IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
Plenary presentation SPL-1-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

Special Plenary Lecture

High-Field Applications of HTS Tape

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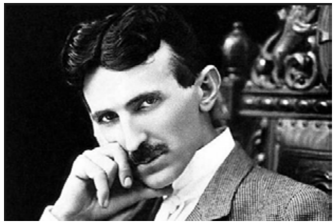
Outline

- Important issues for high-field magnets
- Design options for efficient (high-performance) magnet
- Two major drawbacks of HTS tape vs. LTS wire
- High-current cables with REBCO tape for magnets
- Liquid Helium (LHe)-Free Operation
- Challenges for HTS tape
- Conclusions



(b. 1856, Smilijan, Croatia

Nicola Tesla

Magnetic Field (B) Spectrum

d. 1943, The New Yorker Hotel, Room 3327)

- 10^9 — Neutron stars
- 10^3 — Upper limit (?) of man-made field; Pulse field lasting <1 μs
- 10^2 — Highest man-made DC field (100 T possible, with REBCO tape); NMR (B > 23.5 T: LTS/HTS)
- 10 — Other research magnets—MRI, HEP (B > 15 T: LTS/ HTS); Fusion (HTS ?)
- MRI, Electric power & medical devices; Maglev [LTS; $T_{op} \geq 10$ K: HTS]
- 1 — Permanent magnet (PM)
- 10^{-1}
- Toy magnets
- 10^{-2} — Safe limit for watches, CD
- 10^{-3}
- 5 gauss — US government limit of long exposure for human
- 10^{-4} (1 gauss) — Earth field (~0.7 gauss)
- 10^{-10}
- 10^{-11} — Measurable (chest) "heart" field
- 10^{-12}
- 10^{-13} — Measurable (head) "brain" field
- 10^{-14}
- 10^{-15} — Lower limit of measurement

High Fields

< 0.1 T most people (toy magnets)

1 T PM devices

≥10 T magnetic devices

>20 T NMR

High-Field Applications of HTS Tape
ISS2014 Funabori (11/25/2014)

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Four Important Design Issues for
High-Field *Superconducting Magnet*

- Superconductor— $\mu_o H_{c2}(T)$; $J_c(B, T)$; strength
- Mechanical integrity—magnetic stresses (hoop & radial)
- Overall current density—↗ magnet efficiency ↘ cost
- Protection—to ensure multiple operation

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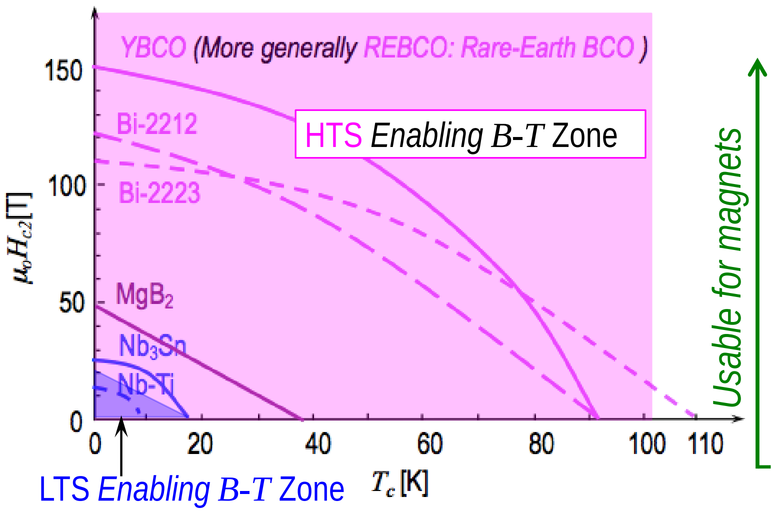
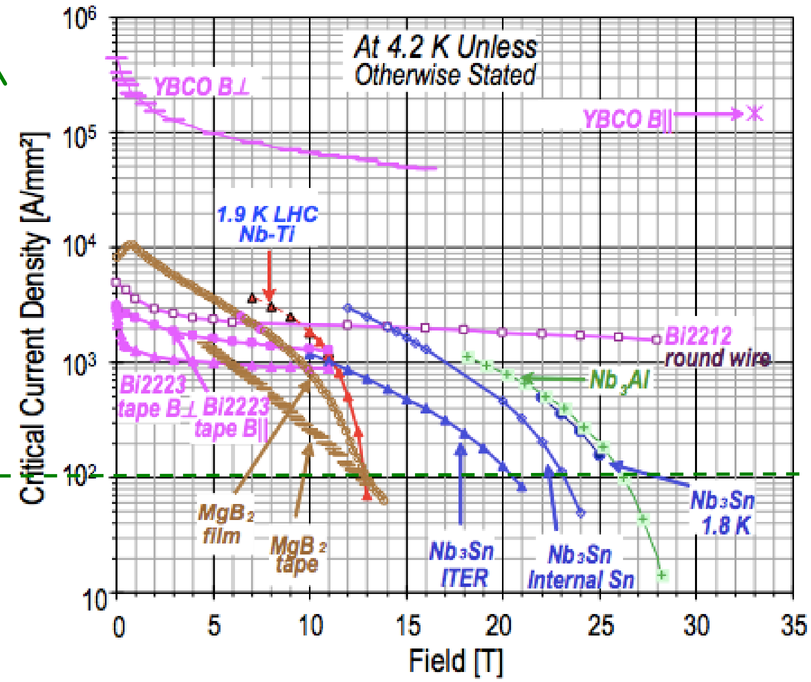
Superconductor: $\mu_c H_{c2}(T)$, $J_c(B, T)$ *& Strength*





- For $B \geq 25$ T, even at $T_{op} = 4.2$ K: HTS indispensable
- For $T_{op} > 10$ K: HTS indispensable
- Because $J_c(B_{op})$ decreases with T: T_{op} *a key design variable*
- Strength: REBCO > all others: For > 25-T magnets: REBCO *preferable*

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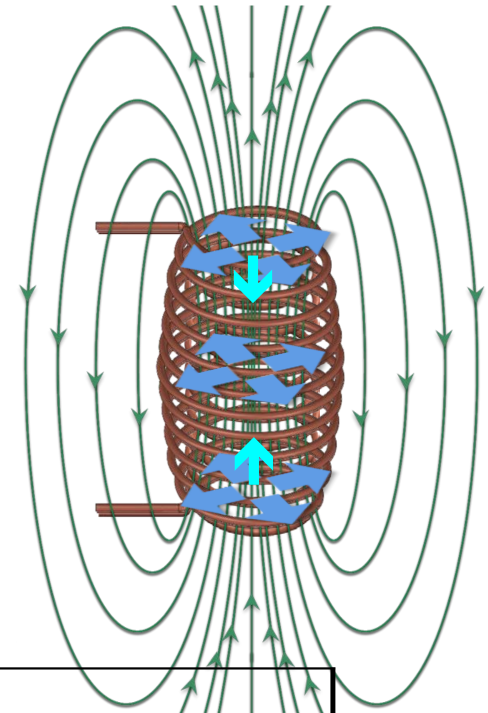
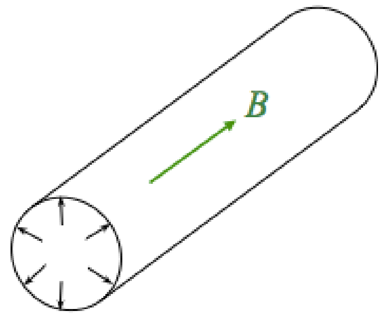
Mechanical integrity
Magnetic Stresses



Magnetic pressure: $B^2/2\mu_o$

For *high-field* magnet, conductor strength extremely, if not the most, important property



Undersea Depth [m]	P_m [atm]	B [T]	f [GHz]	*Remarks*
300	30	2.7	0.12	Maximum for submarines 
11,000	1,100	16.5	0.7	Deepest sea bottom: *Challenger Deep* 
22,100	2,210	23.5	1.0	High-strength stainless steel yields at 14,000 atm
400,000	40,000	100	4.26	

Hoop Stress, σ_θ, *in Solenoid*, vs. *Radial Distance*, $\rho = r/a_1$

$$\sigma_\theta = \frac{\lambda J B_1 a_1}{\alpha - 1}\left\{(\alpha-\kappa)\left[\frac{2+\nu}{3}\left(\frac{\alpha^2+\alpha+1+\alpha^2/\rho^2}{\alpha+1}\right) - \frac{1+2\nu}{3}\rho\right] - (1-\kappa)\left[\frac{3+\nu}{8}\left(\alpha^2+1+\frac{\alpha^2}{\rho^2}\right) - \frac{1+3\nu}{8}\rho^2\right]\right\}$$

- $\sigma_{\theta max}$ at Coil i.d.: $r = a_1$ ($\rho = 1$)

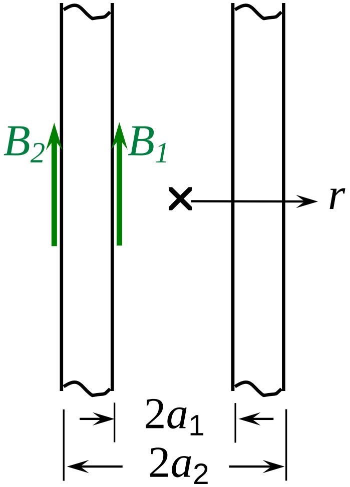
$\alpha = a_2/a_1$

$\rho = r/a_1$

$\kappa = B_2/B_1$*

(*κ = 0 for ∞ long)

$\nu \sim 0.3$



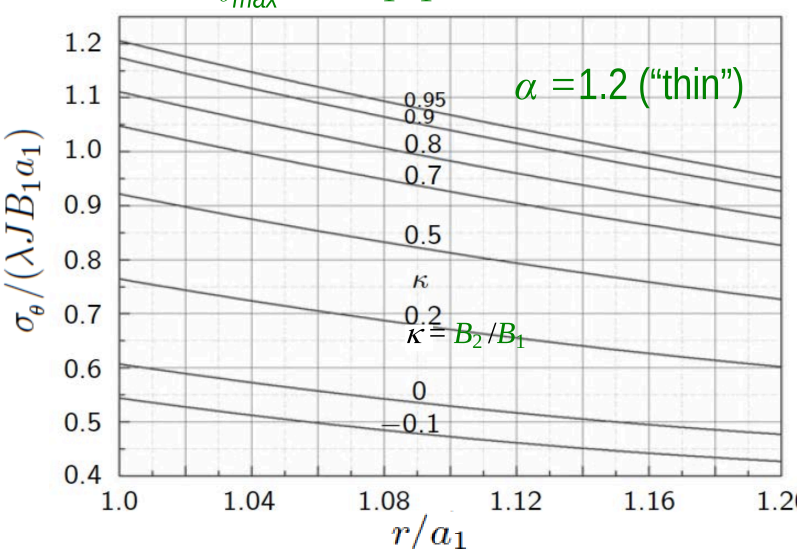
Hoop Stress, σ_θ, *in Solenoid*, vs. *Radial Distance*, $\rho = r/a_1$

$$\sigma_\theta = \frac{\lambda J B_1 a_1}{\alpha - 1}\left\{(\alpha-\kappa)\left[\frac{2+\nu}{3}\left(\frac{\alpha^2+\alpha+1+\alpha^2/\rho^2}{\alpha+1}\right)-\frac{1+2\nu}{3}\rho\right] - (1-\kappa)\left[\frac{3+\nu}{8}\left(\alpha^2+1+\frac{\alpha^2}{\rho^2}\right)-\frac{1+3\nu}{8}\rho^2\right]\right\}$$

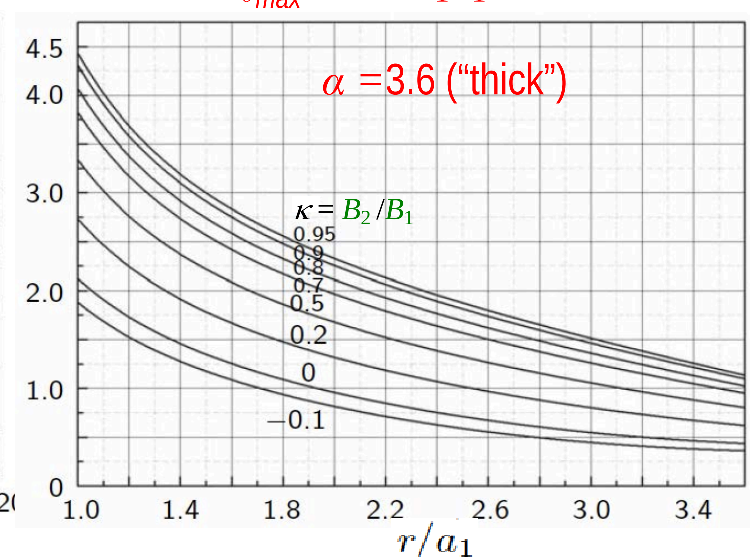
Thin Coil: $\lim_{\alpha\to 1}\sigma_\theta \to \frac{1}{2}(1+\kappa)\lambda J B_1 a_1$

Thick Coil: $\lim_{\alpha\gg 1}\sigma_\theta \to \alpha\left[\frac{(7+9\kappa)+(5+3\kappa)\nu}{12}\right]\lambda J B_1 a_1$

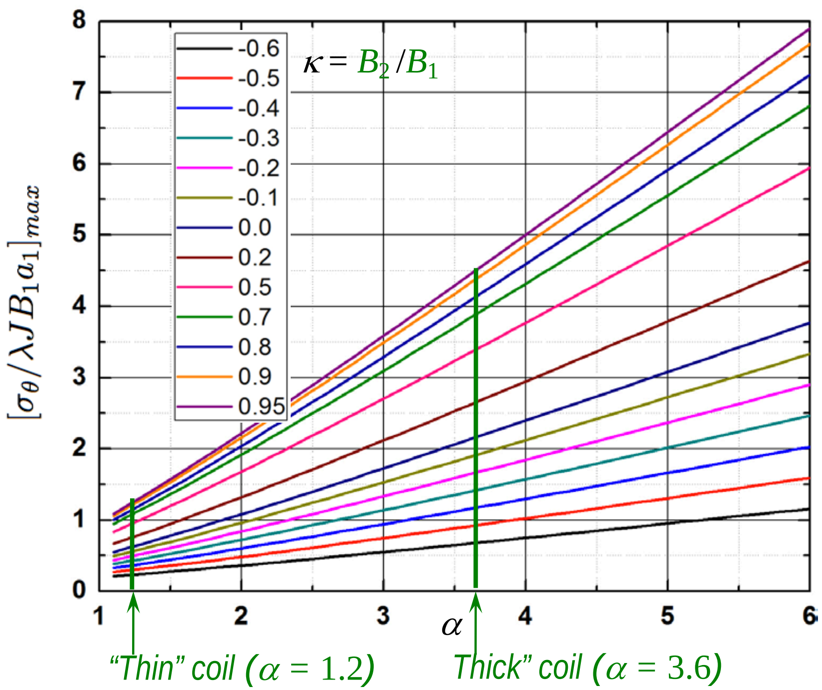
$\sigma_{\theta max} = \lambda J B_1 a_1$ for $\alpha = 1$ & $\kappa = 1$



$\sigma_{\theta max} >> \lambda J B_1 a_1$ for $\alpha >> 1$



Maximum Hoop Stress, $\sigma_{\theta max}$, *at* $r = a_1$



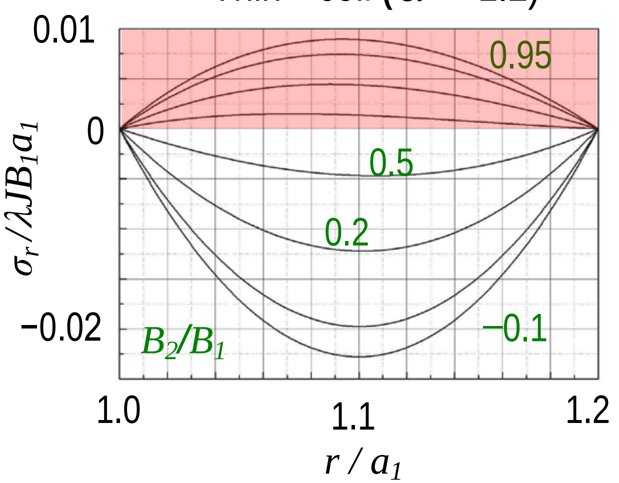
For high-field coil: "thin" radial built, i.e., $\alpha \rightarrow 1$

$$\sigma_{\theta max} \rightarrow \lambda J B_1 a_1$$

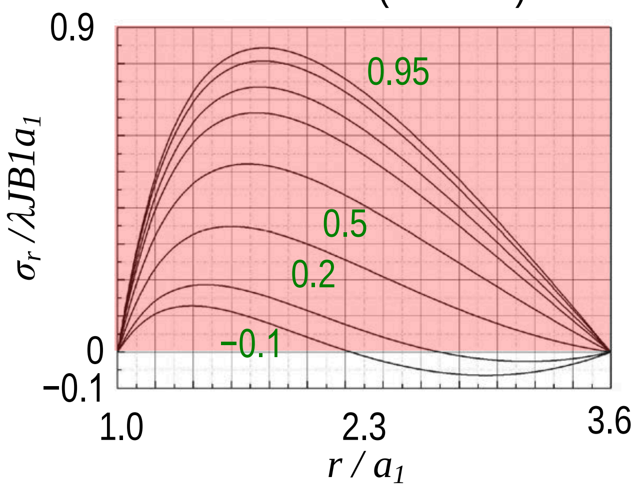
Radial Stress, $\sigma_r/\lambda J B_1 a_1$, vs. *Radial Distance*, $\rho = r/a_1$

$$\sigma_\rho = \frac{\lambda J B_1 a_1}{\alpha - 1}\left[\frac{2+\nu}{3}(\alpha-\kappa)\left(\frac{\alpha^2+\alpha+1-\alpha^2/\rho^2}{\alpha+1}-\rho\right) - \frac{3+\nu}{8}(1-\kappa)\left(\alpha^2+1-\frac{\alpha^2}{\rho^2}-\rho^2\right)\right]$$

"Thin" coil (α = 1.2)



"Thick" coil (α = 3.6)



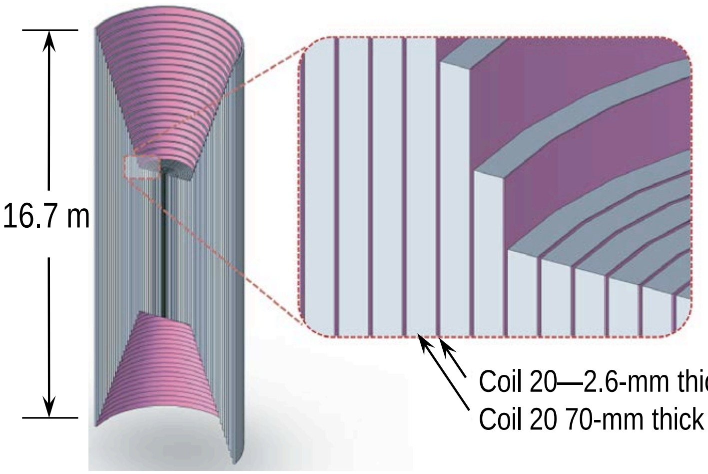
- $\sigma_r < 0$ to keep the winding from separating, Coil, "thin" radial built, i.e., $\alpha \rightarrow 1$

High-Field Magnet: Winding Requirements

- "Thin" radial-build coil, i.e., $\alpha \rightarrow 1$
  - $\sigma_{\theta max}$ < conductor $\sigma_{\theta limit}$ *and* $\sigma_r < 0$
- Large ampere-turns ➔ nested-coil formation of *many thin* coils
- Overbanding also helps to keep $\sigma_{\theta max} < \sigma_{\theta limit}$ and $\sigma_r < 0$

One Extreme Example: 100-T All-REBCO Tape DC *Magnet**

- Comprises 39 "thin" DP coils
- Each coil *heavily* over-banded
  - Total steel band radial build: 2,687.4 mm
  - Total REBCO radial build: 79.3 mm



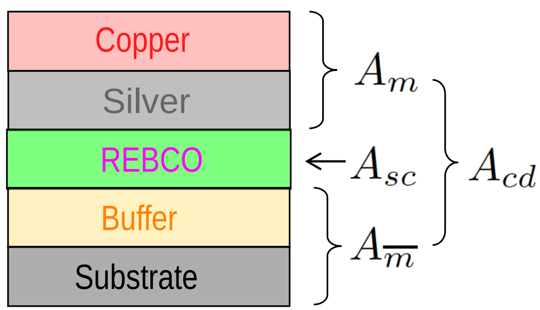
Coil #	$2a_1$	Δa	α
1	20.0	5.3	1.5300
2	60.6	5.3	1.1749
5	224.0	7.9	1.0705
10	833.4	4.9	1.0118
15	1,634.0	3.4	1.0042
20	2,430.8	2.6	1.0024
25	3,232.2	2.6	1.0016
30	4,042.6	2.7	1.0013
35	4,863.0	3.8	1.0016
39	5,549.0	7.6	1.0027
	i.d. [mm]	REBCO build [mm]	

- A steel magnet (strength) shunted by REBCO tape (DC current)

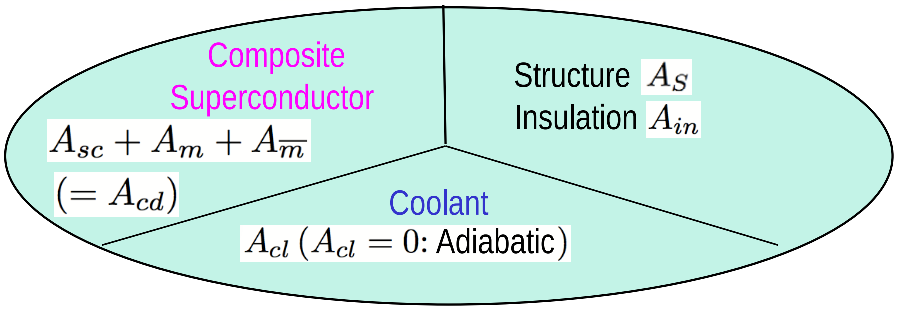
* Y. Iwasa and S. Hahn, "First-cut design of an all-superconducting 100-T direct current magnet," *Appl Phys. Lett.* 103, 253507 (5pp) (2013).

Current Densities

Composite Conductor



Winding Pack (A_{wd})
$(A_{cd} + A_S + A_{in} + A_{cl})$



Current Density	*Relevance*	*Definition*
Critical, J_c	Material development	$\frac{I_c}{A_{sc}}$
Engineering, $J_e (= J_{cd})$	Conductor development	$\frac{I_c}{A_{cd}} = \frac{I_c}{A_{sc} + A_m + A_{\overline{m}}}$
Matrix, J_m	Stability & Protection	$\frac{I_{op}}{A_m}$
Overall, $\lambda J (= J_{overall})$	Magnet efficiency	$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd}+A_S+A_{in}+A_{cl}}$

- $J_c = \infty$ $(A_{sc} = 0)$ *little impact* on J_e or λJ

Design Options for Efficient (High-Performance) Magnet

1. Adiabatic Magnet (A_{cl} = 0)

$$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd} + A_S + A_{in} + \cancel{A_{cl}}} \uparrow$$

Why fusion magnets "cryostable," i.e., $A_{cl} \neq 0$?

Huge mechanical reinforcement within the winding, $A_S >> A_{cl}$:
A_{cl} *little impact* on λJ, i.e., a negligible sacrifice on magnet efficiency

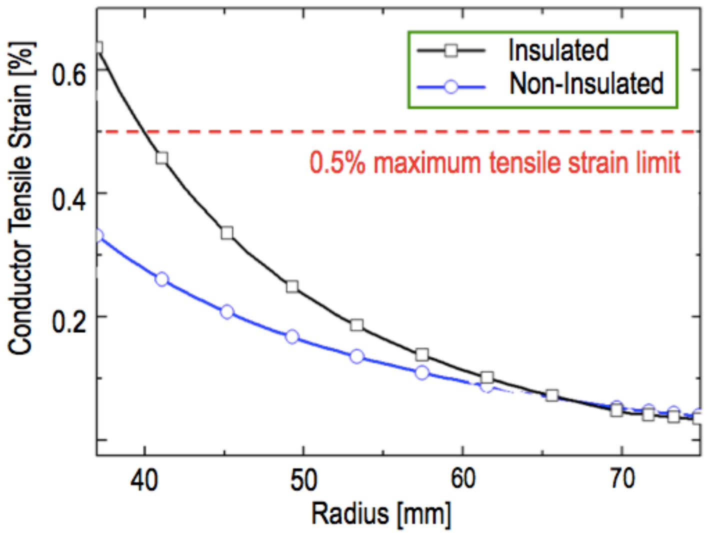
Let's guarantee *stability* by making the winding *cryostable*, i.e., $A_{cl} \neq 0$

For "small" magnets like NMR, MRI, HEP,
λJ enhancement large enough to permit "reduced" stability

Design Options for Efficient (High-Performance) Magnet

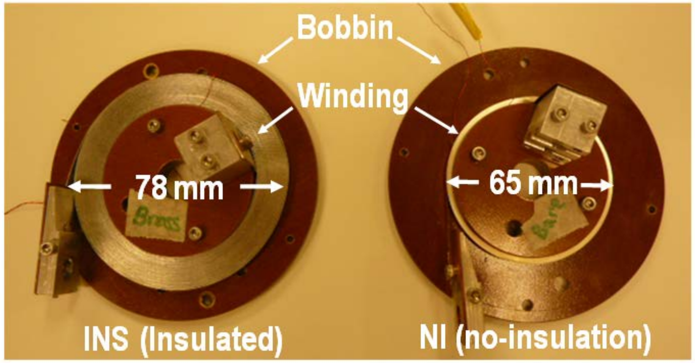
2. Adiabatic-NI (No-Insulation) —Applied to DP Coils of HTS Tape

$$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd} + A_S + \cancel{A_{in}} + \cancel{A_{cl}}} \uparrow$$



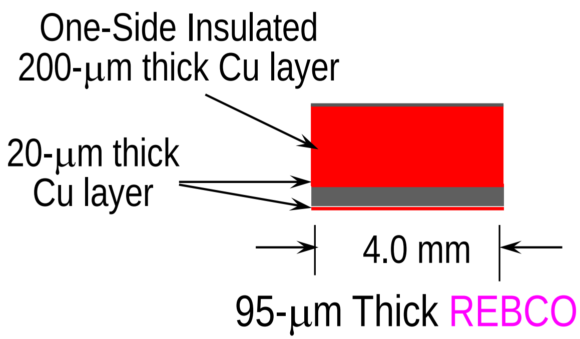
Major Benefits:

- With mechanically weak coolant & insulation gone, *winding robust*
- Current commutation among turns makes NI coil *self-protecting*
- NI coils *compact*, *much more so* than just by the insulation space



Seungyong Hahn, Dong Kuen Park, Juan Bascuñàn, and Yukikazu Iwasa, "HTS pancake coils without turn-to-turn insulation," *IEEE Trans. Appl. Superconduc*. 21, 1592 (4pp) (2011).

NI Pancake Coil: Why So Compact?



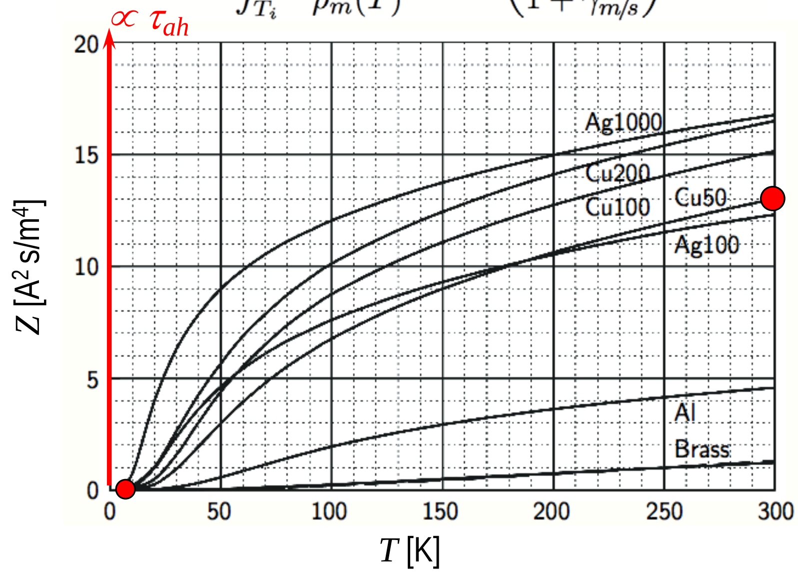
Insulated Pancake

I_{op} = 250 A

$\sim\lambda J$ [A/mm^2]	J_m [A/mm^2]	τ_{ah} [s]
660	1563	0.18
210	260	4.2

Adiabatic Heating of a Quench Zone

$$Z(T_f, T_i) \equiv \int_{T_i}^{T_f} \frac{C_m(T)}{\rho_m(T)}\, dT = \left(\frac{\gamma_{m/s}}{1+\gamma_{m/s}}\right) J_{m_\circ}^2 \tau_{ah}$$

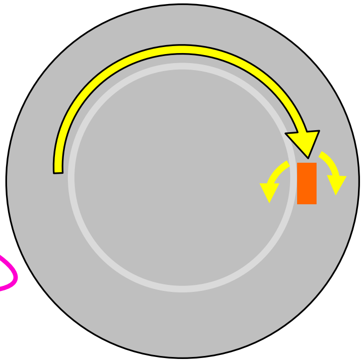


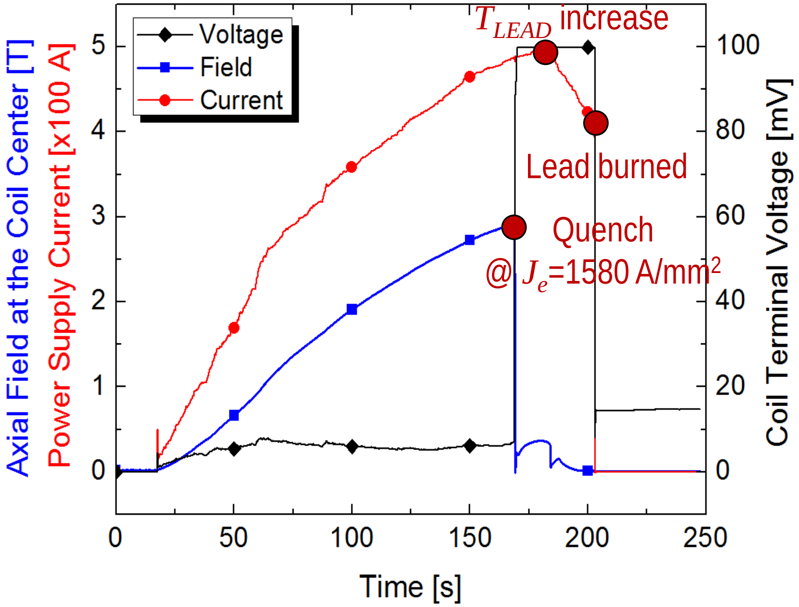
NI Pancake: $\lambda J \sim$ 660 A/mm^2, not because of no-insulation layer, but chiefly of *elimination* of *200-µm thick Cu layer*, *unneeded due to its self-protecting property*

*A Self-Protecting NI Coil @77 K**

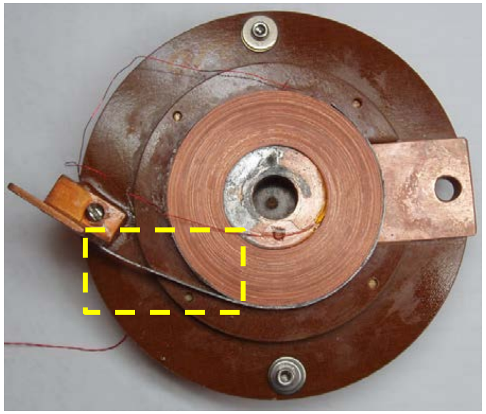
- Coil quenched @I_{op} = 412 A (1580 A/mm²)
- Coil *undamaged* in 20-s "over-current" operation; *Short sample* burned at 90 A

Insulated Pancake: J_m = 1563 A/mm²; τ_{ah} = 0.18 s





NI Pancake 4-mm REBCO, 210-Turn
($2a_1$ = 25.4 mm; $2a_2$ = 53.2 mm)



- Seungyong Hahn, Dong Kuen Park, John Voccio, Juan Bascuñàn, and Yukikazu Iwasa, "No-Insulation (NI) HTS inserts for LTS/HTS NMR magnets," *IEEE Trans. Appl. Superconduc*. 22, 4302405 (5pp) (2012).

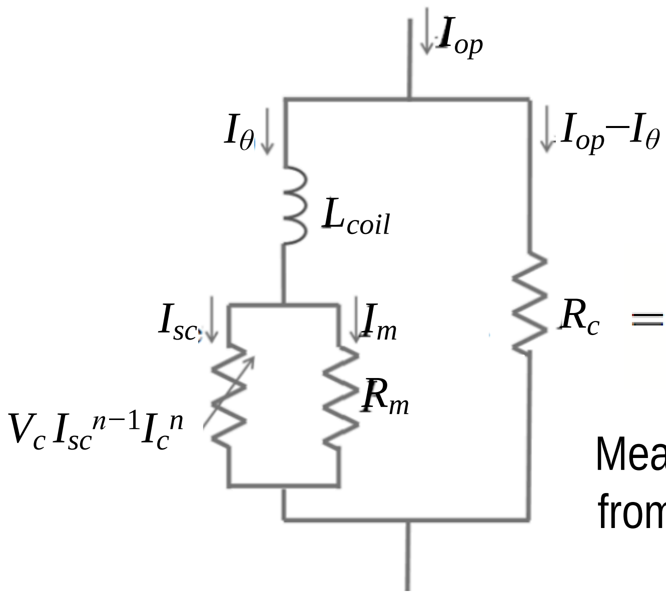
NI DP Coil: Main Drawbacks

NI coil, modeled as an LR circuit (next slide): two main drawbacks

1. Charging Time Delay (L_m / R_m)
   - NI coil best for DC or under "low" time-varying conditions
     - ➢ Suitable applications: NMR; MRI
2. Dissipation under time-varying conditions ($R_m I^2$)

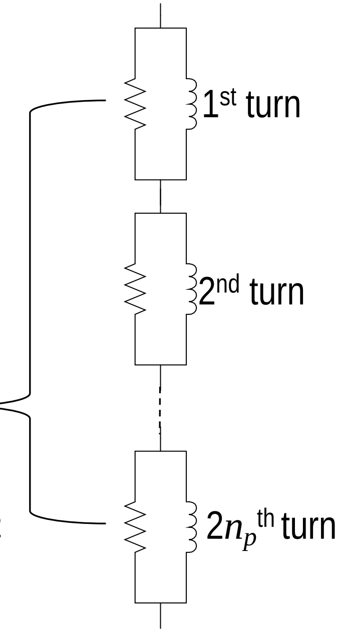
Charging Time Delay

NI REBCO DP Coil: Circuit Model



$$R_c = \sum_{i=1}^{2n_p} R_i = \sum_{i=1}^{2n_p} \frac{R_{ct}}{2\pi r_i w_d}$$

NI REBCO DP coil



Measured R_{ct}: 30—70 μΩ cm^2
from small NI REBCO DP coils

Shunt resistance R_m of a magnet of N_m NI REBCO DP coils, each of $2n_p$ turns

$$R_m = \frac{N_m(2n_p)R_c}{[\ell_m w/N_m(2n_p)]} = \frac{4N_m^2 n_p^2 R_c}{\ell_m w} \quad (1) \quad \rightarrow \quad \tau_m = \frac{L_m}{R_m} \quad (2)$$

*A 26-DP-NI-Coil REBCO Magnet**

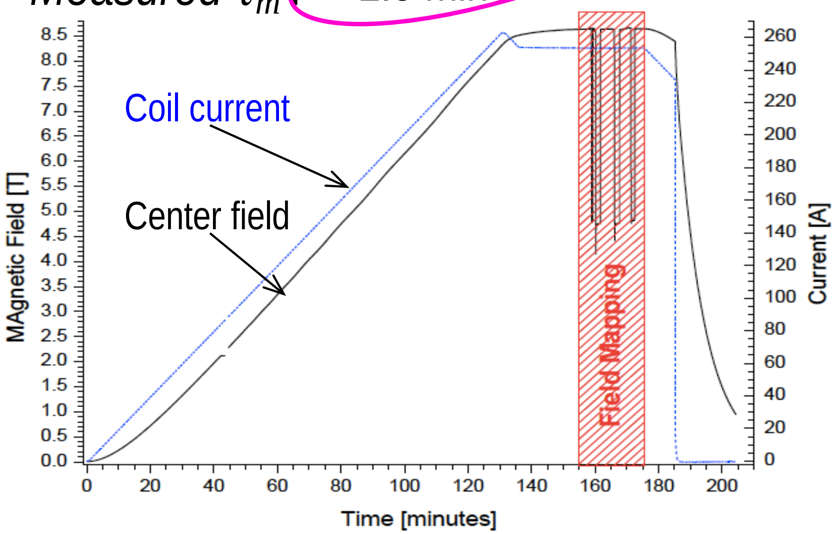
Computed τ_m (Eqs. 1 & 2)

$$R_m = \frac{4N_m^2 n_p^2 R_{ct}}{\ell_m w} = 17.2\ \text{m}\Omega \quad (w = 6\ \text{mm}) \qquad (1)$$

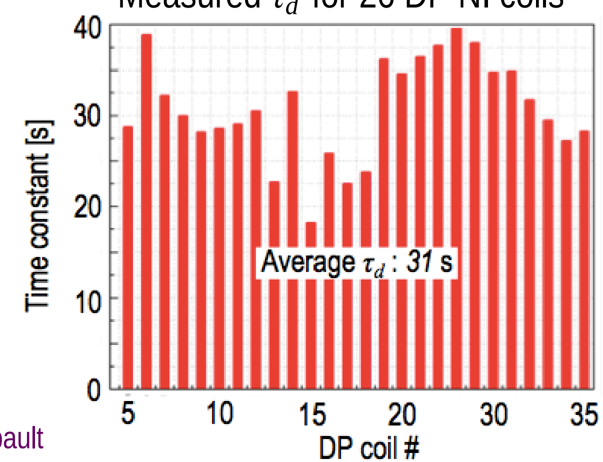
$$\tau_m = \frac{L_m}{R_m} = \frac{2.43\ \text{H}}{17.2\ \text{m}\Omega} = 2.3\ \text{min.} \qquad (2)$$

Measured τ_m : ~ 2.5 min

Total # DP NI Coils (N_m Eq.1)	26
# turns/pancake (n_p Eq. 1)	185
Conductor length (l_m Eq. 1)	3.14 km
Magnet inductance L_m	2.43 H
R_m	17.2 mΩ
τ_m (Eq. 2)	2.3 min.



Measured τ_d for 26 DP NI coils



Equivalent R_{ct} = 35 μΩ cm²

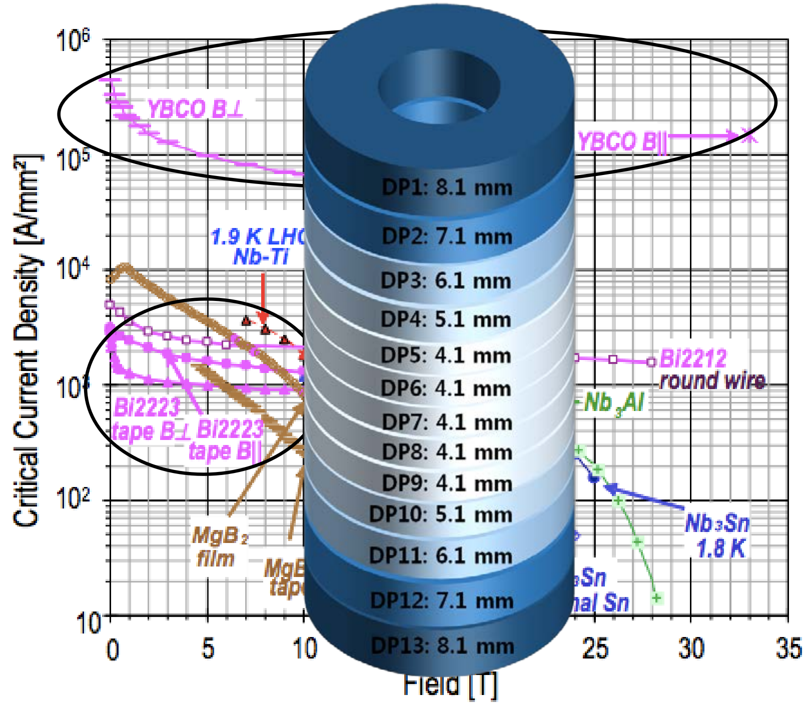
* Yukikazu Iwasa, Juan Bascuñàn, Seungyong Hahn, John Voice, Youngjae Kim, Thibault Lècrevisse, Jungbin Song, and Kazuhiro Kajikawa, "A high-resolution 1.3 GHz/54-mm LTS/HTS NMR magnets," *ASC2014* (August 2014).

Design Options for Efficient (High-Performance) Magnet

3. Adiabatic-NI-MW (Multi-Width)*

MW Winding Formation

- Akin to conductor-grading used in LTS nested coils: *lesser* $I_c(B)$-*performance* conductors for *radially* farther layer-wound coils
- To ameliorate anisotropic $I_c(B)$-performance of HTS tape, *wider* tapes in axially farther DP coils

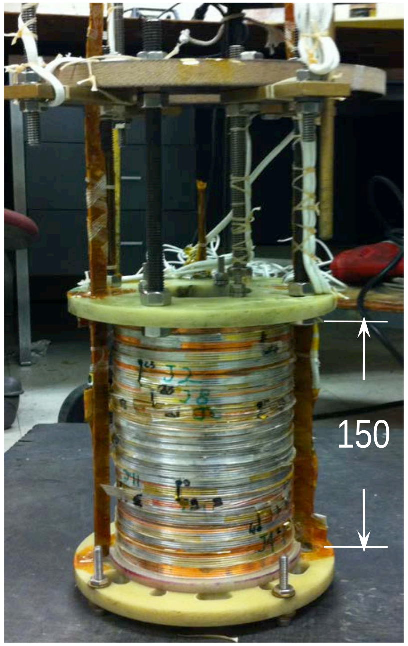


- Clearly this 13-NI-*MW*-DP magnet** (overall height: 150 mm) more efficient than a 13-NI-DP magnet (overall height ~208 mm = 13 × 2 × 8 mm)

* Seungyong Hahn, Youngjae Kim, Dong Keun Park, Kwanglok Kim, John Voccio, Juan Bascuñán, and Yukikazu Iwasa, "No-Insulation Multi-Width winding technique for high temperature superconducting magnet", Appl. Phys. Lett., 103, 173511 (3pp) (2013).

** Seungyong Hahn, Jungbin Song, Youngjae Kim, Thibault Lècrevisse, Young Chu, John Voccio, Juan Bascuñàn, and Yukikazu Iwasa, "Construction and test of 7-T/68-mm cold bore multi-width, no-insulation GdBCO magnet," *ASC2014* (August, 2014).

Adiabatic-NI-MW
— A 7-T (300-MHz)/54-mm bore REBCO Magnet —
(I_{op} = 250 A; T_{op} = 4.2 K; $2a_1$ = 78 mm; $2a_2$ = 101 mm; L = 0.592 H)

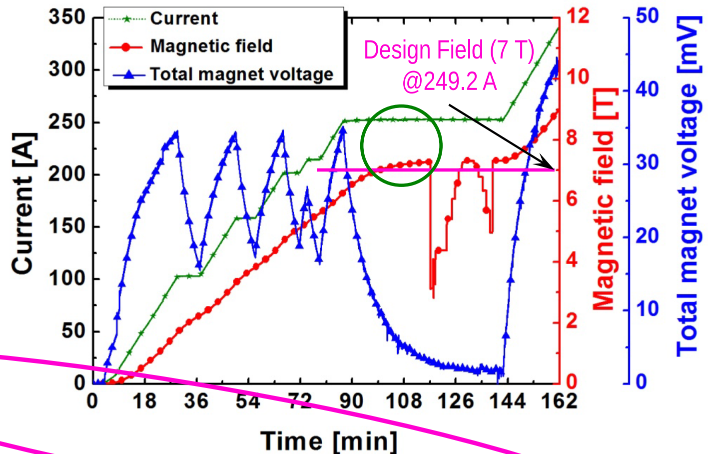


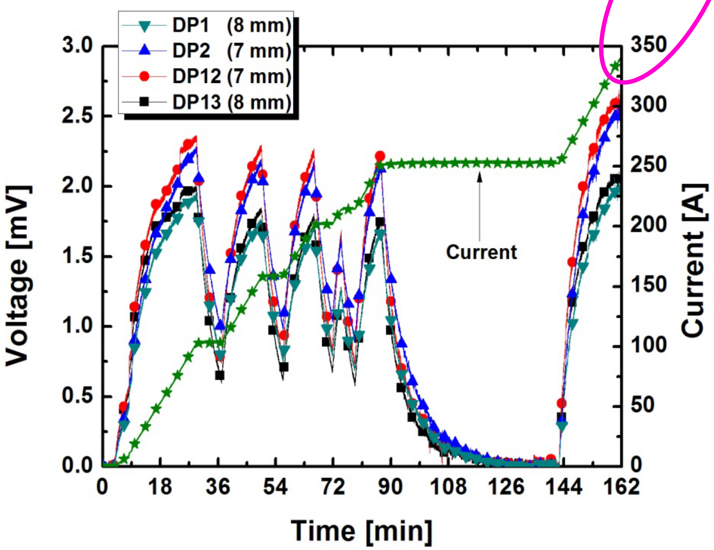
Selected *Averaged* Parameter Values

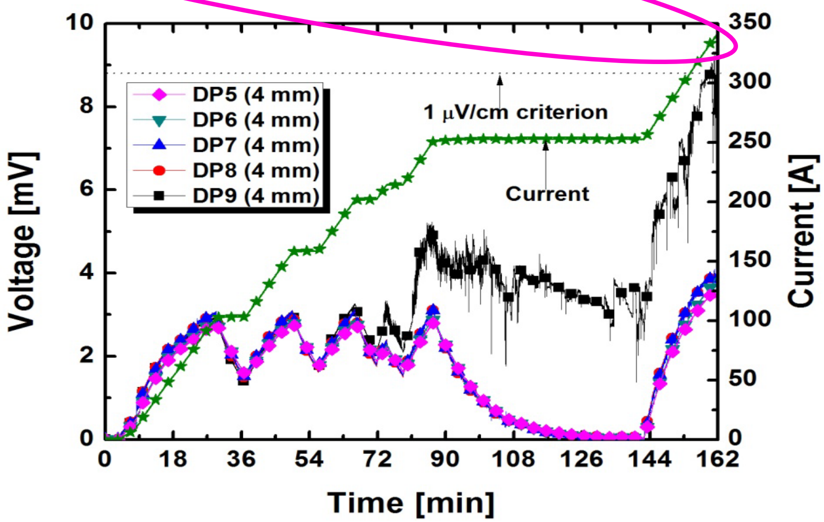
DP #	w [mm]	I_c (tape) [A]	I_c (coil) [A]	R_C [μΩ]	τ_d [s]
1	8.1	300	76.5	197	46
2	7.1	270	70.4	251	37
3	6.1	236	64.1	177	55
4	5.1	271	57.3	288	35
5	4.1	171	51.7	102	103
6	4.1	171	49.4	95	110
7	4.1	171	48.6	549	19
8--13	Bottom half (13—8) similar to top half (1—6)				
				R_m	3.84 mΩ

*Selected Results @4.2 K**

- Achieved 7.31 T (311 MHz) @253.1 A
- Measured charging delay $\tau_d \sim$ 3 min, close to $L/R_m \sim$ 154 s
- Magnet undamaged, even after pushed to an over-current of 343 A



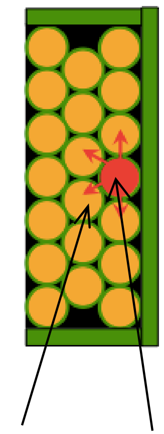




* Seungyong Hahn, Jungbin Song, Thibault Lècrevisse, Yukikazu Iwasa (unpublished, October 2014).

Protection & Normal Zone Propagation (NZP)

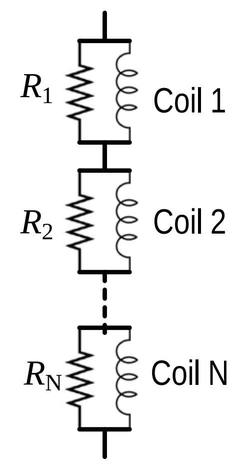
- "Small" LTS magnets rely on "fast" *NZP* velocity to spread out the normal zone to keep the "hot spot" from overheating
- "Large" LTS magnets rely on "subdivision" (by shunt resistors), but the subdivision technique too relies on "fast" NZP velocity
- In HTS magnets, NZP velocities (U_l, longitudinal & U_t, transverse) very slow, compared with those in LTS magnets: if relied only on NZP, an HTS hot spot overheated



$$U_l(T) = \frac{J_m}{C_{cd}(T)} \sqrt{\frac{\rho_m(T) k_m(T)}{(T_{cs} - T_{op})}}$$

for HTS $C_{cd}(T)$ very large ⇨ $U_{l_{HTS}} << U_{l_{LTS}}$

Also for HTS, $U_t(T) < 0.1 U_l(T)$



Protection & Normal Zone Propagation (NZP)

Selected Measured Longitudinal NZP Velocities (U_l)

Superconductor	B_{op} [T]	T_{op} [K]	J_m [A/cm^2]	U_l [mm/s]	Group (Year)
Nb_3Sn	0	12	70,300	511	MIT (1993)
	5	5.5	46,875	526	MIT (1993)
Bi2223	0	40	22,700	1.9	MIT (1993)
YBCO	0	46	1,000–1500	2–8	ORNL (2002)
	0	77	300–1500	3–10	NHMFL (2002)
	5	60	20,000	1	Waseda (2004)
	8	10	28,570	45	Grenoble-Saclay(2013)

HTS magnet must rely on active protection or
be a self-protecting assembly of NI coils

Two Major Drawbacks of HTS Tape vs. LTS Wire

Both stem from a huge difference in their characteristic sizes, d_f
~1000 μm >> ~50 μm

1. Screening-Current Field (SCF), for NMR & MRI magnets
   - SCF $\propto$ magnetization $\propto J_c \times d_f$ (HTS tape >> LTS wire
     - ➘ Spatial field homogeneity
     - New field shimming techniques: HTS shims* & "shaking" field**

* Y. Iwasa, S. Hahn, J. Voccio, D. K. Park, K. Kim, J. Bascuñán, "Persistent-mode high-temperature superconductor shim coils: concept and experimental results of a prototype Z1 high-temperature superconductor shim", *Appl Phys. Lett.* 103, 173511 (3pp) (2013).

** K. Funaki, M. Noda, K. Yamafuji, "Abnormal transverse-field effects in nonideal type II superconductor III. a theory for an AC-induced
decrease in the semi-quasistatic magnetization parallel to a DC bias field, *Jpn J. Appl. Phys.* 21, 1580 (7pp) (1982).
G. P. Mikitik and E.H. Brandt, "Why an ac magnetic field shifts the irreversibility line in type-II superconductors," *Phys. Rev.* B67, 104511 (8pp) (2003).

K. Kajikawa and K. Funaki, "Reduction of magnetization in windings composed of HTS tapes," *IEEE Trans. Appl.Supercond*. 22, 4400404 (4pp) (2012).

Kazuhiro Kajikawa, Gwendolyn V. Gettliffe, Seungyong Hahn, Yong Chu, Daisuke Miyagi, and Yukikazu Iwasa, "Design and tests of compensation coils to reduce screening currents induced in HTS coil for NMR magnet," *ASC2014* (August 2014).

Two Major Drawbacks of HTS Tape vs. LTS Wire

Both stem from a huge difference in their characteristic sizes, d_f

~1000 μm >> ~50 μm

2. AC losses for time-varying applications: HTS Tape >> LTS wire

- Twisted multi-tape Bi2223;*
- Striated or scribed REBCO tape**

* Kazuo Funaki, Yuji Sasasige, Haruo Yanagida, Satoshi Yamasaki, Masataka Iwakuma, Naoki Ayai, Tomonobu Ishda, Yusuke Fukumoto, and Hiroki Kamijo, "Development of low-AC-loss Bi-2223 superconducting multifilamentary wires," *IEEE Trans Appli. Supercond.* 19, 3053 (4pp) (2009).

** Naoyuki Amemiya, Satoshi Kasai, Keiji Yoda, Zhenan Jiang, George A Levin, Paul N Barnes and Charles E Oberly, "AC loss reduction of YBCO coated conductors by multifilamenatary structure," *Supercond. Sci. Technolo*. 17, 1464 (8pp) (2004).

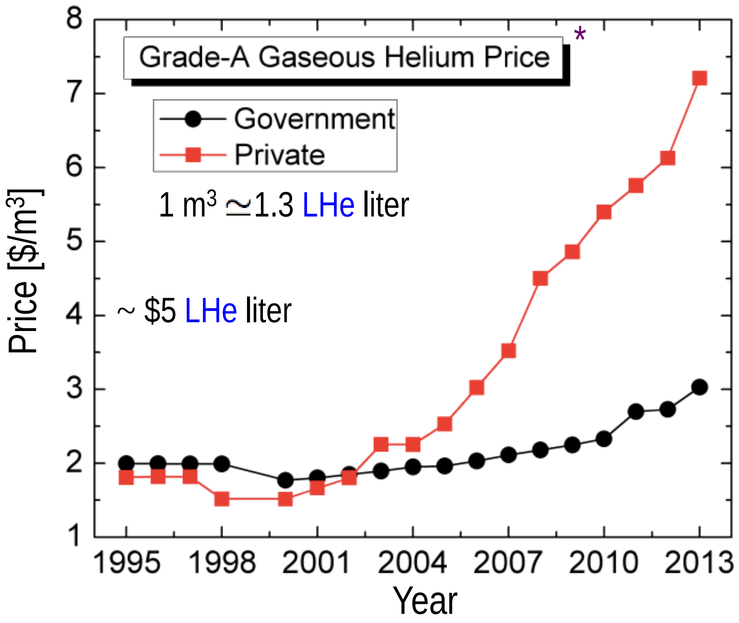
K Suzuki, J Matsuda, M Yoshizumi, T Izumi, Y Shiohara,, M Iwakuma, A Ibi, S. Miyata and Y. Yamada,, "Development of a laser scribing process of coated conductors for the reduction of AC losses," *Supercond. Sci. Technolo*. 20, 822 (5pp) (2007).

O Tsukamoto and M Ciszek, "AC magnetization losses in striated YBCO-123/Hastelloy coated conductors," *Supercond. Sci. Technolo*. 20, 974 (6pp) (2007).

Ibrahim Kesgin, Goran Majkic, Venkat Selvamanickam, "Fully filamentized HTS coated conductor via striation and selective electroplating," *Physica C* 486, 43 (8pp) (2013).

Liquid Helium (LHe)-Free Operation

- LHe-free magnet more relevant, and urgent, than ever as ↗ He price
- LHe-free HTS magnet @T_{op} >10 K easier to meet cryogenic requirements than its LTS counterpart @LHe temperatures



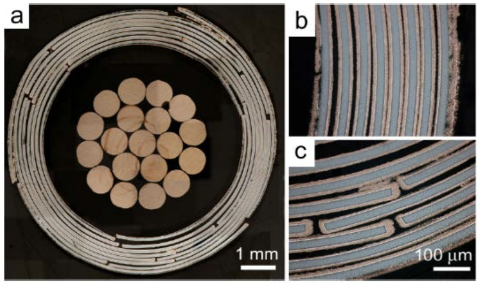
* US Geological Survey (http://minerals.usgs.gov/minerals/pubs/commodity/helium/), *Information, 2012.*

High-Current HTS Cables for Magnets

- $E_{mag} \propto VI_{op}\,\tau$
- In either charging or discharging sequence, ↗ I_{op}: ↘ $V\,\tau$
- For large energy LTS magnet systems, LHC, ITER, $I_{op} > 1\text{kA}$
- Except for power cables, $I_{op} < 500$ A

Recent High-Current REBCO Cables for Magnets

* 4.8 mm x 4.8 mm cross section cable of 32 REBCO tapes (4 mm x 0.01 mm), stacked between Cu strips Twist pitch: 200 mm



** Left: a) 8 layers with 3 dummy conductors, wound around a 5.5-mm former; b) 10 × close -up; c) between layers. *Right:* 6-turn inner layer of a magnet of ϕ7-mm cable.

- Assembly of "many" parallel, twisted REBCO tapes wrapped into a cable
- Technical issues for magnet applications
  - Full exposure to the I_c anisotropy of HTS tape
  - Cross-section unsuitable to tight packing winding: ➘ λJ

* Makoto Takayasu, Franco J. Mangiarotti, Luisa Chiesa, Leslie Bromberg, and Joseph V. Minervini, "Conductor characteristics of YBCO twisted stacked-tape cables," *IEEE Trans. Appl. Supercond.*, 23, 4800104 (4pp) (2013).

** DC van der Laan, XF Lu, and LF Goodrich, "Compact $GdBa_2Cu_3O_{7-\delta}$ coated conductor cables for electric power transmission and magnet applications," *Supercond. Sci. Technol.* 24, 042001 (6pp) (2011).

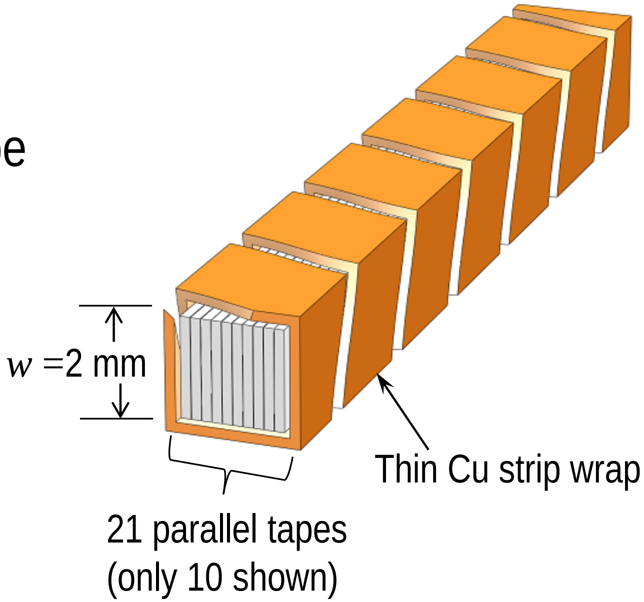
DC van der Laan, PD Noyes, GE Miller, HW Weijers, GP Willering, "Characterization of a high-temperature superconducting conductor on round core cables in magnetic fields up to 20 T," *Supercond. Sci. Technol.* 26, 045005 (9pp) (2013).

*High-Current Cables with REBCO Tape**

- HTS cable designed for magnet: ↗ λJ
- Modular formation of base cables: scalable to high I

Base Cable

- m parallel w-wide, δ-thick, REBCO tape
- m: 10-100 (or even greater)
- w: may range 1-3 mm—here 2 mm
- δ: 70-100 μm thick = REBCO tape



Cable Formation

- Bundle of M x N base cables

* Yukikazu Iwasa (unpublished, August 2012).

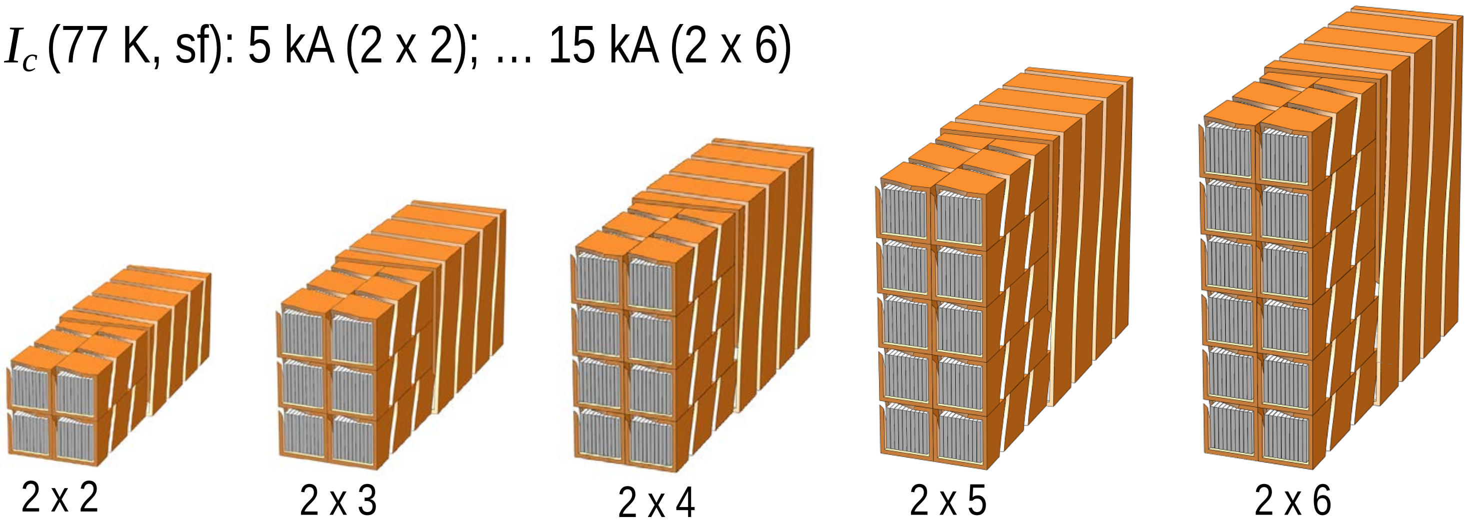
HTS-High Current Cables

Notable Features

- Option: No insulation, inside and outside the cable assembly
  - Applicable to NI and NI-MW winding techniques
- Cu strip wrap, not soldered to the blocks, to allow the cable to be bent
-  or  base orientation in M x N cables to lessen field-anisotropy effects

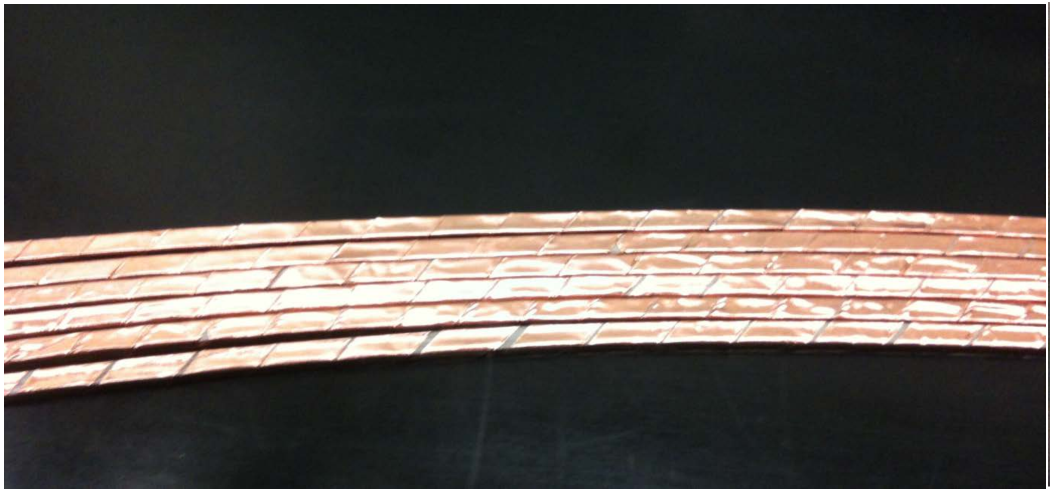
HTS Cables: M =2; N = 2, 3, 4, 5, 6

- I_c (77 K, sf): 5 kA (2 x 2); … 15 kA (2 x 6)



*Practice Base Cable, with Stainless Steel (SS) Tape**

- Base Cable a stack of 20 SS tapes, 2-mm x 0.1-mm
- Wrapped by 5-mm x 0.04-mm Cu strip

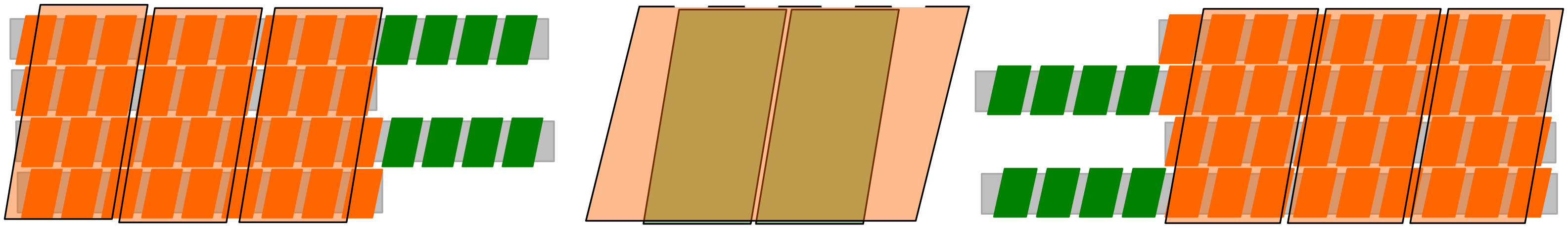


* Yukikazu Iwasa, Yong Chu, Seungyong Hahn, Juan Bascuñàn (unpublished, October 2012).

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
Plenary presentation SPL-1-INV given at ISS 2014, Tokyo, November 25 - 27, 2014.

*Joining Two HTS High-Current Cables (2 x 4)**

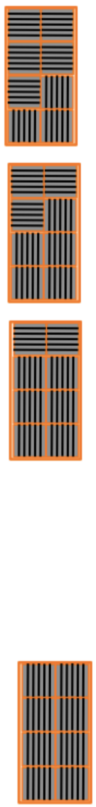
1. Prepare one end of a cable (here 2 x 4), ready for "finger" joint;
   Wrap solder (green) strip over each building block in the joint area
2. Bring together the two ends
3. Wrap wide solder strip over the exposed ends
4. Wrap over the solder-wrapped joint with wide, thin Cu strip, with holes at the top side, to supply additional solder during Step 5
5. Heat up, melt the solder, letting solder penetrate the entire cable ends



* Yukikazu Iwasa (unpublished, August 2012).

Application Examples

DP-Coil Magnet (2 x 4 Cable)



5

3

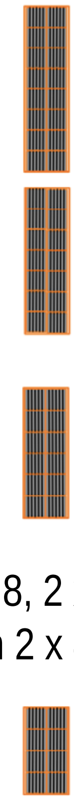
2

≃

DP-MW-Coil Magnet

Top DP

Center DP



2 x 8 *

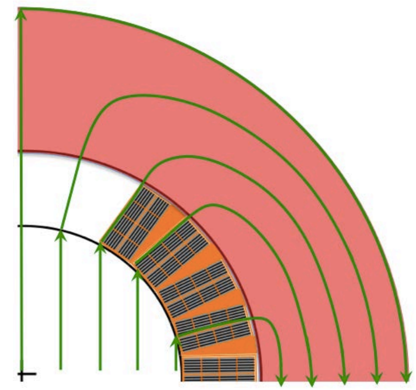
2 x 7 *

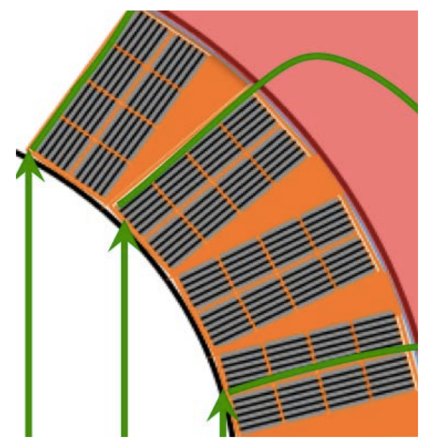
2 x 6

2 x 4

* 2 x 8, 2 x 7, 2 x 6 may be replaced with 2 x 4, 2 x 5 having some

Dipole (& Quodrupole)





Challenges for HTS Tape

- Superconducting splices, for NMR & MRI
  - To date, techniques available only for MgB2 wire* and GdBCO tape**
- Quench detection
- Longer unit length (like LTS, ➔10 km) with *uniform* properties
- Price: competitive vs. LTS

Technology	*Performance*	*Competitor*	*Criterion*
Enabling	Yes	No	Performance
Replacing	No	Yes	Price

* Weijun Yao, Juan Bascuñàn, Seungyong Hahn, and Yukikazu Iwasa, "A superconducting joint technique for MgB$_2$ round wires," IEEE Tran. Appl. Superconduc. 19, 2261 (4pp) (2009).

** Yeonjoo Park, Myungwhon Lee, Heesung Ann, Yoon Hyuck Choi and *Haigun Lee*, "A superconducting joint for $GdBa_2Cu_3O_{7-\delta}$-coated conductors," *Nature Asia Materials* 6, 1 (5pp) (2014). WT-15-INV (Wed. PM)

Conclusions

- For HTS, needed:
  - ➢ Imaginative scientific & industrial applications
  - ➢ Innovative, inspired designs & manufacturing techniques
  - ➢ Money
- For high-field and >10-K applications, with HTS tape, *the sky's the limit*

Thank you

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