High-Current HTS Cables for Magnet Applications

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Applied Superconductivity Conference, August 10-15, 2014, Charlotte, NC, USA

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Outline

- Why now? Why HTS cables?

- Applications and need for high current cables
  - High Energy Physics
  - Fusion
  - NMR/High Magnetic Field Science

- Available conductors
  - BSCCO
  - REBCO

- Cable designs for magnet applications
  - Characteristics
  - Advantages and disadvantages

- Outlook and conclusions

Outline

- Why now? Why HTS cables?

ACT I: WHY

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Why now?

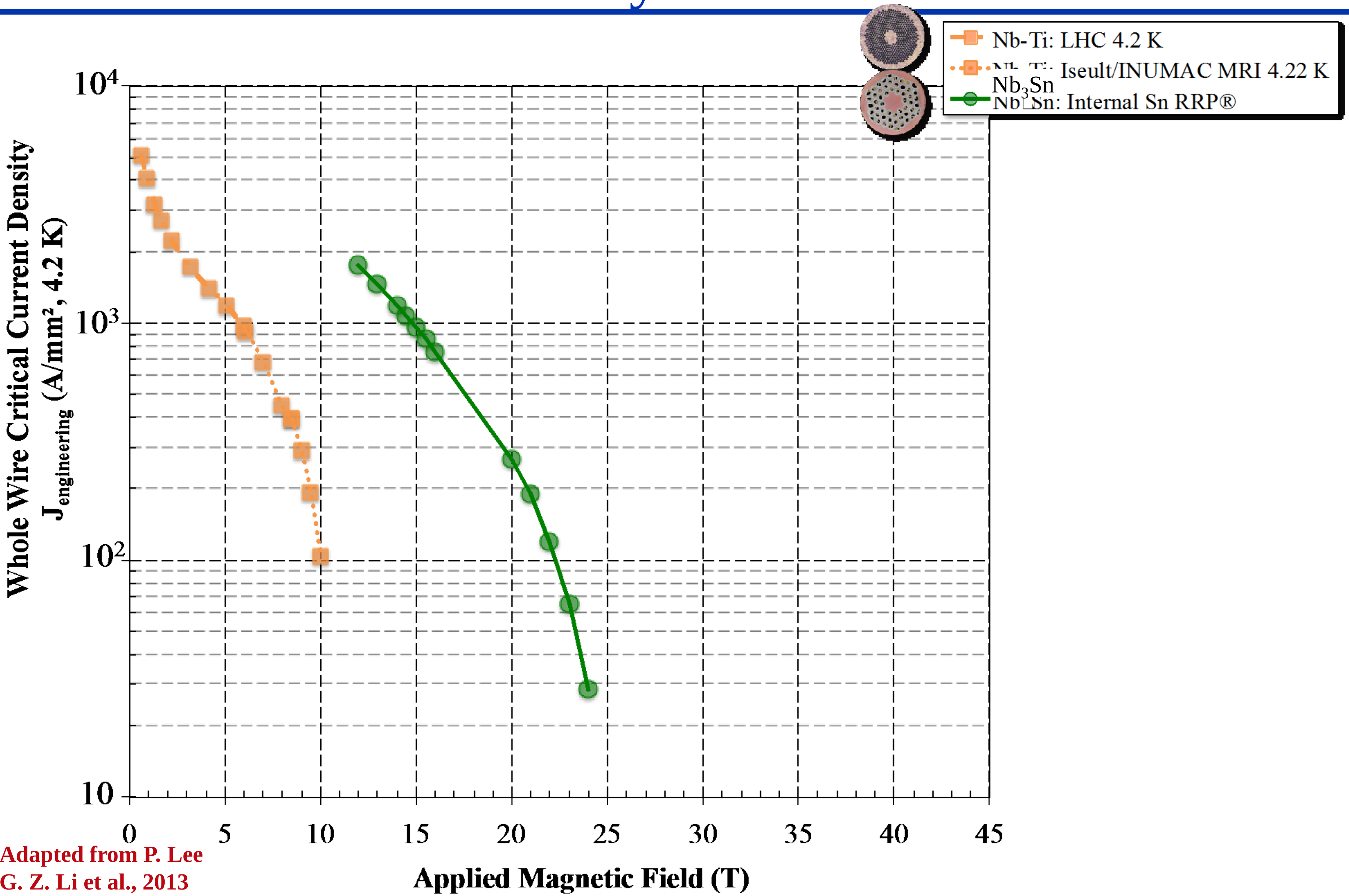
- HTS conductor is improving quickly but needs a push for applications requiring high currents (> 10 kA) & high fields (> 20 T). Cannot rely solely on private sector and power applications.
- Several opportunities in "distant future" but recall time from discovery of Nb_3Sn (1954) and Nb_3Sn magnets in large machines (2015-2020).

We have to start NOW!!!

- High Energy Physics
- Fusion
- Nuclear Magnetic Resonance
- High Magnetic Field Science

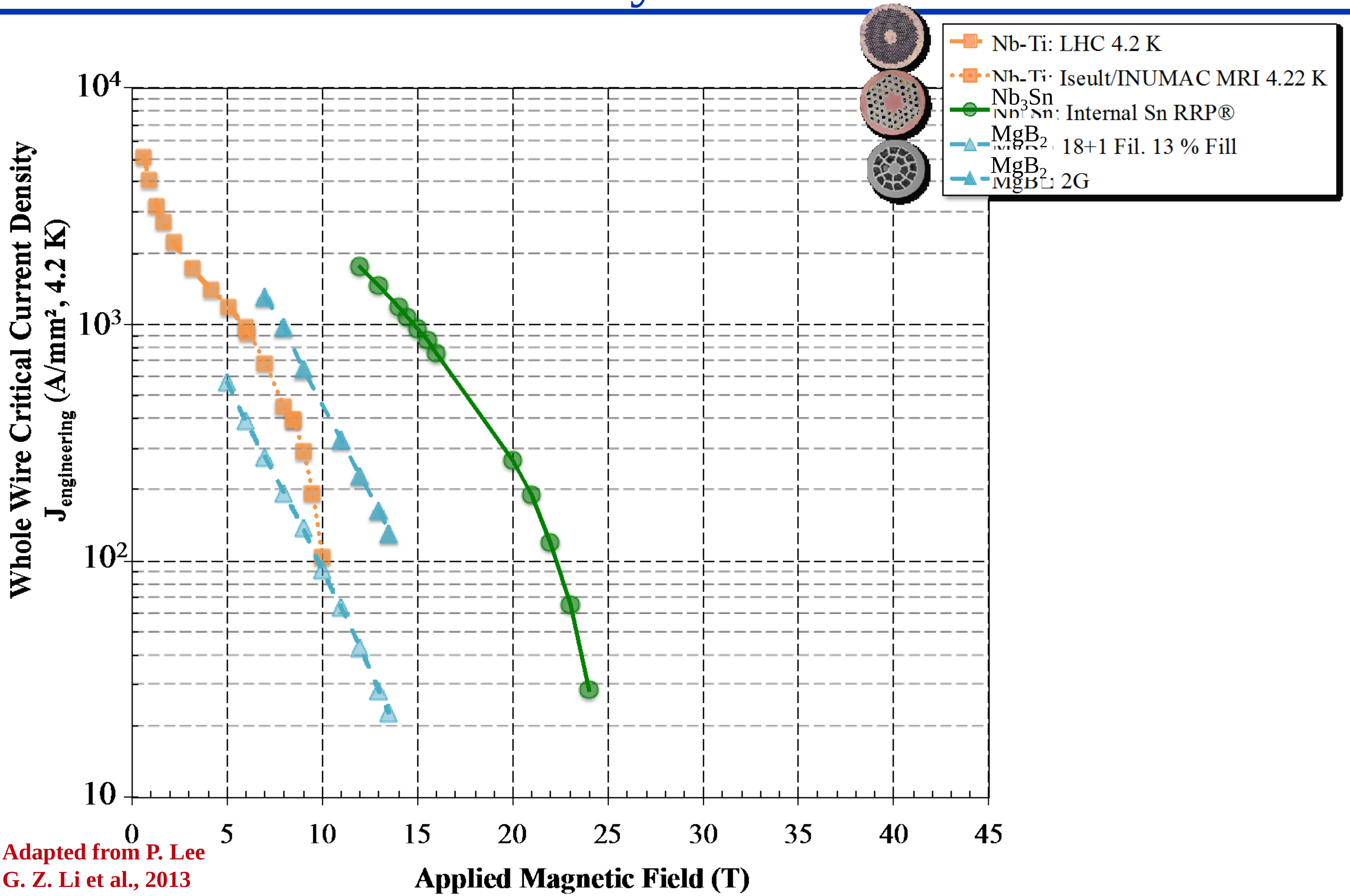
"…If not now, when?"

Why HTS?



Adapted from P. Lee
G. Z. Li et al., 2013
D. Larbalestier, *et al.*, 2014

Why HTS?



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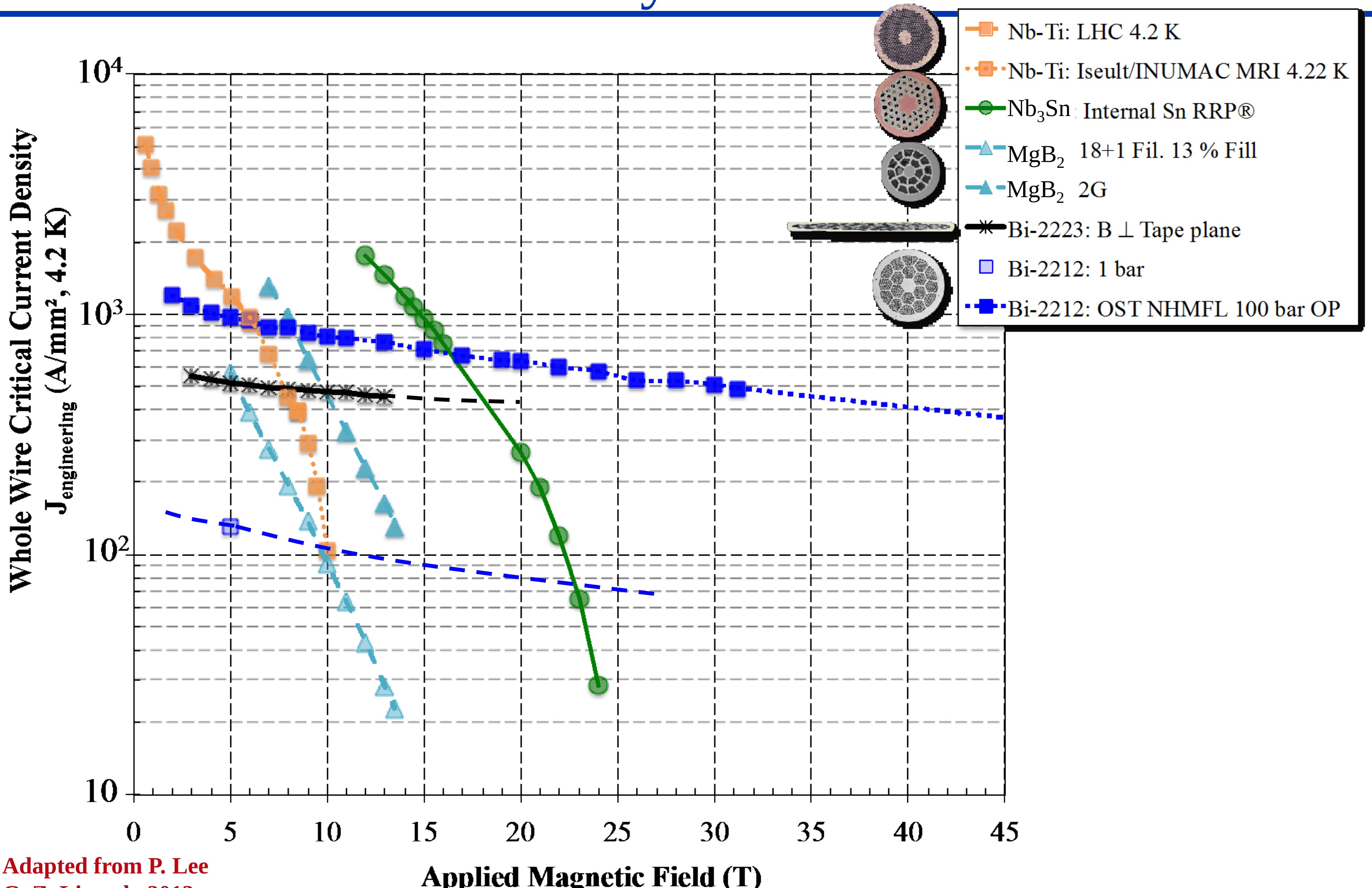

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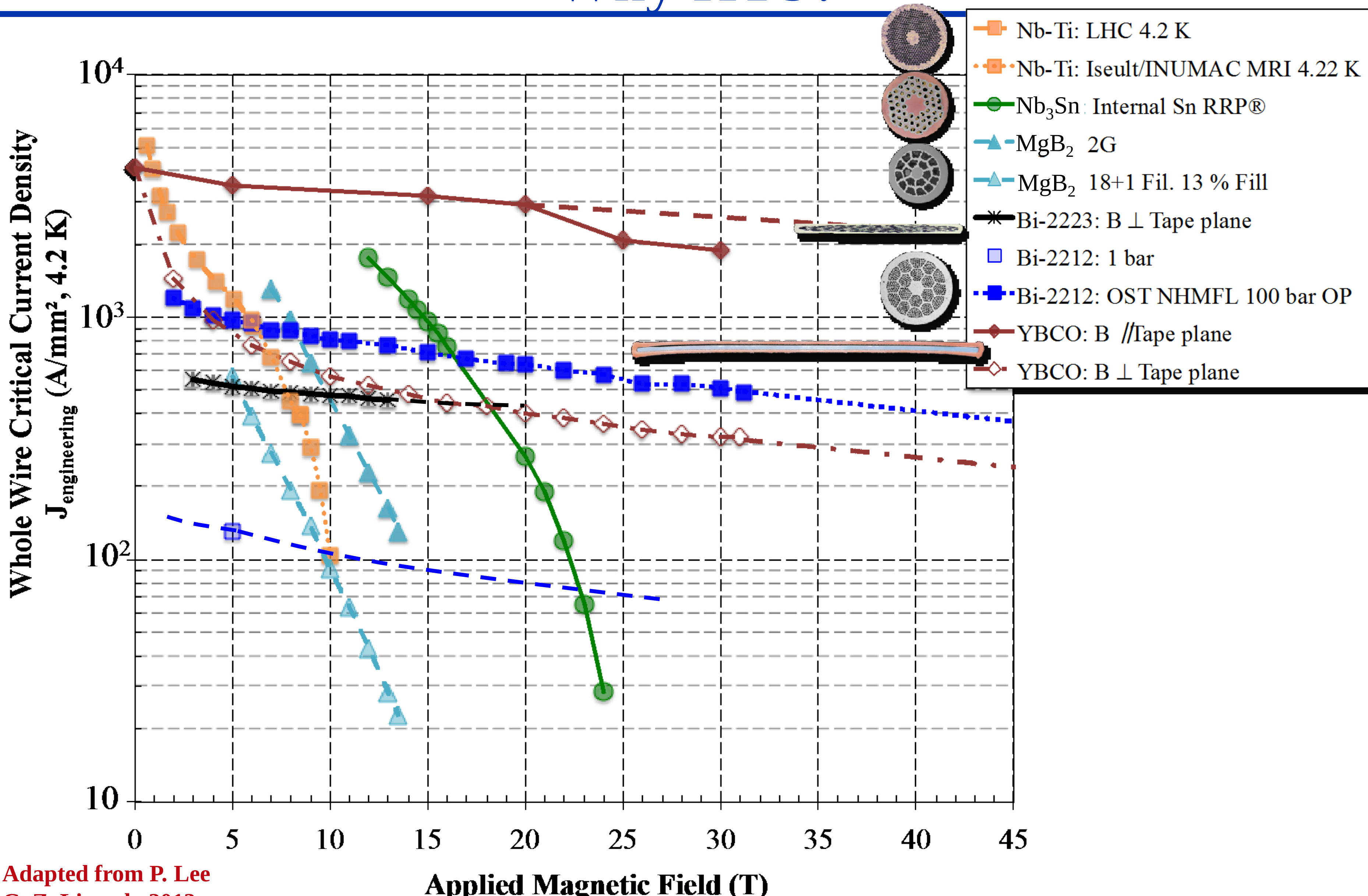

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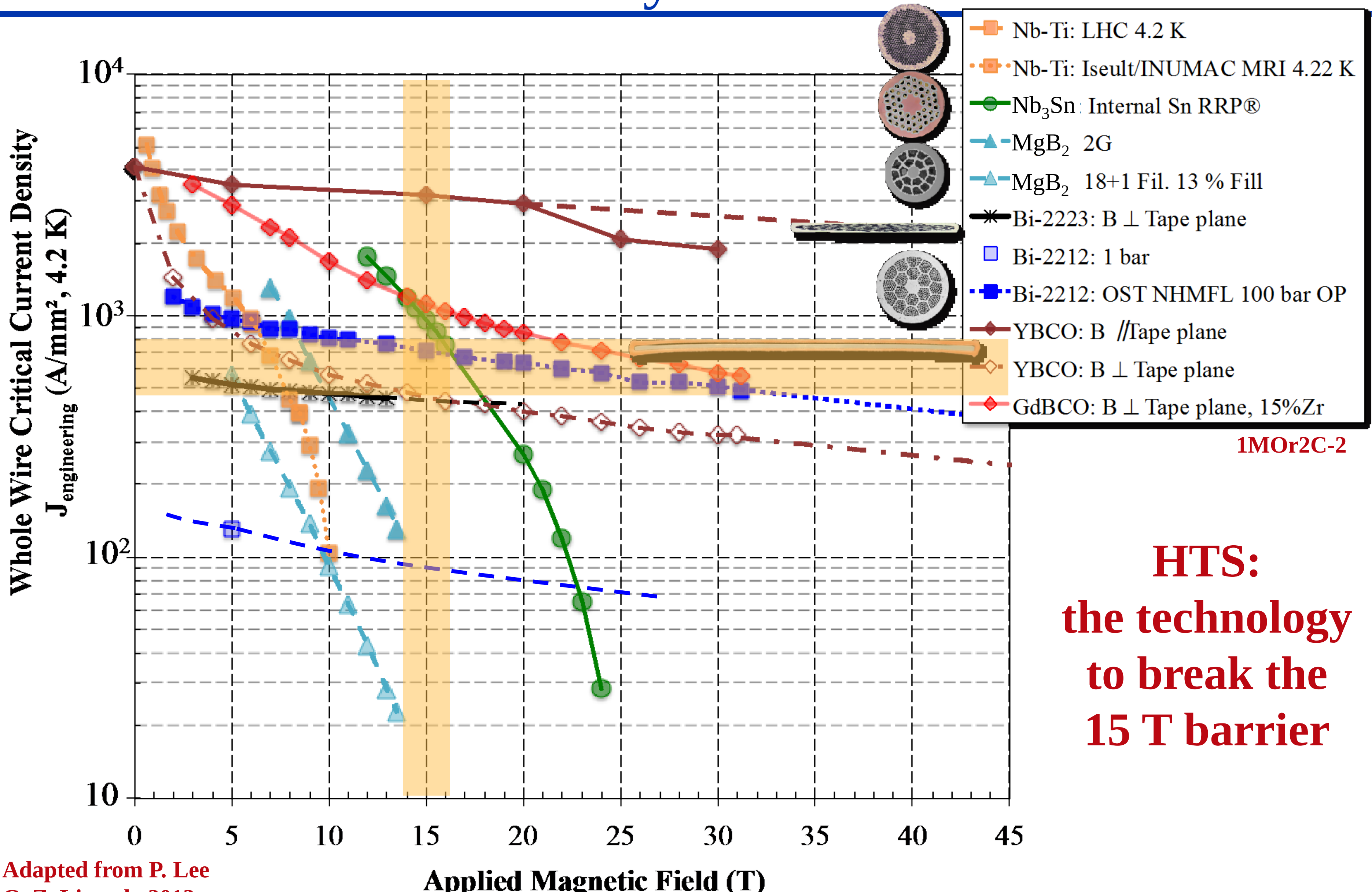
Why HTS?



HTS: the technology to break the 15 T barrier

Adapted from P. Lee
G. Z. Li et al., 2013
D. Larbalestier, *et al.*, 2014

Why HTS cables?

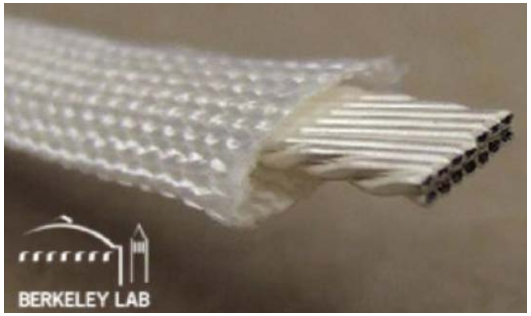
Multi-strand cable has several advantages relative to single wire winding:

- Carry large currents (> 10 kA) maintaining flexibility for winding
- Reduced conductor unit length
- Reduce number of turns
- Smaller inductance for lower coil-to-ground voltages during a quench
- Current redistribution in case of a defect
- Reduced losses through transposition of strands
- Reduce quantity of insulation

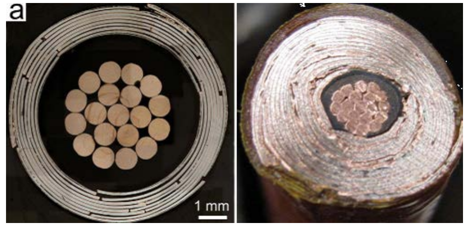
General guidelines for cable design and fabrication:

- Appropriate compaction for mechanical stability and winding ability
- Control of the cable dimensions
- Maintain mechanical and electrical integrity in sharp bends
- Control of inter-strand resistance to minimize eddy current without restricting current re-distribution
- Cooling

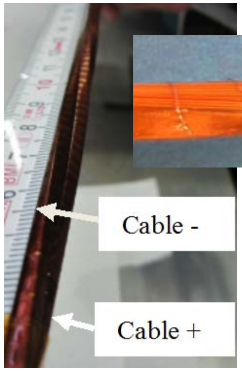
HTS cables



BSCCO-2212 Rutherford cable



CORC-Conductor on Round Core

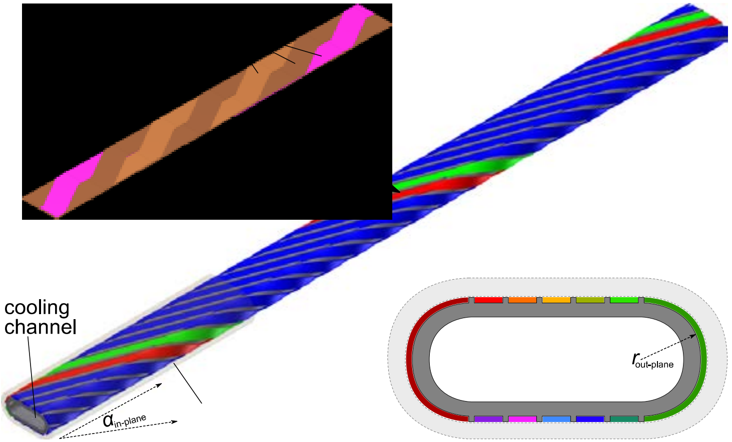


Twisted Pair

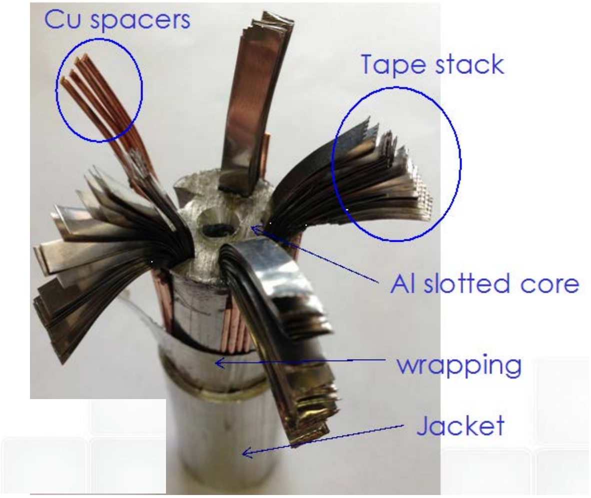
TSTC-Twisted Stacked-Tape Cable

RRI

RACC-Roebel Assembled Coated Conductor



CCRC-Coated Conductor Rutherford Cables



Slotted core HTS CIC conductor

RSCCCT-Round Strands Composed of Coated Conductor Tapes

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ACT II: FOR WHAT

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  - REBCO

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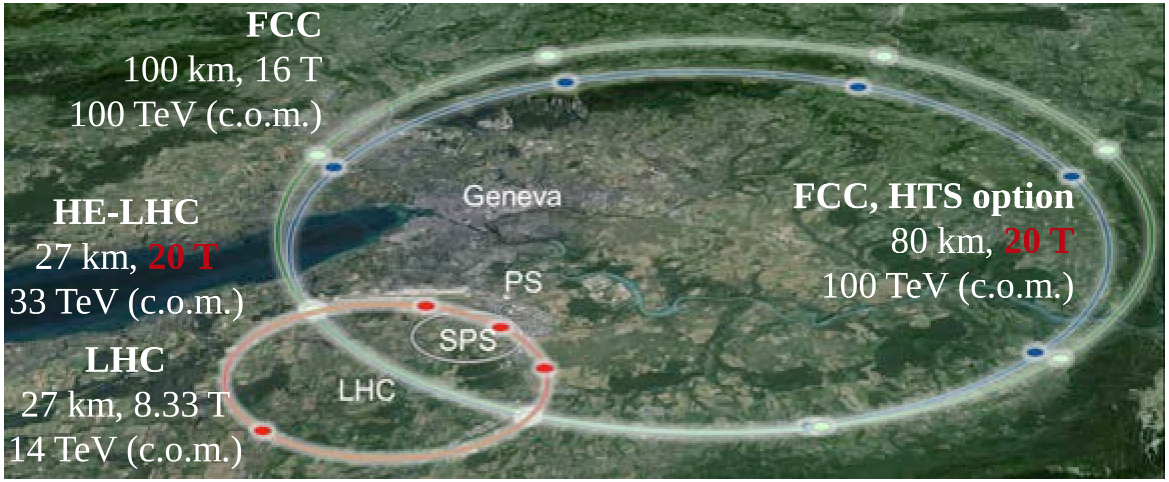
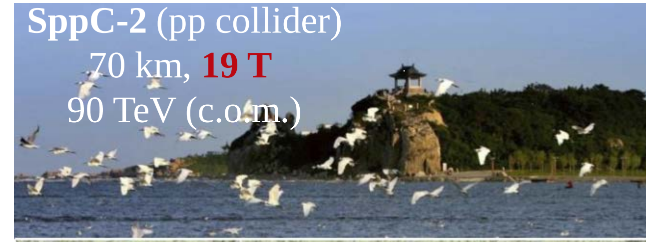
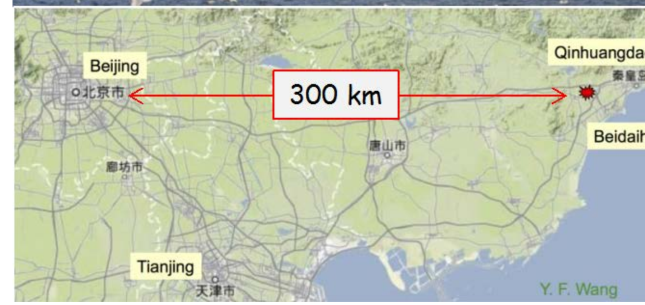
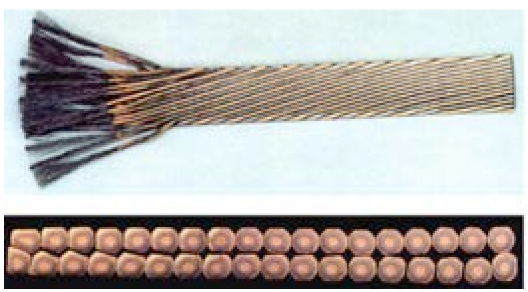
Future Colliders

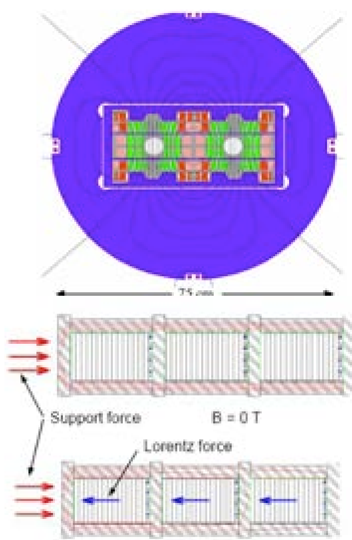






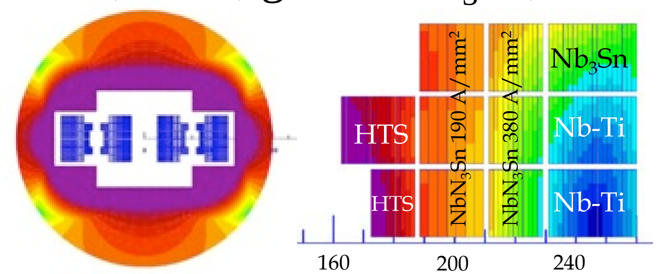


20 T, Nb_3Sn, HTS (Bi2212)



P. McIntyre et al., 2005

20 T, NbTi, graded Nb_3Sn, HTS



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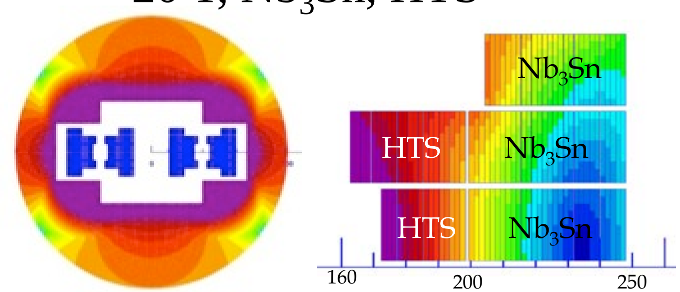


L. Rossi, 2010, L. Bottura, 2013 and F. Gianotti, 2014

E. Todesco et al., 2014

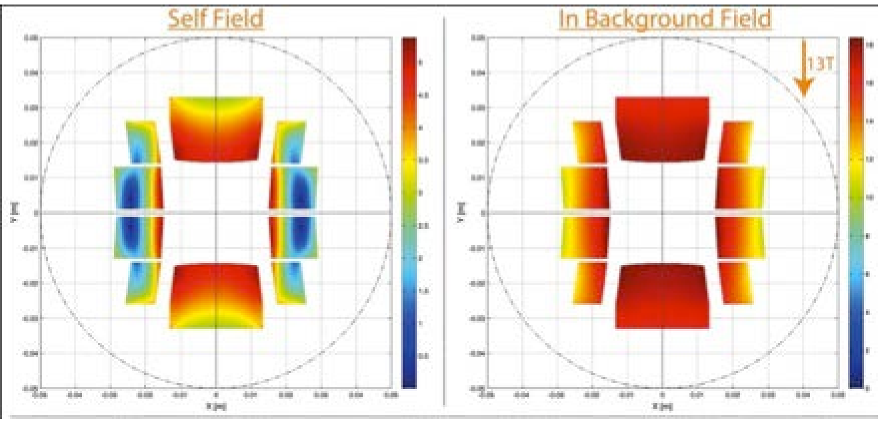
…working towards 20 T

EuCARD project

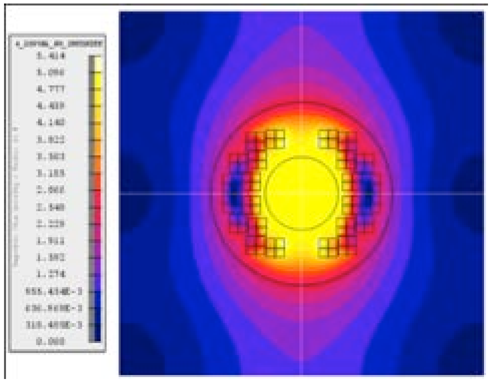
5 T HTS Dipole Magnet Design and Construction

5-10 kA @20 T, 40 mm aperture

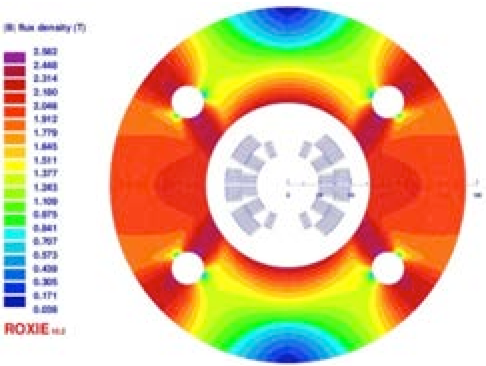
Crystallized blocks concept



by J. van Nugteren, CERN



by J. Himbele, INPG

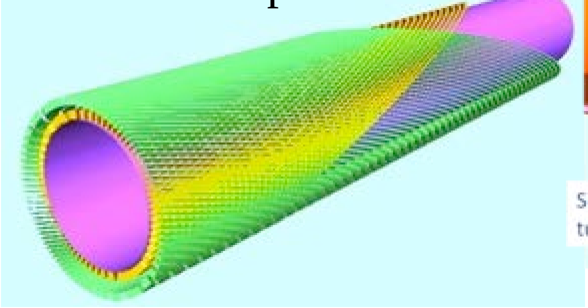


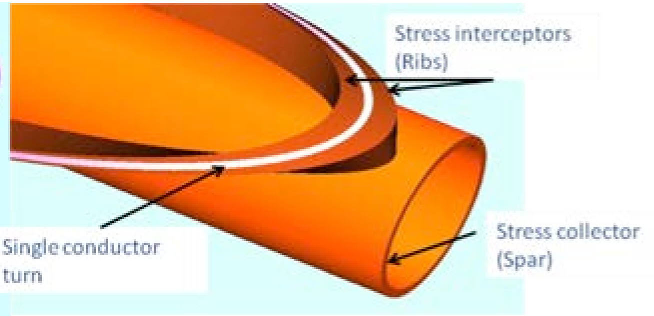
by C. Lorin, CEA

Other ideas…

Canted-Cos-Theta Magnet (CCT)

Bend-able dipole



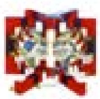


by S. Caspi and L. Brouwer, LBNL

Fusion

Path to power plants through several technology programs:

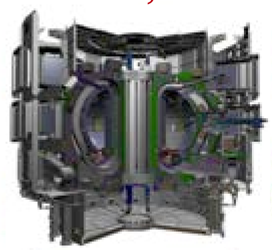
500 tons of Nb_3Sn
TF 11. 8 T, **68 kA**
CS 13 T, **45 kA**



Tore Supra
25 m³
~ 0 MW_{th}
Operation 1988
Plasma duration > 6 minutes

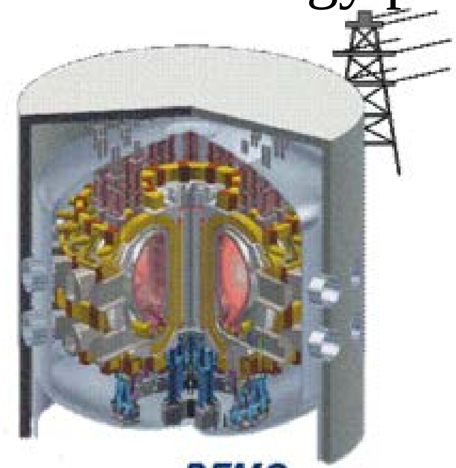
First plasma 1983

JET
80 m³
~16 MW_{th}



ITER
800 m³
~ 500 MW_{th}
First plasma 2020,
D-T operations 2027

Satellites tokamaks
IFMIF



DEMO
~ 1000 - 3500 m³
~ 2000 - 4000 MW_{th}
First plasma 2040-50???

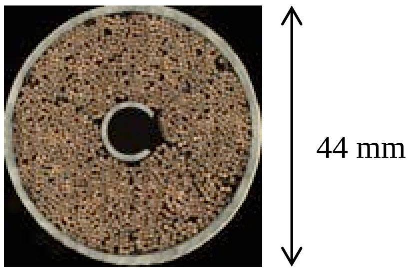
Power Plants

*"Yes we will **only** produce electricity but in the most elegant and exciting way!"*

Large volume, energy and required stability.

Cable requirements in fusion:

- High amperage conductor with large heat removal capability, forced flow cooling
- High stability, high mechanical strength, flexible design
- *Generally* low current density

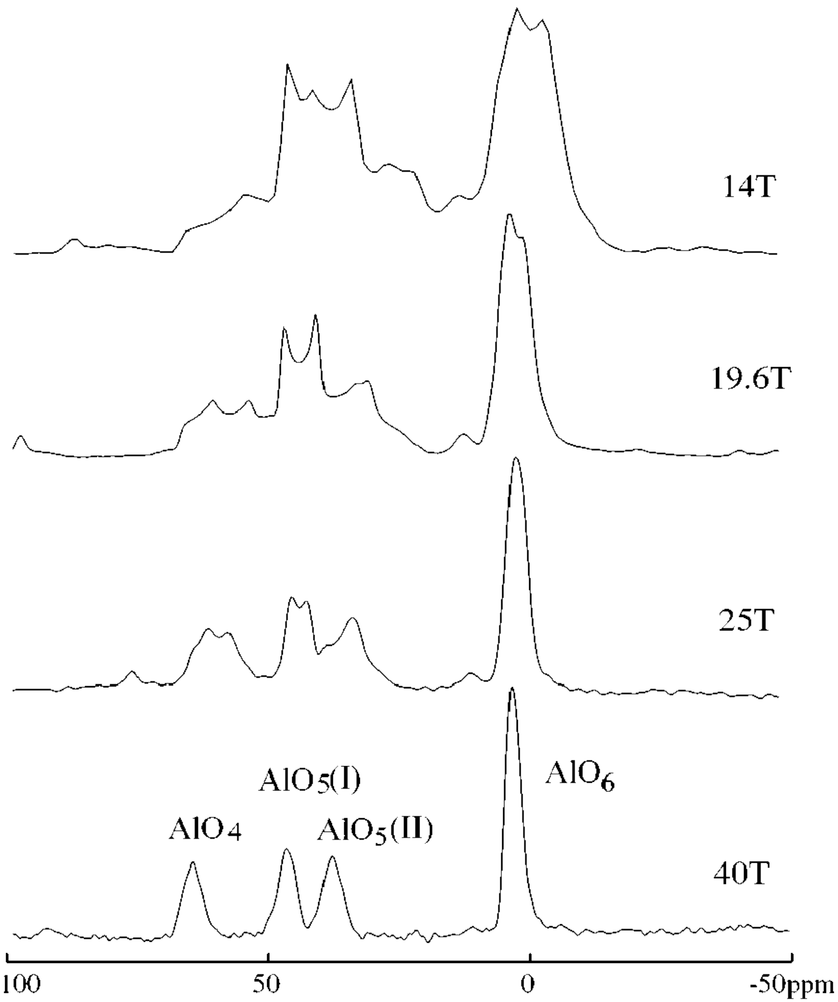


D. Stork, 2009
A. Devred et al, 2012

NMR

Quadratic gain for resolution and sensitivity with magnetic fields.

1 GHz system,
all LTS (23.5 T, 2 K)



Z. Gan et al., 2002

Bruker

- Strong magnetic field intensity
- Spatial field homogeneity
  1ppb/in 5 mm diameter cylinder
- Temporal field stability
  <0.01ppm/hr

…work in progress for high field NMR

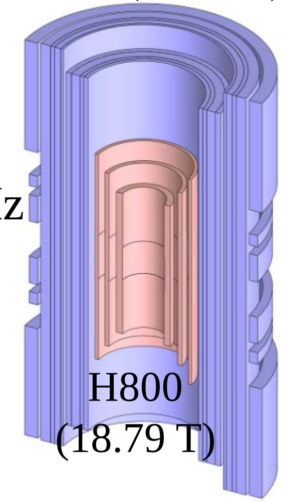
500 MHz
LTS/Bi2223

400 MHz
LTS/REBCO

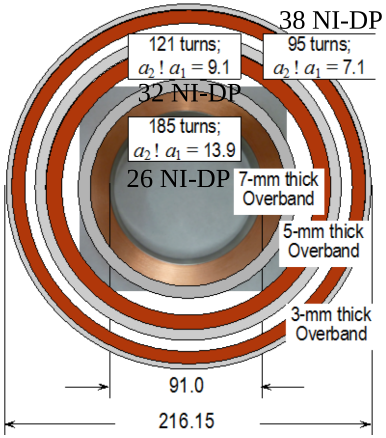
H. Maeda *et al.*, 2014.

1.3 GHz NMR
500 MHz LTS + 800 MHz
HTS insert coil

L500 (11.75 T)

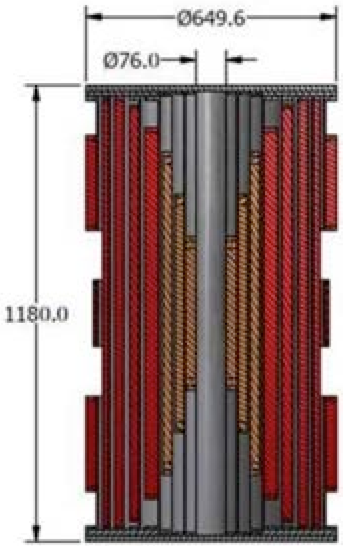


All coils GdBCO, NI-DP



1.3 GHz NMR
15 T LTS, 15 T HTS
BSCCO-2212.

W.D. Markiewicz



H. Maeda, 2014
Y. Park et al., 2014

Challenges in using HTS (REBCO):

- Temporal field drift is large due to screening currents
- Resolution and sensitivity not as good as with LTS
- Tape limited lengths require joints
- Long time persistent operation is possible if joints are superconducting
- Does HTS-NMR need cables?

High Field Solenoids

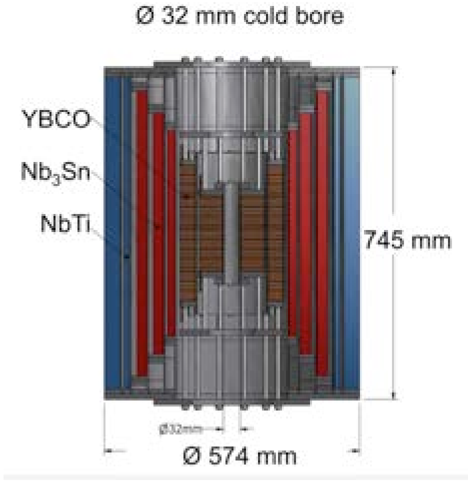
General push for development of next generation high-field magnets:

- Instruments for a 1.5 or 1.6 GHz [30 T] NMR
- Develop 40 T all-superconducting magnet with HTS
- Design and build a 60 T DC hybrid magnet
- Design and build a 20 T, 65 cm bore [MRI] magnet suitable for large animal and human research subjects

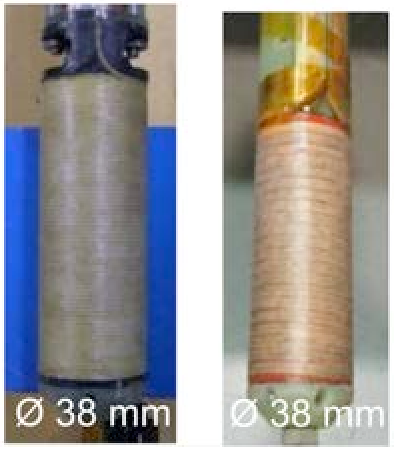
The 4.4 T REBCO insert that reached 35.4 T at NHMFL 2012

Under development @NHMFL:

- 32 T User magnet
- All SC: 15 T LTS, 17 T HTS (REBCO)
- Homogeneity 10^{-4} level

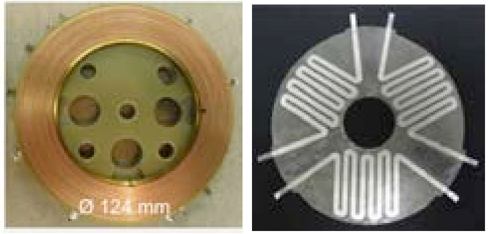


BSCCO and REBCO in 31 T background field



Hoop stress test (760 MPa)

Quench protection studies



Much more in tomorrow's plenary, Greg Boebinger

So…

Several activities centered on HTS for use in high field magnets…

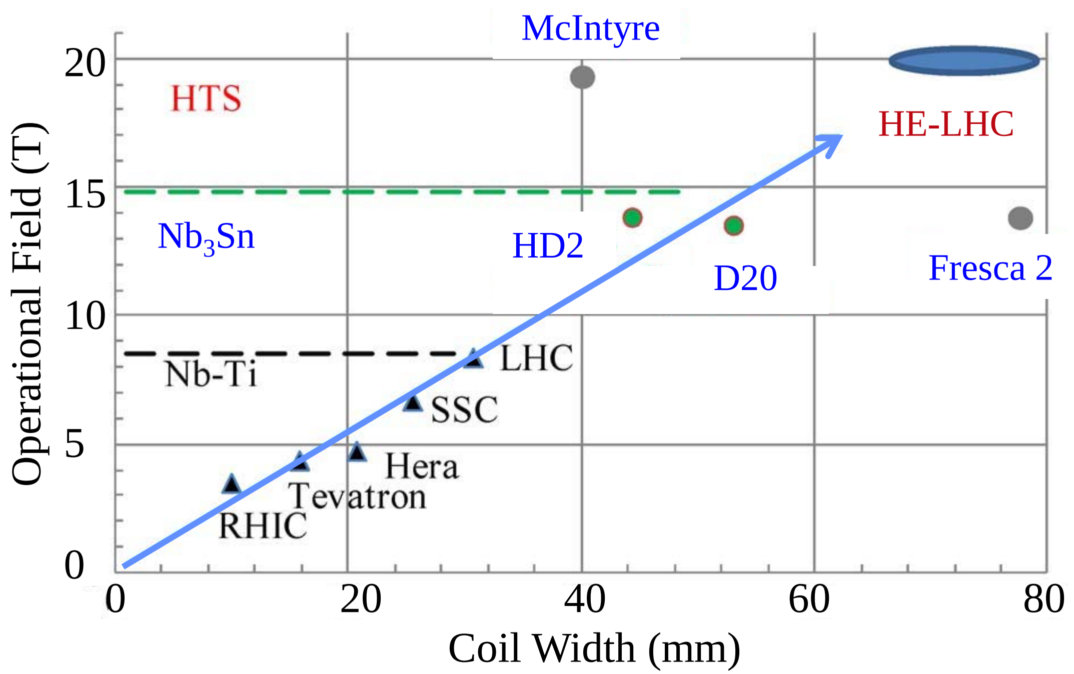
GREAT START!

Plenty of projects require technological advances for high current cables. Where do we start?

Requirement	HEP magnets	Fusion	NMR/ High Magnetic Field Science
Magnetic Field (T) Currents (kA)	20 T **5-20 kA**	12- 18 T **> 50 kA**	**> 30 T** the higher the better > 300 A
Current Density	$J_{overall}$ ~ 400 A/mm^2	$J_{overall}$ < 100 A/mm^2	$J_{overall}$ ~ 300 A/mm^2
Filament size	< 20 μm		
Losses/ Screening currents	< 10^5 J/m^3, slow ramp rates	< 1.6×10^6 J/m^3 for ±12 T	minimal
Stress management at magnet level	< 200 MPa		
Bending radius	Tight (~ cm)	Large (> 3 m)	Limited to strain dependence of conductor
Joint resistance	< 1 nΩ		

L. Bottura, 2013; E. Todesco, P. Ferracin, 2012; H. Maeda, 2014; D. Uglietti, 2014; H.W. Weijers et al., 2011; H.W. Weijers, 2009.

Are we reasonable? *Yes…just learning from history!*



$J_{overall}$ ~ 400 A/mm^2
(stabilizer in strand, voids, structural materials part of the coil, insulation)

→ 20% margin
30% dilution/filling factor
(~15% epoxy filled void, 15% insulation)

J_{eng} ~ 800 A/mm^2

Protection is essential and high $J_{overall}$ is not necessarily the ultimate goal.
So what conductor is available?

E. Todesco et al., 2014

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ACT III: WITH WHAT

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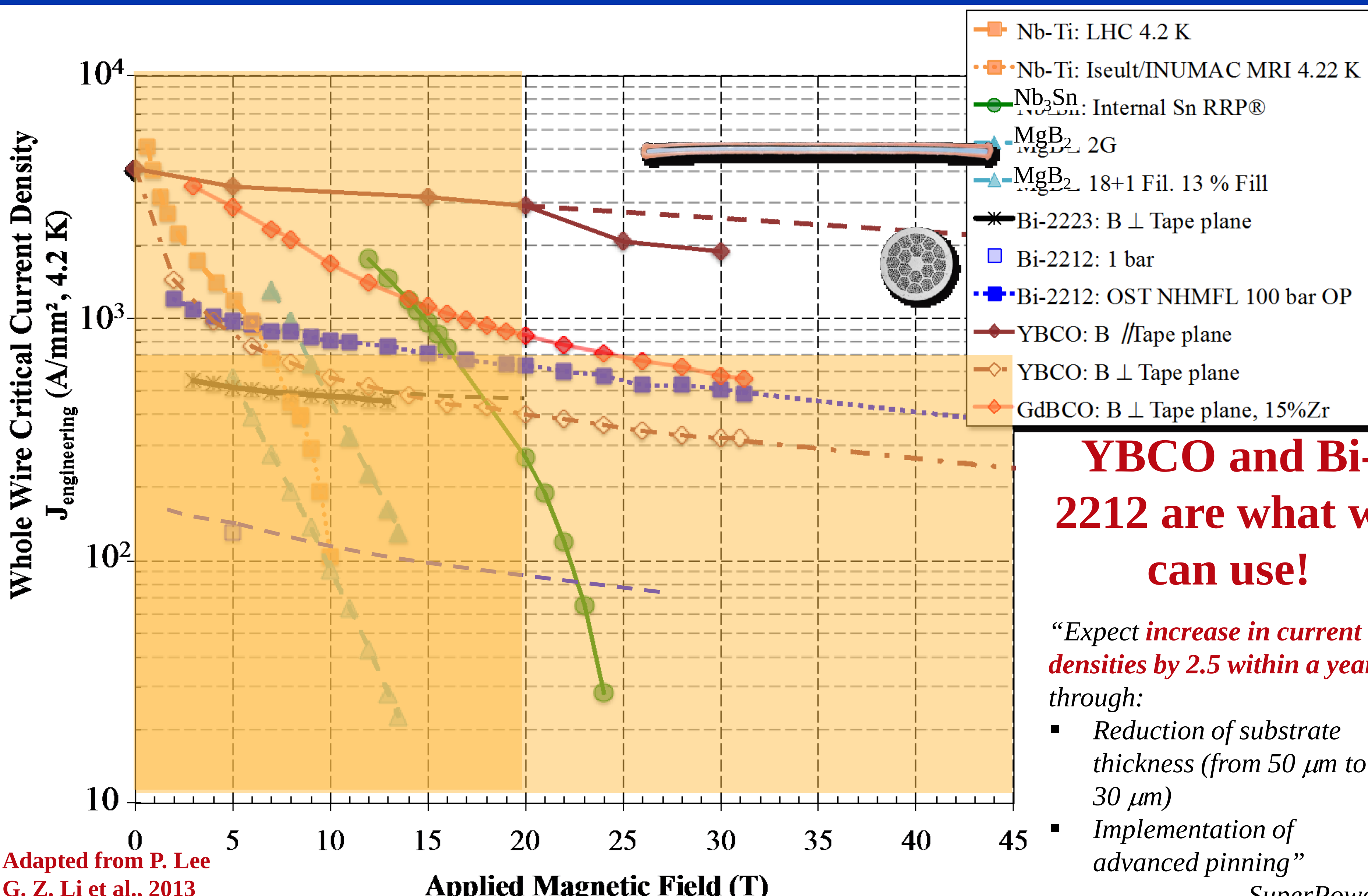
Engineering Current Density JE



Adapted from P. Lee
G. Z. Li et al., 2013
D. Larbalestier, *et al.*, 2014

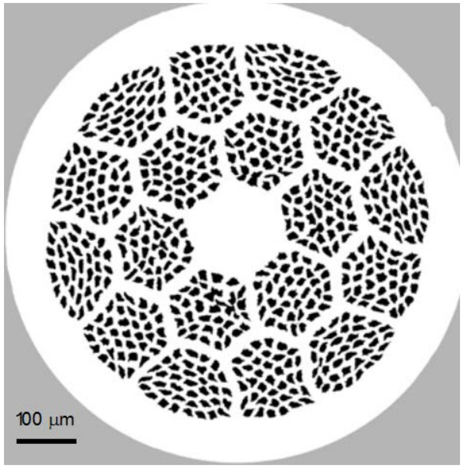
YBCO and Bi-2212 are what we can use!

*"Expect **increase in current densities by 2.5 within a year** through:*

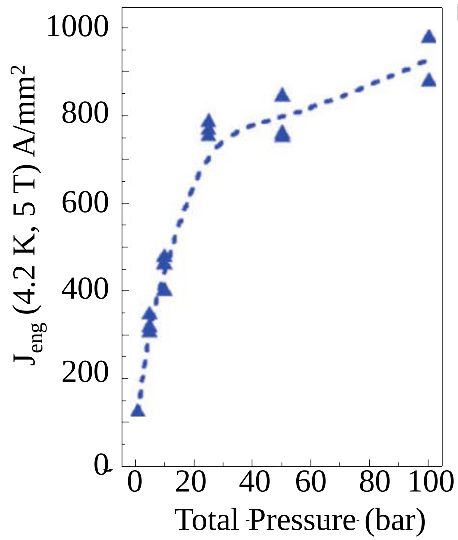
- *Reduction of substrate thickness (from 50 μm to 30 μm)*
- *Implementation of advanced pinning"*

SuperPower

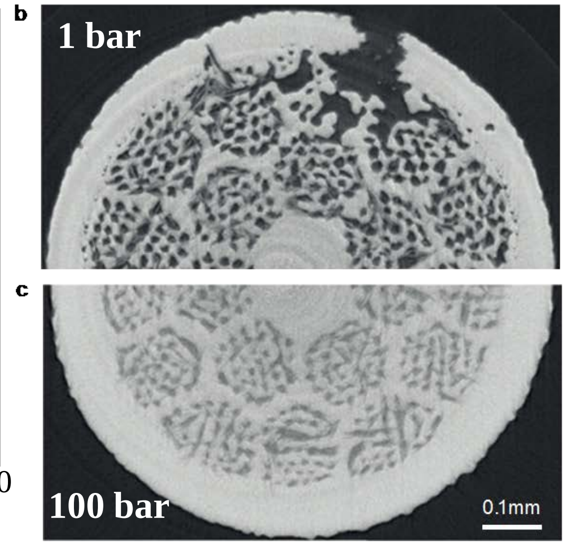
BSCCO-2212 and REBCO



Bi-2212 powder filaments in Ag matrix before HT

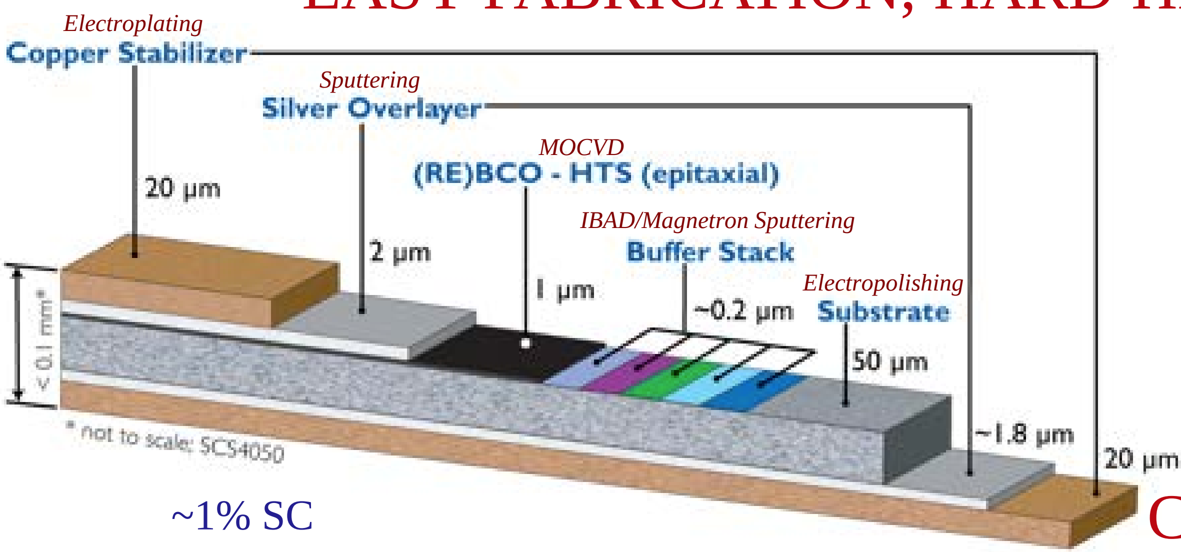


~25-40% SC



Larbalestier, *et al.*, 2014

EASY FABRICATION, HARD HEAT TREATMENT!



- Electropolishing to smoothen Hastelloy® substrate
- Ion beam assisted deposition or sputtering of buffer layers
- Metal organic chemical vapor deposition of the superconductor
- Sputtering of a thin layer of silver
- Electroplating

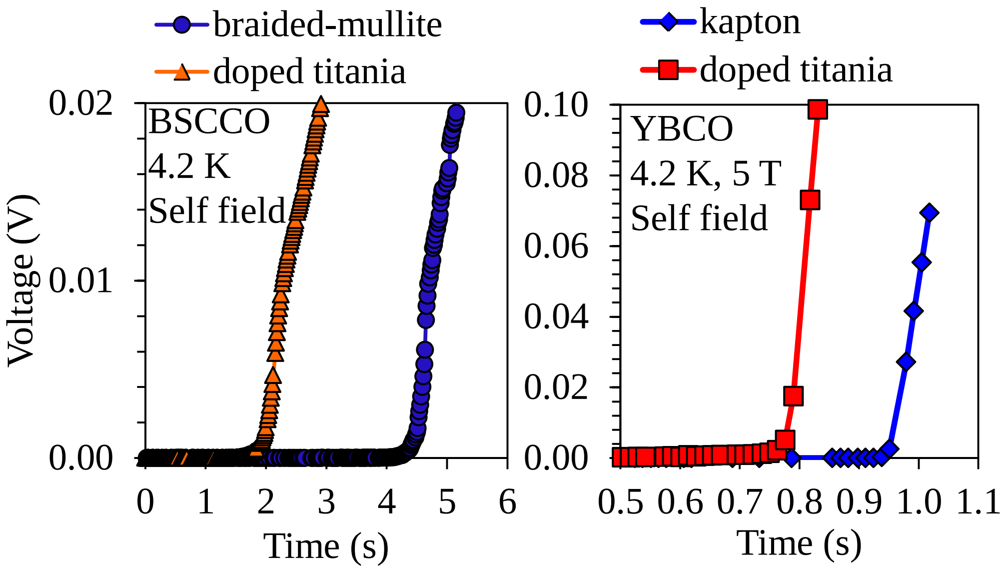
~1% SC

COMPLEX FABRICATION, NO HEAT TREATMENT!

http://www.superpower-inc.com/content/2g-hts-wire

OPEN ISSUE: Quench Detection and Protection

- Time margins to detect, respond and protect ~100-200 ms
- Energy margin at 4.2 K: ~ 1 J/mm^3 for LTS, ~1600 J/mm^3 for HTS
  → problematic for detection!
- NPZ velocities (//) ~ 10-20 m/s for LTS, ~ 0.05 m/s for HTS
  → Even more problematic for detection!

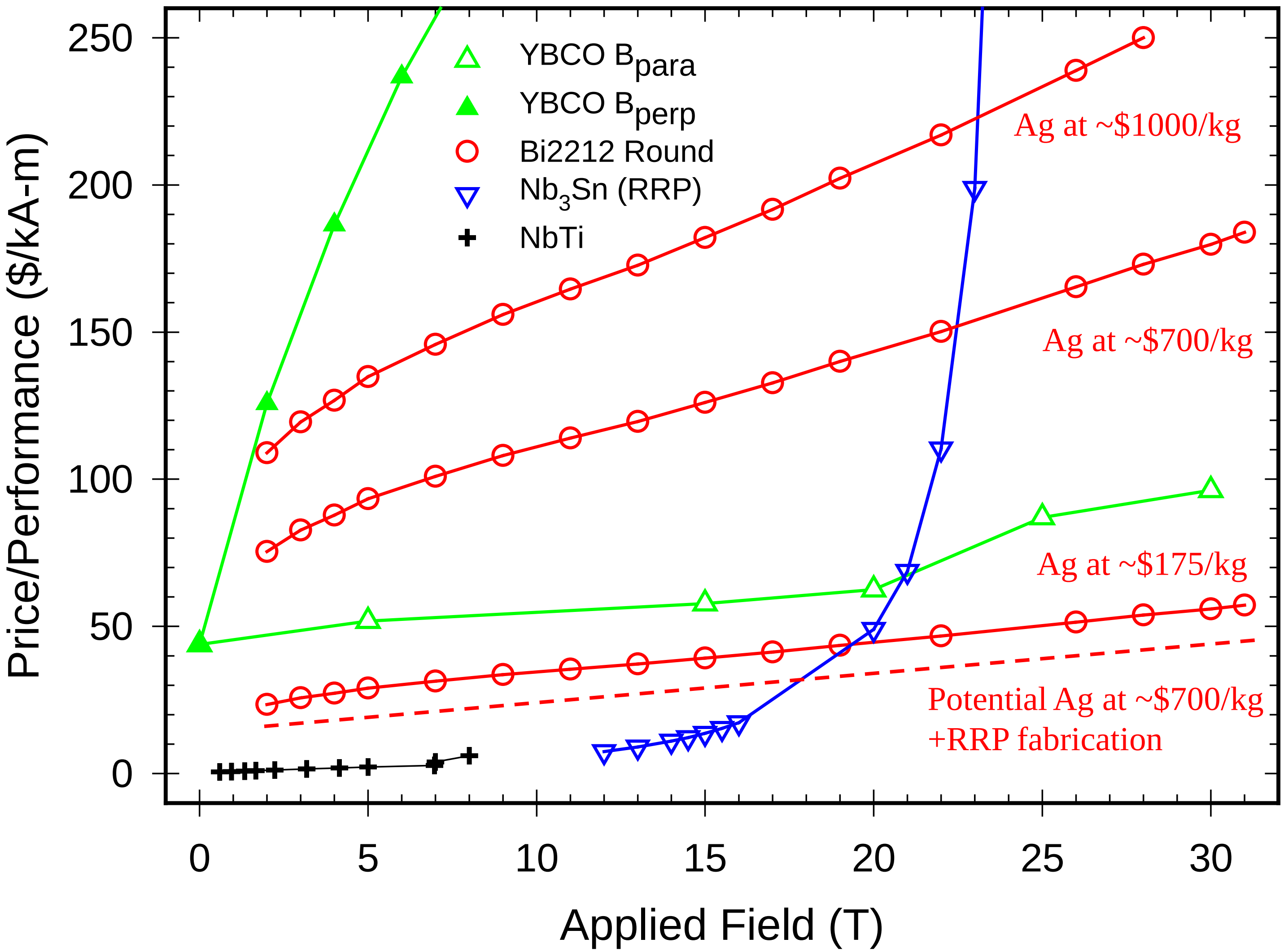


Effect of doped titania electrical insulation:
Higher thermal conductivity (10x)
Higher turn-to-turn velocity (3x)

S. Ishmael et al., 2013

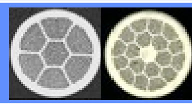
Quench detection and protection remains a challenge!

Cost?



B. Strauss and K. Marken 2014

What we've got here is…

	 **BSCCO 2212**	**REBCO** 
Geometry	Round wire	Tape
Structure	Multi-filamentary, twisted filaments Multifilament round 0.7 to 1.0 mm wire with Ag matrix	Thin-film, Single layer 4-12 mm wide tape, 50% high strength superalloy (Hastelloy®) ~40% is Cu coating
Properties	Isotropic I(B,T,e)	Anisotropic I(B,T,e,ϑ)
Heat treatment	High pressure, high temperature O_2 environment Brittle after heat treatment Wind and React	Reacted conductor Strong but delamination issues React and Wind
SC fraction	25-40%	1%
$J_{engineering}$	High J_{eng} (@ 4.2 K)	High J_{eng} Possible use at T > 4.2 K
Manufacturing	Not an issue	Complex and expensive multilayer deposition process
Needs	Reduce porosity Mastering reaction and pressurization process 890 ±1 °C and 100 bar Reduce strain sensitivity, d_{eff}, and cost Quench detection	From tape to cable Reduce angle dependence Controlled dimensions Reduce d_{eff} (striated?), and cost Quench detection

A. Ballarino, 2014; P. Ferracin , 2013

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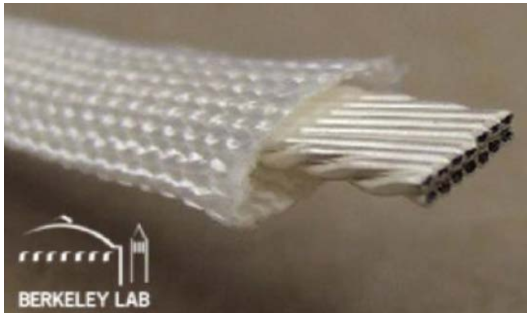
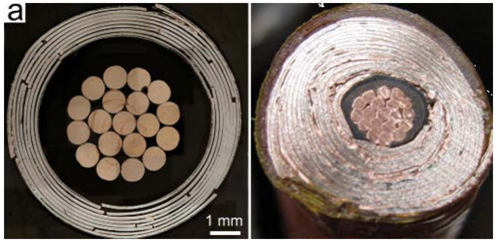
ACT IV: FOR & WITH
JOINING FORCES

Cable Options



BSCCO-2212 Rutherford cable



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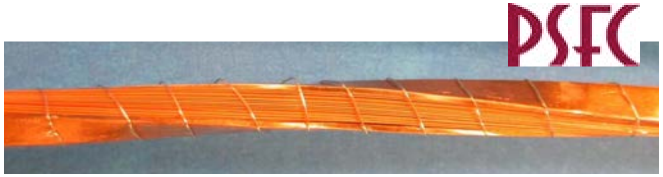
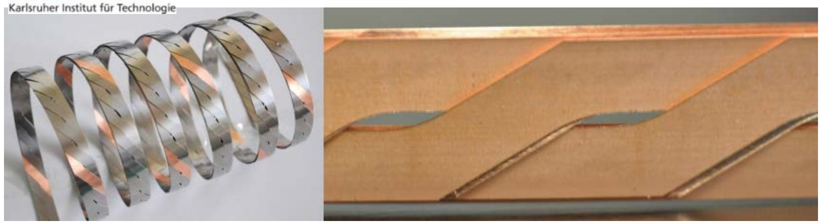
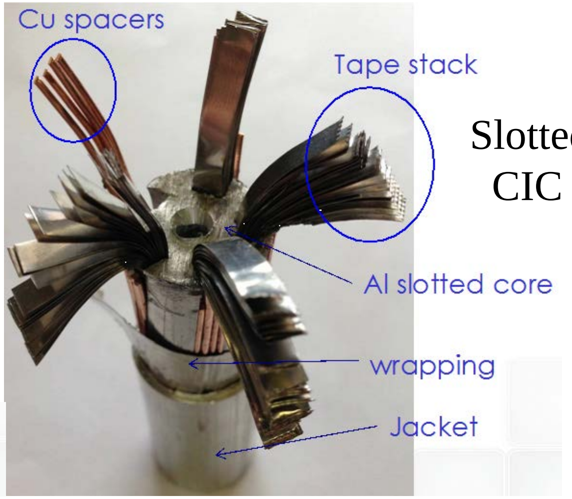


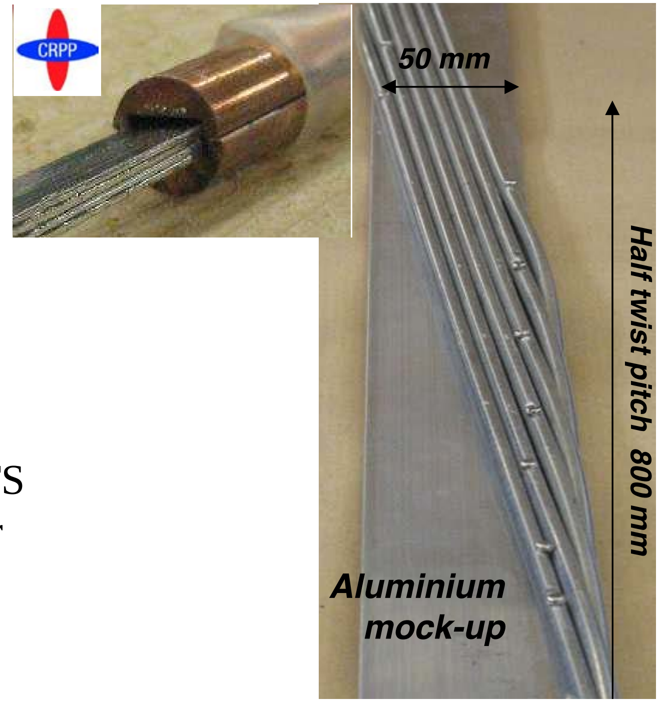
TSTC-Twisted Stacked-Tape Cable



RACC-Roebel Assembled Coated Conductor



Slotted core HTS CIC conductor



RSCCCT-Round Strands Composed of Coated Conductor Tapes

A. Godeke, 2014

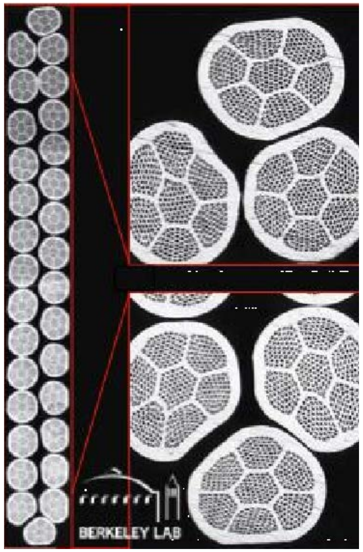
BSCCO-2212 (LBNL, Fermilab)

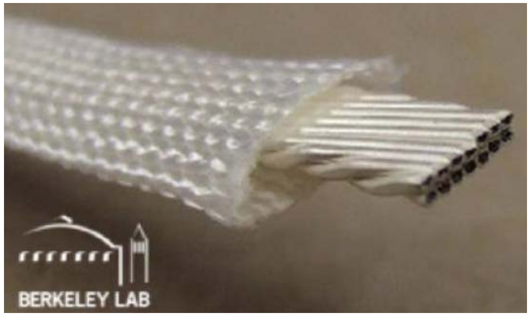
Easy path to 2212 cables through standard Rutherford cable.

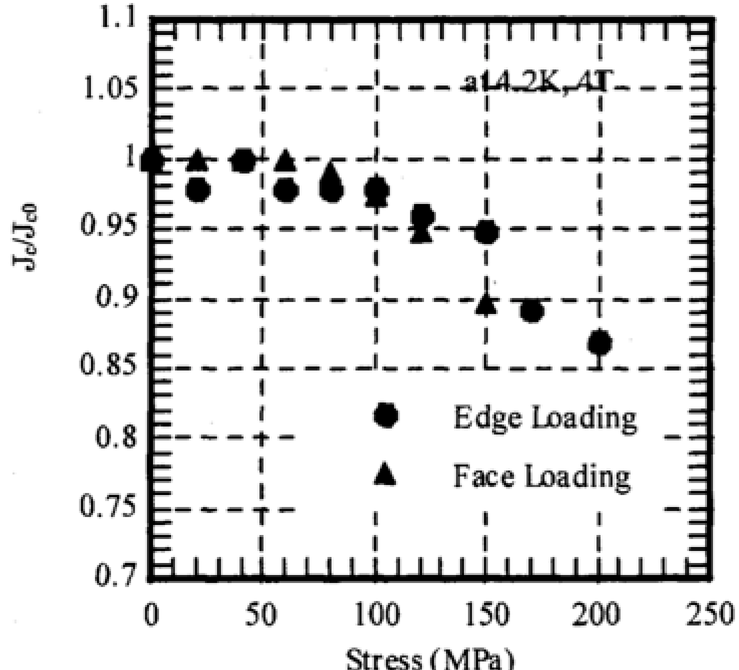
Main challenge finding a furnace at 100 bar to heat treat large coil ± 1 °C!

Rutherford cable characteristics:

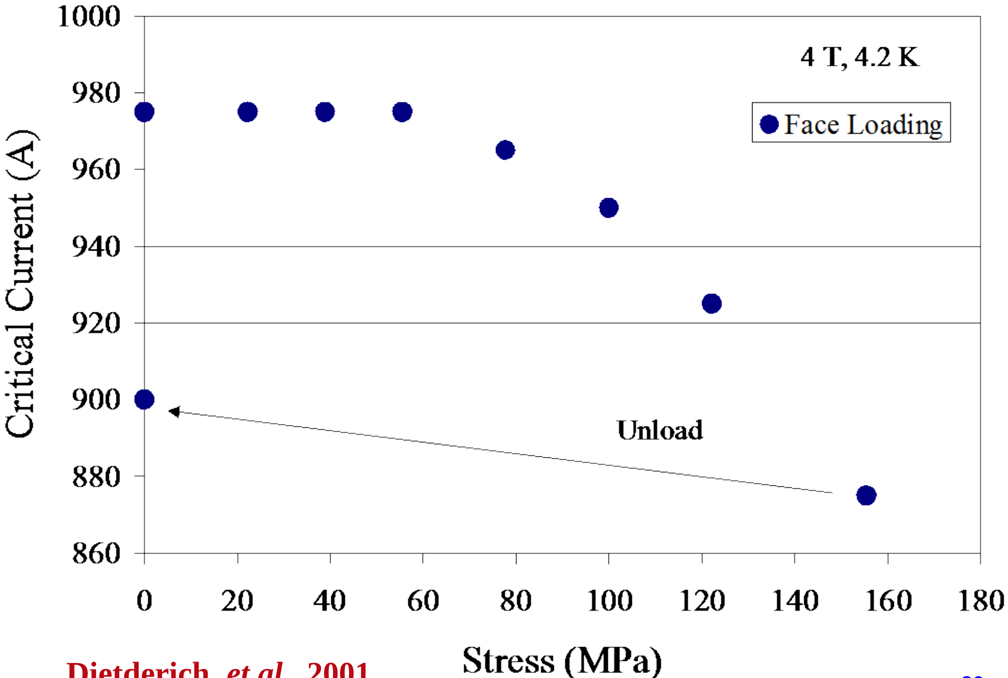
- High packing factor ~85%
- I_c degradation after cabling < 20%
- Sensitive to transverse pressure







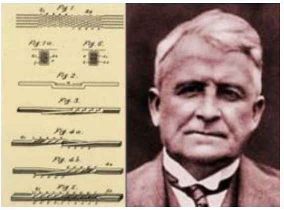
Hasegawa, *et al.*, 2001



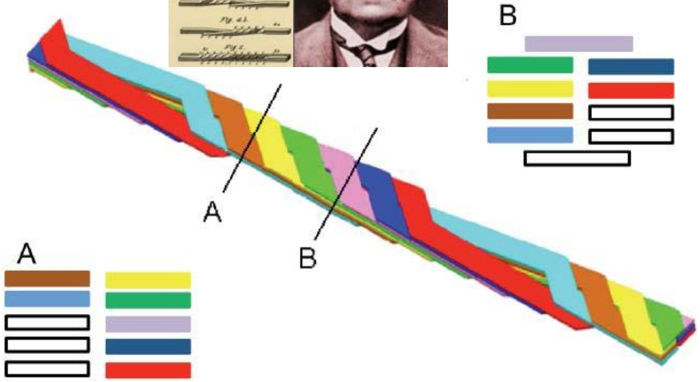
Dietderich, *et al.*, 2001

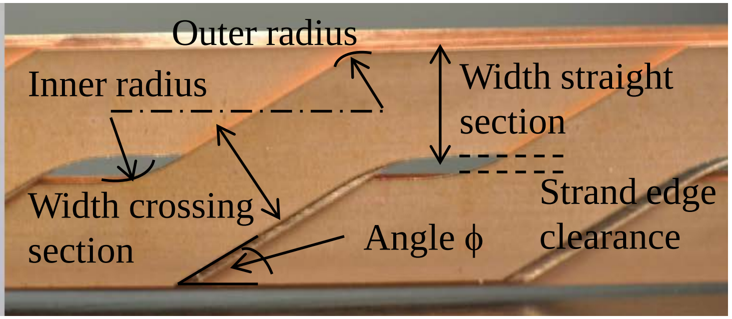
IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) October 2014
Plenary Presentation 4PLA-01 given at ASC 2014, Charlotte, August 10 – 15, 2014.

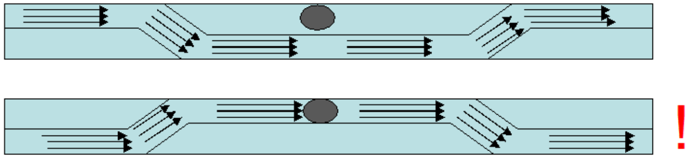
1-REBCO: RACC (KIT, RRI)



1914, original patent by L. Roebel



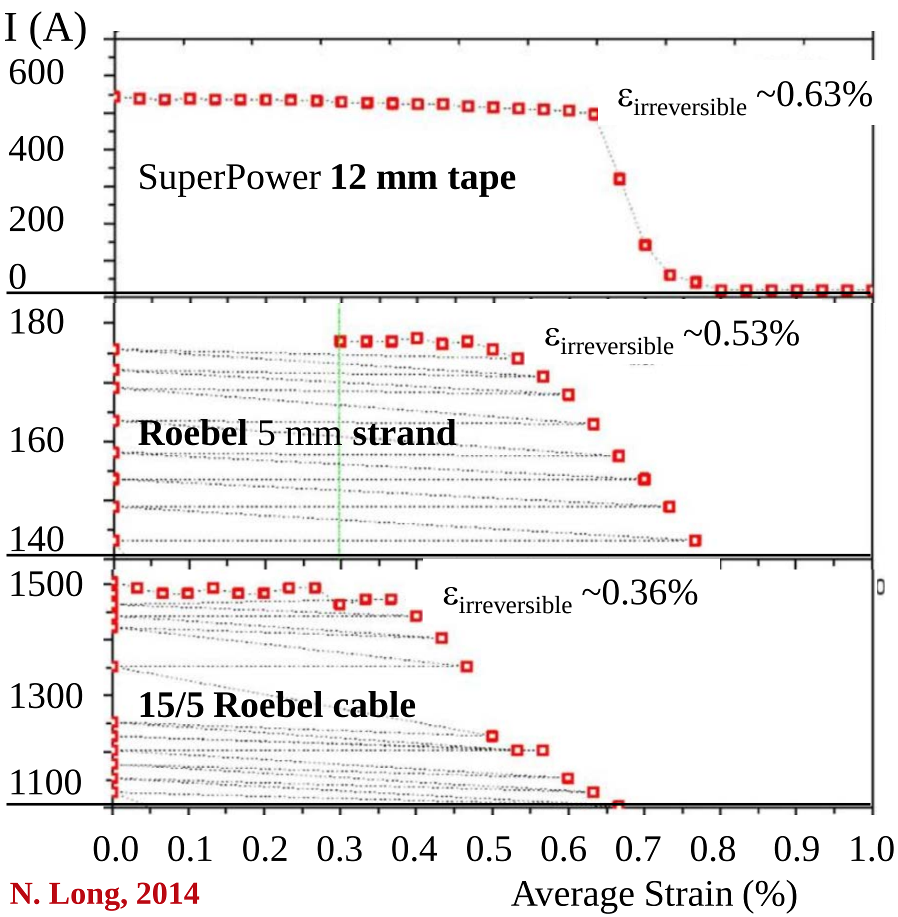




- Meandered tape through punching
- Cable optimization to minimize stress: radii, angle and relative width
- Localized defects in tape to be avoided
- Experimental results available for bending behavior, tensile and transverse load
- Preliminary work on vacuum impregnation with Araldite resin and 50% fused silica

1-REBCO: RACC (RRI, TEST @4.2 K CERN)

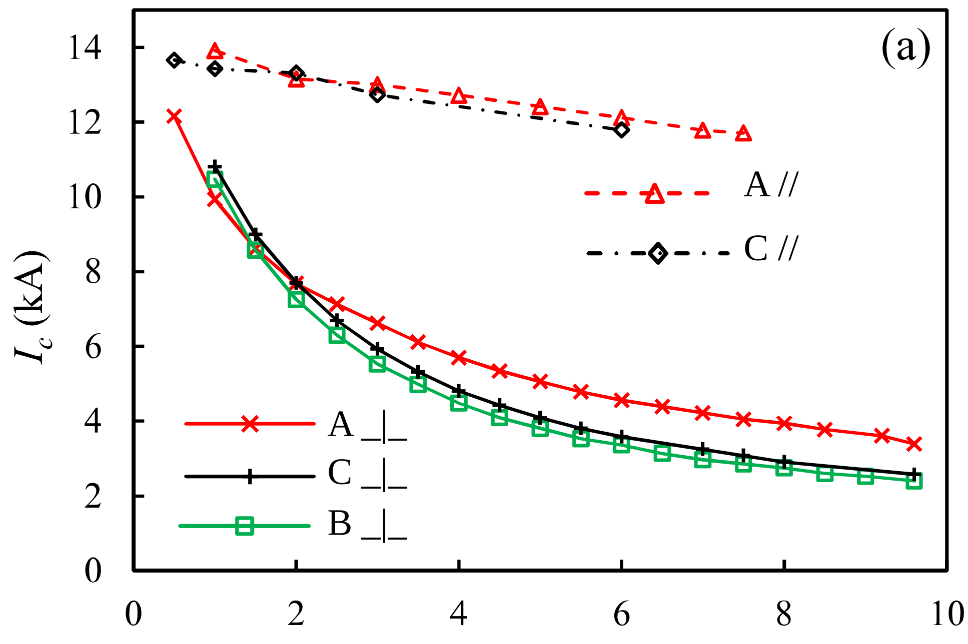
Axial loading conditions



N. Long, 2014

In-field behavior

Cable A: GCS 300 mm pitch 15 strands
Cable B, C: KIT 126 mm pitch 10 strands
NO impregnation

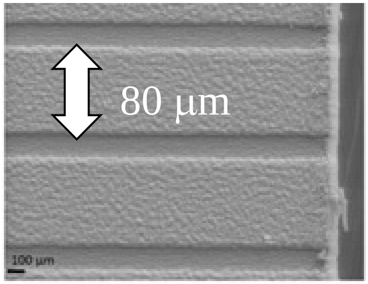


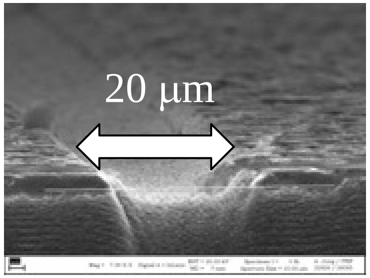
J. Fleiter et al., 2013

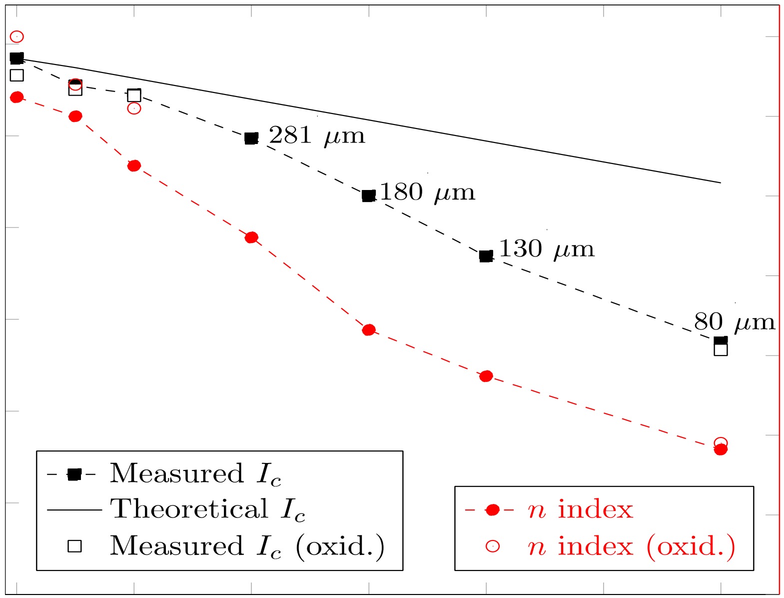
Expected behavior from single tape data and self field effects.

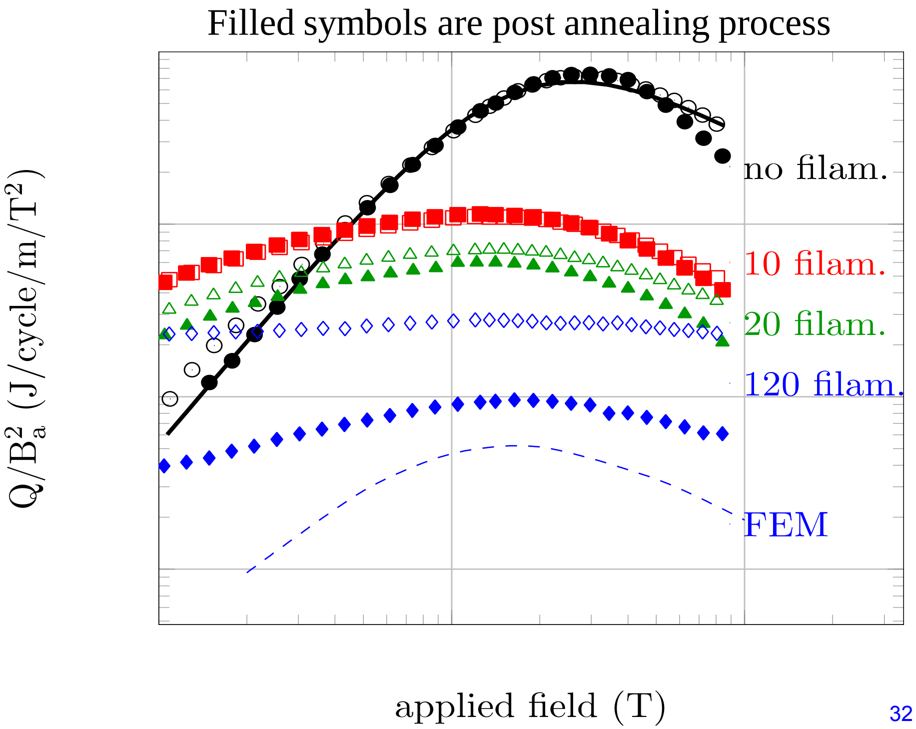
1-REBCO: RACC (KIT)

- Up to 120 Filaments (12 mm width tape)
- Current degradation from material loss and CC inhomogeneity
- Full separation with post annealing in O_2



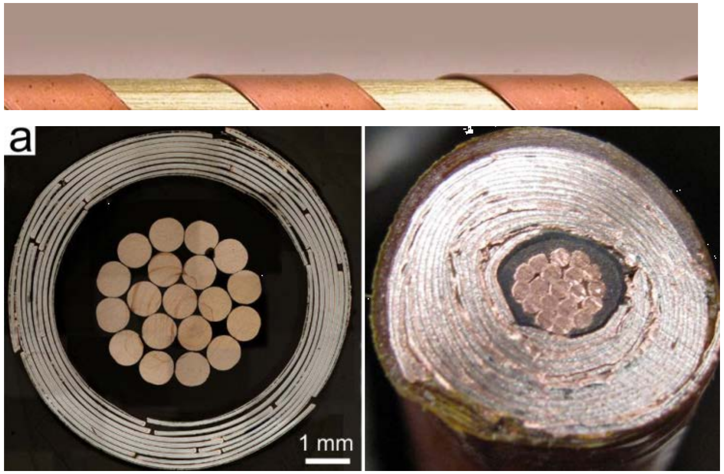






2-REBCO: CORC (Advanced Conductor Technologies LLC)

- Very flexible
- Very high currents and current densities
- Mechanically very strong
- Degradation from cabling < 10 %

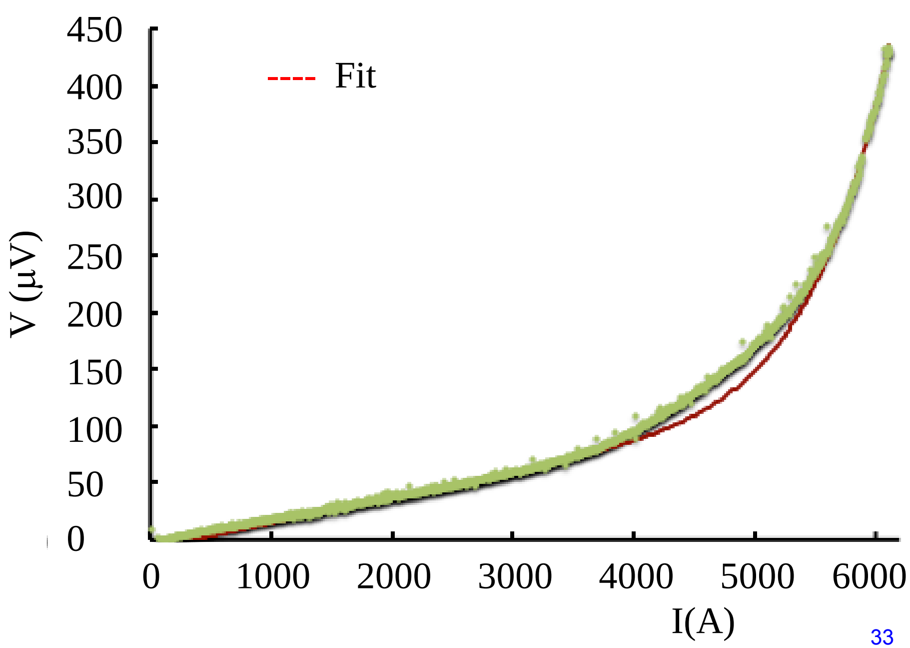


52 YBCO coated conductors, 17 layers, cable O.D. 7.5 mm:

I_{quench} = 6000 A @ 4.2 K, 19 T

I_c = 5021 A @ 4.2 K, 19 T, 1 μV/cm

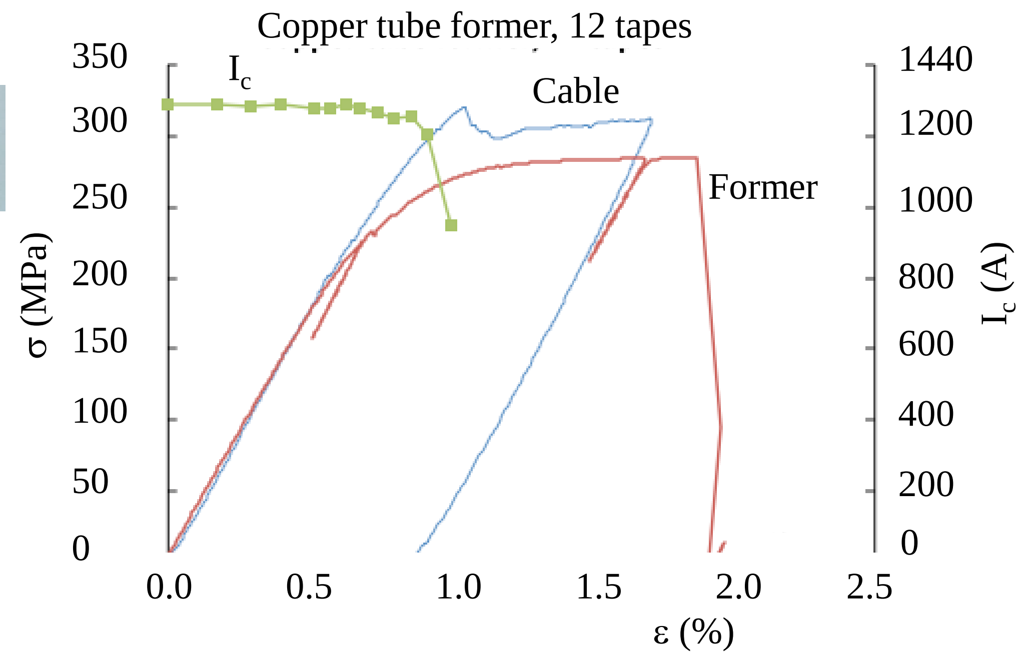
$J_{overall}$ = 114 A/mm^2 @ 4.2 K, 19.0 T



D. van der Laan, 2014

2-REBCO: CORC (Advanced Conductor Technologies LLC)

Testing under axial stress



Other experimental findings:

- No degradation when bending from 10 cm to 6 cm
- Transverse load effects: behavior of I_c depends on gap size between tapes and their copper thicknesses
- Different terminations methods give resistances between 30 and 300 nΩ at 77 K

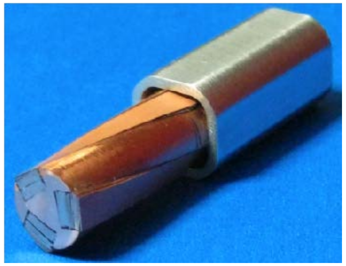
M. Takayasu, 2014

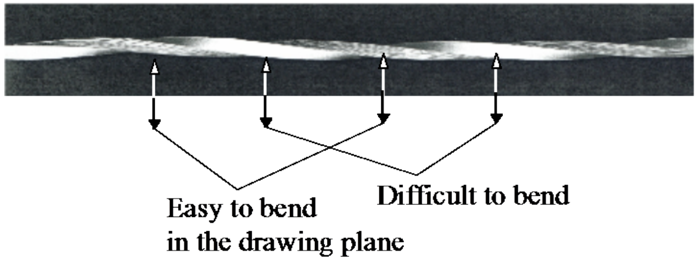
3-REBCO: TSTC (MIT)

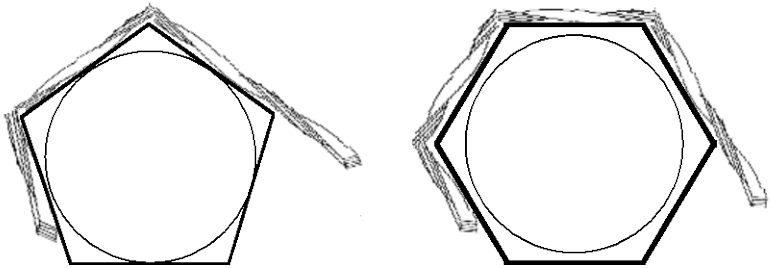
- Simple and compact cabling method
- High tape usage
- Good bendability (less than 6% degradation for bending radius of 140 mm)
- High current density
- Scale-up for large cable fabrication

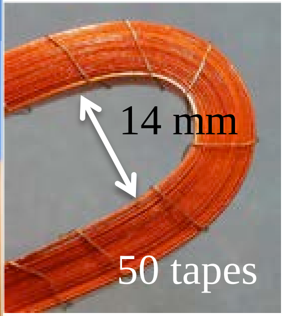
Multi-stage cables

3-channel CICC cable









3-REBCO: TSTC (MIT)

- @NHMFL, 50 tapes, 200 mm twist pitch

I_c = 4.0 kA @ 100 μV/m @ 4.2 K, 19.7 T

~50% of single strand performance

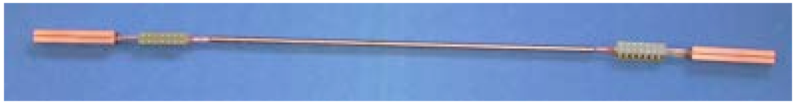
- @KIT, 40 tapes, 200 mm twist pitch

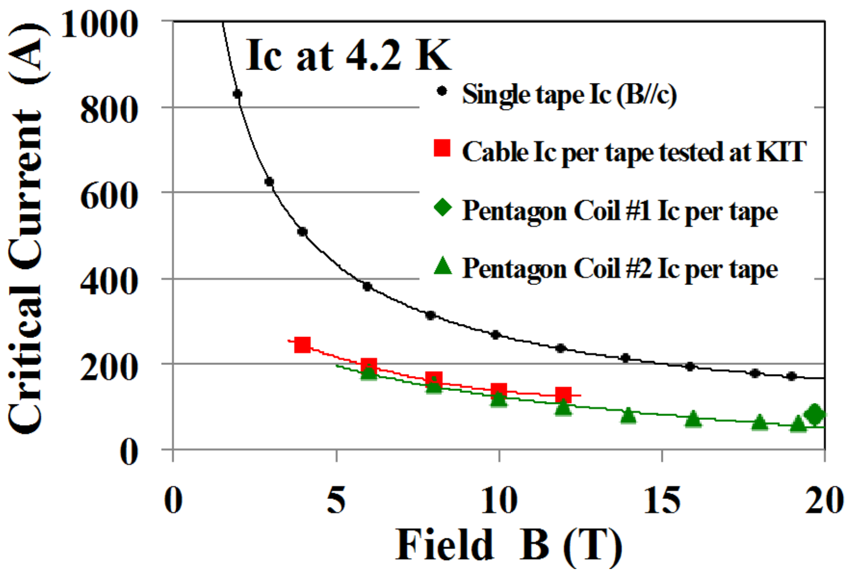
4.2-80 K and fields up to 12 T

I_c = 5.1 kA @ 100 μV/m @4.2 K, 12 T

~50% of single strand performance

additional degradation observed after first field increase (~15%)

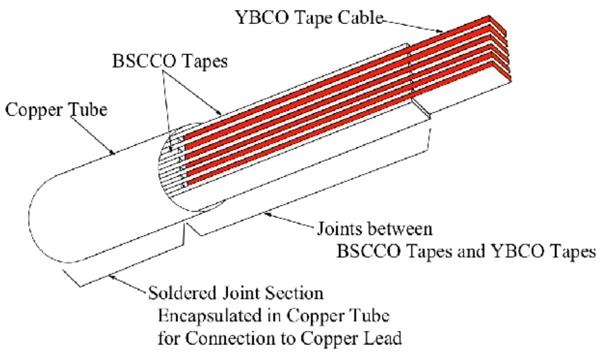


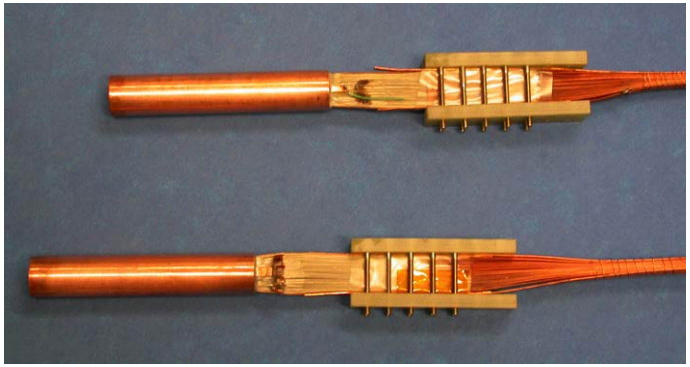


Lorentz load degradation ~ 10-15%
The rest of degradation is NOT permanent and caused by non-uniform termination resistance (non-uniform current distribution).

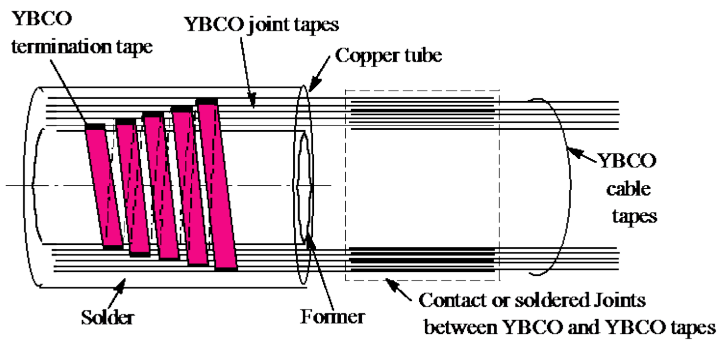
3-REBCO: TSTC (MIT)

YBCO-BSCCO Termination

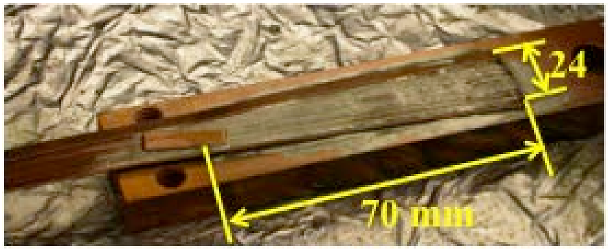




YBCO- YBCO Termination



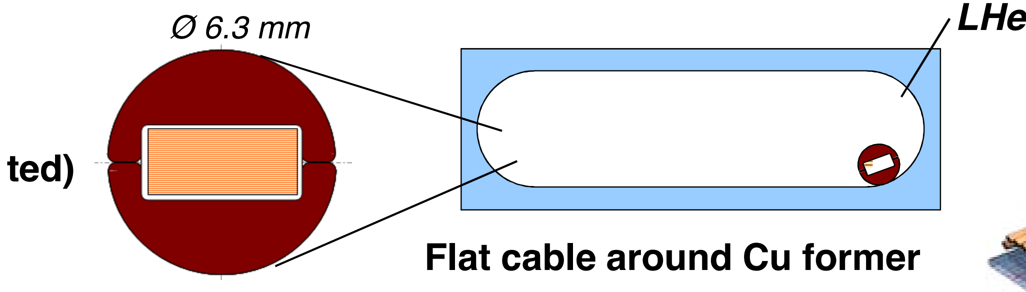
Folding-Fan Soldered Termination



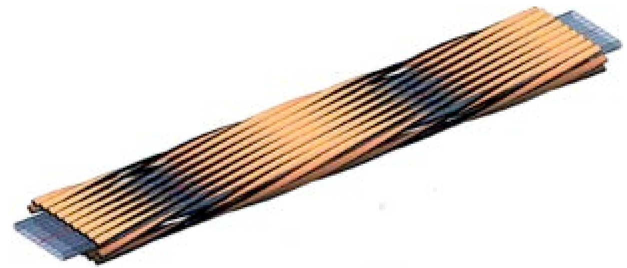
Joint resistances < 10-30 nΩ are feasible

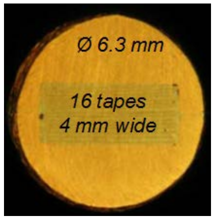
D. Uglietti, 2014

4-REBCO: RSCCCT (PSI)



Flat cable around Cu former





Expected critical current at 12 T, 5 K: 59±2 kA
Strand twist pitch 320 mm
Cable twist pitch 1000 mm

Soldered cable

- mechanically solid (no voids) and has
- low inter-tape resistance (easy current redistribution)

Flat cable

- limits transverse stress accumulation
- has less strain during winding

Twisted strands

- more uniform redistribution of current during ramping
- reduction of coupling losses (expected to be similar to ITER CICC)

Conductor is scalable to 80-kA

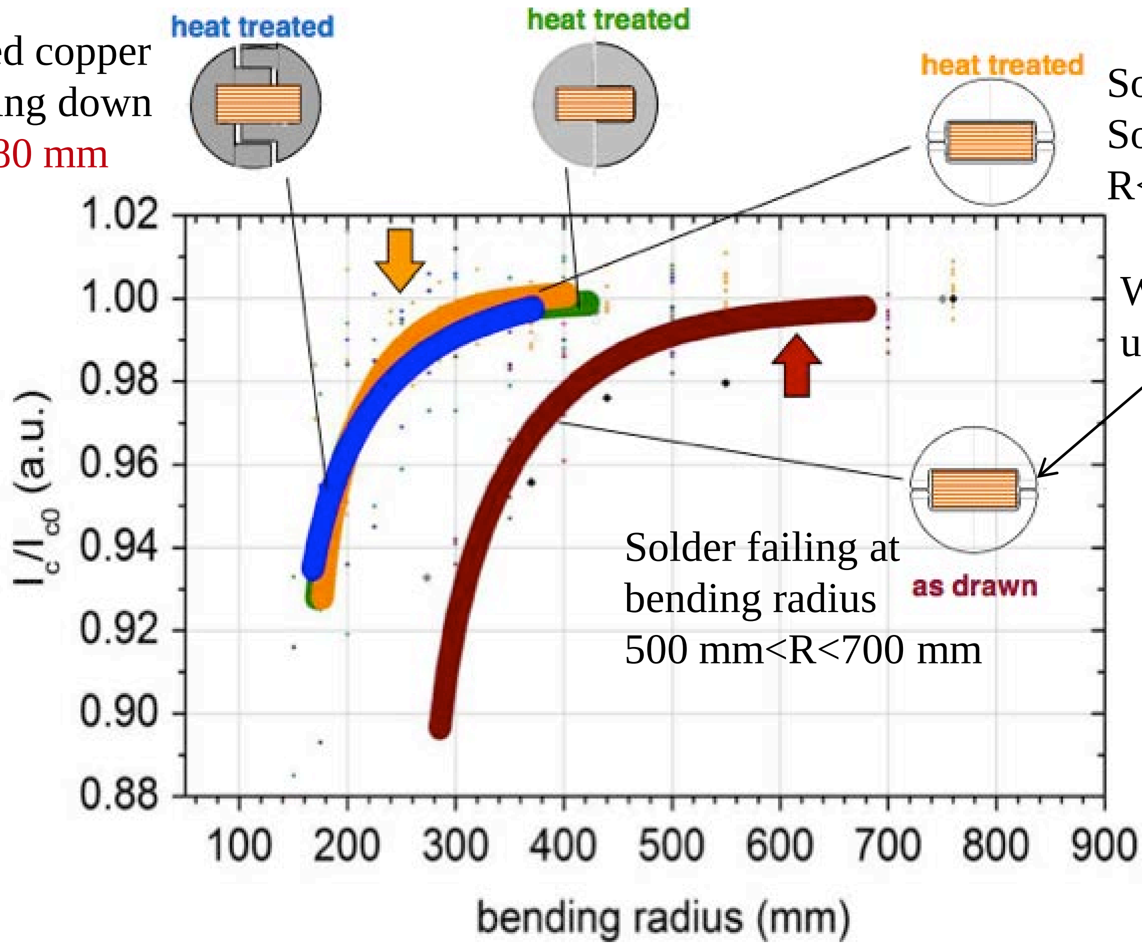
4-REBCO: RSCCCT (PSI)

Bending behavior driven by solder failure.

Softened copper
No failing down
to R<180 mm

Softened copper
Solder failing at
R<240 mm

Weak point
under shear

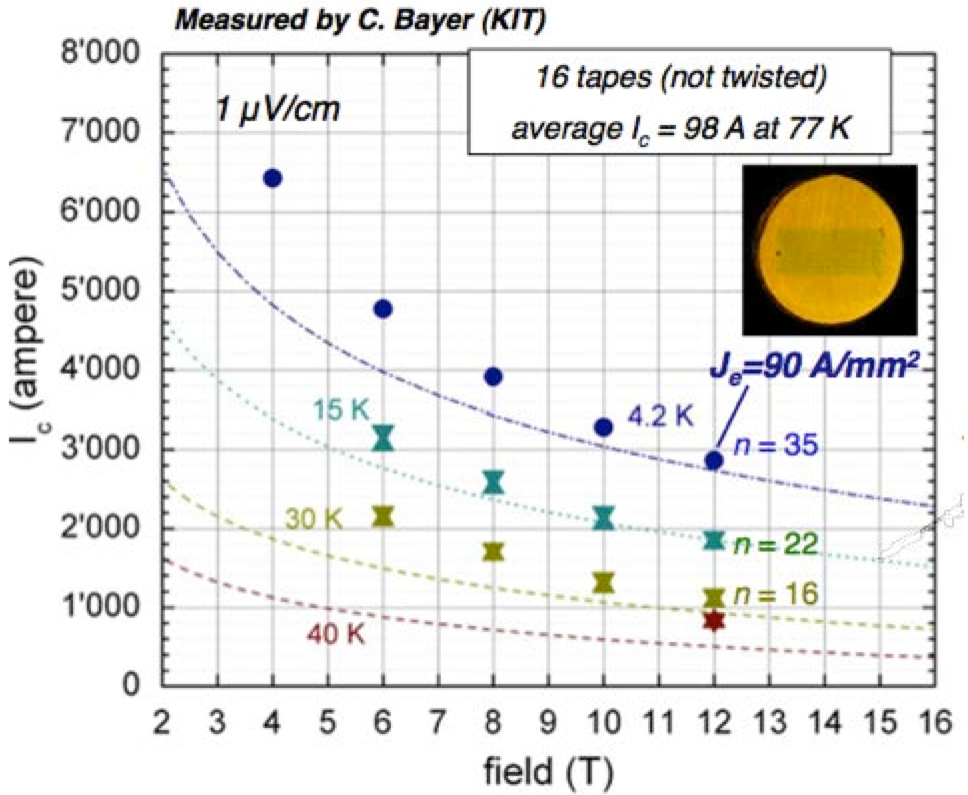


Solder failing at
bending radius
500 mm<R<700 mm

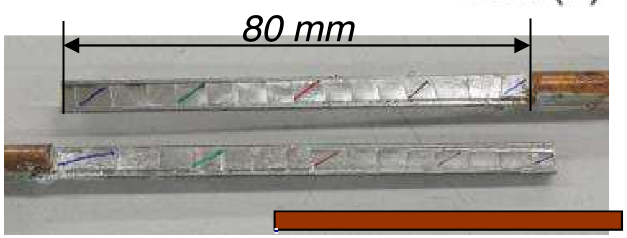
Transverse load limit < 30 MPa with original copper profile (weak in shear).

4-REBCO: RSCCCT (PSI)

In-field behavior between 4.2 and 40 K (field perpendicular to the *ab* plane).
Critical current was in line with tape data.

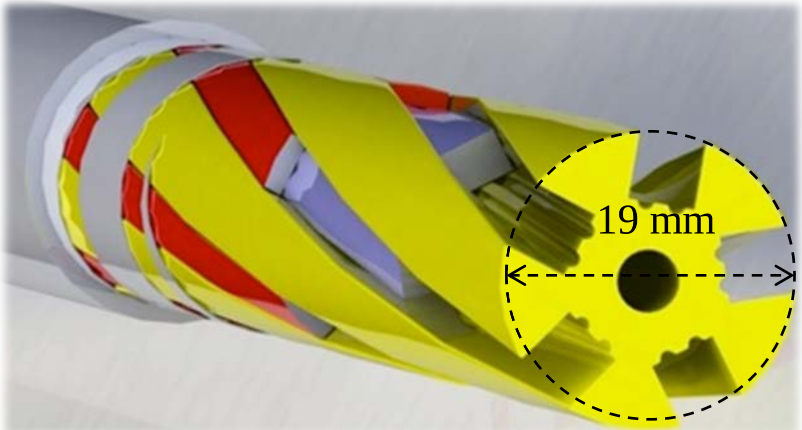


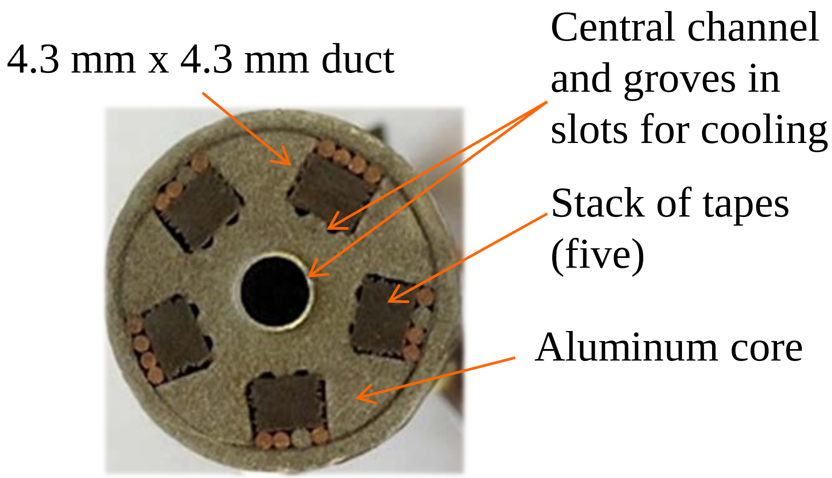
Joint methods

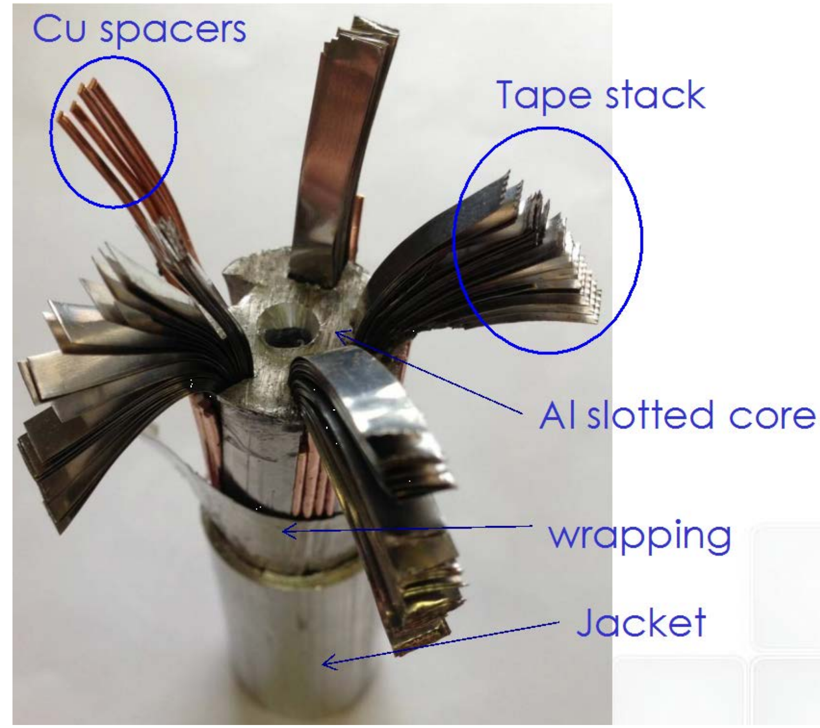


30 nΩ

5-REBCO: Slotted Core HTS (ENEA/TRATOS) 1/2







FEM shows minimal influence among stacks in the cable →

$I_{c,single\_stack} = 2.13$ kA

$I_{c,single\_stack\_in\_5\text{-}stack\_cable} = 1.95$ kA

@77 K, self-field

Fundamental design driver:

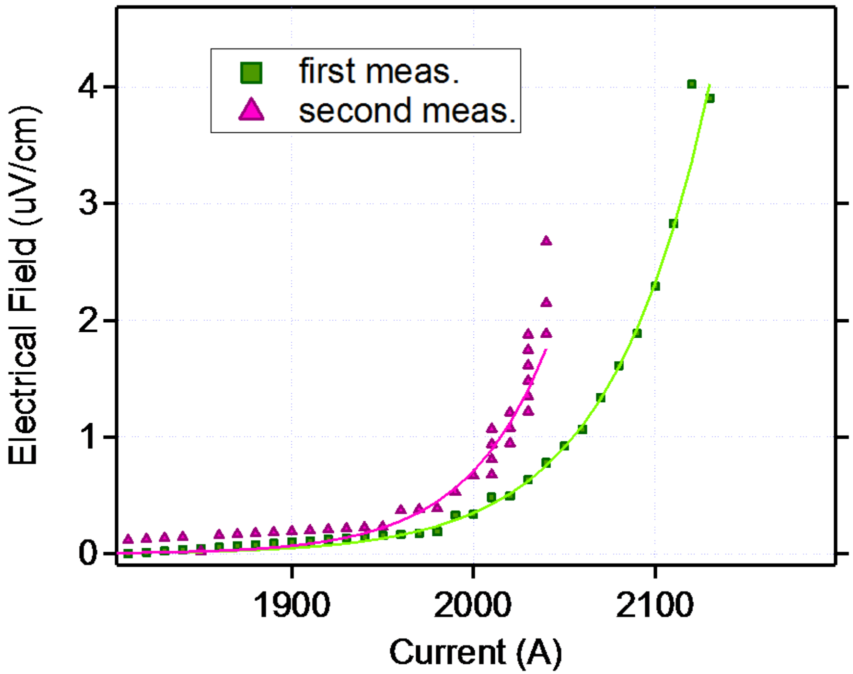
- ***industrial process feasibility***
- design for 10 kA-class cable: 150 2G-wires (5 stacks x 30 wires)

5-REBCO: Slotted Core HTS (ENEA/TRATOS)

- Recent test with ONE slot filled with 18 SuNAM tapes (SCN04150)
- Non-twisted cable

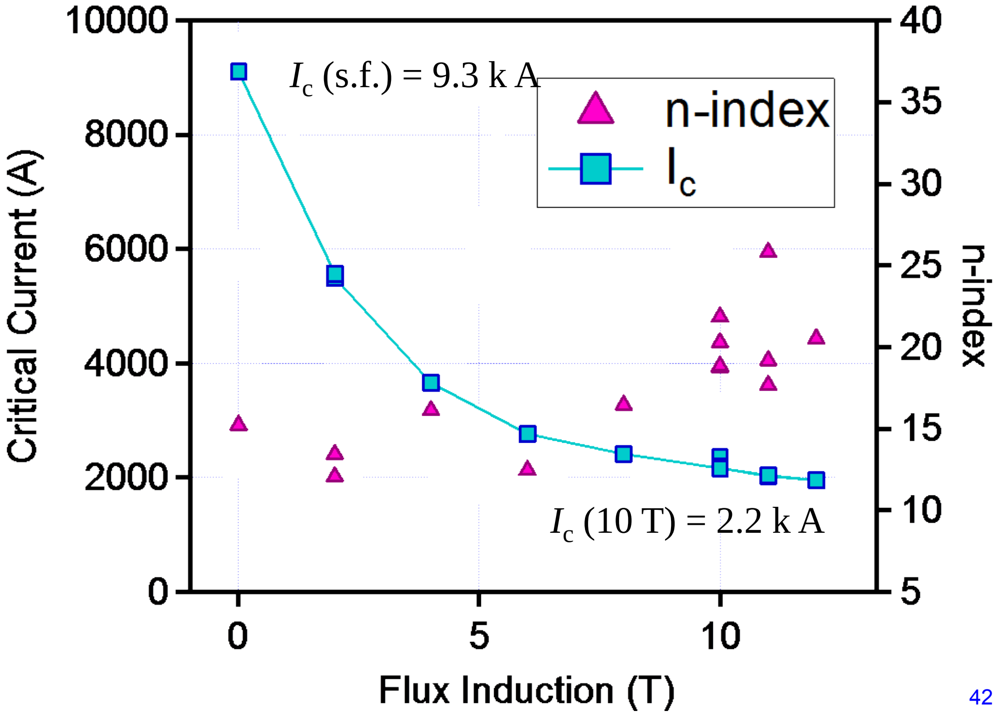
77 K, self field

$I_{c,single\_stack}$ > 2 kA



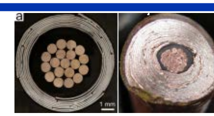
4.2 K, in field // to c-axis

$I_{c,singe\_stack}$ ~ 2.2 kA @10 T



Cables Performance Summary






Cable concept	Rutherford	RACC	CORC	TSTC	RSCCCT	Slotted CIC
Conductor	Bi-2212	REBCO	REBCO	REBCO	REBCO/PIT	REBCO
Tape utilization	NA	mid/high	mid/high	high	high	high
Scale-up	easy	hard	possible	easy	easy	easy
I_{op} (kA) @4.2 K (possible >10 kA)	2.6 (s.f)	> 2 (8 T⊥) > 10 (8 T //)	5 (19 T)	5 (12 T) 4 (19.7 T)	3 (12 T)	> 2 (10 T)
$J_{overall}$ (A/mm^2) @4.2 K	220 (s.f.)	400 (10 T)	114 (19 T)	100 (12 T)	100 (12 T)	~ 40 (10 T)
$\sigma_{transverse,ave}$ (MPa)	< 50	> 50	> 300	< 40	< 30	NA
$\varepsilon_{longitudinal}$ (%)	< 0.3	~ 0.4	> 0.6	NA	NA	NA
Bending radius (mm)		~10 (easy bend)	60 (-2.5%)	~140 (-3.6%)	300	NA
Comments	Transposed	Transposed	Partially transposed	Partially transposed	Partially transposed	Partially transposed

EuCARD2, 2014
Barth, 2014

Outline

- Why now? Why HTS cables?

- Applications and need for high current cables
  - High Energy Physics
  - Fusion
  - NMR/High Magnetic Field Science

- Available conductors
  - BSCCO
  - REBCO

- Cable designs for magnet applications
  - Characteristics
  - Advantages and disadvantages

- Outlook and conclusions

ACT V: FINALE

Is the time for HTS here?

We have HTS conductors with high J_{eng} at high magnetic field:

- REBCO coated conductors

  Ready to wind, strong

  …if only was multi-filamentary, round, easy to make long length and cheap!

- BSCCO-2212

  Round wire, multi-filamentary

  …if only was not so sensitive to strain, in need of complex heat treatment and cheap!

This is an opportunity to push the envelope and have concerted effort in addressing those *"if only"s.*

We can keep working!

Conclusions

- There are plenty of applications for high current cables
- Several cable options are available BUT none of them are ideal
- Current sharing and quench detection/protection need to be addressed

Plenty of room for improvement!
Cable options and their conductors need to be fully characterized as they might show pleasant surprises and offer ideas to re-think our approach to magnets!

Let's keep working!

THANK YOU

Thanks to everyone who ***helped*** and/or let me ***borrow*** material for the talk!

SPECIAL THANKS TO THE SUPPORTING CAST

(in order of appearance):

P. Ferracin, J. Peña, S. Giannelli, L. Bottura, M. Parizh (& colleagues @GE), D. Hazelton, R. Flükiger, P. Lee, D. Larbalestier, Y. Iwasa, E. Todesco, B. Strauss, G. Leisk, N. Allen, M. Takayasu, W. Goldacker, D. van der Laan, D. Uglietti, G. Celentano, A. della Corte, G. De Marzi, L. Muzzi, V. Selvamanickam.

RELEVANT WORK PRESENTED AT THIS CONFERENCE

V. Selvamanickam 1MOr2C-02; **Y. Iwasa** 4LOr2A; **W. Goldacker** 2LOr3C-02; **J. Fleiter** 3LPo1C-05; **A. Kario** 3LPo1C-08; **C. Bayer** 3LPo1C-09; **M. Majoros** 1LOr3A;**X. F. Lu** 1MOr3D; **P. Kruger** 2LOr3C-05; **N. Allen** 3LPo1C-01; **M. Takayasu** 4LPo1H-02; **D. Uglietti** 2LOr2B-01; **G. Celentano** 3LPo2C-02; **A. Augieri** 2LOr3C-01; **G De Marzi** 3MPo2D-06**; S. Ishmael** 1LOr3D-05, **X.F. Li** 1Lor3D-06; **G. Kirby** 2LOr2A-06; **T. Shen** 2LOr2A-07, **E. Demencik** 2MPo1C-09, **H. Lee** 2MOr2A-01, **N. Bagrets** 2MOr2A-03; **F. Douglas** 2LOr3C-04; **F. Grilli** 2LOr3C-05.

Luisa.Chiesa@tufts.edu

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