [21], the noise reduction has been discussed for pulsed power supplies using capacitors, by using disconnecting the DC power supply. We also found the reduction of noise by disconnecting the DC power supply after the supercapacitor was charged in our system. However, in this study, the DC power supply was still connected because the noise was sufficiently reduced by the low pass filter in the measurement system, and the pulse current was generated with the output of the DC source still on.

B. Cryogenics and high magnetic field environment

For a high magnetic field and low temperature environment, a He-gas flow cryostat (Janis Research) was inserted into the 20T cryogenic-free superconducting magnet. To fit the cryostat, the probe was designed with a diameter of 34 mm. In this system, measurements can be carried out from 4.2 K to 77 K, by the He-gas flow or the He-liquid immersion.

C. REBCO coated conductors

REBCO tapes were provided from Fujikura Ltd. in 2020. The width of the tape was 4 mm, and the stabilization layer was either Cu plated on top of the Ag layer or Ag only. The former one was a specially ordered REBCO tapes, the model number FESC-SCH04(40), with 40 μm -thick Cu on the both sides to realize the insert coil prototype of the future 33T-CSM [4], [26]. The latter was the same period lot as the former, prepared for comparison with chemical etching to create micro bridges. The REBCO tape contains artificial pinning centers which strongly enhances the flux pinning force and improves the critical current density under the magnetic fields [13], [27]. The in-field superconducting properties have been measured for the similar model number over a wide range of temperatures [12], [13], [18], [25]. In many previous studies, the critical current at temperatures other than 4.2 K and 77 K was estimated by fabricating micro-bridges from the tapes and then scaling the measurements to obtain the full-width critical current.

Microbridges were fabricated from the REBCO tapes by using pulsed laser or chemical etching. Bridge widths were

TABLE I
SPECIFICATION OF SAMPLES.

Name	FW	L500	L125	L63	C4
Manufacture	Fujikura				
Product No.	FESC-SCH04(40)				FESC-S04
Provided year	2020				
Stabilizer	2 μm Ag and 40 μm Cu on each side				2 μm Ag
Lot. No	20-0105-05				20-0128-01
I_c spec. (A/4 mm)	212-220				226-242
Width	4 mm	500 μm	125 μm	63 μm	4 μm
Process	As-received	Laser etching			Chemical etching
Measurement	Pulse	Pulse, DC		DC	

measured using a laser and an optical microscope. Bridge widths ranged from $4\ \mu\text{m}$ to $500\ \mu\text{m}$, and sample names were defined based on process and bridge width as shown in Table 1. For example, a sample with a laser-etched bridge width of $125\ \mu\text{m}$ is named as L125. The I_c of 4 mm wide FW sample was measured only with pulsed current due to its high I_c , while the I_{cs} of L500 and L125 were measured with both pulsed and DC current to verify the reliability of the pulsed current measurement.

III. RESULTS AND DISCUSSION

A. Generation of pulsed current up to 2 kA

Fig. 2 shows waveforms of currents with and without the probe and the wiring at various current slew rate. As shown in Fig. 2(a), the current waveforms without the probe showed an expected trapezoidal waveform with the slew rate of $1\ \text{MA/s}$. On the other hand, as shown in Fig. 2(b), the waveform changed from trapezoidal to exponential shape with the probe and at $2\ \text{MA/s}$. According to the inset figure, the voltage applied to the current regulator was close to zero during the current sweep. This indicates that the current regulator was functioning almost just as a switch and cannot control the current. In other words, it behaved as an LR circuit with parasitic resistance and inductance, indicating that the current increased exponentially. By fitting the exponential upturn for $2000\ \text{A}$ pulse, the time constant

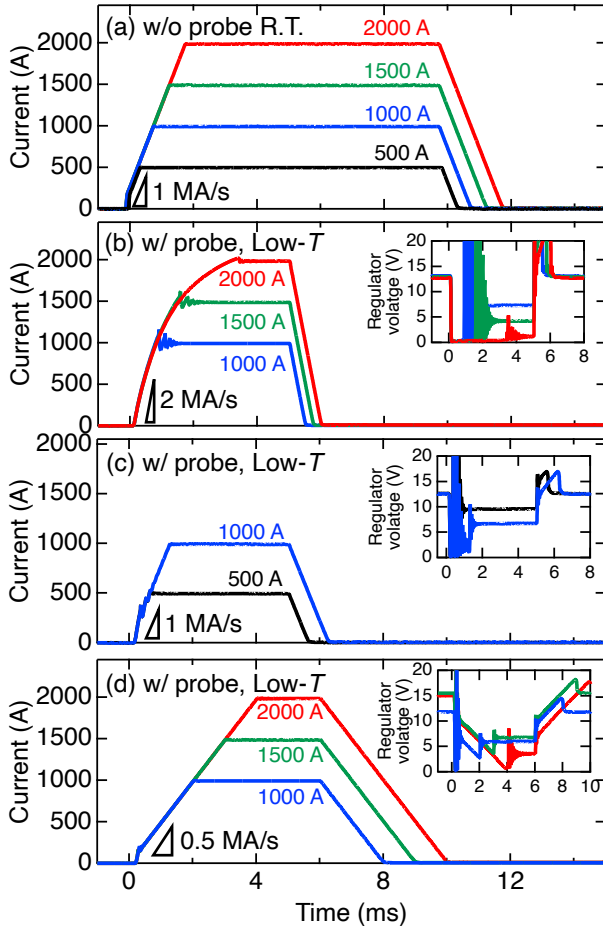


Fig. 2. Current waveforms during pulsed current (a) without probe at $1\ \text{MA/s}$, and with probe at (b) 2, (c) 1, (d) $0.5\ \text{MA/s}$. Inset shows the voltage waveforms on the current regulator.

and the asymptote is estimated as $1.16\ \text{ms}$ and $2110\ \text{A}$, respectively. Assuming the voltage was constant as the initial value of $13.0\ \text{V}$, the parasitic resistance and the inductance are estimated as $6.16\ \text{m}\Omega$ and $7.14\ \mu\text{H}$, respectively. The estimated resistance is reasonable because $20\ \text{m}$ long Cu wire with a cross-sectional area of $100\ \text{mm}^2$ has $3.7\ \text{m}\Omega$ at room temperature and the inner resistance of the supercapacitor is in a range of $1\text{--}2\ \text{m}\Omega$. The estimated inductance is also reasonable because the $20\ \text{m}$ -long twisted pair cable has an inductance of $5\ \mu\text{H}$. It is worth noting that the used cabling with cross sectional area of $100\ \text{mm}^2$ is too thin to carry $2\ \text{kA}$ DC current under standard conditions of natural convection cooling at room temperature. However, it is sufficient to apply pulsed current of $2\ \text{kA}$ and is very suitable for mobile measurements because of its easy handling in the user facility such as our site. In general, power leads with a current capacity of DC $2000\ \text{A}$ requires $500\ \text{mm}^2$ or more. As described above, it has been shown that pulsed current can significantly reduce cable weight and cost of the power cables.

When the probe was attached, no ringing appeared at a slew rate of $0.5\ \text{MA/s}$ as shown in Fig. 2(d). On the other hand, the current waveforms in Fig. 2(b) and (c) showed ringing with a period of $110\text{--}180\ \mu\text{s}$. Since the capacitance of the supercapacitor was $1000\ \text{F}$ and the inductance of the measurement system was about $7\ \mu\text{H}$, the frequency should be over $1\ \text{s}$, indicating that the ringing was not originated by the LC resonance but also feedback error in the current regulator.

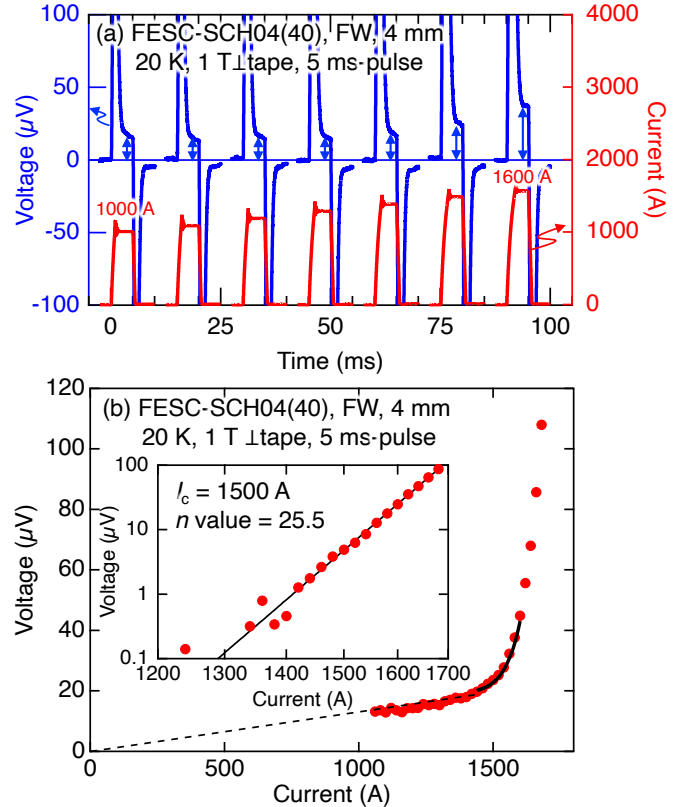


Fig. 3. (a) Waveforms of voltage and current from $1000\ \text{A}$ to $1600\ \text{A}$. (b) Current-voltage curve in the sample FW at $20\ \text{K}$, $1\ \text{T}$. Inset shows log-log plot of the curve after subtracting linear resistance.

B. Current-voltage curve in the REBCO tape obtained from pulsed measurement

Fig. 3(a) shows the current and voltage waveforms at 20 K and 1 T with the 5 ms pulse current from 1000 to 1600 A in 100 A increments. Since the current was increased at 1 MA/s, an overshoot occurred during increasing the current. The current was stabilized within 1 ms after reaching the desired constant current. The voltage showed a decay after the fixing the current. The time constant for voltage decay was estimated to be 0.31–0.38 ms, which is close to the 4 kHz frequency of the low-pass filter built in the precision oscilloscope and corresponds to 0.25 ms. The time constant of the voltage decay tended to reduce as the current increased. This is thought to be related to the process of the flux penetration into the sample due to the rearrangement of the vortex, rather than the attenuation of the voltage simply due to the low-pass filter. The higher the voltage, the faster the vortex rearrangement, which may decrease the decay constant. This is not the purpose of this study, and additional research is desired. For example, such voltage decay was discussed in Ref. [28]. A more detailed discussion is possible for the results at 4 K–20 K with higher n -values and I_c .

Fig. 3(b) shows the current-voltage characteristics obtained from the pulse current-voltage waveforms. First, a voltage appeared proportional to the current, and then it increased in a manner of the power-law above a certain current. To decompose this curve, the low-current region was fitted with a linear dependence. As a result, a resistance of about n Ω was observed. This resistance varied by about 10% depending on the magnetic field and temperature. This may be due to contact resistance, resistance of the stabilizing layer, etc. Inset shows the current-voltage characteristics after subtracting the linear component, and the fitting line is shown with I_c of 1500 A and n -value of 25.5. The measured data is well fitted by the power law. Similar current-voltage curves were measured up to 100 μ V at each temperature and magnetic field, and I_c was calculated for an electric field criterion of 10 μ V/cm. The voltage noise floor was about 0.8 μ V, i.e. 1.3 μ V/cm, which is small enough to determine I_c . Since the voltage was measured for one pulse current in this study, the noise could be reduced further by extending the pulse current duration or increasing the number of pulse measurement integrations. In the previous report [22], the noise was dramatically reduced by touching the probe on the wall of

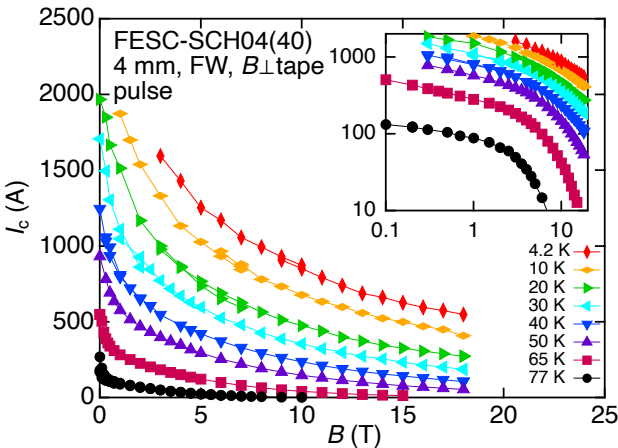


Fig. 4. Field dependences of I_c in the 4 mm-wide REBCO tape (FW) at various temperatures. Inset shows log-log plot.

the cryostat in advance. On the other hand, in this study, the above noise level was achieved without taking probe placement into account. This is thought to be due to the reduction in acceleration caused by the stainless-steel weights and the reduction in induced voltage noise from the probe vibration by changing the signal line to a coaxial cable.

C. Field and temperature dependences of the critical current in the REBCO tape

Fig. 4 shows the magnetic field dependence of I_c at various temperatures for a 4 mm wide REBCO tape with Cu stabilizing layer, FW. The measurements were performed with pulsed currents up to 2000 A. The results show a smooth decrease in I_c with respect to the magnetic field. Inset shows log-log plots of magnetic field dependence, and the change in slope between low and high magnetic fields shows a change from single vortex pinning to collective vortex pinning [15]. The samples measured in this study were fabricated in a similar way to those referred to as FAST in the literature [13], and therefore the microstructure of them is similar. This sample consists of intermittently scattered tilted nanorod-like artificial pinning centers. The origin of vortex pinning is not the subject of this paper. Therefore, we will not enter further into the discussion. The values of in-field I_c at low temperatures and high magnetic fields for the samples of the present study and Refs. [13], [18] matched by about 10%.

This result indicates that it is now possible to measure the field-temperature dependence of I_c not only in bridge samples but also in full-width samples, providing not only a critical surface for magnet design but also access to the discussion of flux pinning, which is necessary for material development of REBCO coated conductors to enhance I_c in magnetic fields. In the present study, I_c measurement at low self-field is possible even at 20 K by using a current of 2 kA. In future, it is expected that I_c measurement at 4.2 K will also be possible at all magnetic fields by using a power supply of 4 kA or higher.

D. Comparison of the measurement with pulsed and DC currents

Fig. 5 shows the current-voltage characteristics using DC and pulsed currents for the sample L500 with 500 μ m width. The temperature and fields were 15 to 19 T and 0 T at 10 K, 20 K,

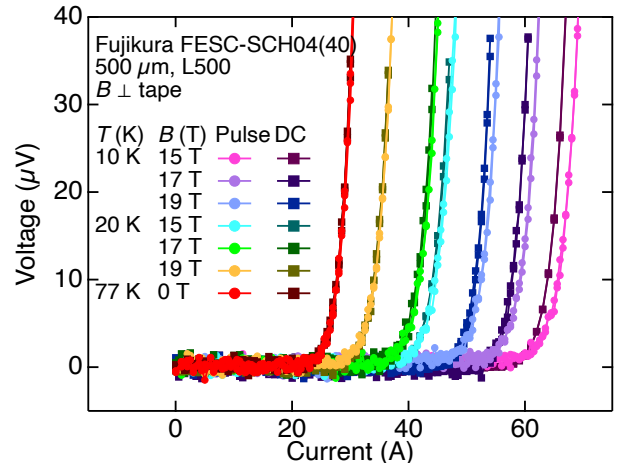


Fig. 5. Comparison of current-voltage curves at various conditions between pulse and DC current.

and 77 K, respectively. When DC current was applied to the probe, the temperature started to rise at 10 K and 20 K when a current around 50 A was applied. At 77 K, where the current is low enough, the difference between the DC and pulse measurement results was negligible. On the other hand, at 10 K and 15 T, where the difference is the largest among them, the I_c s obtained by power fitting also differed by 4 %. The voltage was always larger during the DC measurement, which is thought to be due to the increase of temperature in the sample during the measurement. On the other hand, in the pulsed current measurement, the voltage of the sample remained constant until a voltage was reached about 100 μ V, even at low temperatures, and no thermal runaway behavior was observed during the pulse current. Therefore, since the temperature of the sample was almost constant in the pulsed current measurement, it is considered that a lower voltage was measured than in the DC measurement at higher temperatures. This behavior was particularly pronounced as the current increased. From this result, it should be noted that pulse current measurement may provide very quantitative results in terms of temperature dependence, since pulse current measurement does not generate much heat and does not require consideration of temperature rise when high current is applied at cryogenic temperatures where cooling capacity is small and specific heat is low. On the other hand, the advantage of DC measurement is its low noise. In this measurement, although it cannot be read from the figure, voltage noise of about 0.1 μ V was observed for DC and about 0.8 μ V for pulse. Pulse current can reduce noise by increasing the number of pulse currents, but the DC measurement is performed at 1 PLC, or about 20 ms for each point, and the temporal noise density is considered better for the DC measurement. In this respect,

pulsed current measurements require stronger efforts to reduce voltage noise, including management of Lorentz forces. Another approach to quantitatively measure I_c without causing a temperature rise is to active control of the heater output while the DC current is flowing, assuming the temperature will rise, thereby keeping the temperature constant [17]. Another method is to keep the probe resistance, connection resistance, etc. very low [16], [18].

E. Comparison of the critical current in the REBCO tapes with full-width and micro-bridges

Fig. 6(a) shows the field dependences of I_c per 4 mm-width for each sample at 4.2-5 and 20 K. The results for the sample FW have already previously shown in Fig. 4. The I_c values per 4 mm width were calculated for other samples based on the bridge widths ascertained using optical microscopy; for instance, for the sample L125, the original I_c value was scaled up by a factor of 32. Consequently, while the I_c normalized by width varies for different widths, the magnetic field dependence is consistent across the samples, implying a uniform flux pinning mechanism. Fig. 6(b) details the bridge width's influence on I_c , normalized per 4 mm width, to clarify the effect of the bridge width. The results indicate that I_c per unit width varied by 16% at 20 K, 18 T and 10% at 4.2-5 K, 18 T, compared to the I_c of the full-width sample. This variation could stem from factors such as the degradation of the area surrounding the processed bridges or an inherent I_c distribution in the tape. The discrepancy in I_c based on width is more pronounced than the difference between DC and pulsed currents discussed in section III D, suggesting it is an attribute of the sample rather than the measurement method. Previous studies have shown an I_c distribution within REBCO tapes, as evidenced by the local magnetic field distribution measurements and the boiling of the coolant due to heat generation [29, 30]. Future work should include a quantitative analysis to determine which bridge widths yield reliable I_c values.

Given that the magnetic field dependence is consistent, particularly at low temperatures and high fields, employing the pulsed current method developed in this study to measure full-width I_c , and assessing the magnetic field angular dependence of I_c in bridge-shaped samples, will comprehensively elucidate the I_c characteristics vital for magnet design. To confirm the reliability of I_c measurements using pulsed current, it is essential to quantitatively evaluate the I_c by measuring a full-width sample under large DC currents.

IV. CONCLUSION

We have developed a power supply capable of generating pulsed currents of up to 2000 A with millisecond pulse widths, utilizing a supercapacitor and a current regulator. This system has enabled us to measure the critical current I_c in the REBCO coated conductors within high magnetic fields of up to 19 T and at variable temperatures ranging from 4.2-77 K. The field dependence of I_c , including its self-field, was assessed for REBCO tapes from Fujikura at temperatures as low as 20 K. When comparing the current-voltage characteristics of DC and pulsed

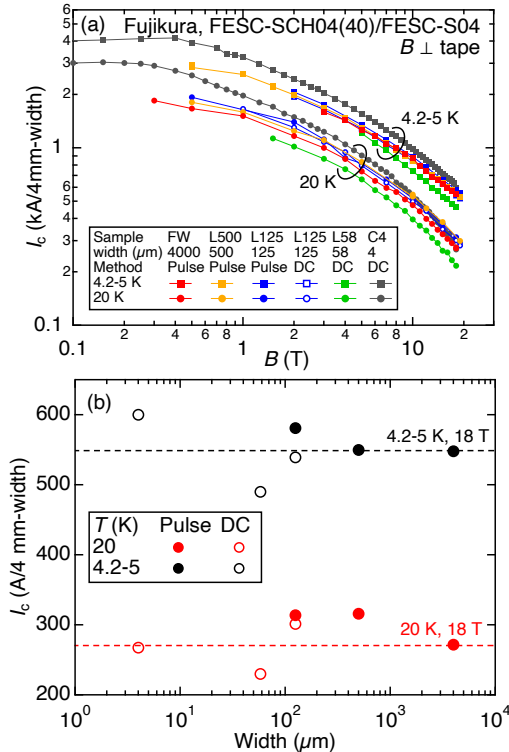


Fig. 6. (a) Field dependences of I_c per 4 mm-width for each sample at 4.2-5 K and 20 K. (b) Width dependence of I_c per 4 mm-width at 18 T at 4.2-5, 20 K.

currents, the I_c value for DC were lower, likely due to the increased temperature of the sample. We also examined the temperature and field dependence of I_c for samples with microbridges-created using laser and chemical-and with a full width of 4 mm. The results showed consistent magnetic field dependence of I_c across the different widths, indicating uneven distribution of I_c within the REBCO tapes. Future enhancements will involve upgrading the pulsed power supply to 5 kA, supported by with a larger supercapacitor. This study's advancements allow for comprehensive measurements of magnetic field and temperature dependence of I_c both bridge and full-width samples, contributing to the magnet design and facilitating discussions on flux pinning, which are essential for developing for REBCO coated conductors with improved I_c in high magnetic fields.

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