TOHOKU
UNIVERSITY

2014 Kyoto
WAMHTS-2

Nov.13-14, 2014, Kyoto, Japan

Deatailed design of a 25 T Cryogen-free Superconducting Magnet (25T-CSM)

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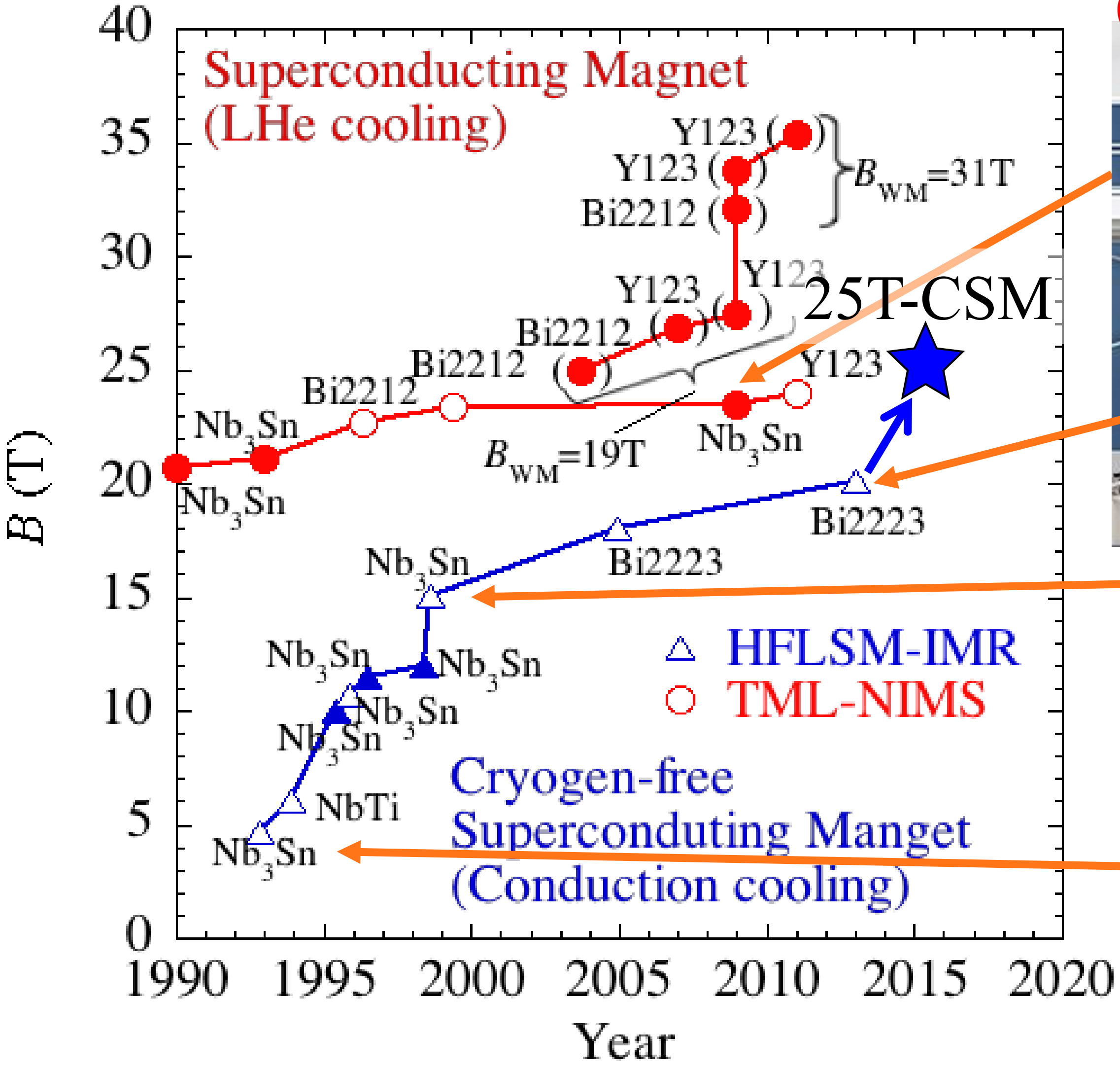
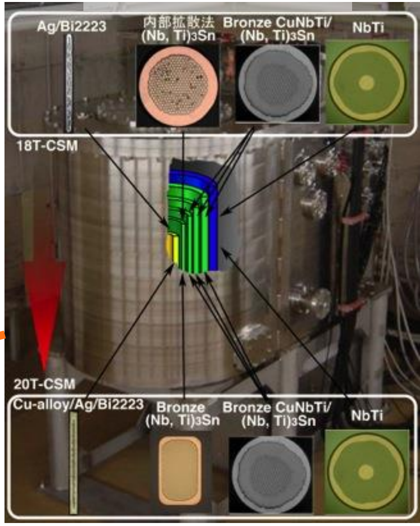
Progress of Superconducting Magnets



1GHz-NMR
(23.5T-ϕ54)

20T-ϕ52



4T-ϕ36

15T-ϕ52

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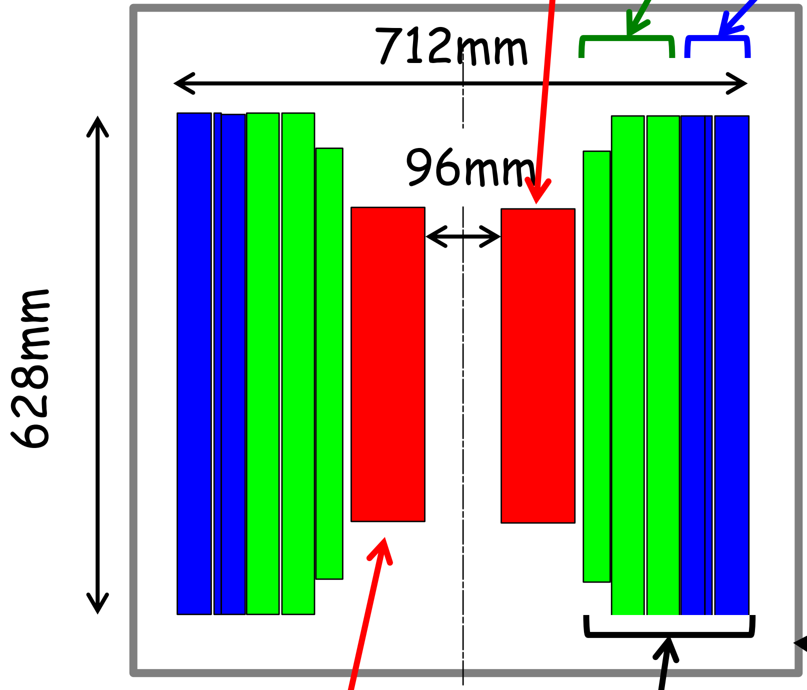
      - Quench protection

Overview of the 25T-CSM

68 GdBCO single pancakes

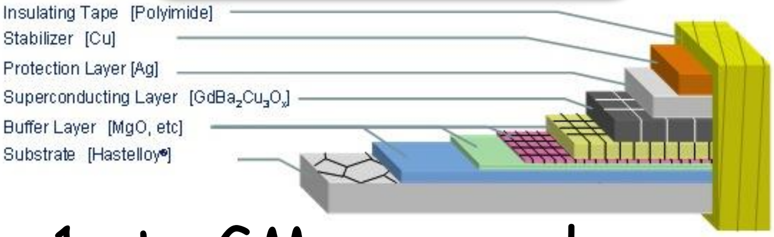
3 CuNb/Nb_3Sn Rutherford solenoid

3 NbTi Rutherford solenoid



LTS part: 14T

HTS part: 11.5T



2 x 1 stg GM cryocooler

2 x GM/JT cryocooler (8.6W@4.3K)

2 x 4K-GM cryocooler (3W@4.2K)

Conceptual design of 25T-CSM

		REBCO	Nb3Sn	Nb3Sn	Nb3Sn	NbTi	NbTi	NbTi
Current	A	135	851					
Inner radius	mm	48.0	150.0	185.9	229.2	272.5	301.3	313.9
Outer radius	mm	140.0	182.9	226.2	269.5	301.3	310.9	355.8
Height	mm	394.4	540.0	627.8	627.8	627.0	628.1	628.1
Coil current density	A/mm²	110.8	68.9	68.9	68.9	71.6	90.0	90.0
No of turns/layer	-	68	80	93	93	95	107	107
No of layer	-	438	18	22	22	16	6	26
Total No of turns	-	29784	1440	2046	2046	1520	642	2782
Bmax	T	25.66	13.77	11.35	8.37	6.83	6.22	5.84
Br	T	4.80	4.65	5.58	5.71	5.71	5.71	5.52
B0	T	11.56	2.43	2.91	2.73	1.91	0.78	3.24
Width of conductor	mm	5.00	6.45	6.45	6.45	6.30	5.57	5.57
Thickness of conductor	mm	0.13	1.83	1.83	1.83	1.80	1.61	1.61
Thickness of layer insulation	mm	0.080	0.075	0.075	0.075	0.075	0.075	0.075
Jcon	A/mm²	207.7	105.8	105.8	105.8	105.8	138.1	138.1
Tcs	K		5.87	7.28	8.58	5.92	6.12	6.32
Averaged compressive stress	MPa	-35	-39	-51	-50	-49	-59	-53
Hoop Stress BJR	MPa	376	219	223	203	154	129	92
Hoop stress Wilson	MPa	461	251	243	200	138	112	52

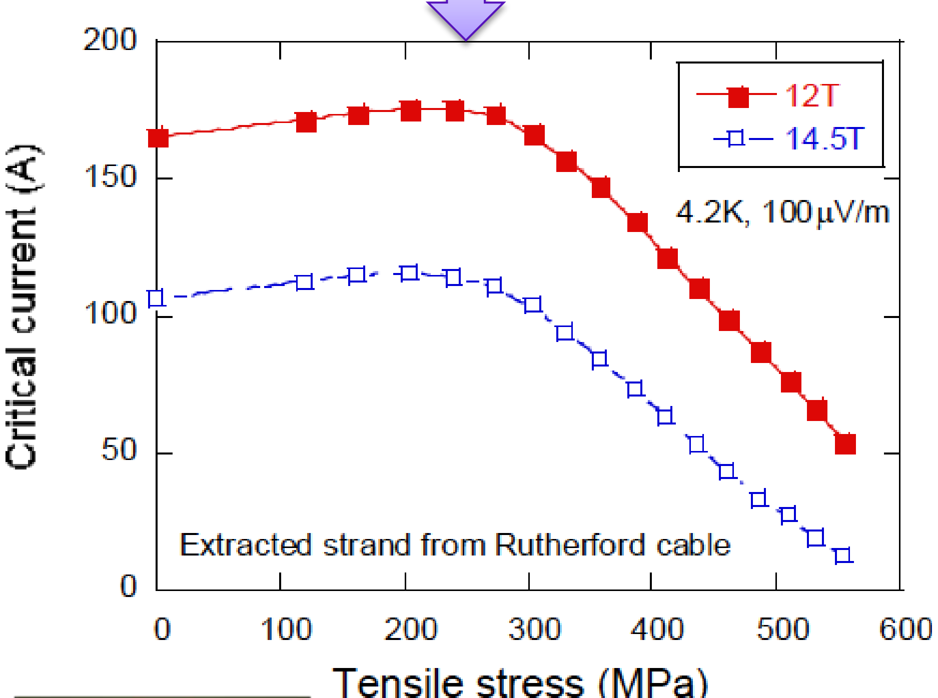
（stress is for a whole cross-section of the conductors.）

L ≈ 97H, Stored Energy ≈ 10.7MJ

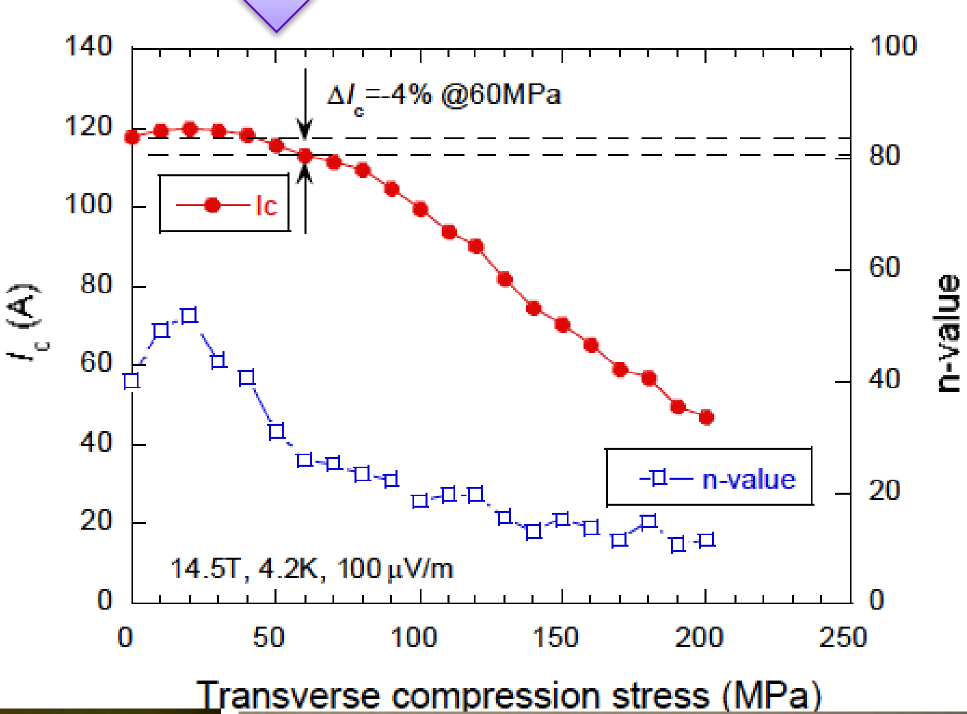
Mechanical stress effects - strand in Rutherford cable-

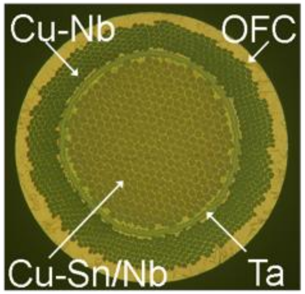
CuNb/Nb_3Sn Rutherford cable

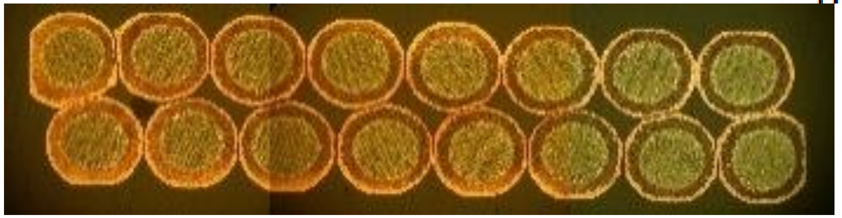
Axial stress
251MPa



Transverse stress
50MPa

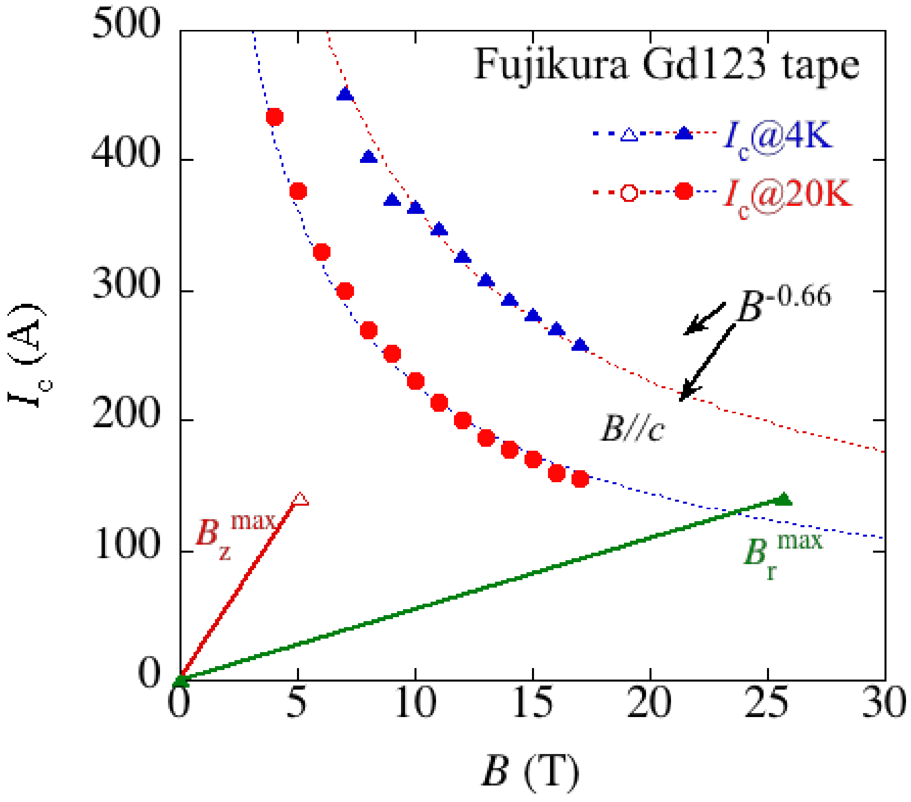


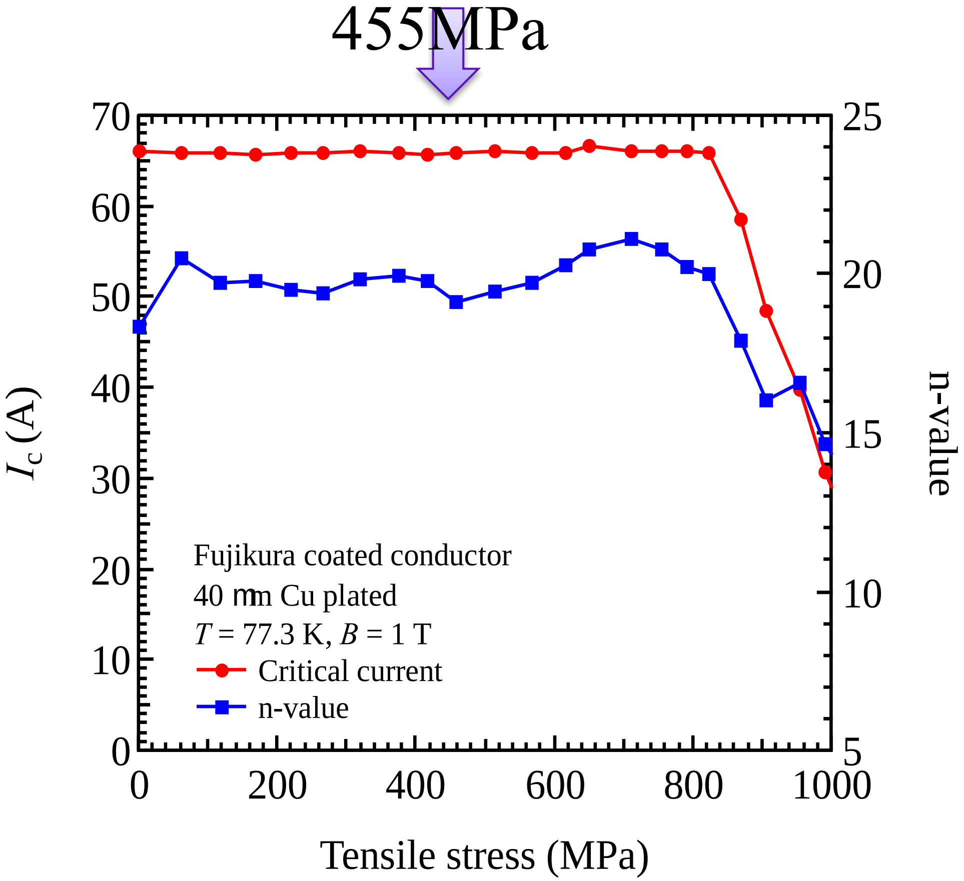




(b) Strand and pre-bent cable for 25T-CSM

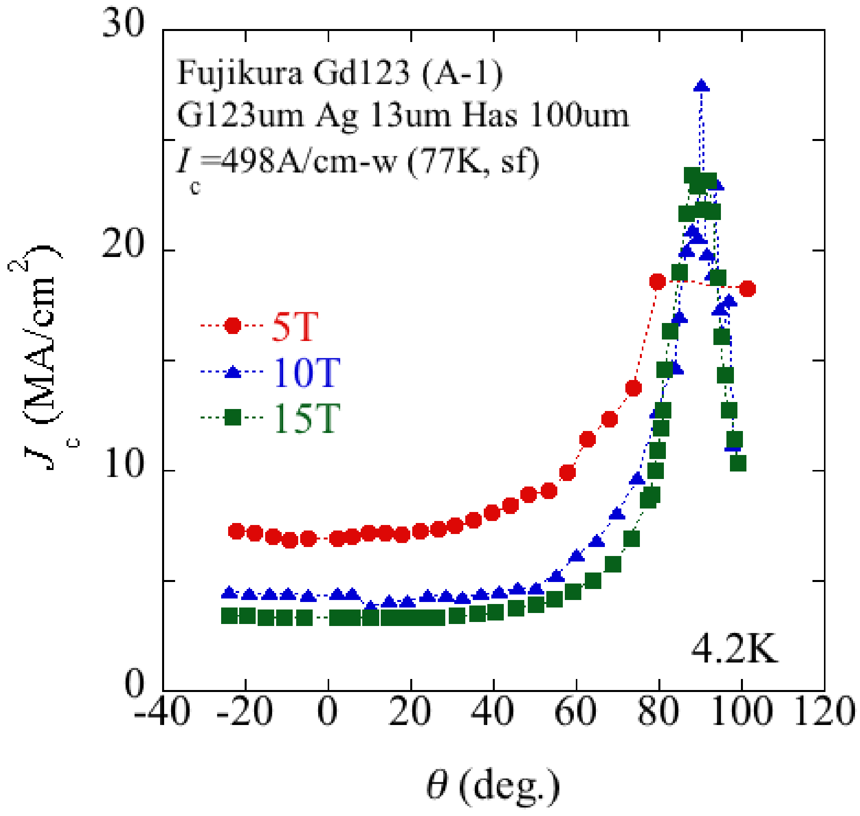
Performance of Gd123 CC

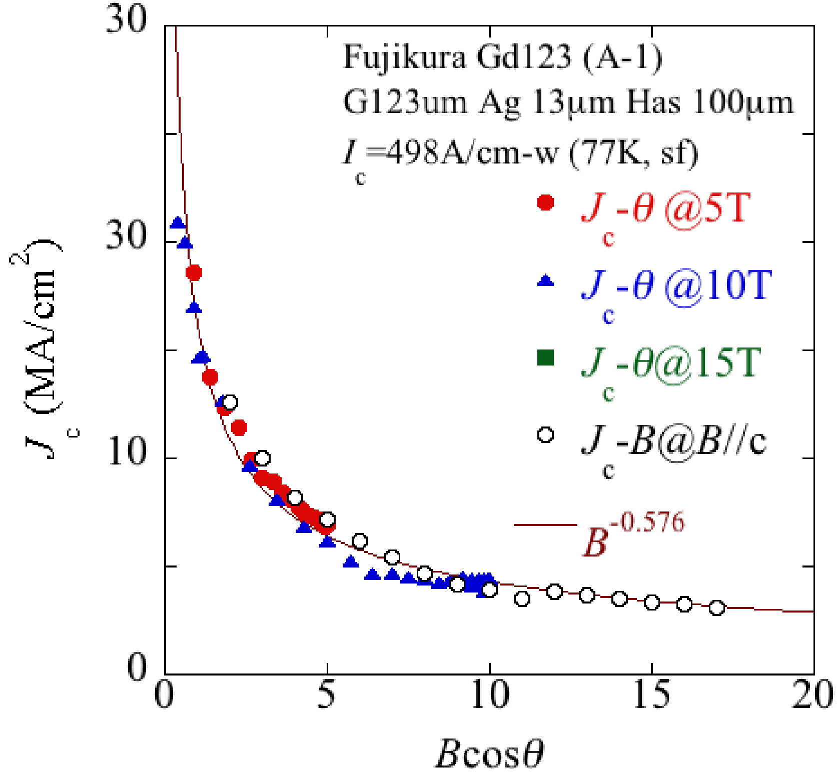




$J_c(B, \theta)$ at 4.2 K

Measured by Fujikura

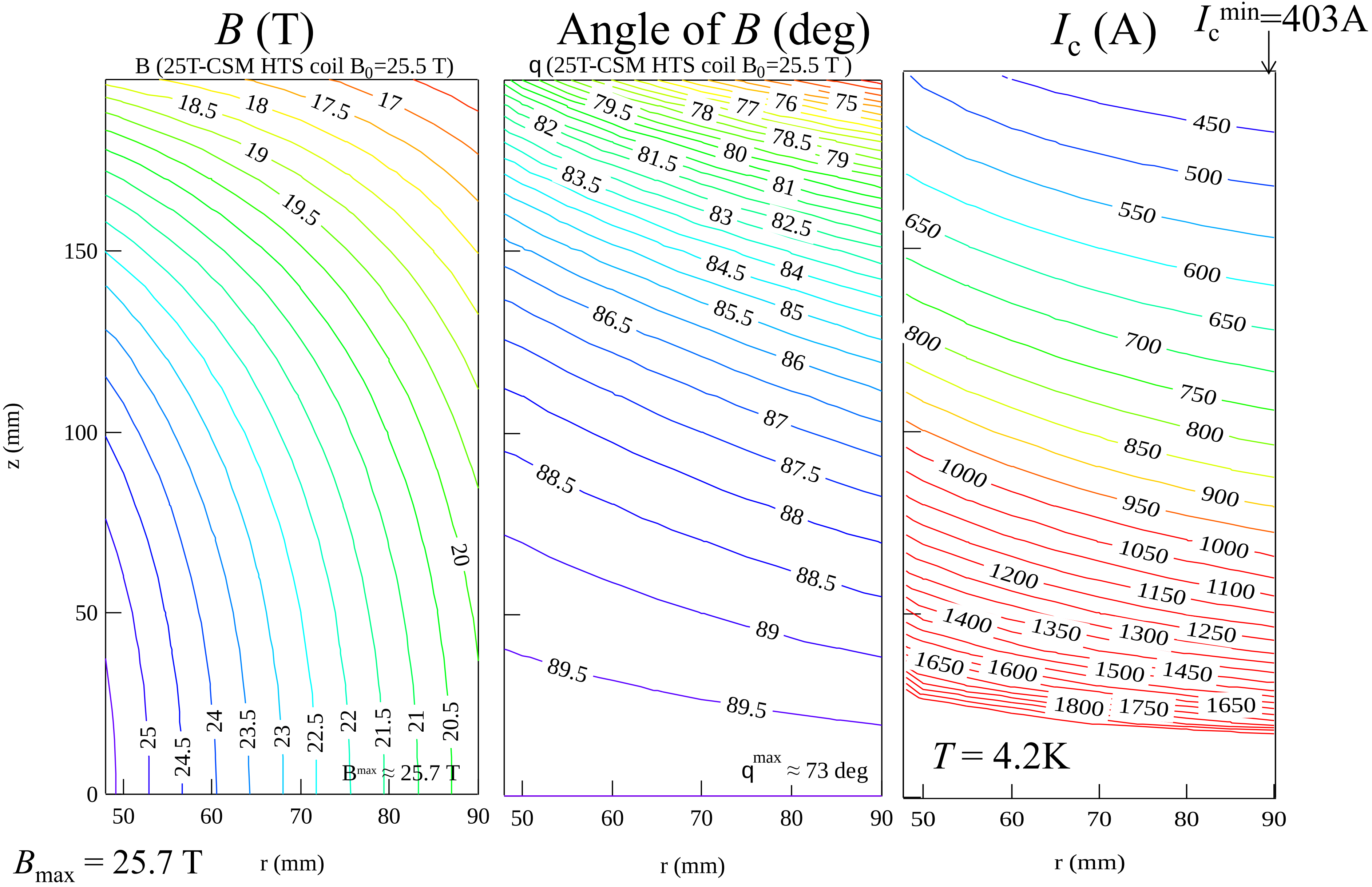




The c-axis component of magnetic field determines $J_c(B, \theta)$.

→ Intrinsic pinning is dominant.

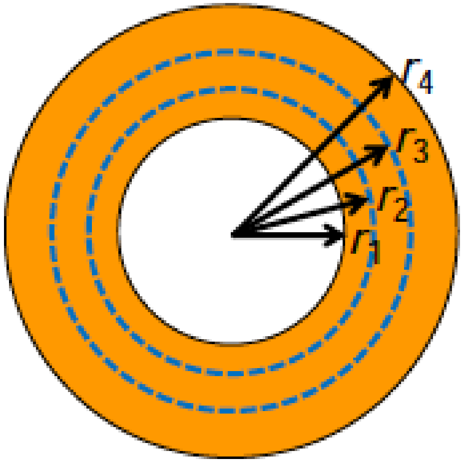
Field and J_c distribution (@25.5T)

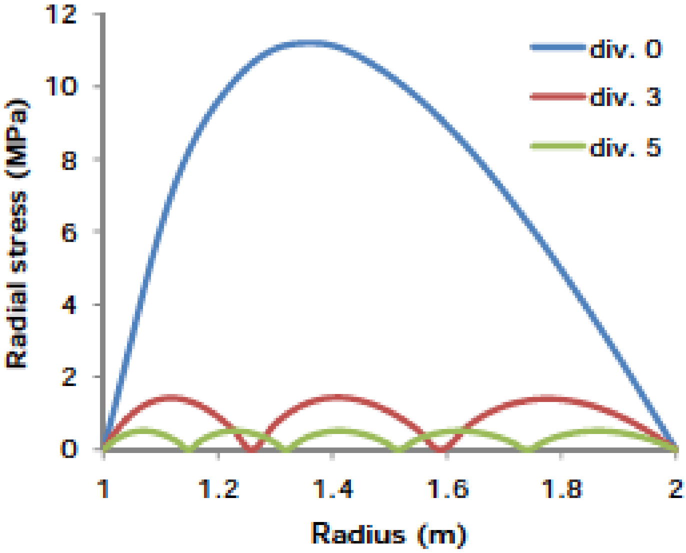


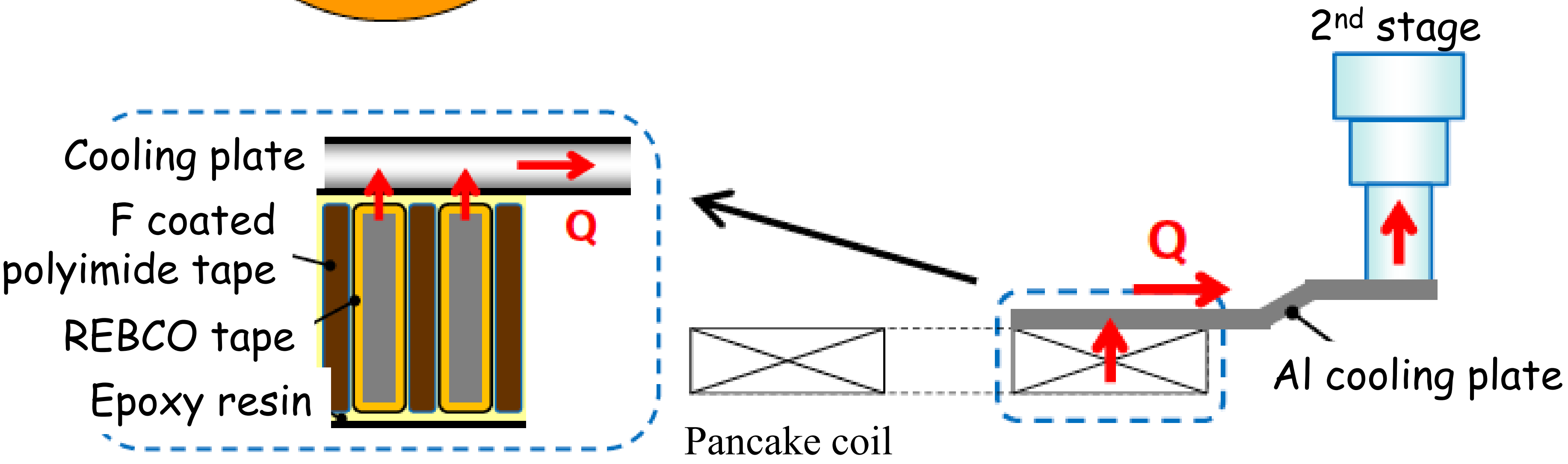
B_{max} = 25.7 T

Epoxy Impregnation (Delamination)

3 sections : $r_i^{out}/r_i^{in} \approx 1.26$
5 sections : $r_i^{out}/r_i^{in} \approx 1.15$

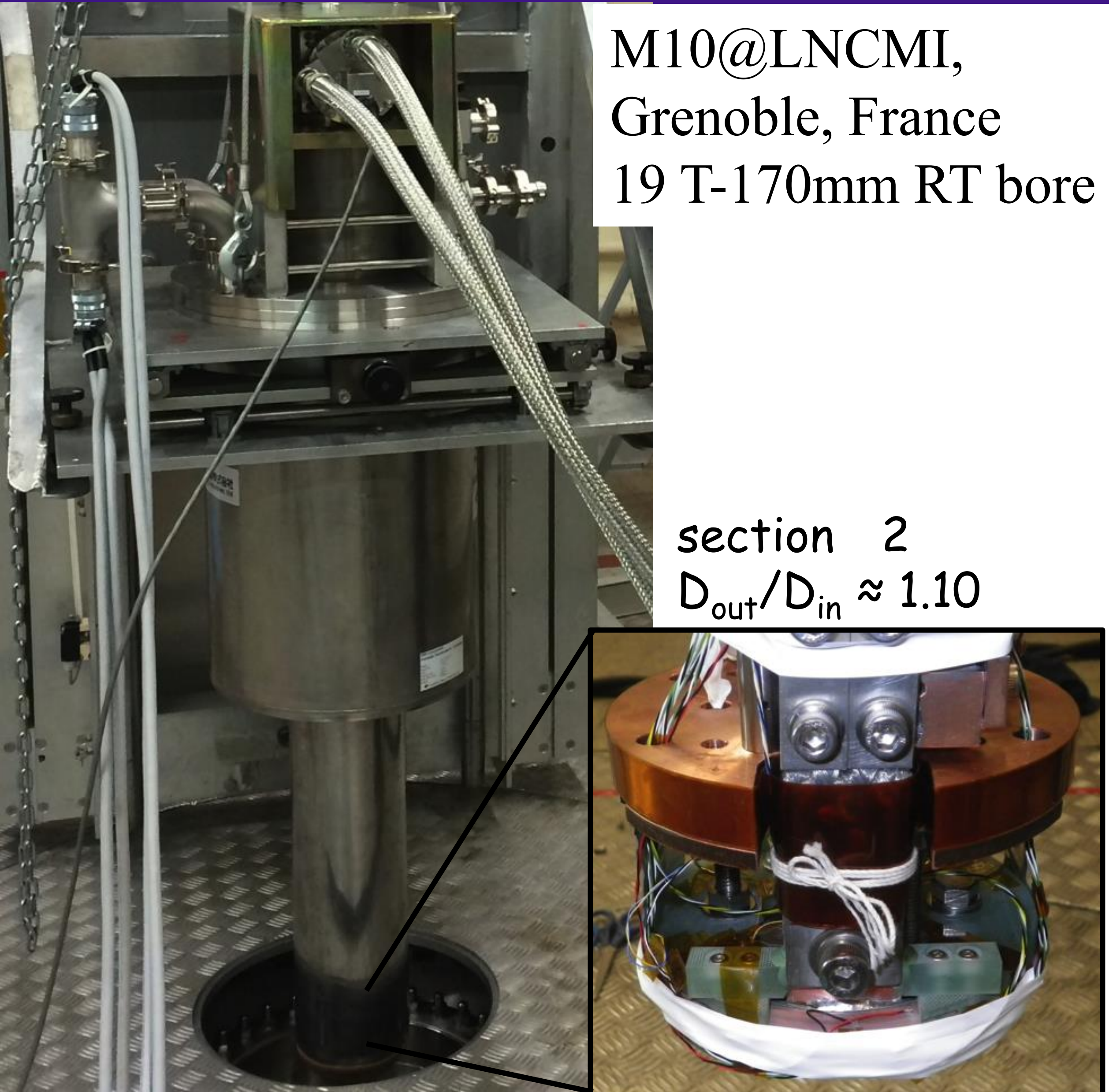






All turns are un-bonded but the edge part is connected to the cooling plate.

R&D test @LNCMI, Grenoble

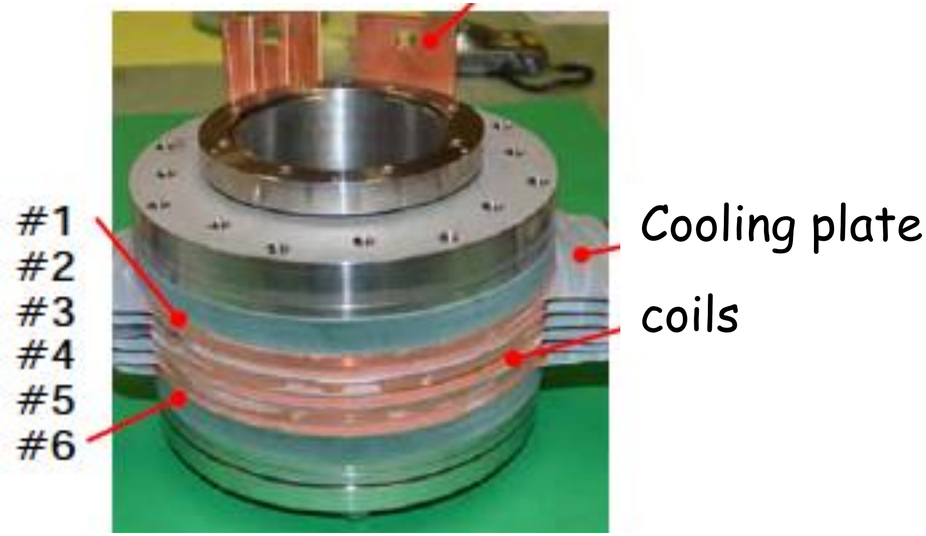


M10@LNCMI,
Grenoble, France
19 T-170mm RT bore

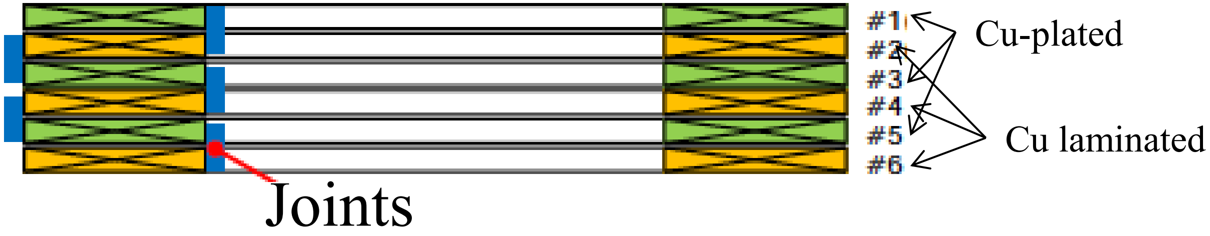
section 2
$D_{out}/D_{in} \approx 1.10$

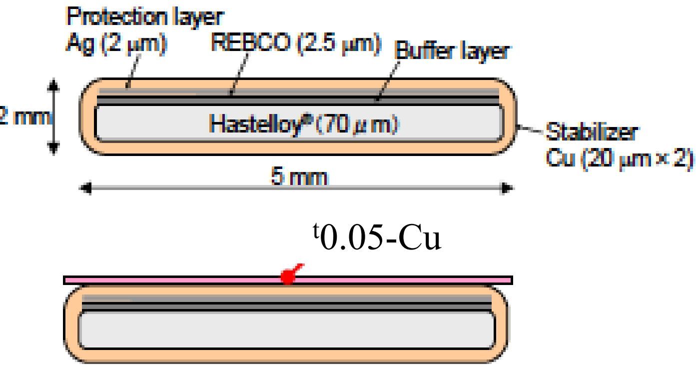
Gd123 coil	
Tape	Fujikura Cu-plated Gd123
Tape Ic	297 A
Tape w	5 mm
Tape tick	0.12 mm
Turn tick	0.18 mm
Coil D_{in}	96 mm
Coil D_{out}	119.7 mm
Coil h	10.7 mm
Turn No.	58 x 2
Tape L	20 x 2 m
Ic@77K, sf	109 A (upper) 108 A (lower)
n-values	28 (upper) 29 (lower)

6 stacked coil

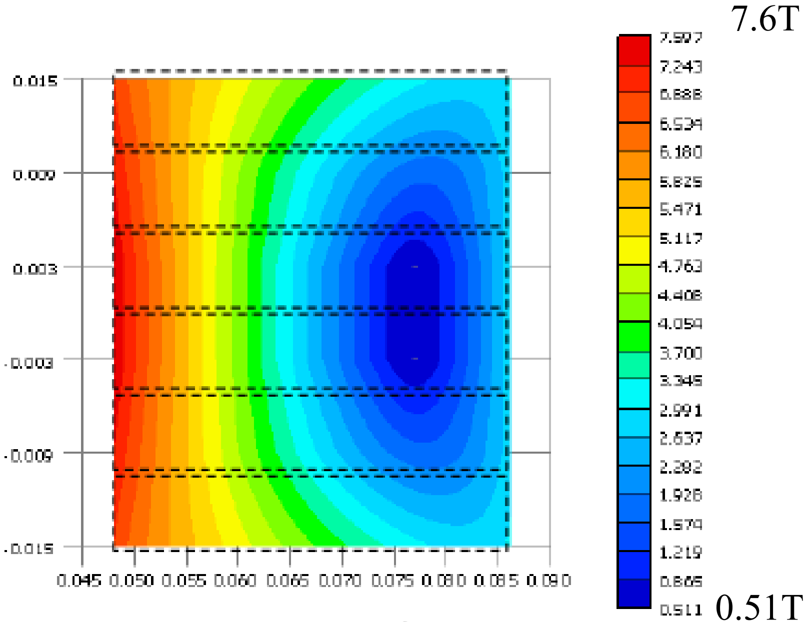


	#1, #3, #5	#2, #4, #6
Tape	Cu-plated Gd123	Cu lamination on Cu plated Gd123
Tape width	5 mm	
Tape thickness	0.12 mm	0.17 mm
Inner diameter	96 mm	
Outer diameter	172 mm	
No of turns	208	160
Tape length	87 m	68 m

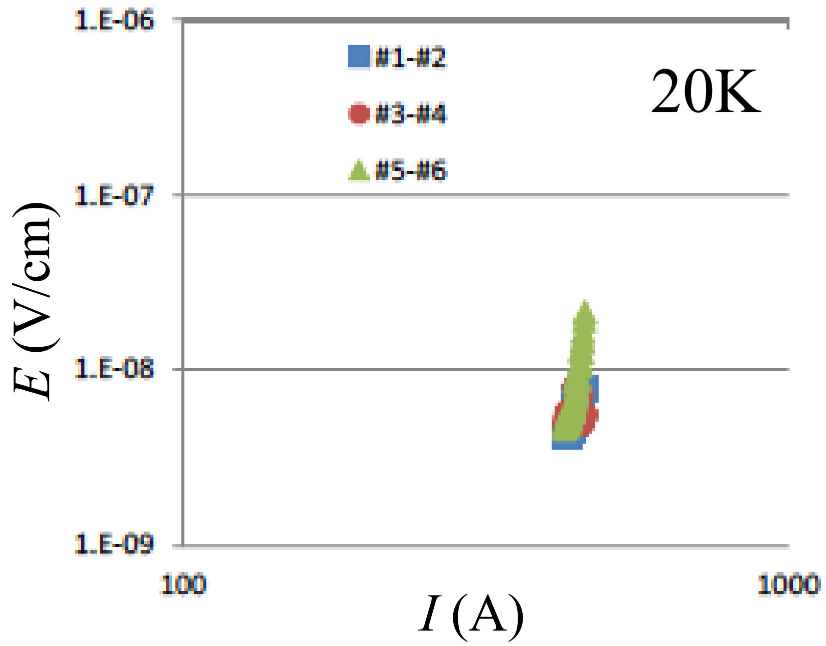




Test results -6 stacked coil-



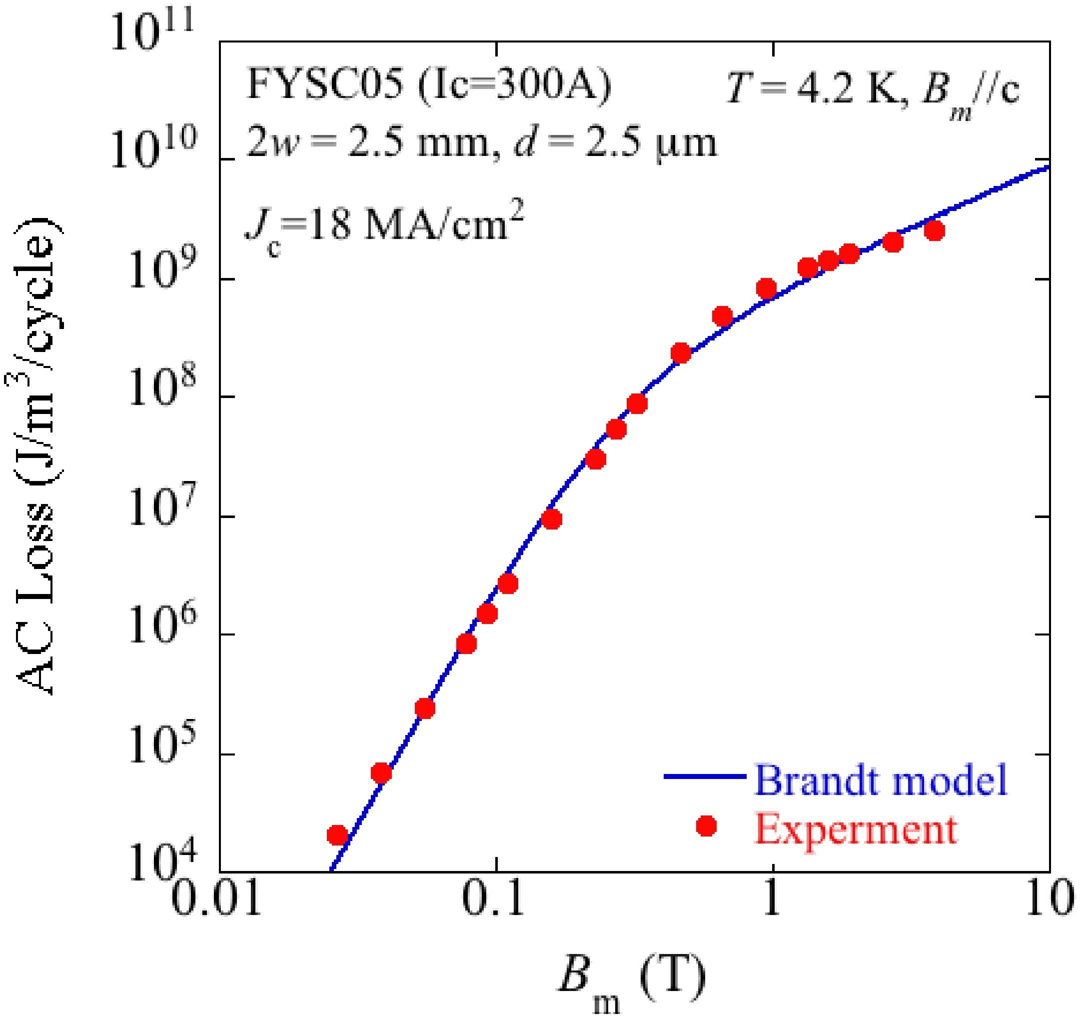
Magnetic field @462 A



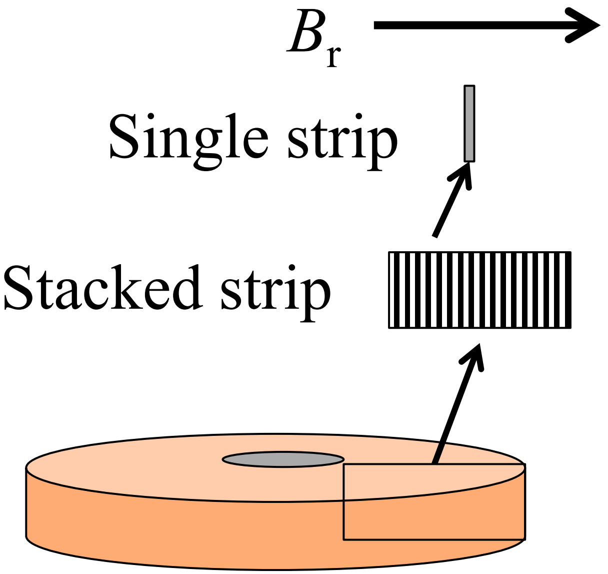
	60 K		50 K		40 K		30 K		20 K	
	I_c(A)	N	I_c(A)	N	I_c(A)	N	I_c(A)	N	I_c(A)	N
#1-#2	-	-	260	25	337	24	416	32	-	-
#3-#4	182	21	-	-	-	-	-	-	-	-
#5-#6	-	-	-	-	-	-	420	32	521	33

AC loss of Gd123 tape

Experimental data were provided by Prof. Iwakuma using the saddle-shaped pick-up coil.



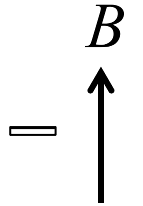
Very good agreement can be seen, but we have to take the effects of stacking into account!



Models of AC loss

Brandt model for a strip (H. Brandt *et al.* , *PRB*, 48(1993)12893.)

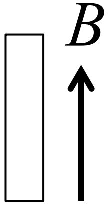
$$W = W_0\left(2\ln\cosh h - h\tanh h\right)$$



thickness << width

Kajikawa model for a slab (Kajikawa et al., 4LPo2B-06, http://arxiv.org/abs/1405.7765.)

$$W = \frac{1}{\lambda}\times\begin{cases}\dfrac{2\mu_0}{3}\dfrac{H_m^3}{H_p} & \text{for } H_m \le H_p\\ 2\mu_0 H_p H_m\left(1-\dfrac{2}{3}\dfrac{H_p}{H_m}\right) & \text{for } H_m > H_p\end{cases}$$

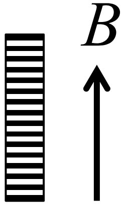


thickness >>width

$\lambda = d/g$ and $H_p = \lambda J_c a.$

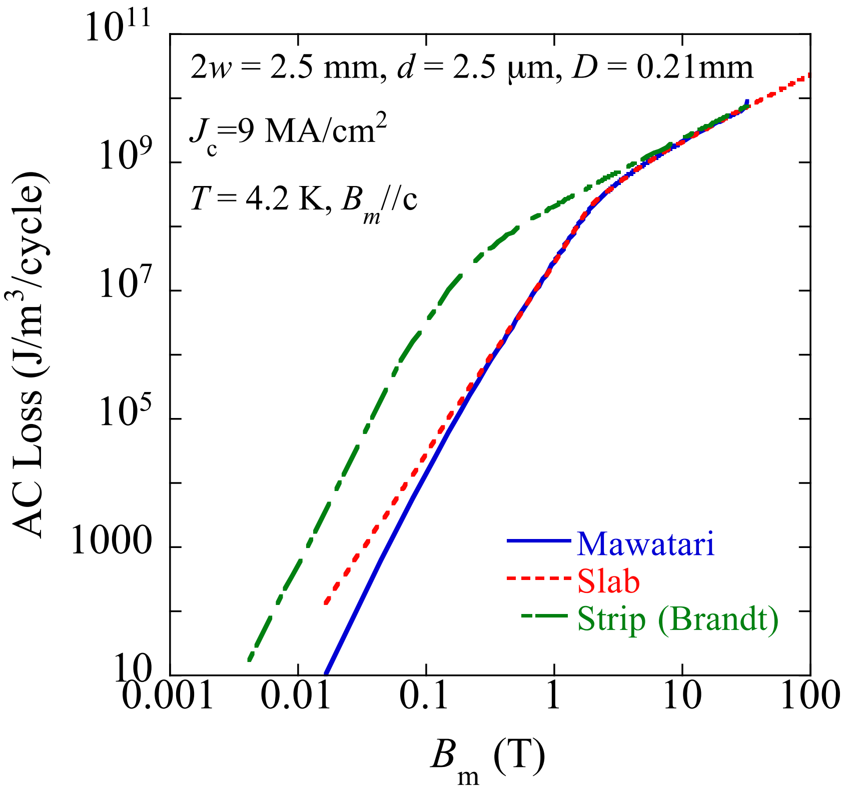
Mawatari model for stacked strips (Y. Mawatari, *PRB,* 54 (1996) 13215.)

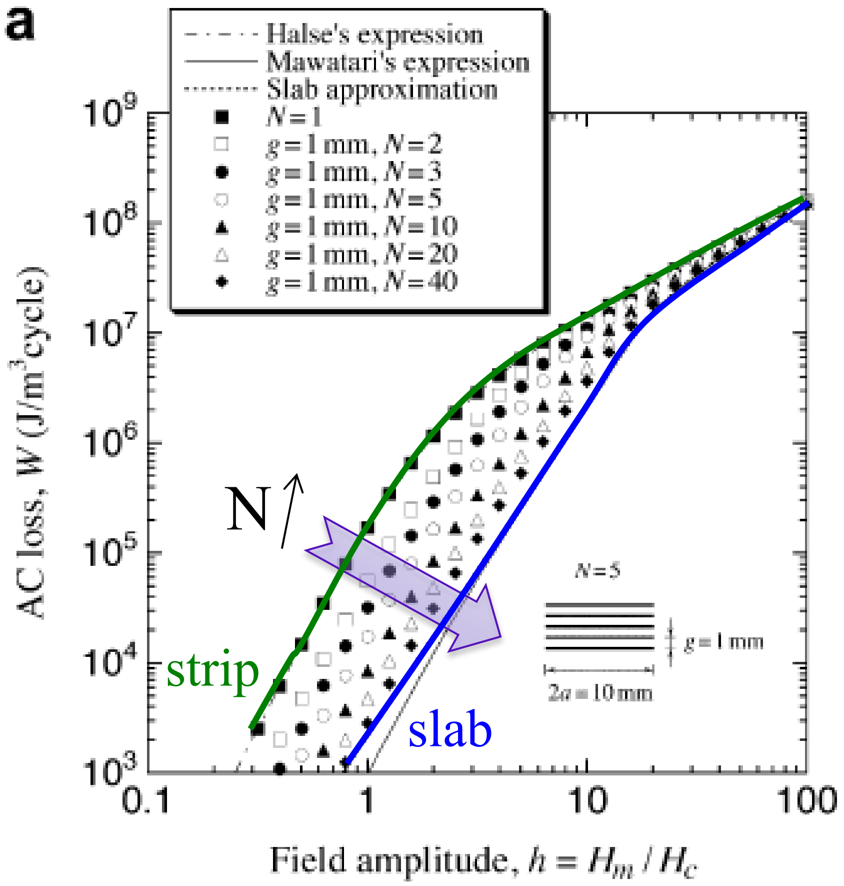
$$W = \frac{W_0}{c^2}\int_0^h (h-2x)\ln\left(1+\frac{\sinh^2 c}{\cosh^2 x}\right)dx$$



$W_0 = \mu_0 J_c w H_c$, $c = \pi w/D$, $h = H_m/H_c$ and H_m is an amplitude of applied magnetic field.

Effect of tape stacking on AC-loss





Kajikawa et al., Physica C 469 (2009) 1436.

1. The AC-loss approaches from the strip model to the slab model, when the number of stacks increases.
2. Due to an increase of B_p by tape stacking, AC losses in low field region decreases.

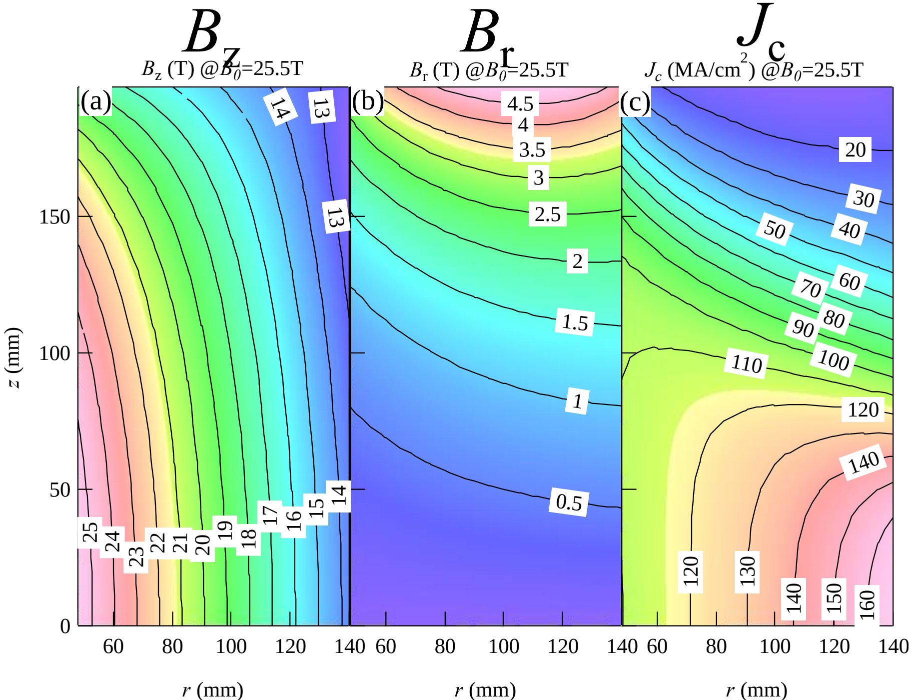
Calculation of AC loss power (time derivative)

- ✓ Slab model

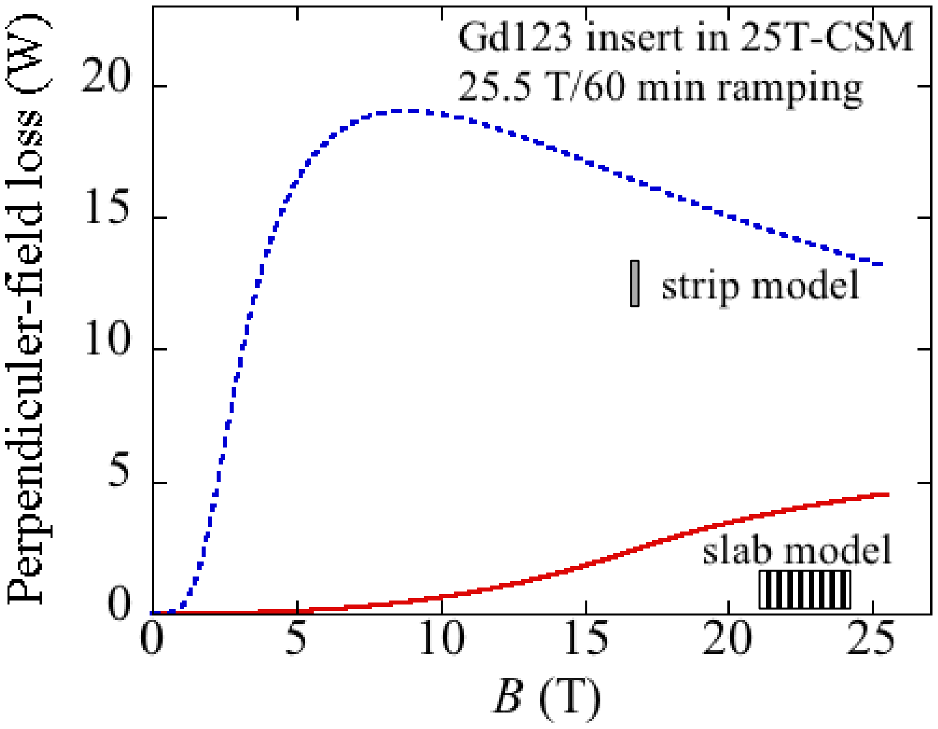
$$\dot{Q}_{slab} = \frac{dQ_{slab}}{dt} = \frac{B_p^2}{2\mu_0} \times \begin{cases} \dfrac{B_e^2}{B_p^2}\dfrac{\dot{B}_e}{B_p} & for\ 0 \leq B_e \leq B_p \\[2ex] \dfrac{B_e^2}{B_p^2} & for\ B_e \geq B_p \end{cases}$$

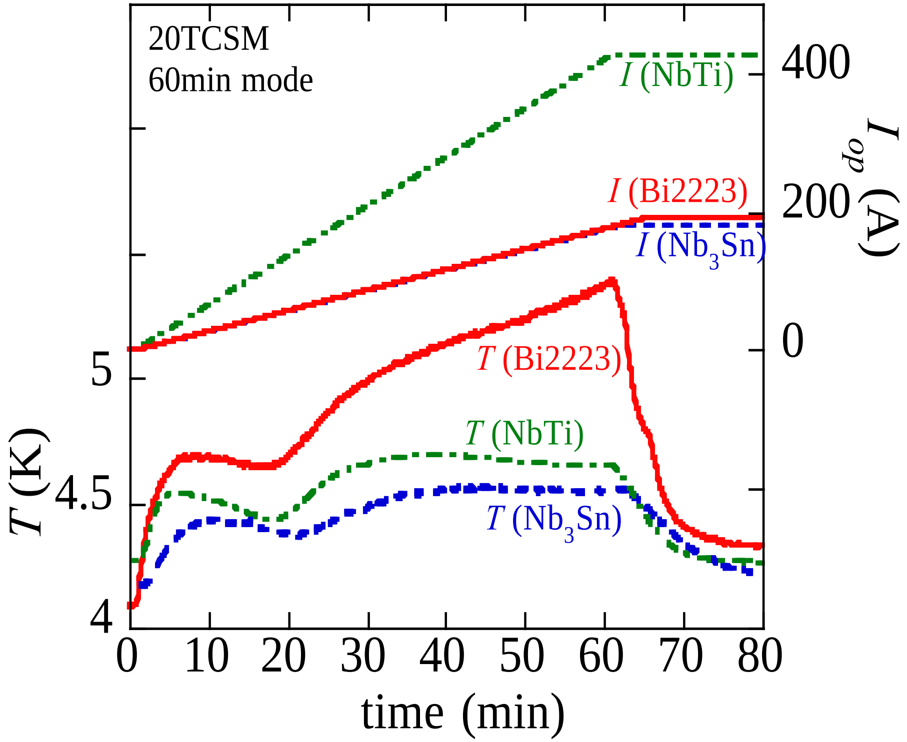
- ✓ Strip model (Brandt) w/o transport current (only external field)

$$\dot{Q}_{\text{strip}} = \frac{W_0}{4}\frac{\dot{B}_e}{B_c}\left(\tanh\frac{B_e}{B_c} - \frac{B_e}{B_c}\text{sech}^2\frac{B_e}{B_c}\right)$$



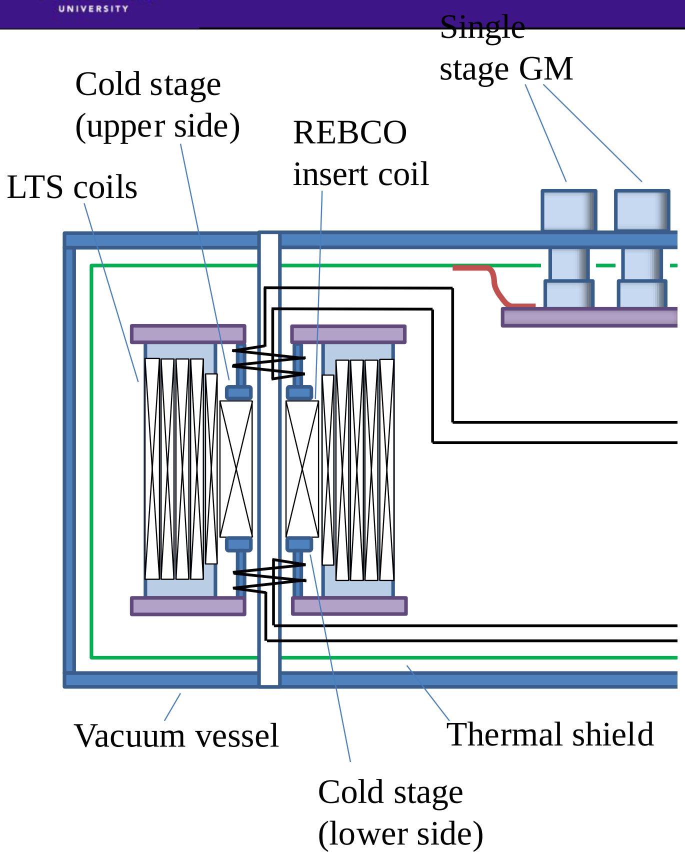
Perpendicular-field loss

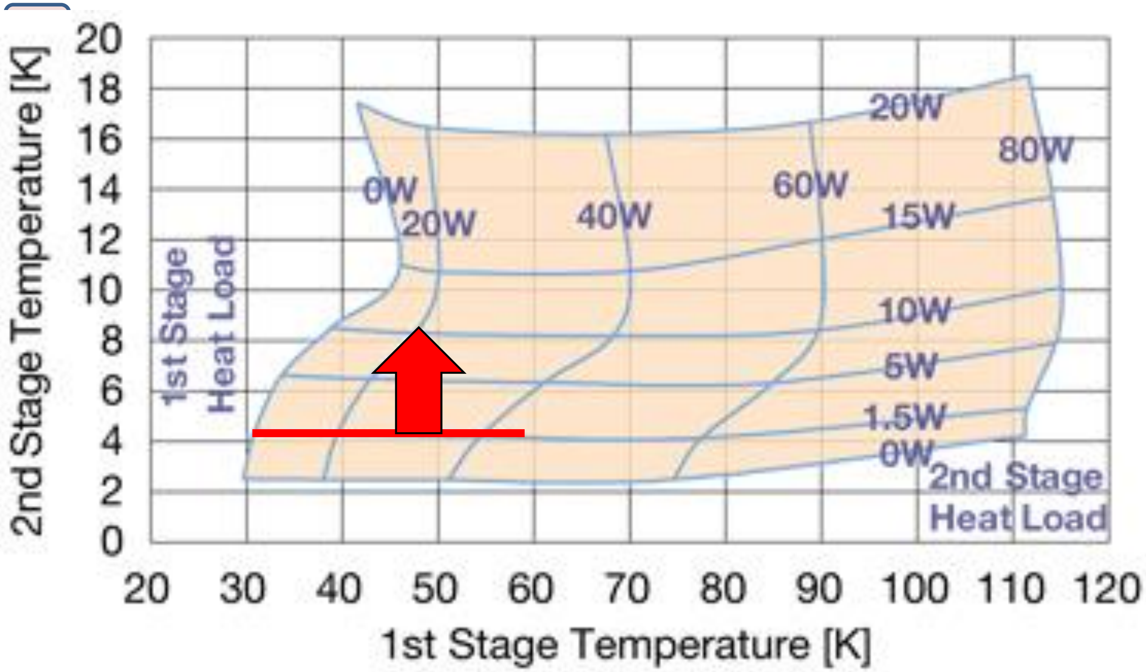




The perpendicular-field ac loss of about 5 W estimated, if the effect of tape stacking, although it is about the twice of loss without the stacking effects (stripe model). In particular, the field dependency are much different each other.

Cooling the HTS coil in the 25T-CSM

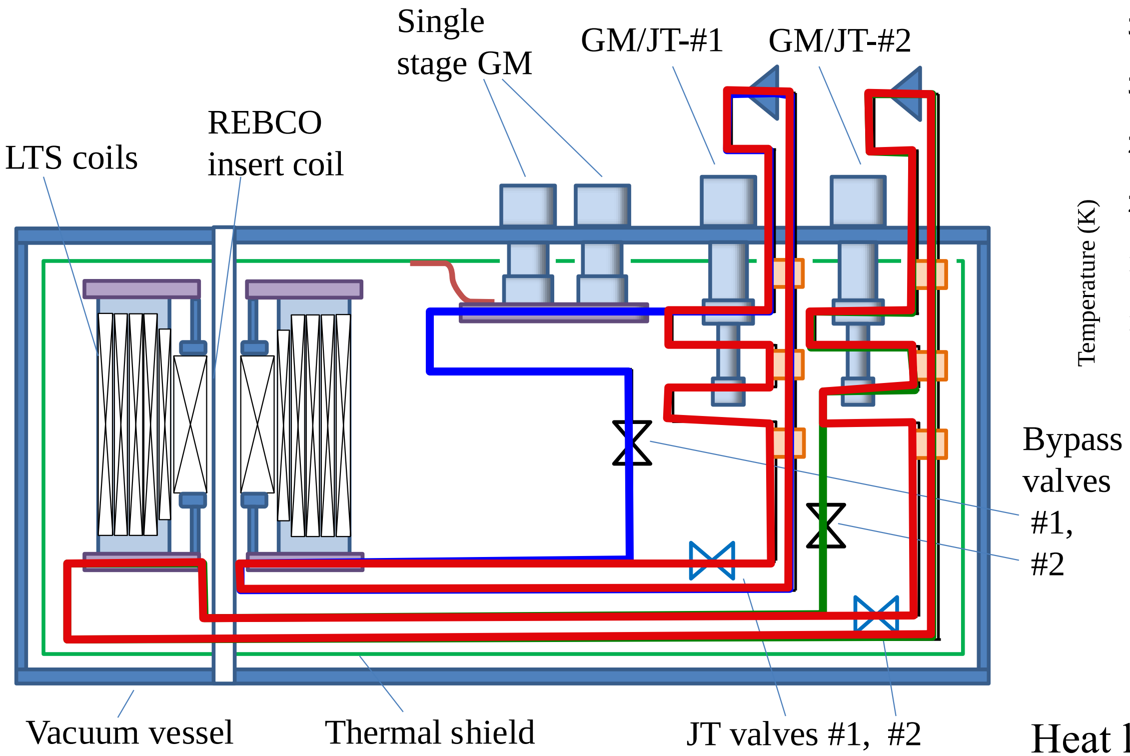


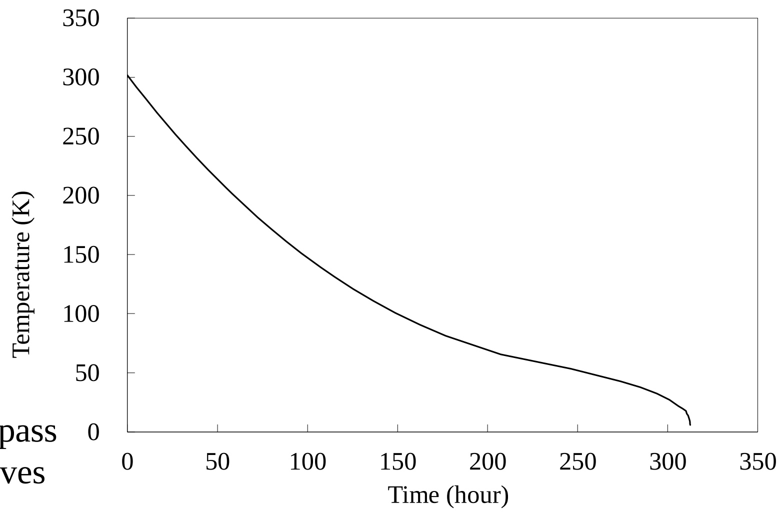


	Heat load
AC-loss of the HTS coils	5-18 W
Joule loss of the junctions	1.33 W
Heat invasion from the support	-0.037 W
Thermal radiation	0.0006 W
Heat load from the cold stage of the power lead	0.18 W
Total	6.5-19.5 W

If the temperature rise to about 10 K is allowed, the heat load of 20 W (10 W/cooler) can be permitted.

Cooling the LTS coil in the 25T-CSM





Cooling modes

mode 1 (300–50 K)
mode 2 (50–20 K)
mode 3 (20–4 K)

Heat load to the GM/JT cryocoolers at 4 K

	Heat load
AC-loss of the LTS coils	2.63 W
Joule loss of the junctions	0.869 W
Heat invasion from the support	0.189 W
Heat invasion from the support of the REBCO coil	0.037 W
Thermal radiation	0.151 W
Heat load from the cold stage of the power lead	1.70 W
Total	5.58 W

Design of a 25T-CSM (modified)

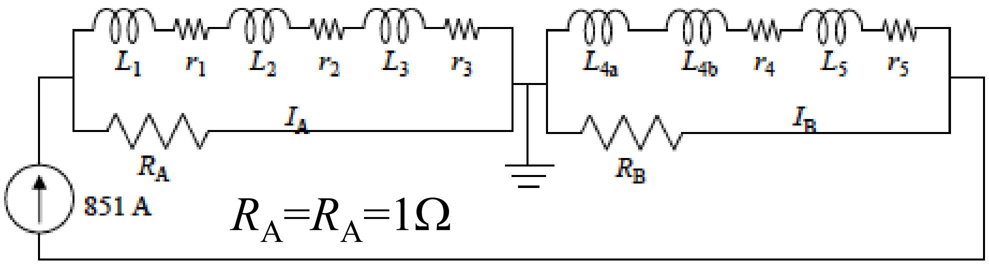
		YBCO	Nb3Sn	Nb3Sn	Nb3Sn	NbTi	NbTi	NbTi
Current	A	140	851					
Inner radius	mm	51	150.0	185.9	229.2	272.5	301.3	313.9
Outer radius	mm	138	182.9	226.2	269.5	301.3	310.9	355.8
Height	mm	408	540.0	627.8	627.8	627.0	628.1	628.1
Space current density	A/mm^2	110.8	68.9	68.9	68.9	71.6	90.0	90.0
No of turns/layer	-	68	80	93	93	95	107	107
No of layer	-	435	18	22	22	16	6	26
Total No of turns	-	29580	1440	2046	2046	1520	642	2782
Bmax	T	25.68	13.77	11.35	8.37	6.83	6.22	5.84
Br	T	4.80	4.65	5.58	5.71	5.71	5.71	5.52
B0	T	11.5	2.43	2.91	2.73	1.91	0.78	3.24
Width of conductor	mm	5.00	6.45	6.45	6.45	6.30	5.57	5.57
Thickness of conductor	mm	0.13	1.83	1.83	1.83	1.80	1.61	1.61
Thickness of layer insulation	mm	0.070	0.075	0.075	0.075	0.075	0.075	0.075
Jcon	A/mm^2	217	105.8	105.8	105.8	105.8	138.1	138.1
Tcs	K		5.87	7.28	8.58	5.92	6.12	6.32
Averaged compressive stress	MPa	-35	-39	-51	-50	-49	-59	-53
Hoop Stress BJR	MPa	417	219	223	203	154	129	92
Hoop stress Wilson	MPa	455	251	243	200	138	112	52

(stress is for a whole cross-section of the conductors.)

$L \approx 97H$, Stored Energy $\approx$ 10.7MJ

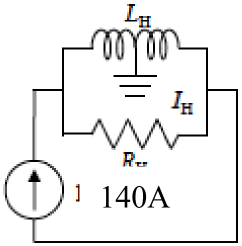
Protection circuit

LTS part

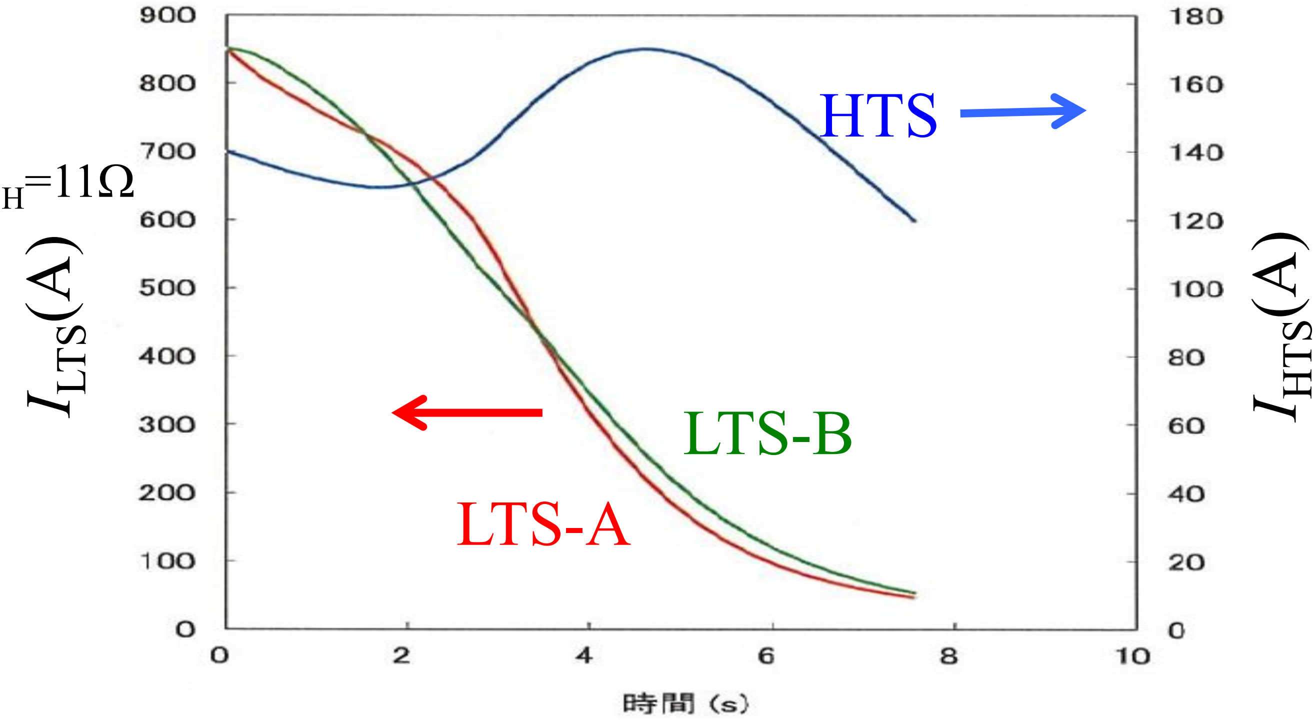


$V_{max} \approx 1.87\text{kV}$

HTS part



R_H=11Ω

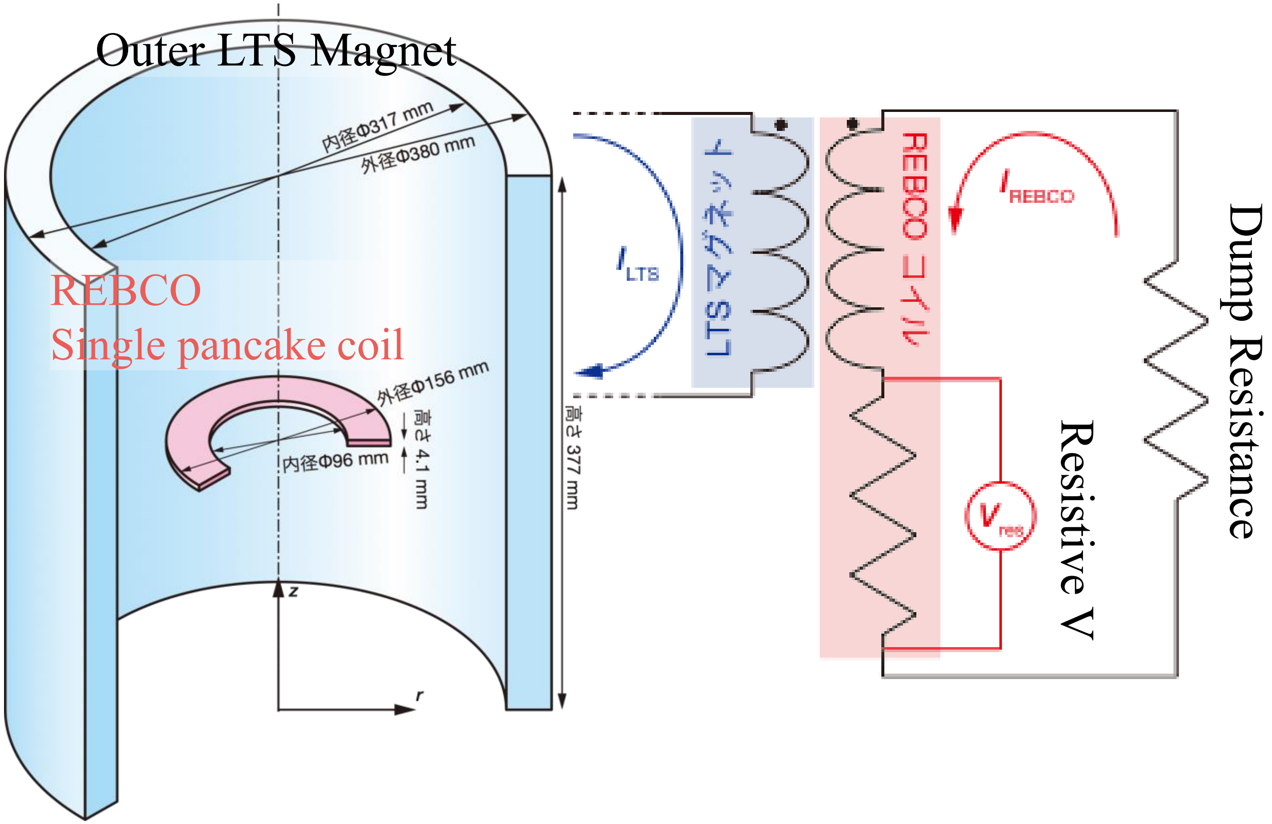


The quench is detected by the balance voltage of LTS.

The quench of HTS is not cared because of its high stability.

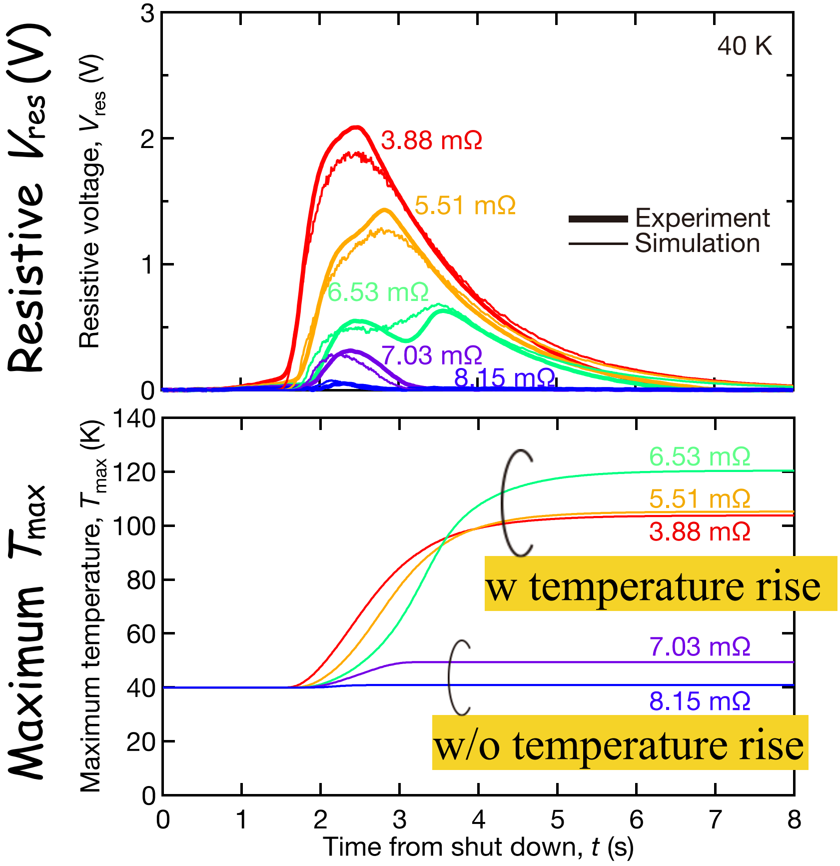
Quench test of small coils

	LTS	REBCO
D out(mm)	380	156
D in (mm)	317	96
Height(mm)	377	4.1
L (mH)	24	1.73
M (mH)	34	
SC thickness(μm)		1.5
Cu thickness(μm)		100



Quench behavior

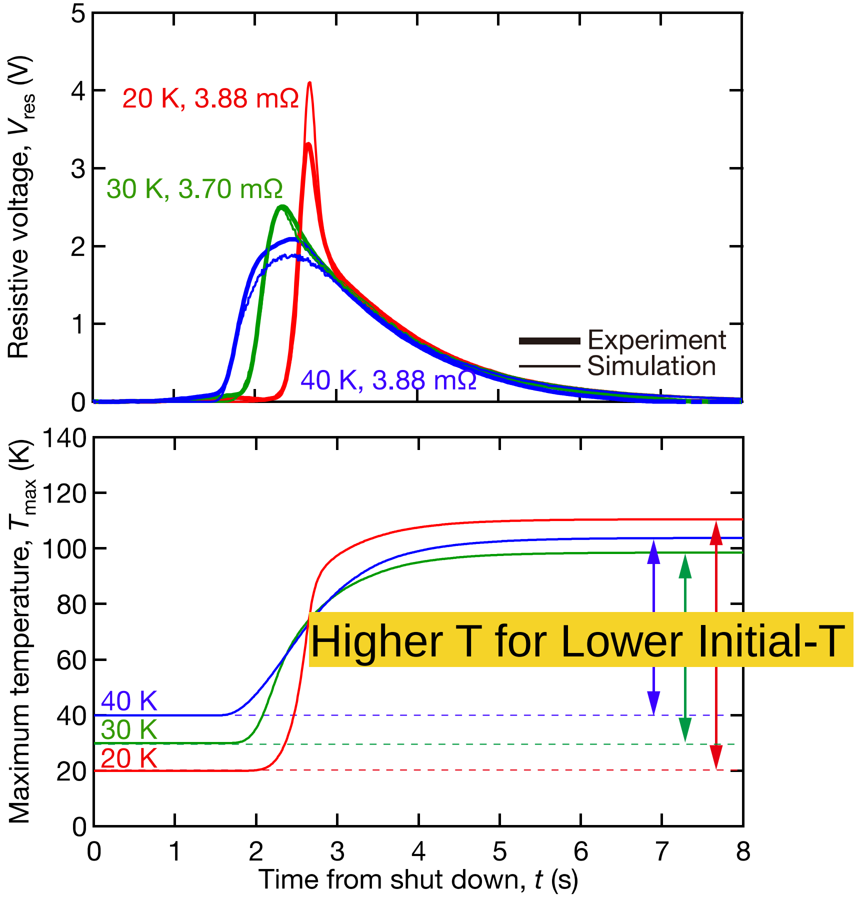
Dump resistance dependence



w temperature rise

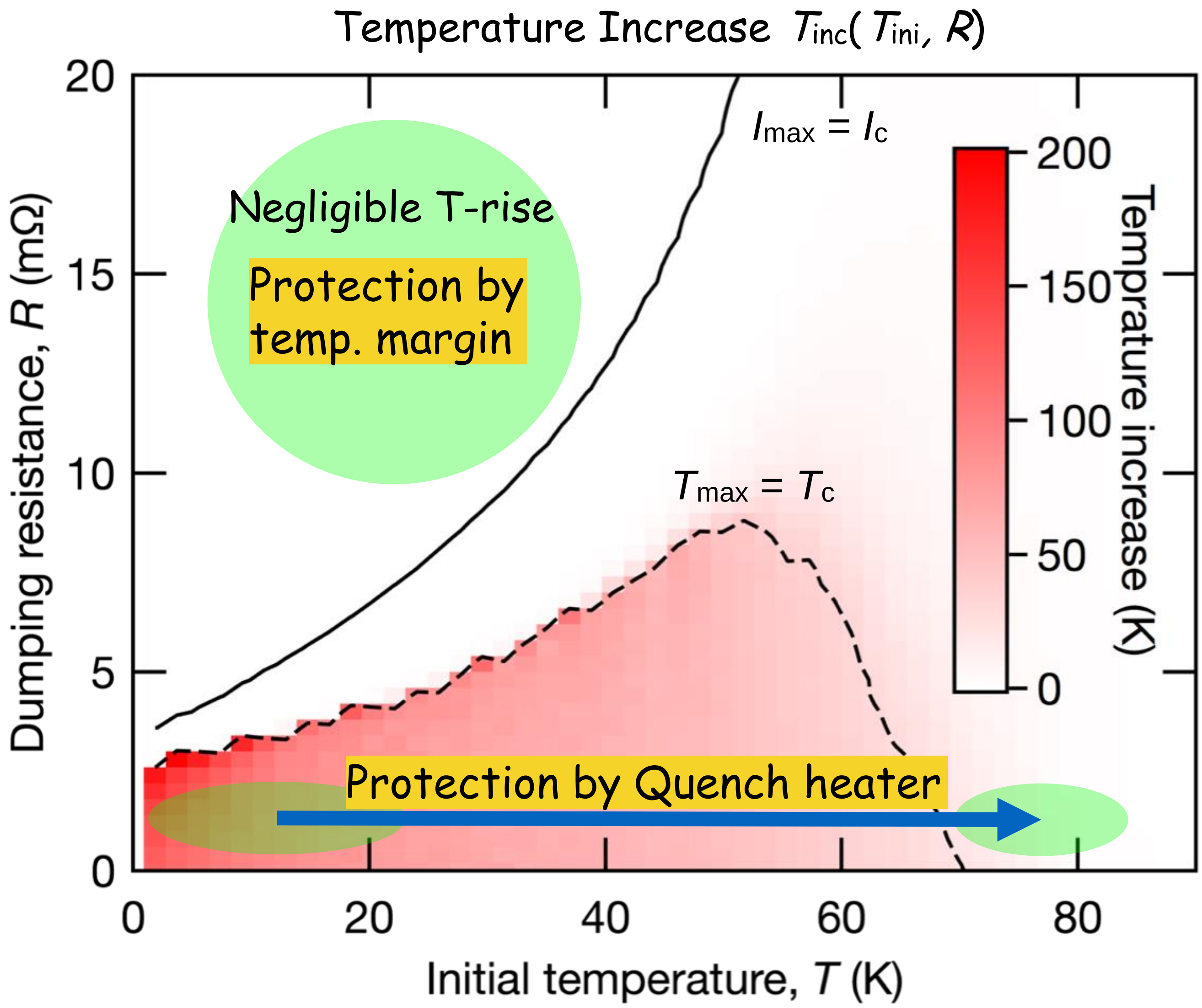
w/o temperature rise

Initial Temp. dependence



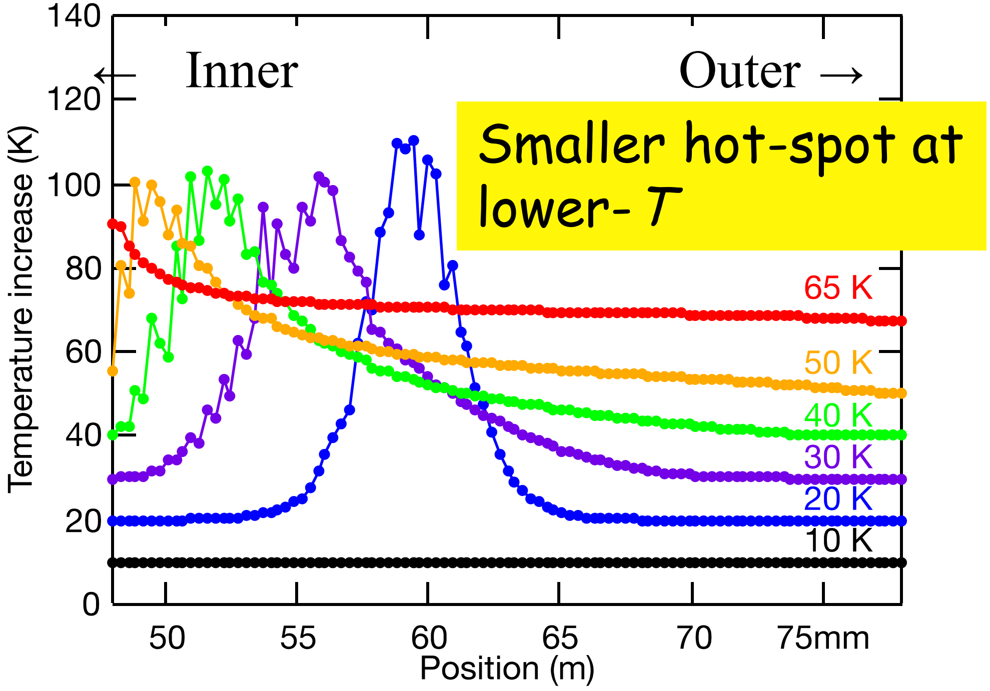
Higher T for Lower Initial-T

Temperature rise



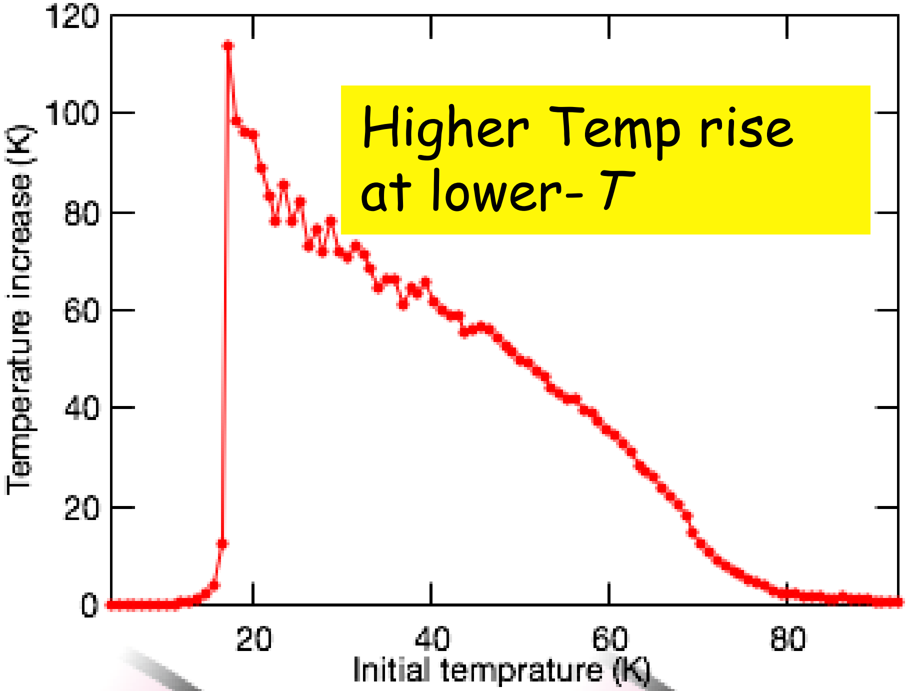
Quench analysis

Temperature rise



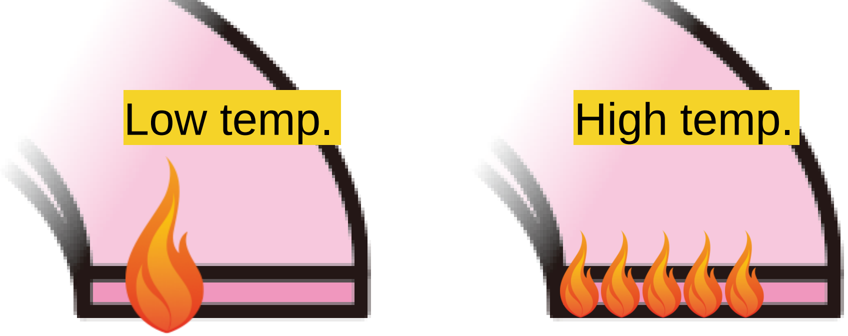
Smaller hot-spot at lower-*T*

Initial-*T* dependence



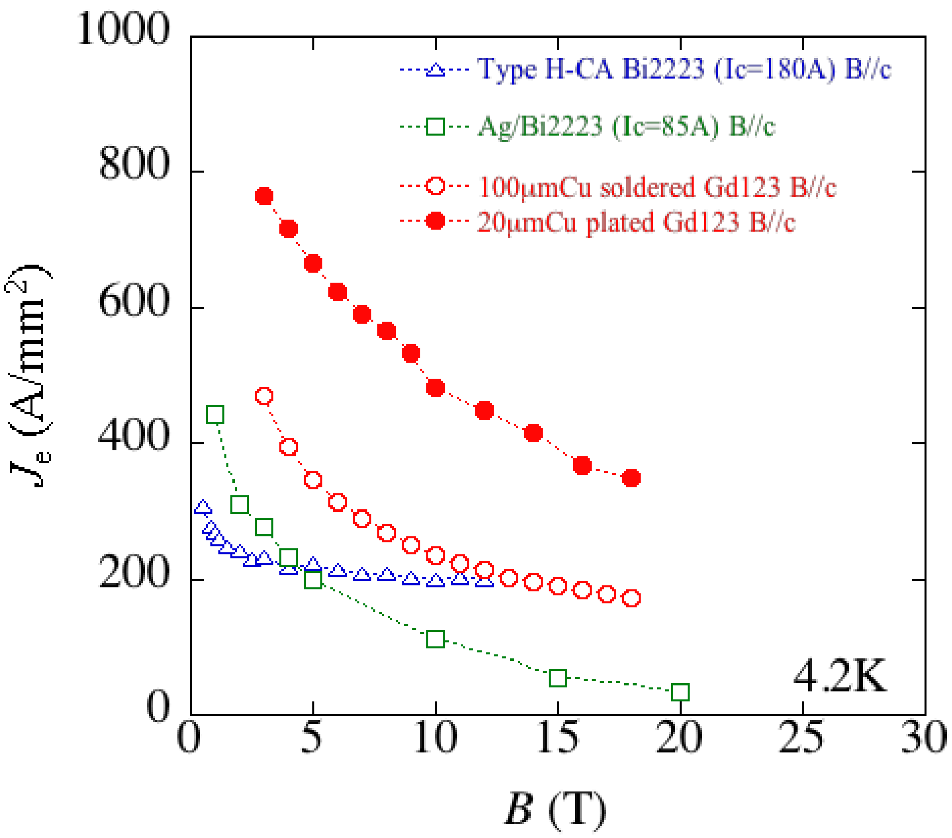
Higher Temp rise at lower-*T*

Initial-T	low	high
Temperature rise	large	small
Hot-spot area	narrow	wide
Risk of burn-out	large	small



Hot-spot at High-T is more safty!

Performance of HTS tapes



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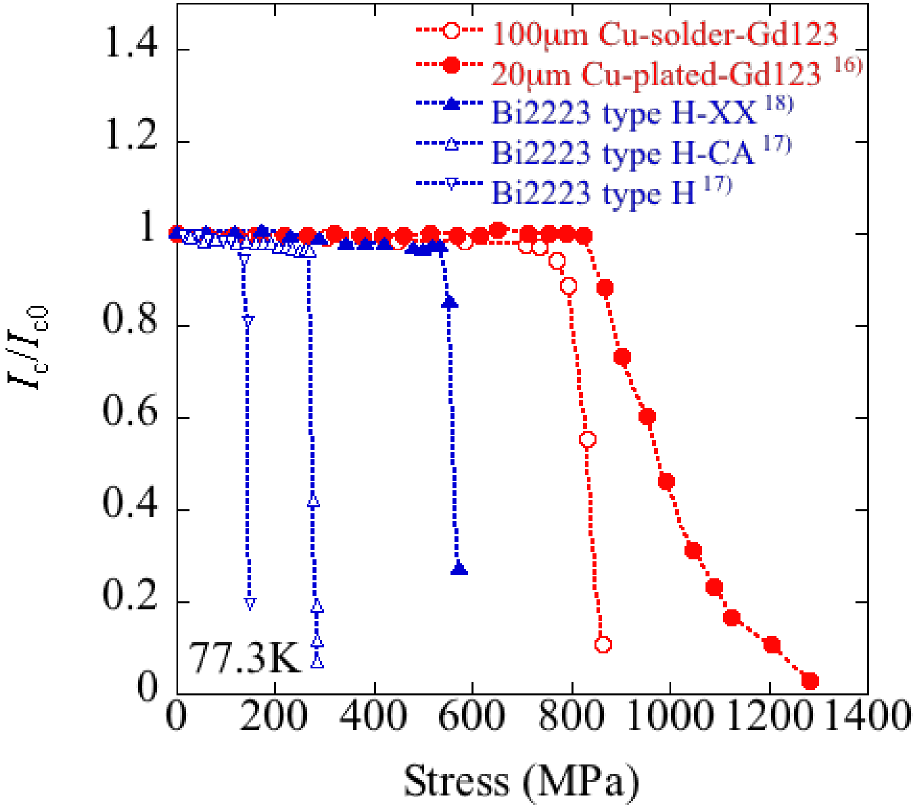
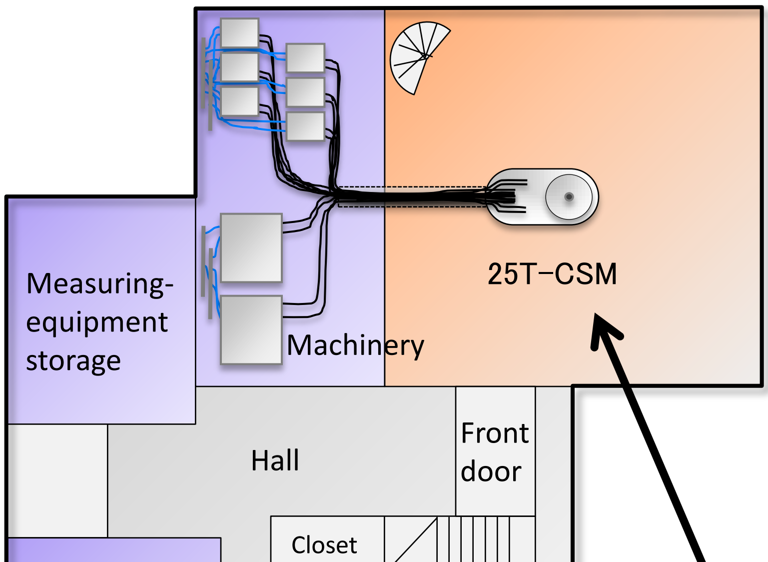


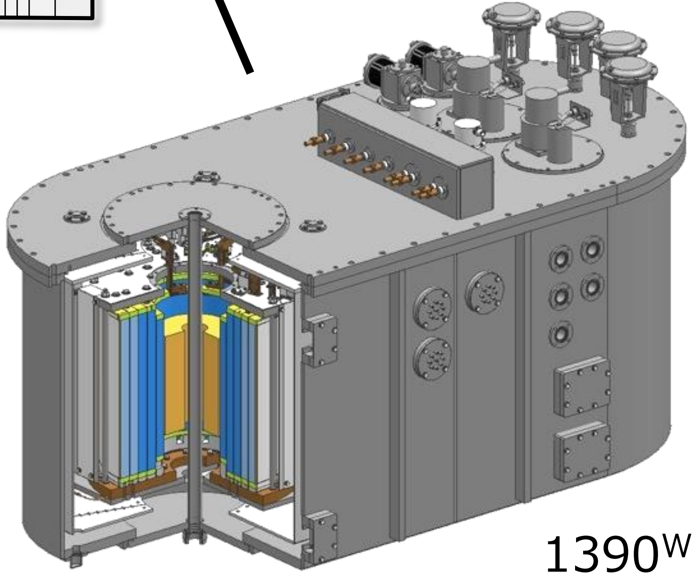
HTS insert for 25T-CSM (modified)

		YBCO	Bi2223
Current	A	140	224
Inner radius	mm	51.1	48.0
Outer radius	mm	140.0	139.3
Height	mm	394.4	391.4
Space current density	A/mm^2	117	112
No of turns/layer	-	68	76
No of layer	-	435	234
Total No of turns	-	29580	17784
Bmax	T	25.66	25.62
Br	T	5.11	4.95
B0	T	11.5	11.50
Width of conductor	mm	5.00	5.15
Thickness of conductor	mm	0.13	0.32
Thickness of layer insulation	mm	0.080	0.07
Jcon	A/mm^2	215	157
Averaged compressive stress	MPa	-35	-32
Hoop stress Wilson	MPa	455	330

HFLSM annex building and 25T-CSM

HFLSM Annex **1F**





$1390^{W}X2840^{L}X1190^{H}$

Summary

The 25T-CSM project is going on now at the HFLSM, Sendai, Japan.

1. We adopted a high stress design for both of LTS and HTS coils.
2. The issues of impregnation, AC losses, quench protection are being overcome.
3. However, we just start to consider the possibility of high strength Bi2223 tape (HT-XX) for the HTS insert.
4. The construction must be finished by March, 2015.