Roebel cable for accelerator magnet applications

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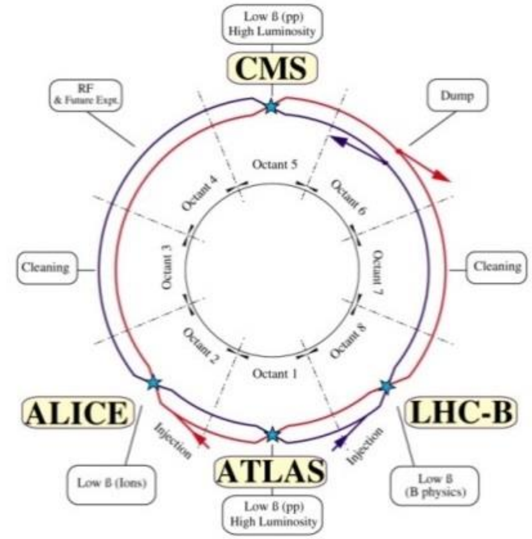
CERN – TE/MSC/SCD

1/10/2013

Context: Particle accelerator



In circular collider:

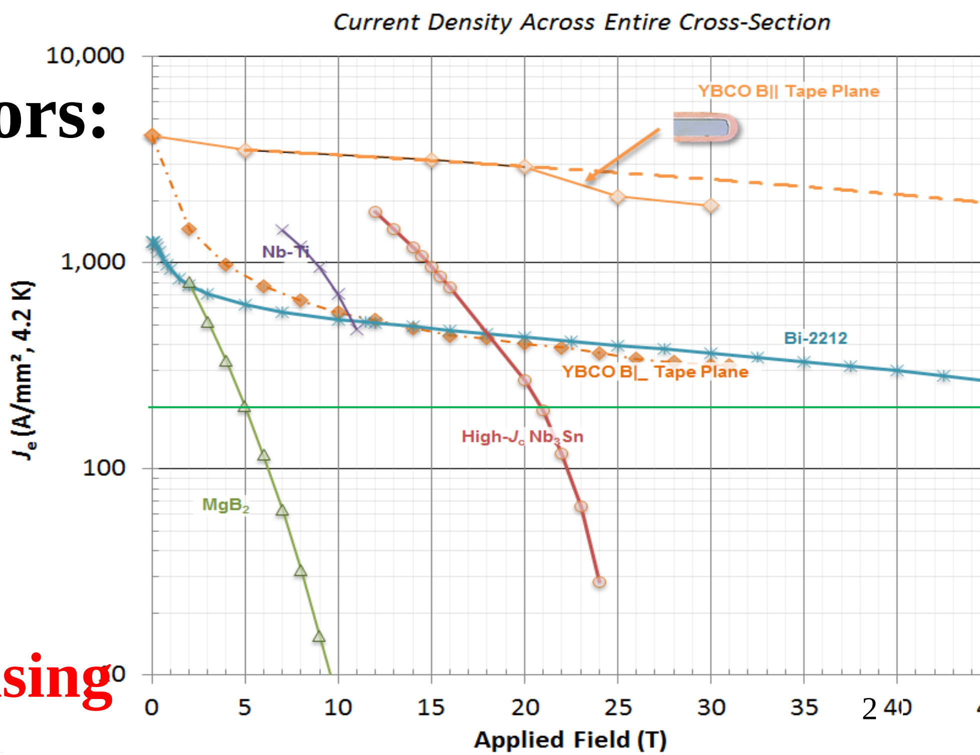
$$E_{beam}[\text{TeV}] \approx 0.3\, B_0\, [\text{T}]\, R_b\, [\text{km}]$$

LHC: E_{beam}=7 TeV and B_0=8.3 T

Further particle discovery => higher energy => higher dipolar field

Four practical superconductors:

- Nb-Ti wire: $B_{0,max}$=9 T
- Nb_3Sn wire: $B_{0,max}$=15 T
- Bi-2212 wire: $B_{0,max}$>30T
- YBCO tape $B_{0,max}$>30T

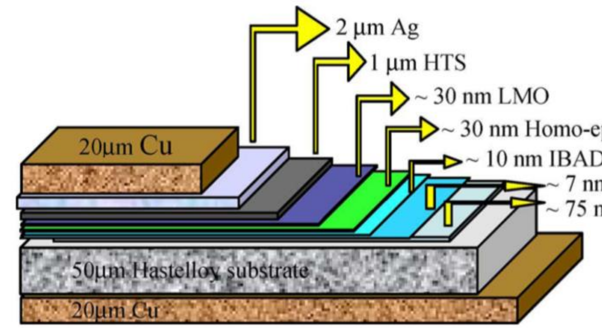


➢ **YBCO and Bi-2212 very promising**

Context: Practical HTS superconductors

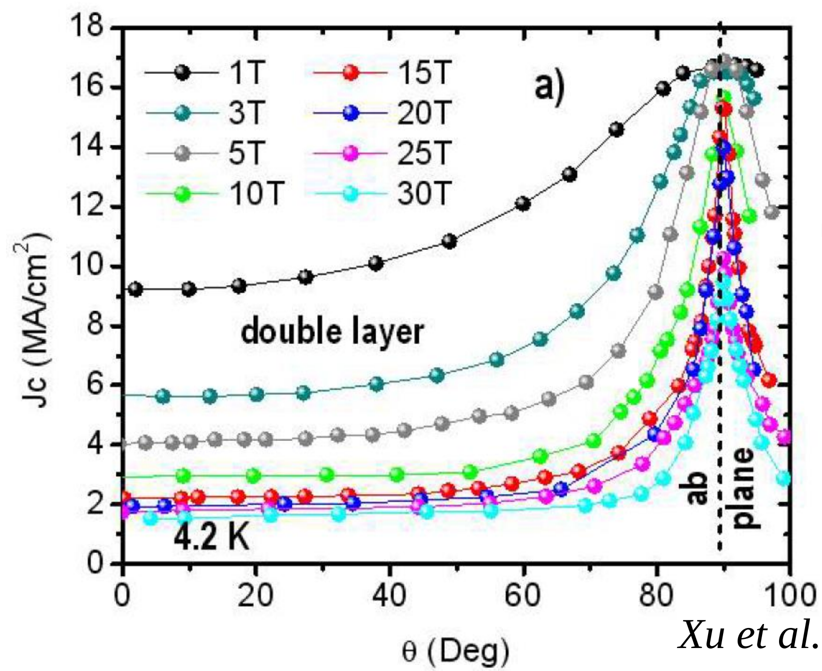
$Bi_2Sr_2Ca_1Cu_2O_8$ wire: $B_{0,max}$>30T

- Weak mechanical properties
- Medium (High) J_{ce} (HT @1(100) bar)
- Delicate heat treatment (O_2 /900°C)
- Isotropic Jc

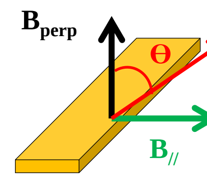


$YBa_2Cu_3O_7$ tape $B_{0,max}$>30T

- Strong mechanical properties
- High J_{ce} in // field, medium in perp.
- No reaction after coil winding
- Anisotropic Jc



Xu et al.



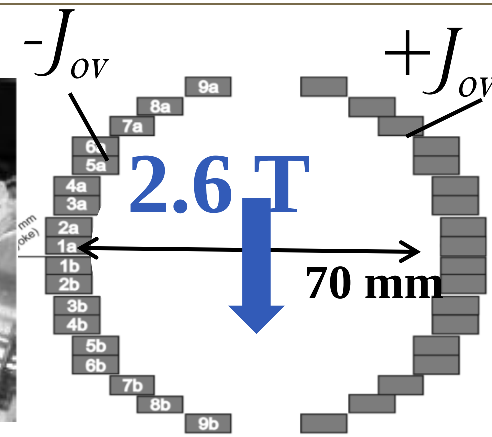
➤ **Focus on YBCO**

➤ **Coil design => account for J_c anisotropy of YBCO**

Context: from small scale to accelerator YBCO magnet

Small scale YBCO dipole tested:

- 2.6 T in 0 T background at 18 K
- J_{ov} :50-100 A/mm^2
- Small stored energy
  =>**Single conductor (~100 A)**



Danfysik

Requirements for YBCO accelerator dipole:

- About 5-7 T in 10-15 T background
- J_{ov} >200 A/mm^2
- Large stored energy=> **High current cable (~10-20 kA)**

Outline

- Context
- Ultimate field of HTS dipole
- Electromechanical properties of YBCO conductor
- Electromechanical properties of Roebel YBCO cable
  - Ic at 4.2 K
  - Current distribution among strands
  - Mechanical properties
  - Failure analysis
- Conclusion

Ultimate field of HTS dipole

In a single layer sector coil (ϕ=60°):

- Central field :

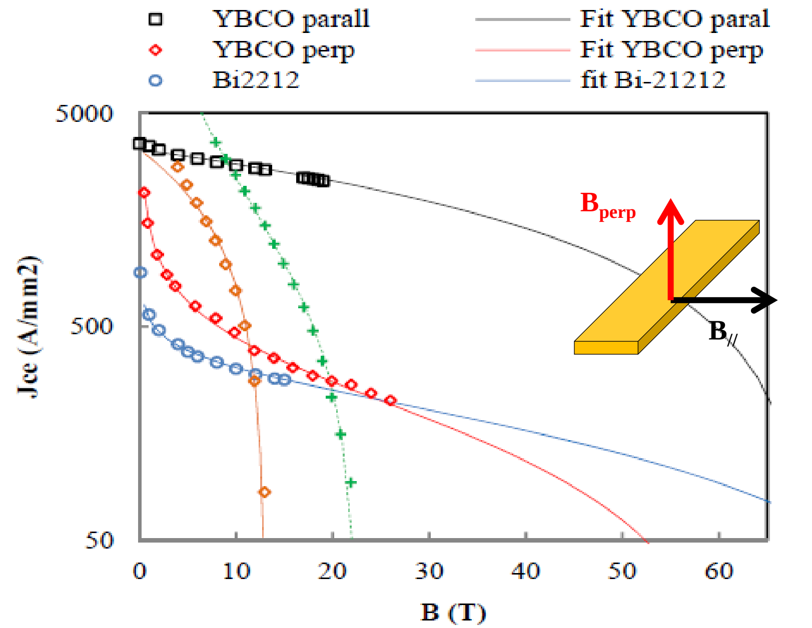
$$B_0 = \frac{B_p}{\lambda} = \frac{2\mu_0}{\pi} w_c J_w \sin(\phi)$$

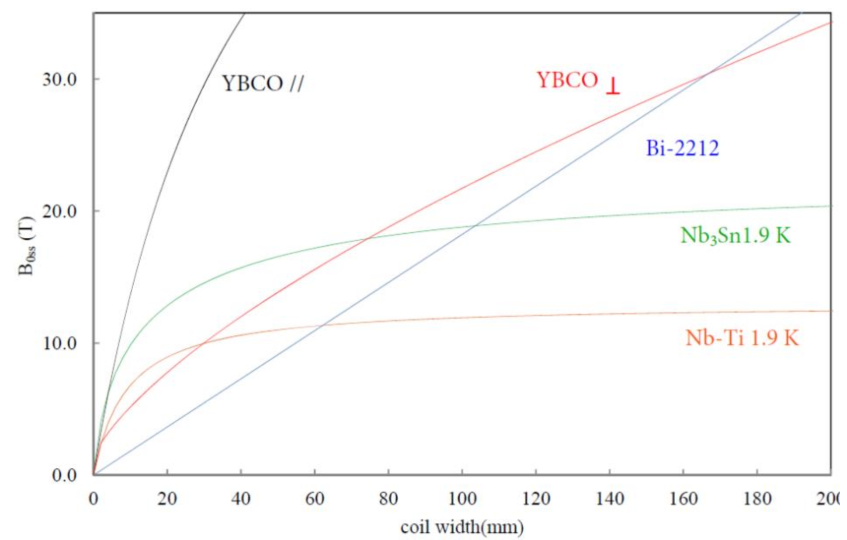
- J_{ce} of YBCO :

$$J_{ce}(B) = \frac{r_0}{B^s} - dB$$

- Ultimate field:

$$B_{0,ss} = \frac{1}{\lambda}\left(\frac{\gamma_0 \lambda w_c K r_0}{1+\gamma_0 w_c \lambda K d}\right)^{\frac{1}{s+1}}$$





- ➢ **No $B_{0,ss}$ saturation for YBCO**
- ➢ **B_0=20 T: w= 80 mm for perp field**

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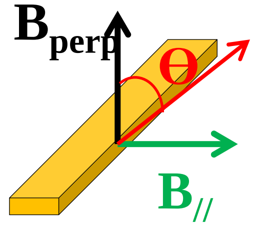
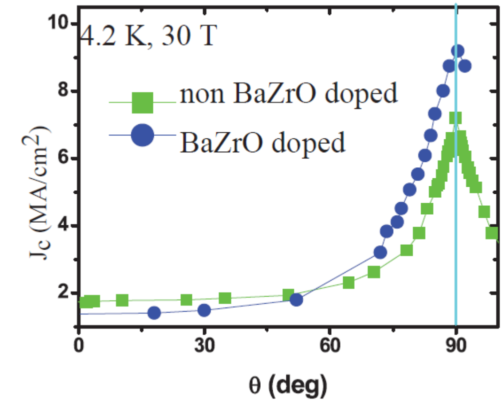
RE-BCO conductor characterization (1/2)

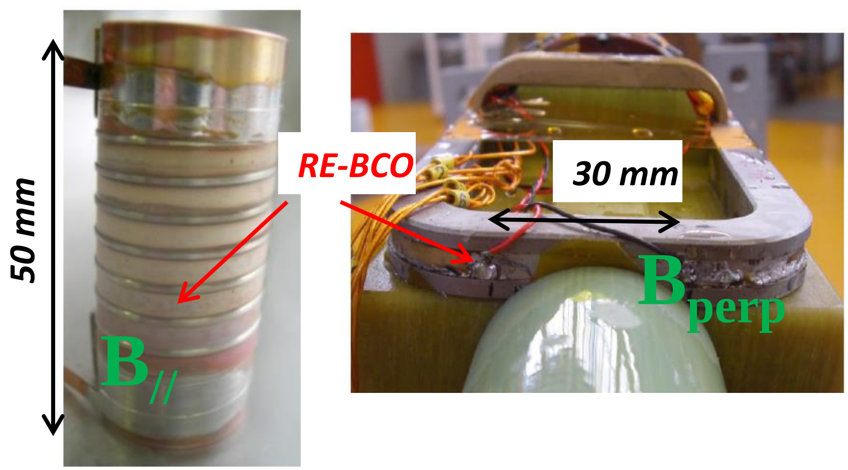
YBCO Jc anisotropic:

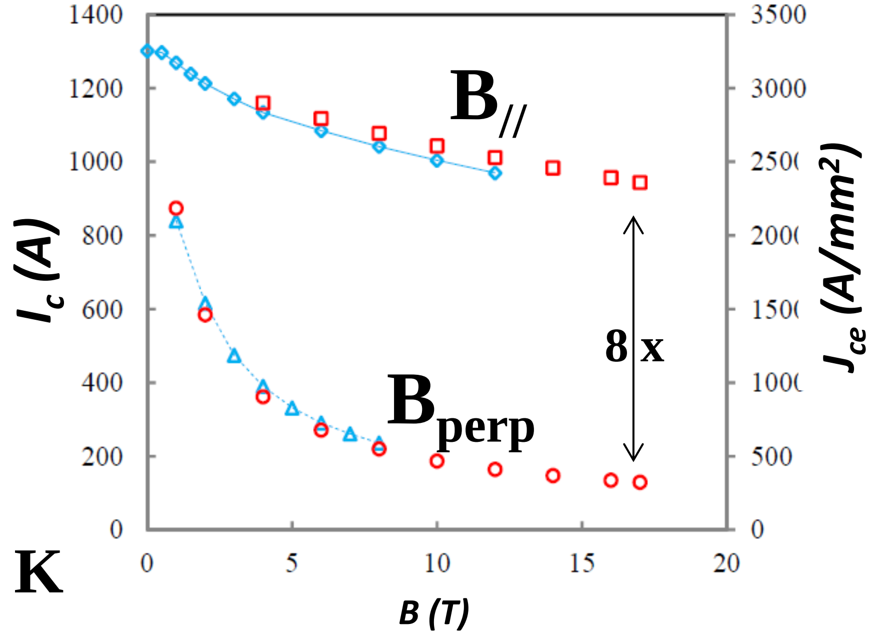
- Max in parallel field
- Min in perp field





Two samples holders (CERN):





No specific increase of I_c: 4.2 K=>1.9 K

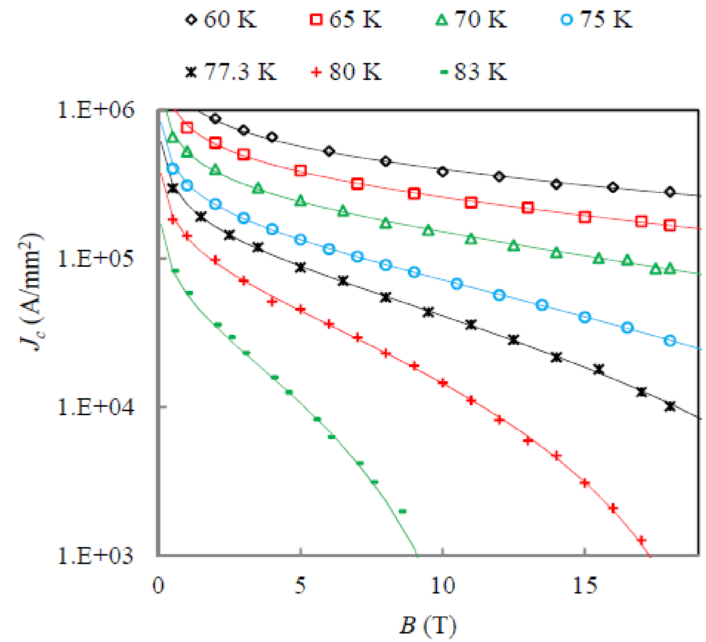
➢ **J_{ce} parameterization needed for magnet/cable design**

YBCO $J_c(B,T,\Theta)$ parameterization

$J_c(B,T)$:Perpendicular and parallel field

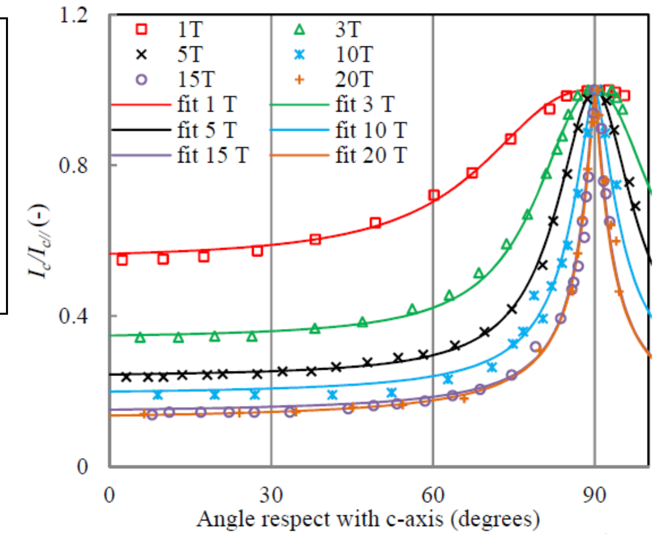
$$J_c(B,T)=\frac{C_0}{B}\cdot\left(\left(1-t^{m1}\right)^{m2}\right)^{n1}\cdot\left(\frac{B}{B_{irr}}\right)^{p}\left(1-\frac{B}{B_{irr}}\right)^{q}$$

$$B_{irr}(t)=B_{irr,0}\left(1-t^{m1}\right)^{m2} \qquad t=\frac{T}{T_{cf}}$$



New Jc(B,T,Θ) parameterization:

$$J_c(B,T,\theta)=J_{c,perp}(B,T)+\frac{J_{c,//}(B,T)-J_{c,perp}(B,T)}{1+\left(\frac{\left|\theta-\pi/2\right|}{e(B,T)}\right)^{g(B,T)}}$$



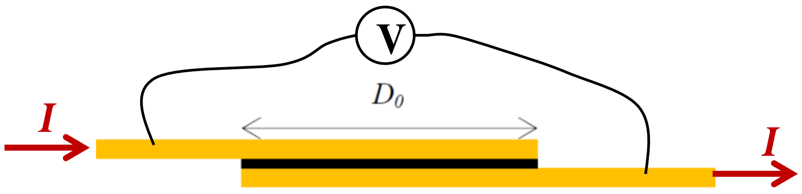
- **Accurate $J_c(B,T,\Theta)$ description over large field and temperature range**

YBCO splice resistance

Unit length of YBCO: 100-500 m

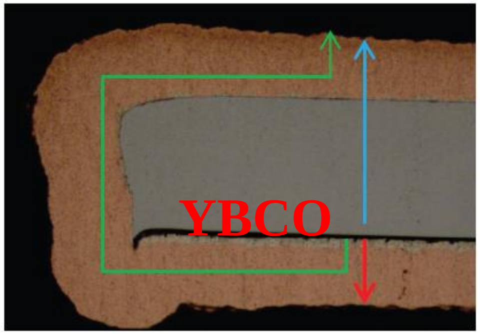
Splice requirement for magnets:

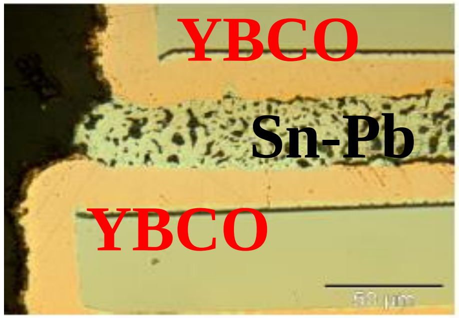
- Low electrical resistance (~n**Ω)**
- High mechanical strength (~200-600 MPa)
- Splicing temperature < 250 °C



Anisotropic splice resistance:

- Face to Face (**33** nΩ. cm²)*
- Back to Face (**851** nΩ. cm²) *
- Back to back (**1186** nΩ.cm²) *





*at 77 K, self field, 4mm SP wide conductor

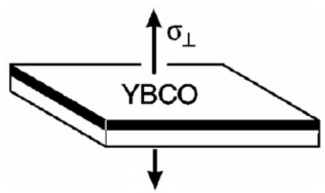
- **Factor 35 between best and worst configuration**
- **Splice resistance is conductor batch dependent**

➢ **Splice resistance dominated by conductor internal resistance**

YBCO stress sensitivity

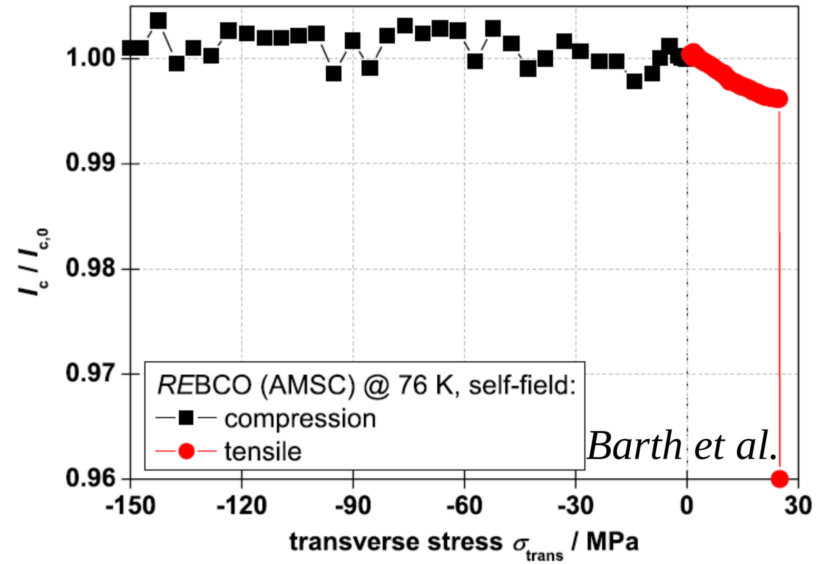
Transverse compression:

- No significant J_c reduction up to 600 MPa
- Fatigue resilient



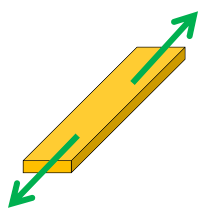
Transverse tension:

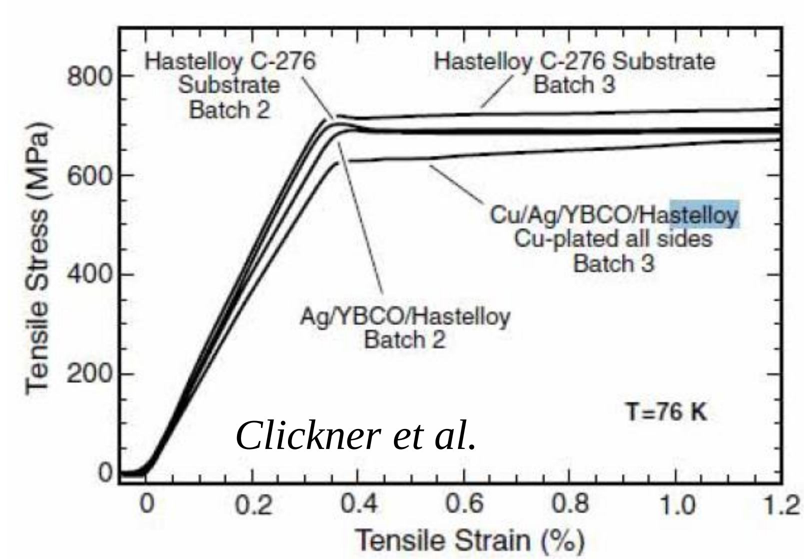
- Delamination strength of only 17-30 MPa
- Impregnation is an issue



Axial tension:

- Yield stress ~650 MPa
- E modulus : 175 GPa

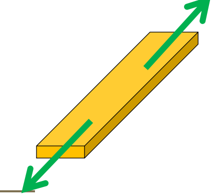




➢ **YBCO subject to delamination**

➢ **Resilient to transverse compression and axial tension**

YBCO axial strain sensitivity



YBCO J_c sensitive to axial strain:

- Reversible J_c reduction for $\varepsilon < \varepsilon_{irr}$

$$J_{c,s,f}(\mathrm{B},\boldsymbol{\varepsilon},\boldsymbol{T}) \propto \boldsymbol{b}(\boldsymbol{B},\boldsymbol{T})\left(\mathbf{1}-\boldsymbol{a}(\boldsymbol{B},\boldsymbol{T})[\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}_{\boldsymbol{m}}]^{2}\right)$$

- Irreversible J_c reduction for $\varepsilon > \varepsilon_{irr}$

$$J_{c,s,f}(\boldsymbol{\varepsilon},\boldsymbol{T}) \approx \mathbf{0}$$

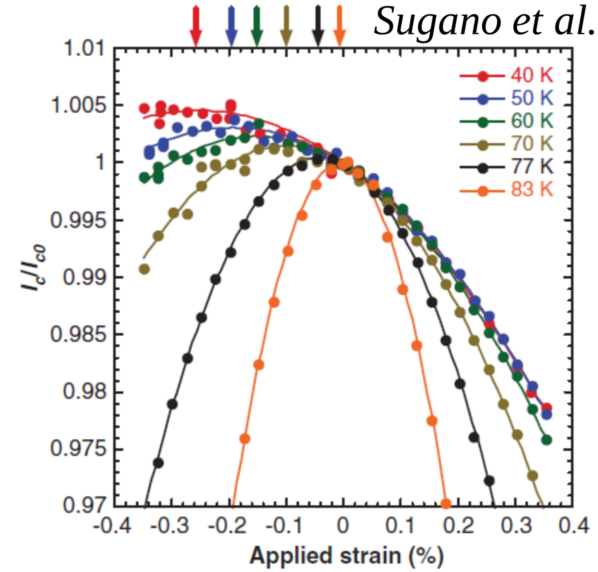
$\varepsilon_{irr,t}$ **=0.6%** $\varepsilon_{irr,c}$ **=-2%**

Strain sensitivity reduced by:

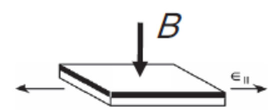
- Lowering temperature
- Reducing field

Strain sensitivity: field, strain orientation and composition dependent

➢ **J_c (*B, 4.2 K, ε*) not yet fully measured**

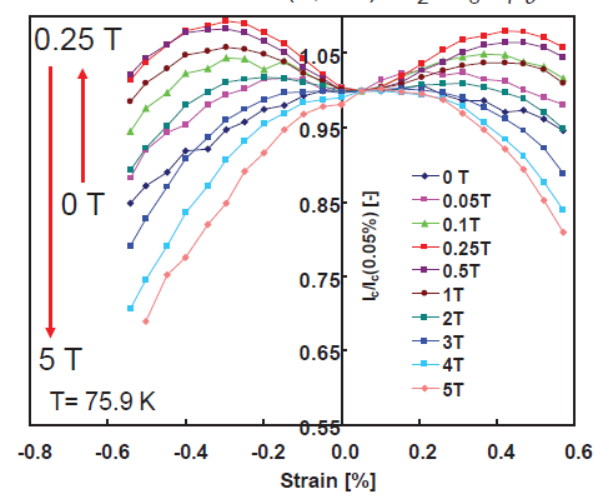


Sugano et al.

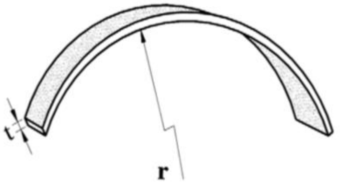


Van der Laan et al.

$(Y,Sm)Ba_2Cu_3O_{7-\delta}$

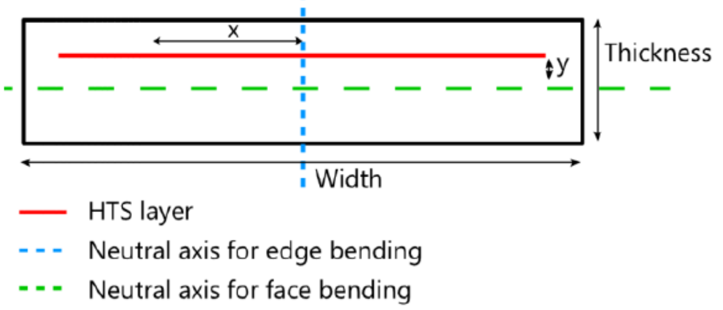


I_c reduction with easy bending



Axial strain state:

$$\varepsilon(R) = y/R$$



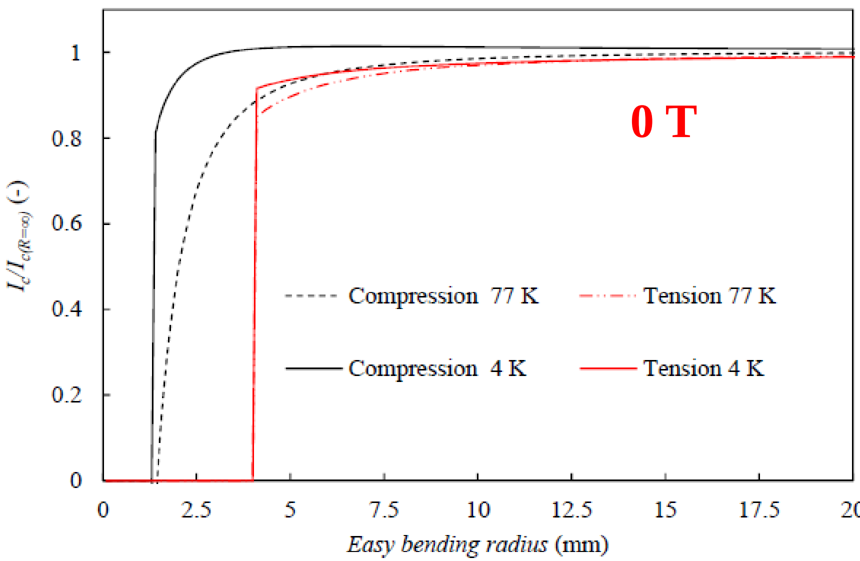
Integration of J_c (ε) over film width (w):

- *Large bending radius* $(R > y/\varepsilon_{irr})$

$$I_c(R,B,T) = \tau w J_{c0,\varepsilon_m}(1-t)^k\left[1 - a(T)\left((y/R)+\varepsilon_m(T)\right)^2\right]$$

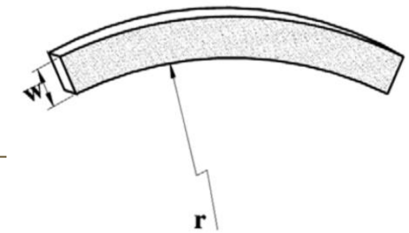
- *Small bending radius* $(R < y/\varepsilon_{irr})$

$$I_c(R,B,T) = 0$$



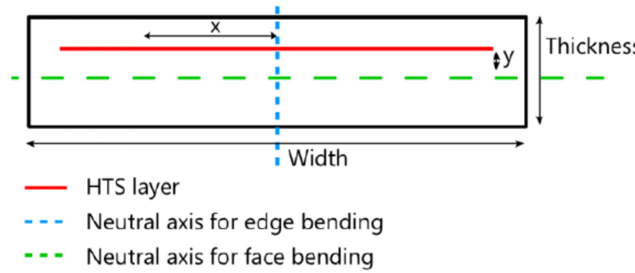
- **Most of I_c reduction due to irreversible strain**
- **Ic more sensitive for YBCO in tension**

I_c reduction with hard bending



Axial strain state:

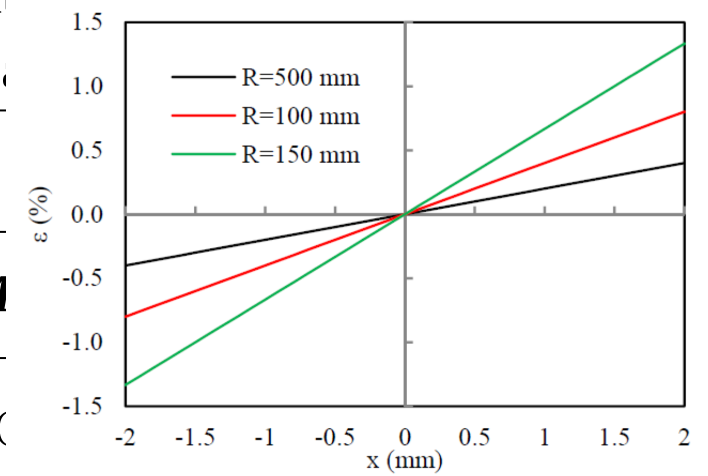
$$\varepsilon(R) = x/R$$



Integra

- **L**

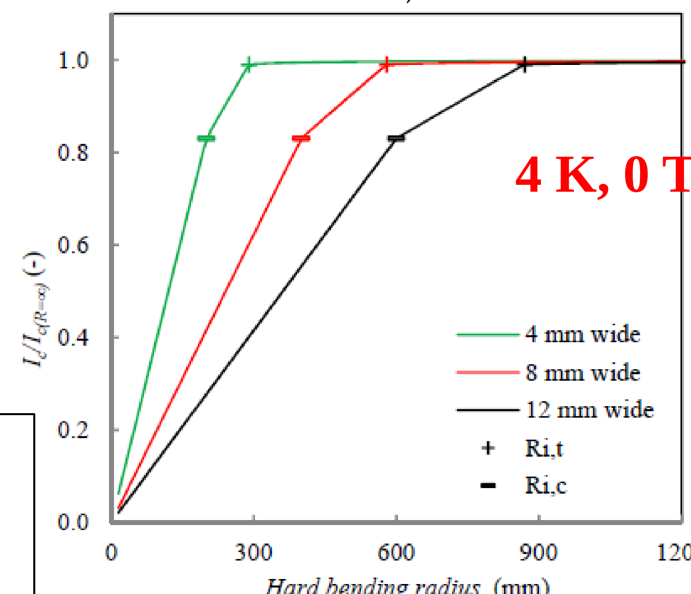
$,2 \;\; R^2 \Big]$



- ***M*** ***$R_{i,t}$)***

$$I_c(\;\; + \frac{a\varepsilon_m w}{2R}\Bigg]$$
$$+ R\varepsilon_{irr,t}\left[1 - \frac{a{\varepsilon_{irr,t}}^2}{3} + a\varepsilon_m\varepsilon_{irr,t} - a{\varepsilon_m}^2\right]\Bigg]$$

$$R_{i,c} = \frac{w}{2\varepsilon_{irr,c}} \qquad R_{i,t} = \frac{w}{2\varepsilon_{irr,t}}$$



- ***Small bending radius ($R<R_{i,c}$)***

$$I_c(R) = \tau w R J_{c0,\varepsilon_m}(1-t)^k\left[-\varepsilon_{irr,c}\left[1 - \frac{a{\varepsilon_{irr,c}}^2}{3} + a\varepsilon_m\varepsilon_{irr,c} - a{\varepsilon_m}^2\right]\right.$$
$$\left.+ \varepsilon_{irr,t}\left[1 - \frac{a{\varepsilon_{irr,t}}^2}{3} + a\varepsilon_m\varepsilon_{irr,t} - a{\varepsilon_m}^2\right]\right]$$

➢ **Wider conductor more sensitive, Most of I_c reduction due to irreversible strain**

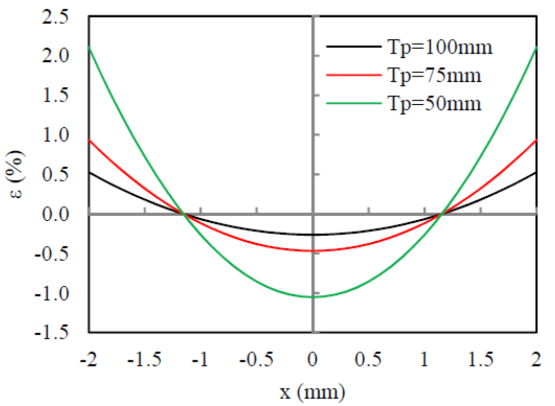
I_c reduction with twisting

Axial strain:

$$\varepsilon_{tw}(T_p) = \frac{2\pi^2}{T_p{}^2}\left(x^2 - \frac{w^2}{12}\right)$$

$$T_{p,i,t} = \pi w\sqrt{\frac{1}{3\varepsilon_{irr,t}}}$$

$$T_{p,i,c} = \pi w\sqrt{\frac{1}{|6\varepsilon_{irr,c}|}}$$



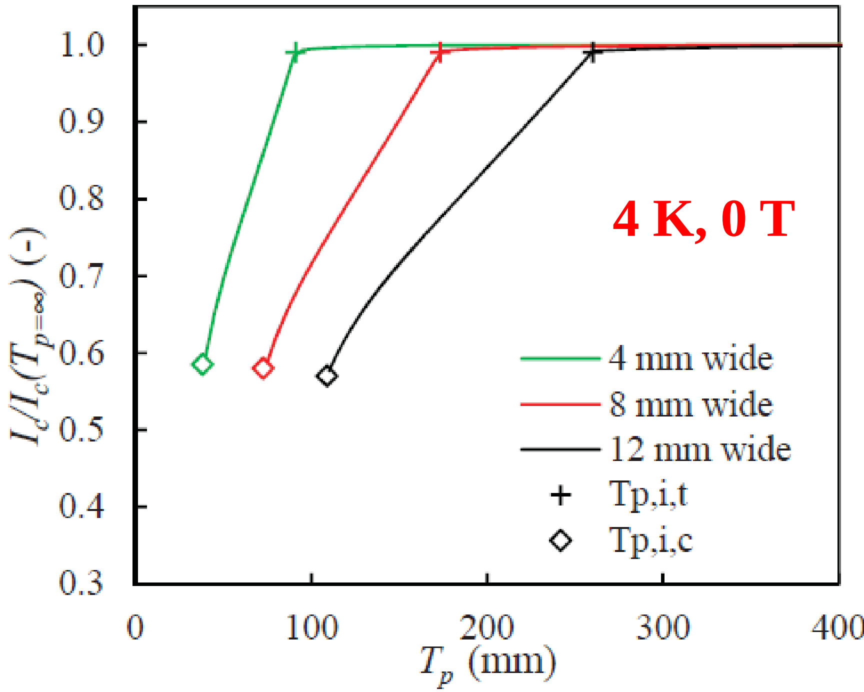
Integration of J_c (ε) over film width:

- ***Large twist pitch ($T_{p,i,t} < T_p$)***

$$I_c(T_p) = \tau w J_{c0,\varepsilon_m}(1-t)^k\left[1 - \frac{a}{180}\left(\frac{2\pi^2 w^2}{T_p{}^2}\right)^2 - \frac{\varepsilon_m{}^2}{2}\right]$$

- ***Medium twist pitch ($T_{p,i,c} < T_p < T_{p,i,t}$)***

$$I_c(T_p) = \tau w J_{c0,\varepsilon_m}(1-t)^k\sqrt{\frac{4\varepsilon_{irr,t}}{c_0} + \frac{w^2}{3}} * \left(1 - \frac{a}{270}\begin{pmatrix} 54\varepsilon_{irr,t}{}^2 + 270\varepsilon_m{}^2 \\ +30c_0\varepsilon_m w^2 + c_0{}^2 w^4 \\ -6\varepsilon_{irr,t}(30\varepsilon_m + c_0 w^2) \end{pmatrix}\right)$$



➢ **Wider conductor more sensitive**

➢ **Most of I_c reduction due to irreversible strain**

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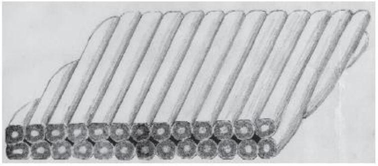
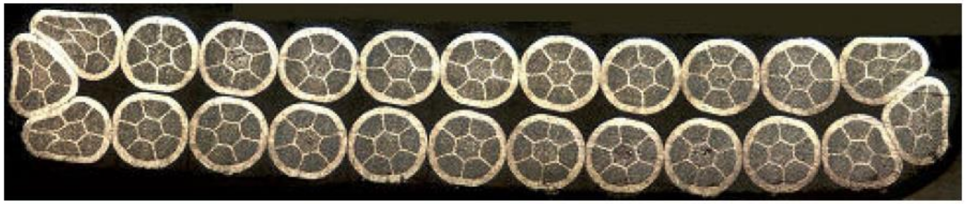
- Ultimate field of HTS dipole
- Electromechanical properties of YBCO conductor
- **Electromechanical properties of Roebel YBCO cable**
  - Ic at 4.2 K
  - Current distribution among strands
  - Mechanical properties
  - Failure analysis
- Conclusion

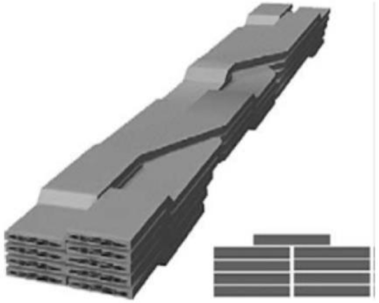
Concepts of HTS high current cable

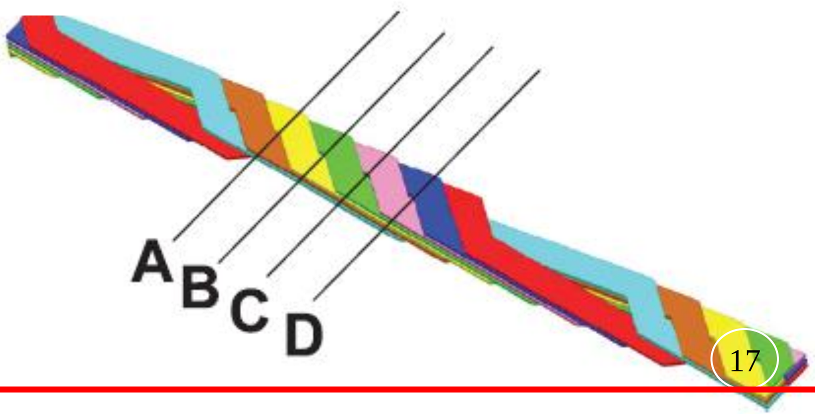
- Rutherford (Bi-2212)
  - **Wires** arranged in two layers
  - Transposed
  - high Pack. Factor





- Roebel (YBCO)
  - **Tapes**
  - Transposed
  - high high Pack. Factor



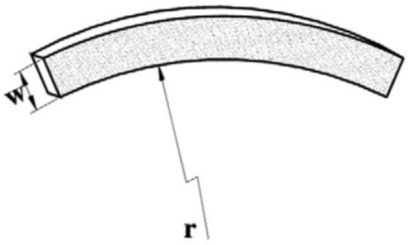


Manufacture of Roebel cable

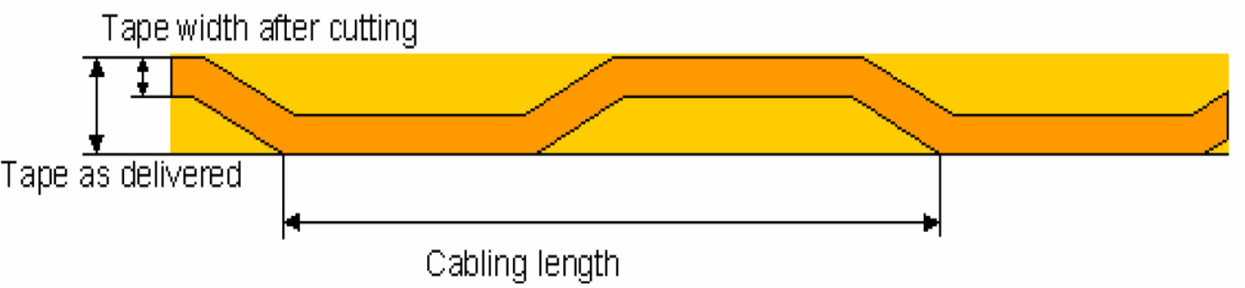
Roebel cable => hard bending of YBCO tapes

Hard bending not possible:

- Mechanical instability
- Ic reduction
- Too large transposition pitch



➢ **pre shaped YBCO tapes: punching process**



Cable pitch

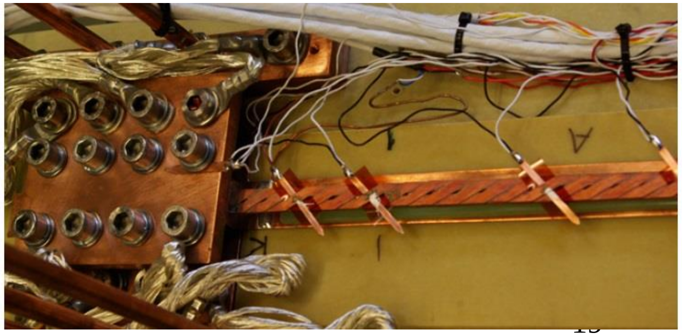
➢ **Roebel cable made of pre-shaped YBCO tapes**

Review of Roebel performances

Measurements performed only at 77 K, 0 T

Laboratory	KIT	KIT	GCS	GCS	GCS	FNAL
Cable width (mm)	12	12	12	5	5	12
Number of strands	16	45	15	9	5	15
Length (m)	0.45	1.1	5	0.5	0.7	2.6
Transposition pitch (mm)	190	188	-	-	300	300
Strand width (mm)	5	5	5	2	2	5
Cable I_c measured ($1\mu V/cm$) (kA)	1.02	2.29	1.10	0.31	0.20	1.01
Sum of individual strands I_c (kA)	1.47	6.73	1.95	0.43	0.25	1.62
I_c reduction due to self flux density (%)	30	66	44	28	19	38

- **strong I_c reduction with self field**
- **Record of 2.29 kA in 45 strands cable**



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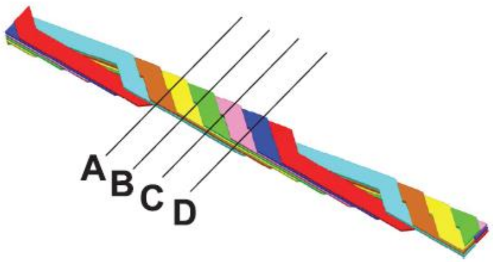
Roebel characterization: experimental details

Two types of 12 mm wide Roebel cables

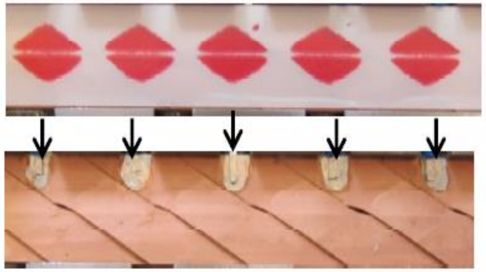
- **KIT**: 10 strands, 126 mm pitch, 0.6 mm thick
- **GCS**: 15 strands, 300 mm pitch, 0.85 mm thick

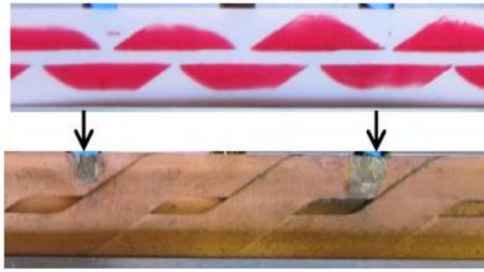


➢ Test at 4.2K => 40 MPa of pre -stress

Sensitivity of Roebel cable to transverse stress

- **GCS cable**
  - No I_c reduction up to 45 MPa
  - 36 % of section efficient=>125 MPa locally
- **KIT cable**
  - 24 % of section efficient =>188 MPa locally





Instrumentation

- **Voltage tapes**
  - cover 1(2) transposition pitch(es) for GCS(KIT) cables
  - Do not disturb the stress distribution
- **Hall probes**

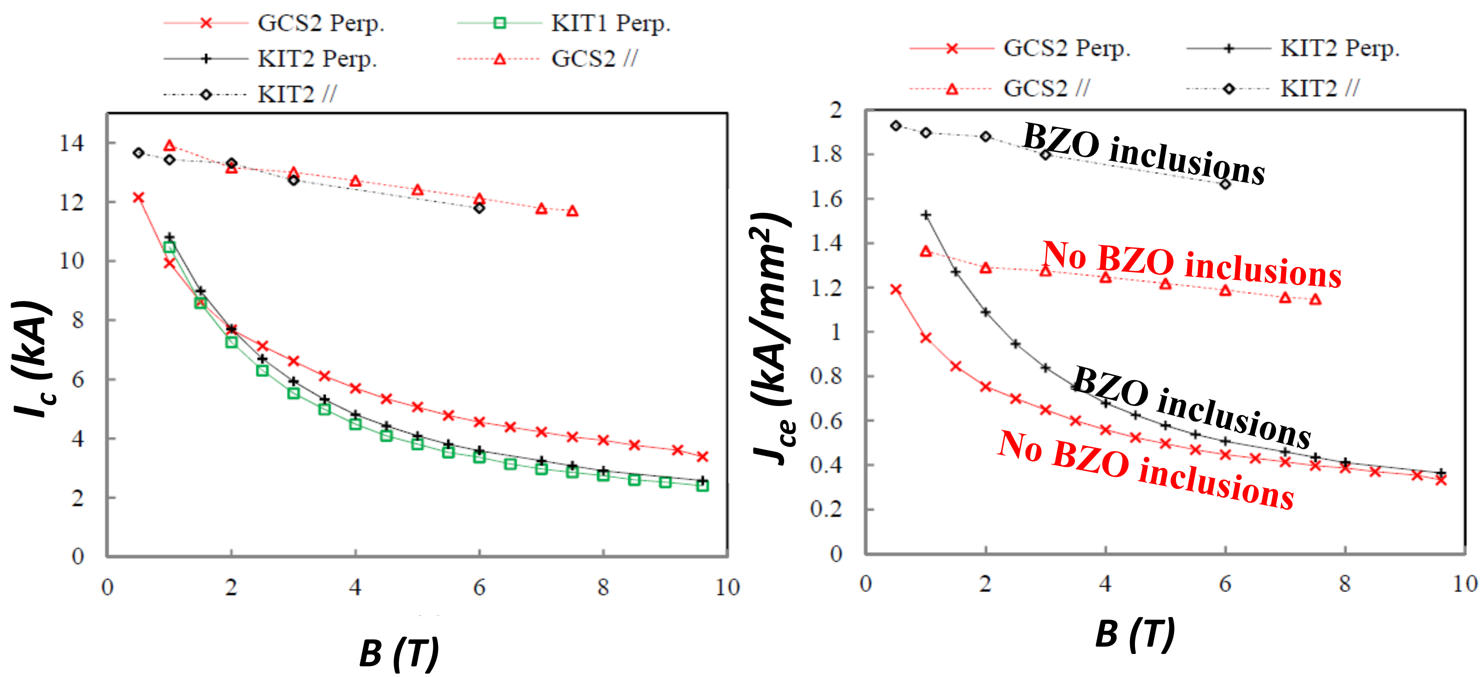
➢ **No I_c reduction with transverse local pre–stress of 125-188 MPa**

➢ **Specific voltage taps implementation**

➢ **No cable impregnation**

Roebel cable I_c

- **World first successful measurements of Roebel cable at 4 K**
  - Cables reached their I_c up to 9.6 T
  - BaZrO doping plays a role in cable I_c
  - 1-3 nΩ splice resistance achieved (≈36-94 nΩ·cm²)

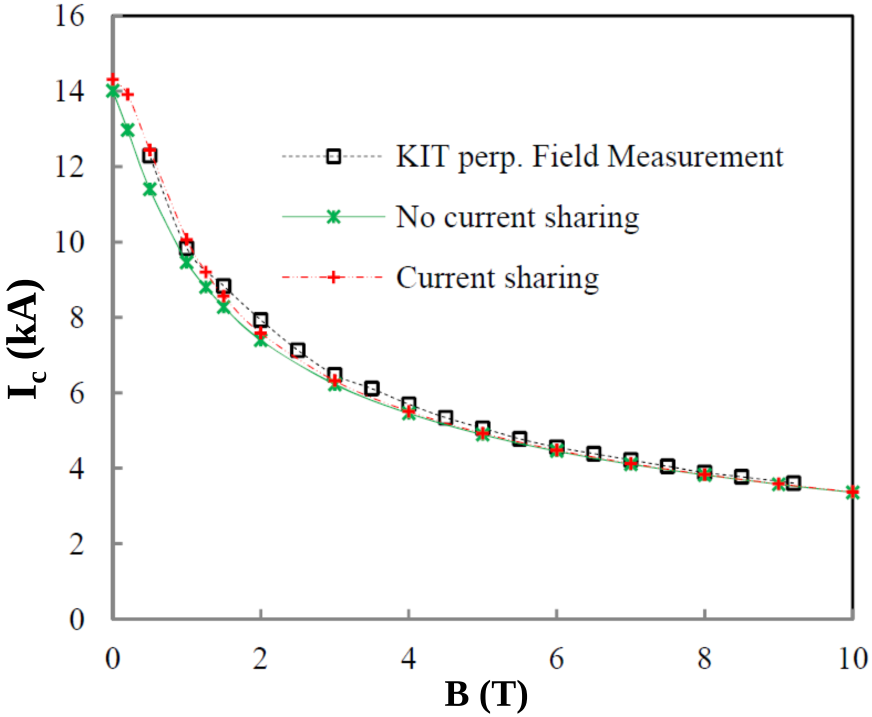


- **I_c > 12 kA, J_{ce} > 1200 A/mm² obtained**
- **Cable I_c depends on the raw characteristics of YBCO tapes**

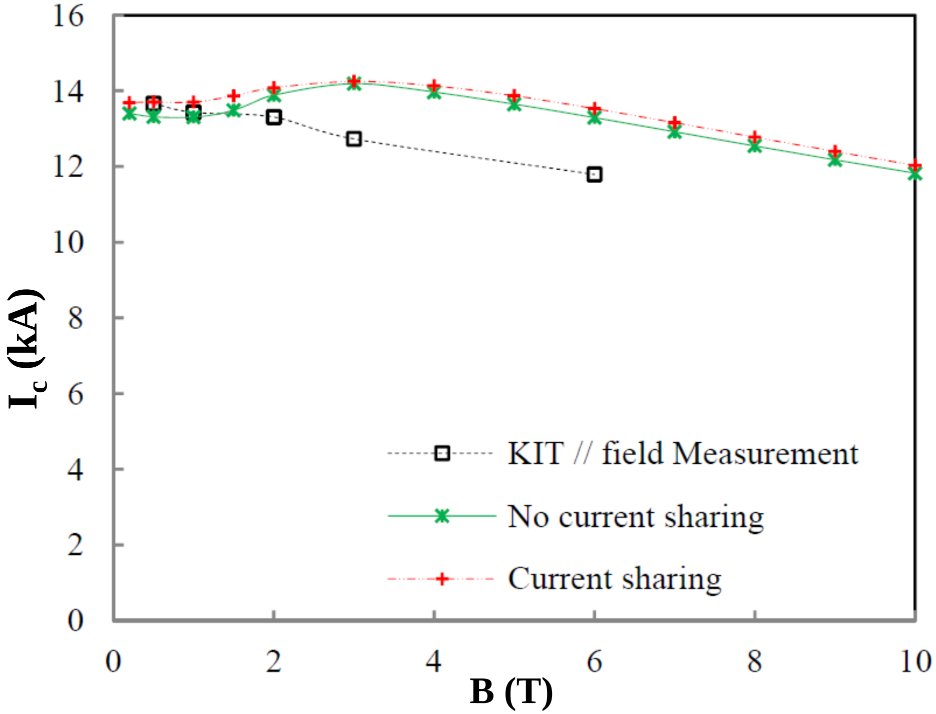
Roebel cable I_c measurements vs. model

Implementation of $J_c(B,T,\Theta)$ in 2D FEM model

- Perpendicular field



- Parallel field



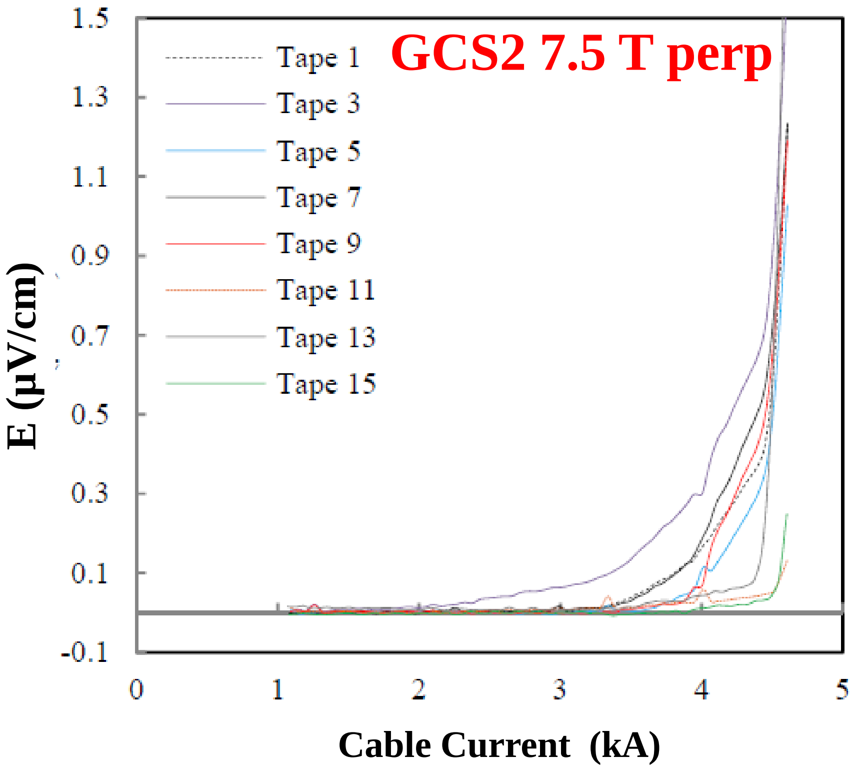
➢ **I_c model in accordance with measurements**

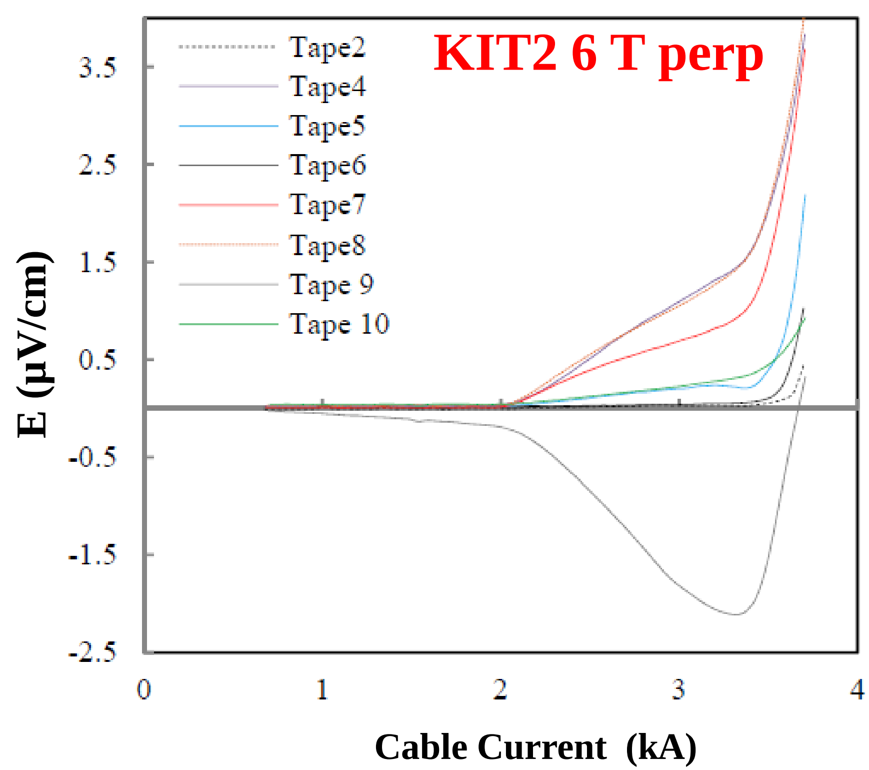
Outline

- Context
- Ultimate field of HTS dipole
- Electromechanical properties of YBCO conductor
- **Electromechanical properties of Roebel YBCO cable**
  - Ic at 4.2 K
  - **Current distribution among strands**
  - Mechanical properties
  - Failure analysis
- Conclusion

Roebel cable: current distribution

- Uneven electric field above a certain current
- I_c defined at 0.2 µV/cm on strand 13 (GCS2 cable)
- Uneven current distribution from hall probes





➢ **Uneven current distribution in Roebel cable : model to understand**

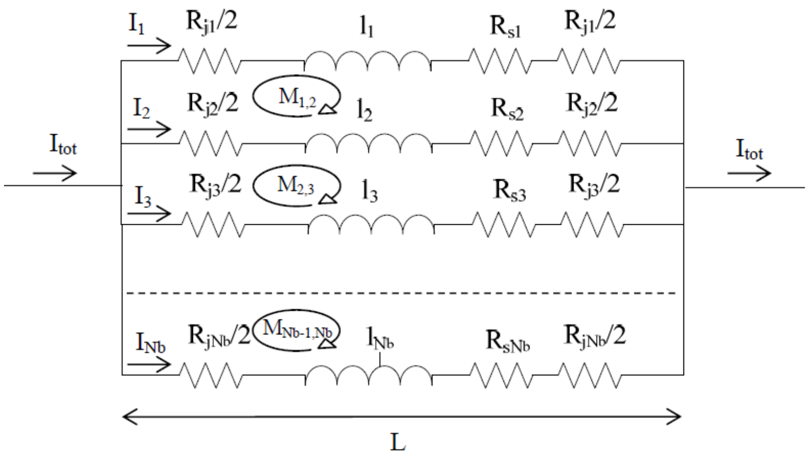
Model of current distribution in YBCO cable

Reasons of uneven current distribution in HTS cables

- Differences in the strand inductances
- Uneven joint Resistances
- Uneven strands I_c

Cable made of insulated strands

- Measured R_a=24μΩ >> 1-3 nΩ
- Voltage in each branch (V_i)



$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ \dots \\ V_i \end{pmatrix} = \begin{pmatrix} l_1 & M_{12} & M_{13} & .. & M_{1i} \\ M_{21} & l_2 & M_{23} & \dots & M_{2i} \\ M_{31} & M_{32} & l_3 & \dots & M_{3i} \\ \dots & \dots & \dots & \dots & \dots \\ M_{i1} & M_{i2} & M_{i3} & \dots & l_i \end{pmatrix} \begin{pmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \\ \dots \\ \dot{I}_i \end{pmatrix} + \begin{pmatrix} R_{s,1}+R_{j,1} \\ R_{s,2}+R_{j,2} \\ R_{s,3}+R_{j,3} \\ \dots \\ R_{s,i}+R_{j,i} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ \dots \\ I_i \end{pmatrix}$$

- Kirchhoff's laws
- Imposed current
- Superconductor resistance

$$\sum_h I_h = 0 \qquad \sum_k V_k = -\frac{d\phi}{dt}$$

$$\sum_{i=1}^{N_b} I_i = I_{source}$$

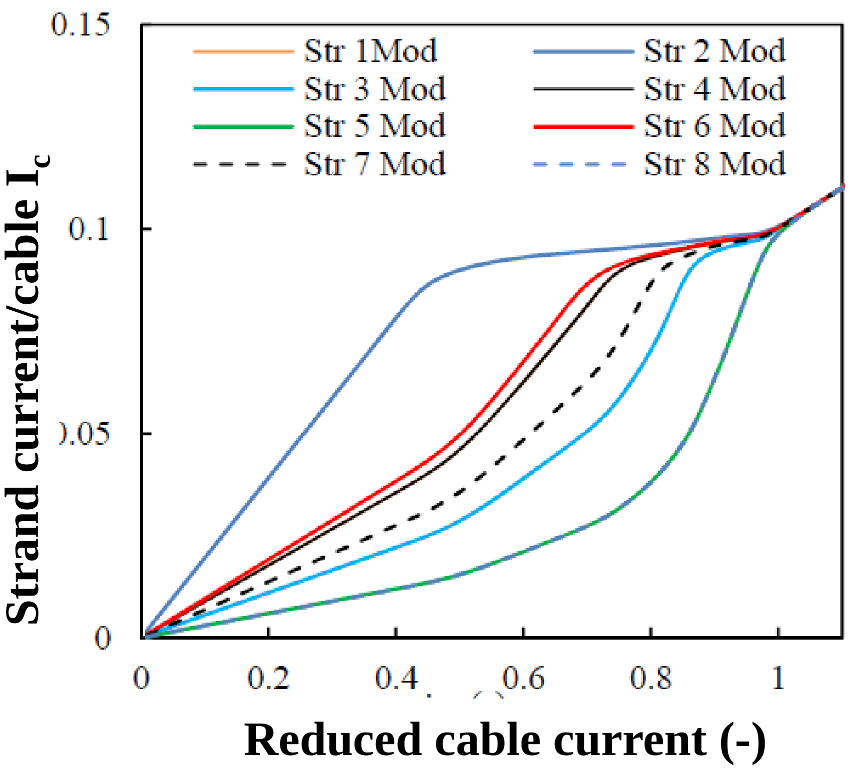
$$R_{s,i} = \frac{LE_c}{I_{c,i}} \left(\left| \frac{I_i}{I_{c,i}} \right| \right)^{n_i - 1}$$

➢ **A non linear system is set and resolved by the Newton method**

Current distribution in Roebel cables

Roebel strands transposed:

- homogeneous strand I_c (on length scale > pitch)
- homogeneous inductances
- Strand joint resistance: fitting parameters



Cable ID	Fitting parameters R_j GCS2 R_j (nΩ)
Strand 1	60
Strand 2	37
Strand 3	77
Strand 4	110
Strand 5	150
Strand 6	60
Strand 7	66
Strand 8	116
Over the 10 and 15 strands of respectively F	
R_{eq} (nΩ)	3.5
Standard deviation of R_j (nΩ)	43

➢ **Uneven strand contact resistance => uneven current distribution**

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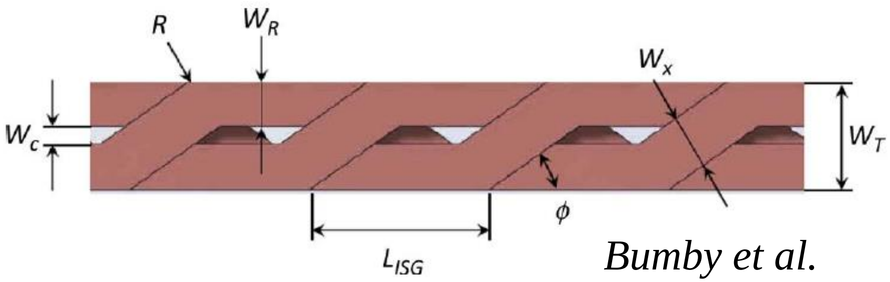
Effect of axial stress on Roebel cable I_c

Failure axial tensile stress:

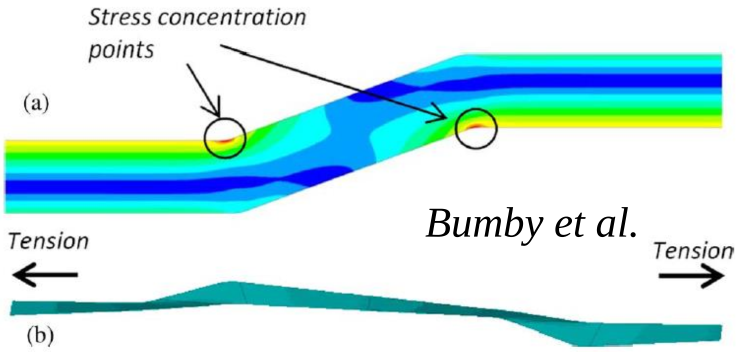
- Straight conductor : 625 MPa*
- Meander tape 146 MPa*
- Roebel cable 113 MPa*

Bumby et al.

➢ **Meander structure strongly weaken the good properties of YBCO conductors**



Bumby et al.



Bumby et al.

➢ **Tuning of cable parameters to reduce the stress sensitivity**

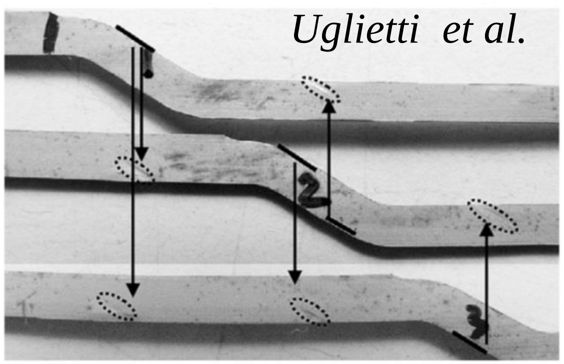
Effect of transverse stress on Roebel cable I_c

Failure transverse compressive stress:

- Straight conductor : >600 MPa*
- Meander tape >600 MPa*
- Roebel cable ≥45 MPa (CERN)

**Uglietti et al.*

➢ **Roebel topology weaken the good properties of YBCO conductors**



Uglietti et al.

➢ **Distribute transverse load by: Impregnation, management of topology and copper strips interleaved**

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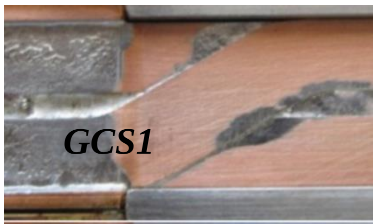
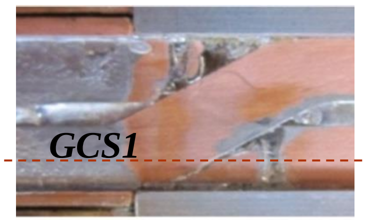
Roebel cable failure at high J_{ce}

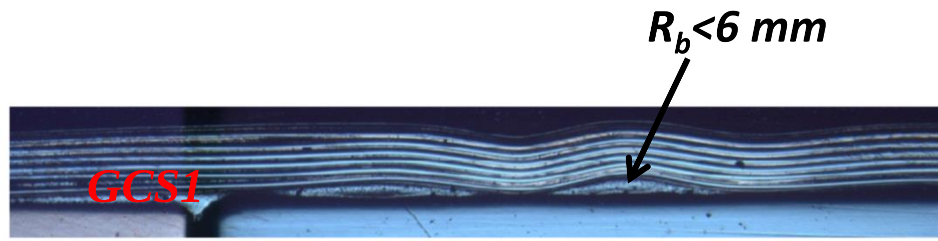
GCS Roebel cables irreversibly damaged **at B>6T, J_e>1200 A/mm²** .

- ➢ **KIT Roebel cable not damaged (12 mm² copper shunt)**

Damaged cable GCS1: 27% of I_c reduction



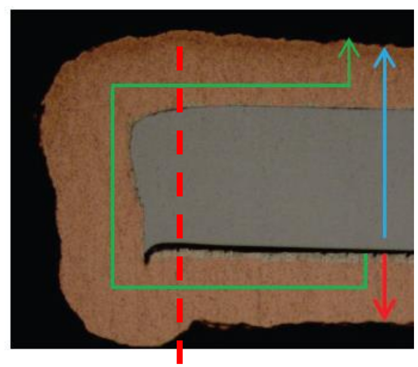


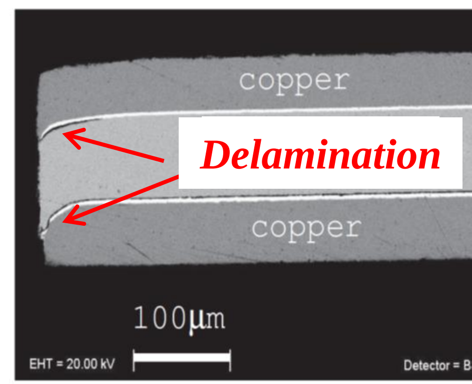


- ➢ **T > 500 K during quench=> Cable buckling=> radius lower than critical one**

Punching process of strands:

- initiate delamination
- Remove low resistivity current path
- Expose HTS to moisture





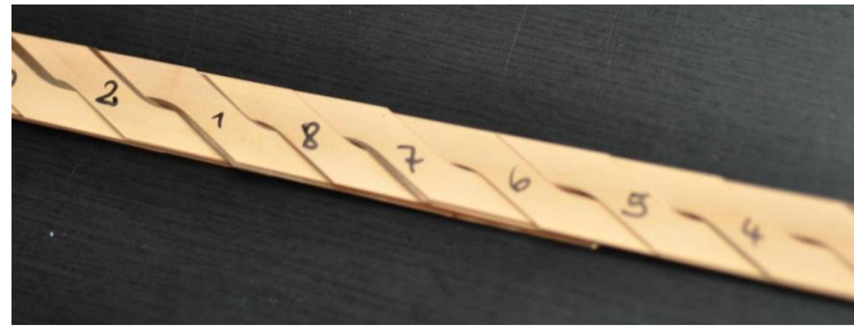
- ➢ **Roebel strands: weak electrical protection**
- ➢ **Avoid buckling: cable impregnation**

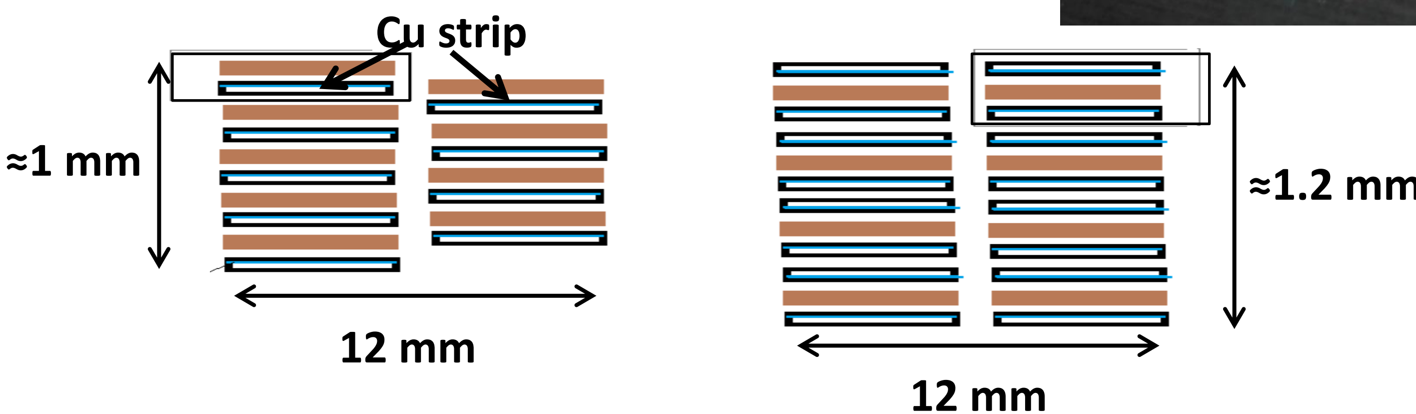
Roebel cable: improvements of protection

➢ Copper strips interleaved between strands

Soon tested at CERN:

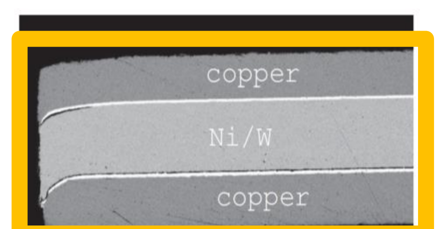
- *9 YBCO tapes + 9 Cu strips*
- *16 YBCO tapes + 8 Cu strips*





➢ Plating of meander strands after punching

Proposed to manufacturer



Conclusion

- YBCO conductor: promising material to generate dipolar field >20 T
  - High J_c, B_{irr}
  - High mechanical strength: axial and trans compression
  - Delamination issues

- Electromechanical behaviour of YBCO fully understood
  - Characterisation and parameterization of $J_c(B,T,\Theta)$
  - Ic reduction with bending and twisting $\mathbf{R_{min,easy}}$**=4 mm,** $\mathbf{R_{min,hard}}$**=900 mm**
  - Splice resistance **33 nΩ. cm²**
- Roebel cable: a valid concept for high field magnets
  - Transposed
  - High I_c (12 kA @ 7 T), high J_{ce} (1200A/mm^2 @ 7 T)

- Perspectives for Roebel cable:
  - More current (~20 kA)
  - Avoid strand delamination (protection/ uniform strand joint resistance)
  - Reduce strand I_c inhomogeneity
  - Improve protection