WAMSDO

CERN, 19 - 23 May 2008

Advances in HTS materials

Pascal Tixador
Grenoble INP / Institut Néel-G2Elab

Preamble

- "The how & why of high field SC solenoids"
  - J. Schwartz MT 20 plenary talk

- Thanks to:
  - A. Usoskin, EHTS
  - M. Rickel, A. Allais, Nexans
  - Grenoble colleagues

Outline

- Limitations of LTS, HTS abilities
- HTS: key points
- BiSrCaCuO PIT 1G wires
- YBaCuO Coated Conductors 2G wires
- HTS insert magnets
- Conclusions

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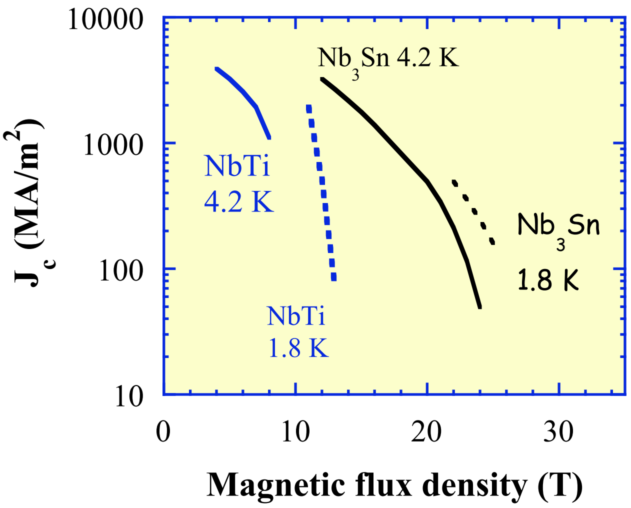
Introduction: limitations of LTS

- $J_c(B)$



Upper limit of "classical" LTS: ≈ 23 T

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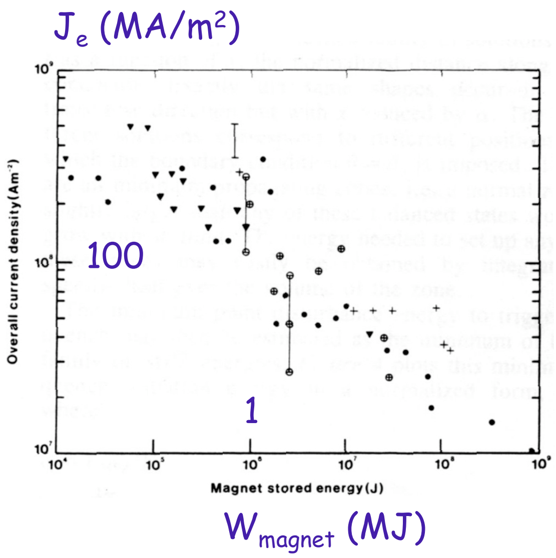
Limitations of LTS

• Other limitations

Two other limitations:
- stability
- protection



M. Wilson, Cryogenics, **31**, 499

Limitations of LTS

• Stability

$$MQE = H(T_{cs}) - H(T_o) \quad (adiabatic)$$

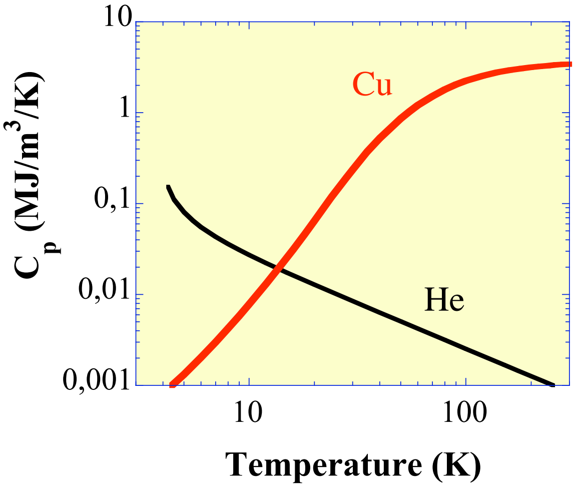
$$MQE \approx c_p(T_o)\left(T_c^*(B) - T_o\right)\left(1 - \frac{I}{I_c}\right)$$

=> Low for LTS

Limitations of LTS

- **Stability**

$$MQE \approx c_p(T_o)\left(T_c^*(B)-T_o\right)\left(1-\frac{I}{I_c}\right)$$



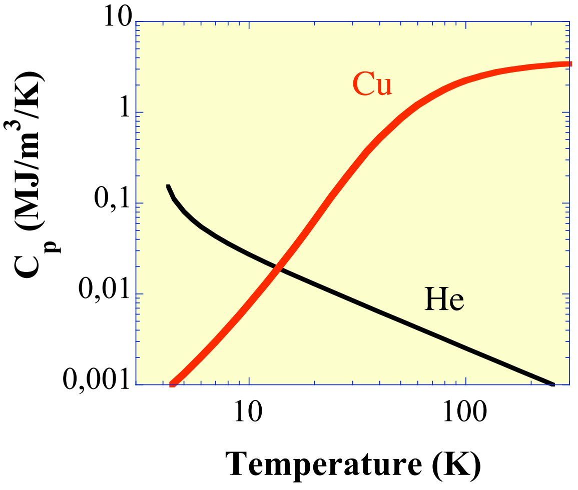
Stability increases with temperature

Helium: interest decreases with temperature

Limitations of LTS

- **Protection**

$$v_p \approx \frac{J}{c_p}\sqrt{\frac{\rho_n \lambda}{T_f - T_o}}$$



Protection not a real issue for LTS but could be for HTS

LTS limitations: summary

- $J_c(B)$
- Stability
- Protection

High demands for very high field (25, 30, 50 T) superconducting magnets (NMR, high energy physics, …)

Not possible with LTS

? HTS ?

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High field magnets

Mechanics becomes more & more difficult with increasing fields

$$\sigma \approx J\ B\ R \quad (solenoid)$$

$$J = 100\ MA/m^2\ ;\ B = 20\ T\ ;\ R = 50\ mm : \sigma = 100\ MPa$$

$$\Rightarrow \begin{cases} \sigma_c \\ \varepsilon_c \end{cases} \quad high$$

$$\sigma_c = \sigma\left(I_c = 0.95\ I_c(\sigma = 0)\right)$$

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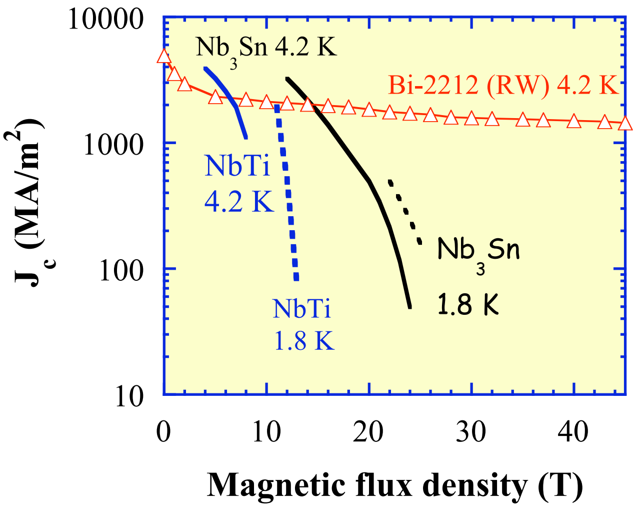
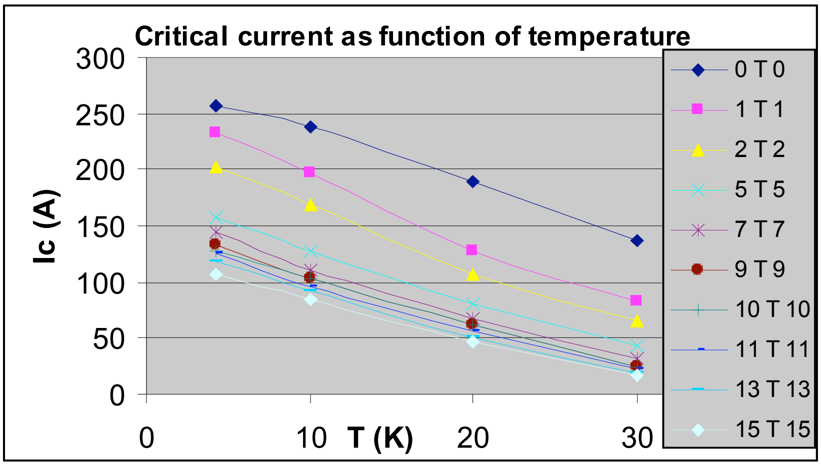
J_c(B) - LTS / HTS



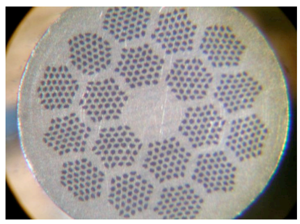
Very high interest for HTS
(@ low temperature)

J_c(B, T) Nexans

- Temperature influence



Nexans
Round wire
Bi-2212



Courtesy from J.M. Rey (CEA-IRFU)

HTS for high field magnets

$J_c(B, T)$

Stability (MQE (T_o + (T_c-T_o)))

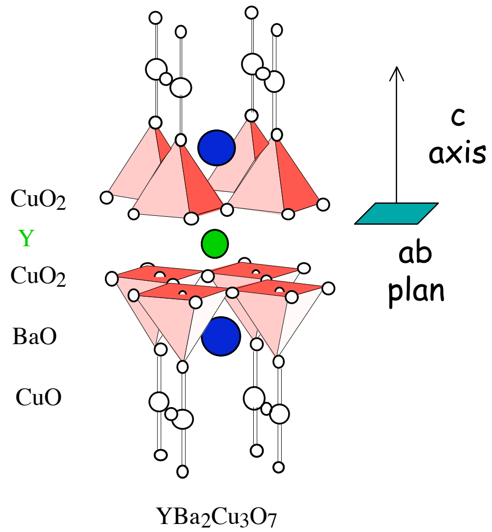
Protection

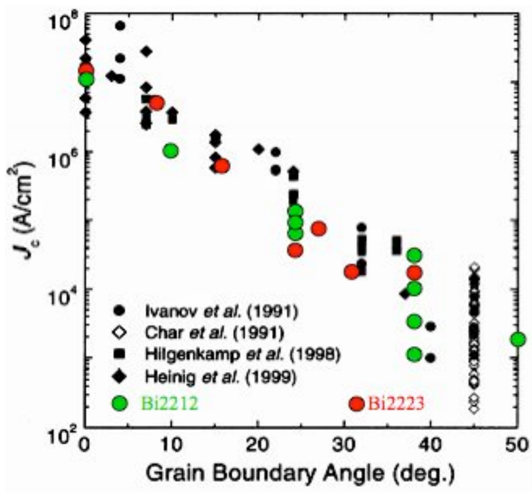
Mechanics (HTS: brittle ceramics)

$$\sigma_c^{int} = some\ tens\ MPa\ (20\ MPa)$$

HTS materials
Key points

Grain alignment is one key



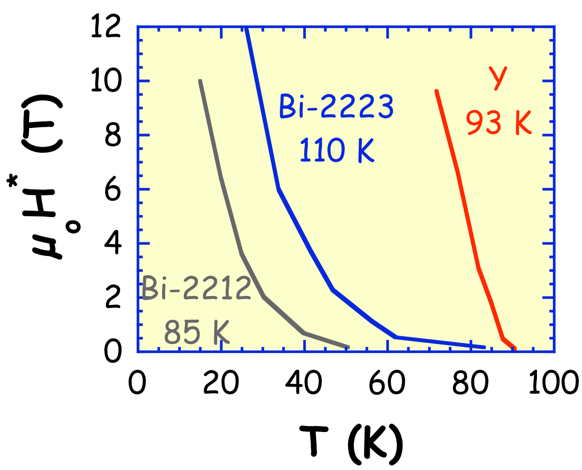


Architectures to provide the texturation on infinite lengths

Make a infinite length single crystal and flexible, robust ….

Irreversibility field

H* : relevant field for applications

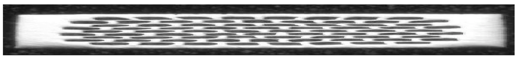


Bi:
- T < 30-35 K

Y:
- T < 60-70 K

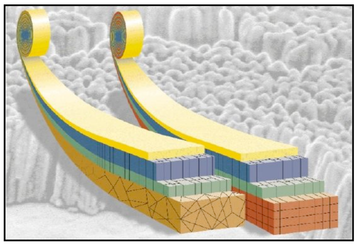
HTS wires

1 G (BiSrCaCuO)
PIT wires & tapes



- Km lengths
- Metallurgical process
- Cost (Ag (O_2 perm.))
- H*(T)

2 G (YBaCuO)
Coated Conductors



Siemens

- 100 m lengths
- Thin film technology
- H*(T)
- Potential low cost

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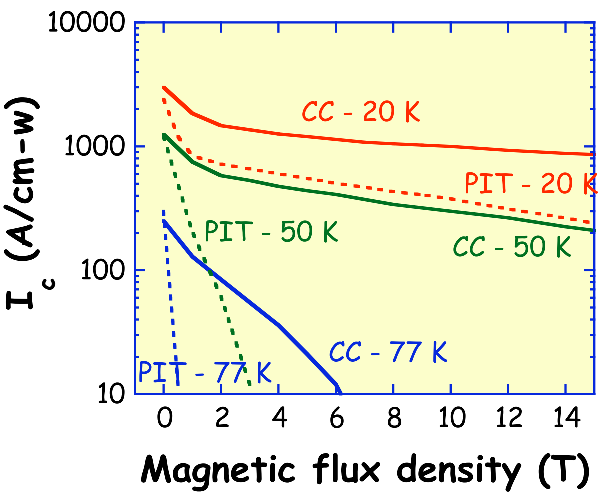
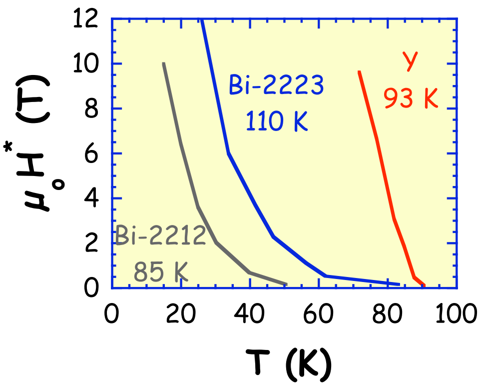
Critical characteristics





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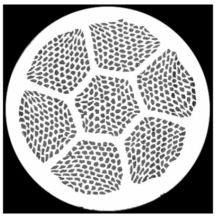
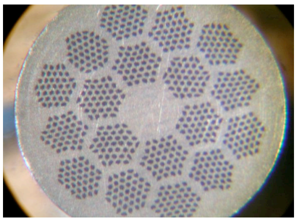
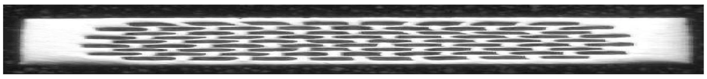
BiSrCaCuO PIT 1G wires

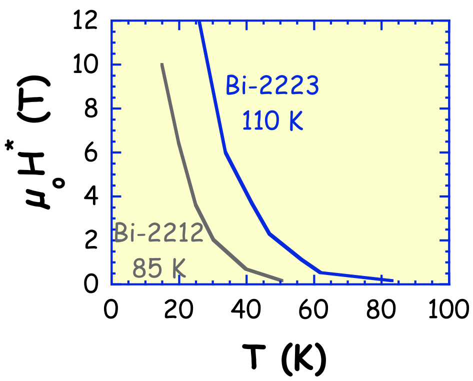


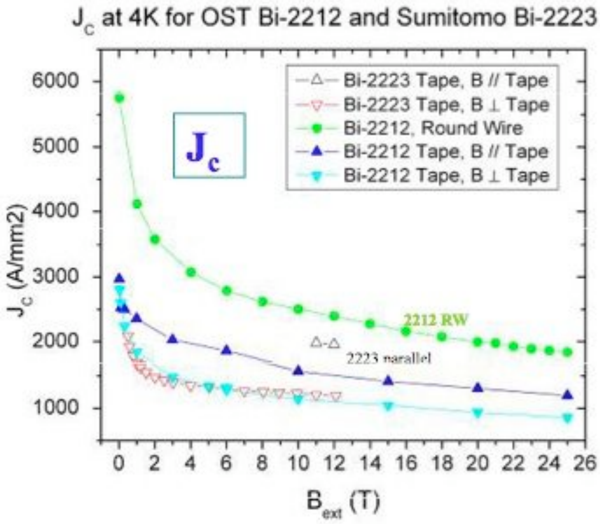




1G: BiSrCaCuO PIT

- $Bi_2Sr_2CaCu_2O$ (Bi-2212)
- $Bi_2Sr_2Ca_2Cu_3O$ (Bi-2223)



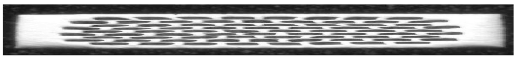


D. Larbalestier

T < 20 K $J_c(B)_{Bi-2212} > J_c(B)_{Bi-2223}$

Bi-2212 still not well understood.

1G: BiSrCaCuO PIT



Bi-2212 / Bi-2223

- ✓ Bi-2212: R & W or W & R
- ✓ Bi-2223: R & W

Shape not ideal

- Anisotropic
- AC loss (B_{tr})
- High I cables

Siemens

Bi-2212

Better shape

- Isotropic
- AC losses
- Rutherford
- CIC

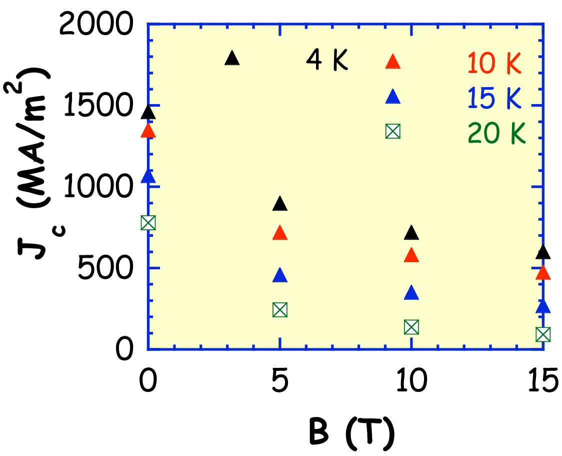
✓ Bi-2222: R & W or W & R

Bi-2212 round wire shows very high J_c

Bi-2212 round wire for high field magnets

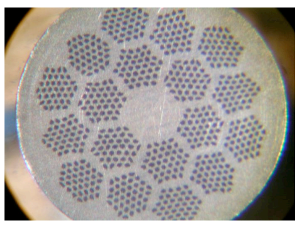
J_c(B, T)

Nexans



Courtesy from J.M. Rey (CEA-IRFU)

Nexans Round wire Bi-2212



Ø = 0.8 mm
SC: 10 %

Bi-2212 Rutherford cables Nexans

Ø = 0.8 mm

- I_c^{max} = 398 A (4.2 K, 0 T)
- I_c^{ave} = 244 A (4.2 K, 0 T)
- J_e^{max} = 790 MA/m² (4.2 K, 0 T)
- J_c^{max} = 2 940 MA/m² (4.2 K, 0 T)

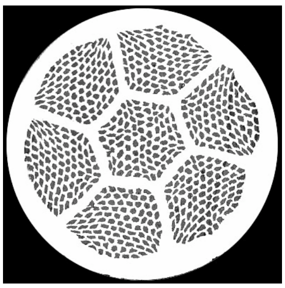
Nexans
Korea
Courtesy
A. Allais

20 strand Rutherford cable I_c > 3 000 A @ 4.2 K

30 strand Rutherford cable I_c > 4 000 A @ 4.2 K

J_c(B, T)

OXFORD INSTRUMENTS

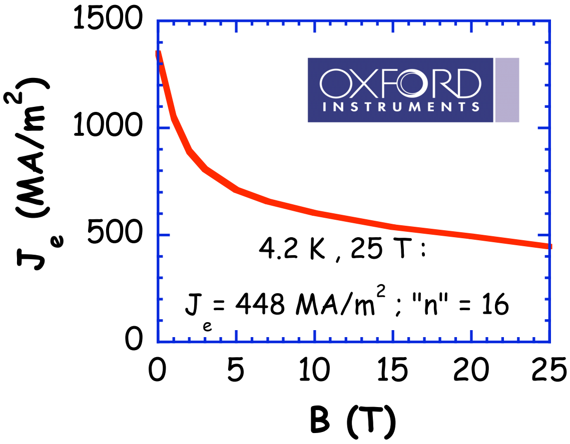


Ø = 0.8 mm
(Nexans powder)

J_e not J_c

J_c (0 T, 4.2 K) = 4800 MA/m²
J_c (25 T, 4.2 K) = 1600 MA/m²

OST 2212 Wire (Billet PMM030224)
Ø = 0.8 mm, SC : 28 %
J_e normalized to total cross section

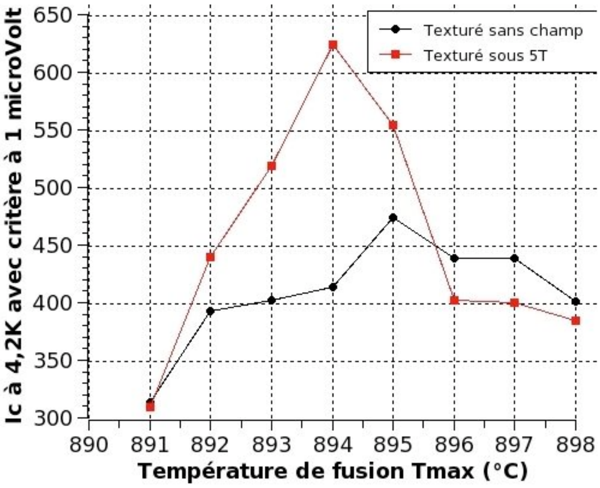


A. Vostner
(EFDA meeting, Barcelona 8-9 May 2007)

Still a lot of works

Bi-2212 still not well understood.

Possible improvement: under field elaboration

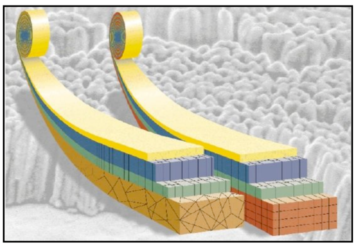


I_c

+ 40 %

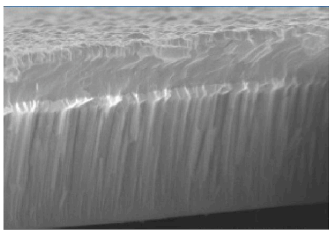
Courtesy from L. Porcar, CNRS-IN

YBaCuO Coated Conductor 2G wires



Siemens

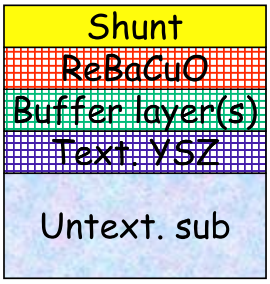
Theva



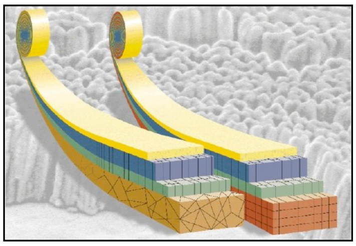
Theva

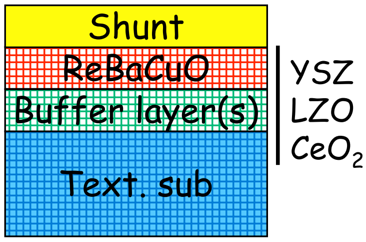
YBCO CC key : hyper texturation

- Two main routes
  - Textured substrate (RABiTS)
    - Ni alloys (mech. deform. (rolling) and annealing)
  - Layer texturation above a substrate (IBAD)
    - YSZ textured by ion beam above SS



Ion Beam Assisted Deposition

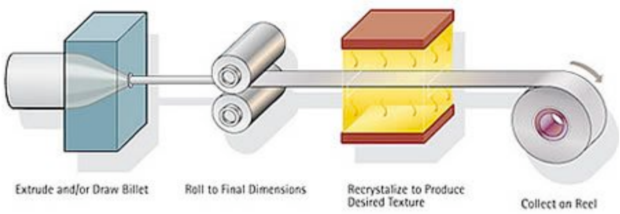




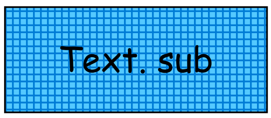
Rolling Assisted Biaxially Textured Substrates

YBCO CC key : hyper texturation

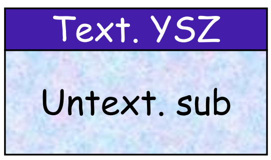
Rolling Assisted Biaxially Textured Substrates



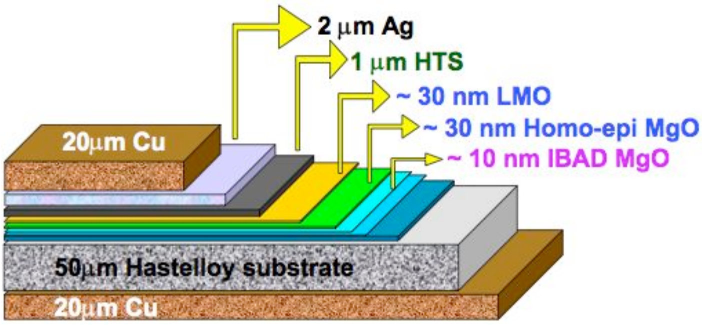
Substrate:
- Rolling
- Annealing
- Electropolishing

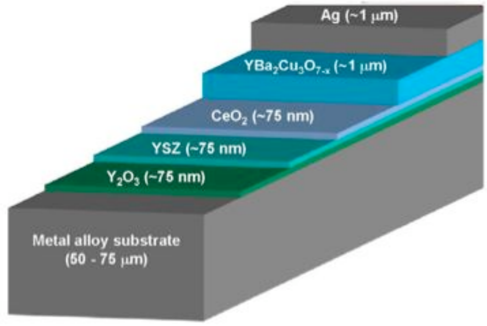


Ion Beam Assisted Deposition



Two examples





SuperPower Inc.

790 m, 190 A/cm-w
(World record, sept. 07)

American Superconductor

94 m, 350 A/cm-w
Pilot line (720 km/year)

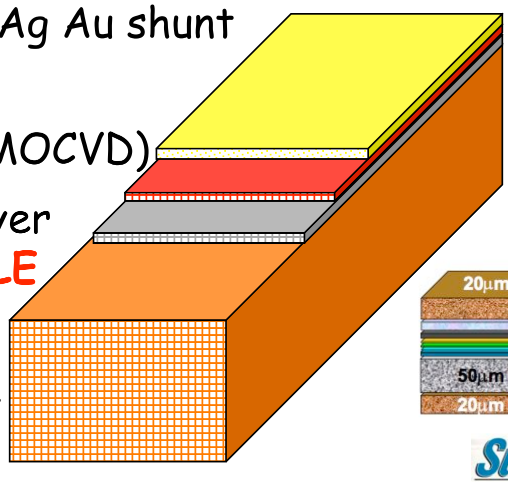
Simpliest architecture

Ag Au shunt

YBaCuO layer (MOCVD)

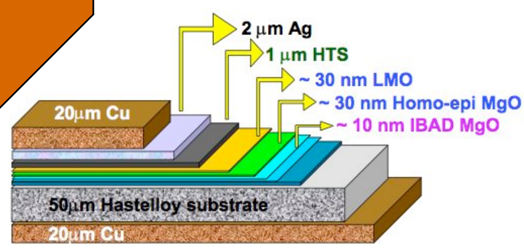
LZO buffer layer (MOD) **SINGLE**

NiW substrate



MADISUP ANR project

(IN, LMPG, CRETA Grenoble)



SuperPower Inc. IBAD

J_c = 8000 MA/m^2 (77 K, 0 T)
(short sample)

T. Caroff and al., SUST, 21 (2008)

Very promising result
Low cost conductor

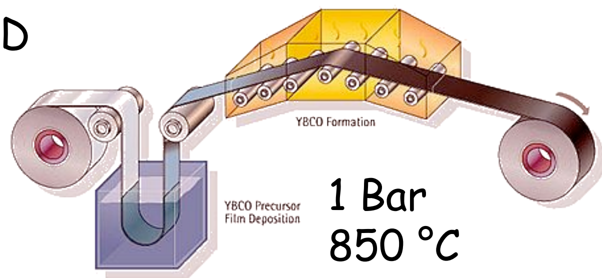
Coating methods

- Physical coating: very effective, expensive
  - PLD : Pulsed Laser Deposition
  - Thermal evaporation
  - Sputtering
- Chemical coating: delicate, lower cost (pres. mat. velocity)
  - MOD : Metal Organic Deposition
  - MOCVD : Metal Organic Chemical Vapor Deposition
  - Spray pyrolysis

All chemical method route very promising for cost

Chemical low cost route

MOD

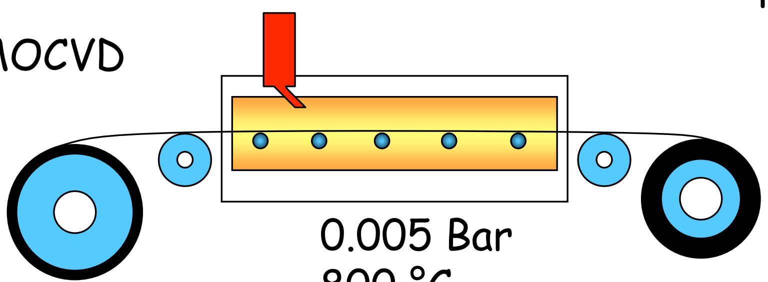


1 Bar
850 °C

+ Shunt deposition

Annealing (Oxygenation)

MOCVD

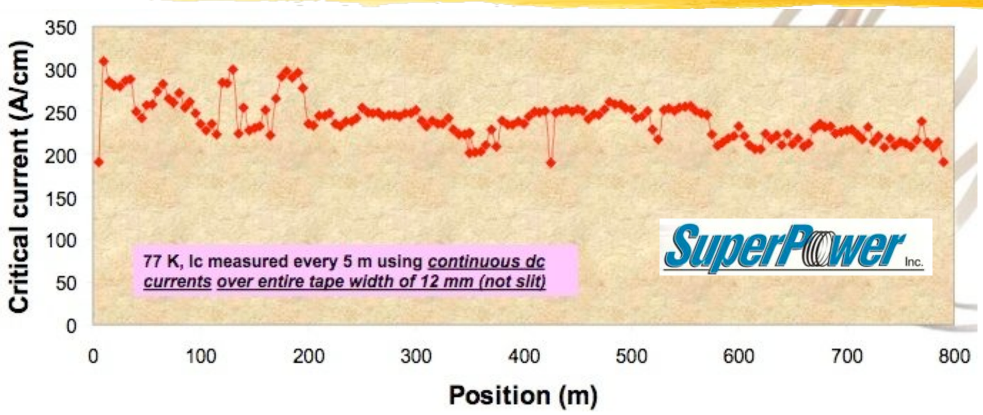


0.005 Bar
800 °C

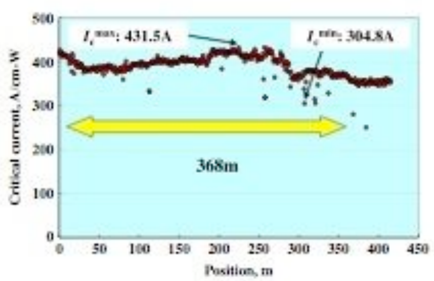
CC main state of the art

Company	Country	Conducteur architecture	Short samples		Long lengths		
			I_c (A/cm)	J_c (MA/cm^2)	I_c (A/cm)	Length (m)	I_c*L (A/m)
Fujikura	Japon	$GdBCO_{PLD}/CeO_{2PLD}/GZO_{IBAD}$	540	2.2	305	368	112 166
SRL-ISTEC	Japon	$YBCO_{MOCVD}/CeO_{2PLD}/GZO_{IBAD}$	480	1.2	213	245	52 185
		$YBCO_{MOD}/CeO_{2PLD}/GZO_{IBAD}$	735	2.4	250	56	14 000
SuperPower -inc	USA	$YBCO_{MOCVD}/LMO_{PLD}/MgO_{PLD}/MgO_{IBAD}$	721	2.2	190	790	150 100
					362	103	37 284
AMSC	USA	$YBCO_{MOD}/CeO_{2PLD}/YSZ_{PLD}/Y_2O_{3\ PLD}/NiW_{RABiTS}$	560	4	400	94	32 900
EHTS	Germany	$YBCO_{PLD}/CeO_{2PLD}/YSZ_{IBAD}$	574	3.6	253	100	25 300

CC main state of the art

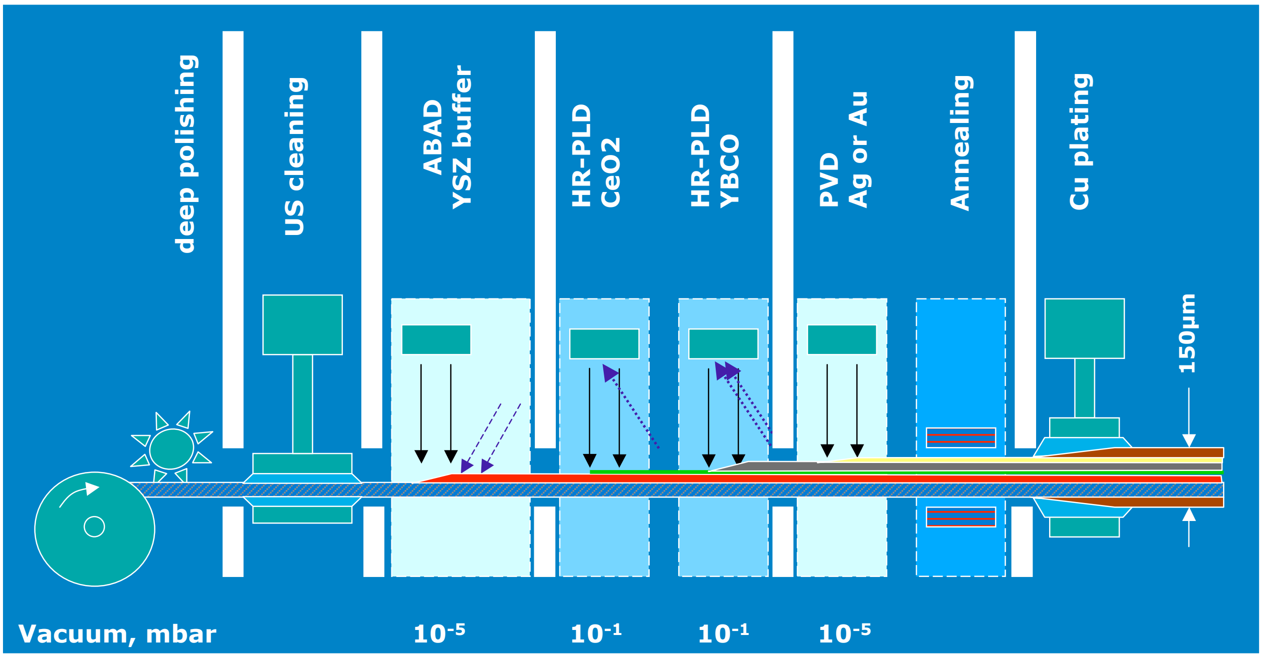


790 m
190 A/cm-w



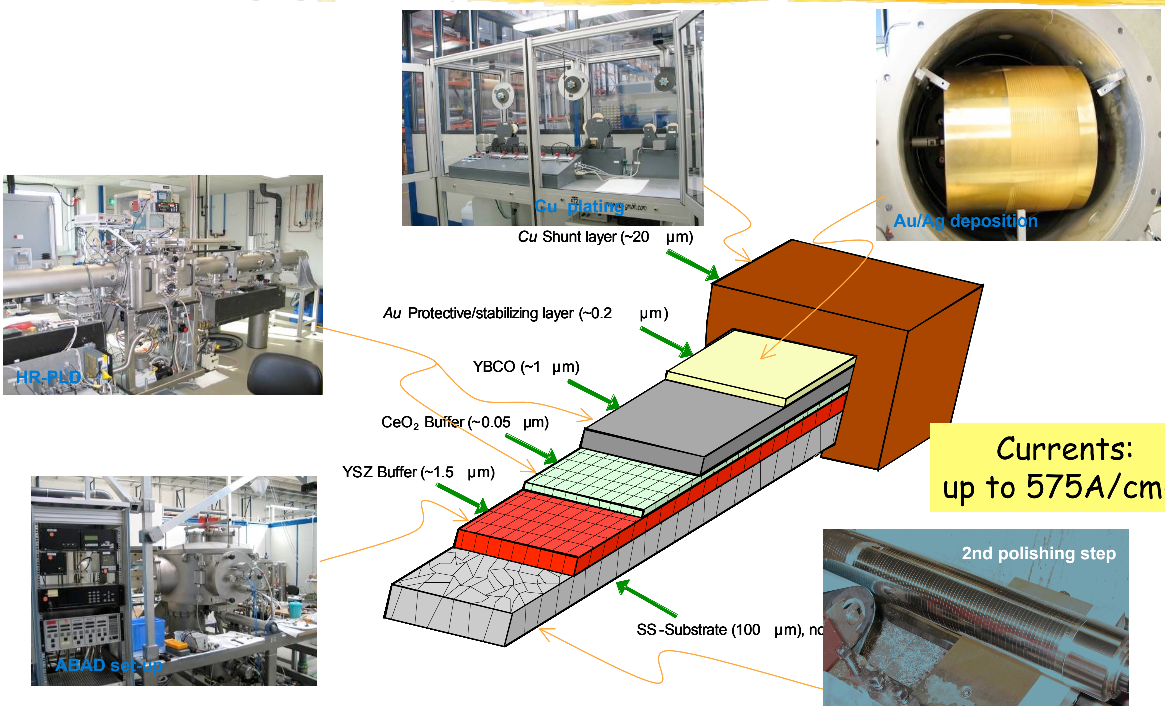
368 m
350 A/cm-w
Fujikura group

EHTS CC processing route



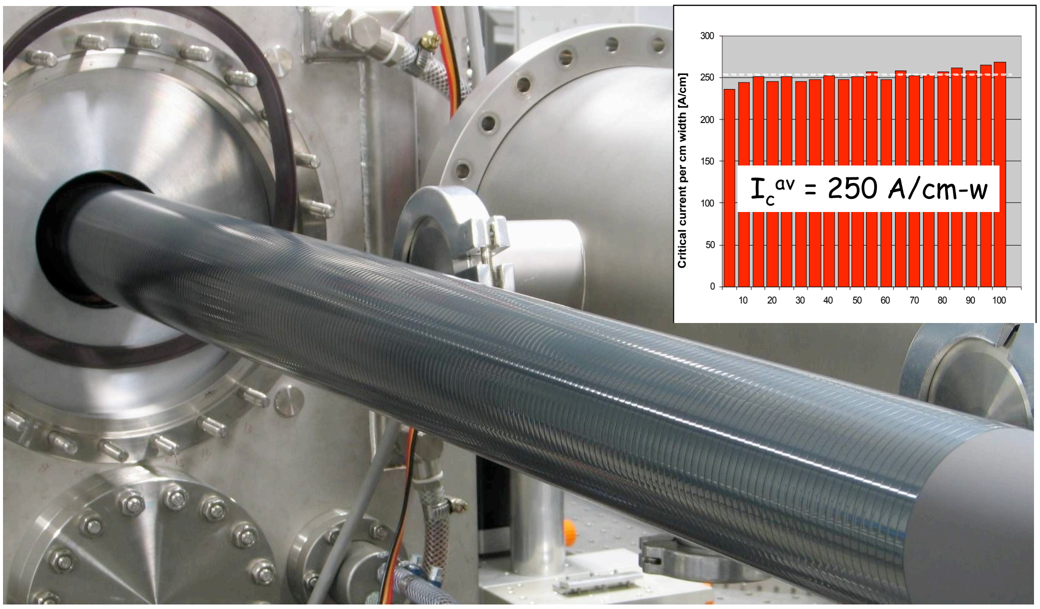
Courtesy from A. Usoskin, EHTS

EHTS - YBCO CC process

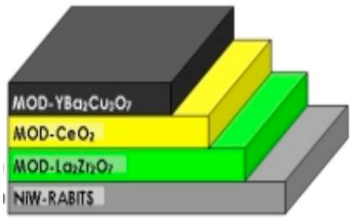


Currents:
up to 575A/cm-w

EHTS - 100 m YBCO CC



Nexans CC developments



Goals and Strategy

- Excellent performance-to-price ratio
  - Simplest architecture
  - All Chemical Solution Deposition process

Cooperation

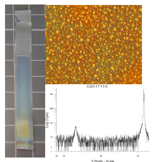
- NiW RABITS with Evico (Dresden), Grenoble INP
- MOD-LZO on NiW with ISC (Würzburg), IFW (Dresden), Grenoble INP
- MOD-CeO_2 on MOD/LZO-NiW with ISC (Würzburg), ICMAB (Barcelona)
- YBCO processes (ICMAB, UCAM, Uni Augsburg, Theva, IOT/PerCoTec)

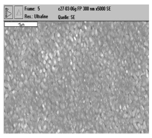
Courtesy from M. Rickel, Nexans

Nexans CC current status

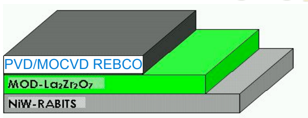
- MOD-LZO on NiW:
  - Up to 10 m long high-quality tape pieces routinely produced
  - Upscaling to 50 m length ongoing

- MOD-$(Ce,Gd)O_2$ on MOD-LZO/NiW
  - conditions for deposition on the lab scale
- REBCO process established:
  - MOD-TFA for up to 1m lengths
  - e-beam (Theva) and MOCVD (PerCoTech) for up to 10 m
  - HLPE process (UCAM) on the lab scale





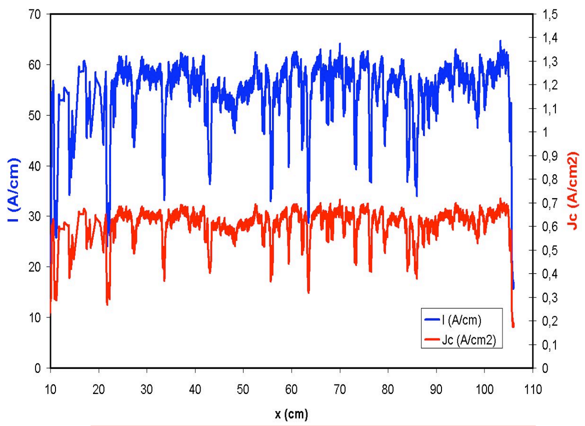
Nexans long length CC



Works with Theva and IOT/PerCoTech

THEVA: e-beam Process

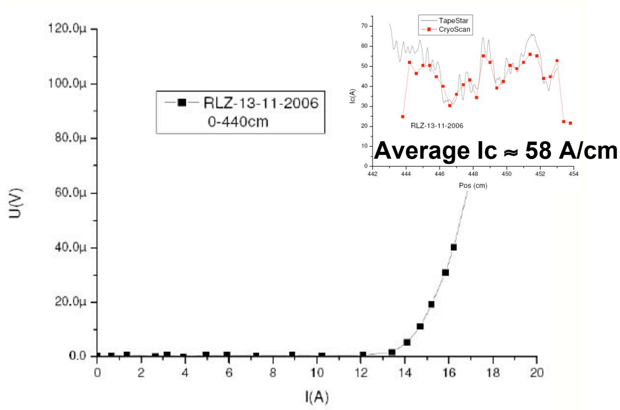
DyBCO (900nm) on 1 m longLZO(100 nm)/NiW



Average $I_c \approx 62$ A/cm-w

IOT/PerCoTech: MOCVD Process

YBCO (700 nm) on 4.4 m long LZO(100 nm)/NiW



End-to-end I_c = 21 A

Still a lot of works: J_c improv.

$J_c(B)$ is governed by vortex pinning

=> nano-scale (ξ) defects in the YBCO layer

=> thin film process induces many defects

Still far from the theoretical limit ($J_{depairing}$)

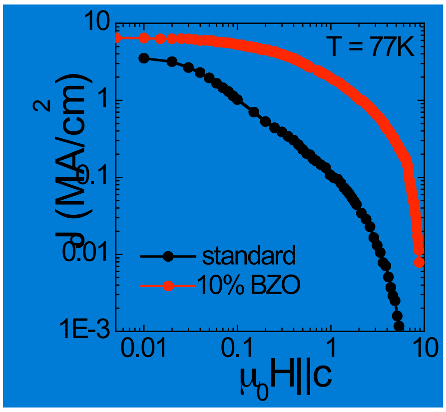
Find the right defect for vortex pinning.

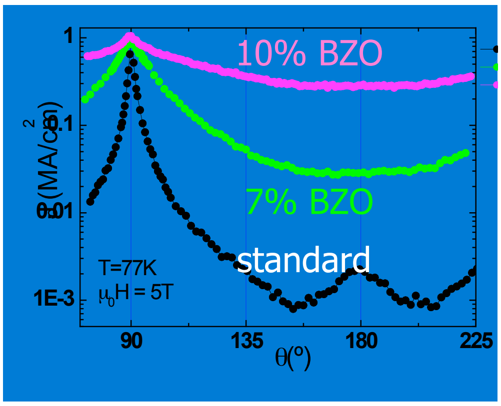
Some ways: nanodot

BZO-YBCO nanocomposites

Modification of the TFA precursor solution by addition of Ba and Zr salts

=> BZO nanodots





J_c(sf, 77K) = 6.5 MA/cm²

J_c(1T, 77K) = 2.2 MA/cm²

H_{irr} (77 K) = 10.7 T

Mechanical properties

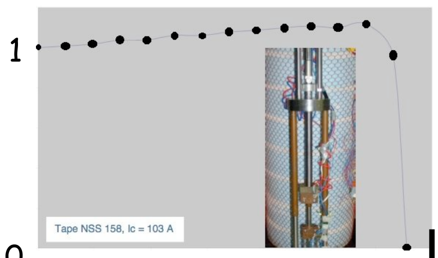
- HTS: brittle ceramic material (≈ 20 Mpa)
  - Mechanical reinforcement

1G: matrix (AgMg) & SS reinforcement

200 - 250 MPa

2G: substrate

- SS (600 MPa)



Courtesy A. Usoskin

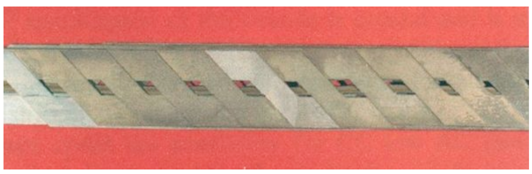
- NiW (200 MPa) composite substrate (350 MPa, AMSC)

HTS cables

- Need for high current cables
  - Round shape suits
    - Rutherford
    - CIC

  - Tape much more difficult
    - Roebel cables

Siemens



Courtesy from Goldacker, FzK

HTS magnets (insert)

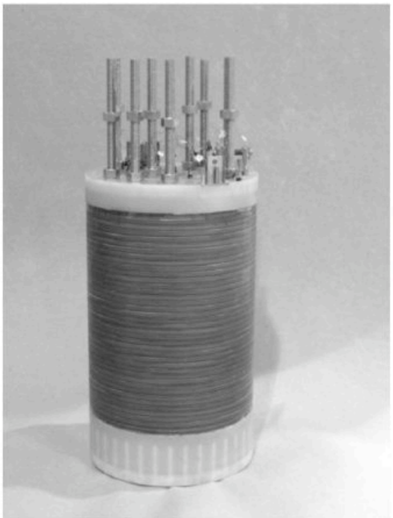
See tomorrow:
W & R Bi-2212 acc. Magnet technology
G. L. Sabbi

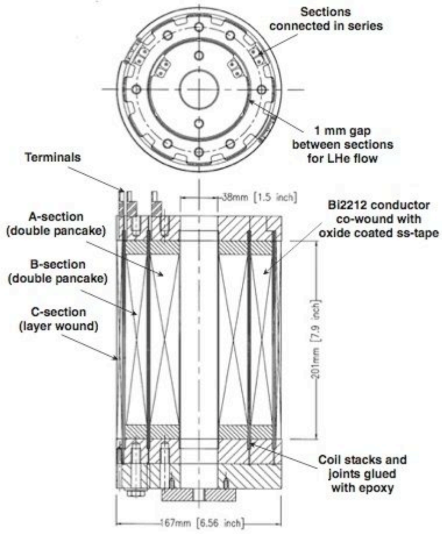
HTS magnets: key issues

- Protection : quench induces degradation
  - ✓ Key parameters: T_{max}, dT/dt, dT/dx
  - ✓ Detection (low v_p)
- Mechanics
  - ✓ Reinforcement

Bi-2212 insert magnets

Bi-2212 5 T insert coil at Tallahassee
25 T (5 T + 20 T)





$\varnothing_i$ = 38 mm

$\varnothing_e$ = 160 mm

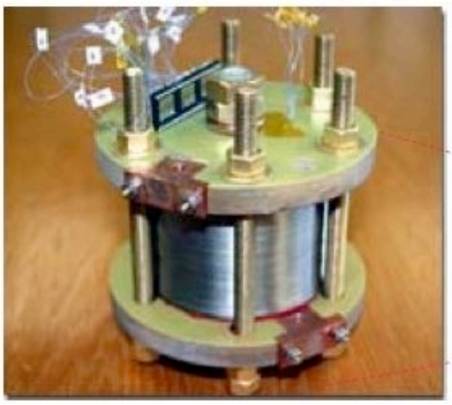
R & W tape

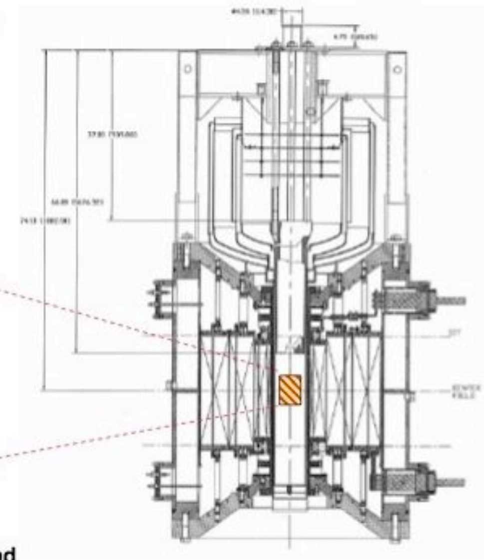
$J_{winding}$ = 90 A/mm^2

YBCO CC insert coil

SuperPower Inc.

Insert coil tested in NHMFL's unique, 19-tesla, 20-centimeter wide-bore, 20-megawatt Bitter magnet





2G HF insert coil showing terminals, overbanding and partial support structure. Flange OD is 127 mm.

B_e = 0 T: B_{YBCO} = 9.8 T ; B_e = 19 T: B_{YBCO} = 7.8 T (B_{tot} = 26.8 T)

Conclusions

- HTS show abilities for high field magnets
  - J_c(45 T, 4 K) > 1000 MA/m^2
  - MQE (T > 4K) higher / LTS
  - *Quench remains an issue*
- Bi-2212 round wire an excellent candidate
  - Improvement margins
  - Support required, niche appl. (single powder producer)
- Y-coated conductor another candidate
  - Mechanical performances (IBAD)
  - *Tape form not ideal* (round wire: holy grail (J. Schwartz))

Thank you!