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Berkeley Center for Magnet Technology (BCMT)
Accelerator Technology and Applied Physics Division (ATAP)
Lawrence Berkeley National Laboratory
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R&D toward ReBCO high current cable with low ac loss, small SCIF, and high robustness against normal transition

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KYOTO UNIVERSITY

JST MIRAI 未来社会創造事業

References

[1] N. Amemiya, M. Shigemasa, A. Takahashi, N. Wang, Y. Sogabe, S. Yamano and H. Sakamoto, “Effective reduction of magnetization losses in cop-per-plated multifilament coated conductors using spiral geometry,” *Superconductor Science Technology*, vol. 35, no.2, Feb. 2022, Art. no. 025003, doi: 10.1088/1361-6668/ac3f9c.

[2] M. Shigemasa, Y. Sogabe, A. Takahashi, S. Yamano, H. Sakamoto and N. Amemiya, "Magnetization loss measurements of spiral copper-plated multifilament coated conductors with various filament and conductor widths," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, Sept. 2022, Art no. 8200806, doi: 10.1109/TASC.2022.3170865.

[3] N. Amemiya, N. Wang, M. Shigemasa, A. Takahashi, Y. Sogabe, S. Yamano and H. Sakamoto, "Measurements of coupling time constants and geometry factors of coupling losses in spiral copper-plated multifilament coated conductors," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 6602005, doi: 10.1109/TASC.2022.3167928.

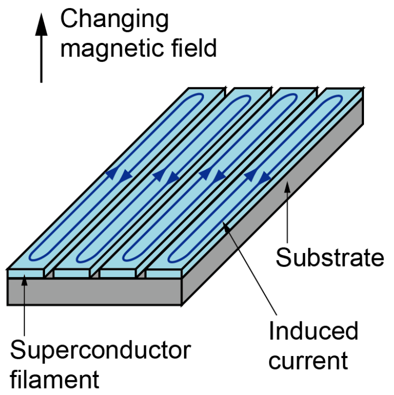
[4] N. Amemiya, N. Tominaga, R. Toyomoto, T. Nishimoto, Y. Sogabe, S. Yamano and H. Sakamoto, “Coupling time constants of striated and copper-plated coated conductors and the potential of striation to reduce shielding-current-induced fields in pancake coils,” *Superconductor Science Technology*, vol. 31, no. 2, Feb. 2018, Art. no. 025007, doi: 10.1088/1361-6668/aa9d24.

[5] N. Amemiya, Y. Zhao, X. Luo, G. Xu, Y. Li and Y. Sogabe, "Current-sharing between filaments and voltage – current characteristics of copper-plated multifilament coated conductors," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, Sept. 2022, Art no. 8001005, doi: 10.1109/TASC.2022.3168622.

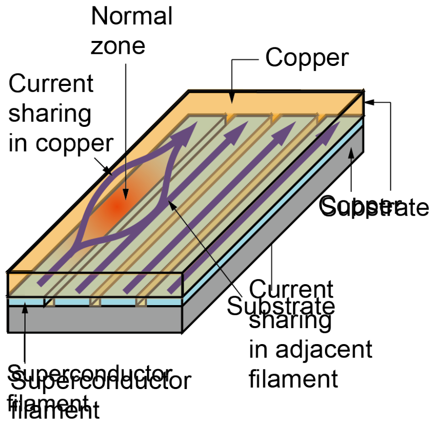
[6] X. Luo, Y. Zhao, Y. Sogabe, H. Sakamoto, S. Yamano and N. Amemiya, "Thermal Runaway of Conduction-Cooled Monofilament and Multifilament Coated Conductors," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 4, June 2022, Art no. 6600609, doi: 10.1109/TASC.2022.3141970.

Multifilament ReBCO coated conductors and copper plating

Pros and cons of copper-plated multifilament coated conductor

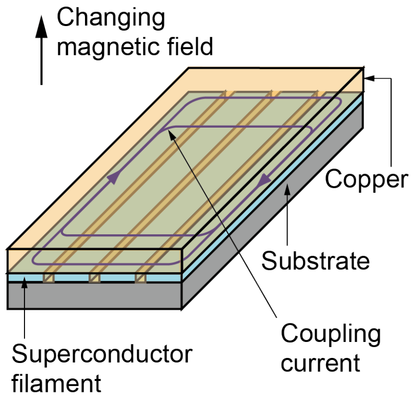


AC loss (and SCIF) can be reduced by striating wide superconductor layers into narrow filaments.



If we plate copper on the entire group of filaments,

copper allows the current sharing and improves the robustness against normal transition.

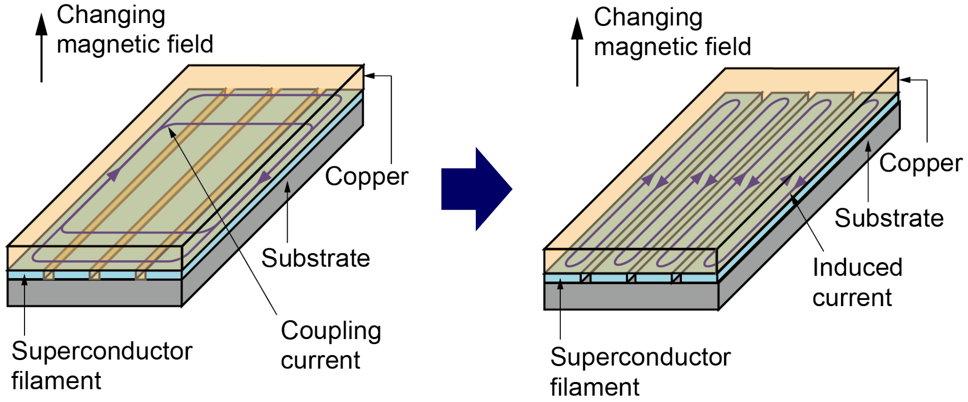


Under ac transverse magnetic fields, filaments are coupled by coupling current and behave like a wide monofilament, generating large ac loss.

AC loss can be reduced ***only after the decay of coupling current***, which unfortunately decays quite slowly in non-twisted conductors.

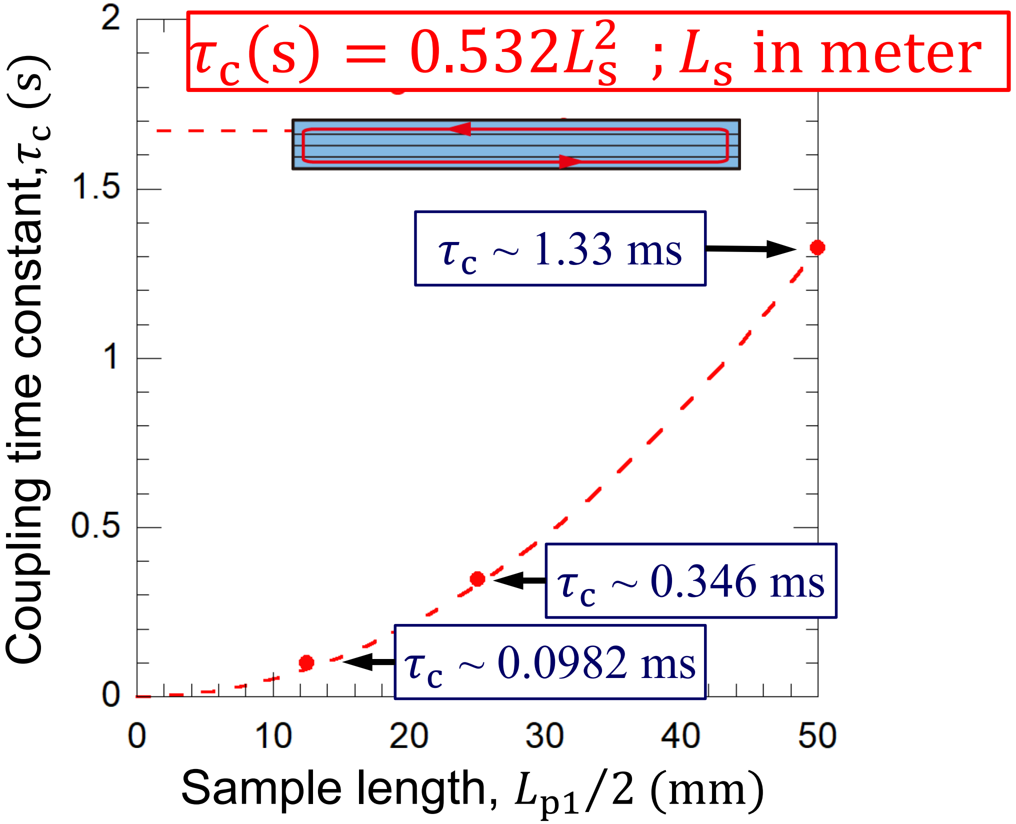
[4] doi: 10.1088/1361-6668/aa9d24

How long does it take to decay of coupling current?



How long does it take?

We measured **coupling time constants, τ_c,** which is the decay time constants of coupling currents, in straight striated coated conductors.



In 100 m-long conductor, $\tau_c \sim 5{,}000$ s

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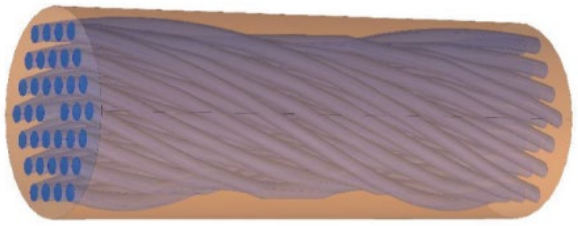
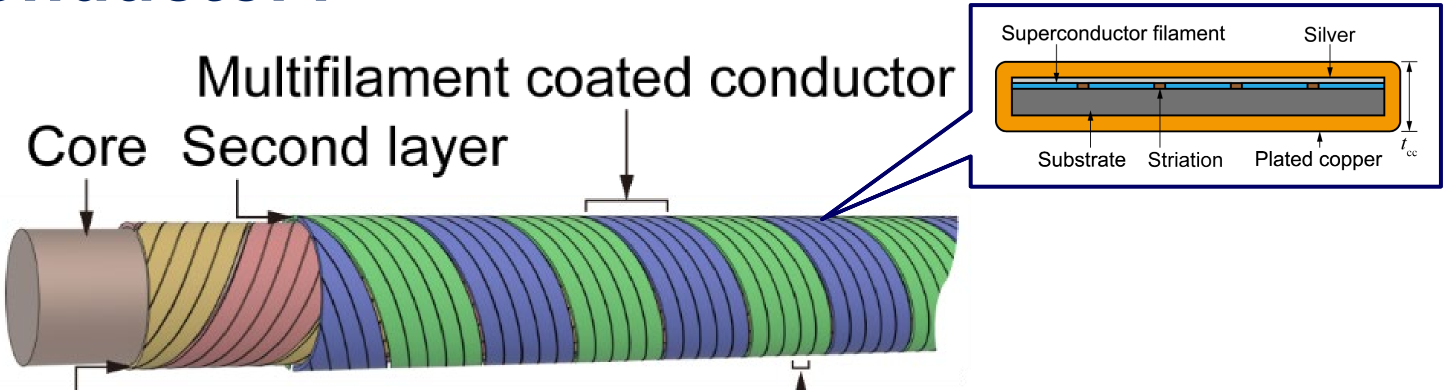
Concept of SCSC cable

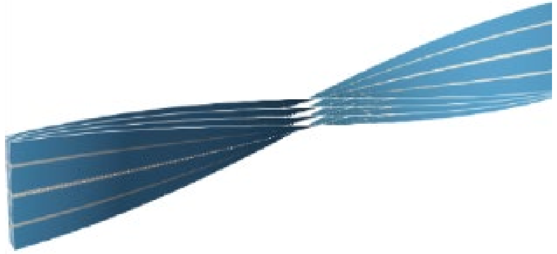
[1] doi: 10.1088/1361-6668/ac3f9c

How to decay coupling current quickly in copper-plated multifilament coated conductor?



Twisting round LTS wire





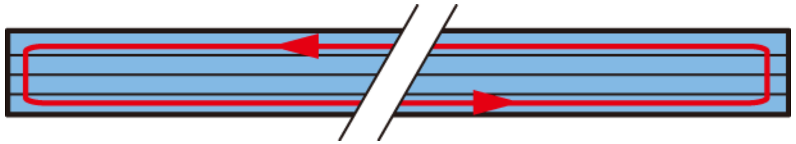
Twisting flat HTS tape

Winding copper-plated multifilament coated conductors spirally on a round core

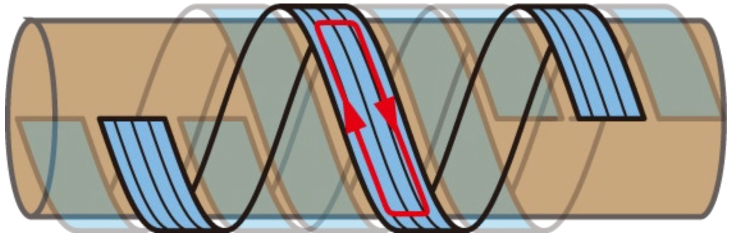
SCSC cable (double "SC" cable, standing for Spiral Copper-plated Striated Coated-conductor cable)

CORC®-like cable with *copper-plated multifilament* coated conductors

Coupling currents in flat straight and spiral copper-plated multifilament coated conductors



$L_c \sim$ entire length of coated conductor (L_s)



$L_c \sim$ half pitch of spiral along Coated conductor $(L_{p1}/2)$

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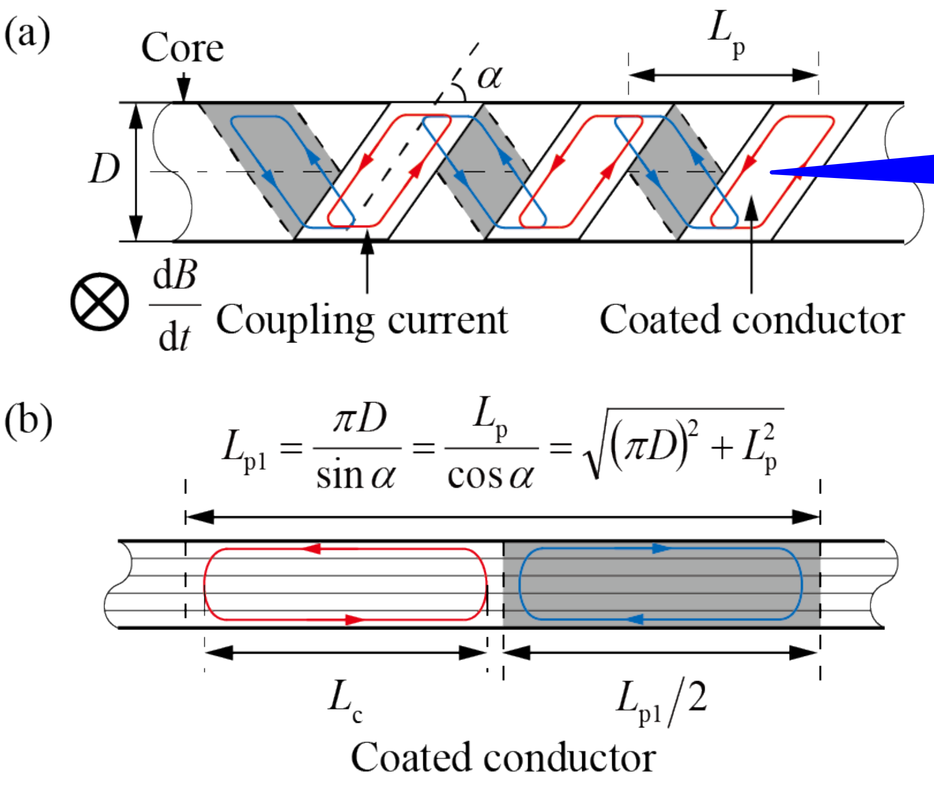
[1] doi: 10.1088/1361-6668/ac3f9c

Coupling current loop in SCSC cable



Coupling current confined in half pitch of spiral

$$L_c \sim \frac{1}{2} L_{p1} = \frac{1}{2}\sqrt{(\pi D)^2 + L_p^2} = \frac{1}{2} \cdot \frac{\pi D}{\sin\alpha}$$

- Quick decay of coupling current
- Independent of the entire conductor length

Experimental results: ac loss reduction

Effect of spiral geometry to decouple filaments

We compare ac losses of

- straight copper-plated striated coated conductors

and

- spiral copper-plated striated coated conductors.

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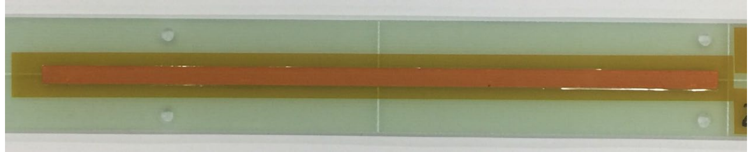
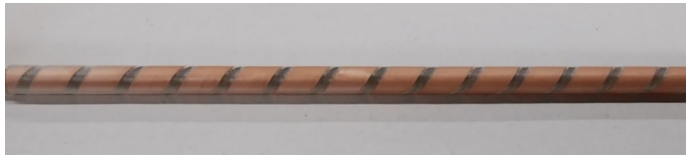
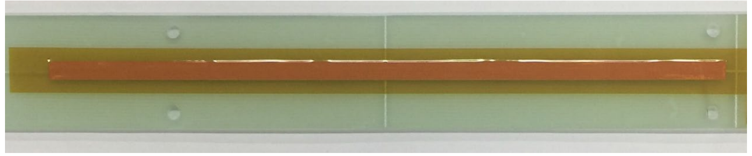
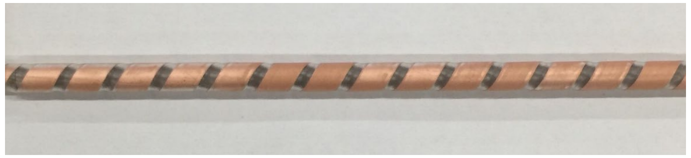
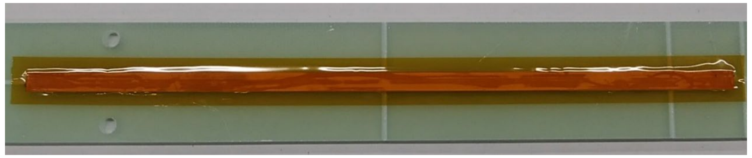
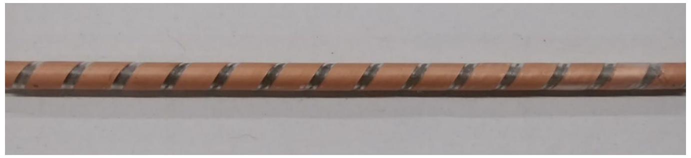
Prepared straight and spiral samples

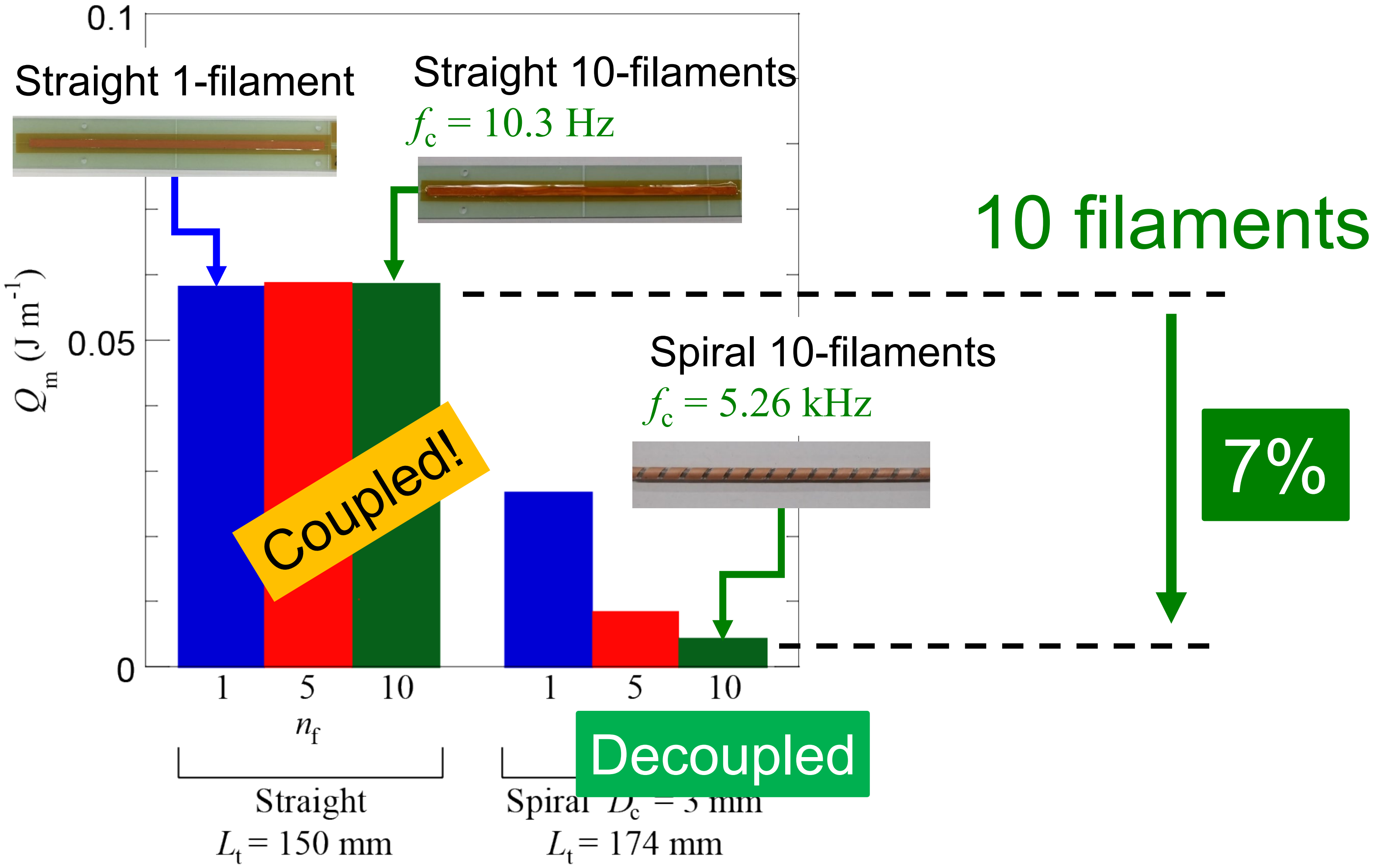
Name	Filament width	Straight	Spiral (1 layer, 1 tape)
		t_{Cu} = 20 μm (per side)	t_{Cu} = 20 μm (per side) D_c = 3 mm, a = 55 deg
Tape length l_t		150 mm	174 mm
B2-a2	4 mm		
B2-b2	0.8 mm		
B2-c2	0.4 mm		

[1] doi: 10.1088/1361-6668/ac3f9c

Magnetization losses in straight and spiral samples

$f = 65.44$ Hz

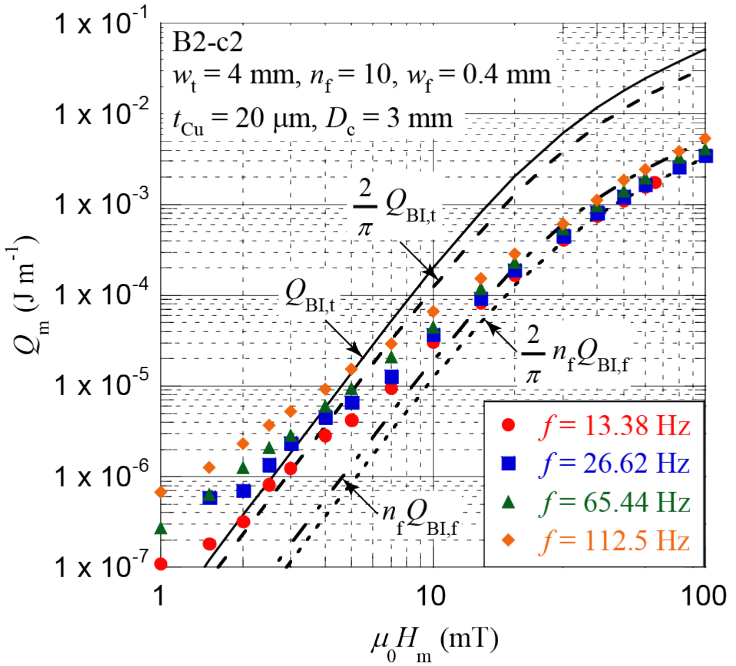
$\mu_0 H_m = 100$ mT



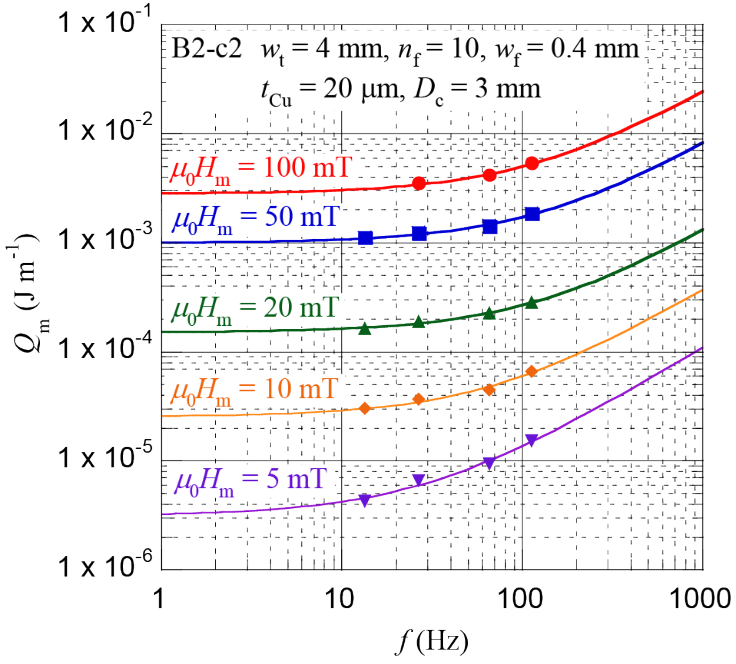
Detailed magnetization loss characteristics of spiral copper-plated striated coated conductors

[1] doi: 10.1088/1361-6668/ac3f9c

Magnetization losses and their frequency dependences



Field-amplitude dependence of magnetization loss



Frequency dependence of magnetization loss

$$Q_m = Q_h + kf$$

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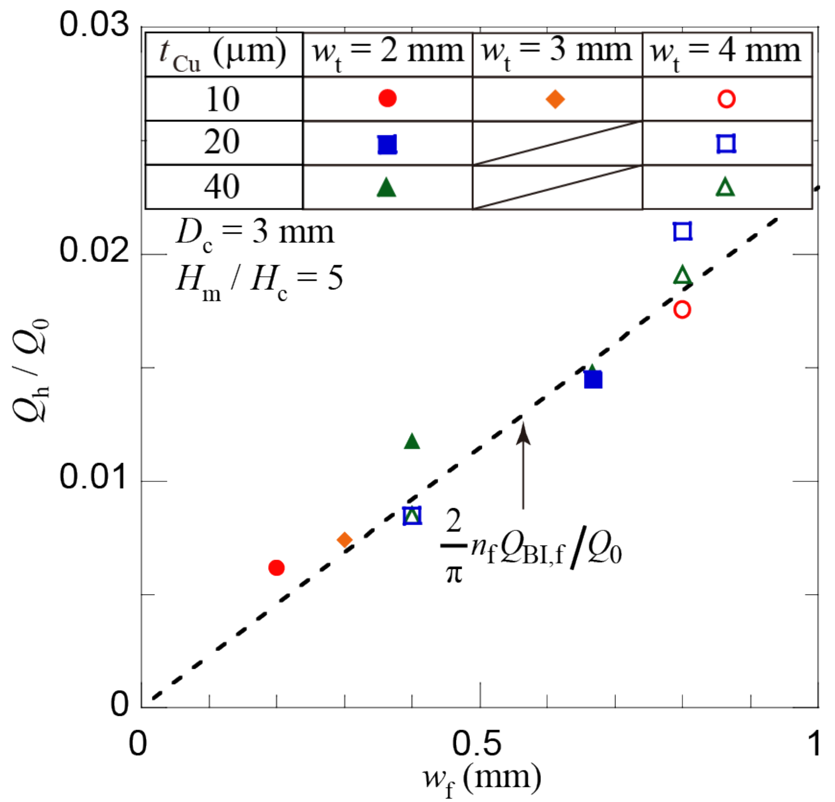
Specifications of samples

Specifications of samples

Width of tape	w_t	2 mm, 4 mm
Number of filaments	n_f	1, 3, 5, 10
Width of filaments	w_f	2 mm, 4 mm (monofilament) 0.2 mm, 0.4 mm, 0.67 mm, 0.8 mm
Thickness of Copper-plating per side	t_{Cu}	40 µm, 20 µm, 10 µm
Thickness of Hastelloy substrate		30 µm
Diameter of core	D_c	3 mm, 5 mm
Spiral angle		55 degree
Length of tape in sample		174 mm

[2] doi: 10.1109/TASC.2022.3170865

Influence of filament width on hysteresis losses



Hysteresis losses can be reduced by decreasing filament width.

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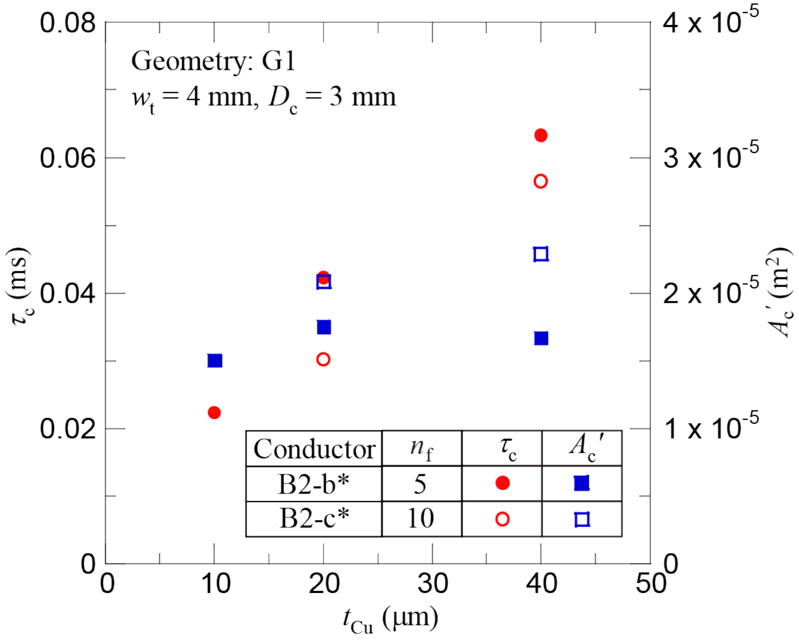
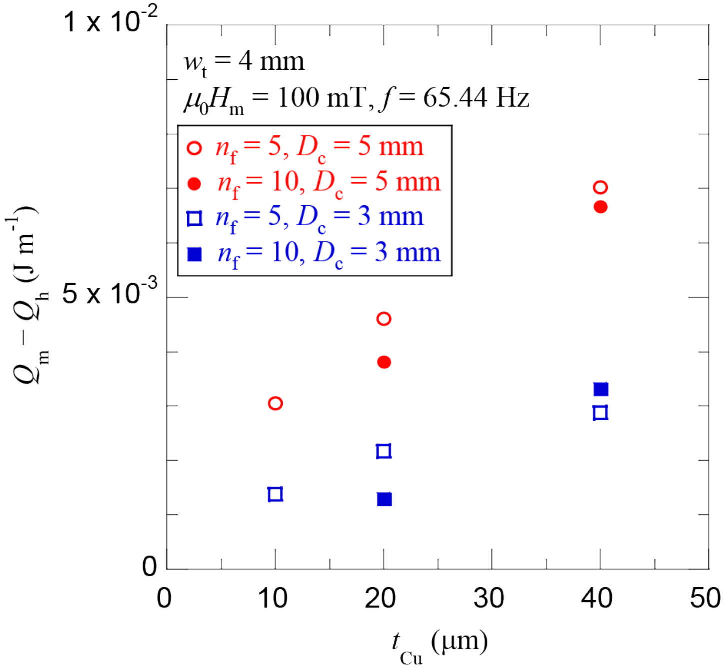
Left: [3] doi: 10.1109/TASC.2022.3167928, right: [1] doi: 10.1088/1361-6668/ac3f9c

Influence of copper thickness on coupling losses

$$Q_{\mathrm{c,analytical}} = A_c' \frac{\mu_0 H_m^2}{2} \cdot \frac{2\pi f \tau_c}{(2\pi f \tau_c)^2 + 1}$$



Conductor	n_f	τ_c	A_c'
B2-b*	5	●	■
B2-c*	10	○	□



Coupling losses loss can be reduced by decreasing copper thickness.

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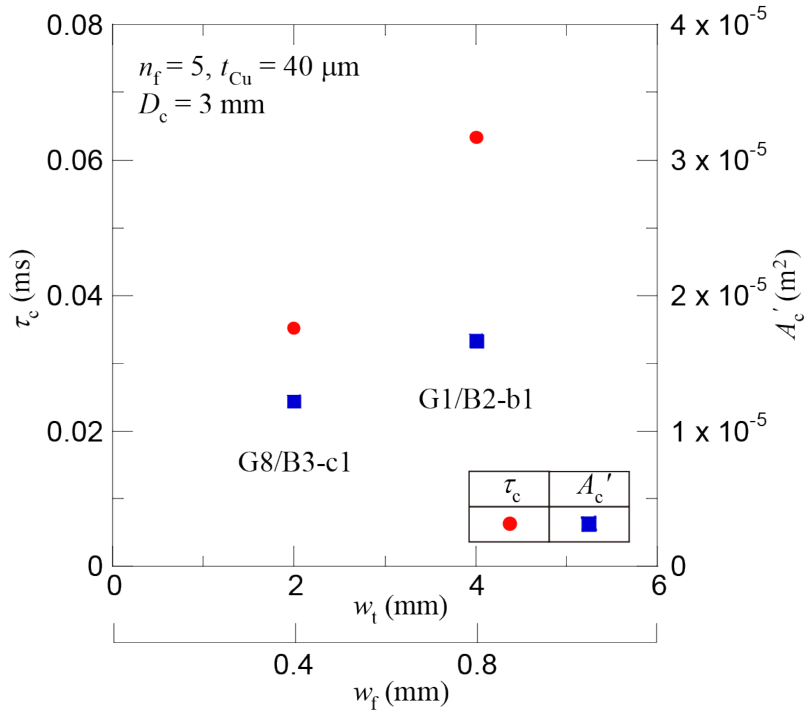
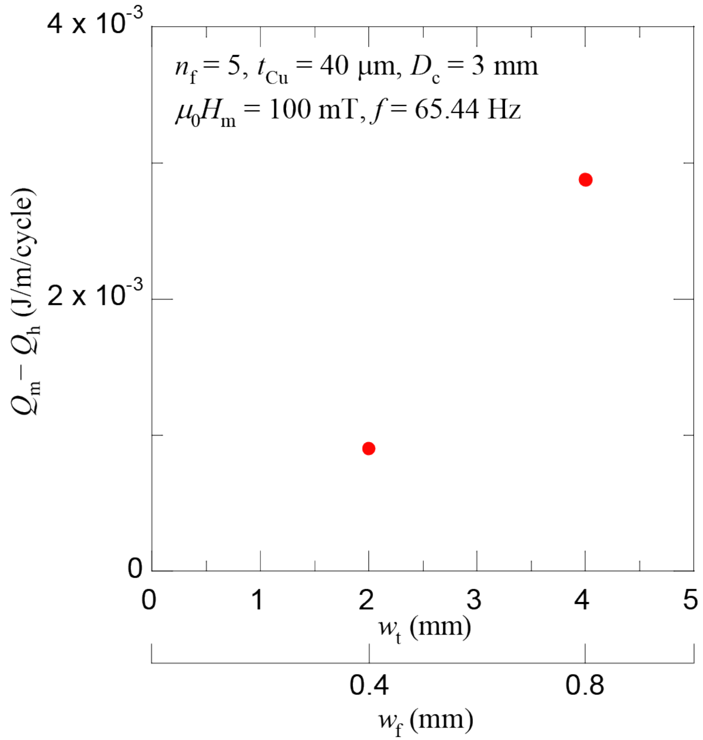
Left: [3] doi: 10.1109/TASC.2022.3167928

Influence of conductor (tape) width on coupling losses

$$Q_{\mathrm{c,analytical}} = A_{\mathrm{c}}' \frac{\mu_0 H_{\mathrm{m}}^2}{2} \cdot \frac{2\pi f \tau_{\mathrm{c}}}{(2\pi f \tau_{\mathrm{c}})^2 + 1}$$



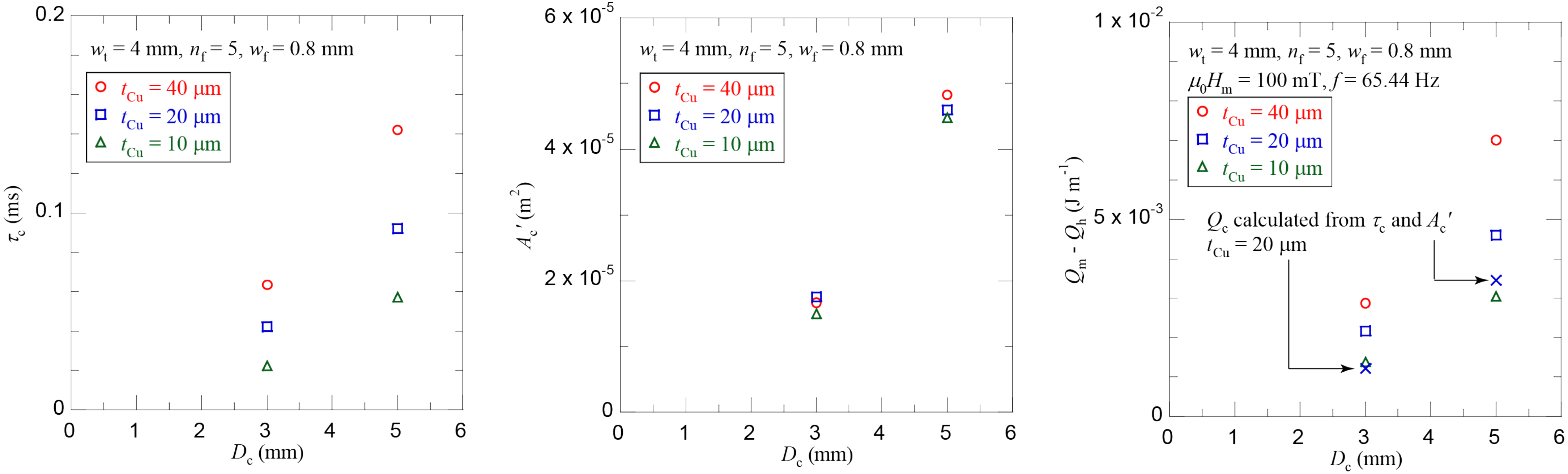


Coupling losses loss can be reduced by decreasing conductor width.

right: [1] doi: 10.1088/1361-6668/ac3f9c, updated

Influence of core diameter on coupling losses

$$Q_{\text{c,analytical}} = A_c' \frac{\mu_0 H_m^2}{2} \cdot \frac{2\pi f \tau_c}{(2\pi f \tau_c)^2 + 1}$$

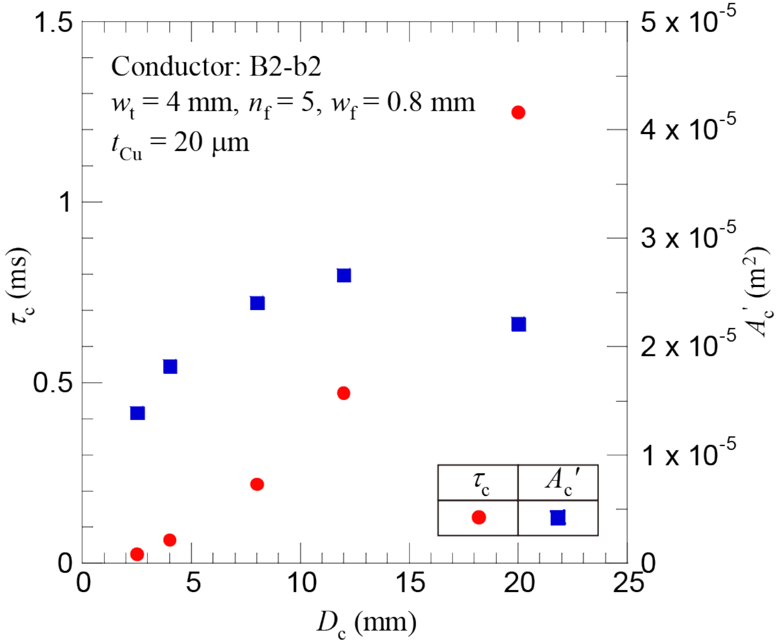


Coupling losses loss can be reduced by decreasing core diameter.

[3] doi: 10.1109/TASC.2022.3167928

Influence of core diameter on coupling losses – Suppl.

$$Q_{c,\mathrm{analytical}} = A_c' \frac{\mu_0 H_m^2}{2} \cdot \frac{2\pi f \tau_c}{(2\pi f \tau_c)^2 + 1}$$



Coupling losses loss can be reduced by decreasing core diameter.

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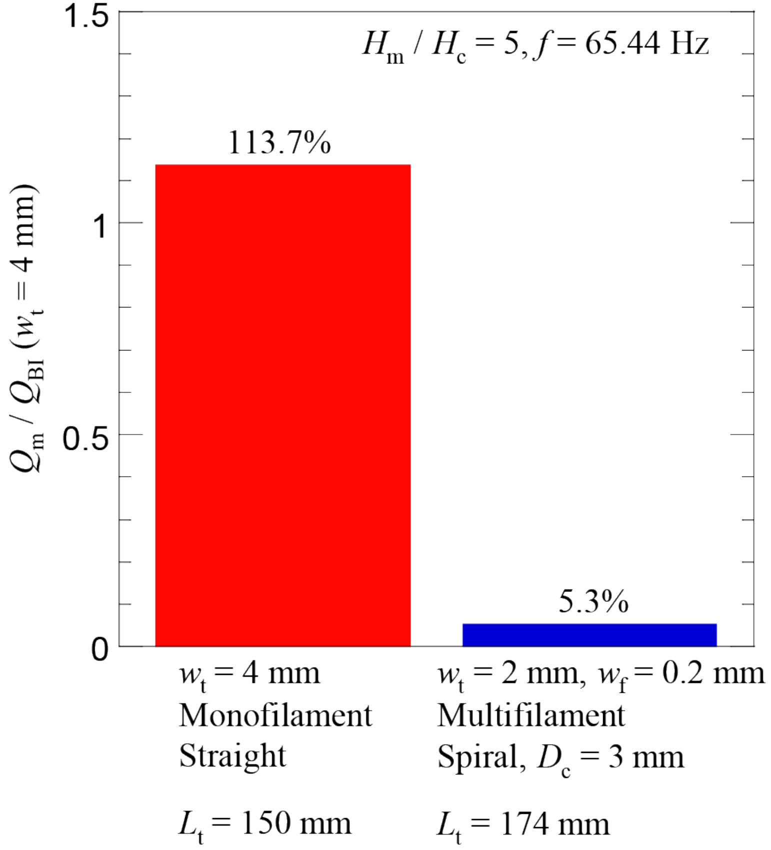
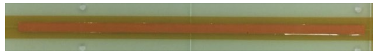
Summary of approach to reduce magnetization loss

- Hysteresis losses can be reduced
  - by decreasing filament width.
- Coupling losses loss can be reduced
  - by decreasing copper thickness,
  - by decreasing conductor width,
  - by decreasing core diameter.

[2] doi: 10.1109/TASC.2022.3170865

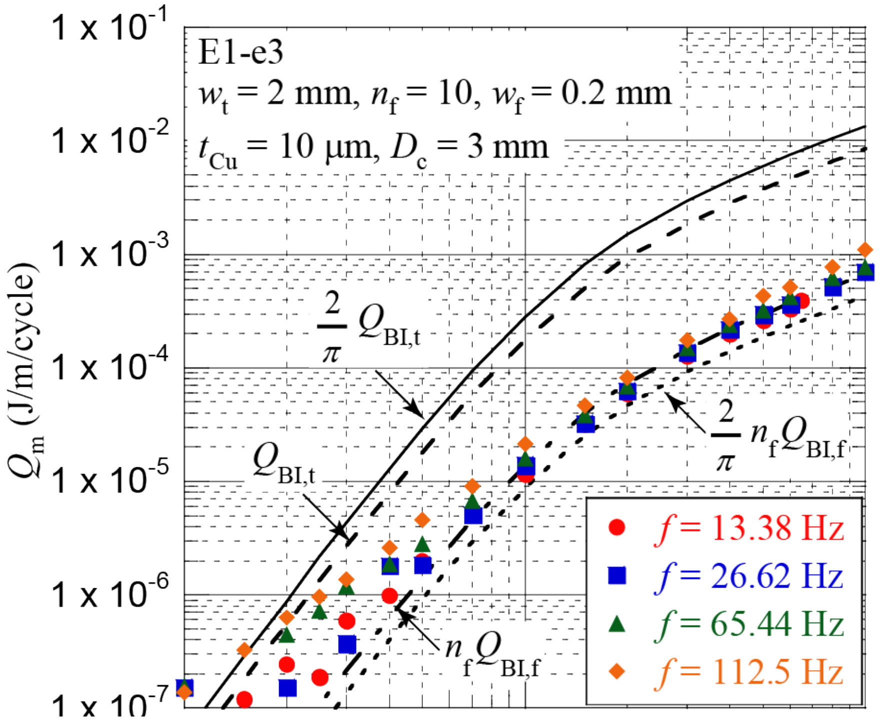
w_t = 2 mm, n_f = 10 (w_f = 0.2 mm), D_c = 3 mm





Monofilament, straight
20210127-3, 88.5 mT

10 filament, spiral
20210927-1, 37.9 mT



E1-e3#2 SP_G3
w_t = 2 mm, w_f = 0.2 mm
Multifilament
Spiral, D_c = 3 mm
L_c = 174 mm

10 filament, spiral
20210927-1

Magnetization loss reduction to 1/20 of that of 4 mm-wide flat coated conductor

Experimental results: current sharing, stability, and protection

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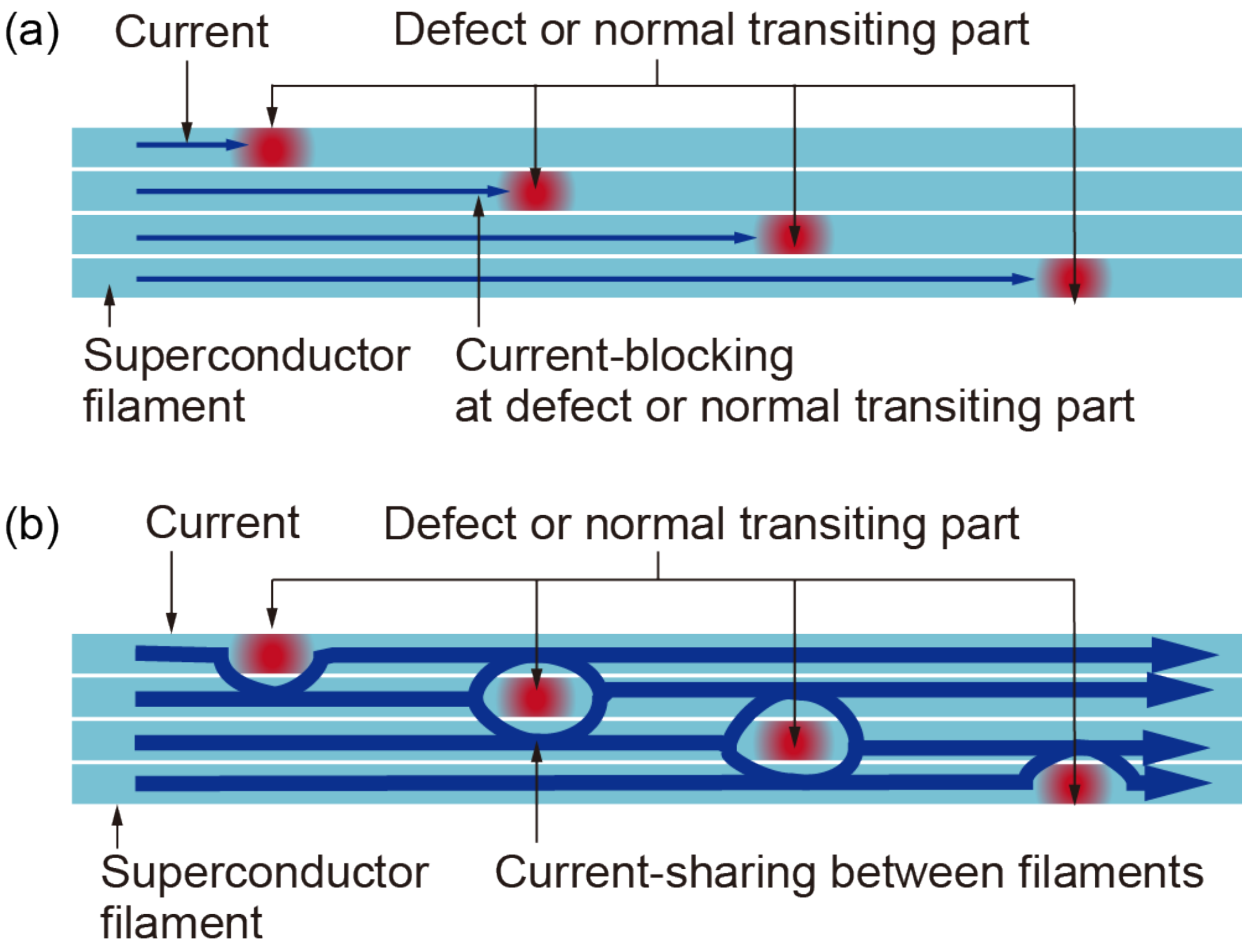
Current sharing and *V*–*I* characteristics in copper-plated multifilament coated conductors

[5] doi: 10.1109/TASC.2022.3168622

Importance of current sharing and experimental arrangement

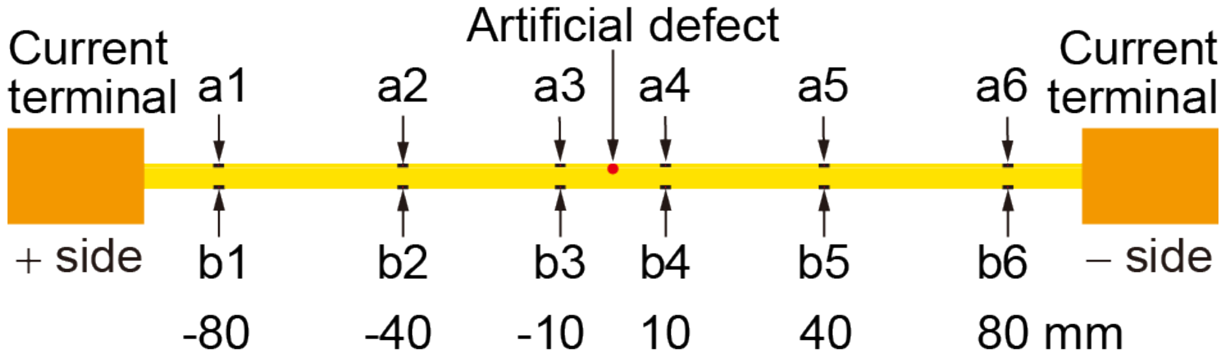


[5] doi: 10.1109/TASC.2022.3168622

Specifications of samples and arrangement of voltage taps

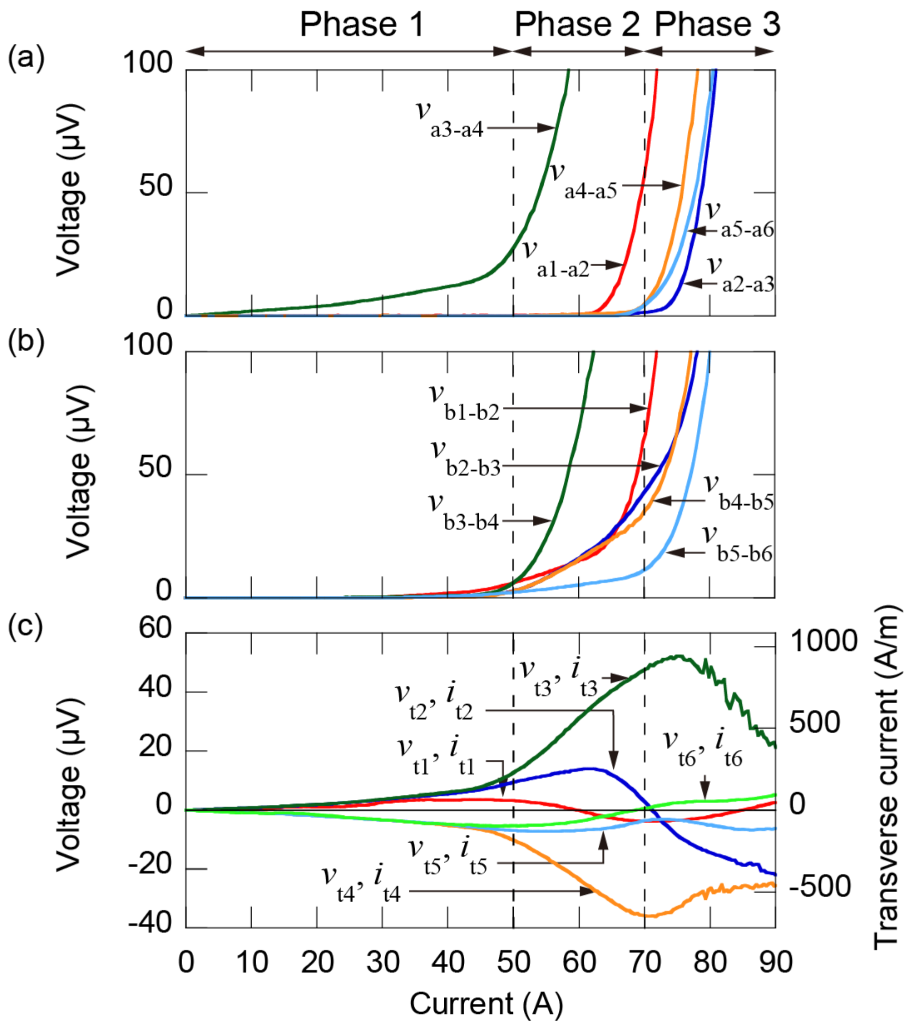
Specifications of samples

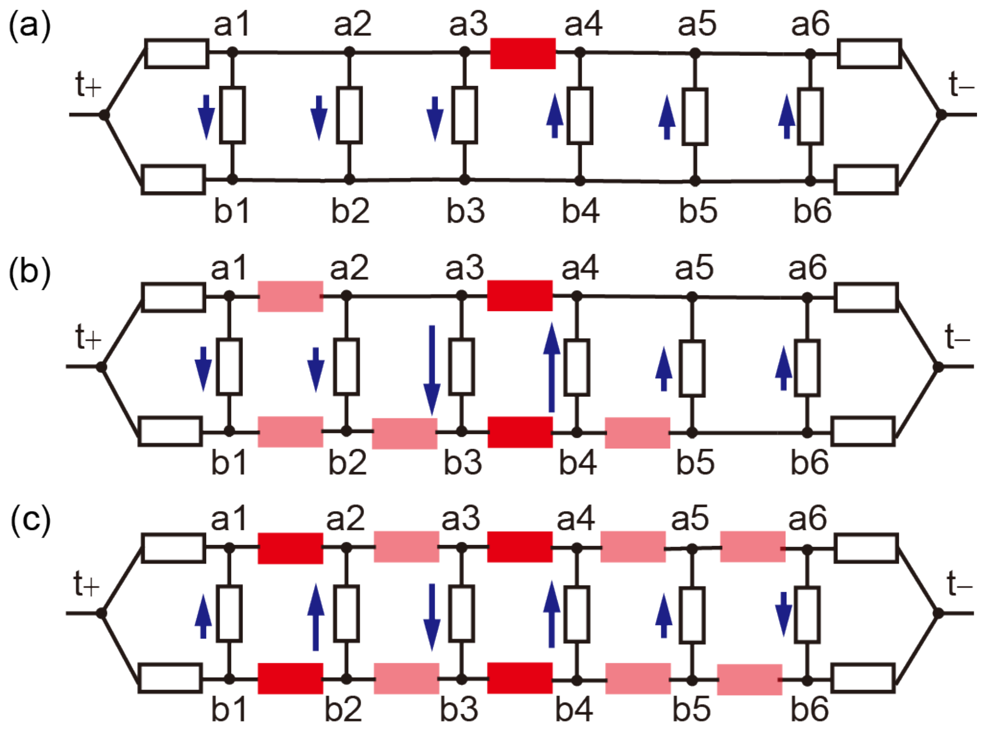
Tape type of SuperPower Inc.		SCS4050AP
Width of tape	w_t	4 mm
Number of filaments	n_f	5
Thickness of Copper-plating per side	t_{Cu}	20 µm
Thickness of Hastelloy substrate		50 µm
Total length		235 mm
Effective length between current terminals		175 mm



[5] doi: 10.1109/TASC.2022.3168622

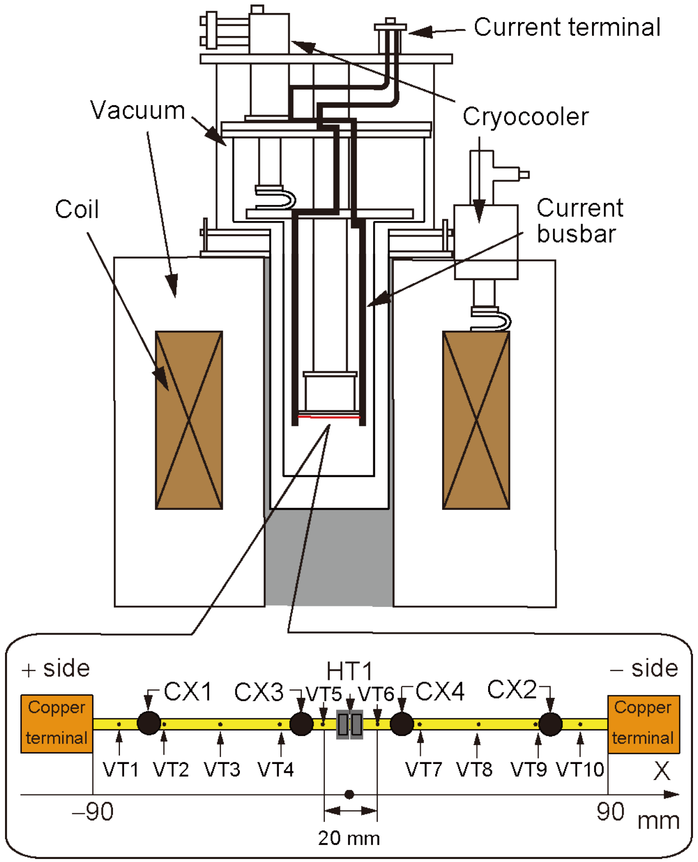
Current sharing and *V–I* characteristics: with local defect

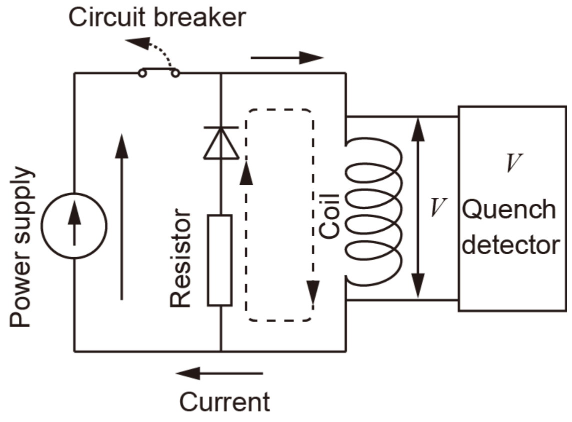


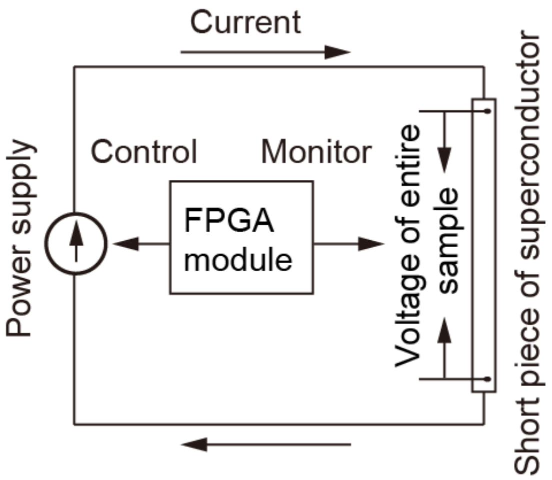


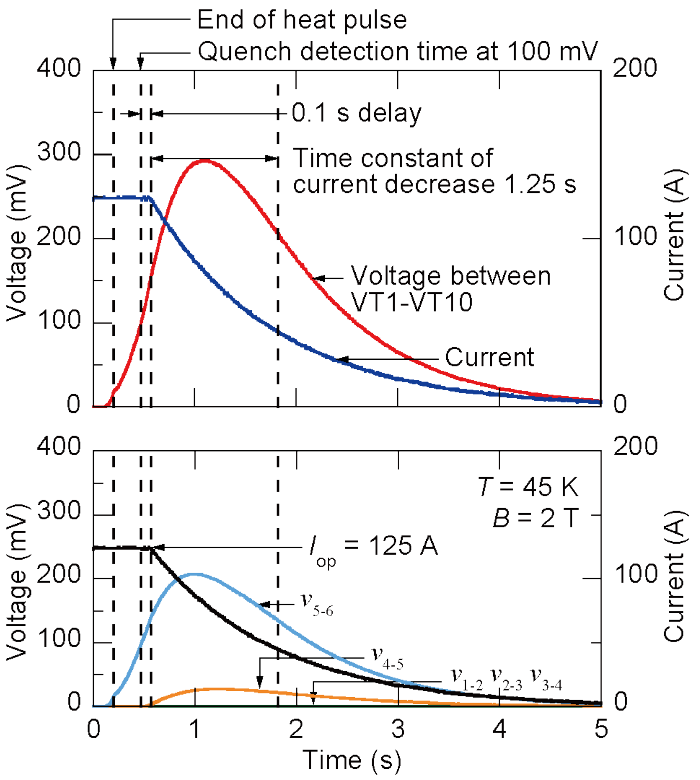
Impact of striation on protection against quench / thermal runaway

Experimental setup and procedure



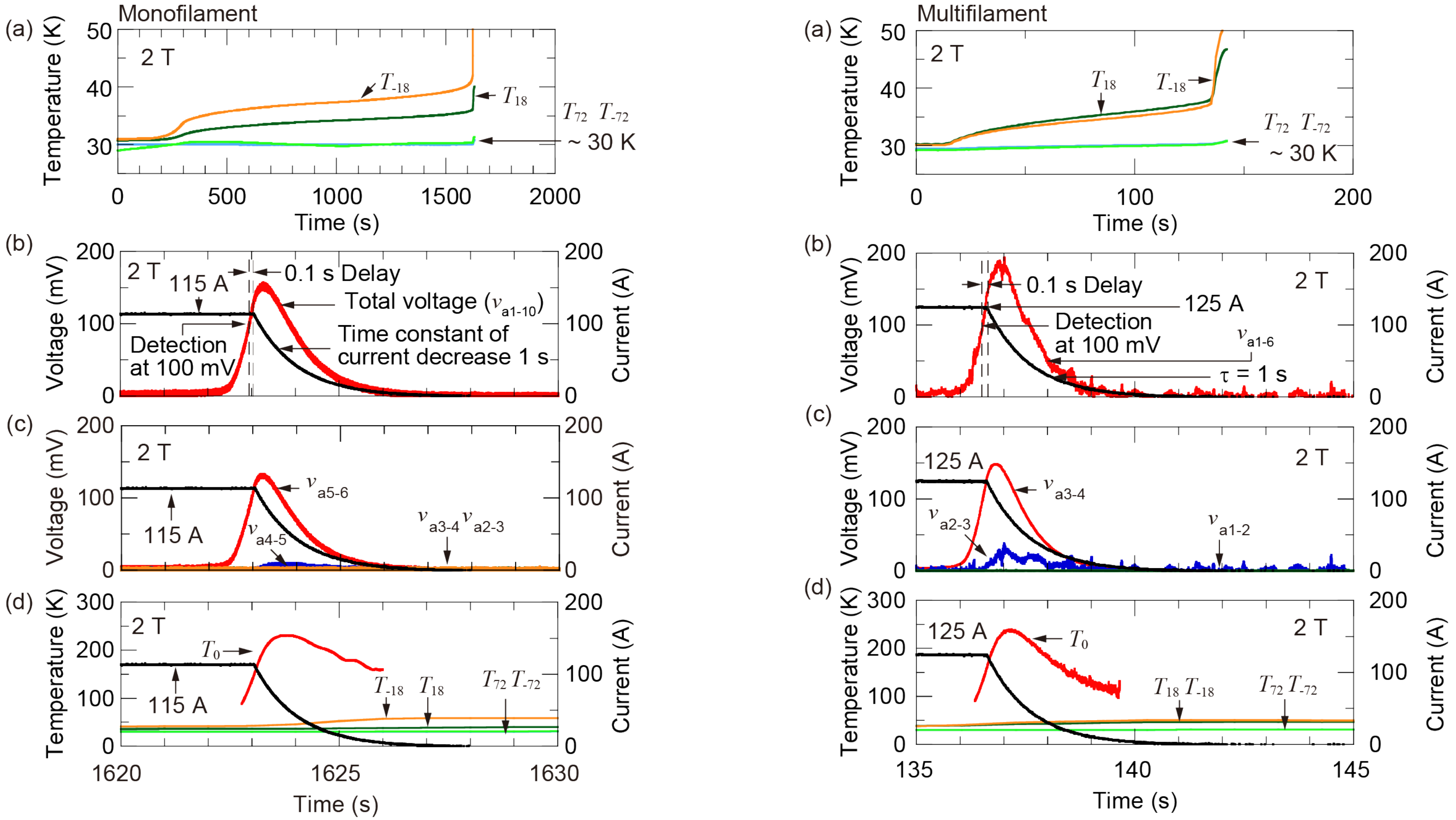






[6] doi: 10.1109/TASC.2022.3141970

Example of voltages/currents/temperatures of thermal runaway detection and protection processes



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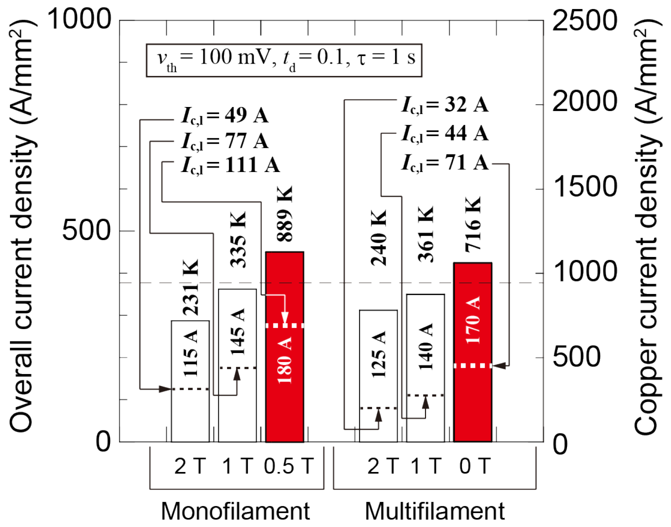
[6] doi: 10.1109/TASC.2022.3141970

Summary of detection and protection against thermal runaways initiated at local bending defect



Sample	Protectable current
Monofilament	150 A
Multifilament	150 A

Sample	I_t (T, B)	Holding time until thermal runaway	$I_{c,l}$ before and after thermal runaway	n before and after thermal runaway
Mono-filament (one sample)	115 A (30 K, 2 T)	~ 30 min	before: 49 A after: 49 A	before: 16 after: 15
	145 A (30 K, 1 T)	~ 30 min	before: 77 A after: 79 A	before: 17 after: 18
	180 A (30 K, 0.5 T)	~ 10 min	before: $I_{c,l}$ = 111 A, n = 20 after: burnt out	
Multi-filament (one sample)	125 A (30 K, 2 T)	~ 2 min	before: 32 A after: 32 A	before: 10 after: 9
	140 A (30 K, 1 T)	~ 4 min	before: 44 A after: 43 A	before: 8 after: 9
	170 A (30 K, 0 T)	~ 3 min	before: $I_{c,l}$ = 71 A, n = 5 after: linear V-I	

Conclusion

- The spiral geometry of copper-plated multifilament coated conductor decouples filaments electromagnetically and is effective to reduce magnetization losses.
- Copper plating allows current sharing between filaments and helps protection against quench / thermal runaway.