CCA 2016

Development of REBCO superconducting coils for MRI operating in subcooled LN_2 at 65 K

M. Iwakuma[1], K. Nabekura[1], K. Yun[1], K. Yoshida[1], A. Tomioka[2], M. Konno[2], A. Ibi[3], T. Machi[3] and T. Izumi[3]

1) Kyushu University

2) Fuji Electric Co. Ltd.

3) AIST

Sept. 13, 2016, Aspen in US

KYUSHU UNIVERSITY Fuji Electric AIST

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Ac Loss Reduction by Scribing (AC)

in Transformers with REBCO tspes

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= Magnetization Reduction by Scribing (DC)

2. Scribing effect in

Small Test Coils with REBCO Tapes for MRI

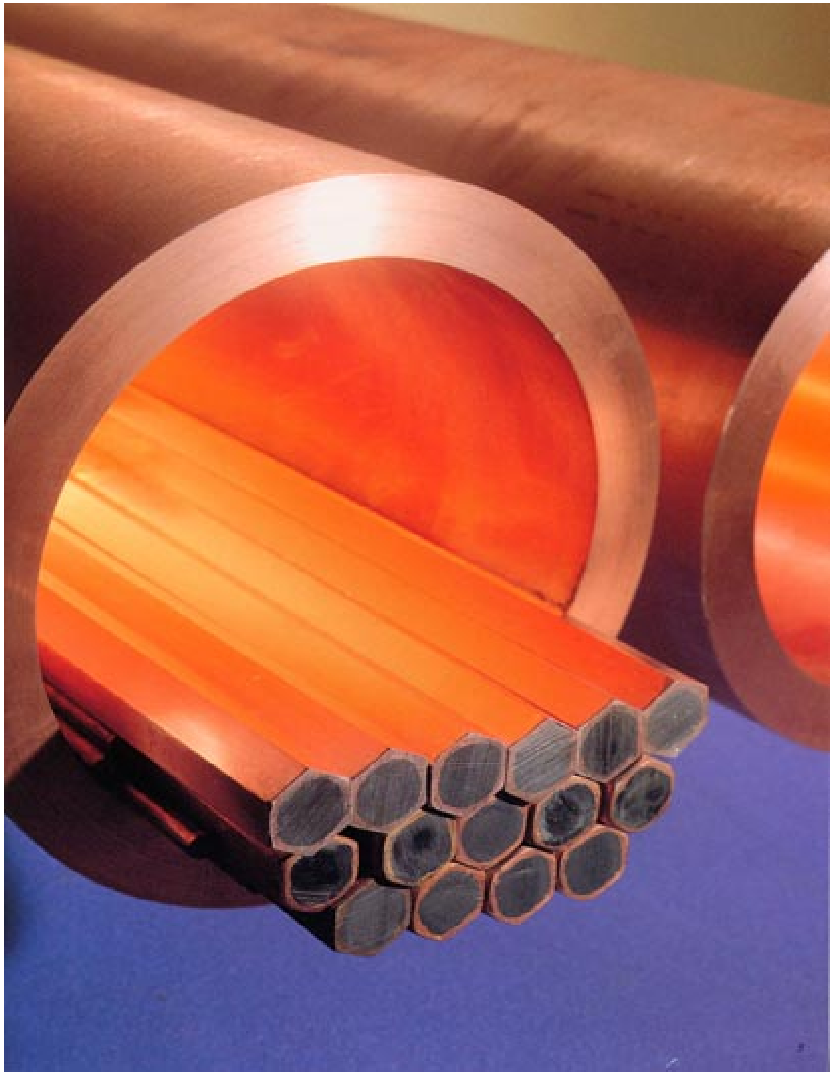
3. Summary

Ac loss reduction for ac use by scribing

1. M. Iwakuma et al., "Development of a 3ϕ-66/6.9kV-2MVA REBCO Superconducting Transformer", IEEE Trans. Appl. Supercond., Vol. 25, No.3, 2015, Article No. 5500206.

2. M. Iwakuma et al., "Development of REBCO superconducting power transformers in Japan", Physica C, Vol. 469, 2009, pp. 1726-1732.

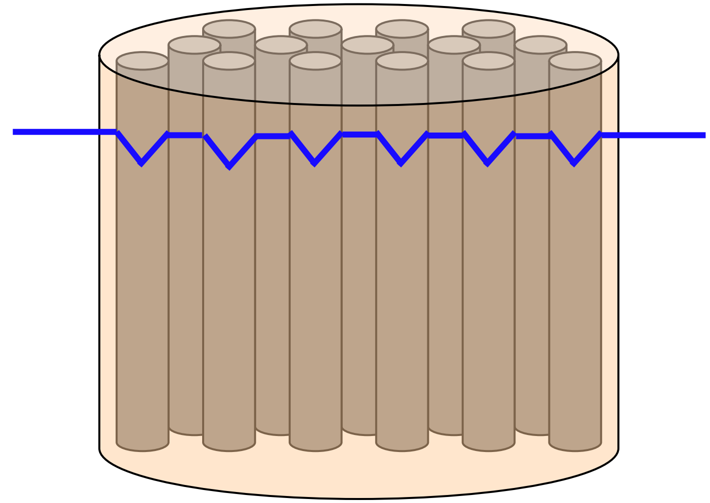
Conventional Method for M & Ac Loss Reduction, i.e. Multifilamentization and Twisting, is not Applicable.



Fine filaments

→

Reduction of pinning loss

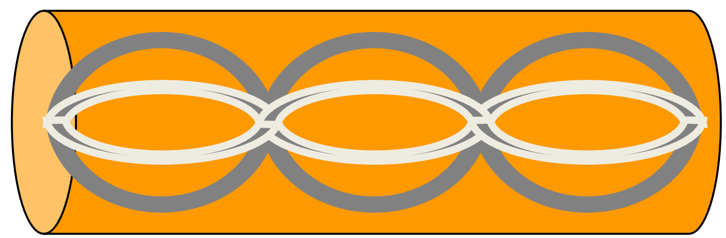


$$W = \oint B dH = \oint M dH \propto J_c d_f B_m \quad \text{for } B_m > B_{fp}$$

Twist & high-resistivity matrix

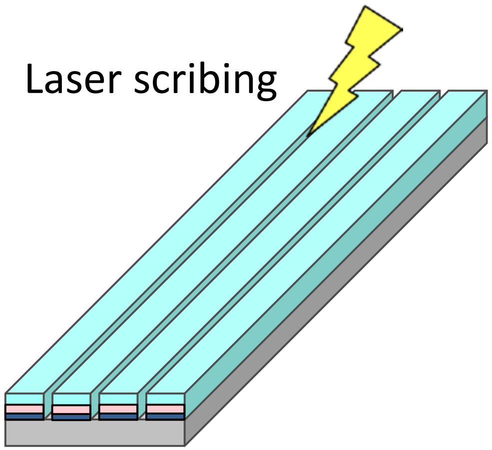
→

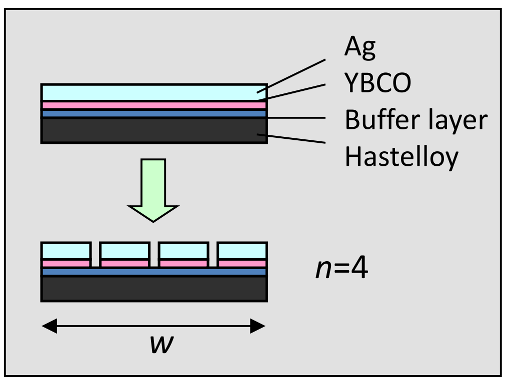
Reduction of coupling current loss

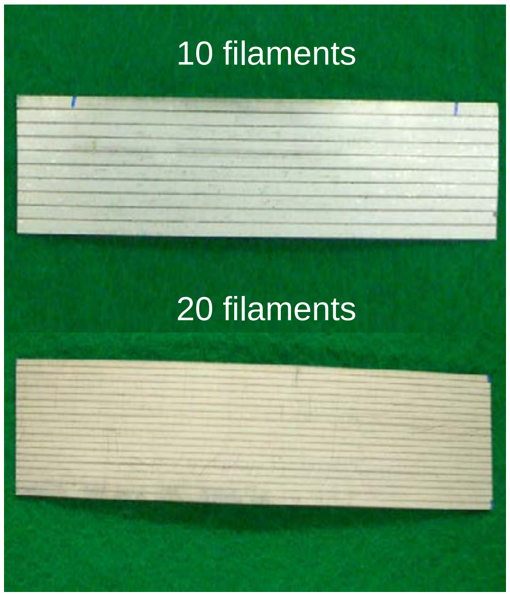


Ac loss reduction of superconducting thin tapes

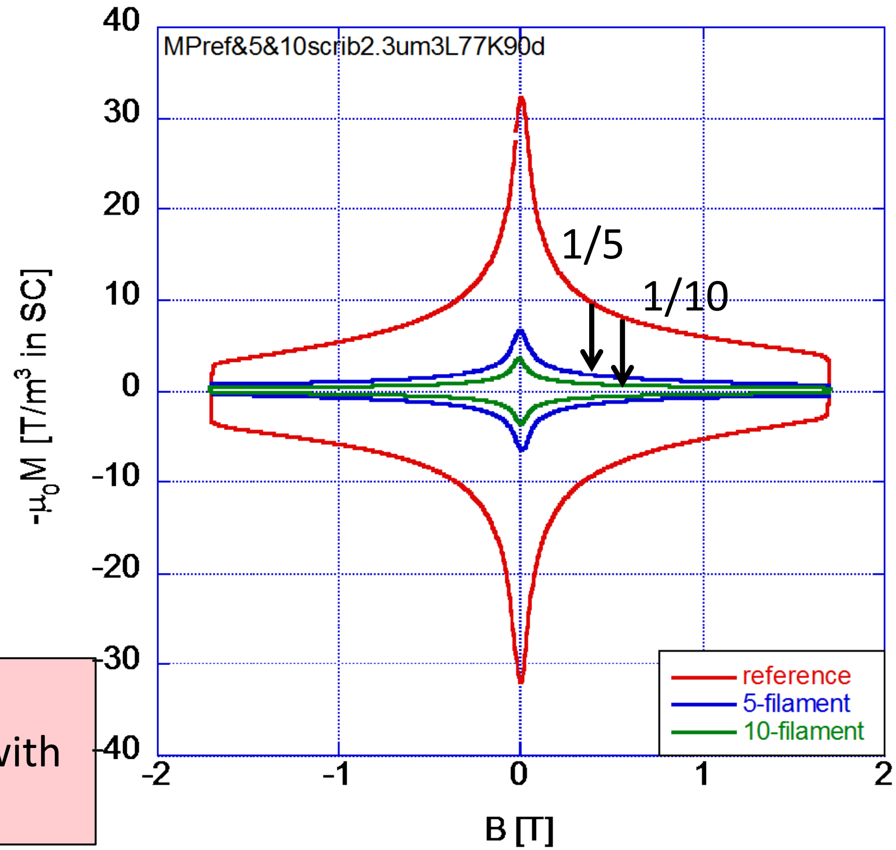
Combination
- Multifilamentization by laser-scribing
- Special winding process



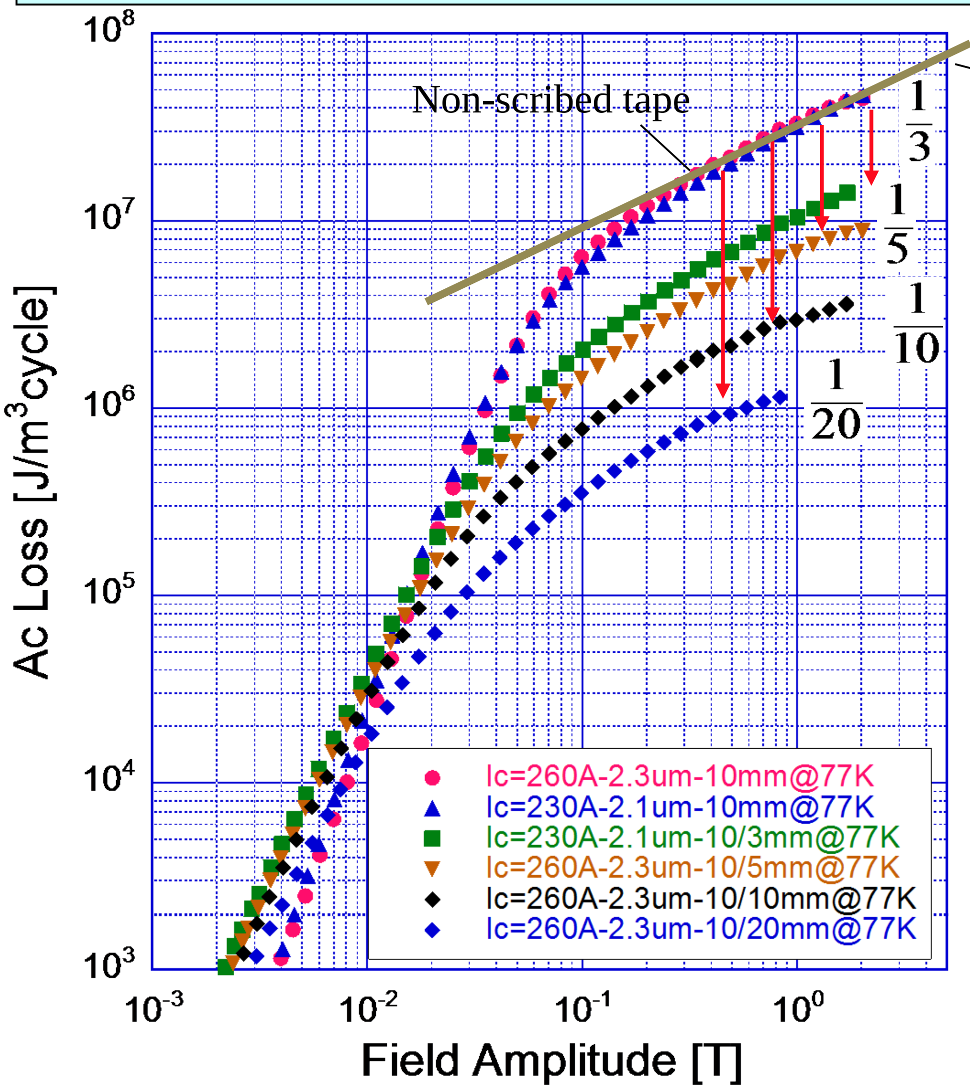




Buffer layer : Insulator
⇒ Filaments are insulated with each other



Ac losses in 1-, 3-, 5-, 10- and 20-filament short straight tapes



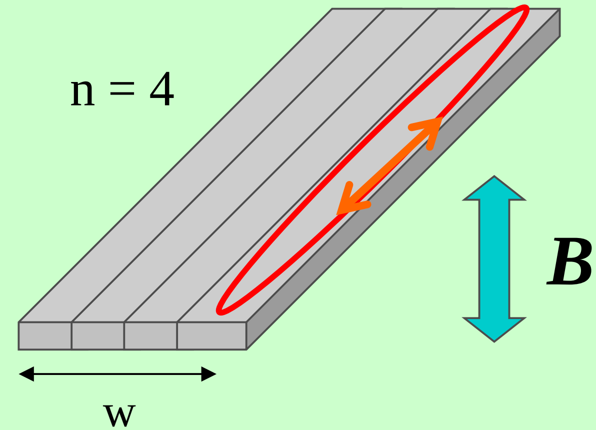
Approximate expression of ac loss

$$W = \frac{\alpha}{\gamma} B_m^{\gamma} \frac{w}{n}$$

Number of filaments

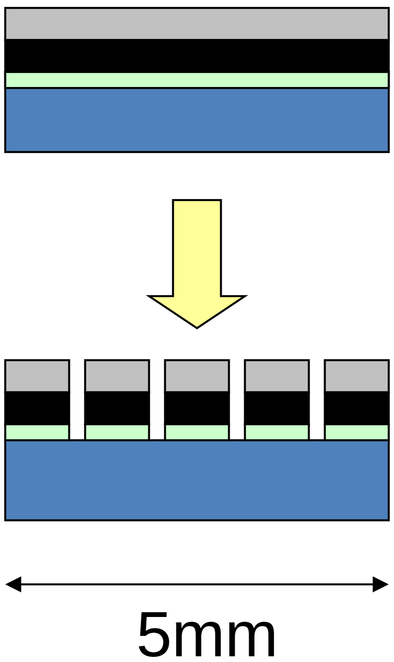
α, γ: pin parameter

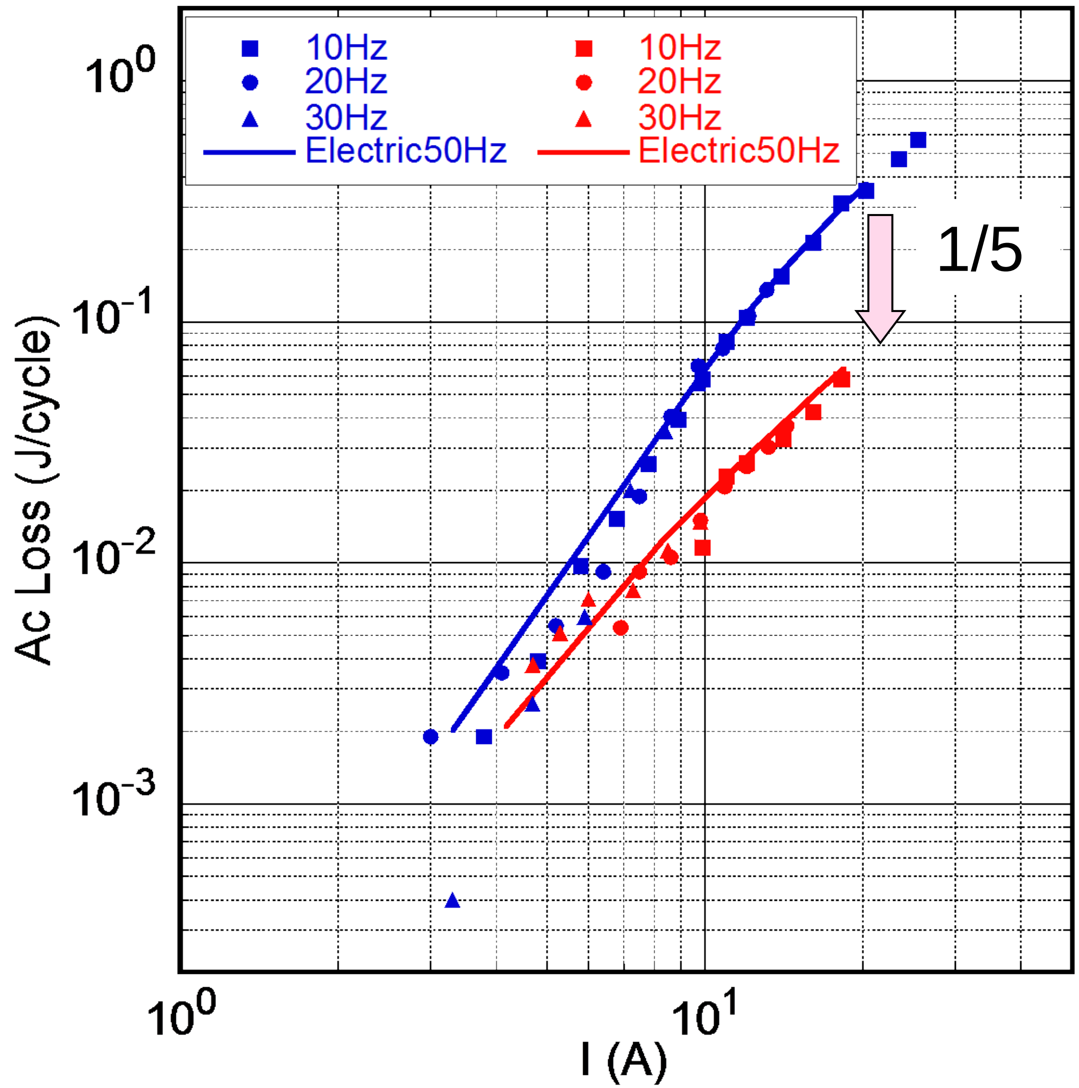
B_m : magnetic field amplitude



Ac loss in a short tape is reduced by scribing in inverse proportion to the number of filaments as theoretically predicted. → Nearly perfect insulation among the filaments

10-turn × 19-layer coil with 5mm wide 5-filament tape

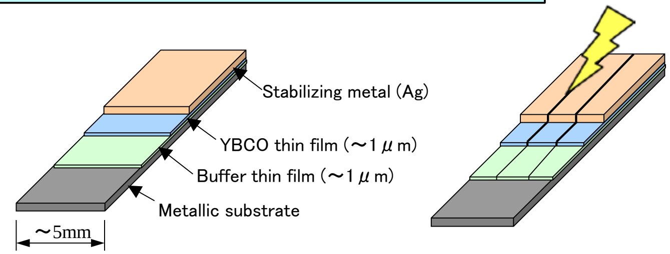




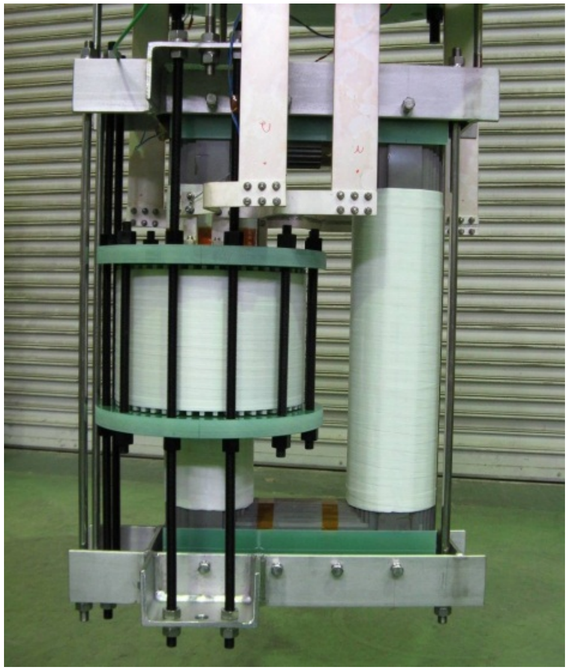
Verification of ac loss reduction with small test transformers

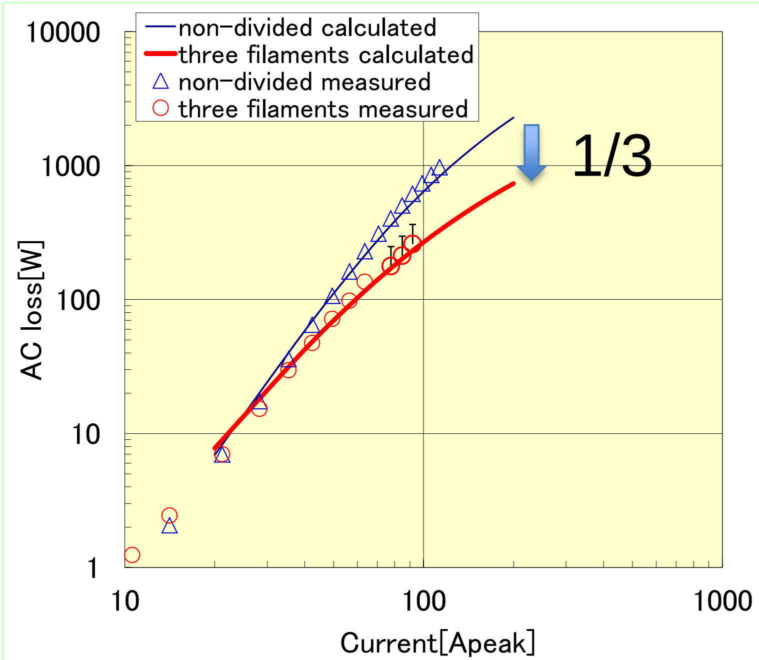
Parameters of Test Transformers for Ac loss Reduction

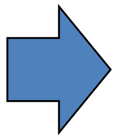
Capacity	215 kVA
Number of phase	1
Rated Voltage (Pri./Sec.)	1075 V / 1075 V
Rated Current (Pri./Sec.)	200 A / 200 A
Load	5.4 W
Inner diameter (Prim. /Second.)	183 mm / 128 mm
Outer diameter (Prim. /Second.)	226 mm / 171 mm
Height (Prim. /Second.)	107 mm
Turn number of each winding	20 turn x 20 layer = 400
1turn voltage	2.69
Total length of GdBCO tapes	445 m



The present 1/10 model transformer was reduced only in current capacity as compared with the designed 20 MVA one. So the applied magnetic field was lower than the penetration field of the GdBCO tape. Hence we made small test transformers and verified the ac loss reduction by our technique.

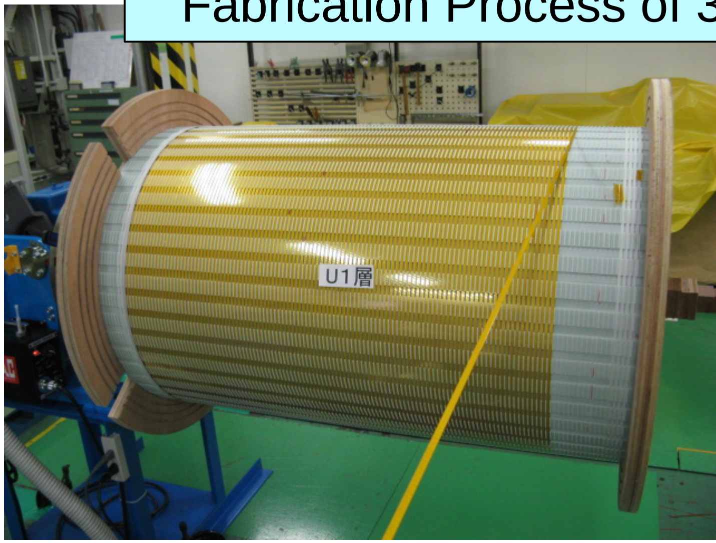


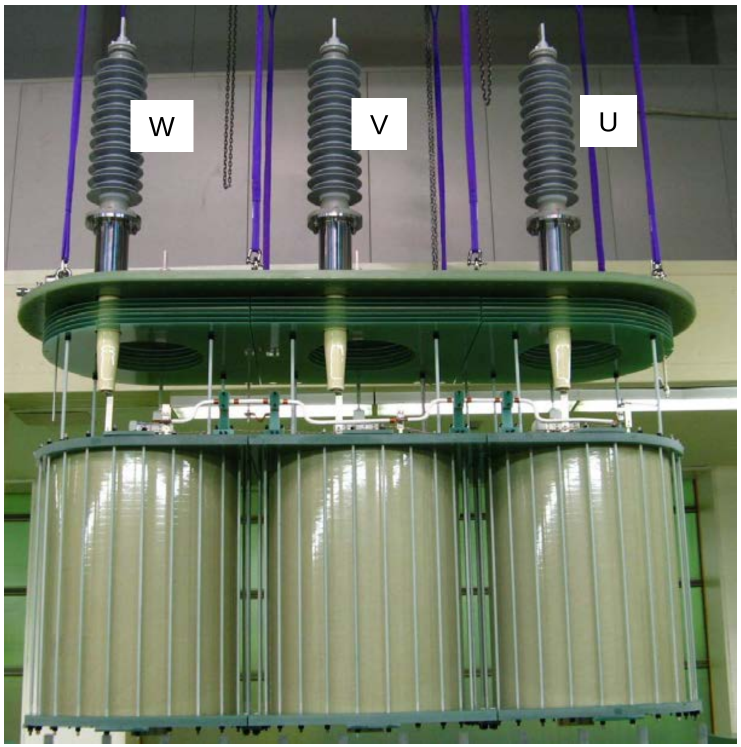


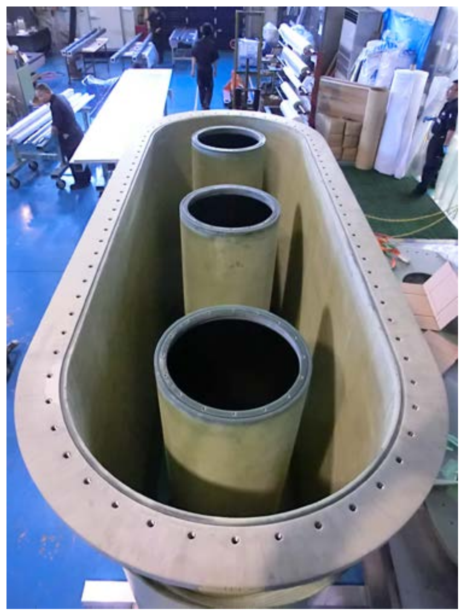


3ϕ-66/6.9kV-2MVA SC Tr.

Fabrication Process of 3⎞-66/6.9kV-2MVA superconducing transformer







3⎞-66/6.9kV-2MVA superconducing transformer system

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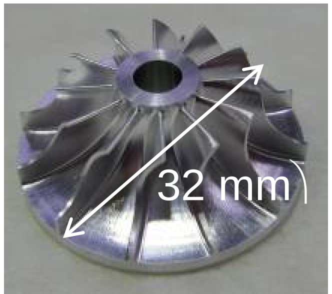
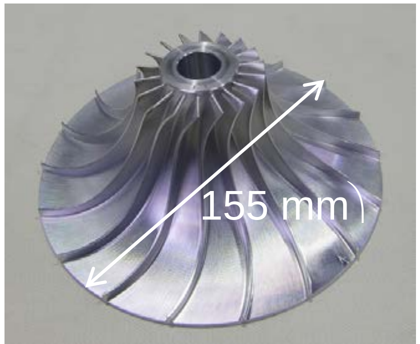
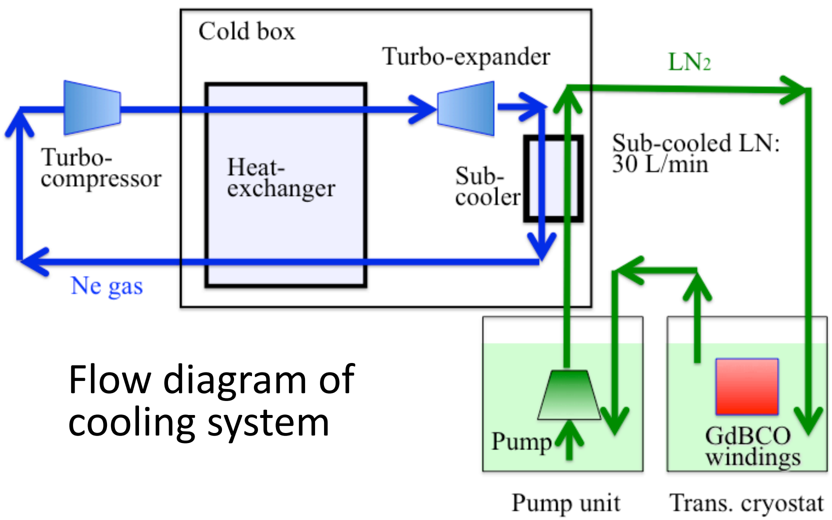
Ne turbo-Brayton refrigerator system



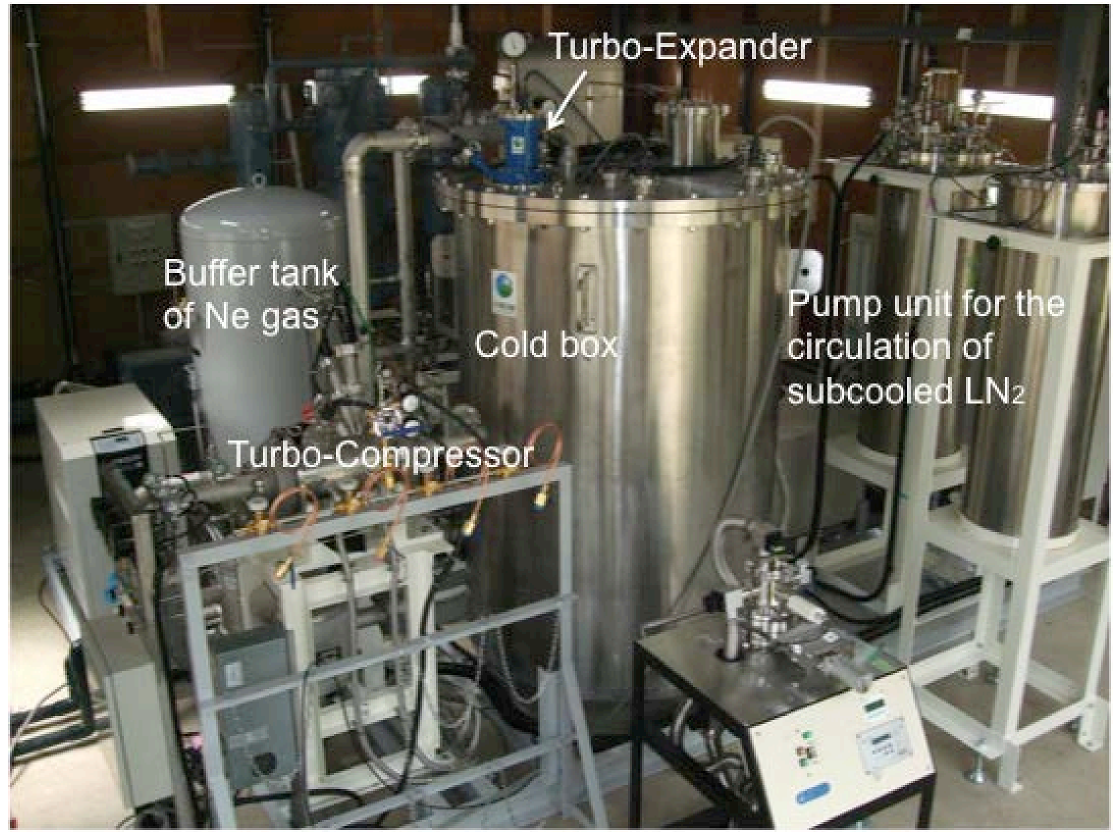
Impeller of expander



Impeller of compressor



Flow diagram of cooling system



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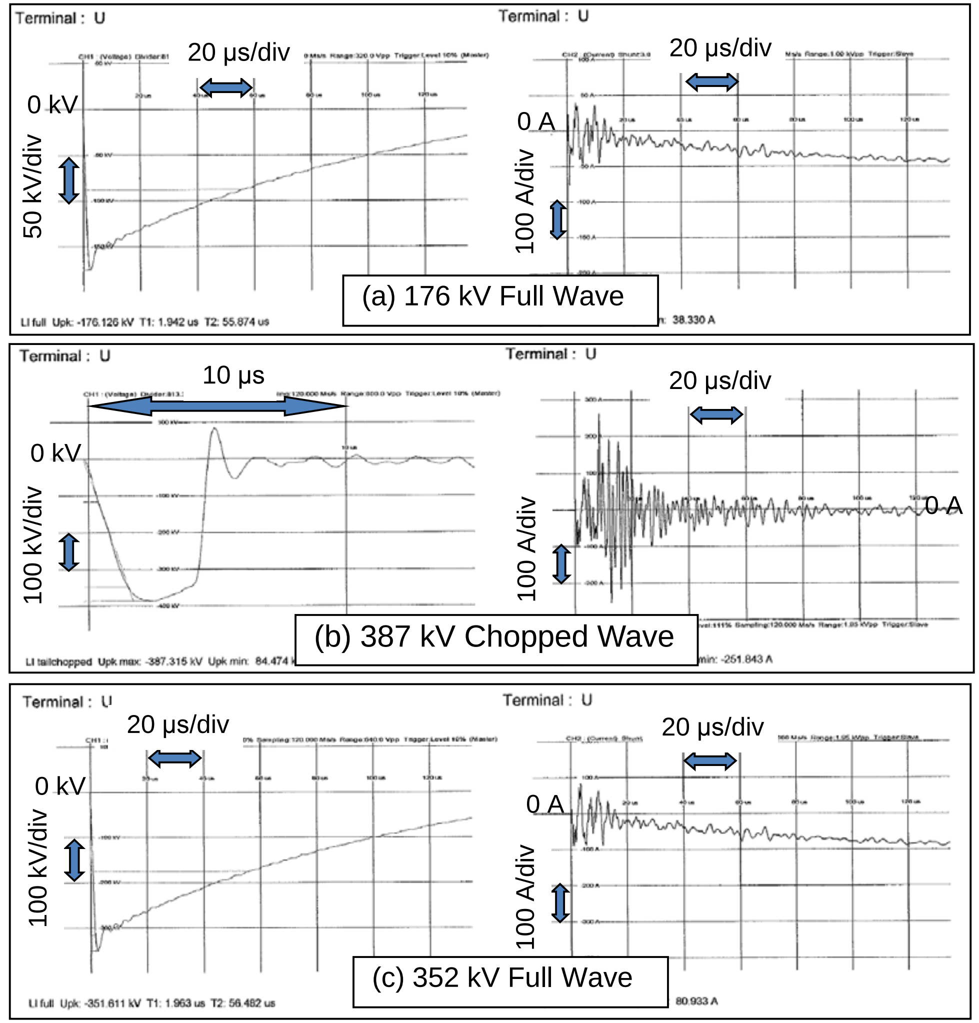
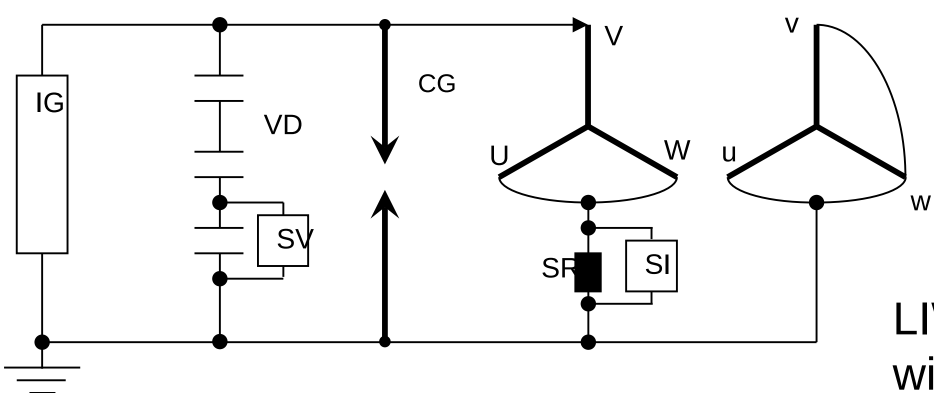
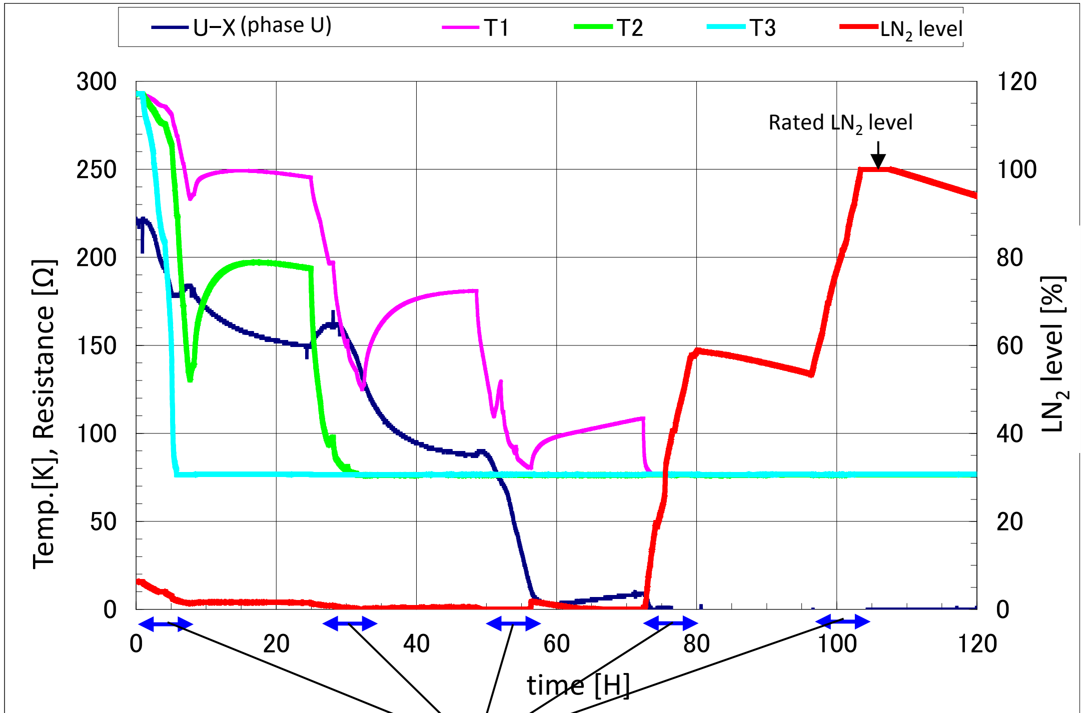
Insulation test：350kV Impulse, 140kV AC excess voltage



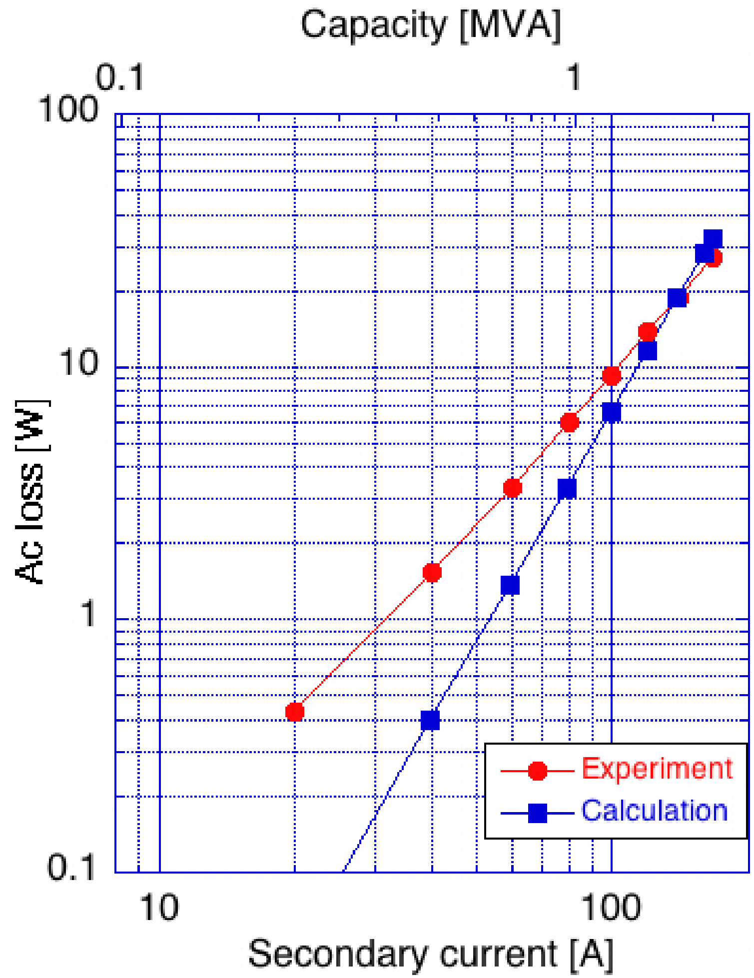


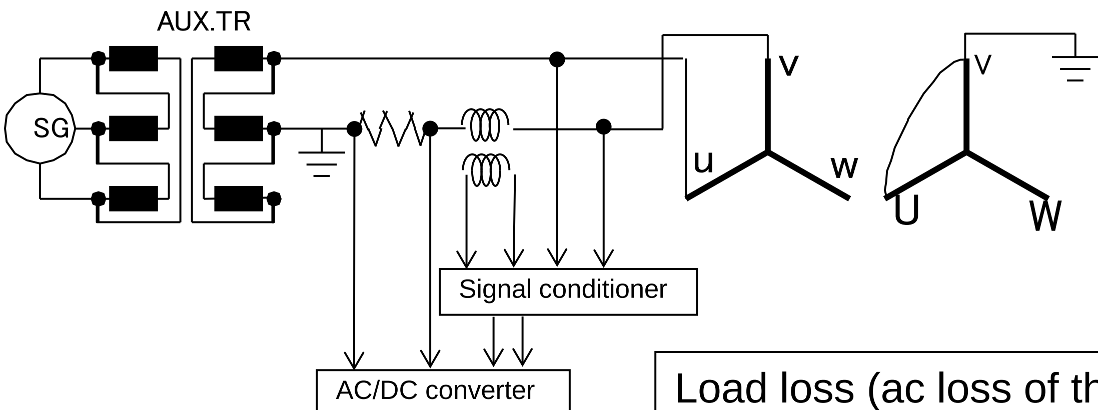
LIWL:350kV, Power frequency AC excess voltage withstand level:140kV for 1 min.

Bath-cooled with LN_2 at 77K and rated operation



Injecting time was 39 hours.
Injected LN_2 4450 L, reserved LN_2 2800 L





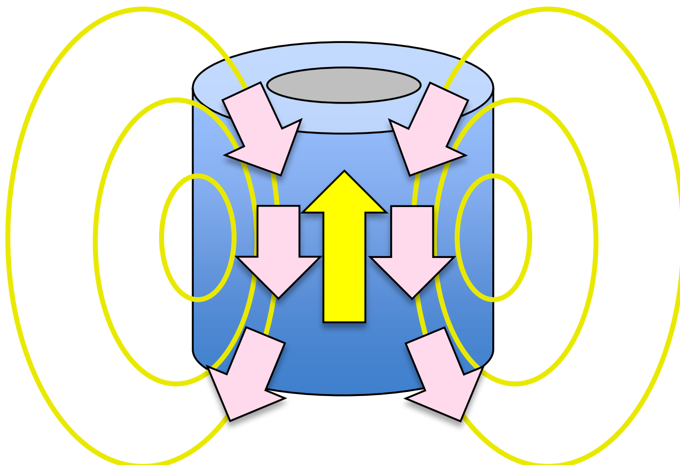
Load loss (ac loss of the windings) : 27W;No load loss (iron loss):8kW

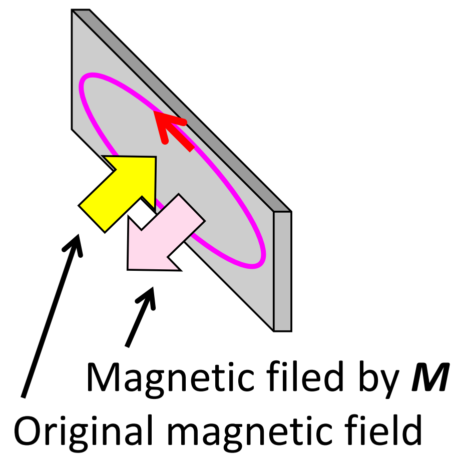
Magnetization reduction for dc use by scribing

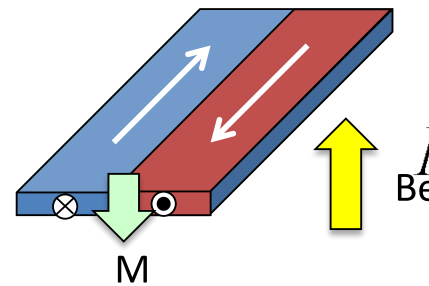
1. M. Iwakuma et al., "New Method for Quick Decay of Shielding Current in REBCO Superconducting Coils", IEEE Trans. Appl. Supercond., Vol. 26, No.4, 2016, Article No. 4403209.

2. M. Iwakuma et al., "Relaxation of Shielding Current in Test Coils for MRI with REBCO Superconducting Scribed Tapes", IEEE Trans. Appl. Supercond., Vol. 26, No.3, 2016, Article No. 4401505.

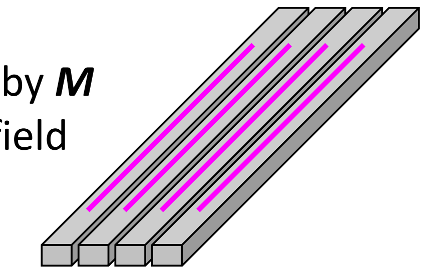
Uniformity of magnetic field under ppm order is required







$$M = \frac{\mu_0 I_c}{4h}$$



$$M = \frac{\mu_0 I_c}{4hn}$$

Produced magnetic field by the induced shielding current disturbs the uniformity of original magnetic field in space.

Shielding current decays due to flux creep and/or flux flow.

Here magnetization, ***M***, is defined as the magnetic moment, ***m***, due to the induced shielding current per unit volume.

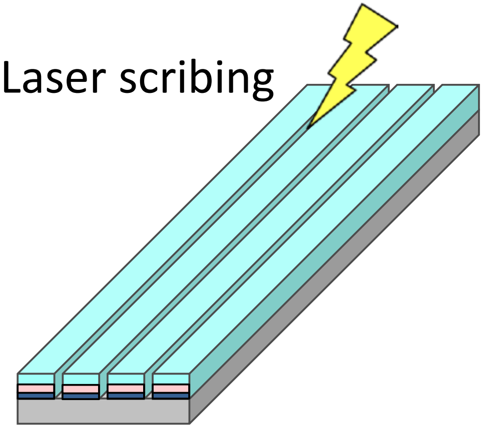
⇒ We can say ***M*** disturbs the uniformity of magnetic field in time and space.

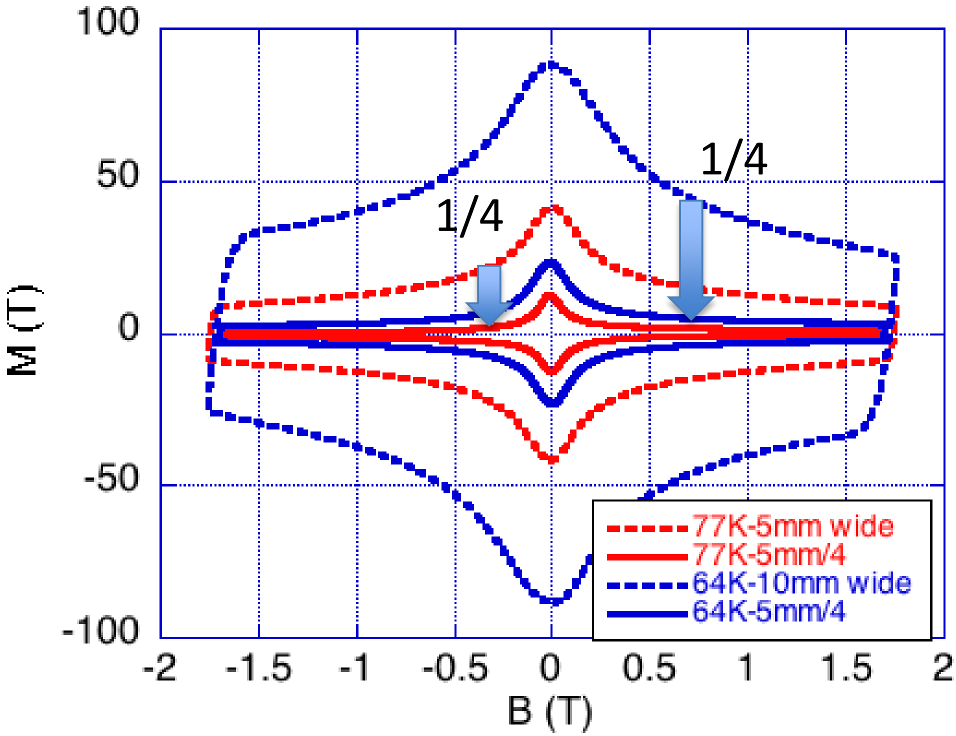
⇒ It is necessary to reduce ***M*** itself for the uniformity of magnetic field.

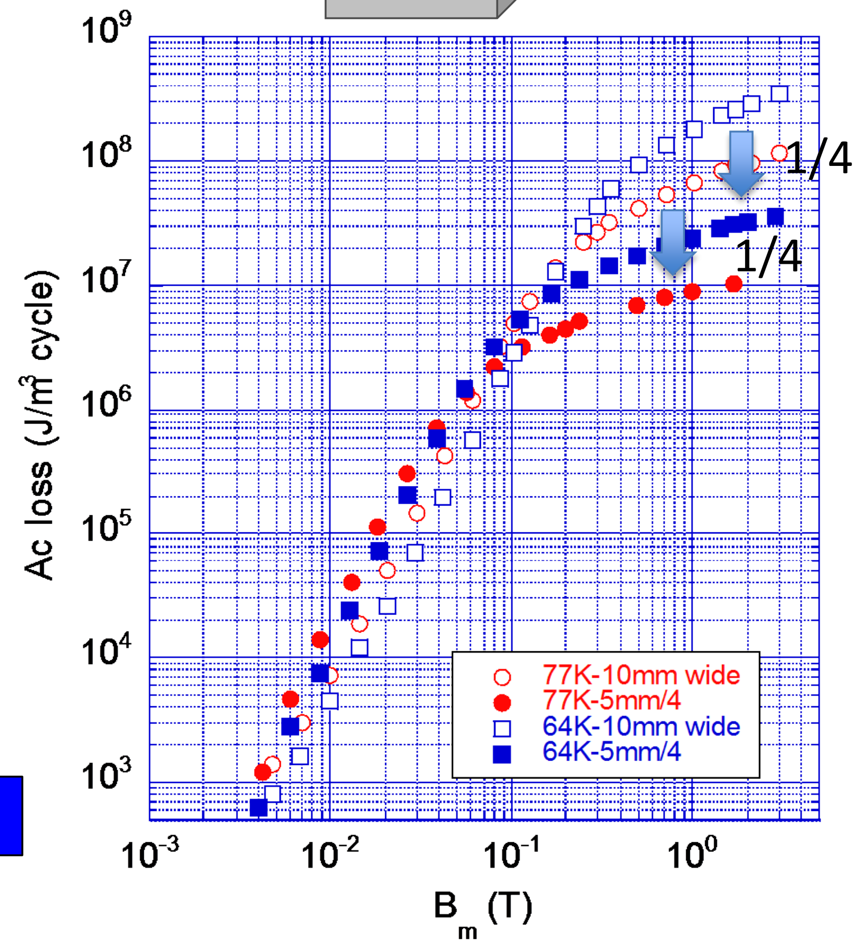
M reduction = Ac Loss Reduction

$$W = \oint H\, dM = -\oint M\, dH$$

Laser scribing

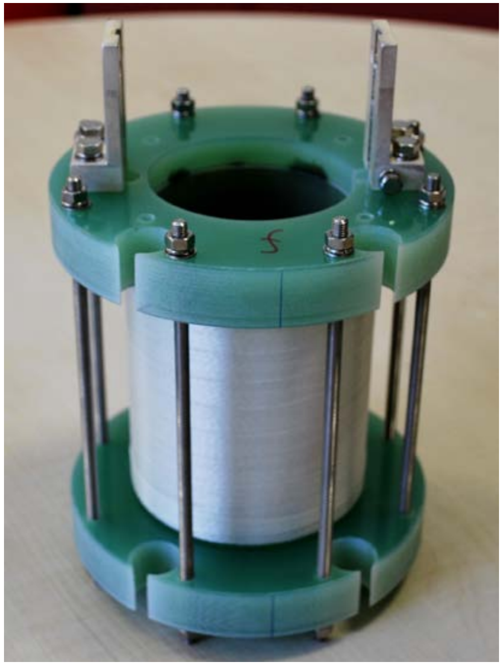






***M* reduction is made by scribing & special winding.**

Test Coils with Non-scribed GdBCO and Scribed EUBCO

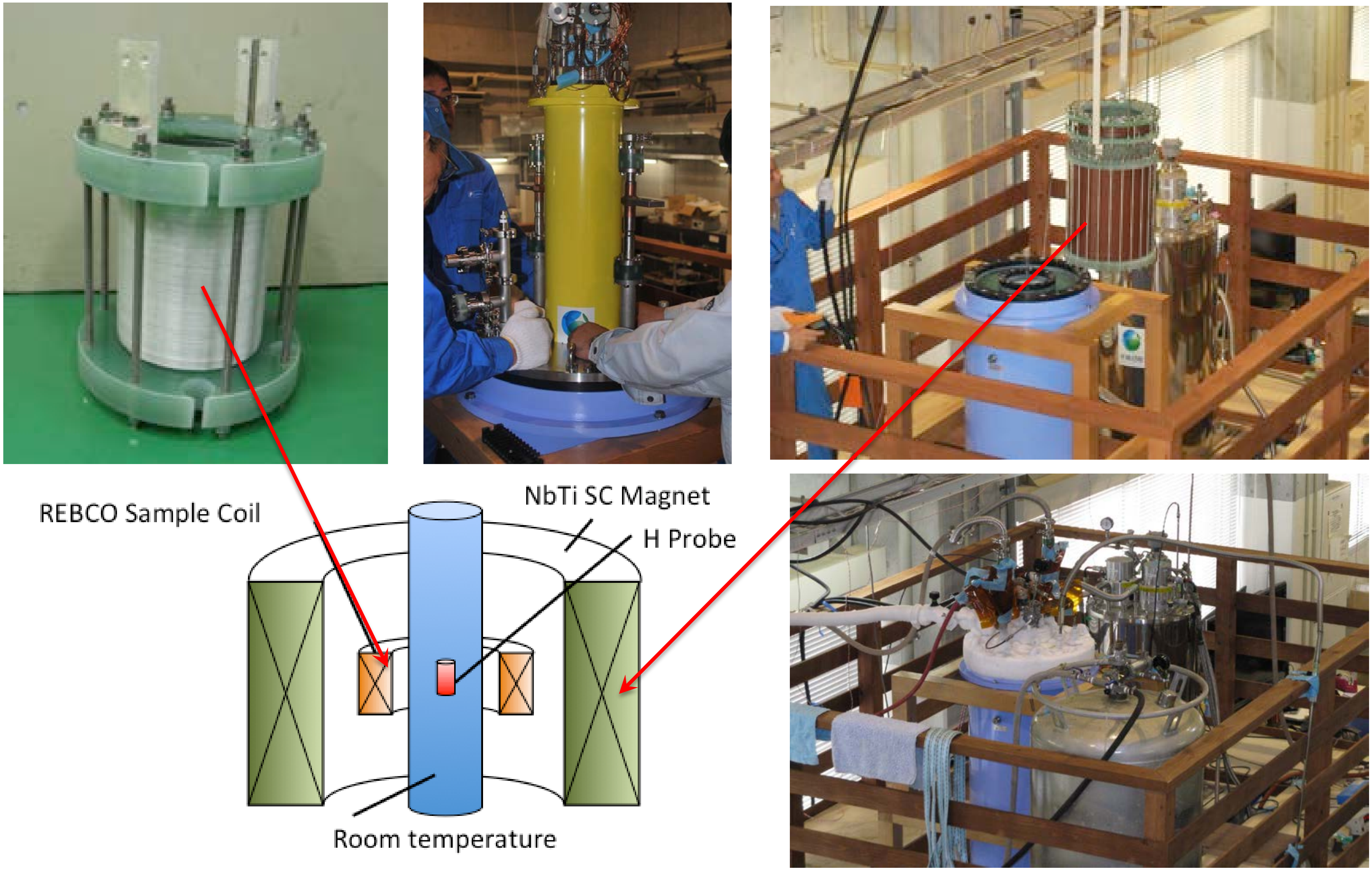


19 turn x 6- or 20-layer Solenoid

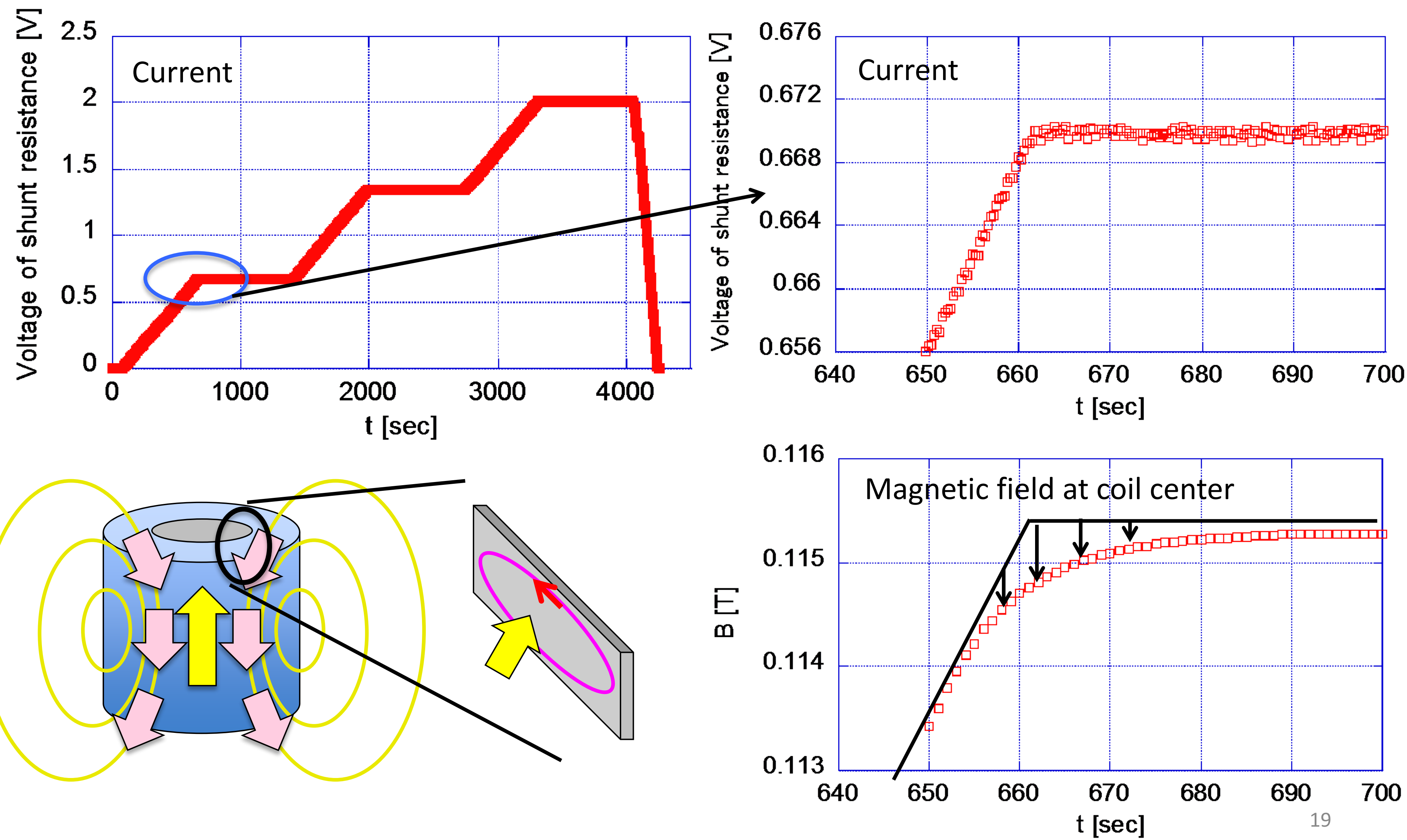
Scribed EuBCO Tape

Width of tape	5 mm
Thickness of tape	112 μm
Length of tape	100 m, 30 m
Substrate	Hastelloy (100 μm)
Buffer layer	CeO_2+$LaMnO_3$+MgO+Y_2O_3+$Gd_2Zr_2O_7$
Superconducting layer	GdBaCuO (1.6 μm), EuBCO+$BaHfO_3$ (1.52 μm)
Number of filaments	1, 4
Ic of tape (@77K, s.f.)	219.5 A, >300 A
Winding	Solenoid (19 turn / layer, 20 or 6 layers)
Hight of winding	102 mm
Inner diameter of winding	80 mm
Outer diameter of winding	86.0 , 81.8 mm
Bobbin	GFRP
Produced magnetic field	3.42 mT/A, 1.14 mT/A
Ic of coil (@77K)	75A, 140A

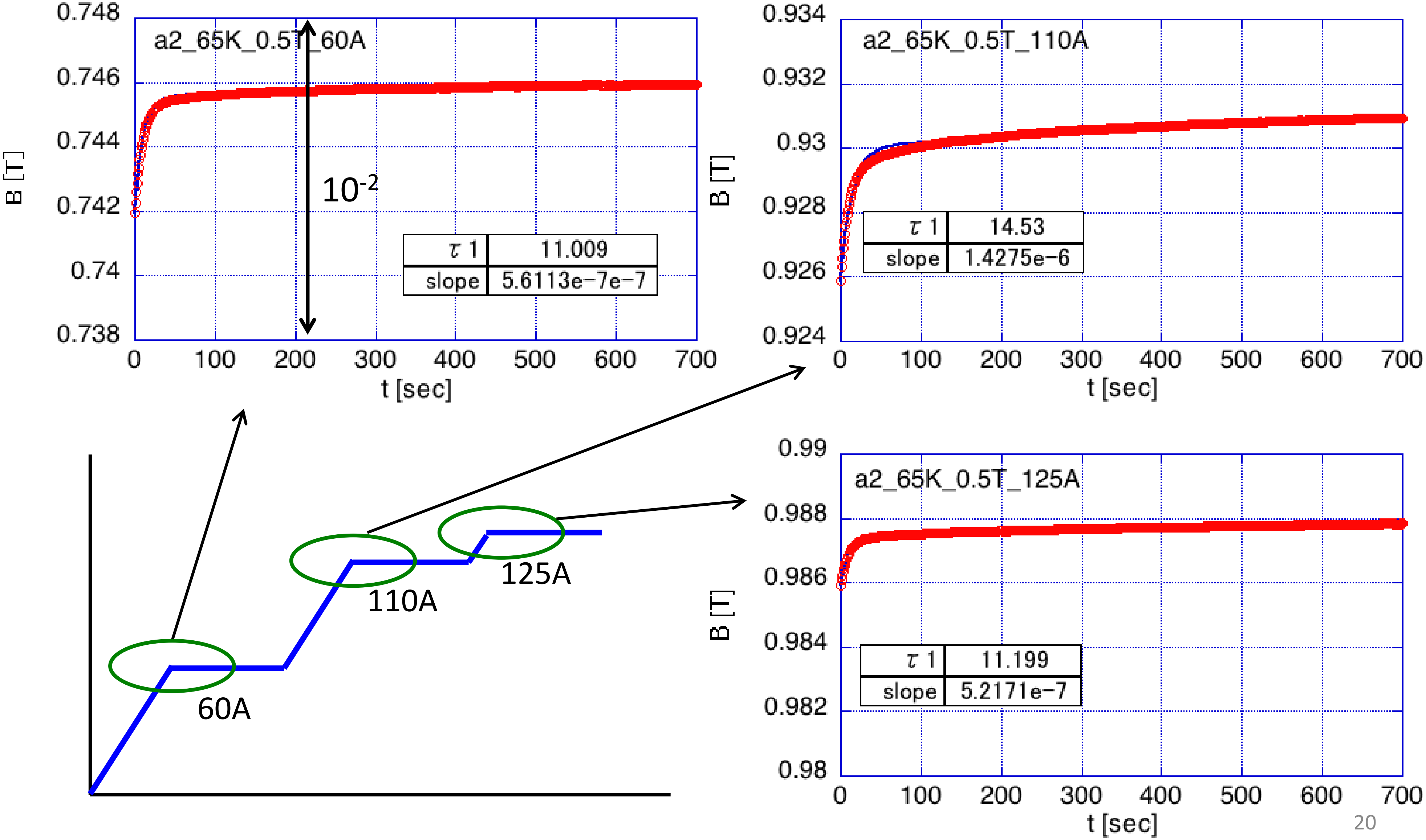
Experimental Setup (in background field by NbTi Magnet)



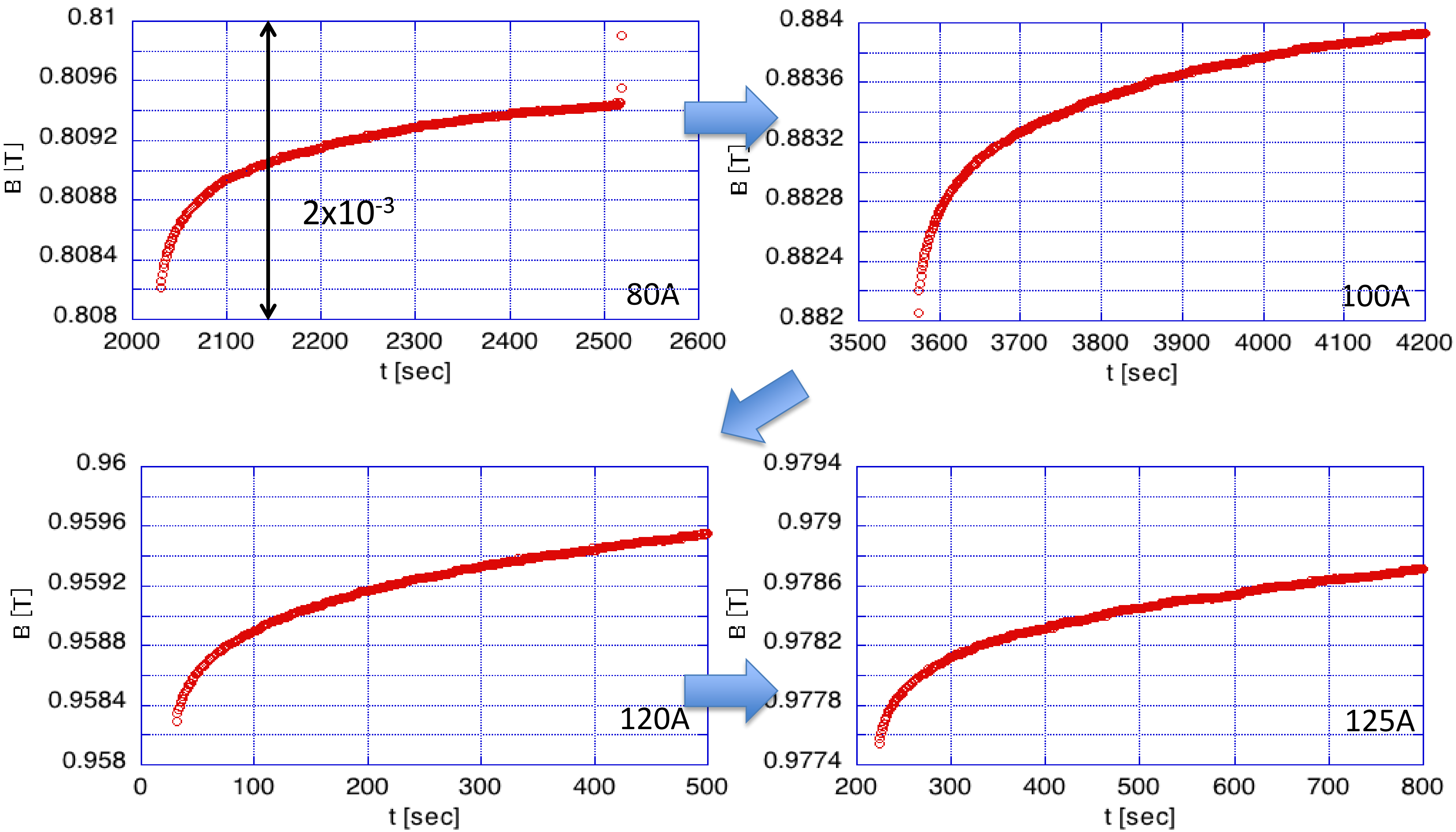
Variation of Current and Magnetic Field



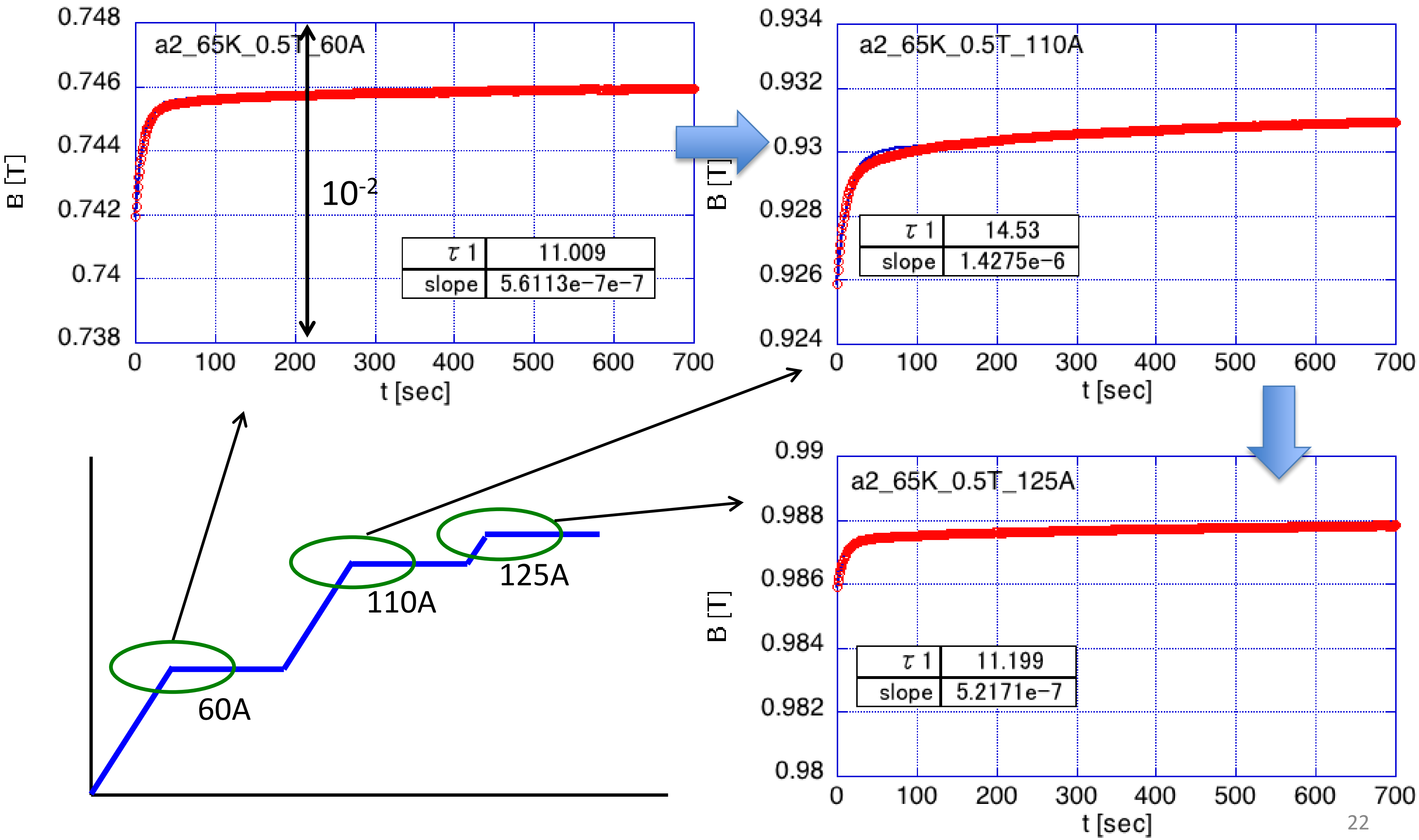
65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)



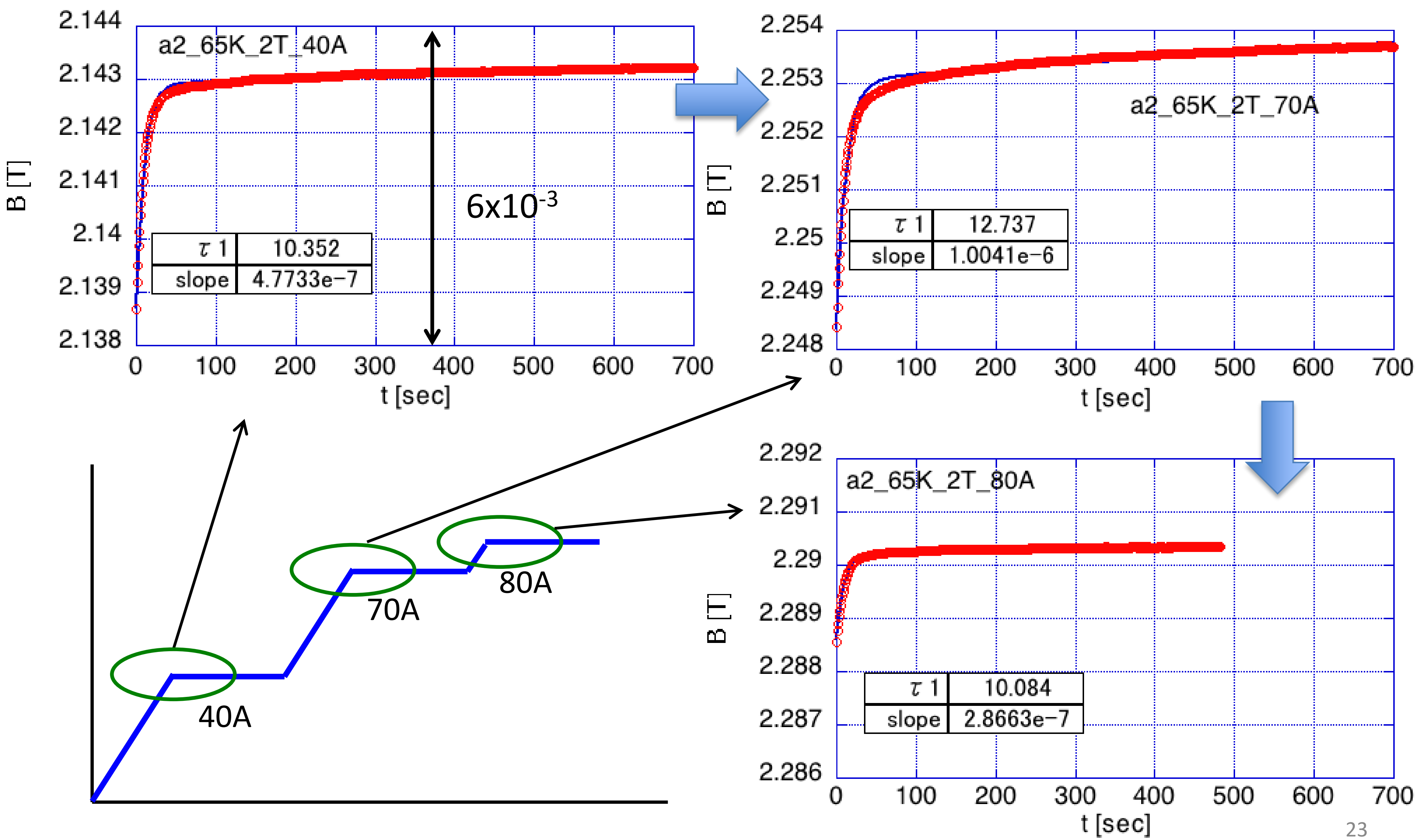
65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)



65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)

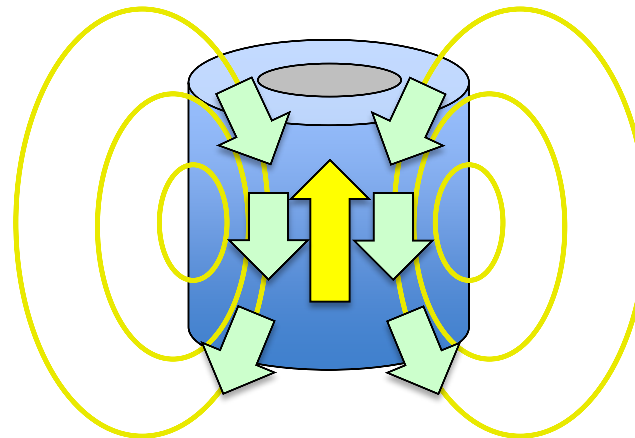


65K, 2T (GbBCO 100m, 19-turn, 20-layer)



Analysis

$$B_{center} = B_0 + B_1\left(1 - e^{-\frac{t}{\tau_1}}\right) + B_2\left(1 - e^{-\frac{t}{\tau_2}}\right) + \cdots$$



Contribution by each turn or each part

In the case of decay time constant τ >> t

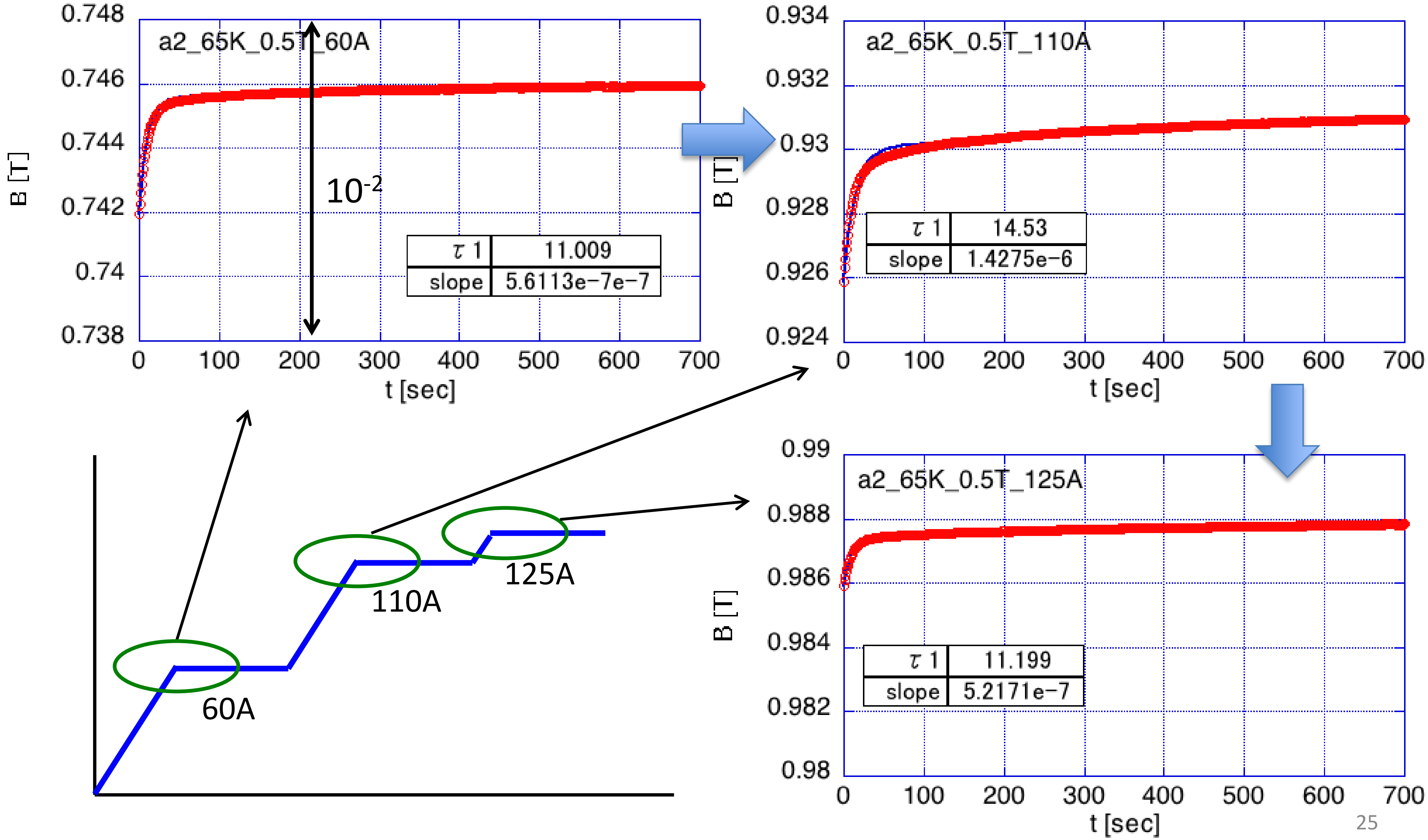
$$B_i\left(1 - e^{-\frac{t}{\tau_i}}\right) = B_i\left(1 - \left(1 - \frac{t}{\tau_i} + \frac{1}{2!}\left(\frac{t}{\tau_i}\right)^2 - \frac{1}{3!}\left(\frac{t}{\tau_i}\right)^3 + \cdots\right)\right)$$

$$= B_i \frac{t}{\tau_i}$$

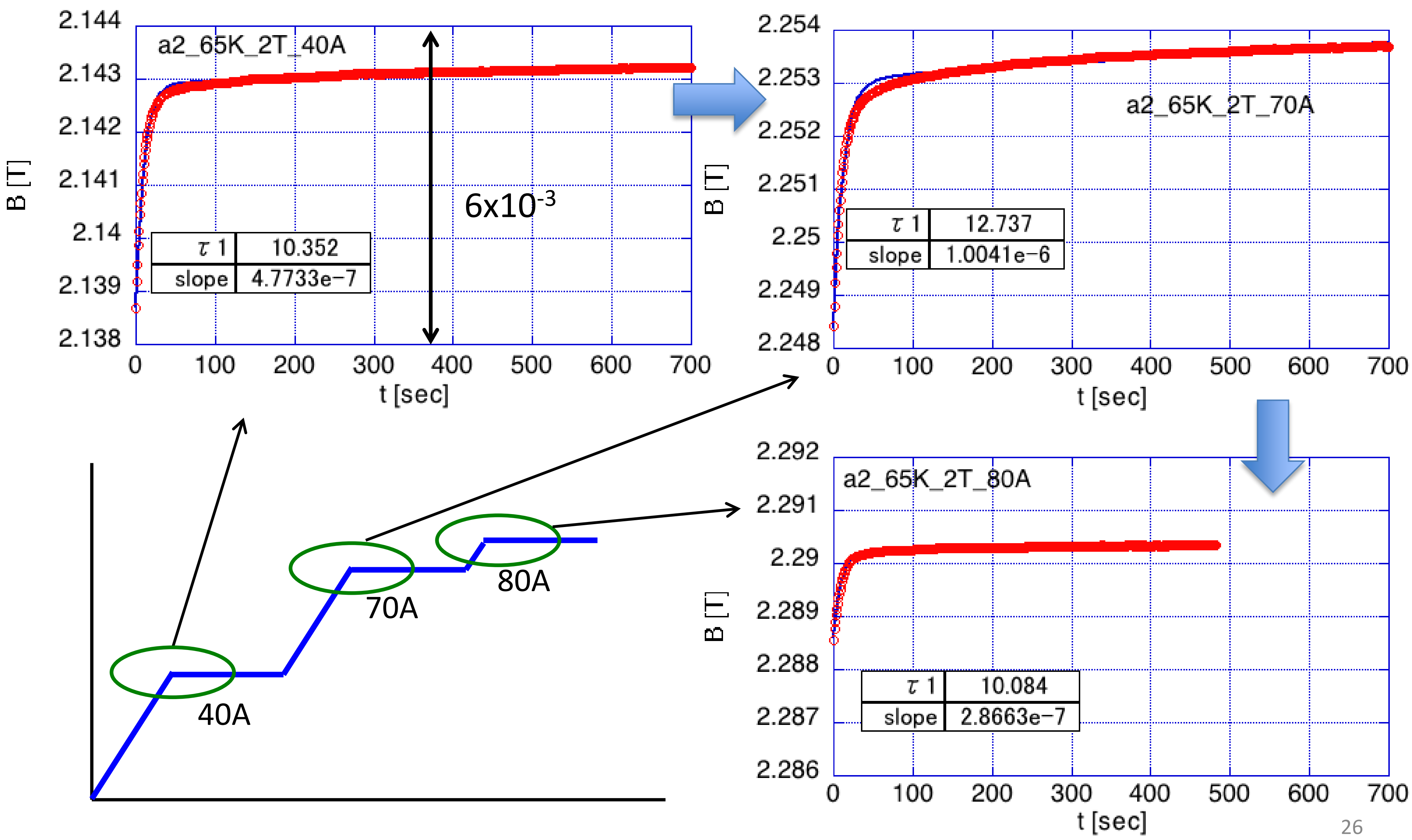
$$B_{center} = B_0 + B_1\left(1 - e^{-\frac{t}{\tau_1}}\right) + B_2 t$$

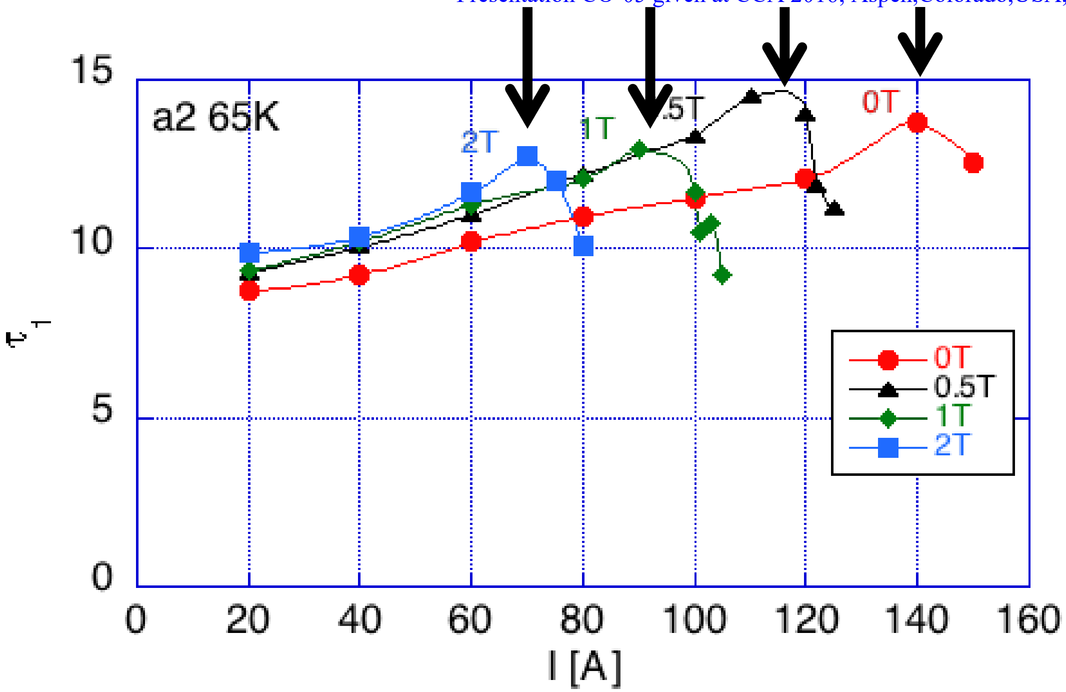
Let us pay attention to decay time constant, τ_1, and gradient of linear part, B_2

65K, 0.5T (GbBCO 100m, 19-turn, 20-layer)



65K, 2T (GbBCO 100m, 19-turn, 20-layer)

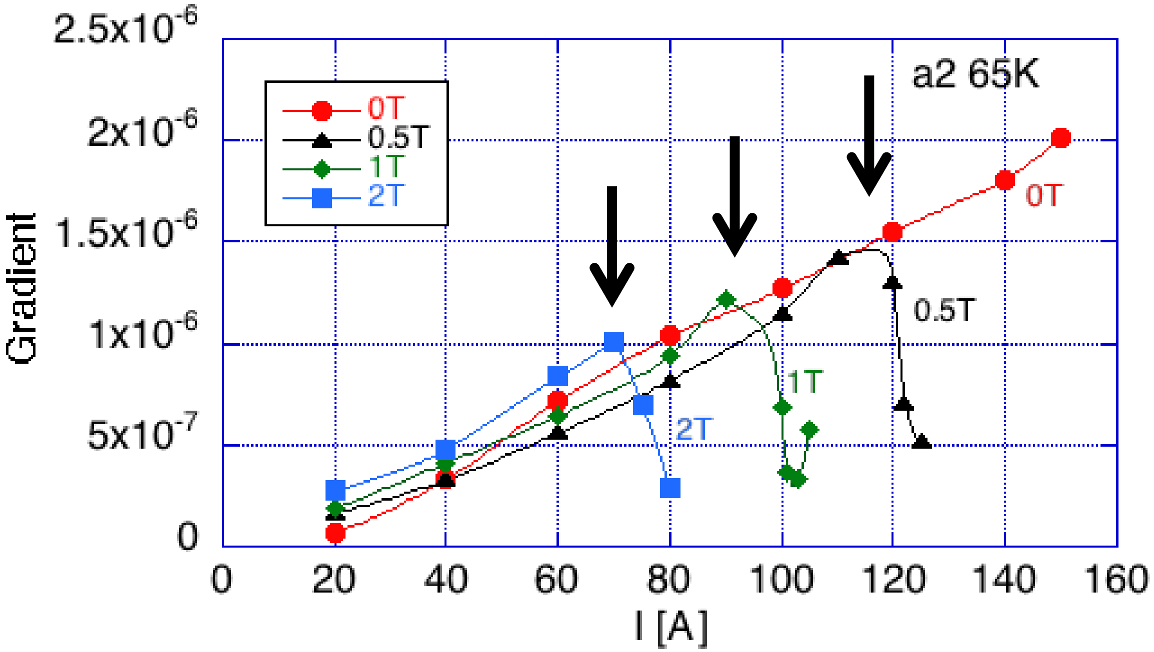


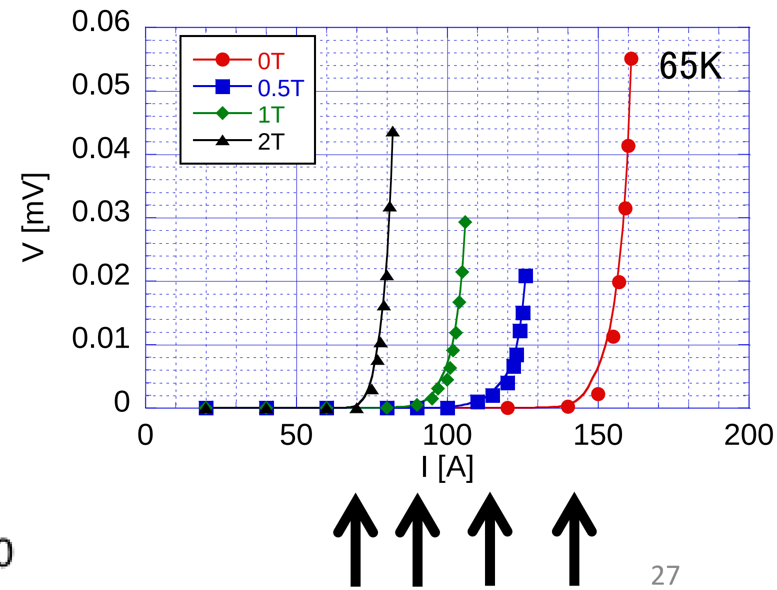


$$B_{center} = B_0 + B_1\left(1 - e^{-\frac{t}{\tau_1}}\right) + B_2 t$$

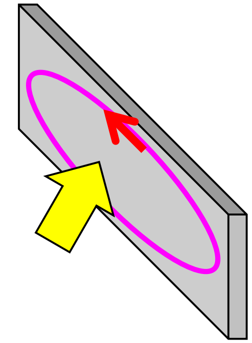
T_1 and B_2 do not depend on B and increase with I for $I < I_{th}(B)$.

T_1 and B_2 start to decrease for $I > I_{th}(B)$.
$I_{th}(B)$ is proportional to $I_c(B)$.

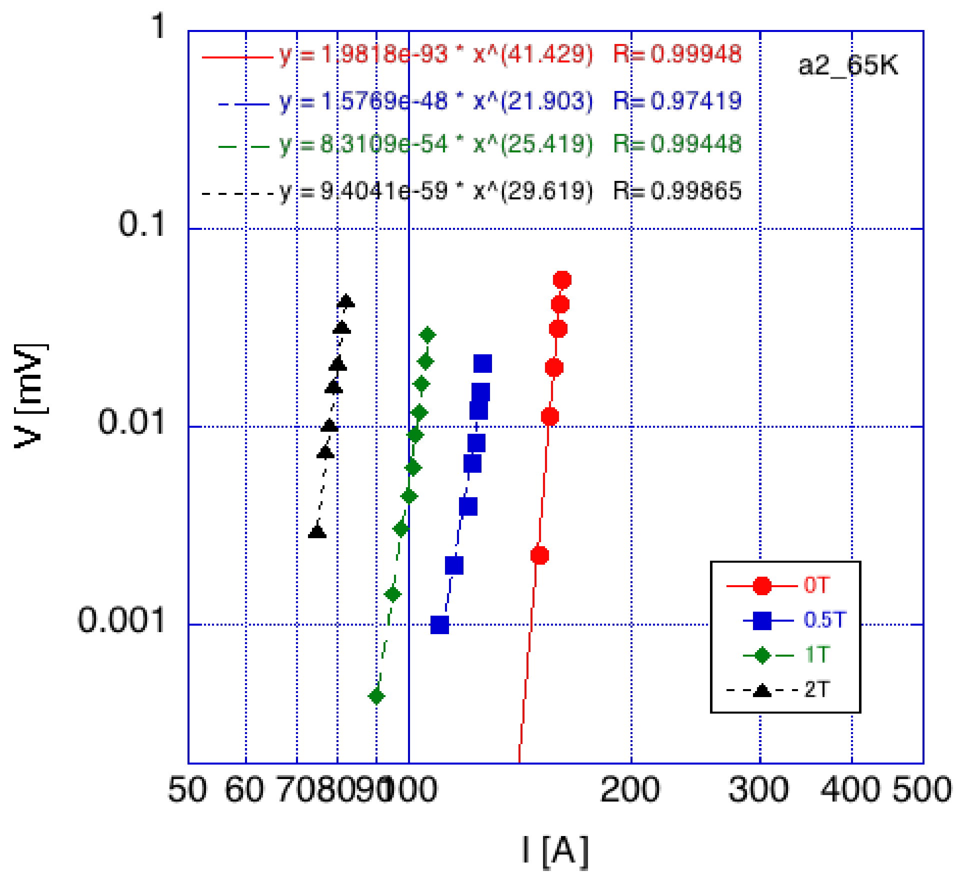


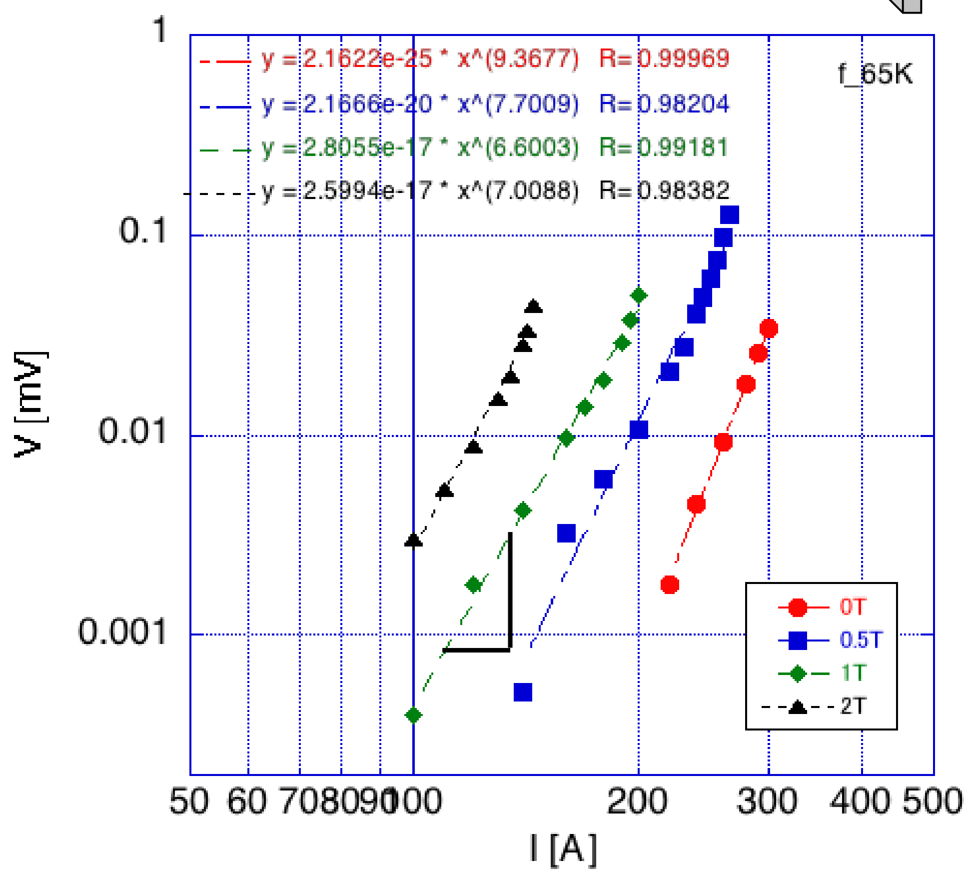


I-V curve



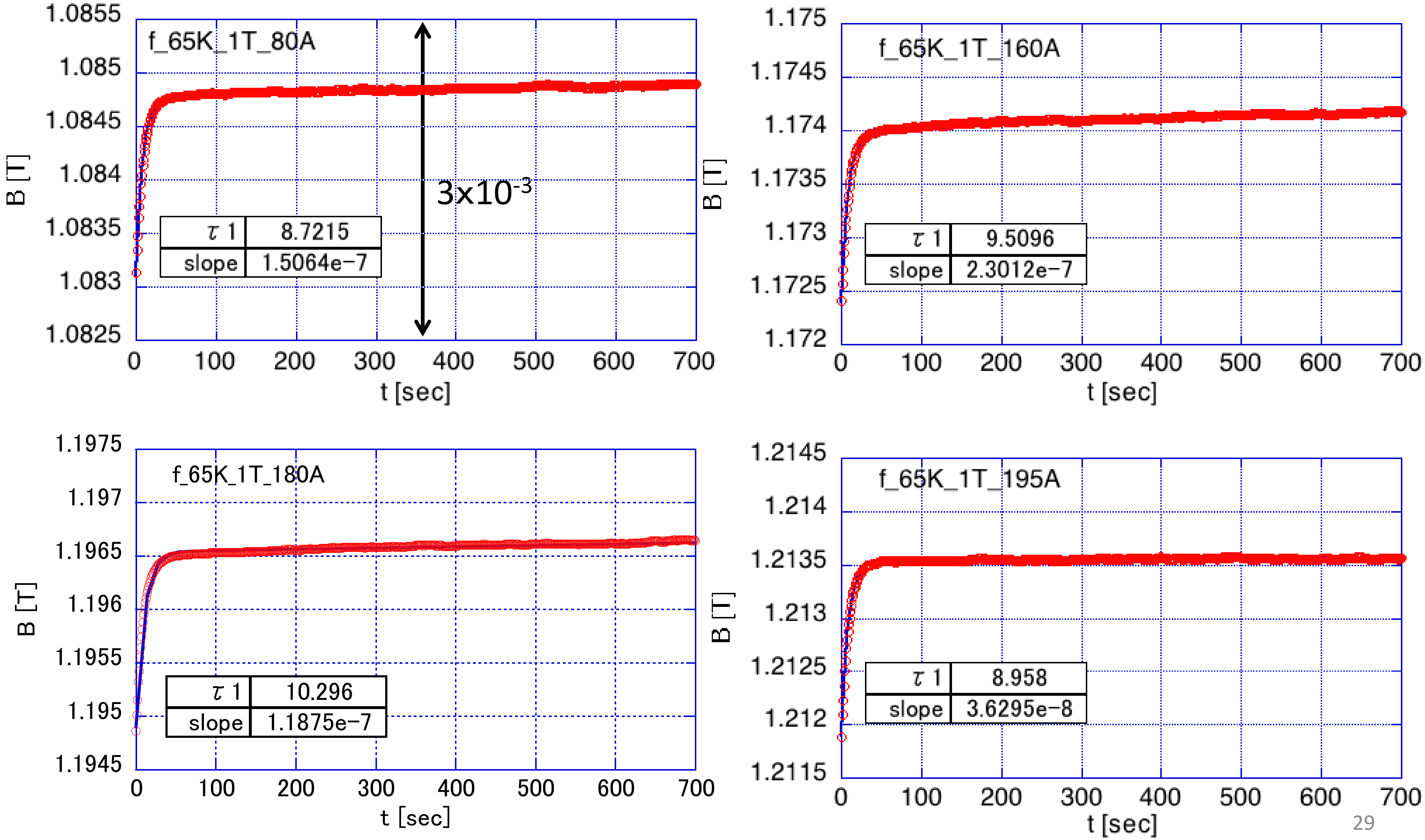
$$B_{center} = B_0 + B_1\left(1 - e^{-\frac{t}{\tau_1}}\right) + B_2 t \qquad \tau = \frac{L}{R} \qquad R = \frac{V}{I} = \frac{V_c}{I_c}\left(\frac{I}{I_c}\right)^{n-1}$$

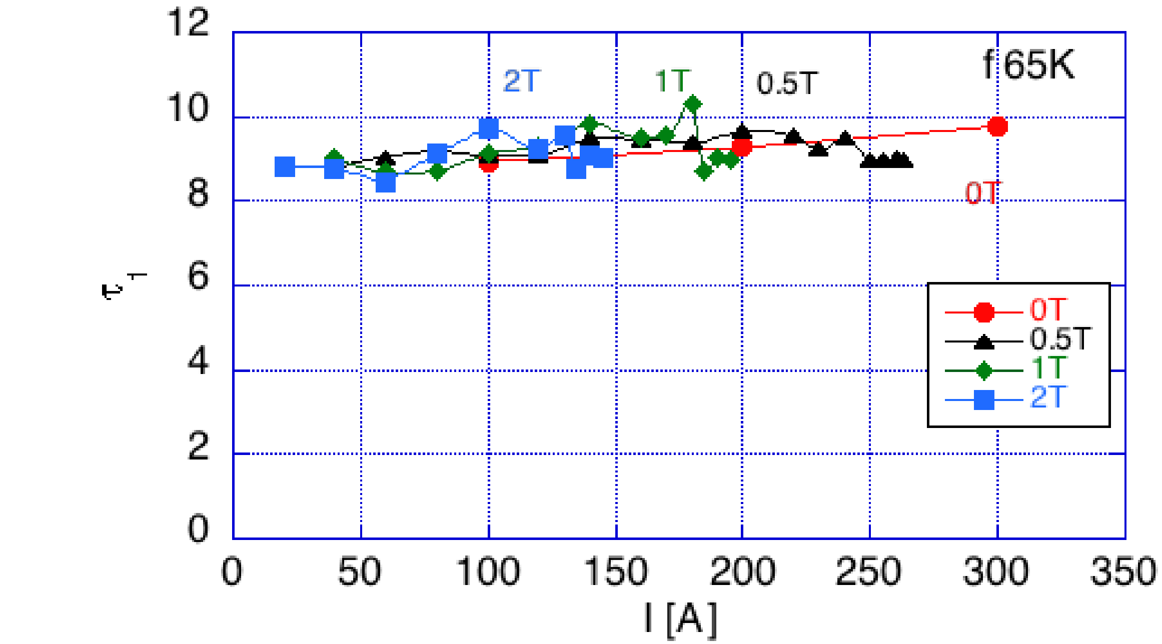




Equivalent resistance becomes larger with current and then decay time constant becomes small.

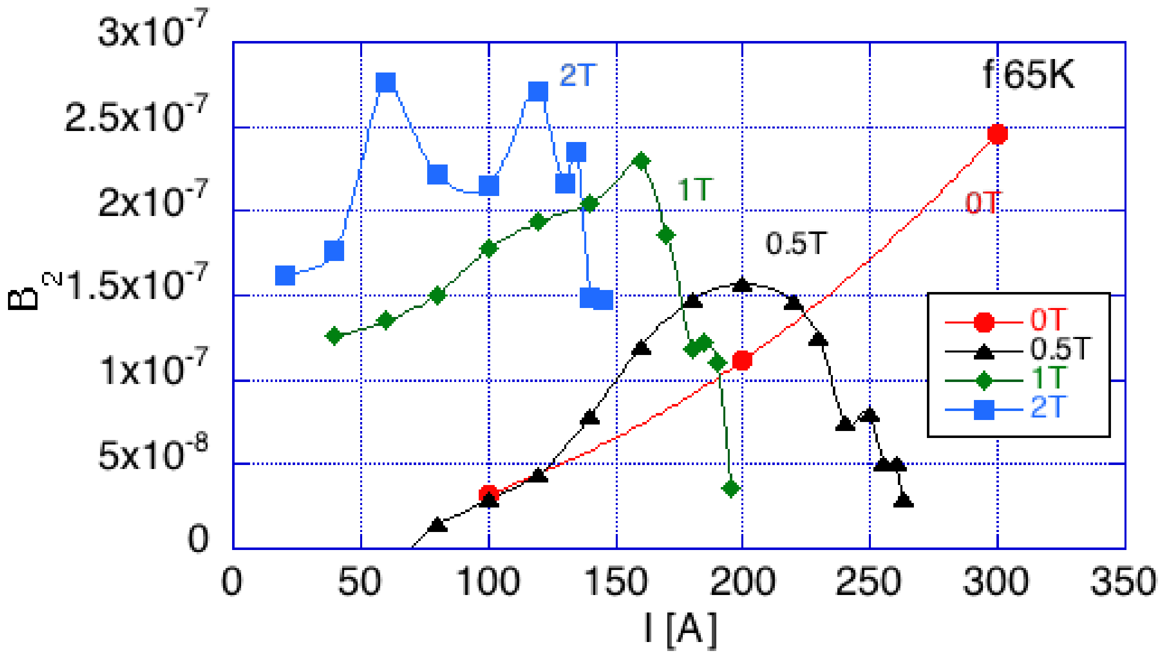
65K, 1T (Scribed EuBCO 30m, 19-turn, 6-layer)

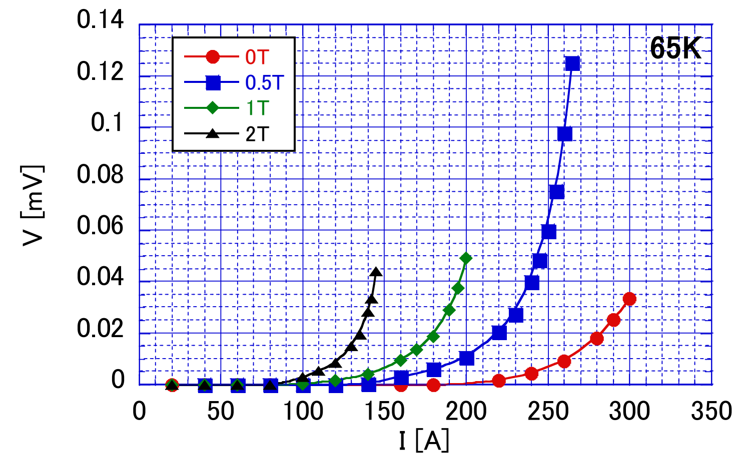


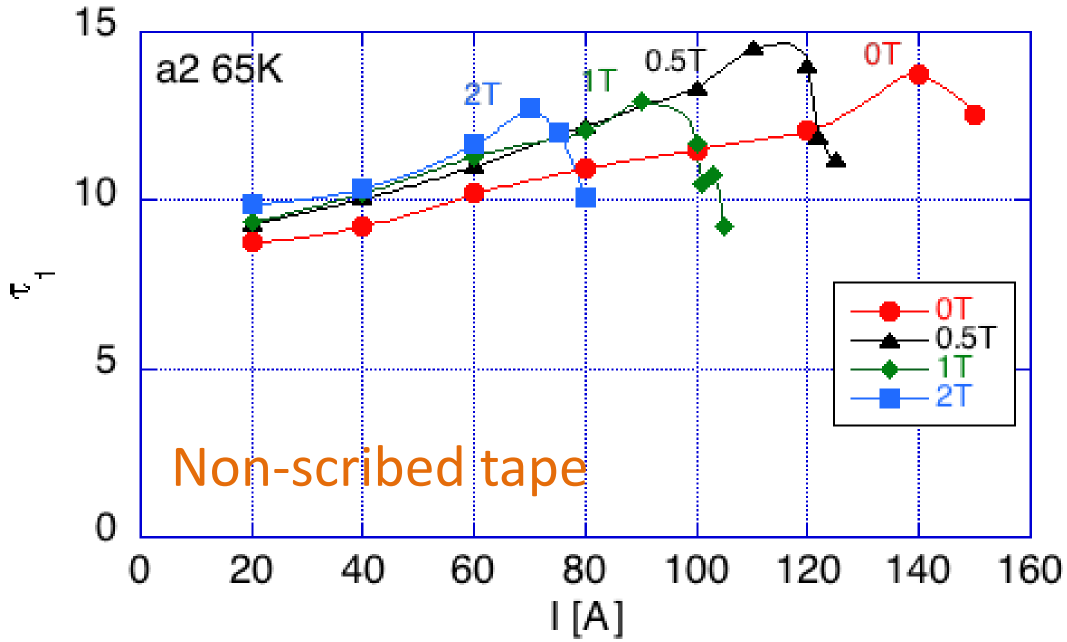


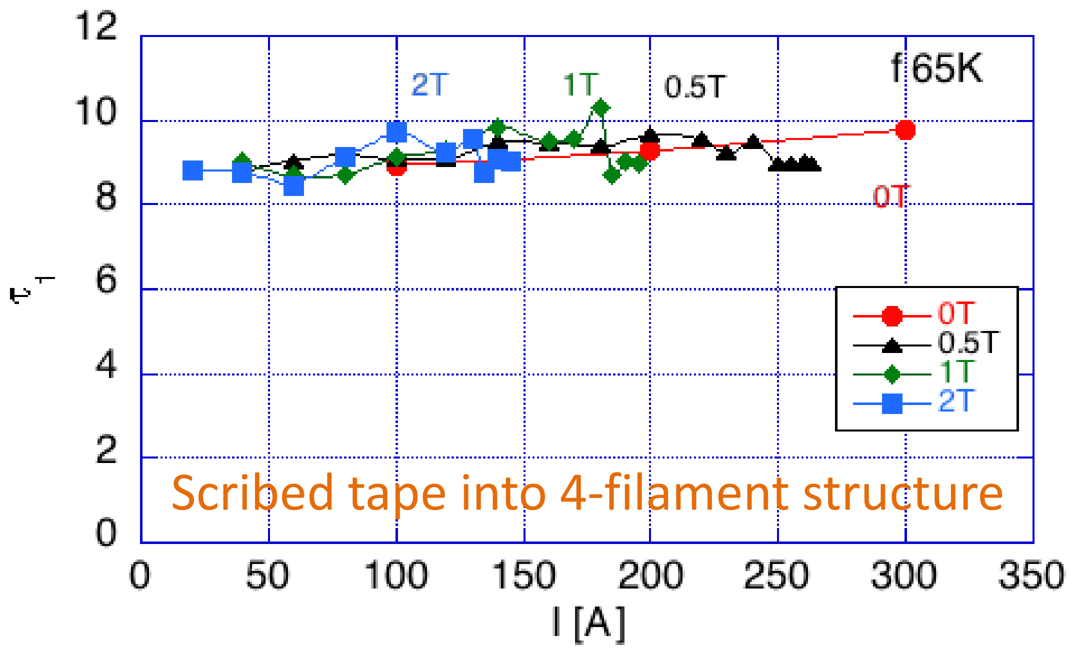
T_1 and do not depend on B.
B_2 increase with I and B for I < I_{th}(B).

T_1 and B_2 start to decrease for I > I_{th}(B).
I_{th}(B) is proportional to I_c(B).







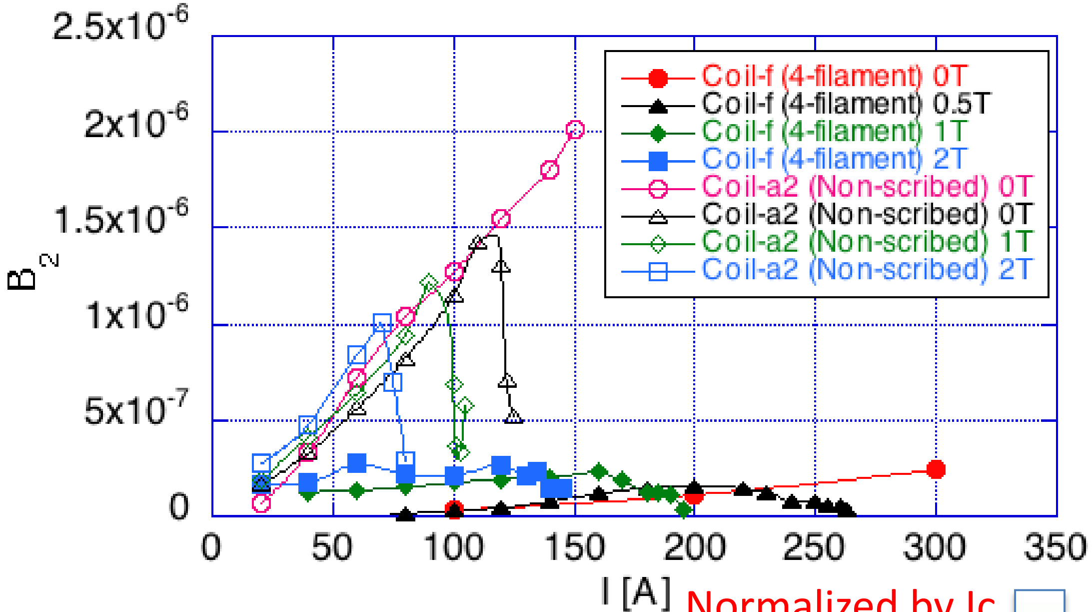


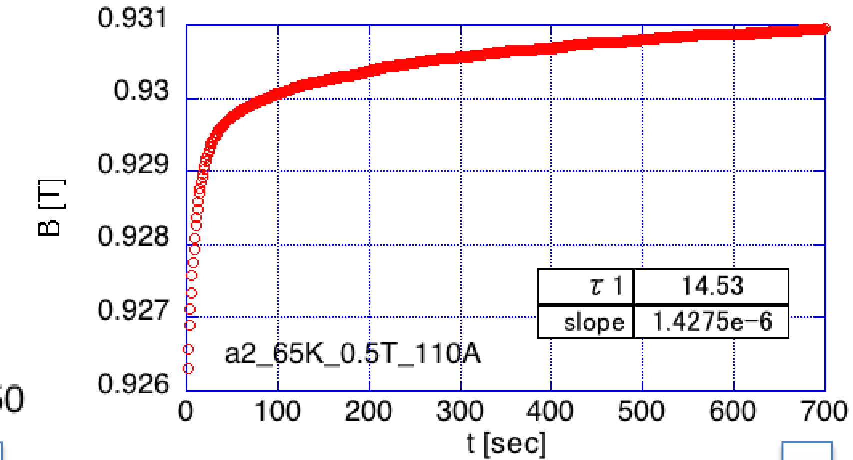
Comparison of τ_1

↓

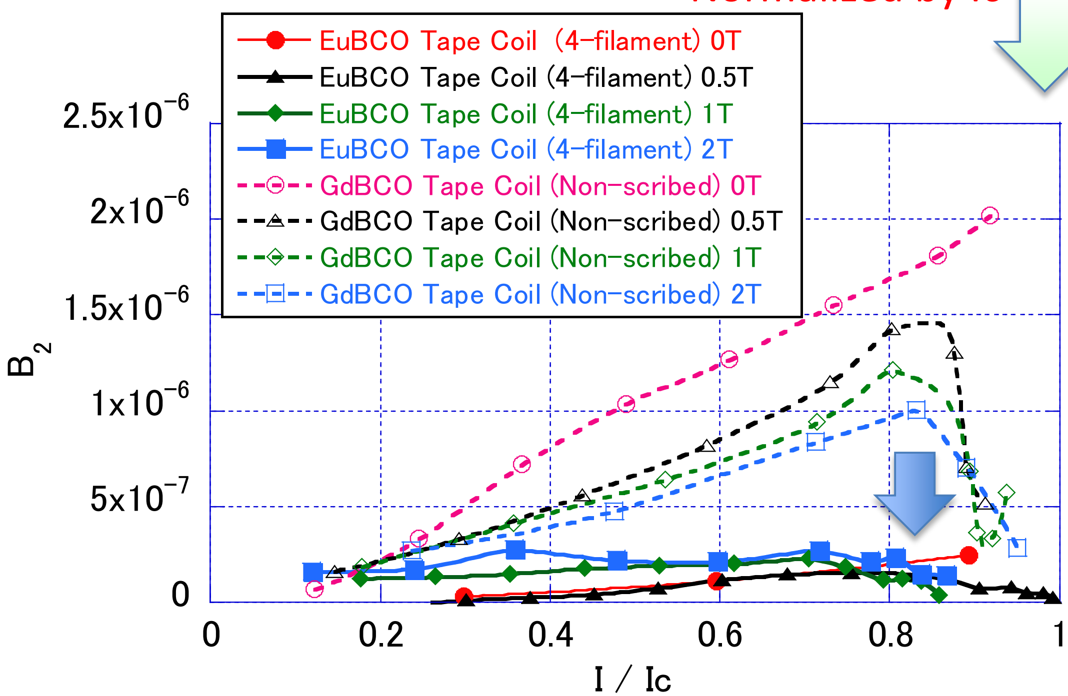
Little difference

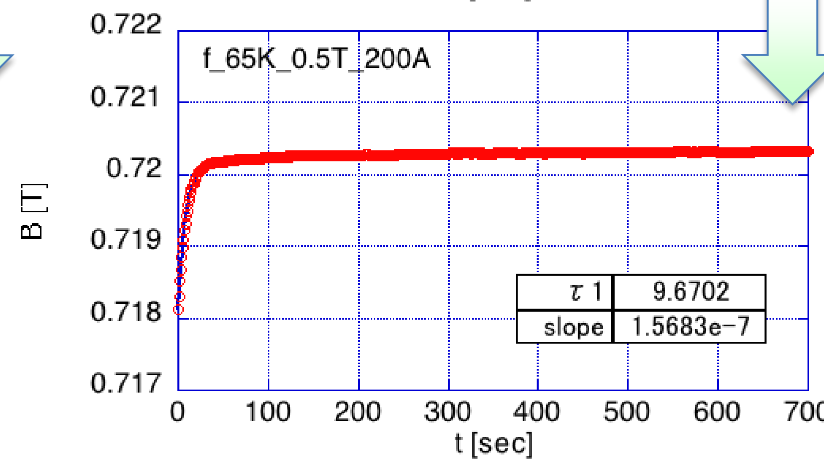
Comparison





Normalized by Ic

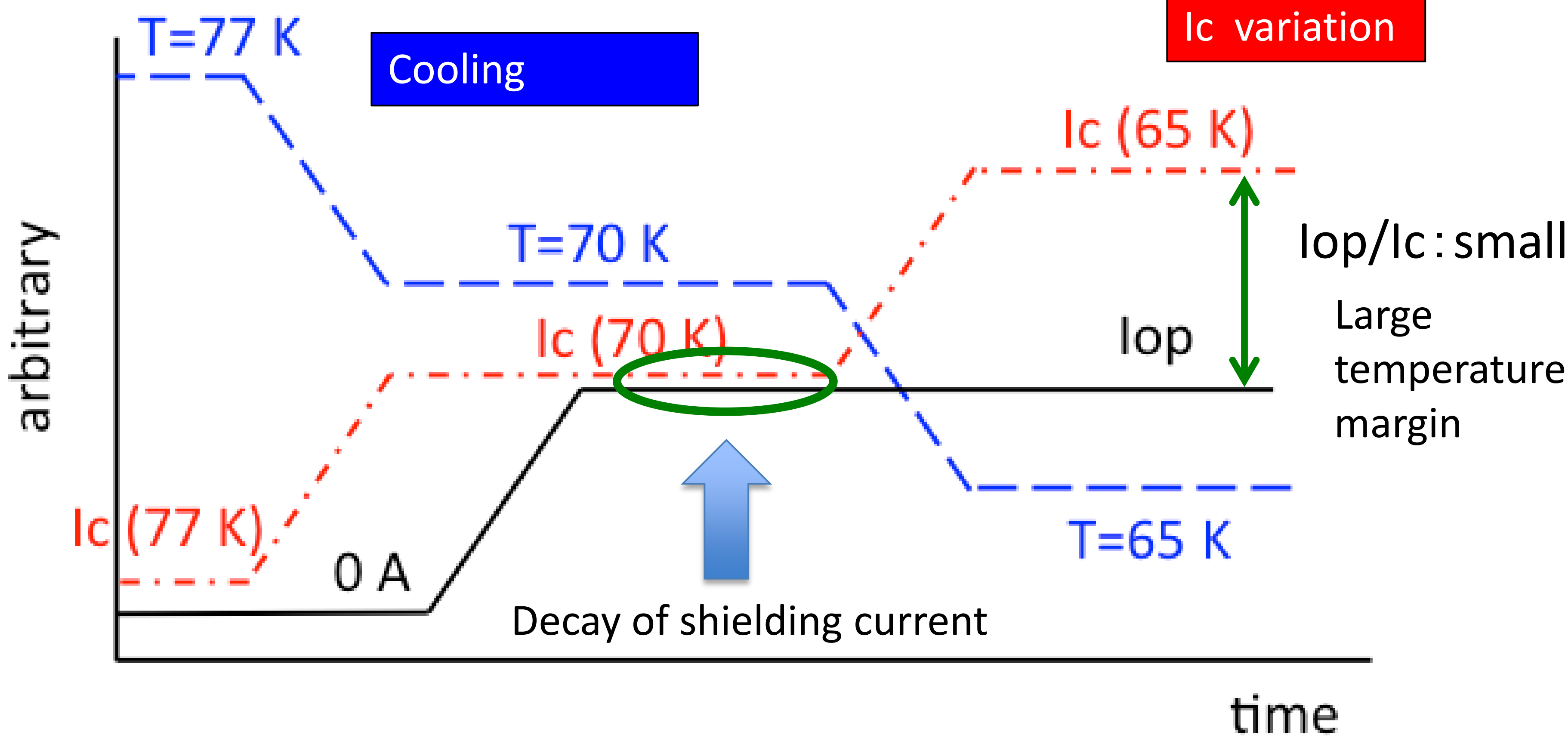




Gradient was much reduced by scribing.

Scribing brings about benefit for DC use.

Operating pattern of MRI magnets to enhance the decay of shielding current



3. Summary

(1) Magnetization and ac loss of REBCO SC tapes can be reduced by scribing & special winding.

(2) It brings about benefits for both of ac and dc uses.

(3) Improvement in superconducting property of REBCO tapes will realize operation in subcooled LN_2 at 65 to 77K.

(4) It brings about very good cooling condition and high stability.