HTS cables and conductors for high field magnets – a review

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- Motivation
- Magnets
- Overview of HTS wire and tapes
- Cable (conductors) for fusion magnets
- Cable for high field dipoles
- High field solenoids
- Summary

Motivation

Why superconducting magnet?

Despite the high cost of the superconducting material and the additional costs of cryostats and cooling systems, superconducting magnets are a cheaper alternative than resistive magnets, whose capital cost (power supply, water cooling) and running costs are larger than the one of superconducting magnets.

Why cable?

In large magnet (size >1 m) low inductance (large ampere/turn) are needed for fast ramping and dis-charging (limiting the quench voltages).

Upper limits to operating current (ampere/turn) is mainly the power supply cost and complexity.

Motivation

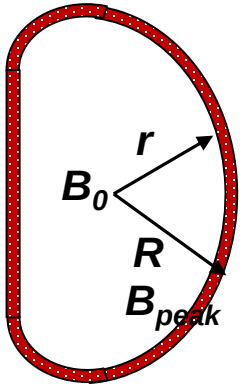
Why HTS for magnets?

OPPORTUNITIES	CHALLENGES
• **Higher operating temperatures** than LTS.	Cost balance: cryoplant and cryostat costs vs. conductor cost. Which coolant? LH? Cryogen free?
• **Higher operating field** than LTS.	Structural materials become quickly the limit, not $J_c(B)$. $BRJ_{eng}<\sigma_{critical}$
• **Cost**: today coated conductors are more expensive than LTS, but are much "younger" than Nb_3Sn and have large margin for improvements.	Will ever low-cost coated conductors be produced?

Background

The cable design is determined by the type of magnet.

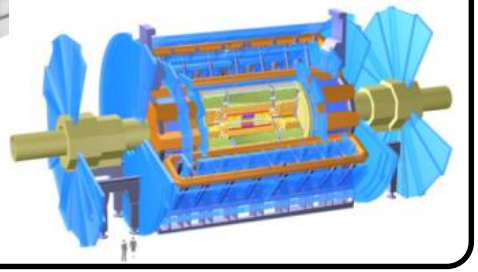
Fusion magnets



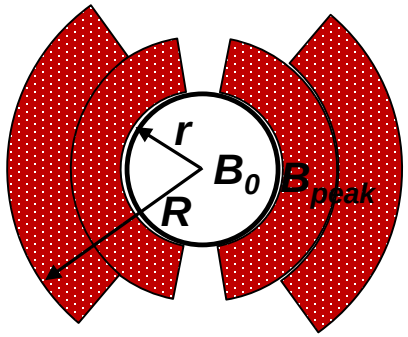
R/r ~ 1
Thin winding

Large bore
$B_{peak}/B_0 > 1$

Superconductor is far from the center ⇒ **J_{eng} is not important**



High field dipoles

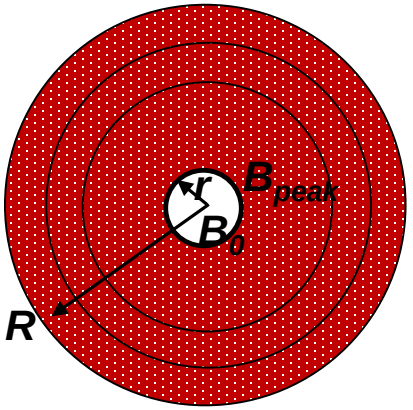


R/r >> 1
Thick winding

$B_{peak}/B_0 \sim 1$
Small bore

Superconductor is close to the center ⇒ **J_{eng} must be high**

High field solenoids



R/r >> 1
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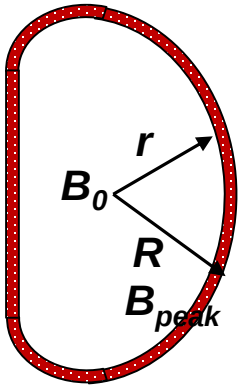
Fusion magnets



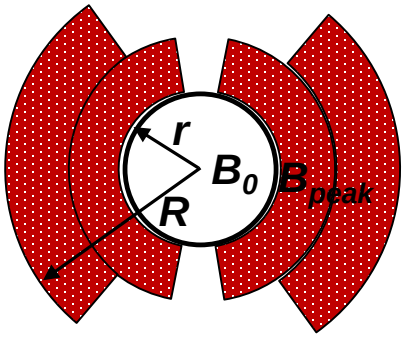
Beam bend. force
σ_{trans}=**BI**

Hoop force
σ=BIR

Steel can be distributed in the winding, low J_{eng} is tolerable.

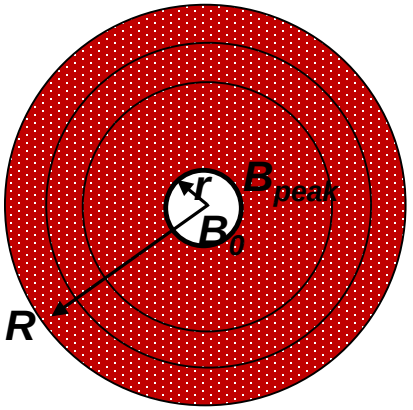
The mechanical structure should be dimensioned, for example, for 12 T even if the central field is only 5 T.

High field dipoles



Beam bend. force
σ_{trans}=**BI**

High field solenoids



Hoop force
σ=BIR

If reinforcement is distributed in the winding, J_{eng} goes down.

If the magnet is kept together from the outside, there is stress accumulation leading to large transverse pressure. For example σ_t<150 MPa for Nb_3Sn.

HTS tapes and wires overview: Bi based

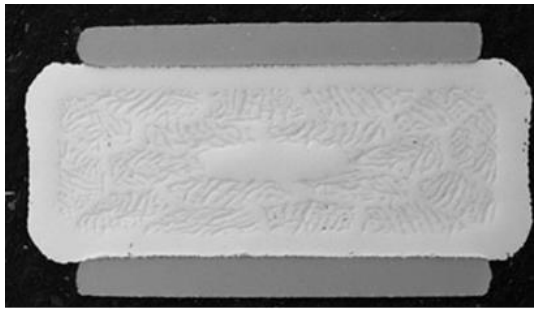
Bi2212 W&R

Bruker-OST is the only manufacturer of long wire (km). WST has R&D wires.

New producers of precursors in US: Metamateria, nGmat

Solid Material Solutions:

- High strength reinforcement (400 MPa)
- Hydrostatic drawing and high powder quality: high J_c even at 1 bar heat treatment.



20~25% f.f.

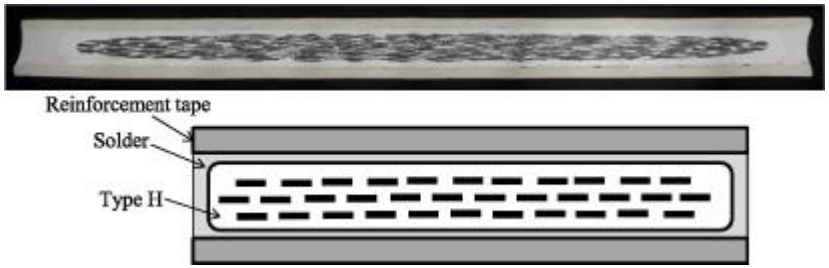
BI-BSSCO R&C&W

Sumitomo make long length (km), high J_c, high strength tapes:

- I_c(77 K)>200 A (80 A in the 90's)
- Tensile strength >450 MPa for Type HT-NX (120 MPa in the 90's)

A Godeke et al 2017 Supercond. Sci. Technol. 30 035011

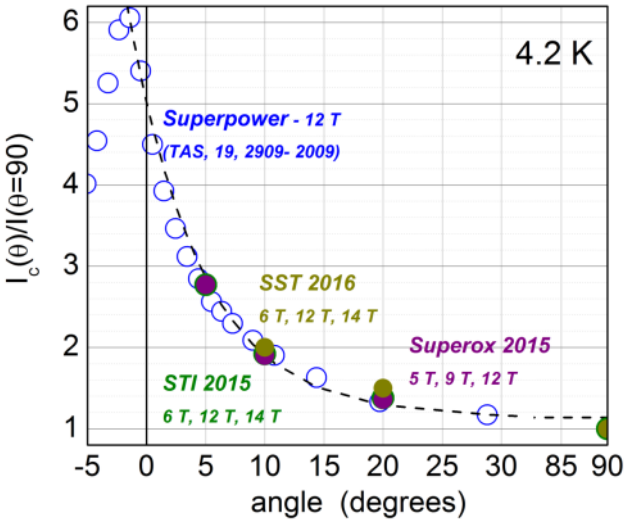
20~25% f.f.



COMMENT
Bi2223 was used in many power cables between 1995 and 2005. Today the I_c and tensile strength are much higher. It could be used for large high field magnets.

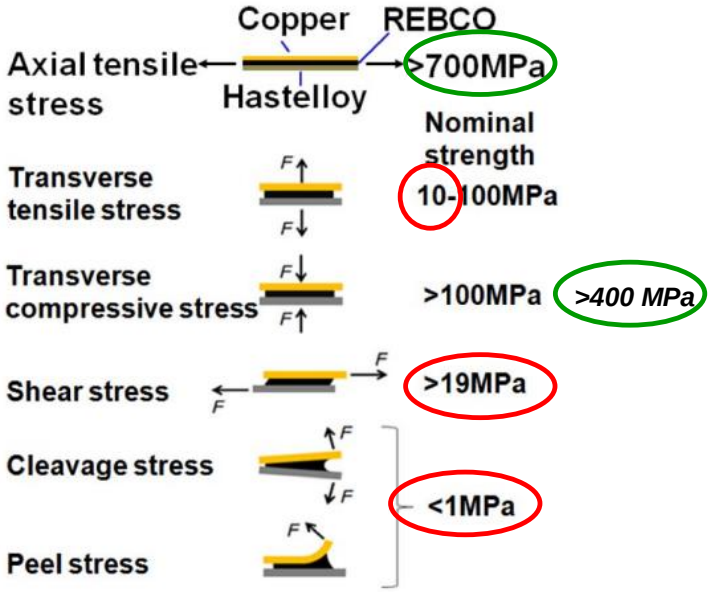
HTS tapes and wire: REBCO

~1% f.f.



R&C&W

Tensile strength:



Critical current anisotropy ~ 5

Tensile strength anisotropy >50

H. Maeda et al., TAS **24** (2014) 4602412

OPPORTUNITY: gain in I_c if the cable/magnet design exploits the anisotropy

OPPORTUNITY: very high tensile strength

CHALLENGE: avoid at all cost shear and cleavage stresses in cables/magnets

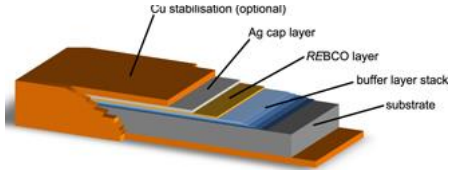
COMMENT

Among all the manufacturer, only D-nano and Oxolutia have a potential low cost process.

HTS tapes and wires overview

Bi2212

Bi2223



REBCO

1988
1990
1995
2000
2005
2010
2015
2017
2025

2 years

IGC
OST
Showa
Vacuumschmelze
Nexans
WST
Bruker-OST

5~8 years

Innost
AMSC
Vacuumschmelze
WST
Sumitomo

20 years

AMSC
Fujikura
Superpower
>10 companies

COMMENT - We lost some HTS manufacturers on the way.

HTS tapes and wire

HTS have been promising materials, for too long (>25 years).

Either they start to be used extensively in applications (electro-technical?), like NbTi was for MRI or Nb_3Sn for NMR.

Or disappear (NbZr, V_3Ga, $PbMo_6S_8$, Nb_3Al).

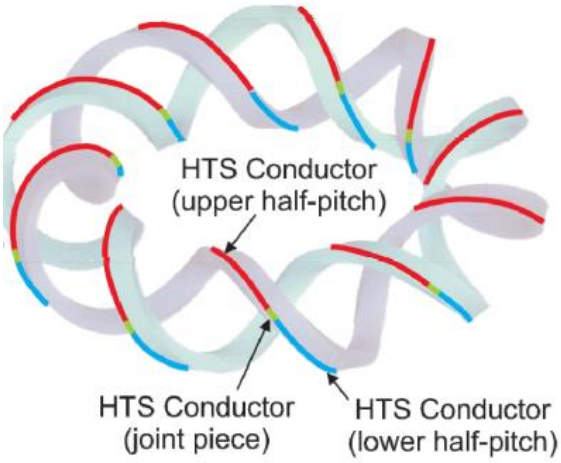
Or eventually remain just a very special product (very small quantities, very, very expensive) for niche market (replacement of resistive magnet, NMR>1.2 GHz, "special applications").

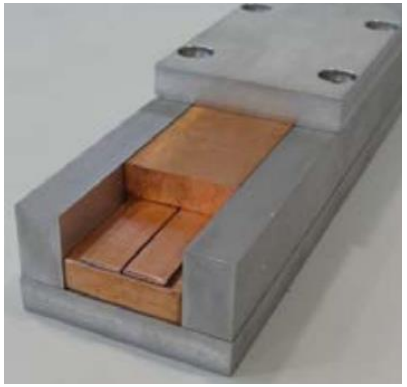
Unless you want make yourself the wires…

R&D magnets, dipoles and lab magnets will not be able to keep in business >10 HTS manufacturer for ever.

Cables for fusion magnets

Stacked, non twisted (NIFS)



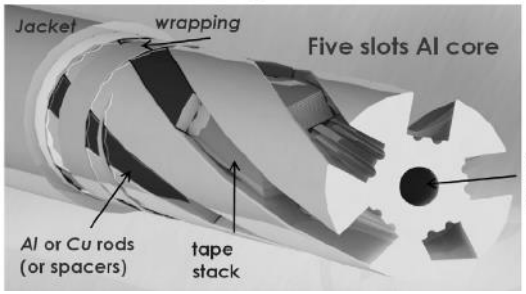


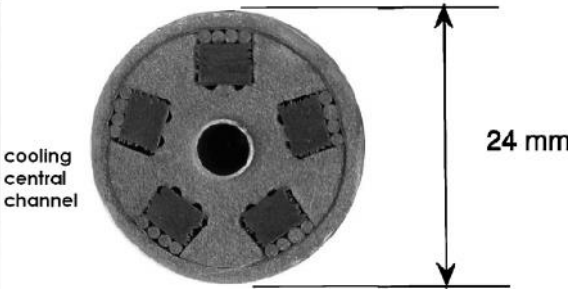
Non transposed tapes, current redistribution at the joints (every few meters).
Simplify construction of huge helical coils.
No need for km long tapes.
Field parallel to tape width.

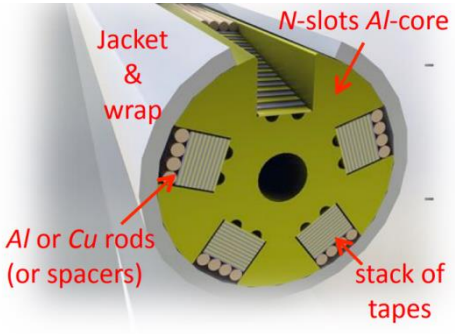
100 kA at 5 T, 4.2 K

COMMENT
Would be applicable to high field dipoles?

Stacked slotted matrix (ENEA)



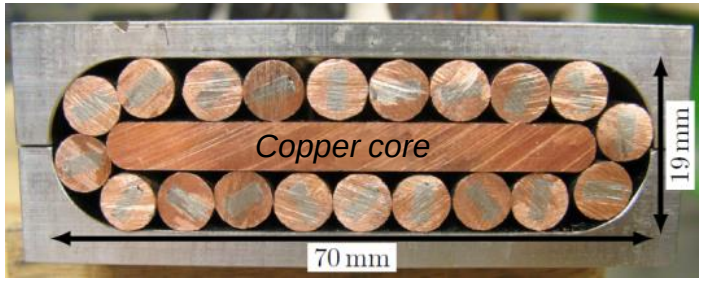


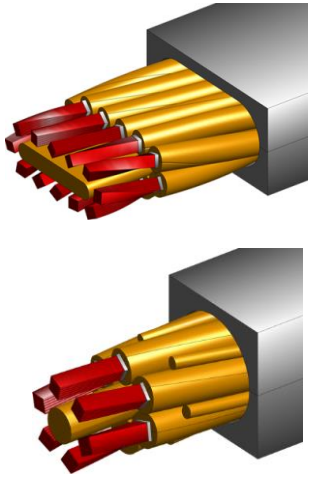


Made on industrial equipment. Ask companies what is feasible and what is not.

Cables for fusion magnets

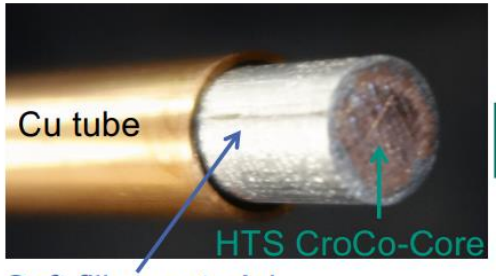
Twisted stacked, round or flat (SPC)





Tested at about 60 kA at 5 K, 12 T

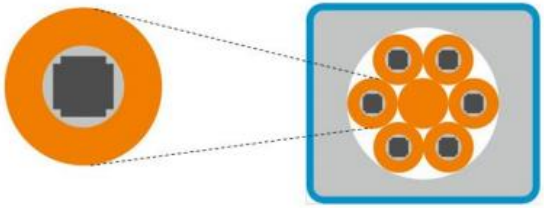
Twisted stacked, round (KIT)



Solder matrix is continuously casted around the tape stack, then inserted in a copper tube.

Next KIT approach for fusion magnet conductors

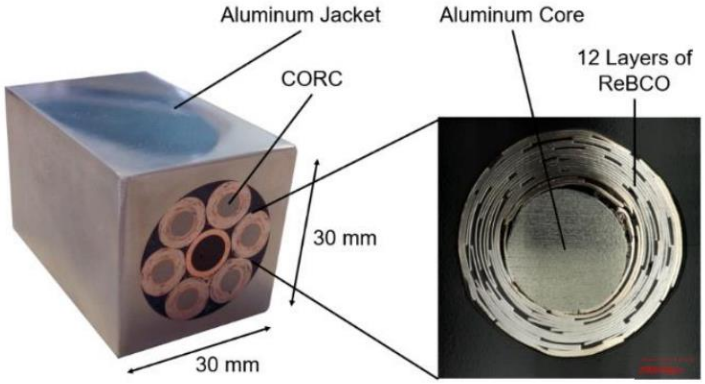
will be based on concentric HTS CroCos around a central copper core

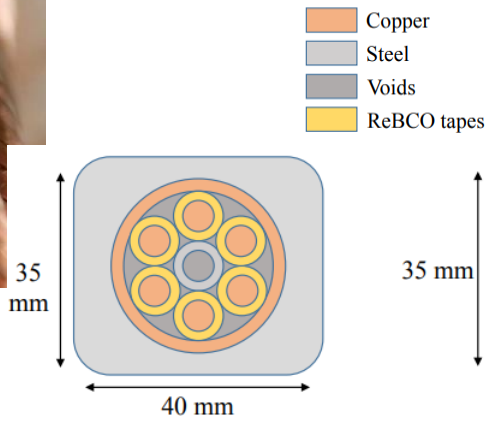


Cables for fusion magnets

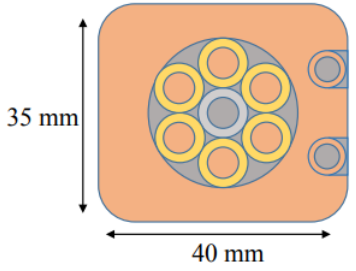
CORC multi stage (Advanced Conductor Technologies)

Concept of power cable (90's), exploit the flexibility and asymmetry (ceramic in compression) of coated conductors.
The cable is also very flexible.





Fusion cable: steel jacket, forced flow cooling



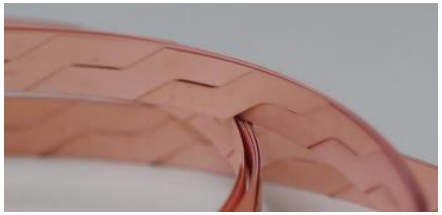
Detector cable: copper jacket, conduction cooling

All the above mentioned concepts have:

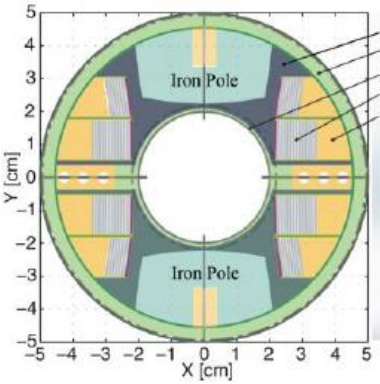
- Very large operating currents (>50 kA)
- Low J_{eng}
- Large steel and copper cross section
- Allocate space for coolant

Cables for high field dipoles

REBCO Roebel cable - aligned block (CERN)



Exploit the anisotropy of I_c in REBCO: the field is aligned with the wide face of the tape.



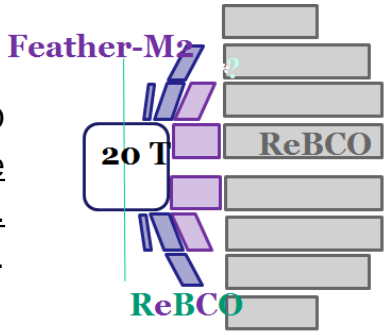
KIT, BEST, Superox

Punch then Cu coating (reduce delamination) ✔

Optimised design: tolerance to large transverse stresses. ✔

Punching with feedback system: length is not limited. ✔

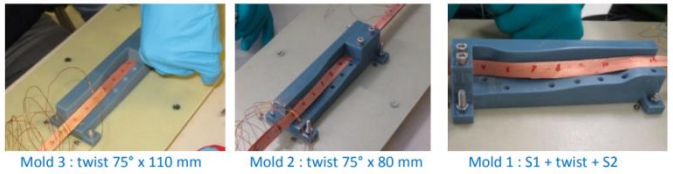
Van Nugteren: 20 T all REBCO dipole: exploit the high transverse pressure limit (400 MPa).
In solenoids is already done.



REBCO Roebel cable - Cos theta (CEA)

Coil ends are critical: bending and torsion

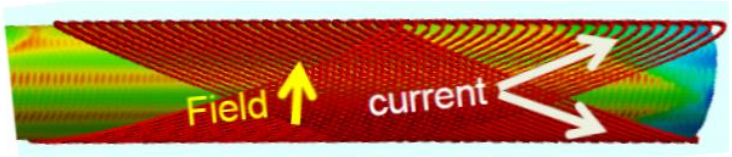
– Tests in collaboration with KIT on Desing B→ OK !

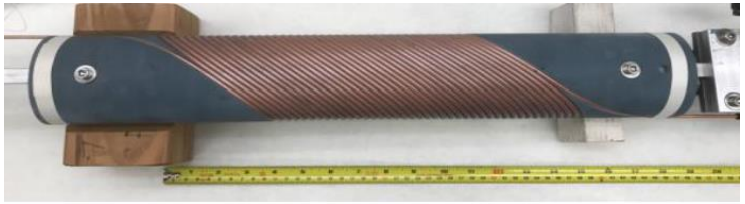


Twist strain: ε ϵ [-0.16 % ; 0.31%]

Cables for high field dipoles

CORC cable – Canted Cosine Theta (Berkeley)

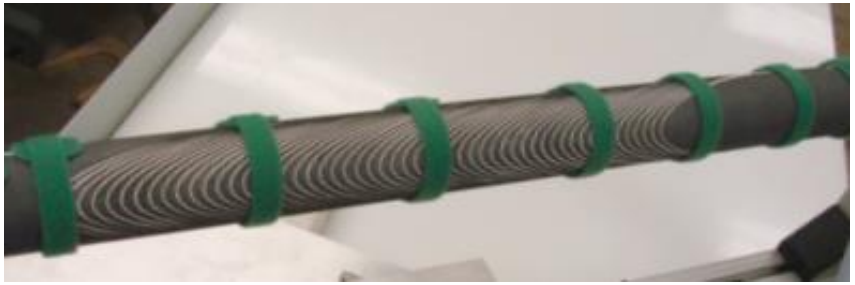


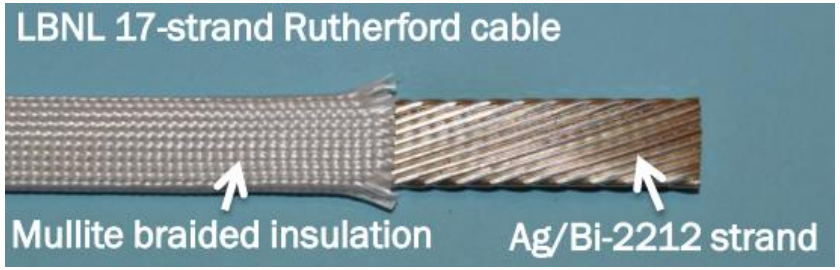


One of CCT advantages is to intercept forces. It is not really needed for coated conductors.

Rutherford Bi2212 - CCT (Berkeley)

Bi2212 wires (and Rutherford cables) can not take large transverse pressures (<120 MPa).
CCT is good for them.

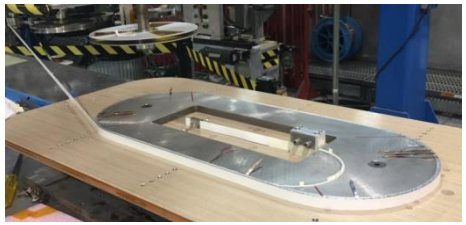


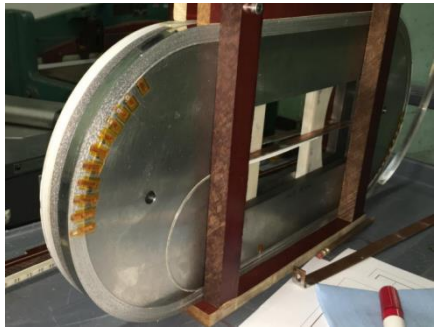


Cables for high field dipoles

Single tape - Common coil (Brookhaven)

The Nb_3Sn BNL common coil dipole reached the computed short sample field (100%) in 2006



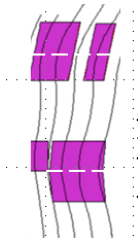


Nb_3Sn: R&W

REBCO: R&W

At 4.2 K: 680 A in HTS coil (about 1 T), 7'000 A in LTS outsert.

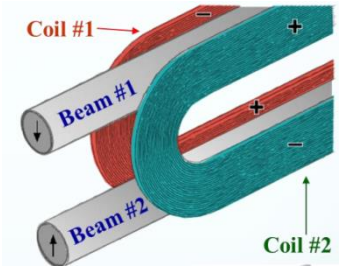
8.7 T



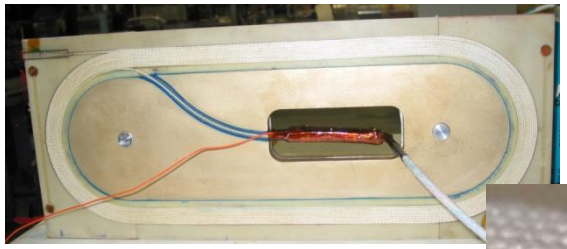
Field alignment not only to increase J_c but also to reduce magnetization

CORC- Common coil (Brookhaven)

But a stack or single tape will always have a higher J_{eng} than a CORC



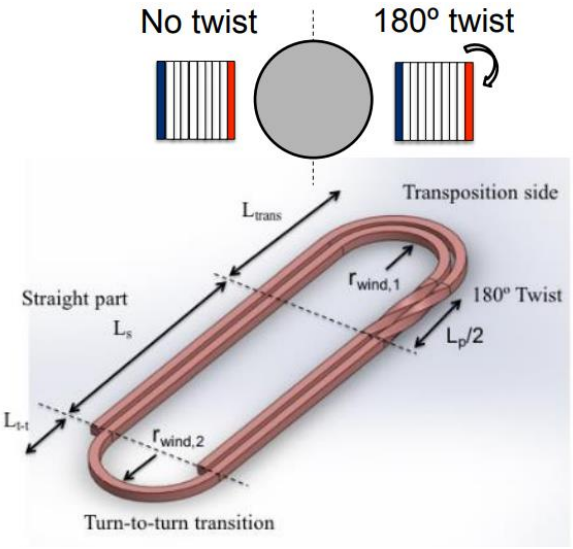
Bi2212 Rutherford- Common coil (Brookhaven)



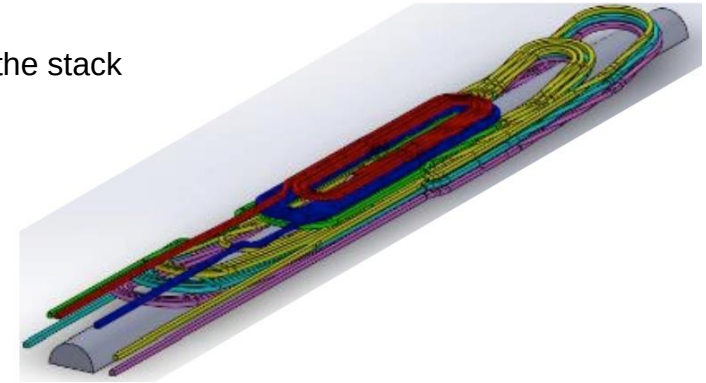
W&R

Cables for high field dipoles

REBCO Twisted stacked – block coil (University of Grenoble/NEEL/Ge2LAB)



Conductor: stack of soldered pairs (face to face).
Possible current redistribution in the stack to improve current homogeneity



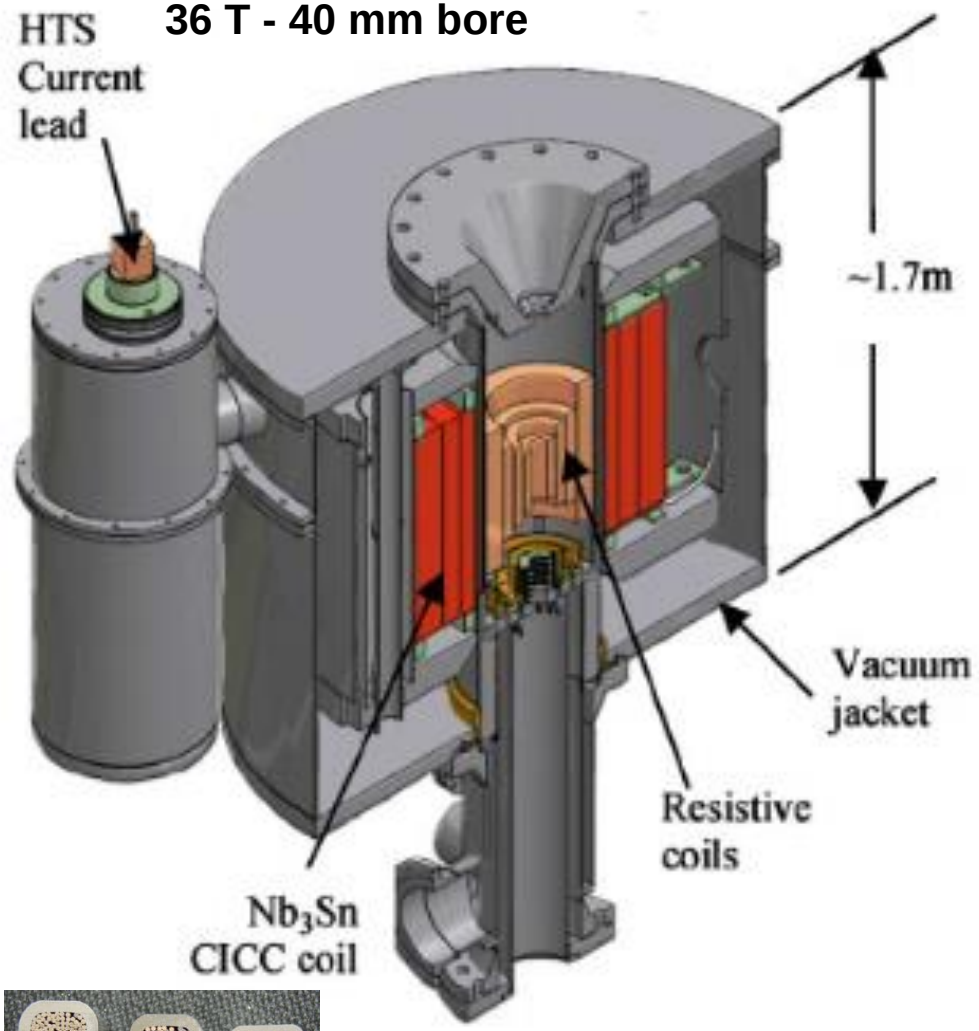
Are REBCO cable actually really necessary in all high field magnets?

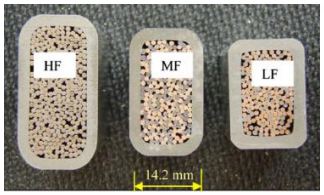
High field solenoids

NHMFL

Mark Bird et al 2013 TAS 19 (2009) 1612-5

36 T - 40 mm bore





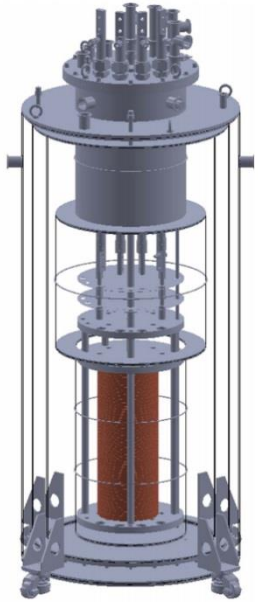
NHMFL

20 T - 52 mm bore

MIT – NHMFL - SuNAM

26 T - 35 mm bore

Sangwon Yoon et al 2016 Supercond. Sci. Technol. 29 04LT04



KBSI-NHMFL-SuNAM

35 T - 40 mm bore

Kwangmin Kim et al 2017 Supercond. Sci. Technol. 30 065008

σ=BRJ

Are HTS cables really needed for very high field solenoids?

Summary

- Higher operating temperature, field and lower costs are opportunities for HTS magnets. Several cables concept for dipoles and fusion magnets have been developed and are progressing.
- For cable magnet designers: do not pretend round coated conductors or higher Jc. Exploit tape/wire advantages, mitigate defects.
- High field (>20 T) solenoids will probably not need cables at all, because of the compact size.

- Having a valid, performing HTS cable and a suitable magnet design is not enough, if the HTS manufacturers get out of business. Large projects (DEMO, FCC) needs large amount of tape, but other applications (electro-technical?) should provide the stable market in which tape/wire manufacturers make money and prosper.

Thanks for your attention

POST TENEBRAS LUX