CCA2025

International Workshop on Coated Conductors for Applications

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Winding of accelerator magnets

Diego Perini

On behalf of CERN, TE-MSC-HSD team

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- Some examples of what can be wound today using REBCO tapes
- Nominal and accidental loads during manufacturing
- Winding technique and tools
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Introduction

REBCO tapes are ‘delicate’. A mistake or an unforeseen charge (**accidental load**) can heavily affect the possibility of carrying current.

On the other hand, the tapes can withstand relatively heavy loads in certain directions if the situation is well controlled.

The best of the cables can not help if the coils are not wound correctly. **Without perfect coils we do not go far**.

The coil manufacturing is one of the first steps of a magnet fabrication chain. **Winding** implies a lot of **technical aspects** that must be mastered. Theory and practice.

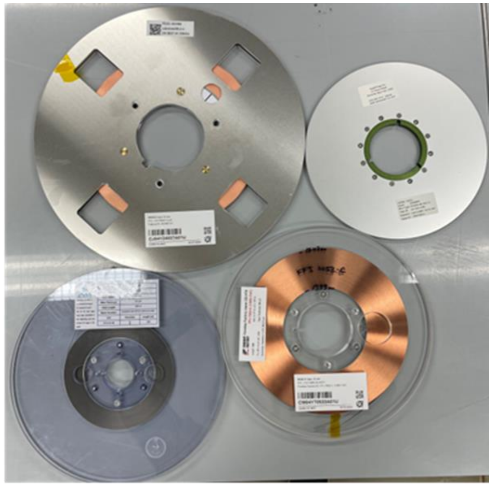
Tests to settle tools and procedures are fundamental and can take longer than what we would like. But it is a well invested time.

The coils that we wind today – limits and possibilities

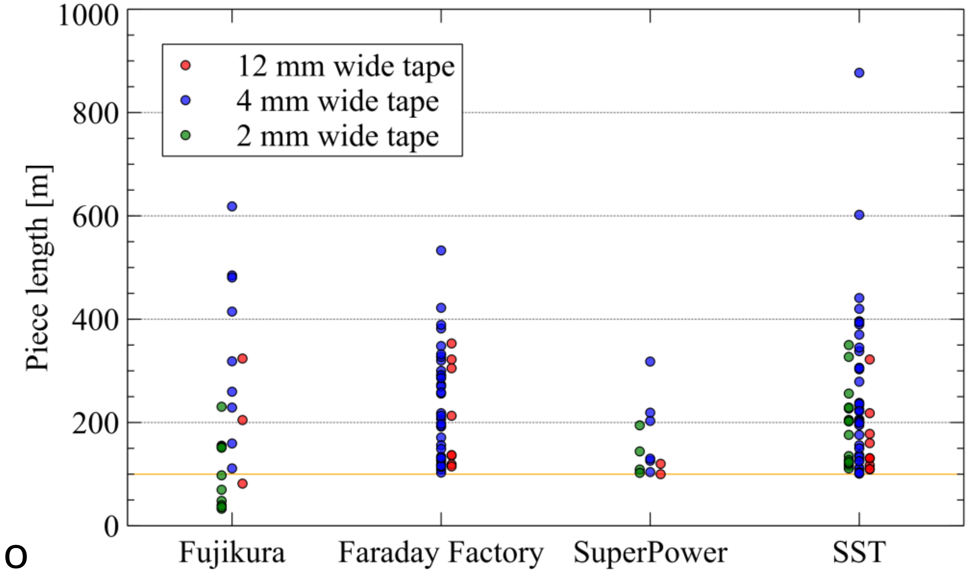
REBCO conductor is available in tapes of various width.

The production length is of the order of some hundreds of meters per piece. The situation will improve, but for the time being, this is a tight boundary for the length of the coils we can produce (half a meter for a double pancake coil using 12-mm tapes)

There are ideas and tests going on, but so far, we do not have transposed (twisted) cables. Just stacks of tapes.

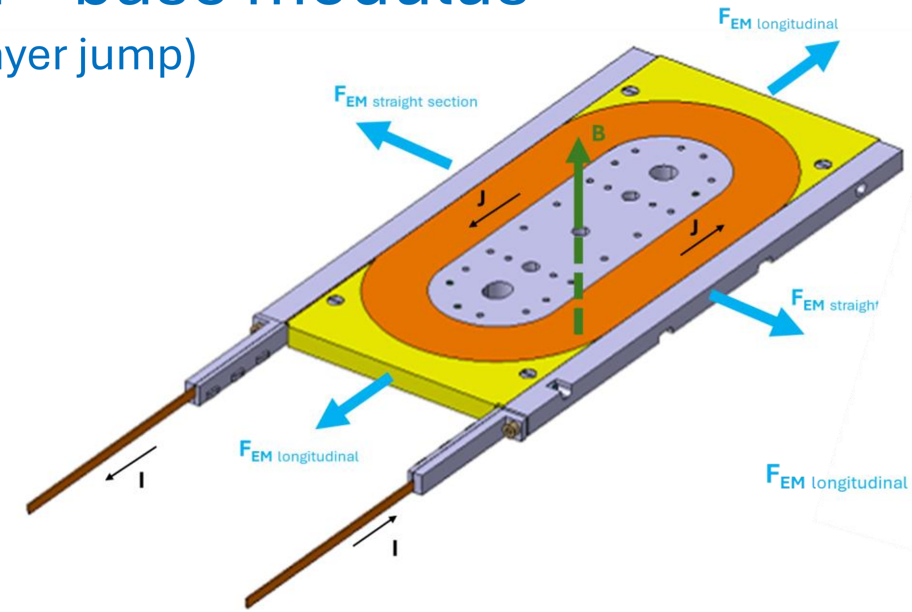


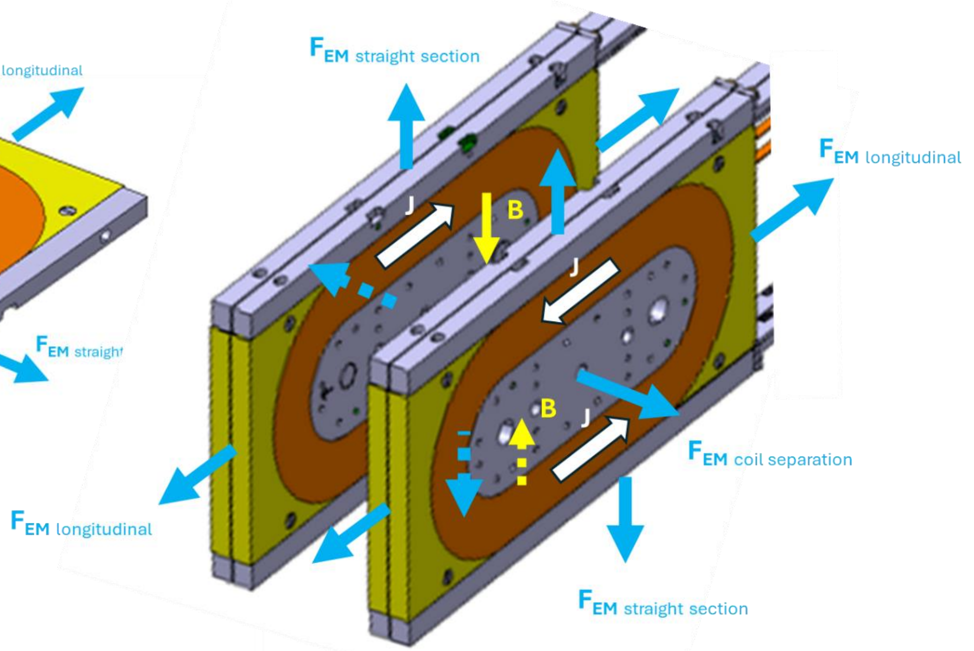
Courtesy A. Ballarino

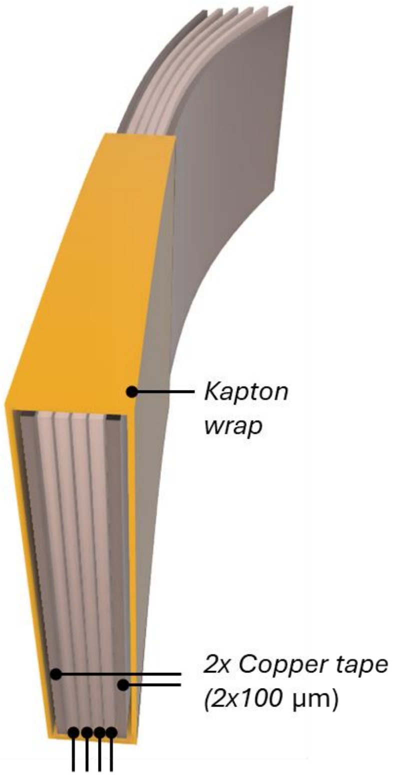


Single coil configuration – base modulus

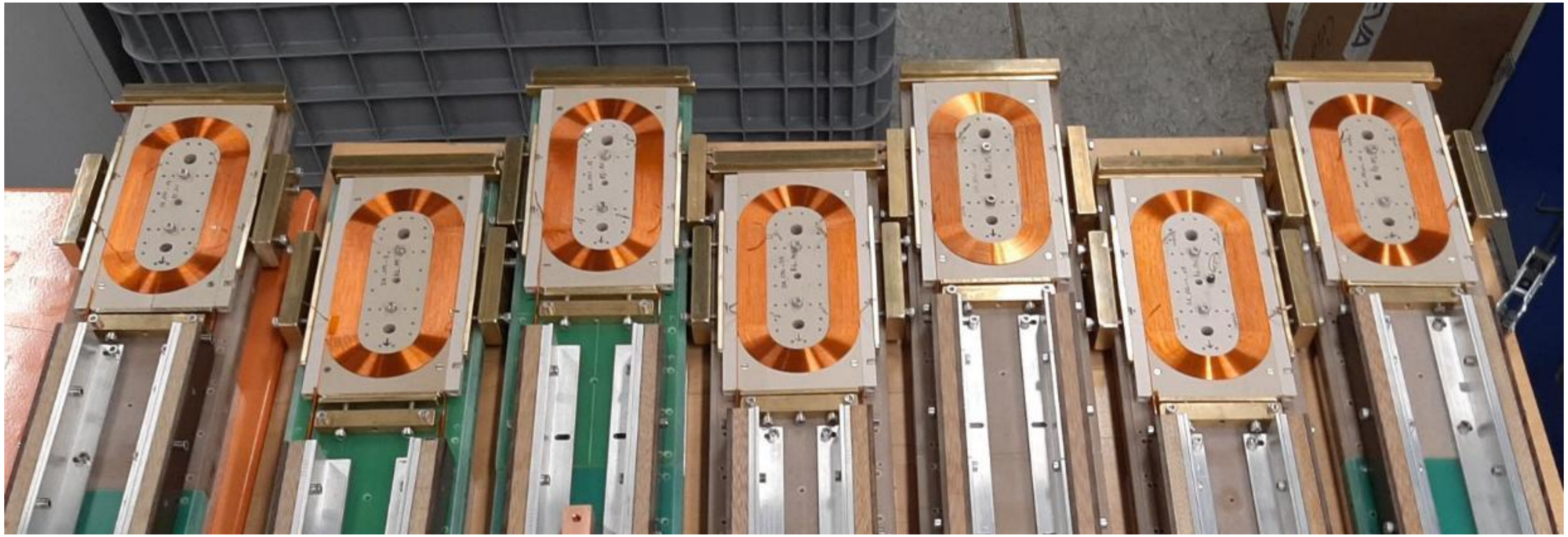
(double pancake windings, internal layer jump)

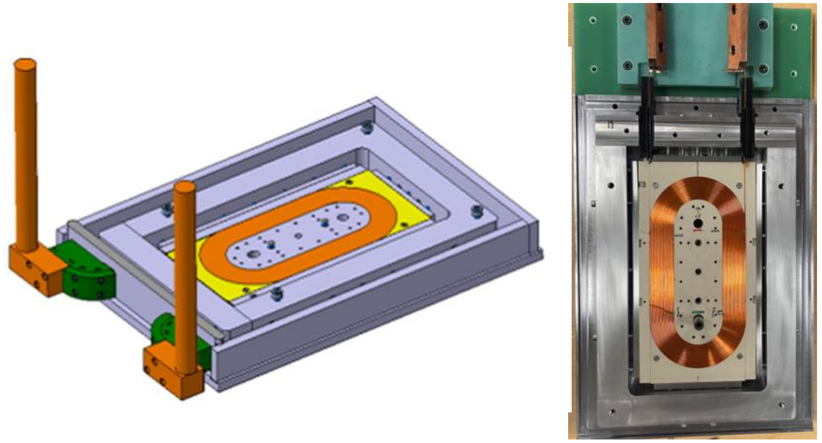




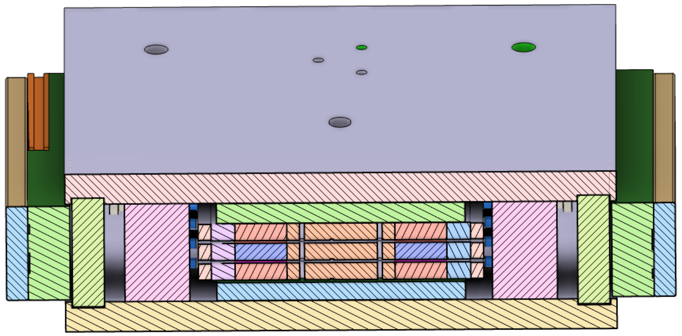


Example of a dielectric insulated cable.
Courtesy A. Baskys

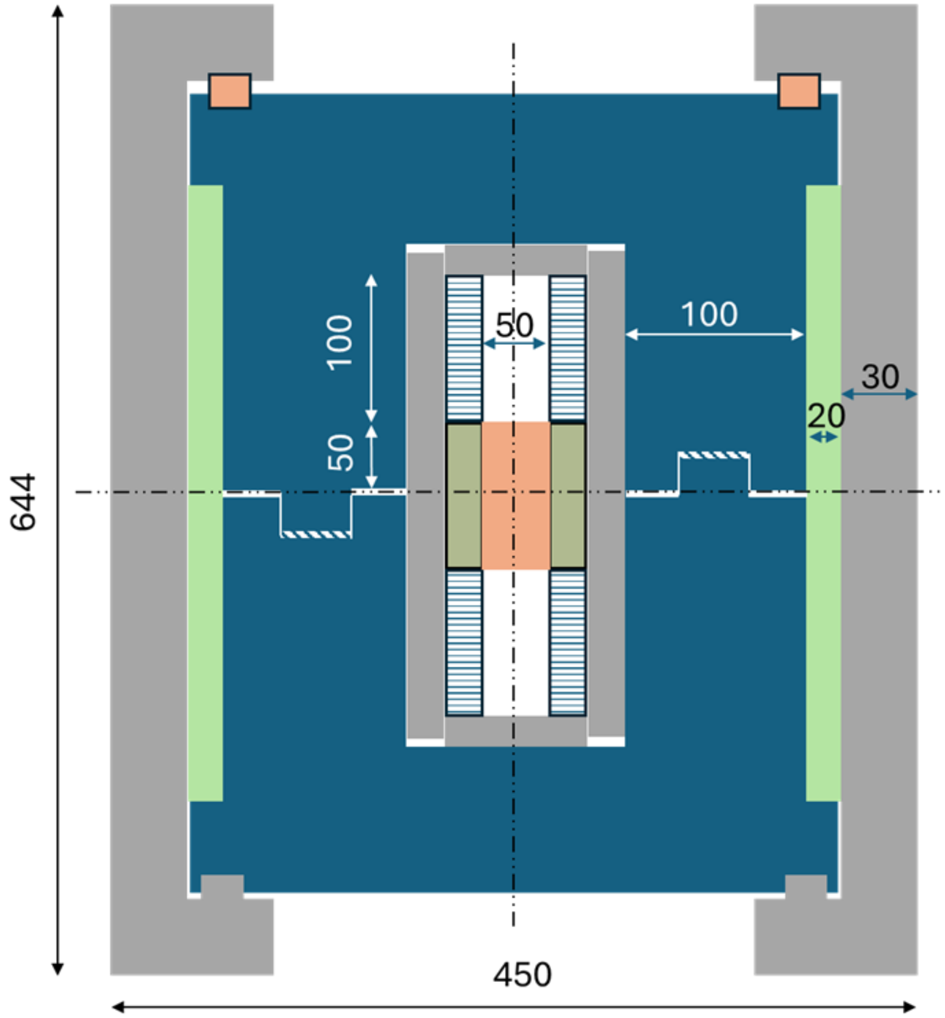




Structure for one double-layer racetrack coil (**2.65 T** in center, **5.2 T** peak field @ 4.5 K). Nominal current 2000 A.

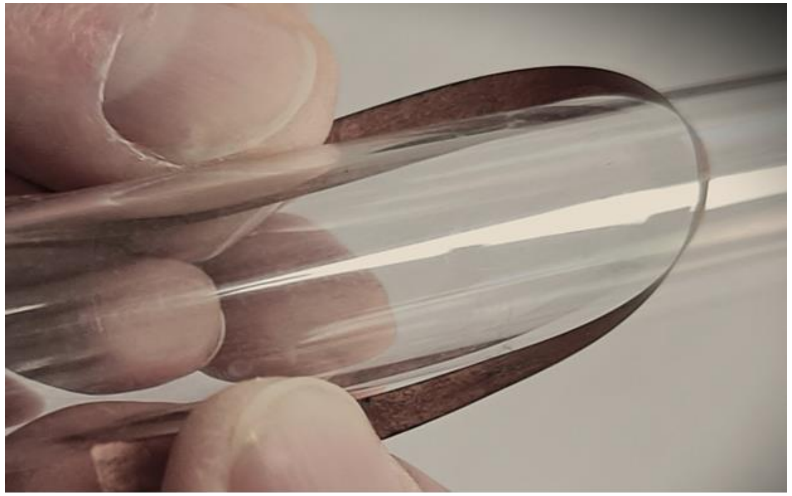


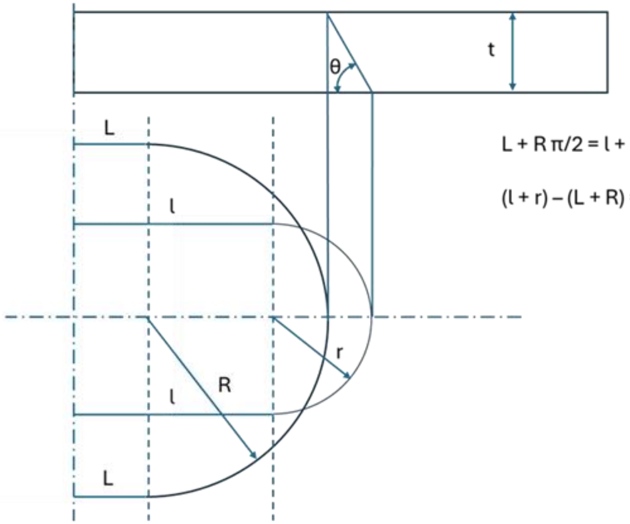
Structure for up to three double-layer racetrack coils (**5.8 T** in center, **9.7 T** peak field @ 4.5 K). Nominal current 2000 A.



Preliminary design of a 10 T common coil dipole using 12-mm wide tapes. Scalable to higher fields.

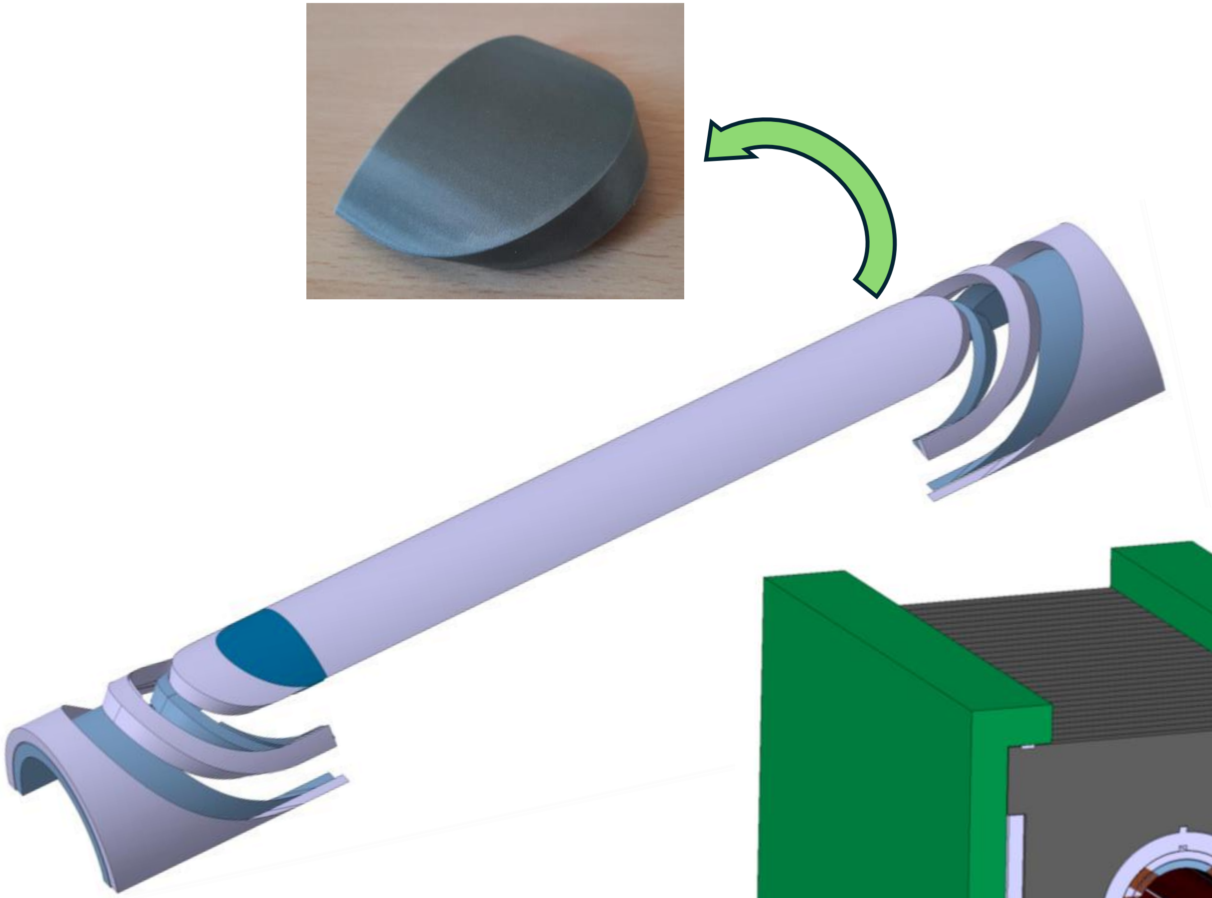
Cos(θ) coils – possible

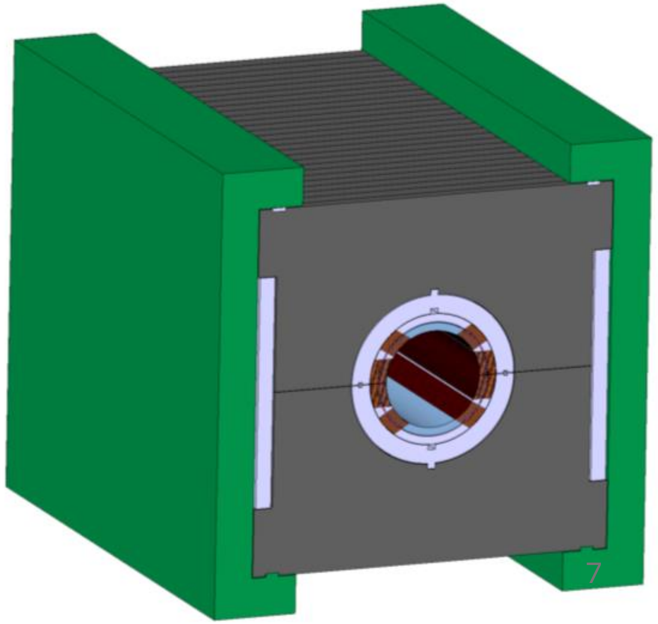




$$L + R\pi/2 = l + r\pi/2$$

$$(l + r) - (L + R) = t/tg\theta$$

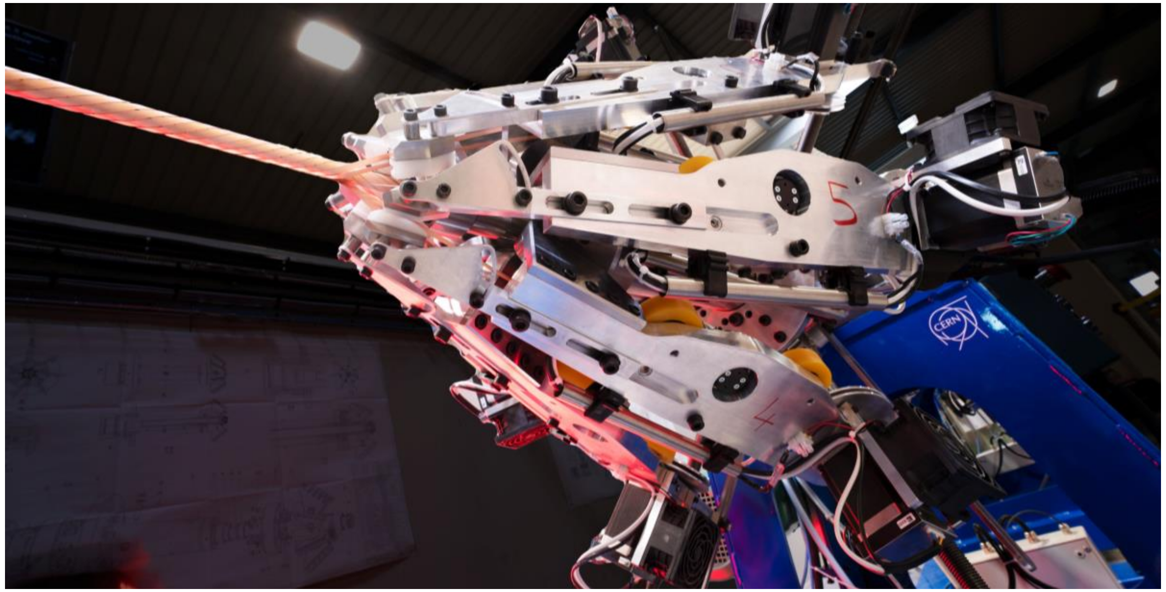




Other possible cable configurations

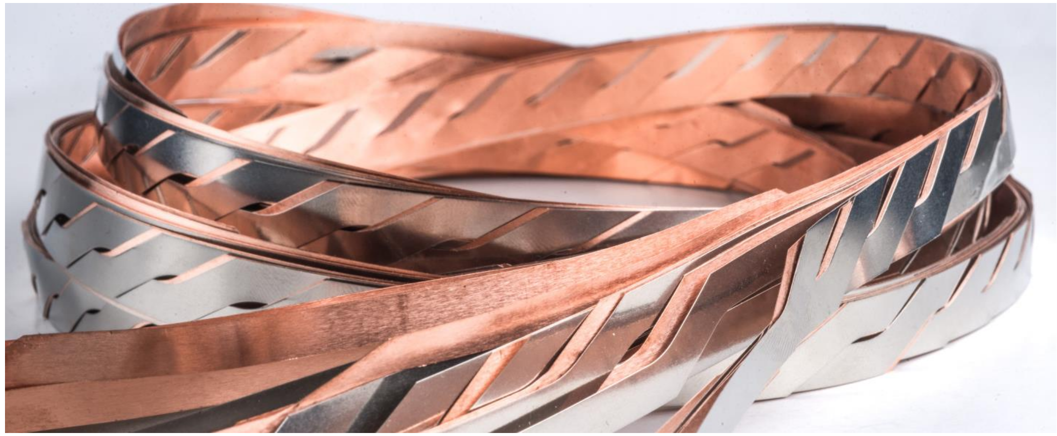
Round cable

- Twisted
- Good for CCTs
- Minimum curvature radius
- J engineering



Roebel cable

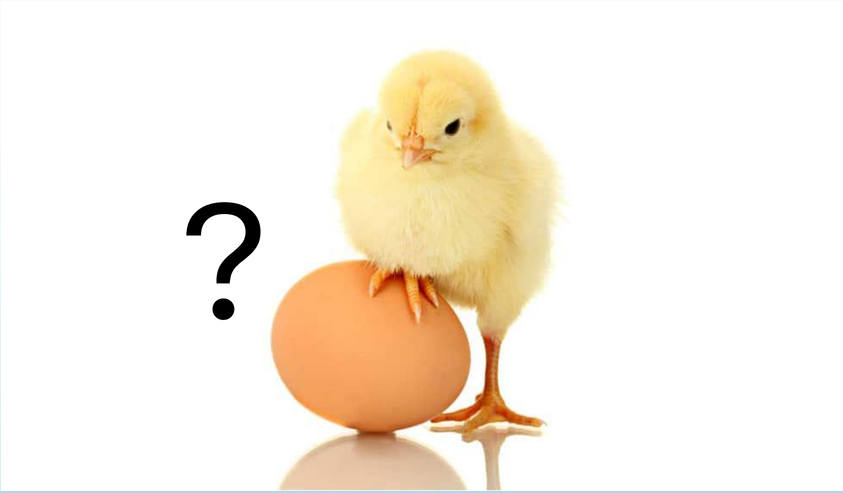
- Transposed
- Shape stability
- Scrap



Things can go wrong during coil winding and magnet assembly

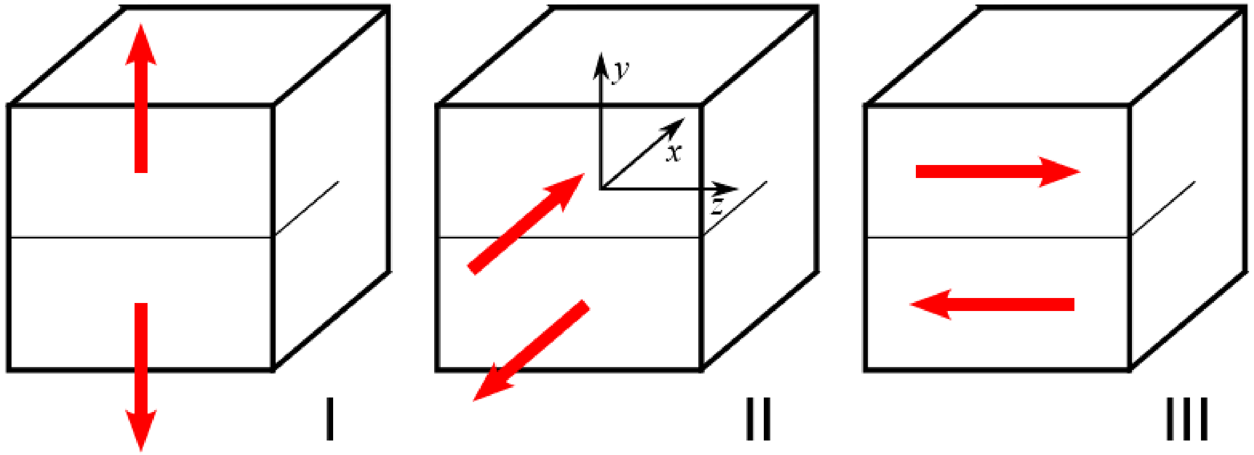
- Accidental loads

- Discontinuities (different parts in contact)

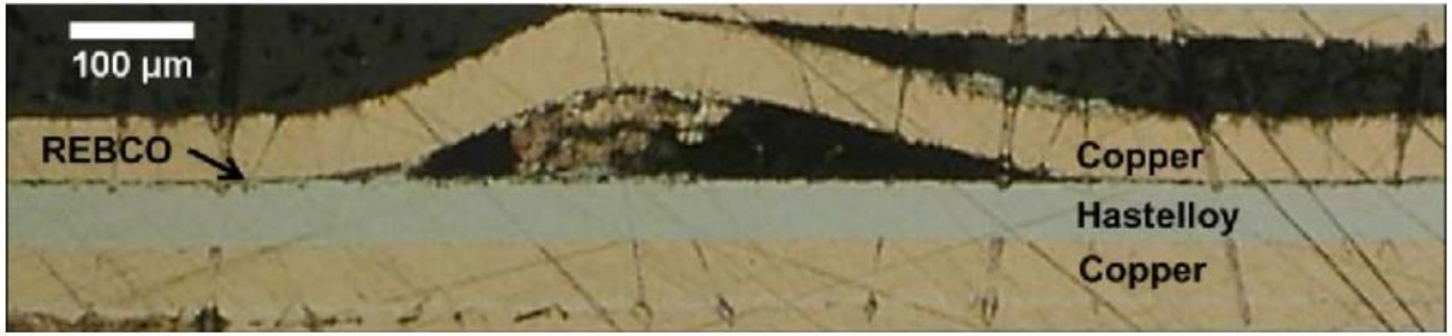


Discontinuities can trigger accidental loads – Accidental loads are particularly dangerous close to discontinuities

Direction of the loads - 1



The three ways of opening and propagating a crack.
Essentially traction or shear.

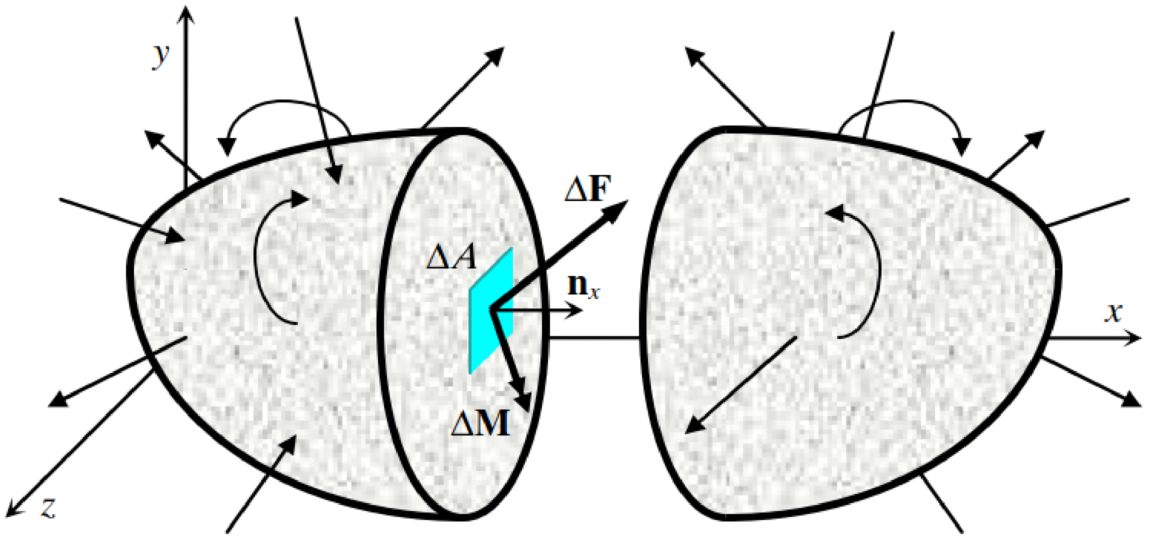


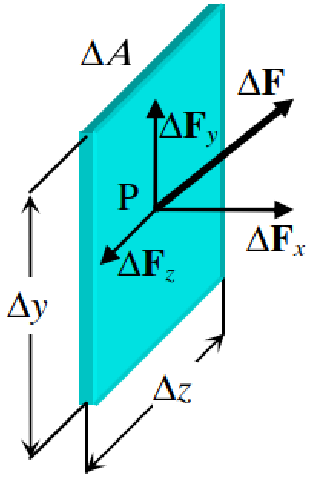
DOI:10.1109/TASC.2012.2237496Corpus ID: 23648869
G. Majkic and others
Investigation of Delamination Mechanisms in IBAD-MOCVD REBCO Coated Conductors

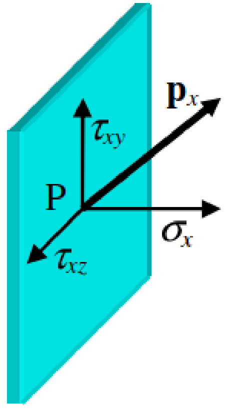
Delamination damages in REBCO tapes appear already at stress levels of the order of 10 MPa while the longitudinal traction resistance is much higher (hundreds of MPa without critical current degradation).

DOI:10.1088/0953-2048/28/4/045011
C.Barth, G. Mondonico, C. Senatore
Electro-mechanical properties of REBCO coated conductors from various industrial manufacturers at 77 K, self-field and 4.2 K, 19 T

Direction of the loads - 2





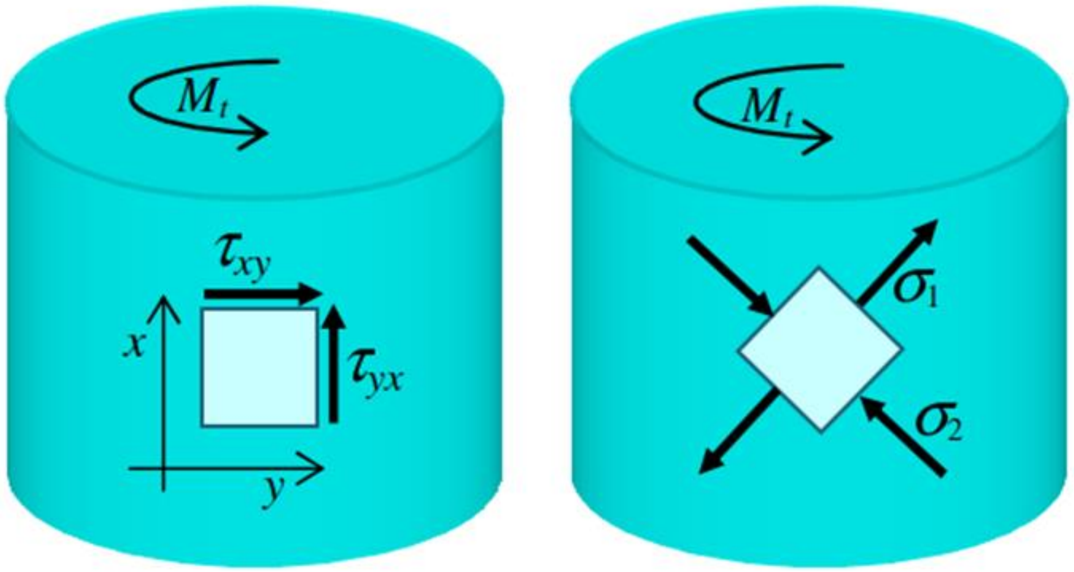


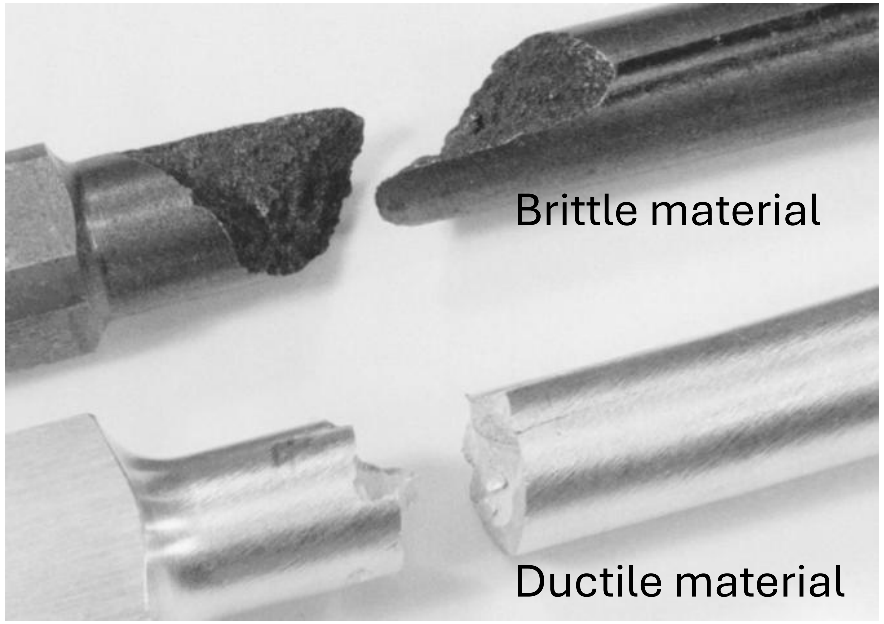
A homogenous body in equilibrium under a given system of external forces presents a unique distribution of internal forces. In each point it is possible to define the stress matrix:

$$\boldsymbol{\sigma} = \begin{bmatrix} \mathbf{p}_x & \mathbf{p}_y & \mathbf{p}_z \end{bmatrix} = \begin{bmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix}$$

The values σ and τ are orientation dependent

Direction of the loads - 3





As an example, a pure torsion in a cylinder, originates shear along certain directions and traction and compression along other directions

Direction of the loads - 4

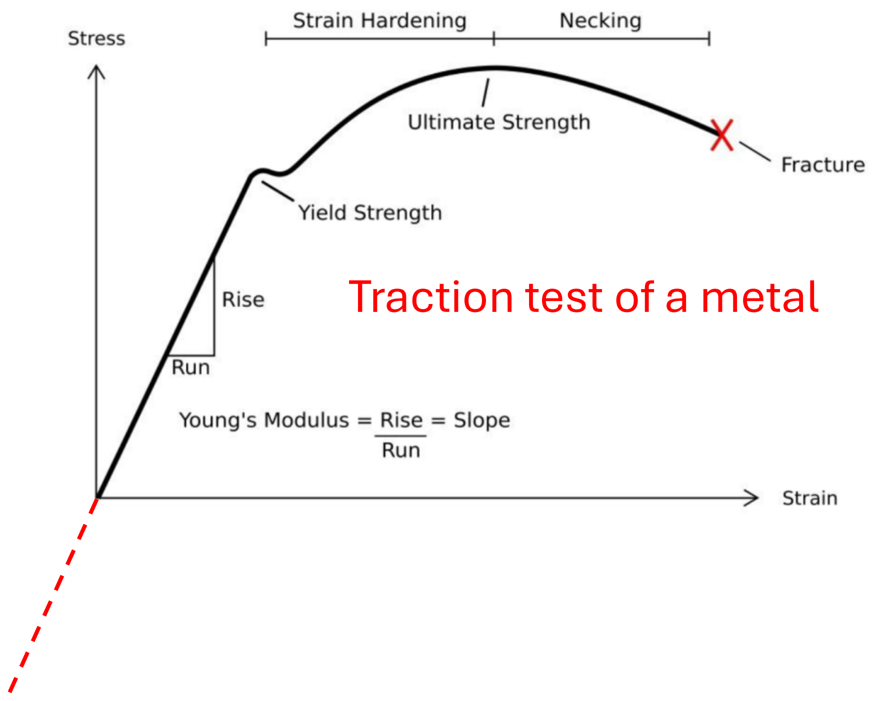
With **complex geometries**, like a **winding**, the stress distribution in some points (the matrix) can present 'undesirable' or 'dangerous' components.

It is difficult to measure correctly coil mechanical properties.
It is very easy to estimate and compute in a wrong way.

Normalized traction tests to measure material properties are carried out on simple geometrical configurations. Generalization to complex, non isotropic configurations are not straightforward.

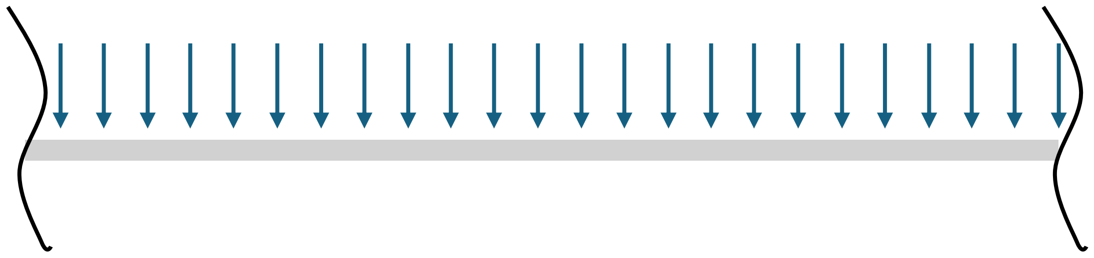
Compression tests are not foreseen in the norms. Results can be affected by the way they are measured

The tapes and the cables are made of different materials bound together. We are far from the homogeneous, linear material of the stress matrix. 'Directional' differences can be large.



Compression – Uniform or localized - 1

Case A) - Uniform compression

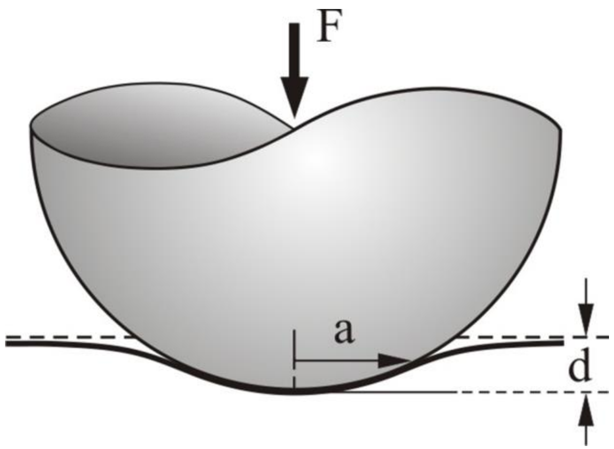


In this condition, the load that can be applied to a REBCO tape without damaging it, can be up to 200 MPa (flat configuration).

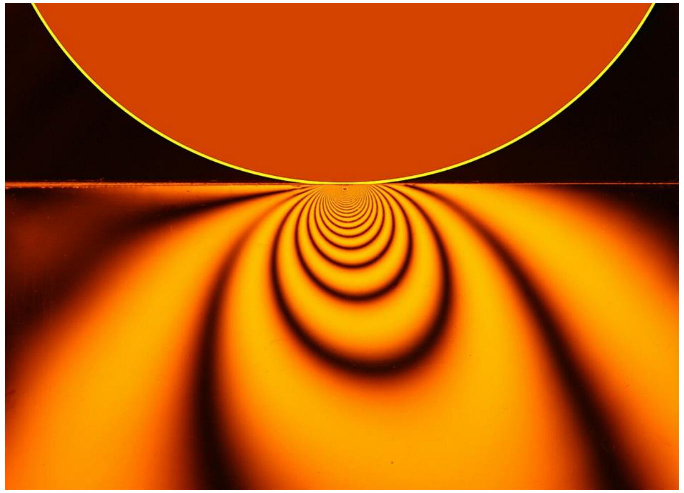
Compression – Uniform or localized - 2

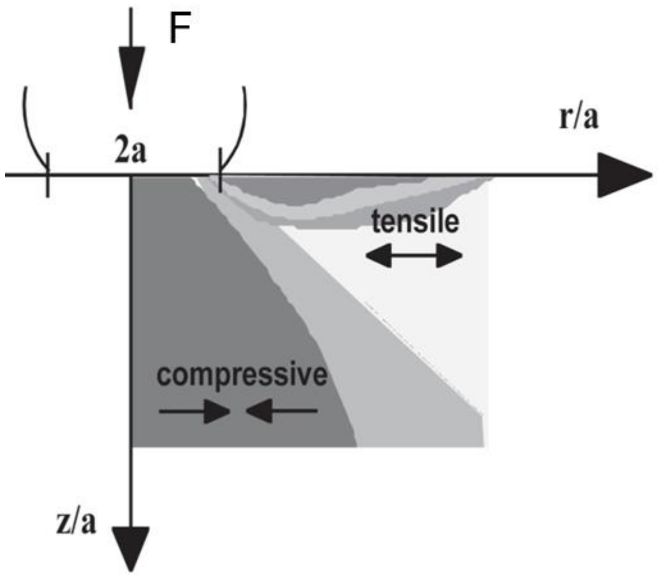
Case B) – Single force.

A localized compressive force can originate shear and traction in the adjacent regions



- Hertz analysis valid for linear conditions and homogenous bodies.
- When considering plasticity and composites, the situation becomes less clear. Lack of data or tests.



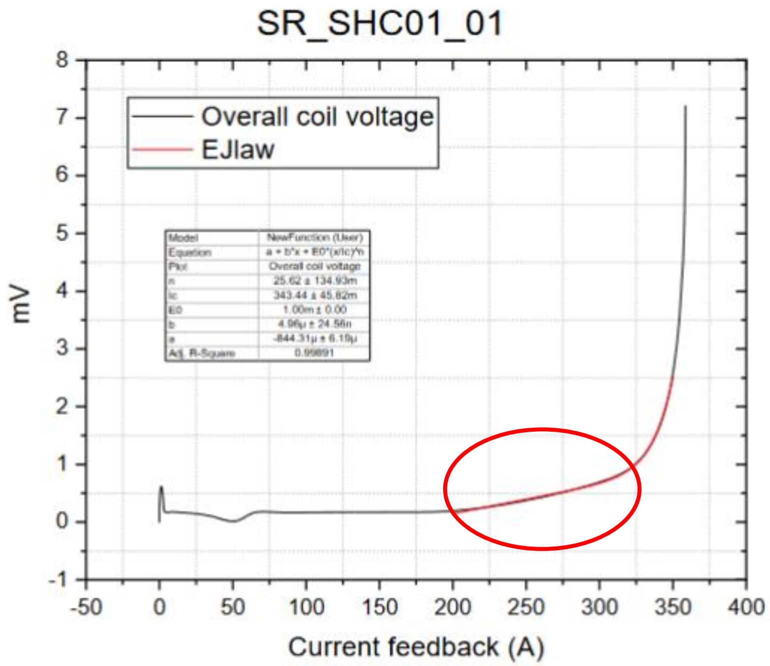


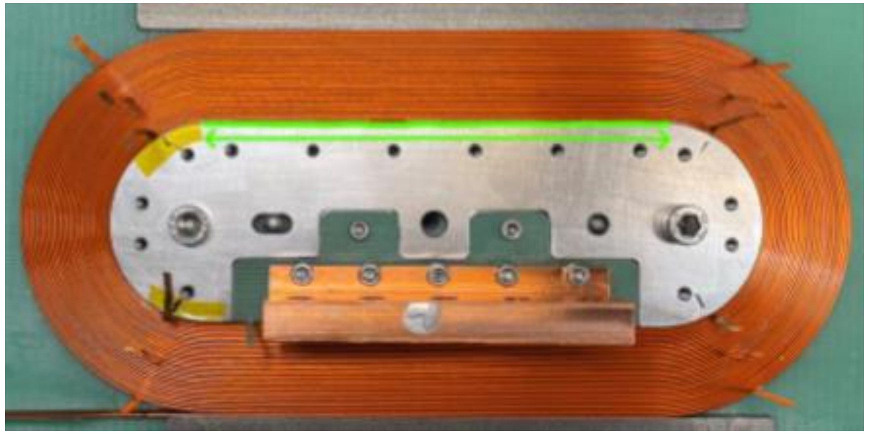
Localized forces of few N can damage a REBCO tape.

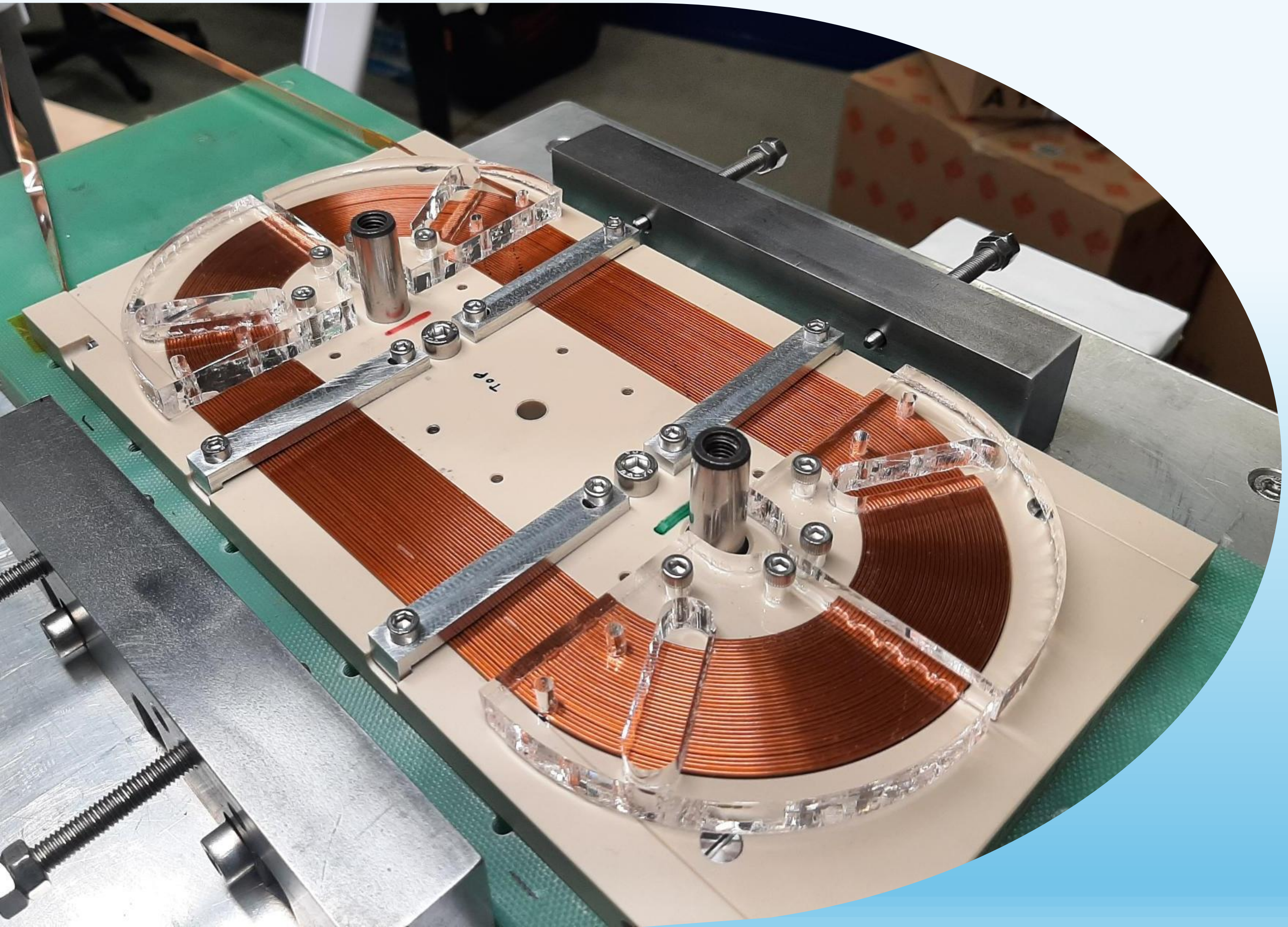
Accidental loads – Unforeseen forces that generate traction (or shear)

Local accidental loads can appear in case of:

- **Not optimized winding and manufacturing tools**
- Geometrical discontinuities (for example between straight part and ends)
- Defects of the shape of the tape respect to the theoretical configuration (for example cutting or distorted edges).
- Tolerances of adjacent coil retaining parts





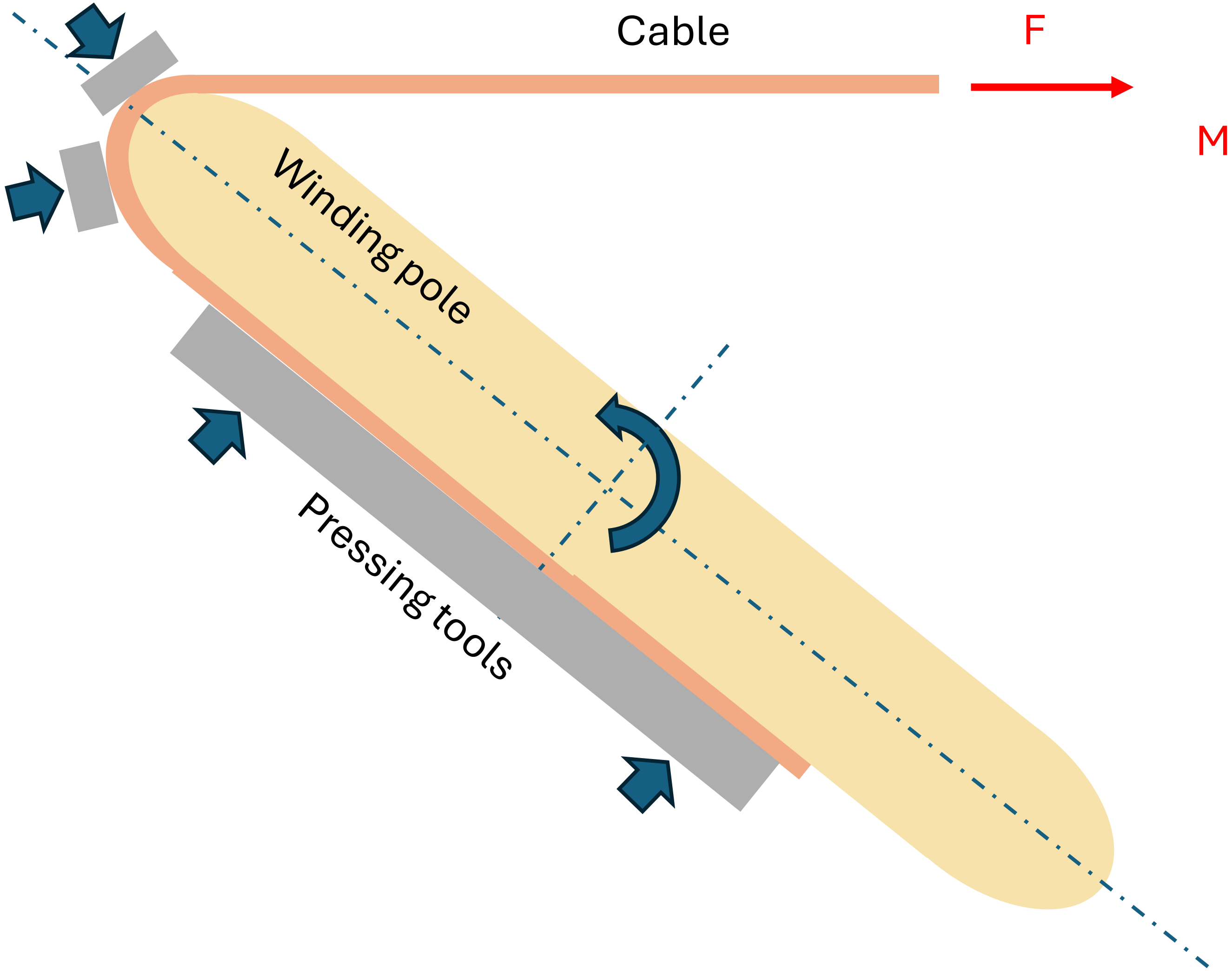


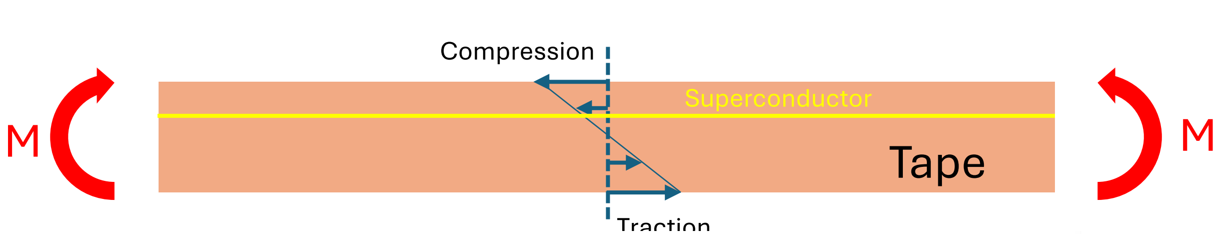
Winding process

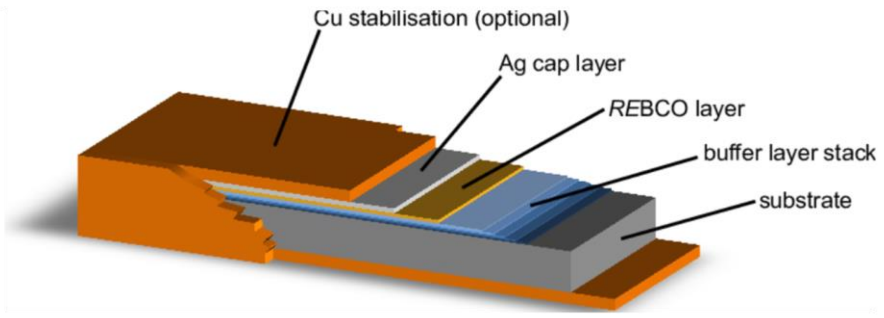
Techniques

Tools

Winding process - 1





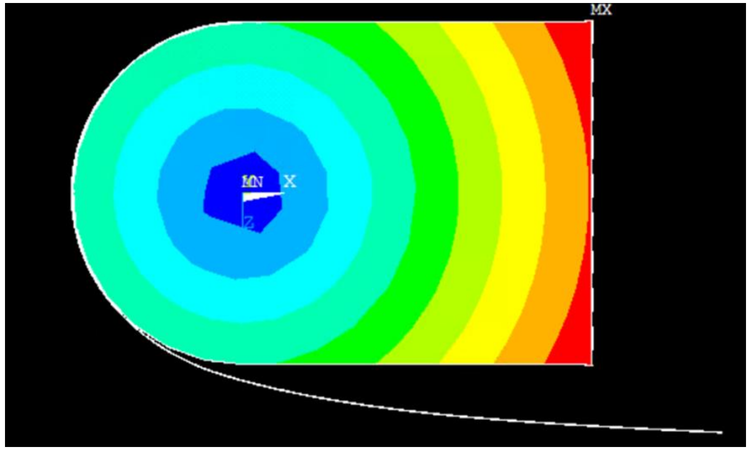


Minimum curvature radius (safe order of magnitude):

- 20-25 mm if the superconductor is on the traction side
- 5-10 mm if the superconductor is on the compression side

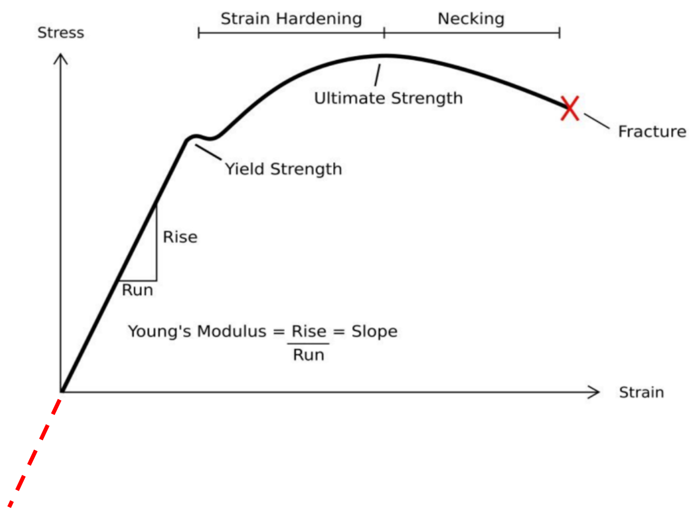
The first turns of a cos(θ) coil have small radius of curvature

Winding process - 2



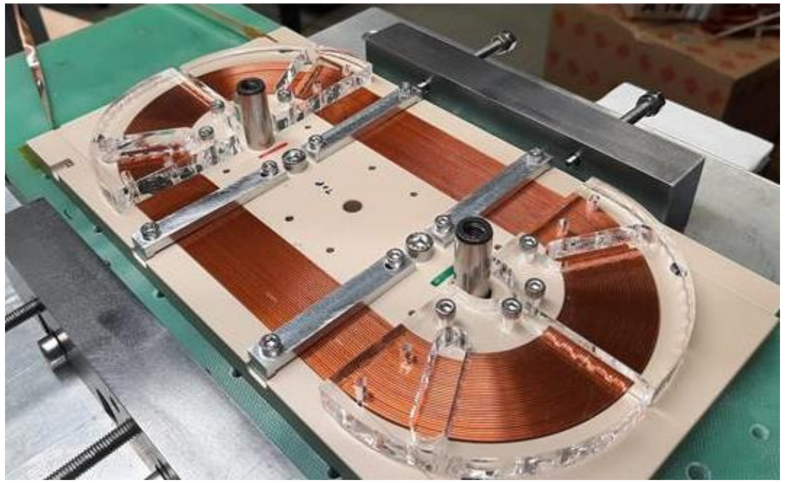
The bending process implies large deformations of the tapes.

- In some regions the yield strength is reached while others stay in the elastic regime. Stored internal stresses.
- The cable must be kept in place using tools.

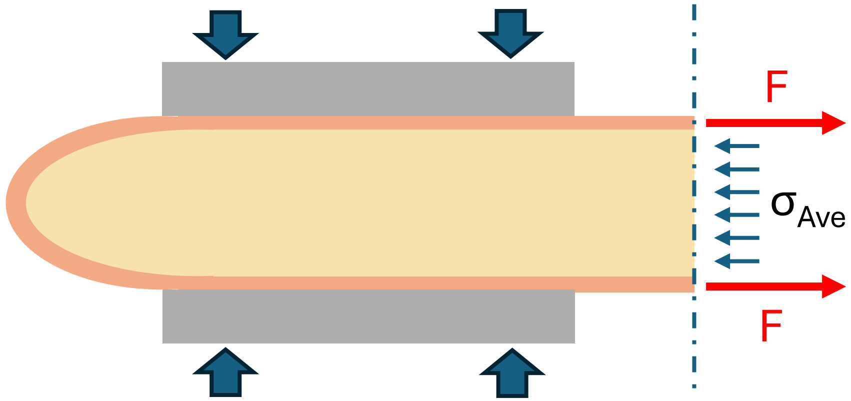


At the end of the manufacturing:

- Metal impregnated coils can be handled easily.
- Polyimide insulated, dry coils need to be kept in shape by tools and by the support structure.



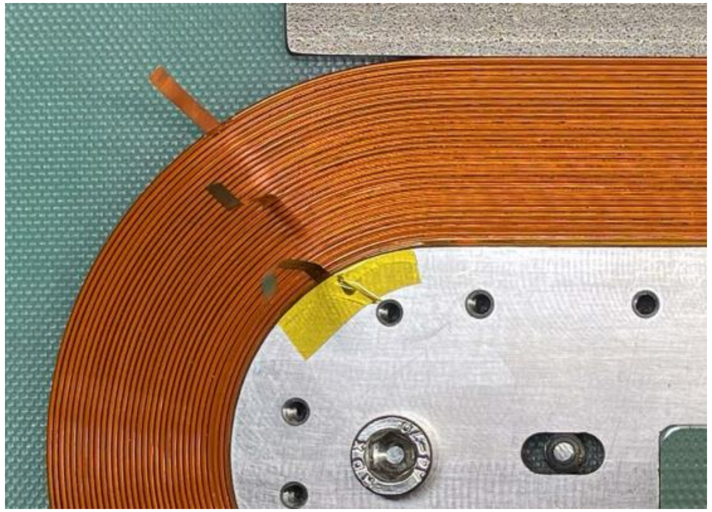
Winding process - 3

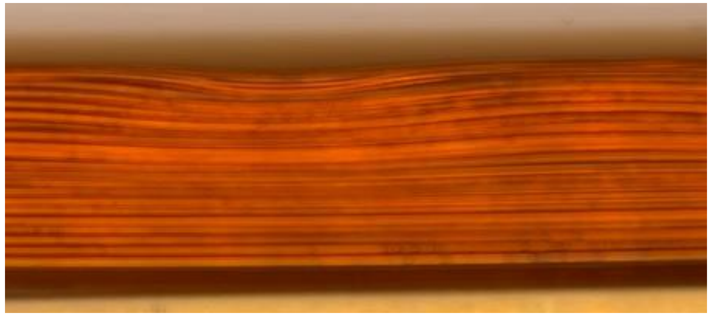


In case of no friction:

$$2\,F = 2\,\sigma_{Cable}\,A_{Cable} = A_{Pole}\,\sigma_{Ave} \qquad A_{Pole} >> A_{Cable}$$

- The further turns, partially compress the pole and the previous turns.
- The tension in the first turns decreases during the winding.
    - With soft ends, as in polyimide insulated cables, the tension of the first turn goes to zero after a few turns. Some waviness can appear at the end of the bent / beginning of the straight part.
    - To avoid or limit this phenomenon, the winding tension is reduced turn by turn from about 50 MPa in the beginning to half of this value in the end. An increase of the winding tension would not help since the ends would be more deformed.

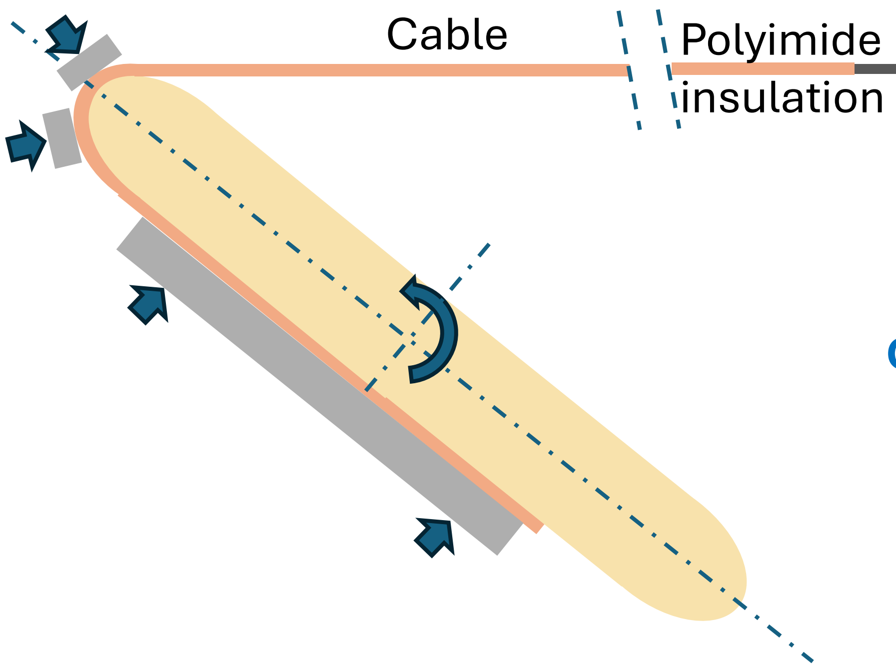


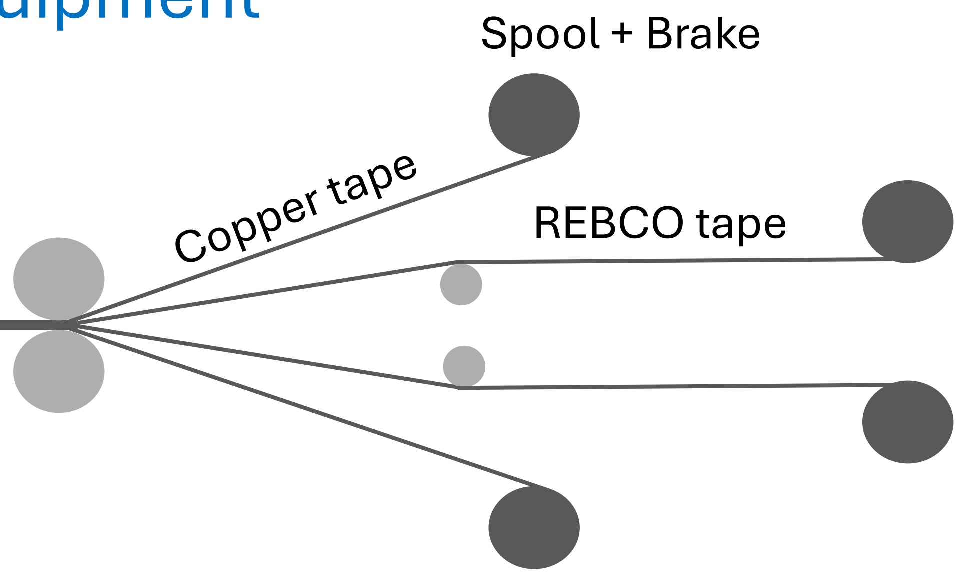


- Metal insulated coils are more rigid, and this problem is less pronounced. The winding tension is often higher.

Winding equipment

Relatively simple winding machine (one or two turning axes)





Complicate braking system (controls on tape advancement)

In the curved part, the tape toward the inside follows a systematic shorter path with respect to the tape on the outside.

This originates waviness in the coil if nothing is done.

The brakes and the control system change the advancement of the different tapes to compensate the different paths.

Conclusions

Efforts are ongoing to develop alternative cable geometries that incorporate aspects of filamentarization and transposition.

For the time being we can wind cables made of stacks of tapes.

The length of the tapes is a limit to the maximum length of a coil.

Local, accidental loads can represent a serious risk for a coil (formation of cracks or of a delamination with consequent deterioration of the superconducting properties.

The winding procedures and the winding parameters must be carefully defined and tested before starting the coil production. Then an adequate quality control must be implemented to assure a correct reproducibility during production.

Thank you for your attention