Prospects for the use of HTS in high field magnets for future accelerator facilities

A. Ballarino
CERN, Geneva, Switzerland

Outline

- Introduction
- HTS Conductors
  - State of the art development
  - Conductor choices for high fields
  - HTS Cables
- Application to high field magnets
  - HTS Magnet design aspects
  - Coils demonstration
  - Developments for a viable HTS technology
- Conclusions

- **Introduction**
- **HTS Conductors**
  - State of the art development
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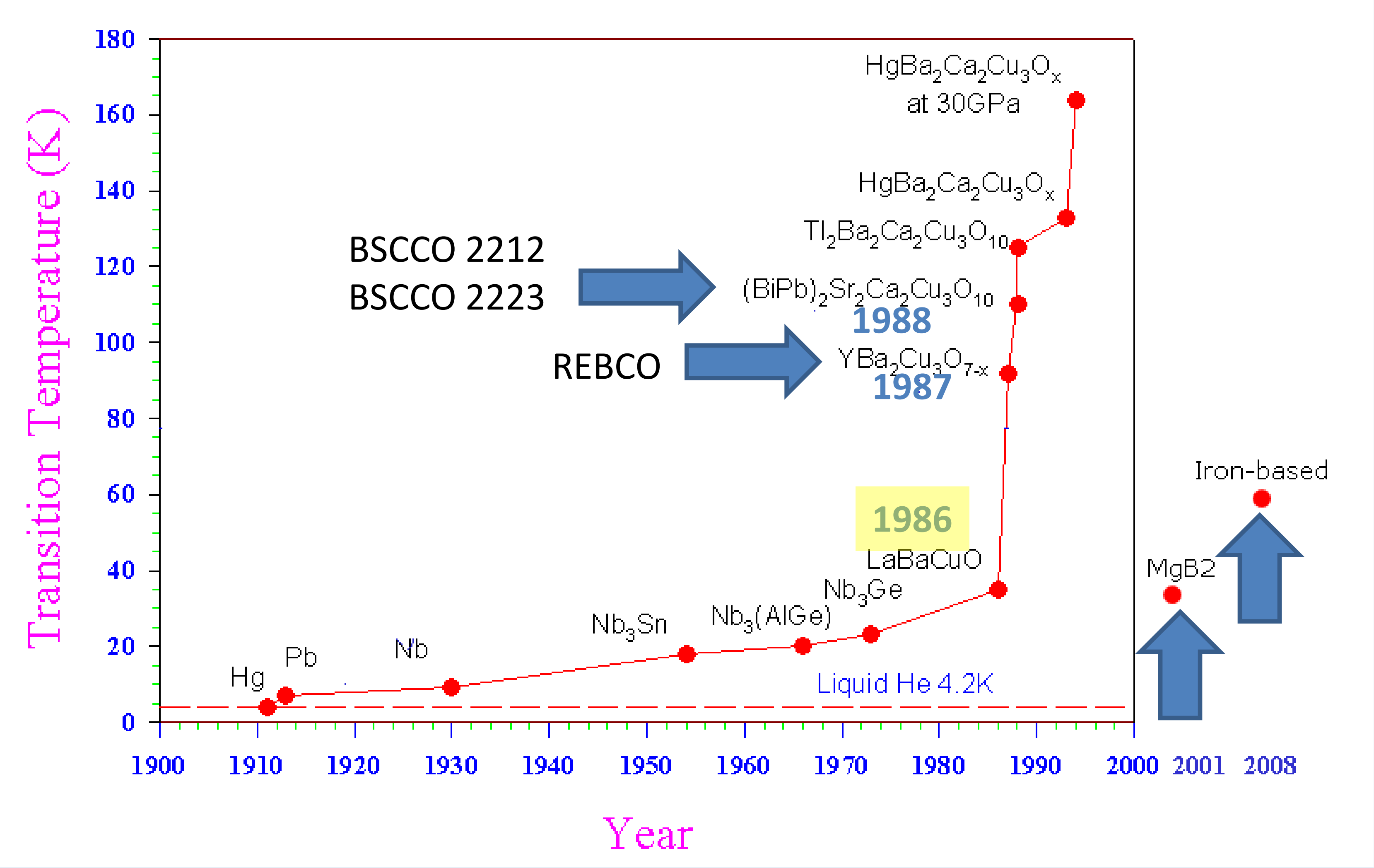
- **Conclusions**

Transition temperature of superconductors



Properties of superconductors

	Tc(0) [K]	Bc2(0 K) [T]	ξ (nm)
Nb-Ti	9.5	14.4	~ 6
Nb_3Sn	18.3	28-30	~ 4
REBCO	93	> 100	~ 2
BSCCO 2212	95	> 100	~ 1
BSCCO 2223	110	> 100	~ 1

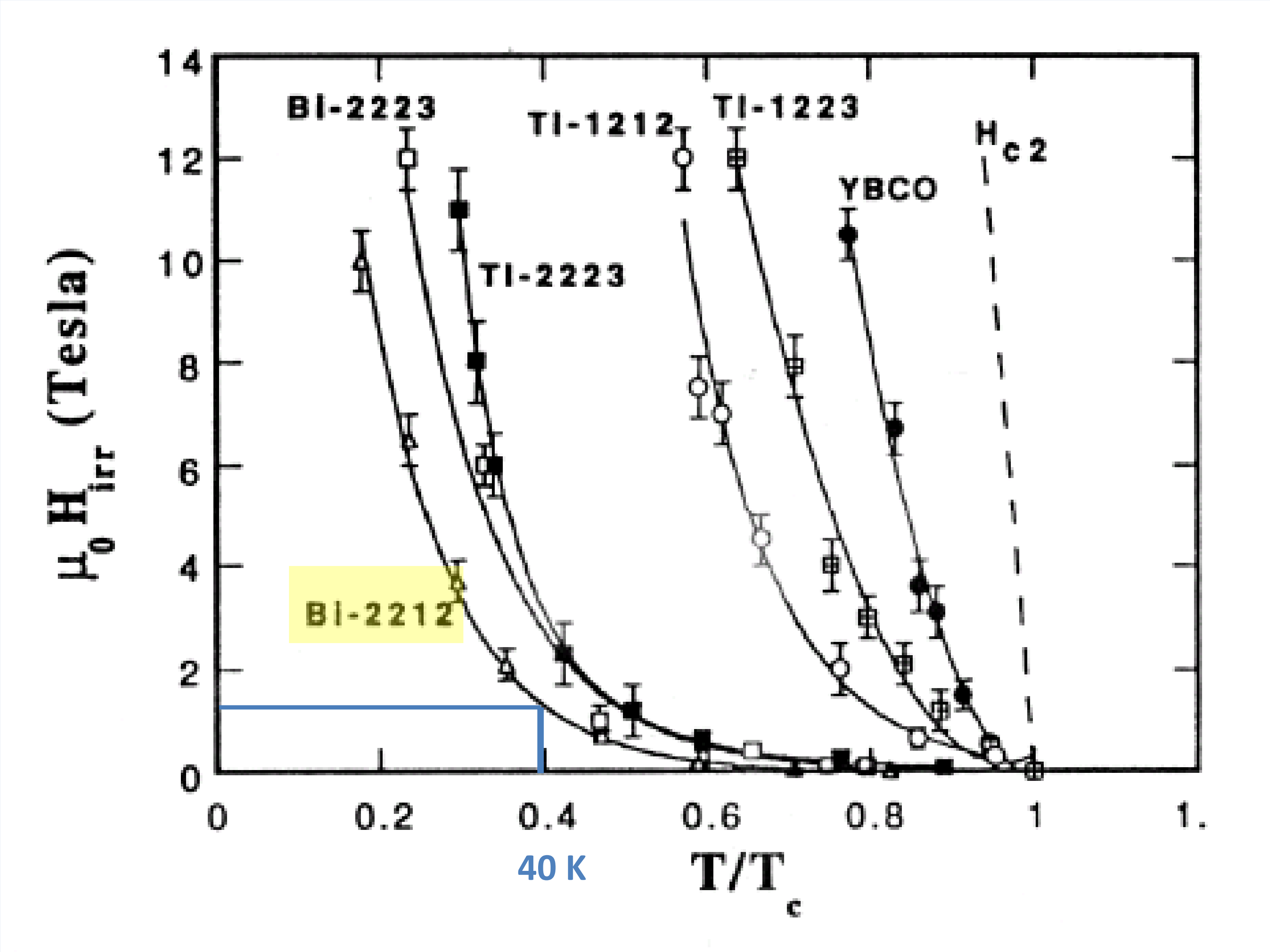
Bc2(0 K) > 100 T

Bc2(0) = upper critical field at 0 K
ξ = coherence length

Properties of HTS superconductors

- $Hc_2(T)$ much higher than for Nb-Ti and Nb_3Sn
- But, thermal fluctuation effects depress the irreversibility field (Birr) at which Jc = 0 well below Bc2, except at low T

Irreversibility line of HTS



Properties of HTS superconductors

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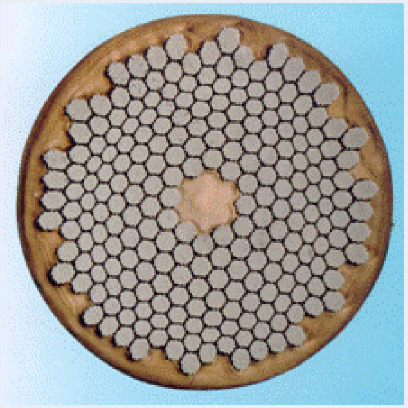
High fields → Low (liquid helium) temperature

High field for HTS superconductors

Nb-Ti

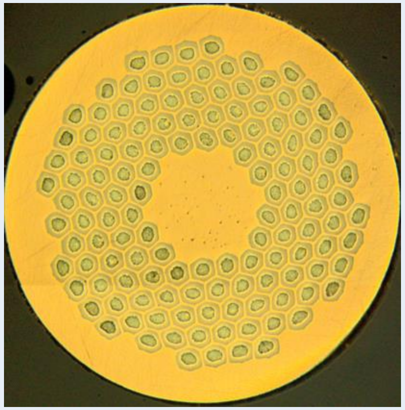


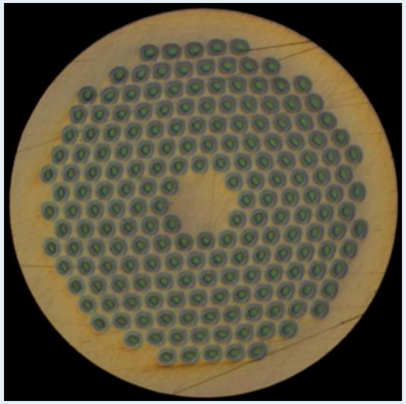
~ 1200 t in LHC

Up to 10 T

Nb_3Sn

RRP 132/169 PIT 192





~ 25 t for Hi-Luminosity LHC

~ 600 t for ITER

Up to 15- 16 T

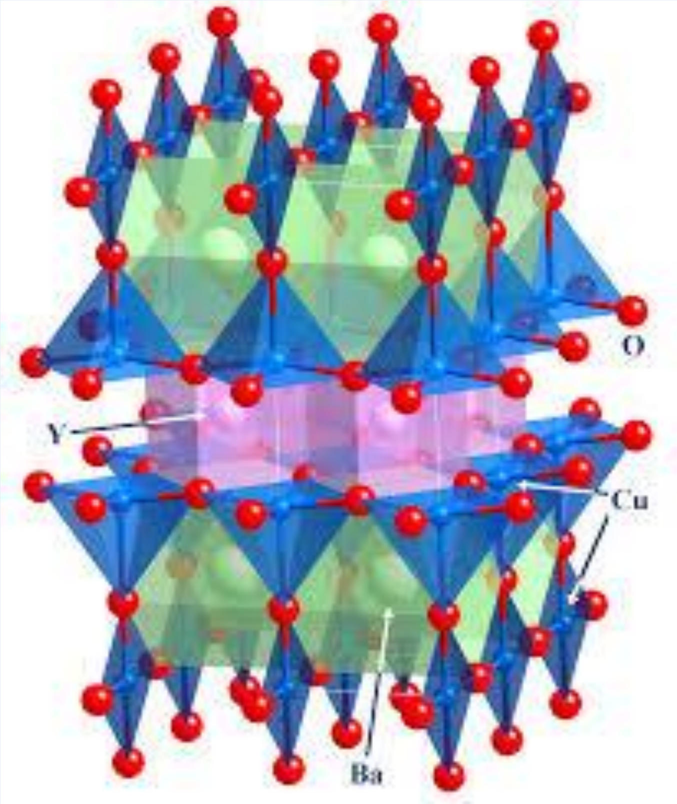
HTS at 4.2 K and for fields above 16 T

Challenges of HTS superconductors

Copper oxides HTS (cuprates)

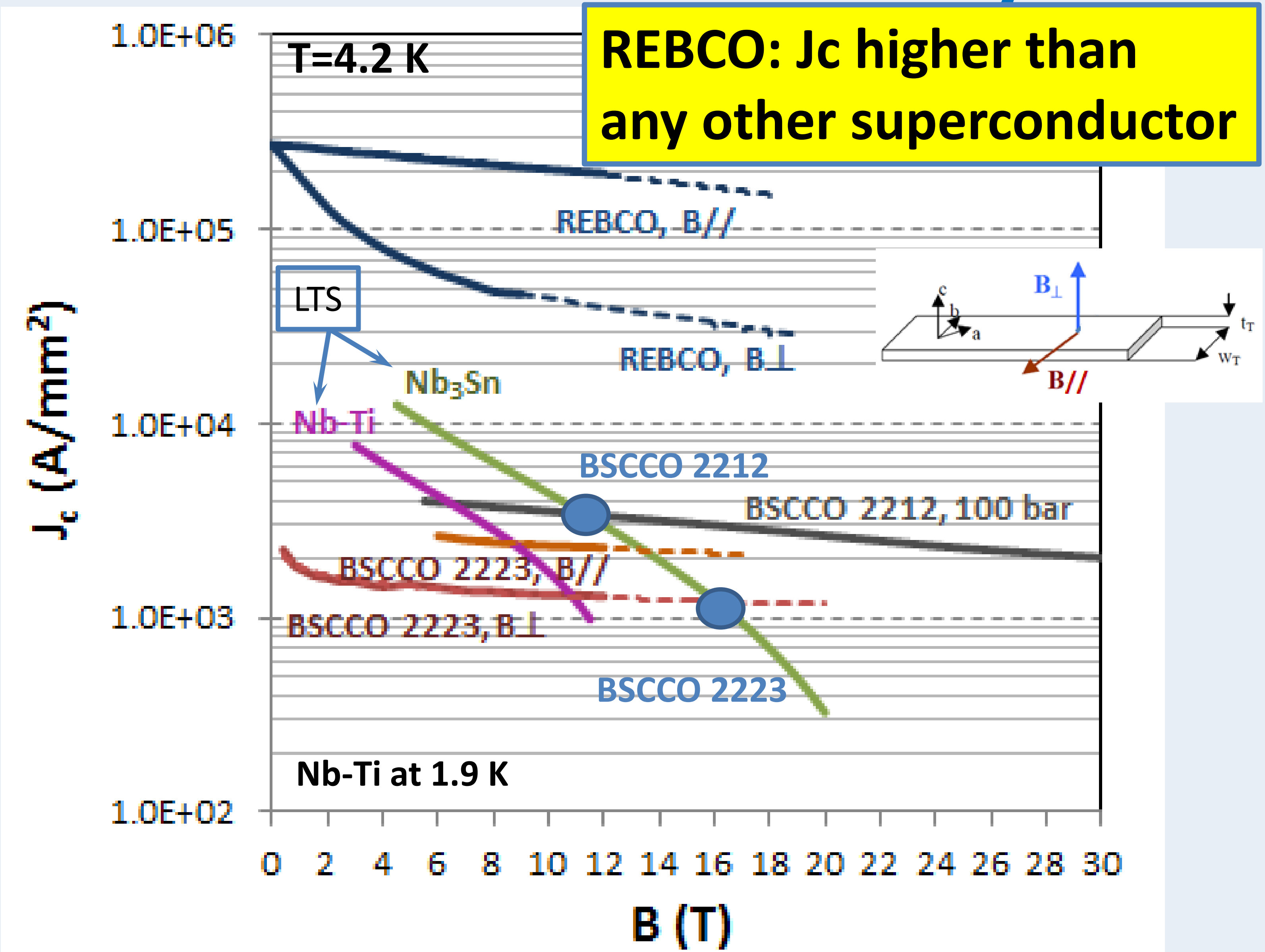
- ➢ Layered crystal structure
- ➢ Orientation of grains needed
- ➢ Brittle ceramic materials

➔ Long time R&D



Ex. $YBa_2Cu_3O_7$ (YBCO)

Critical current density



Measurements performed at CERN on commercial materials. The Nb-Ti curve is at 1.9 K
BSCCO 2212 measurements performed at NHMFL

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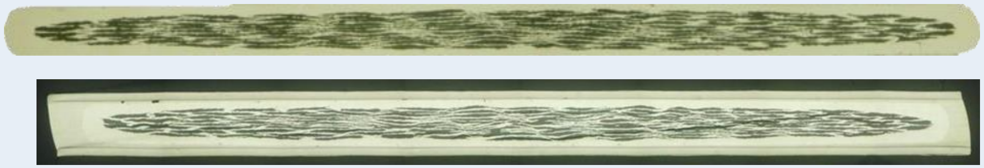
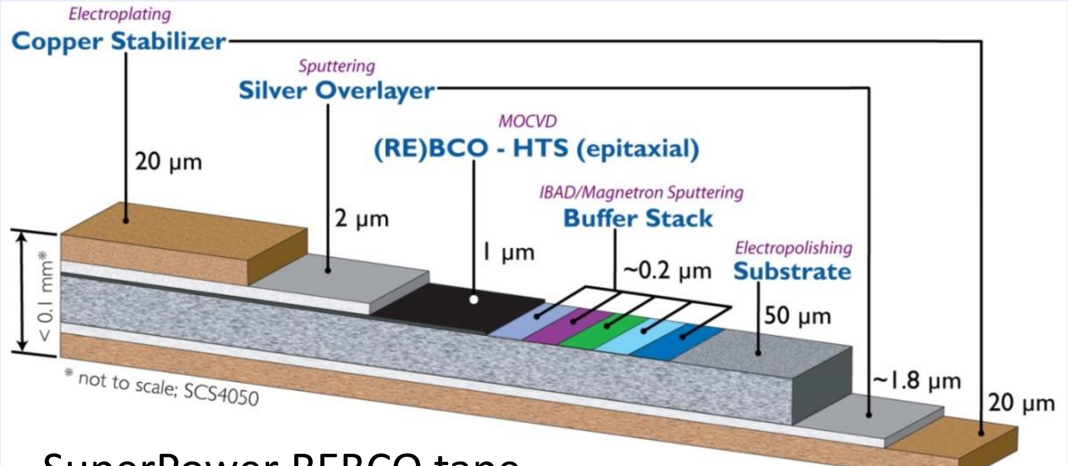
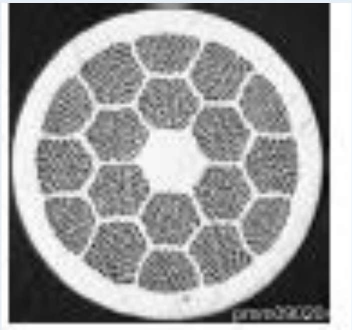
HTS Conductor Choices



Sumitomo DI-BSCCO tape



SuperPower REBCO tape



OST BSCCO 2212 wire

BSCCO 2223

Multi-filamentary tape

~ 4.3 mm × 0.23 mm

~ 40 % SC

REBCO

Coated Conductor Tape

~ 4 mm × 0.16 mm

~ 1% SC

BSCCO 2212

Multi-filamentary wire

Φ = 0.8-1.4 mm

~ 30 % SC

BSCCO 2223 tape

Most mature superconductor

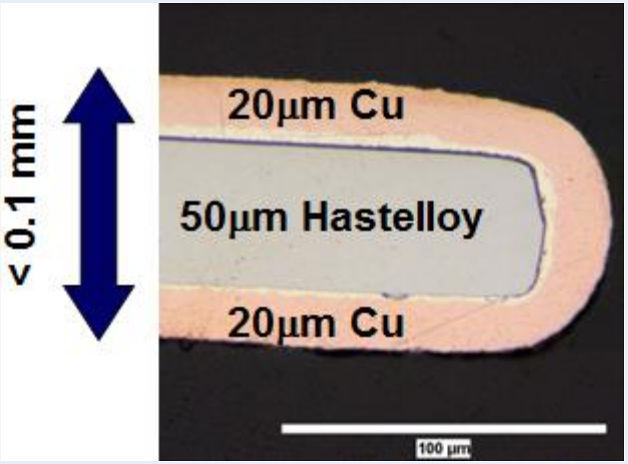
DI-BSCCO 2223 (Sumitomo)

Unit lengths of up to **300-400 m**
Production capacity @ Sumitomo = **1000 km/year**
Implemented **quality control**
Ic variation over unit length **< 3 %**

Good mechanical properties
$\varepsilon_c = 0.57\ \%$
$\sigma_c = 430$ MPa

Je(77 K, s.f.) up 150 A/mm^2
Je(4.2 K, B⊥=17 T) up to 400 A/mm^2

REBCO tape



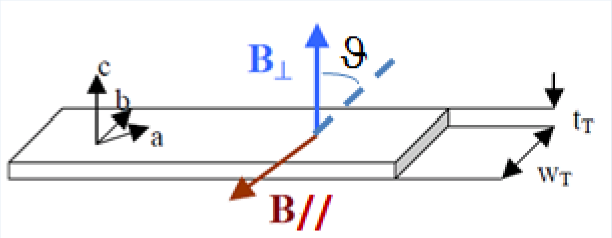
Tapes based on bi-axially textured YBCO film

Highest Jc than any other superconductor

Substrate (Hastelloy C, Stainless steel) thickness ~ 50 µm
Superconductor thickness ~ 1 to 5 µm
Unit lengths of up to 100-200 m
Good mechanical properties
σ_c > 550 Mpa
It is wound as reacted conductor: Wind and React technology

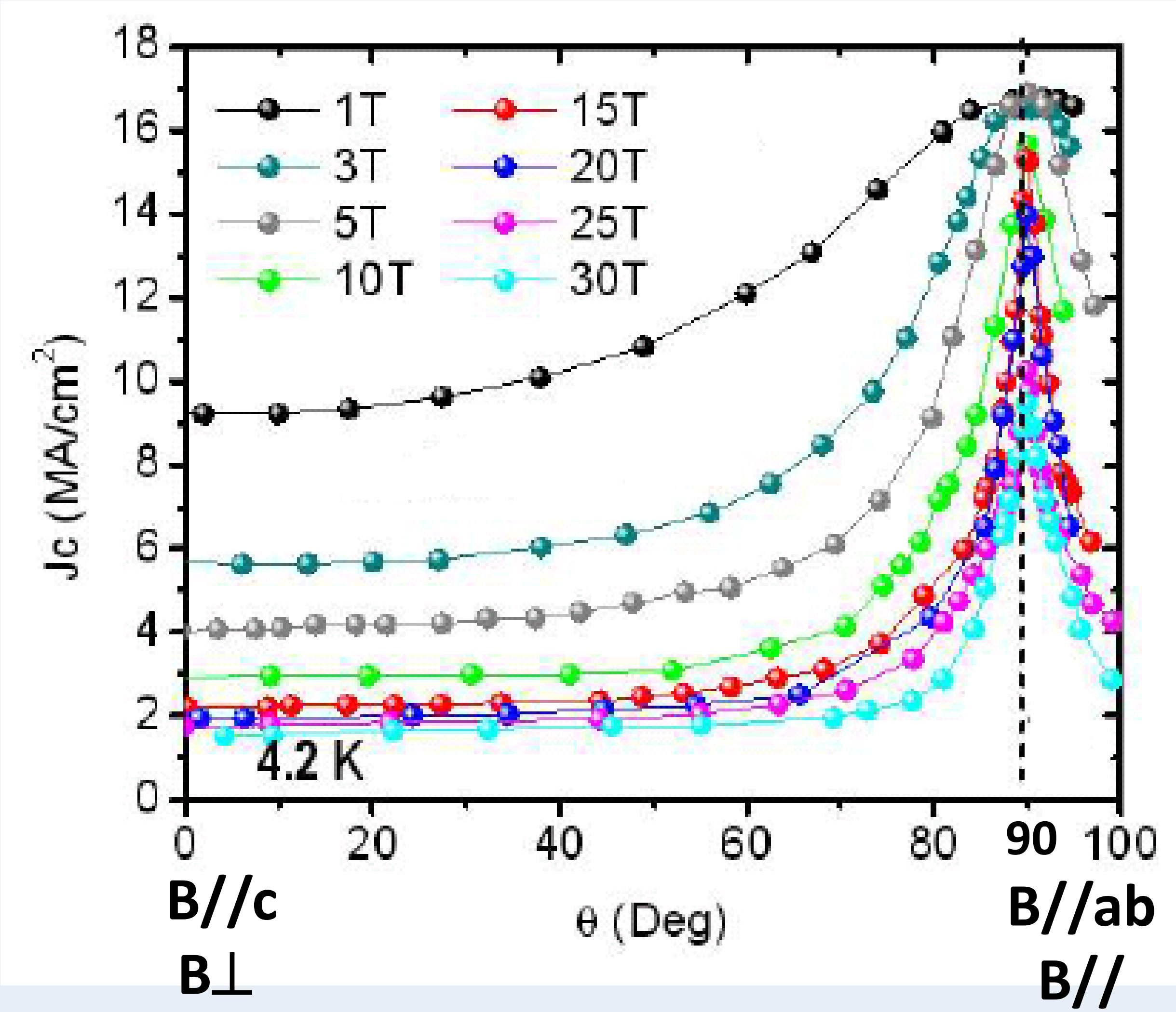
Several manufacturers (Europe, USA, Korea, Japan, Russia)

Ic anisotropy



REBCO, BSCCO 2223

Ic(B,T,ϑ)



Xu et al, NHMFL

REBCO tape

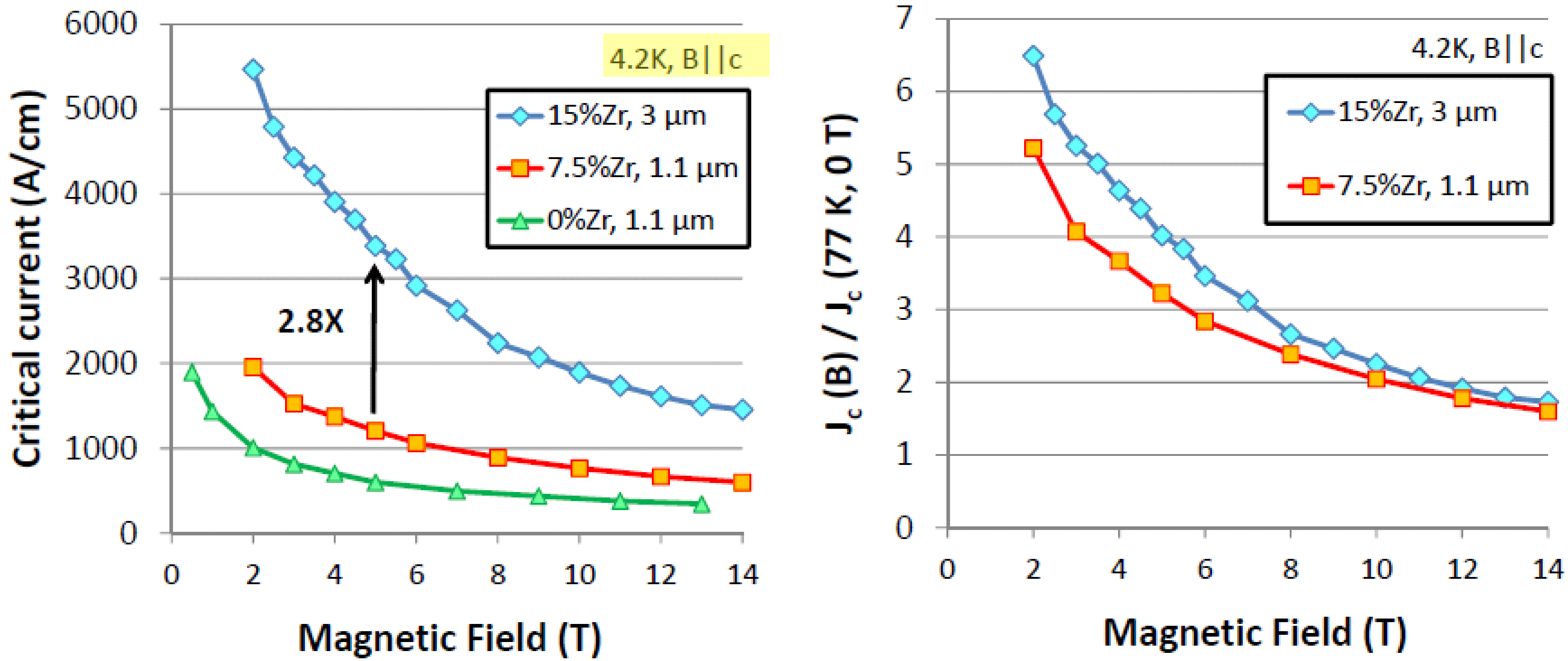
Potentials for **Je enhancement** by reduction of thickness of substrate and increase the thickness of superconducting layer (texture vs thickness)

Addition of nanoscale defects (nanoparticles and nanorods) with strong pinning properties for **enhancement** of in-field **Jc** - BaZrO3 (BZO) nano-columns

REBCO tape

UNIVERSITY of HOUSTON

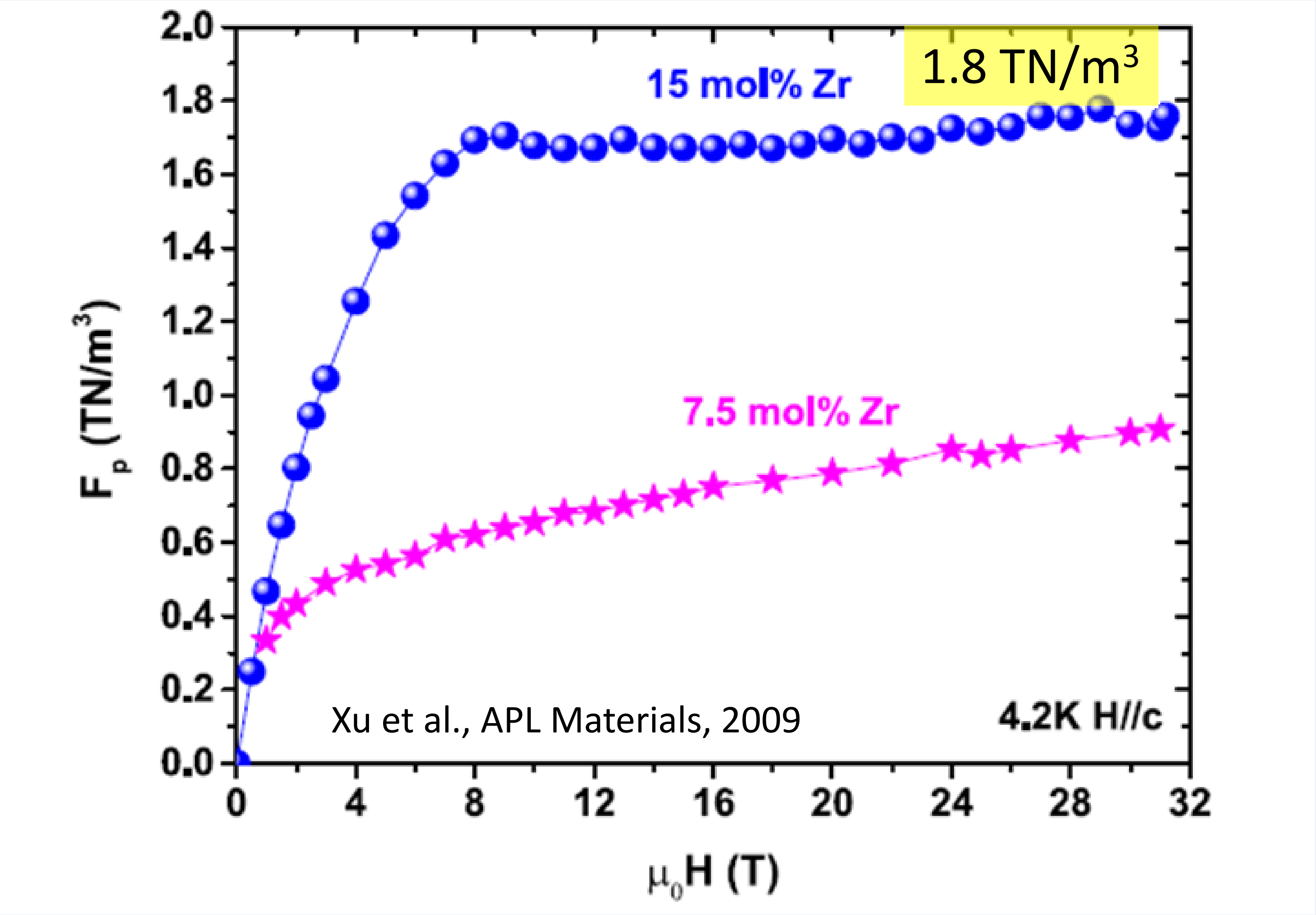
SuperPower Inc. A Furukawa Company



Measurements by J. Jaroszynski, D. Abraimov, X. Hu and D. Larbalestier, NHMFL

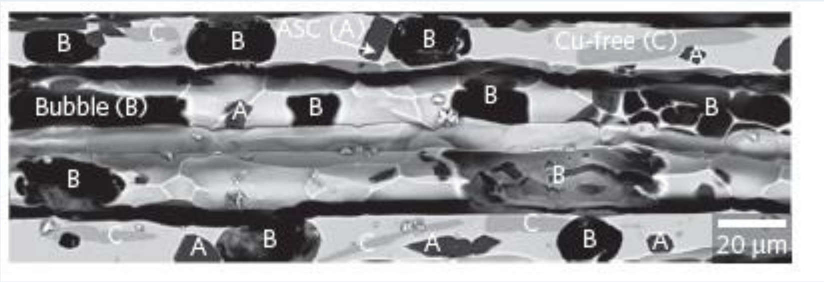
Je(4.2 K, B⊥ = 20 T) ~ 1000 A/mm^2

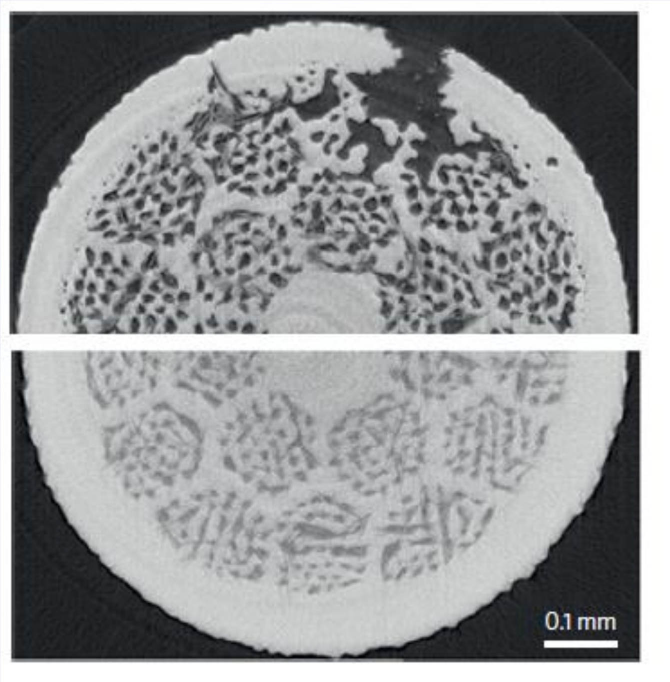
Pinning force in REBCO



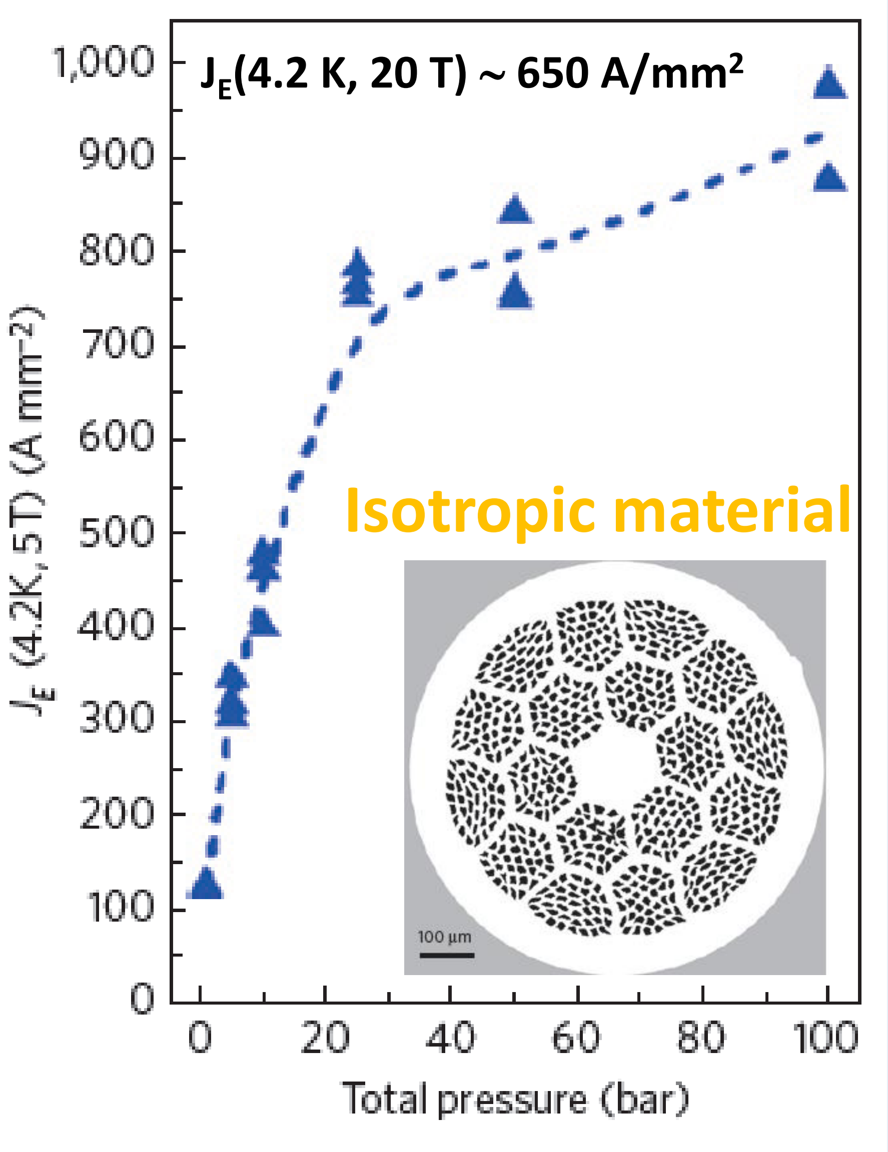
Fp(Nb-Ti) ~ 17 MN/m^3 (4.2 K and 5 T)

BSCCO 2212 round wire



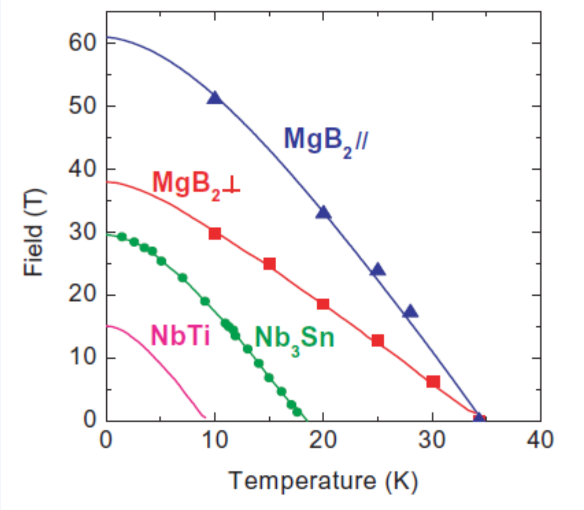


D. Larbalestier et al,
Nature Materials, NMAT 3887



It requires Wind & React technology

MgB_2 tape and wire



H_{c2} of optimally dirty MgB_2 exceeds those of NbTi and Nb_3Sn

- Potentially large H_{c2}
- Excellent chemical and mechanical compatibility with high-strength alloys (steels)
- Weak-link free grain coupling

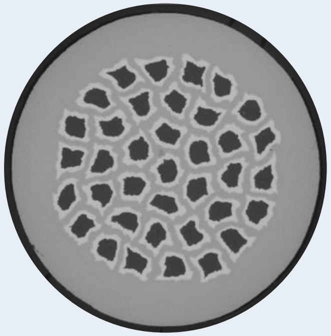
- Round wire
- Well-knowm PIT technolgy
- Low raw material cost
- Moderate anisotropy

Lack of natural defects may be the responsible for fast decrease of Jc in increasing fields

Needed enhanchment of H_{c2} and H_{irr} in wires

MgB_2 wire

Industrial Wire



Φ = 0.85 mm
Round MgB_2
Columbus wire
CERN-Columbus
development

Superconducting Links for Hi-Luminosity LHC

Reached @ CERN
20 kA @ 24 K
2×20 m long MgB_2 cables

First demonstration of high-current capability in MgB_2 cables

Low-field application for electrical transfer lines

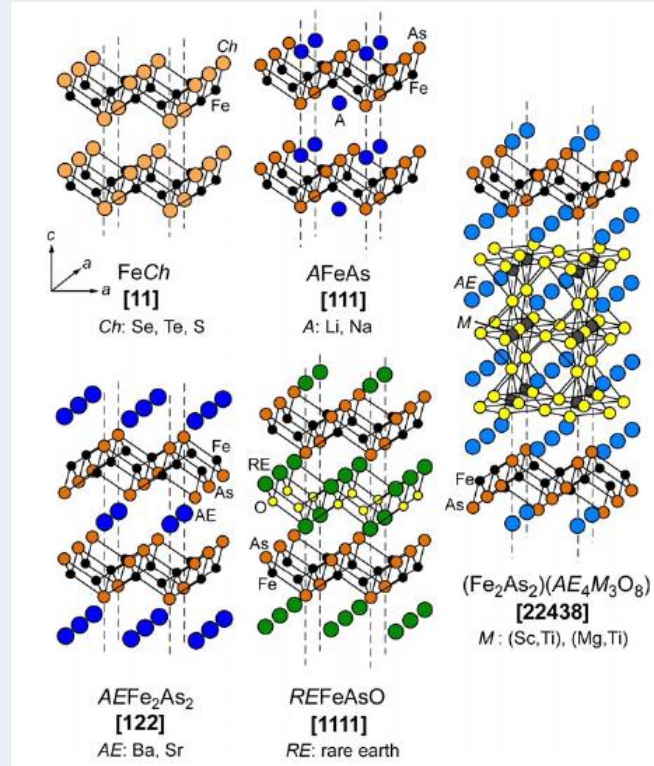
Iron-based superconductors

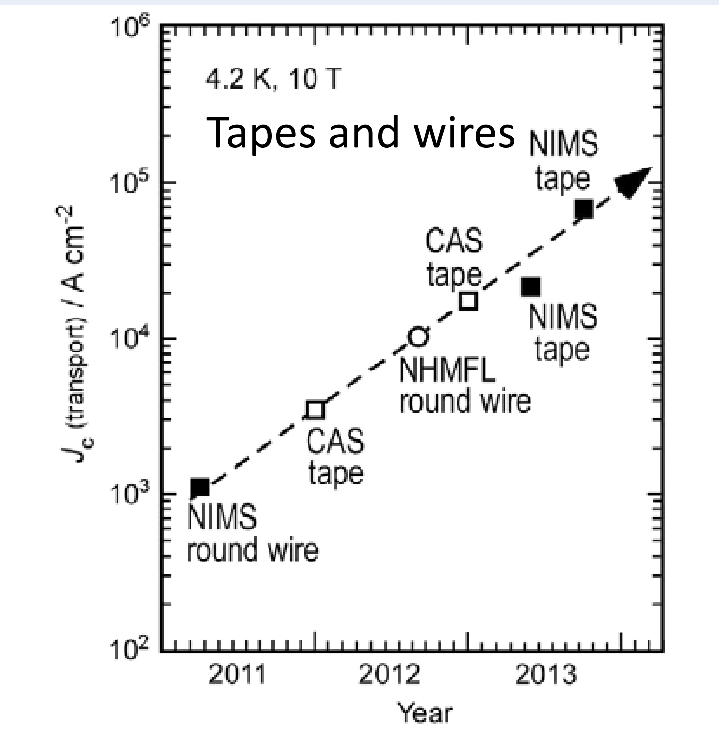
Tc up to 56 K

High Bc2 – Bc2(0) up to 100-200 T

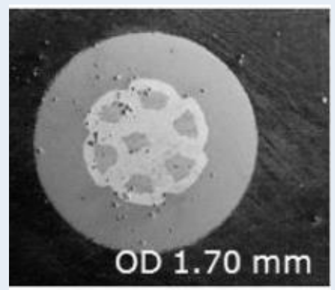
ξ~ 1-3 nm

Low electromagnetic anisotropy





H. Kumakura, NIMS



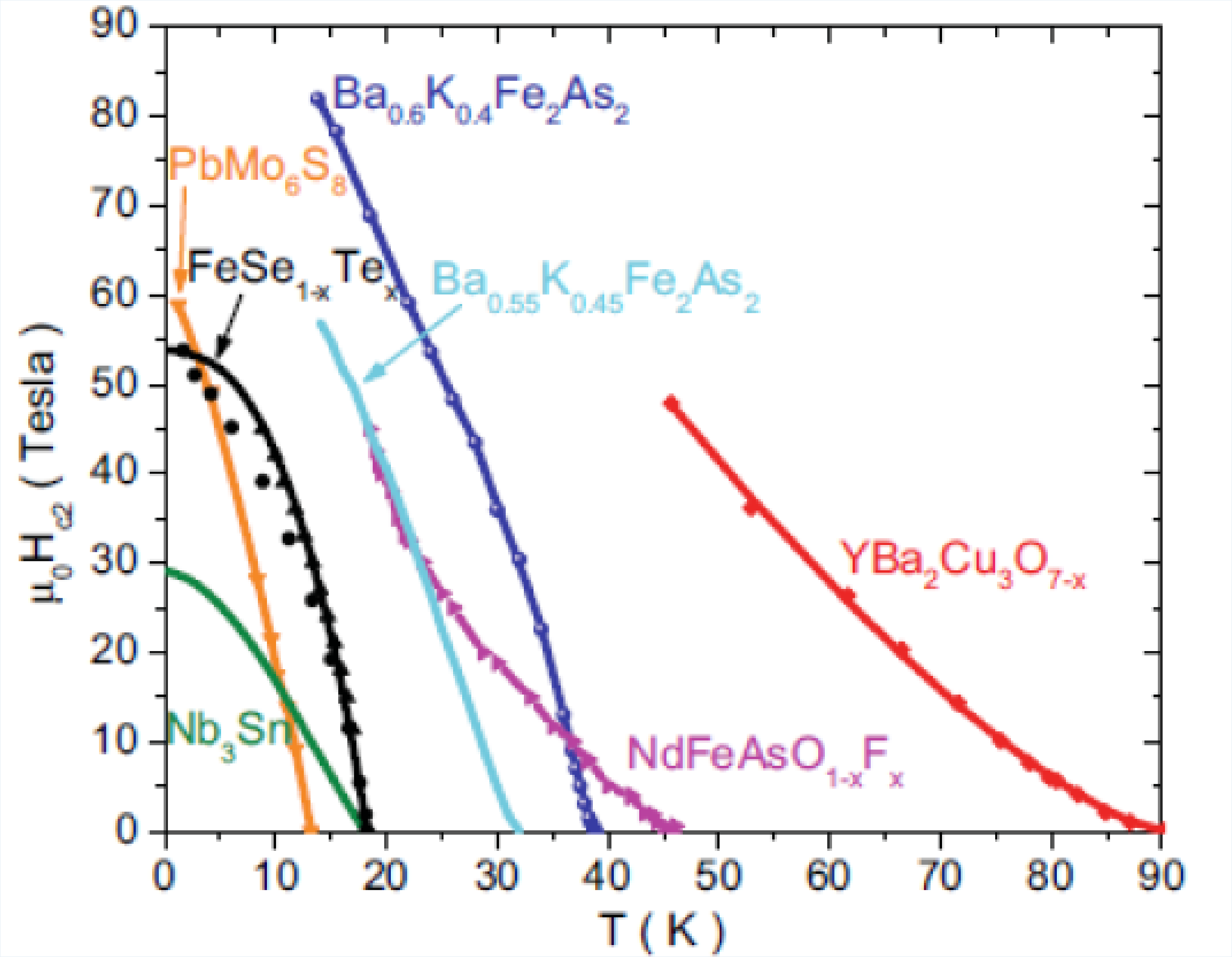
Wire

Tape

Coated conductor

Iron-based superconductors

Upper Critical field Bc2(T)



C. Tarantini et al., ASC Center

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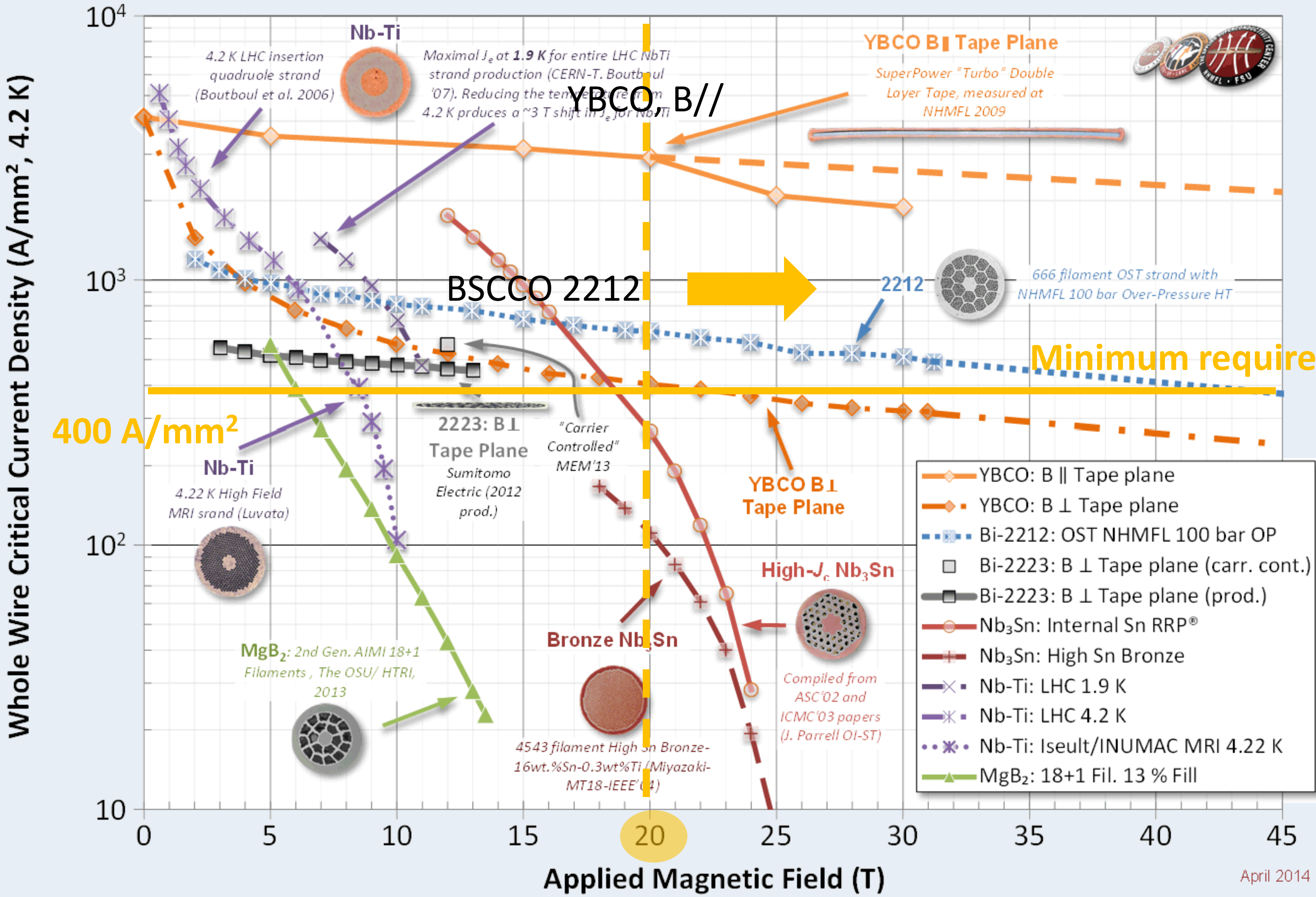
Engineering critical current density



Graphic courtesy of P. Lee, ASC Center at NHMFL

Summary of conductor characteristics

BSCCO 2223	REBCO	BSCCO 2212
Tape	**Tape**	**Wire**
Multi-filamentary	**Thin-film**	**Multi-filamentary**
Single-layer	Twisted-filaments	Twisted-filaments
Anisotropic	**Anisotropic**	**Isotropic**
$I(B,T,\vartheta)$	$I(B,T,\vartheta)$	$I(B,T)$
New cables	**Reacted conductor**	**High pressure HT**
Lower Je	**High Je**	**High Je**
L~300 m	L=100-200 m	Not an issue

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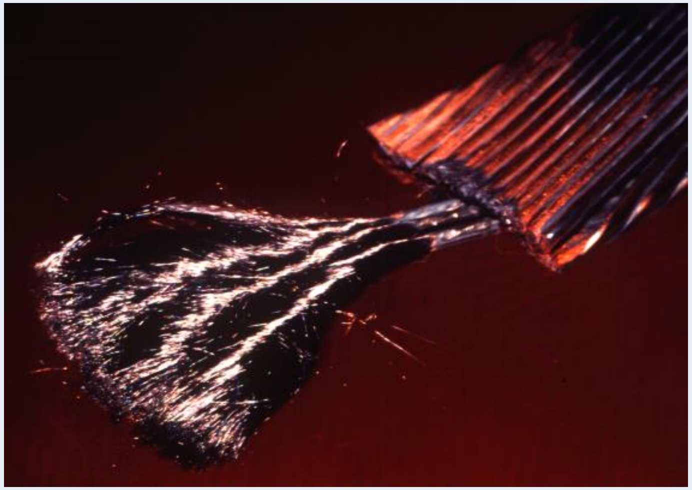
Superconducting cables cables

Superconducting cables for accelerator technology:

- High current
- High compactness → High Je
- Full transposition
- Dimensional accuracy
- Controlled inter-strand resistance
- Good mechanical properties
- Windability

Nb-Ti LHC Rutherford cable

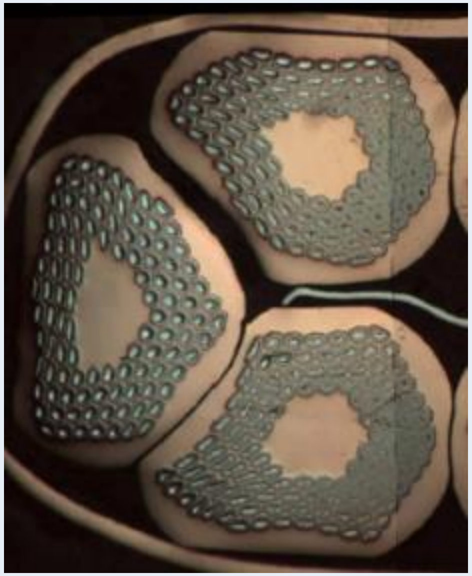


Rutherford cables made from **Nb-Ti** and **Nb_3Sn round wires**

Large Hadron Collider: 7600 km (1200 tons)
Nb-Ti Rutherford cables

Superconducting cables cables

Nb_3Sn Hi-Luminosity LHC Rutherford cables



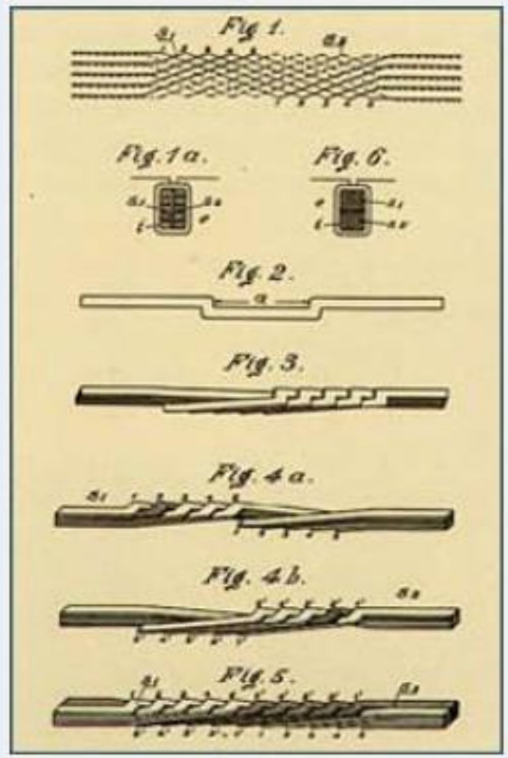
Rutherford cables from BSSCO 2212 round wires

D. Dietderich et al., LBNL

REBCO and BSCCO 2223: the tape geometry requires new cable concepts

REBCO Roebel Cables

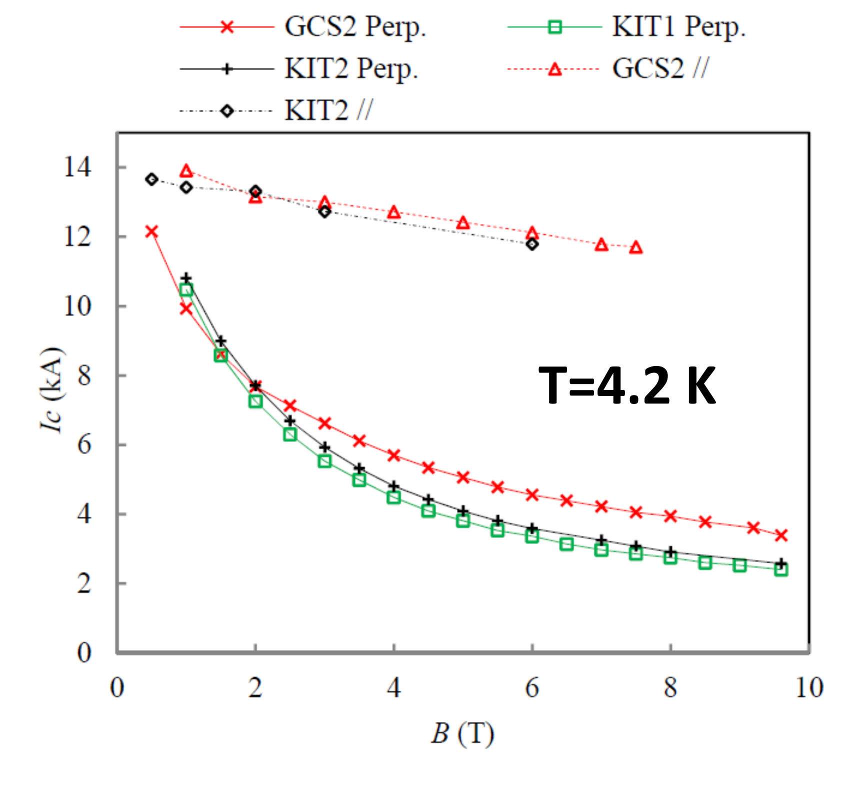
Meander-tape cut from a 12 mm wide REBCO tape

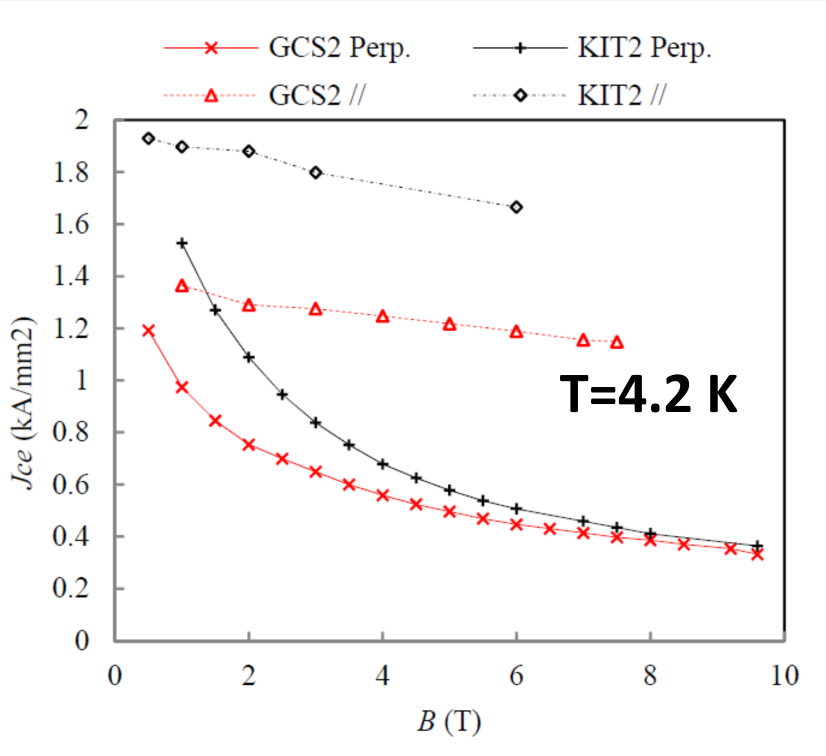


Patent (1912) of Ludwig Roebel (BBC) Low-loss Cu cables for power generators

Cables produced by KIT and General Cable Superconductors from commercial REBCO tape

REBCO Roebel cables





Ic (B⊥=9.6 T, 4.2 K) = 3.4 kA
Je (B⊥=9.6 T, 4.2 K) = 400 A/mm²

J. Fleiter, PhD thesis

- **Measurements performed at CERN show current capability**
- **Required management of stress and of stress distribution**

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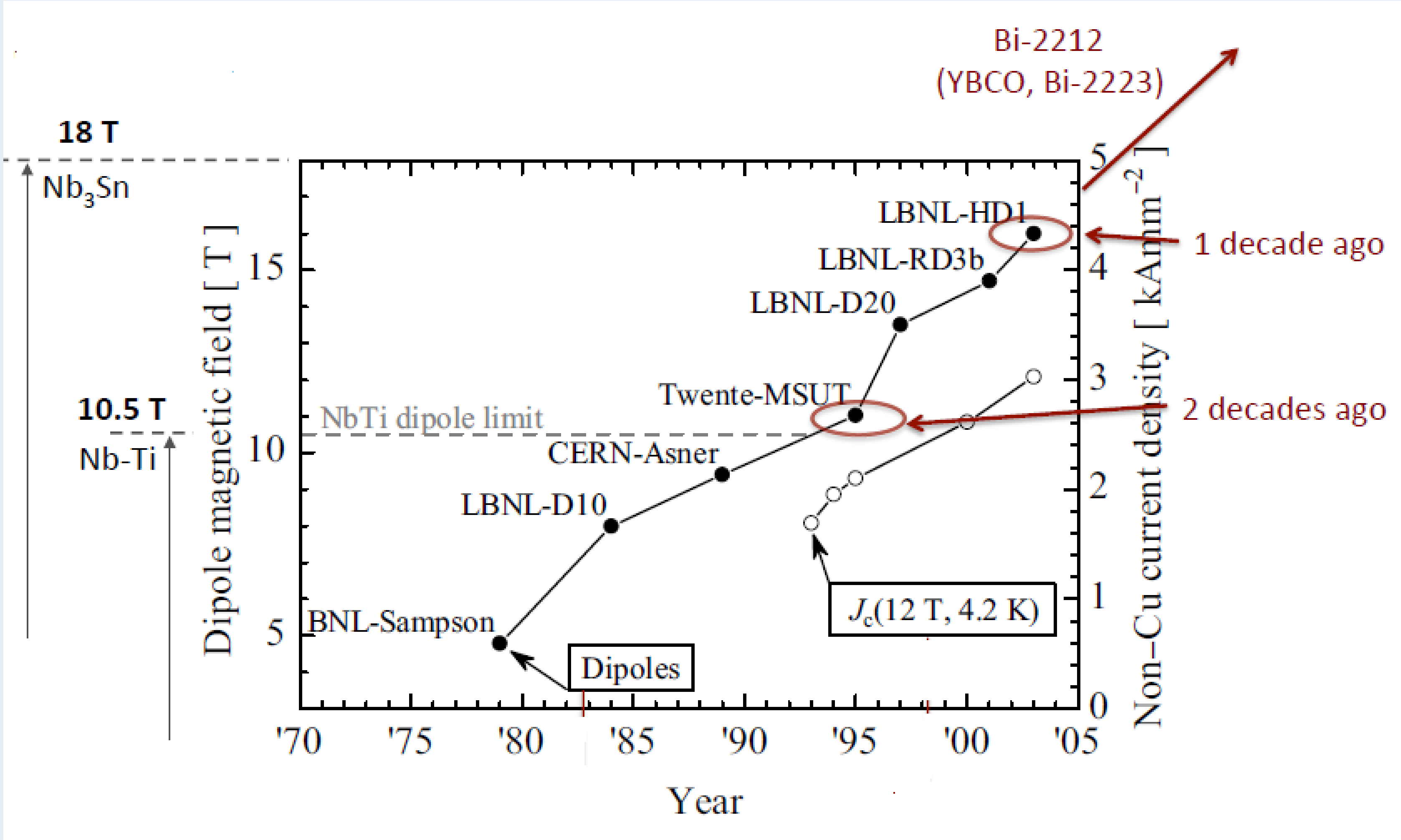
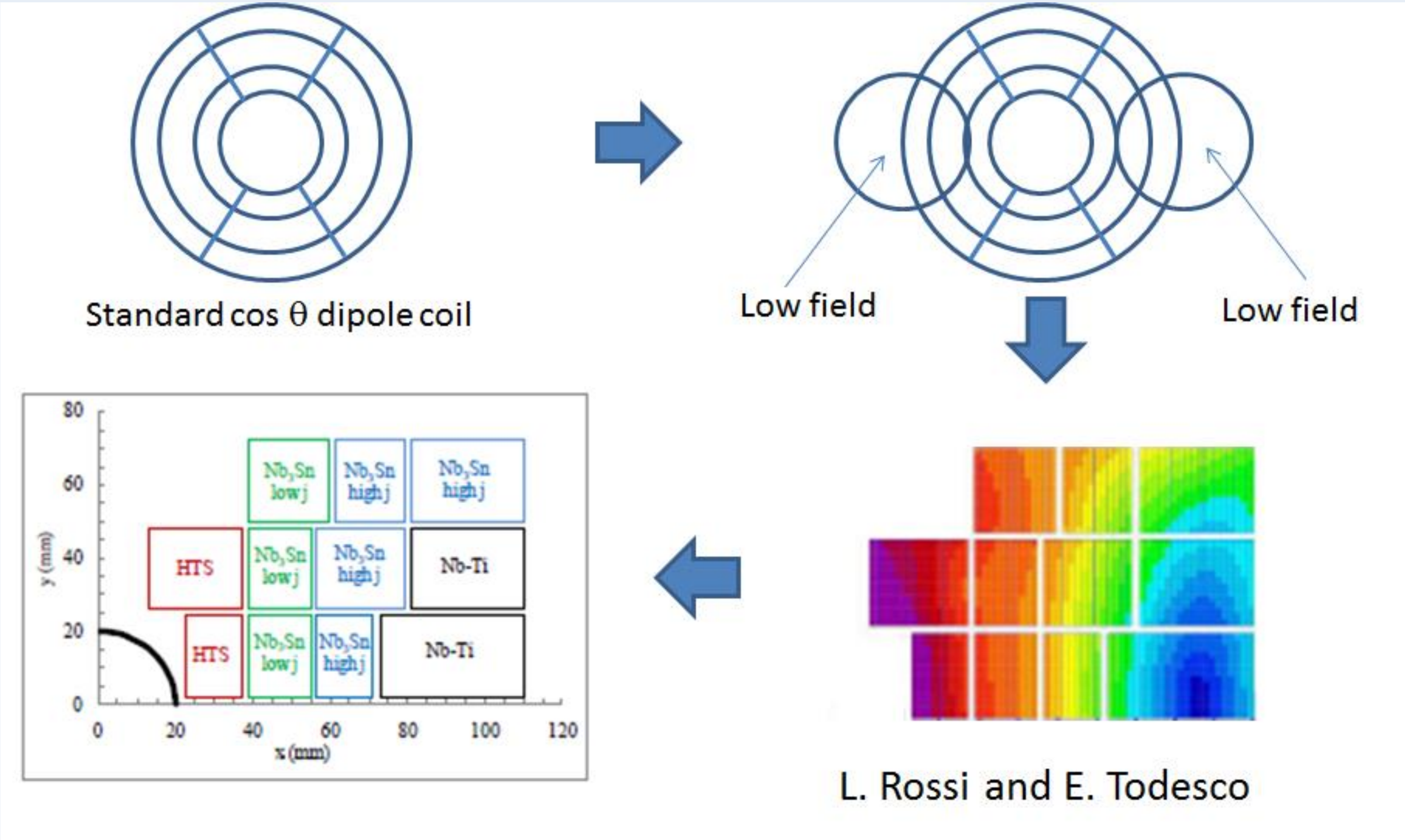
Field of Nb_3Sn dipole magnets



Plot courtesy of A. Godeke, LBNL

High-field magnets

Graded-block design



20 T for 100 TeV in 80 km

Cosine theta type magnet, **Nb-Ti** and **Nb_3Sn** and **HTS** insert. Bore Φ = 40 mm

20 T magnet in 80 km tunnel					
	Width (mm)	Average radius (mm)	Overall Jc (A/mm2)	Strand Jc (eng) (A/mm2)	Conductor mass (t)
HTS layer	25	32.5	231	600	1409
10 mm collar					
Nb_3Sn layer 1	20	65	193	386	2930
Nb_3Sn layer 2	20	85	385	770	3685
20 mm collar					
Nb-Ti layer 1	15	122.5	337	523	5275
Nb-Ti layer 2	15	137.5	433	672	5925

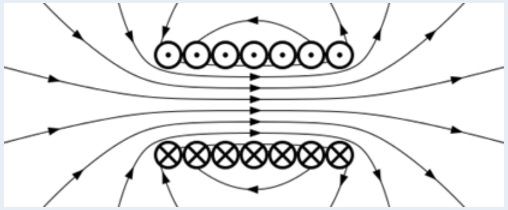
1400 tons of HTS + 6600 tons Nb_3Sn + 11300 tons of Nb-Ti

~13 times Nb_3Sn for ITER ~10 times Nb-Ti for LHC

HTS High-field magnets

HTS Solenoids to provide focusing

- Very high fields (> 30 T, hybrid, LHe operation)
  Next generation of high resolution NMR
- REBCO tape well-suited. It is wound in pancakes with stainless steel for both insulation control of the large hoop (and radial) stresses



Conductor considerations:

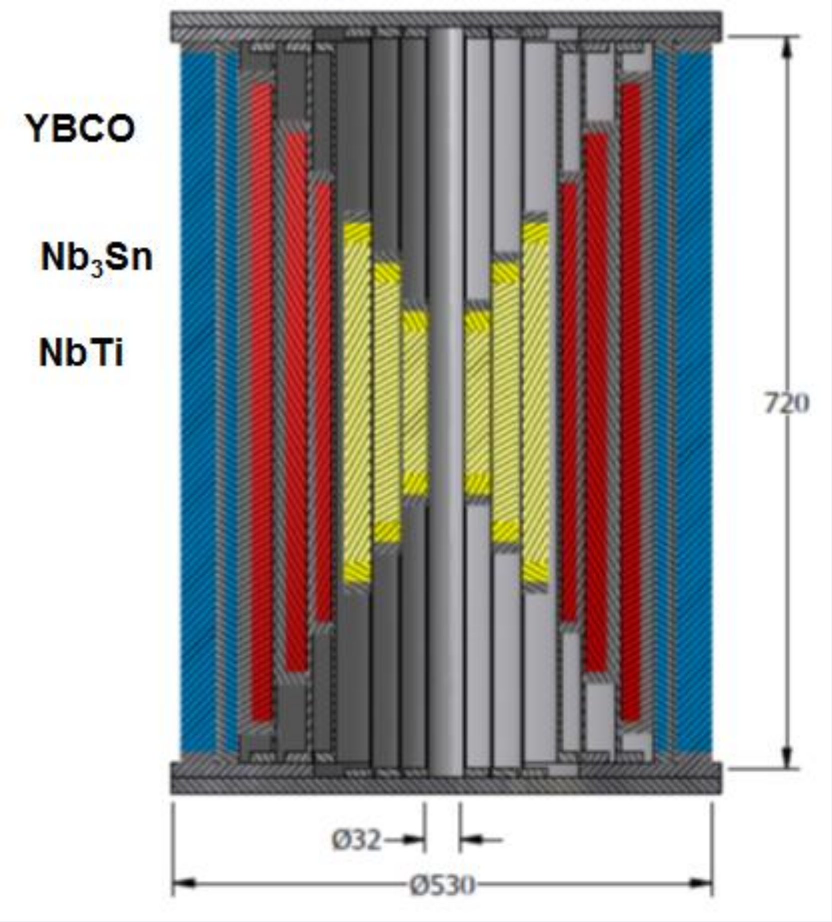
(+) Field parallel to the tape plane

(+) Mechanical reinforcement to mitigate radial forces

HTS High-field magnets

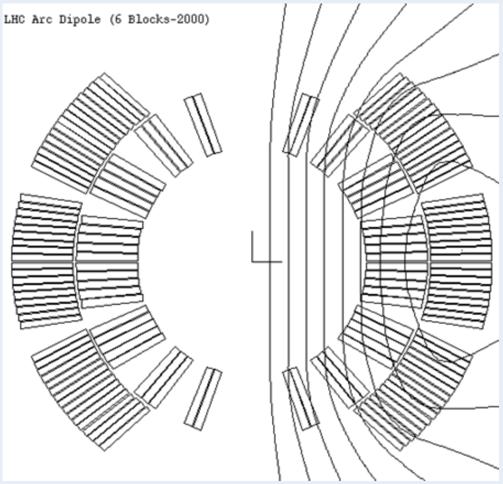
32 T User magnet at NHMFL

Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Current	186 A
Inductance	436 H
Stored Energy	7.54 MJ

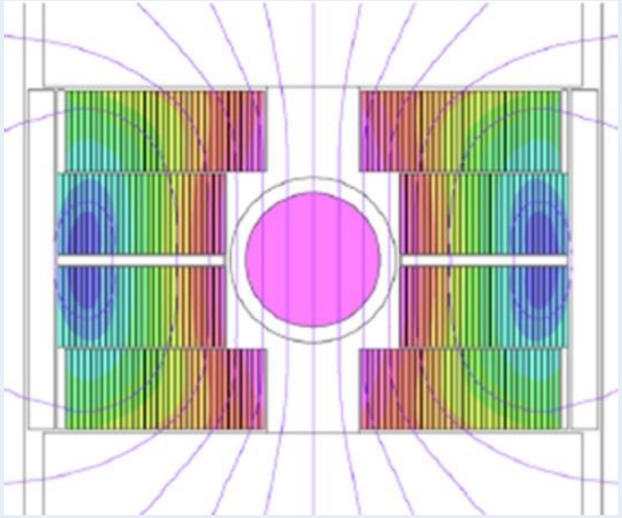


HTS High-field magnets

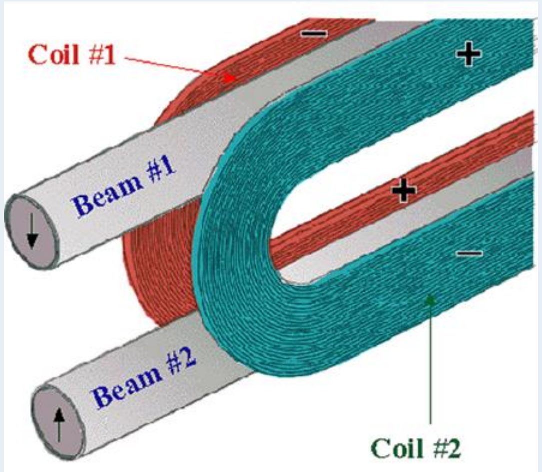
Cosϑ - LHC Dipole



Block design



Common-coil design (R. Gupta, BNL)



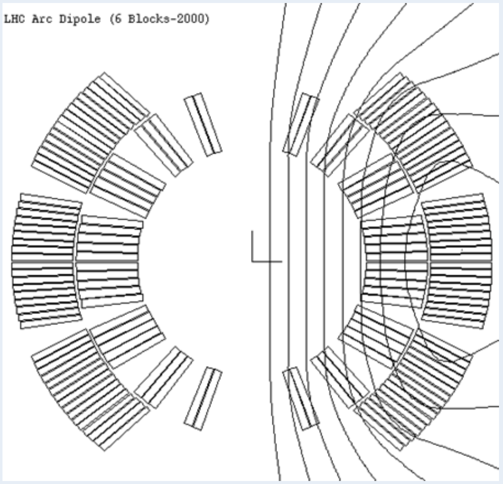
Field direction →
Isotropic conductor

Field direction →
REBCO tape
Stress easier to manage

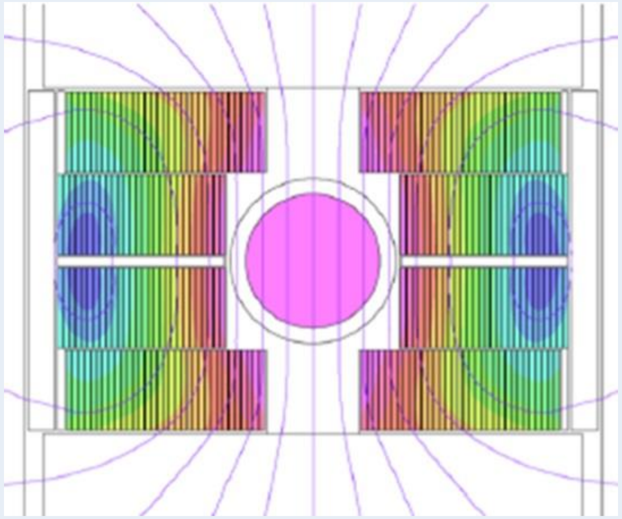
Field direction →
Isotropic conductor

HTS High-field magnets

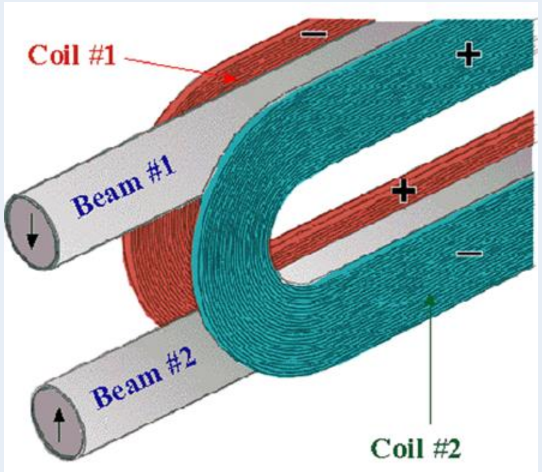
Cosϑ - LHC Dipole



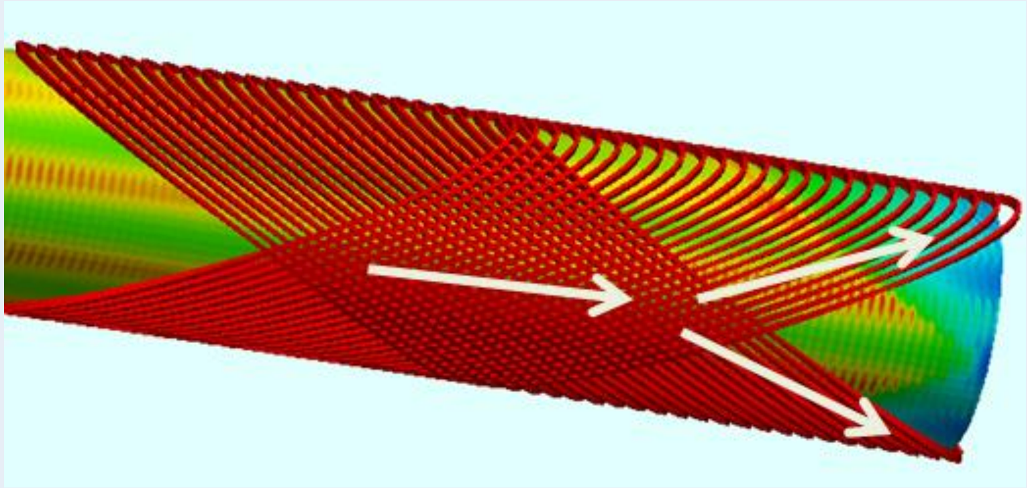
Block design

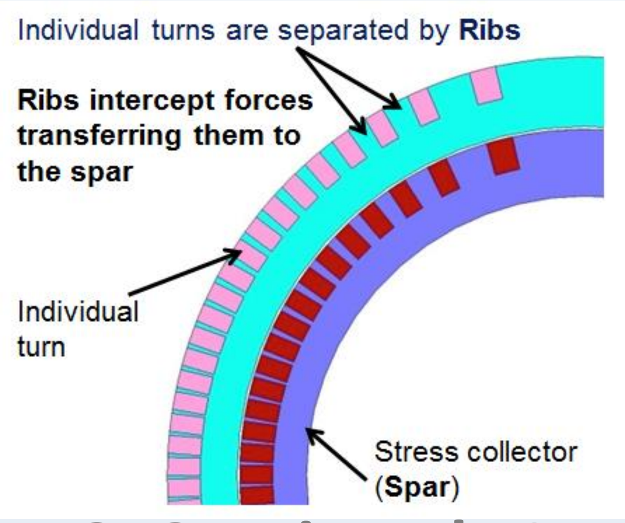


Common-coil design



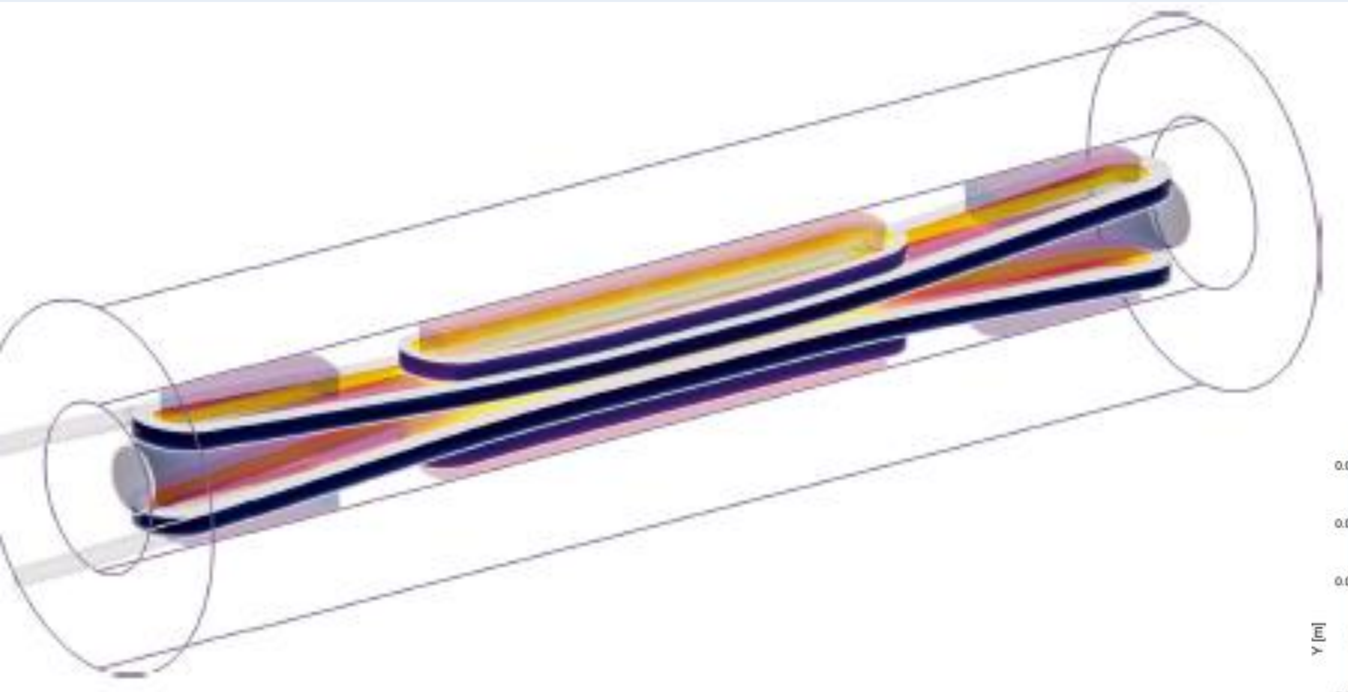
Canted Cosϑ Dipole





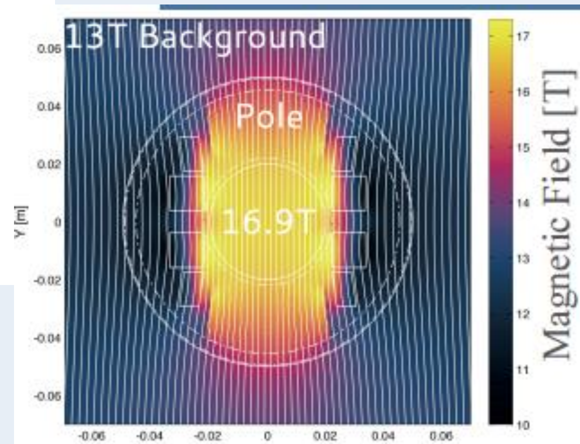
Stress interception and management, S. Caspi et al., LBNL

HTS Aligned coil block design

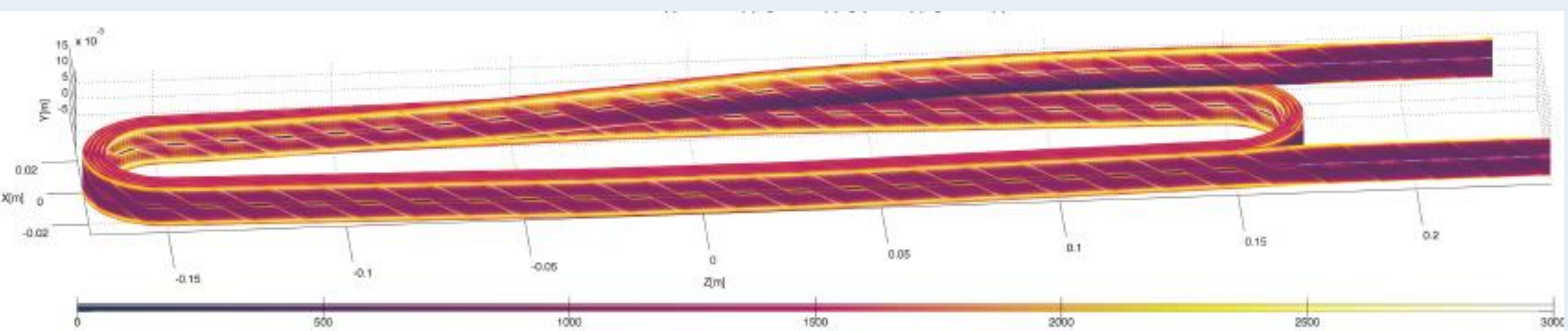


Aperture = 40 mm

5 T in a background field of 15 T



J. Van Nugteren and G. Kirby, CERN, Eucard 2



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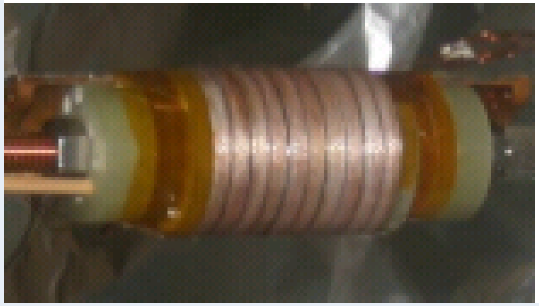
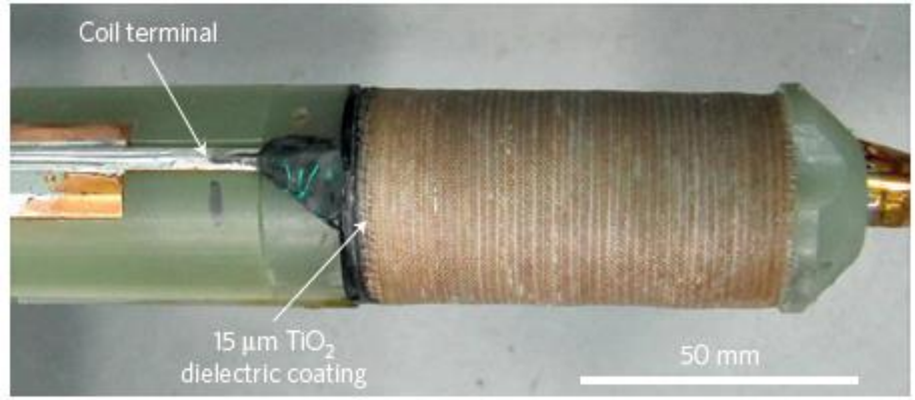
HTS Coils Demonstrators

33.8 T, REBCO, NHMFL

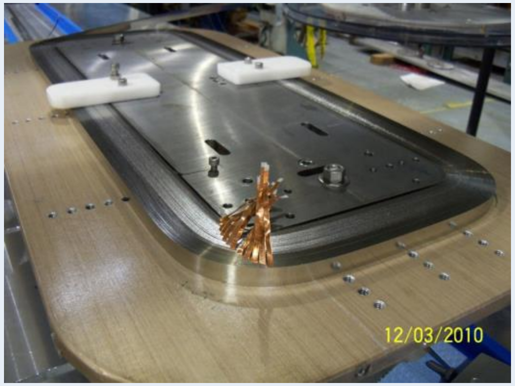


REBCO coil
2.8 T in background field of 31 T
H.. W. Weijers et. al, 2008

33.8 T, BSCCO 2212, NHMFL



BSCCO 2212 coil, heat treatment at 10 bar
2.6 T in background field of 31.2 T
D. Larbalestier et al, NMAT 3887



REBCO and BSCCO 2223 coils
R. Gupta et al., BNL

BSCCO 2212 coil from Rutherford cable
A. Godeke et al, 2010

- Introduction
- HTS Conductors
  - State of the art development
  - Conductor choices for high fields
  - HTS cables
- Application to high field magnets
  - HTS Magnet design aspects
  - Coils demonstration
  - Developments for a viable HTS technology
- Conclusions

Quench protection

Low quench propagation

- **Quench <u>detection</u>**

  Sensitive systems to detect in the 10-20 mV range

- **Quench <u>protection</u>**

  Fast propagation of resistive zone

Technologies to be developed

Need for mastering technologies for coil fabrication with HTS materials:

- **Electrical insulation techniques**
- **Electrical joints techniques**
- **Winding techniques**
- **For BSCCO 2212: high pressure on coils during high temperature heat treatment - Wind & React technology**

Conclusions (1/3)

- **HTS Conductors are available today with characteristics that make them suitable for use in high field magnets**

- **Demonstration coils show capability. There is a clear route to boosting solenoids to > 30 T, and work is on going to find a route to use in dipole magnets**

Conclusions (2/3)

- Differences with classical LTS conductors are such that the use of HTS materials in high field magnets requires a major **rethink of existing technology** and mode of operation

- **Prototype coils** shall be made in order to to learn about HTS performance in magnets

- HTS conductors are presently **expensive**. A large application (like MRI for Nb-Ti) would be required to justify boosting production to a level that would enable significant cost reduction

Conclusions (3/3)

- More recent conductors are potentially more affordable than those presently available, but a determined R&D effort is needed to boost the performance to a level that would be useful for improving the field in a high field magnet

A magnet can never perform better than the conductor it is made of

Thanks for your attention