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# Transverse stress in Roebel cables: design parameter space

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# Outline

- Electrical characterization of Roebel cable with enhanced stabilization
- Transverse stress in Roebel cables: design parameter space
  - Prints of Roebel cables
  - Effective section of KIT and GCS cables
  - Design parameter space

# Characterization of Roebel cable in FRESCA (1/4)

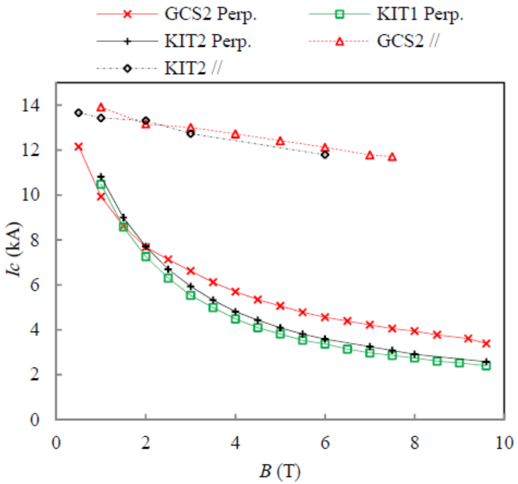
## Measurements at 4.2 K in FRESCA in ⊥ and // fields of up to 10T

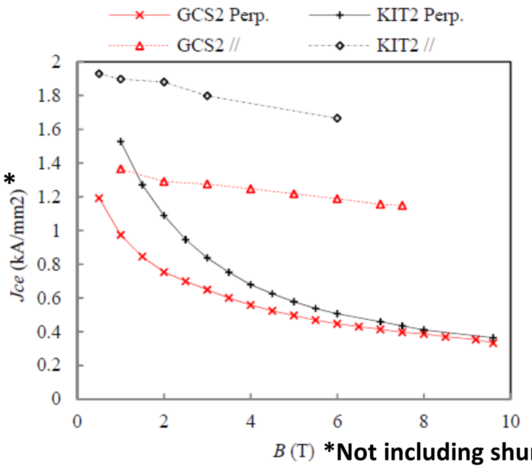
**No degradation of Ic**

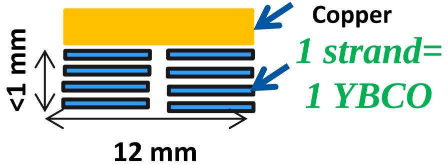
**Previous measurements:**

- **KIT** 126mm pitch, **10** strands
- **GCS** 300 mm pitch **15** strands
- 12 mm$^2$ copper shunt
- No impregnation
- Vtaps on almost each strand
- Hall probes

**B// : $I_c$>11 kA, low joint resistance**



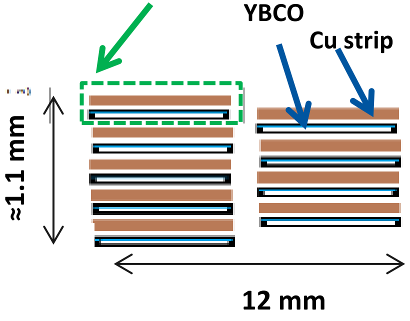



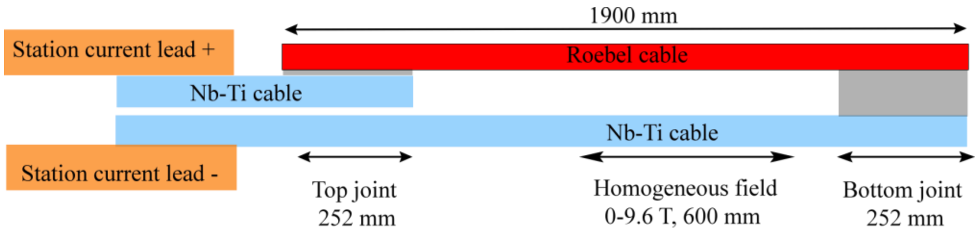

J. Fleiter et al., Electrical characterization of REBCO Roebel cables Supercond. Sci. Technol. 26 (2013)

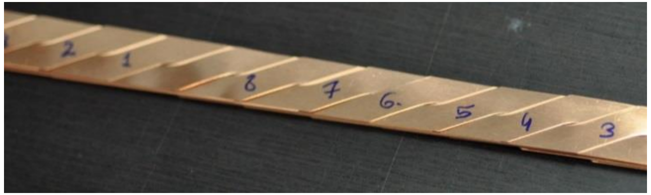
# Characterization of Roebel cable in FRESCA (2/4)

## KIT cable with enhanced stabilization

- **9 YBCO** strands
- **Enhanced stabilization** : **9** interleaved **copper** strands
- $T_p$ =126 mm, Width=12 mm
- No impregnation
- Vtaps on each strand



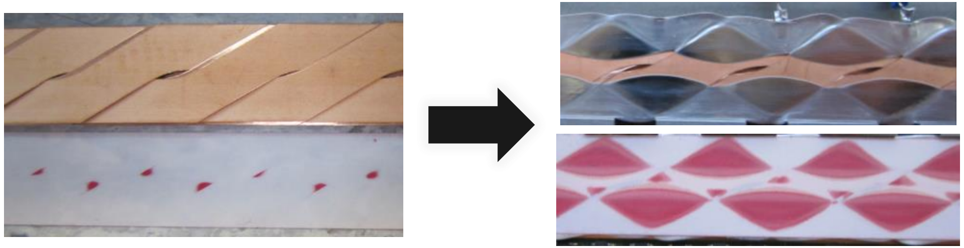



# Characterization of Roebel cable in FRESCA (3/4)

- 30 MPa transverse pre-stress for characterization
- Effective section ($E_s$) found to be  2%

**Large peak stress (1.5 GPa) → plastic deformation and $I_c$ reduction**

- Use of Sn-Pb shims => $E_s$ increases to ~35%



Red patches indicate stresses >10 MPa

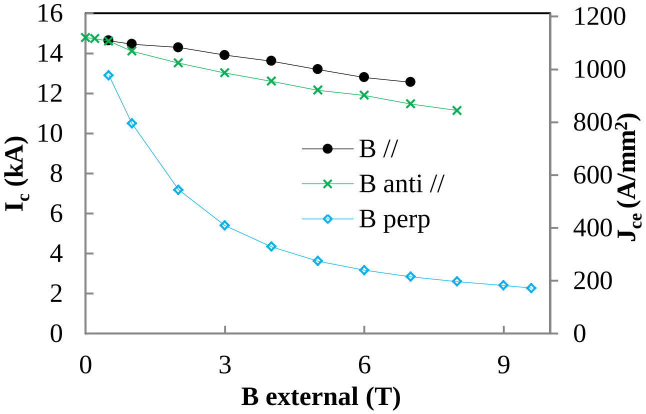
Yield stress of Sn-Pb ~60 MPa

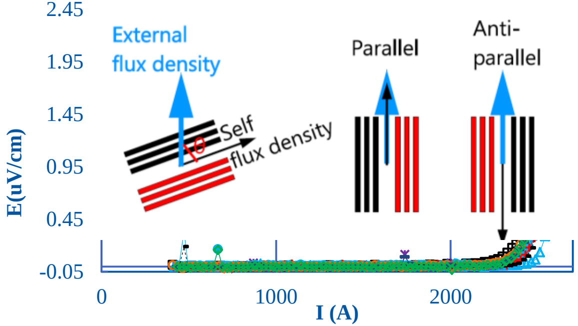
➢ **Shimming: possible method for managing $E_s$**

# Characterization of Roebel cable in FRESCA (4/4)

- Measured $I_c$ and $J_{ce}$
  - **B (perp,9.6 T)**: **2.3 kA - 190 A/mm²**
  - **B (//, 7 T)** : **13 kA - 900 A/mm²**
- With respect to previous 10 strands cable: **-12%** of $I_c$ in **perp field, +9%** of $I_c$ in **// field**
- **8 quenches** at **13 kA**, 900A/mm² , **20 mV threshold**

  **Ic reduction < 3.5%**
- Low joint resistance =1 nΩ, Homogeneous current distribution




➢**Good quench performances**

➢**Next test : very high current Roebel cable ($I_c$~20 kA: 16 YBCO+8 copper)**

# Outline

- Characterization Roebel cable with enhanced stabilization
- Transverse stress in Roebel cables:  design parameter space
  - Prints of Roebel cable
  - Effective section of KIT and GCS cables
  - Design parameter space

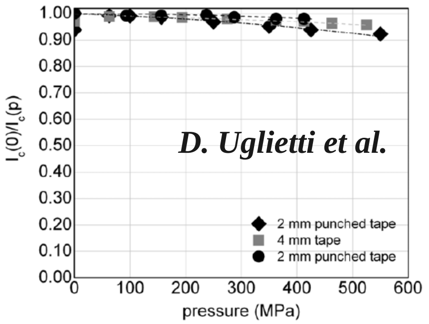
# Which is the transverse effective surface of a Roebel cable?

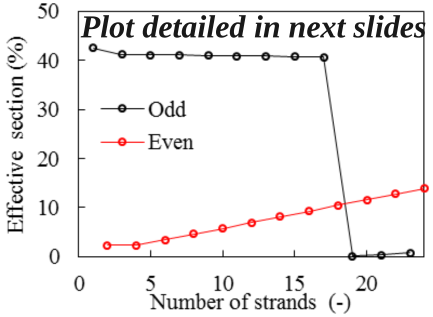
- Stress of **100-200 MPa** in high field magnet coils
- YBCO resilience ~ **600 MPa**

➢ **Effective section >= 40 % to contain peak stress and control inter-strand resistance**

- **Impregnation helps** to distribute stress **but**:
  - Process of impregnation under **stress**
  - $\mathbf{E_{epoxy} << E_{conductor}}$
  - **Issues** with **delamination**
  - **Do not reduce** interstrand **resistance**

➢ **Management of $E_s$ in dry Roebel cables = > experimental and numerical tools**



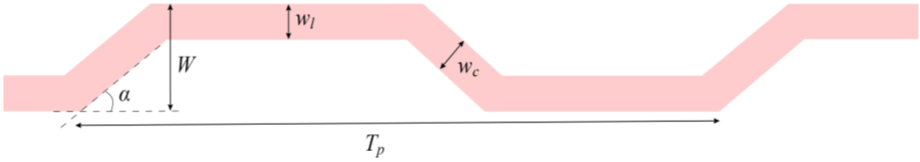



# Measurement of transverse effective section

## Various 12mm wide Roebel cables

- **KIT** $T_p$=126mm, $N_b$=2-10
- **GCS** $T_p$=300 mm, $N_b$=15-24

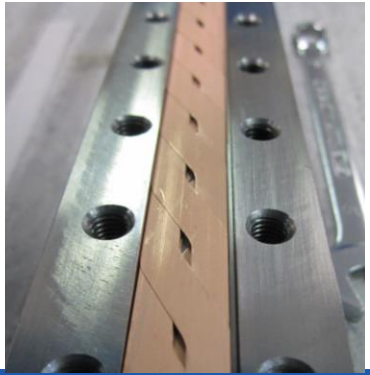
| Manufacturer | KIT | GCS |
|---|---|---|
| Tape thickness (mm) | 0.1 | 0.1 |
| W (mm) | 12 | 12 |
| $w_l$ (mm) | 5.5 | 5 |
| $w_c$ (mm) | 5.5 | 6 |
| $T_p$ (mm) | 126 | 300 |
| α (°) | 30 | 30 |




## Mould and Fujifilm paper to make prints (300 K)

- 300 mm long stainless steel mould
- HS film (10-50 MPa)
- Average stress of 30 MPa

Red patches indicate stresses >10 MPa

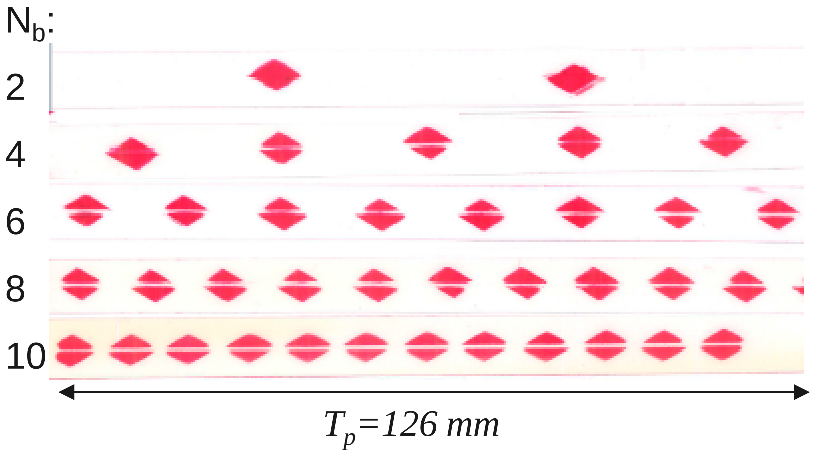


# Prints of KIT Roebel cables

Work to be presented at ASC

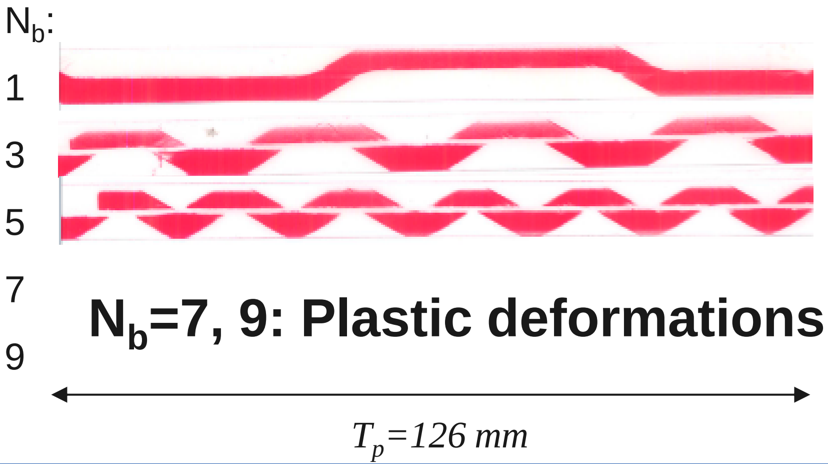
## Even number of strands:

- **Symmetric** distribution
- **Stress** patches at **crossings**
- **Low** effective **section**




## Odd number of strands:

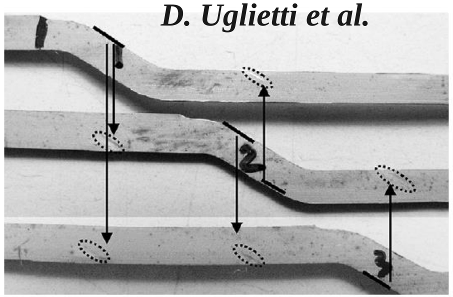
- **Asymmetric** distribution
- **Large** effective **section but interferences** at large **Nb (Nb=7 and 9)**



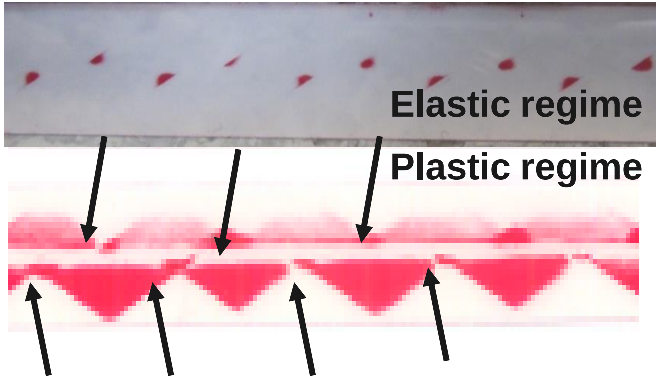
# Plastic deformations of Roebel cable

For specific configurations, strands were stamped during experiment

- **KIT 7,9 strands**
- **GCS 19,21,23 strands**




**Prints of KIT 9 cable**



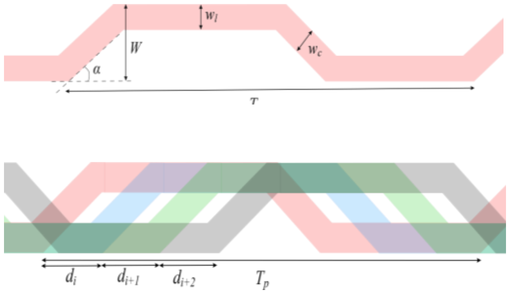

Stamped cables:

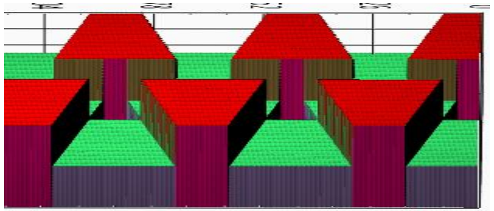
- **tiny** effective section in **elastic** regime (<2%)
- **larger** effective section in **plastic** regime (>30%) =>Irreversible **reduction of $I_c$**

➢ **Stamped cables have degraded $I_c$**

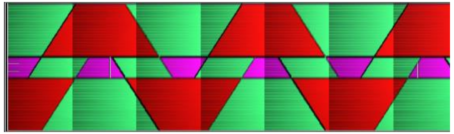
# Semi-analytical 2-D model

- **Model** compute **cable thickness** (~ $t_{tape}$) as function of $T_p$, $N_b$, W, $w_l$, di, and α
- **Elastic strain** regime, no impact of tape thickness
- ➢ **Transverse loads on thicker spots of the cable**
- Cable thickness post processed to Red&Grey image



*3 strands cable*



*3 strands cable top view*

***Red=thicker spots ($t=t_{max}$) =>stress***

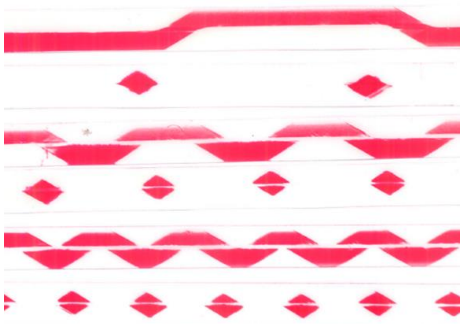
***Grey =thinner spots ($t<t_{max}$) =>no stress***

➢ Model allow to compute print and effective section of cable

# Cable prints: model vs. measurements

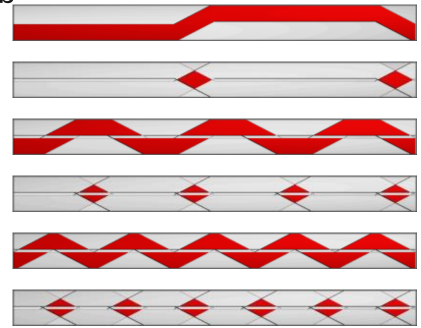
## KIT cables

Experiment



Model

$N_b$:
1
2
3
4
5
6

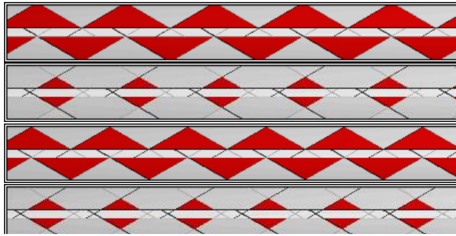


## GCS cables

Experiment

Model

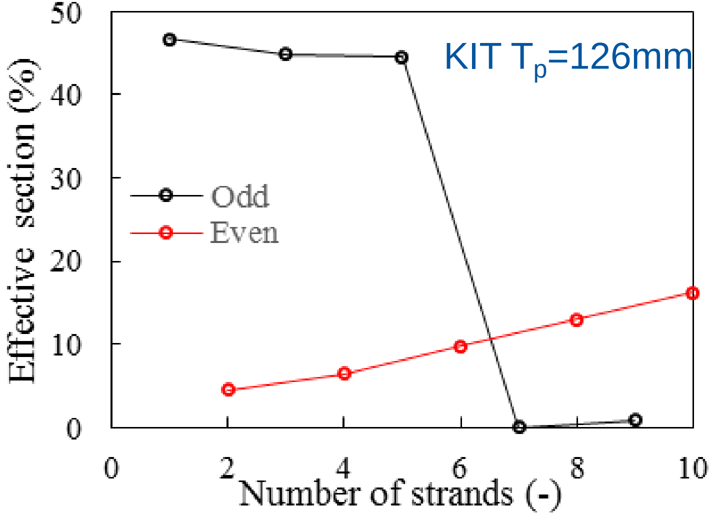
$N_b$:
15
16
17
18

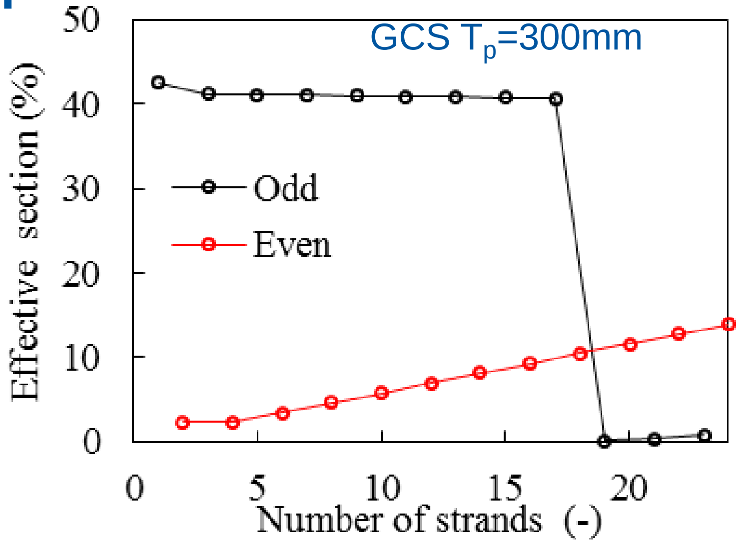


- ➢ **Perfect agreement between computed prints  and measurements**

# The effective section of Roebel cables

## Estimation of $E_s$ from the computed prints



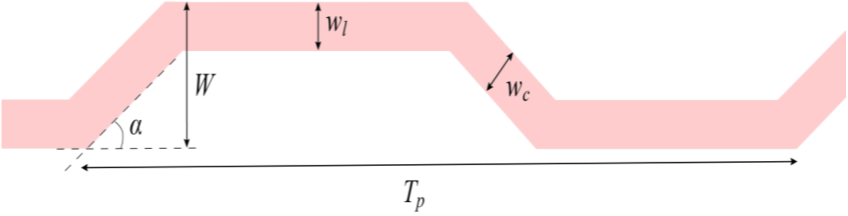




Even number of strands: $E_s$=4-16%

Odd number of strands : $E_s$ =40-50% for $N_b$<$N_c$

# Transverse stress: design parameter space

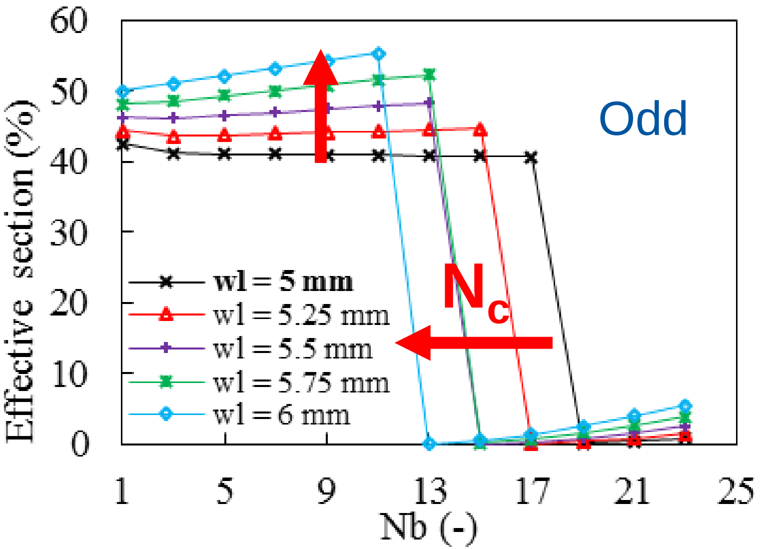
## Illustrated with a case study:

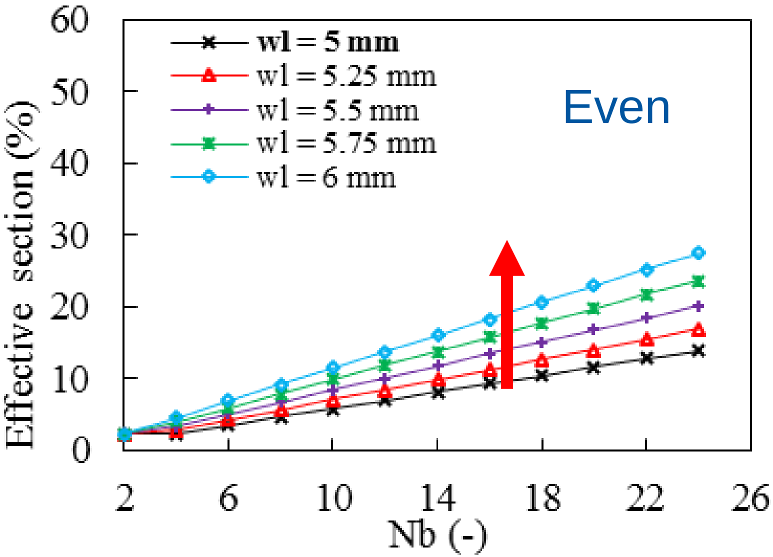


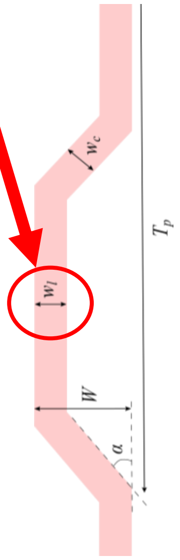

- Meander tape
  - $T_p$= 300 mm, Alpha=30°
  - W= 12 mm, $w_l$= 5 mm $w_c$=6 mm
- Cable $N_b$=2-24
- 2-D model in elastic strain regime
- Parametric analysis of $E_s$ as function of $w_l$, wc,α,Tp
- $N_c$: critical odd number of strand before $E_s$ drops to 0

# Design parameter space: longitudinal width ($w_l$)

## Increase of $w_l$=> increase meander tape $I_c$ and reduce lateral sponging



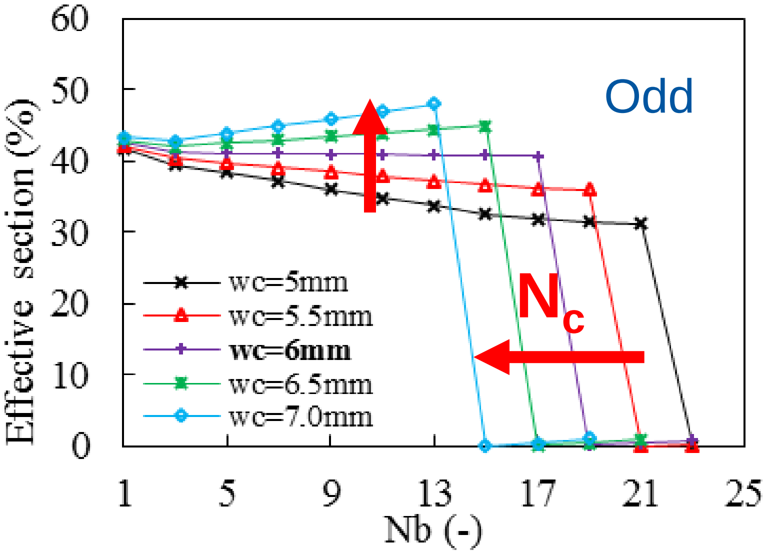



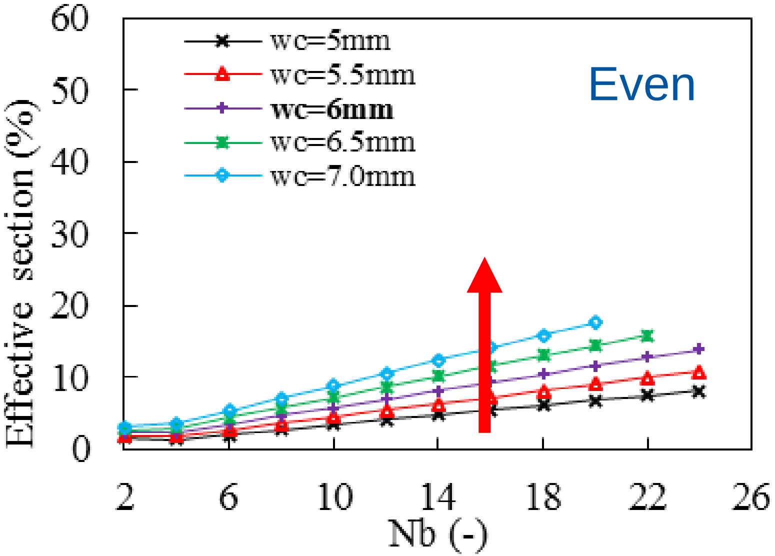



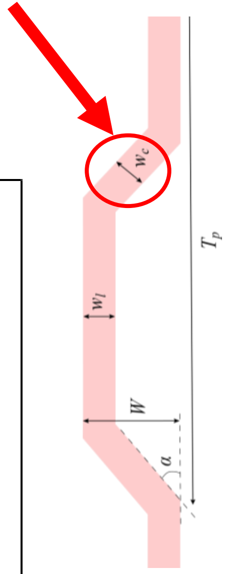
- **Rise of $w_l$ => increase of $E_s$ (odd&even) but decrease of $N_c$ (odd)**

# Design parameter space: longitudinal width ($w_c$)

## Increase of $w_c$=> increase meander tape $I_c$



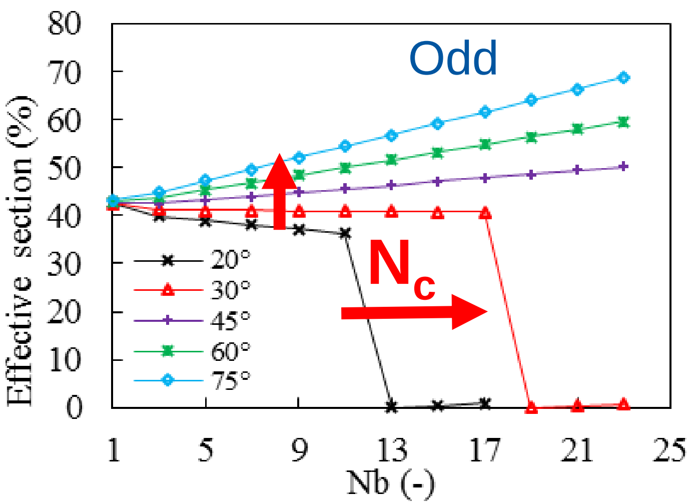



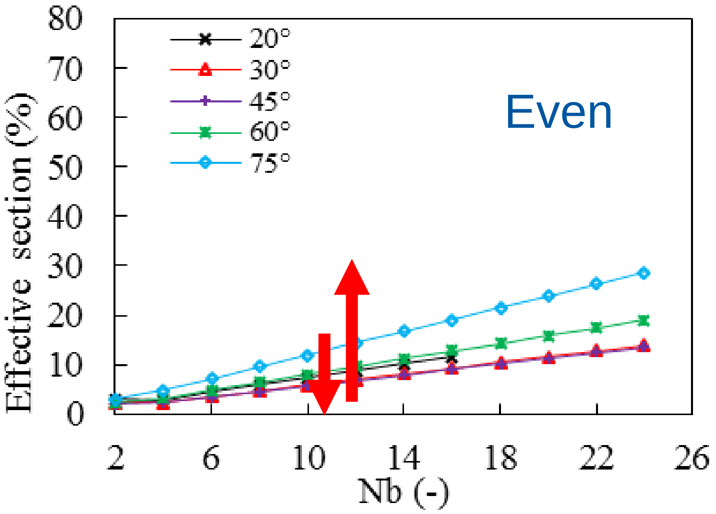



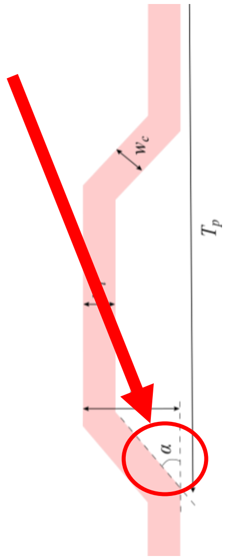
- **Rise of $w_c$ => increase of $E_s$ (odd&even) but reduce $N_c$ (odd)**

# Design parameter space: crossing angle (α)

Increase of α=> increase $N_{bmax}$ , longitudinal mechanical properties?



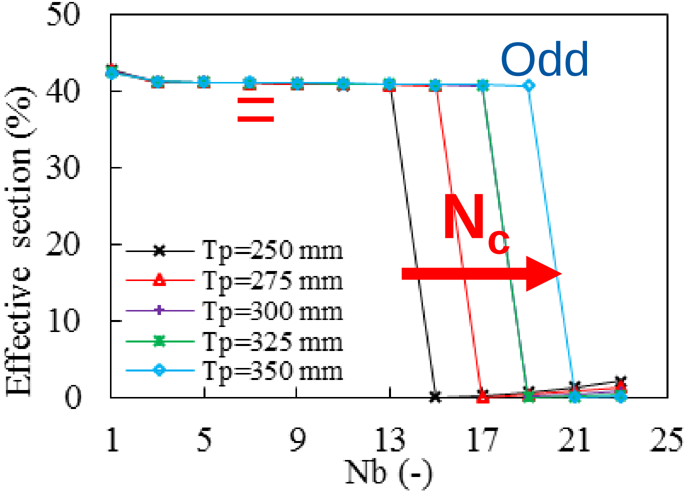



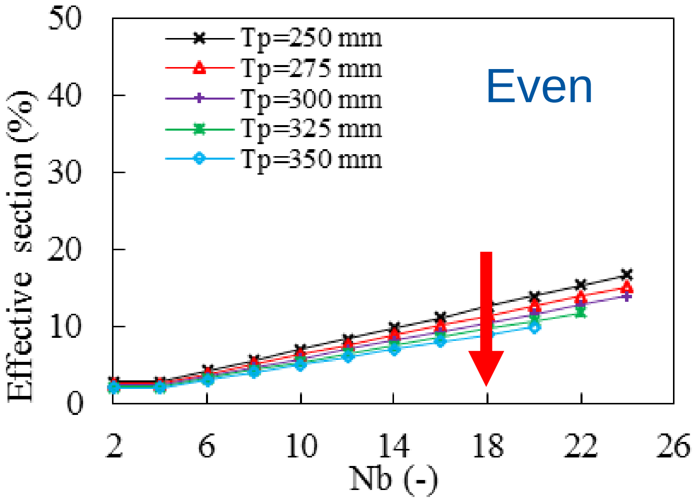



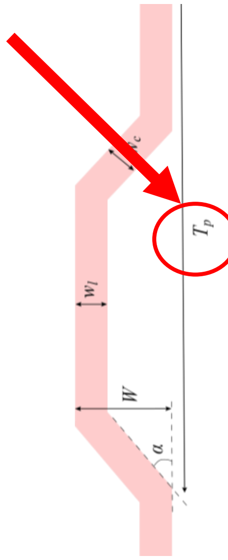
- **Rise of $w_c$ => increase of $E_s$ (odd&even) and $N_c$ (odd)**

# Design parameter space: transposition pitch ($T_p$)

## Increase of $T_p$=> less flexibility for bending



- **Rise of $T_p$ => increase $N_c$ (odd) and reduce $E_s$ (even)**

# Conclusions

- Successful characterization in LHe of high-current Roebel cables about 2 m long
  Handling and understanding of mechanical stress, development of low-resistance joints

- Roebel cable with enhanced stabilization
  - High performances: $I_c$ @10 T=2.3-10 kA , $J_{ce}$=190-900 A /mm$^2$
  - Good quench performances at high current
  - Homogeneous current distribution

- Roebel cable transverse effective section
  - 2D- model to compute prints and $E_s$
  - Typical $E_s$ values: 50% (odd) and 20% (even)
  - Avoid numerous odd number of strands (plastic deformations)
  - Room for optimization: increase α, manage $N_b$

- After having decided the operating current and field, we can elaborate the optimised cable configuration

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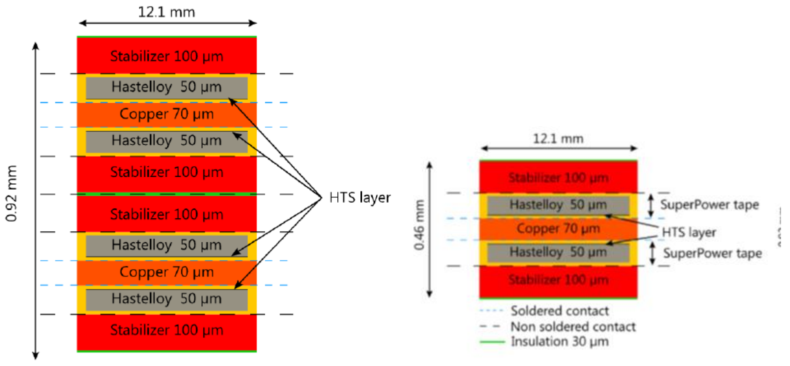
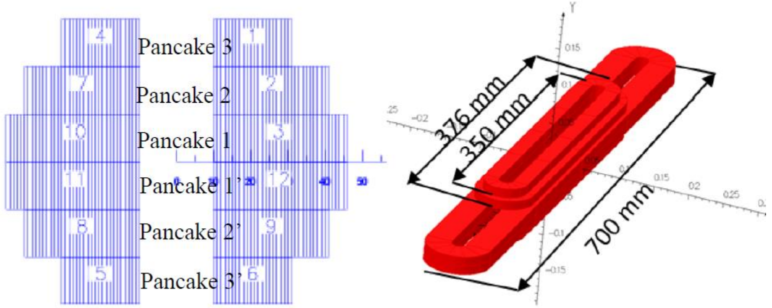
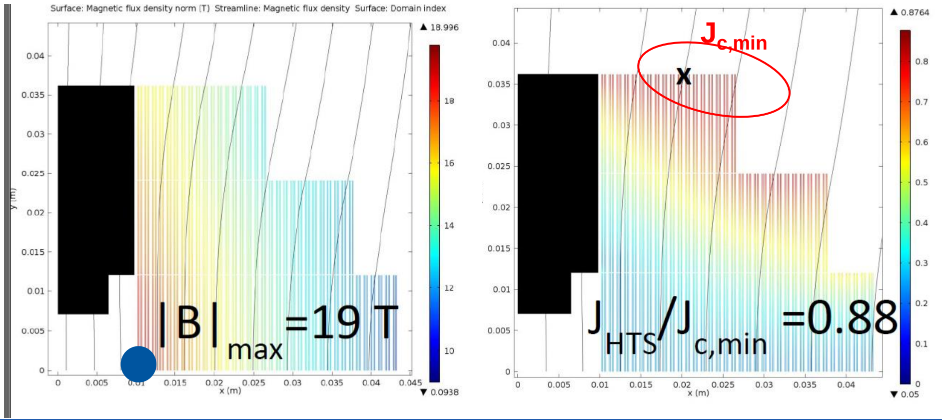
# EuCARD1 the HTS insert




<u>EuCARD1 dipole: **6 T** from **HTS**, 13 T from $Nb_3Sn$</u>

- Cable=2 sub-cables (each 2 YBCO tapes+ Cu)
- $I_{nom,cable}$= 2.8 kA @ ($B_0$=19 T),
- $R_{min}$= 10 mm
- Critical spot of coil: 15 T, 77° (@$B_0$=19 T)



# EuCARD1 HTS sub cable qualification

- Critical spot of coil: 15 T, 77° (@$B_0$=19 T)
- $J_c$ (15 T, 77°)>$J_c$ (10 T, 0°) => **qualification in FRESCA**

## Characterization at CERN of sub cable

- 4 K, B⇦: **$I_c$ (9.6 T)=1.8 kA**, n= 40-50, $R_j$=76 n⎵ (intrinsic)
- 77 K,0T, $I_c$ =734 A, **No damage at $R_b$=10 mm**