PEPR Suprafusion
SF-Cond Project

Design and development of a helical cabling machine for HTS cables at CEA Cadarache

G. Succi, A. Torre, M.-A. Saadat, D. Durville,

C. Nguyen Thanh Dao, F. Cazaban, P. Claverie, N. Cazanave, T. Martin

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OUTLINE

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- Present status, planning, and qualification

Introduction

- One *key* objective of SF-Cond is to *develop the ability to procure conductors* for fusion applications, internally to the IRFM (Research Institute for Magnetic Confinement fusion).
- Conductor length must be in the order of several tens of meters.

Helically-Wound Round Cables (HWRCs) are **our preferred choice**:

1) *Isotropic* superconducting properties: I_c does not depend upon the applied field angle.
2) Optimal *bending* properties, which allow for non-planar coil geometries.
3) Tape geometrical configuration favours *current sharing* among tapes.
4) Withstands *high Lorentz forces and stresses*.
5) *Limited AC losses* (e.g. coupling, thanks to twist-pitch).
6) *Adaptability and scalability*: from small to big core diameters, layer, and tape number.

This topic is outside the scope of the European – Chinese collaboration but, we believe, of interest to everyone

Building a cabling machine at CEA Cadarache (1/2)

First question: is there a solution already available on the market?

- Yes, *in principle*.
  - Conductor lengths from private companies can be expensive, ~100 €/tape/m.
  - Limited by their production lines (other requests, flexibility limit).

- *Otherwise*, we could perform the cabling internally
  - Allows for **higher flexibility** in the cable design.
  - Allows being <u>independent</u> and manufacture cables at our own discretion.
  - *Saves cost* → 'just' purchasing the tapes

Cabling parameter	Interval
Core diameter, ϕ_{core}	2 – 20 mm
Total no. tapes, n_{tapes}	up to 100
No. layers, n_{layers}	up to 40
Tape tension, T	5 – 20 N
REBCO-layer side	Inward
Twist-pitch, t_p	min. 10-15 mm
Cable diameter, ϕ_{cable}	2.5 – 25 mm

Building a cabling machine at CEA Cadarache (2/2)

We chose to build the machine ourselves

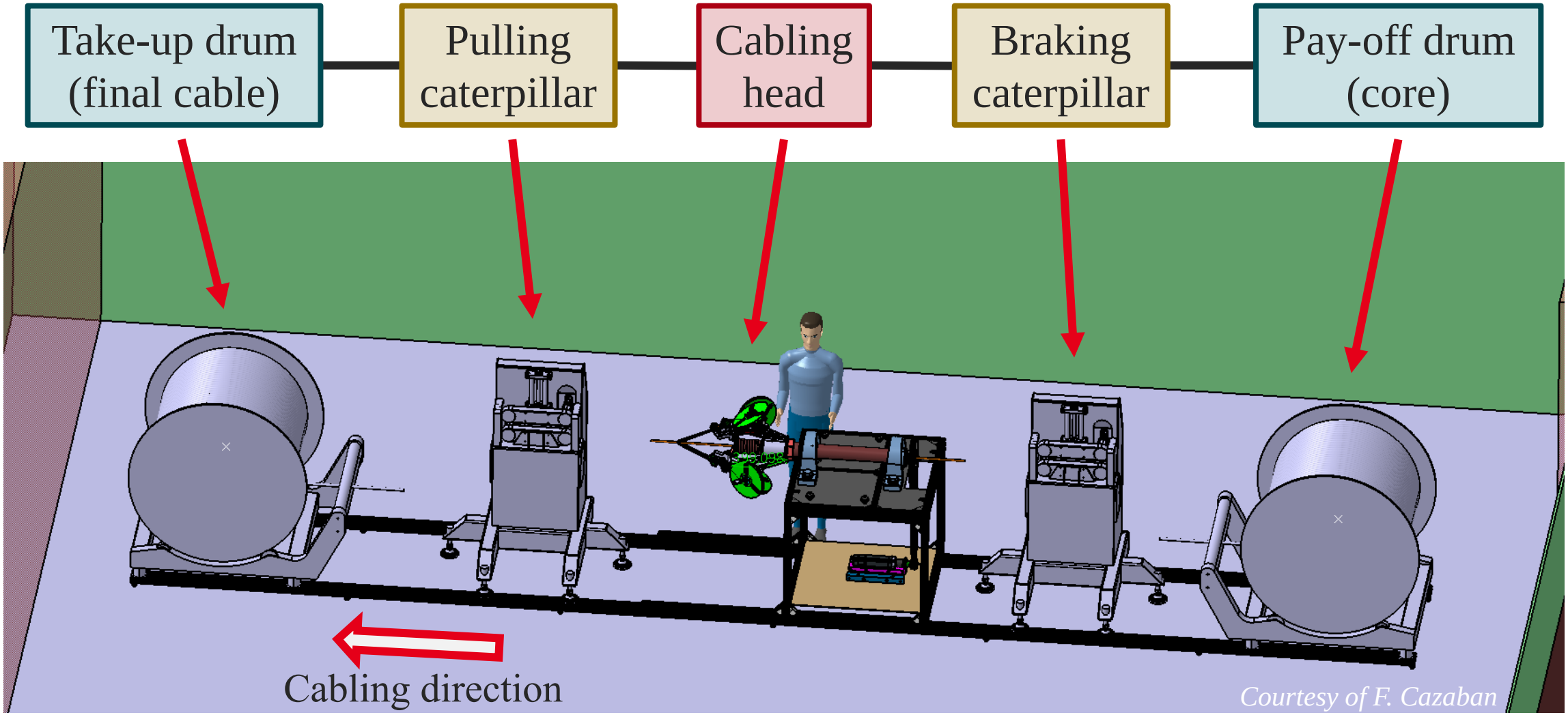
- *For research purposes*
- Much technical challenge
- Time consuming (~ 1 – 1.5 years to the first cabling trials)

BUT

- We have the technical competence to do it (mechanics, automation)
- Cheaper than a *turnkey solution*
- Full control on the design parameters, very high flexibility

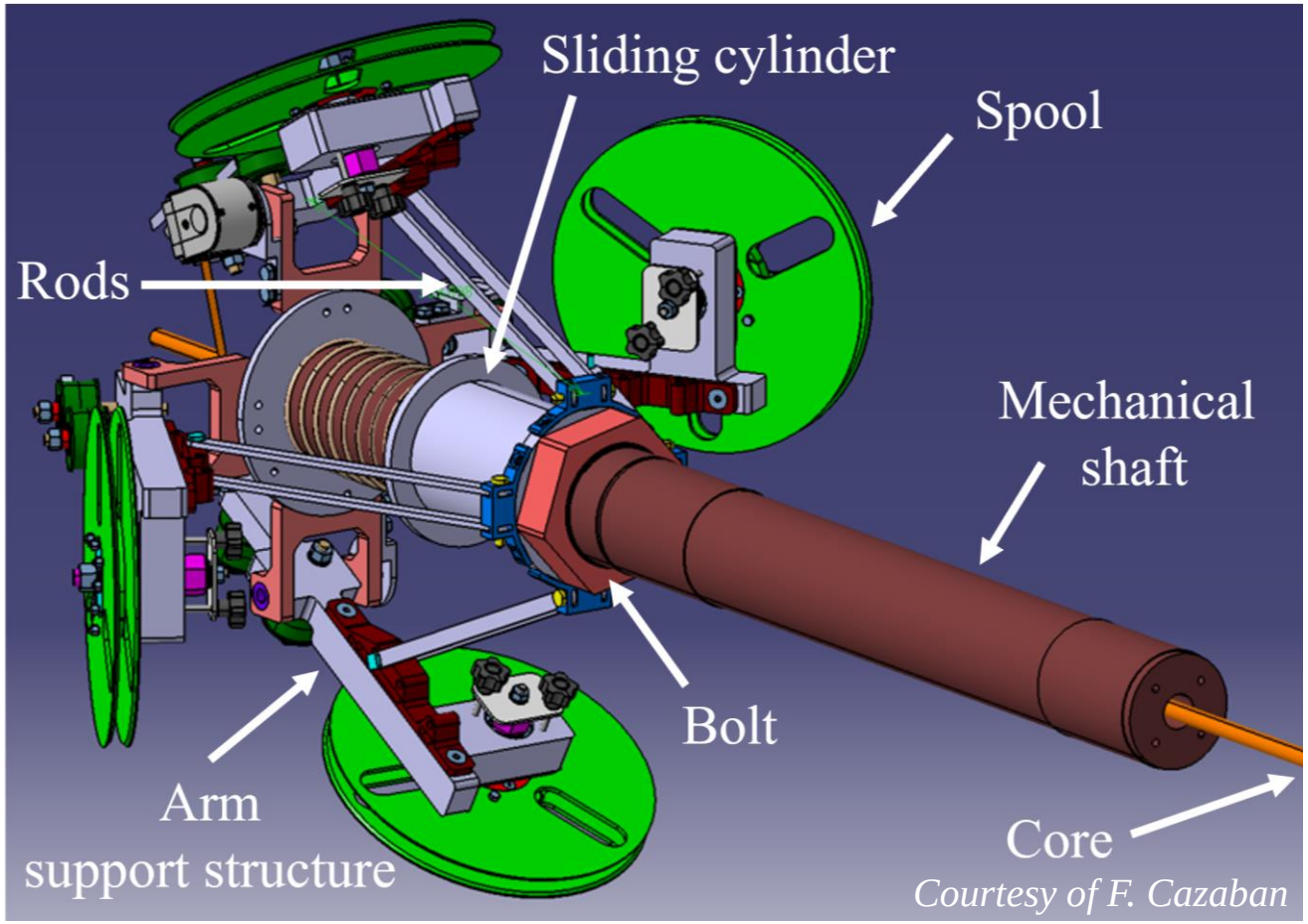
The cabling line

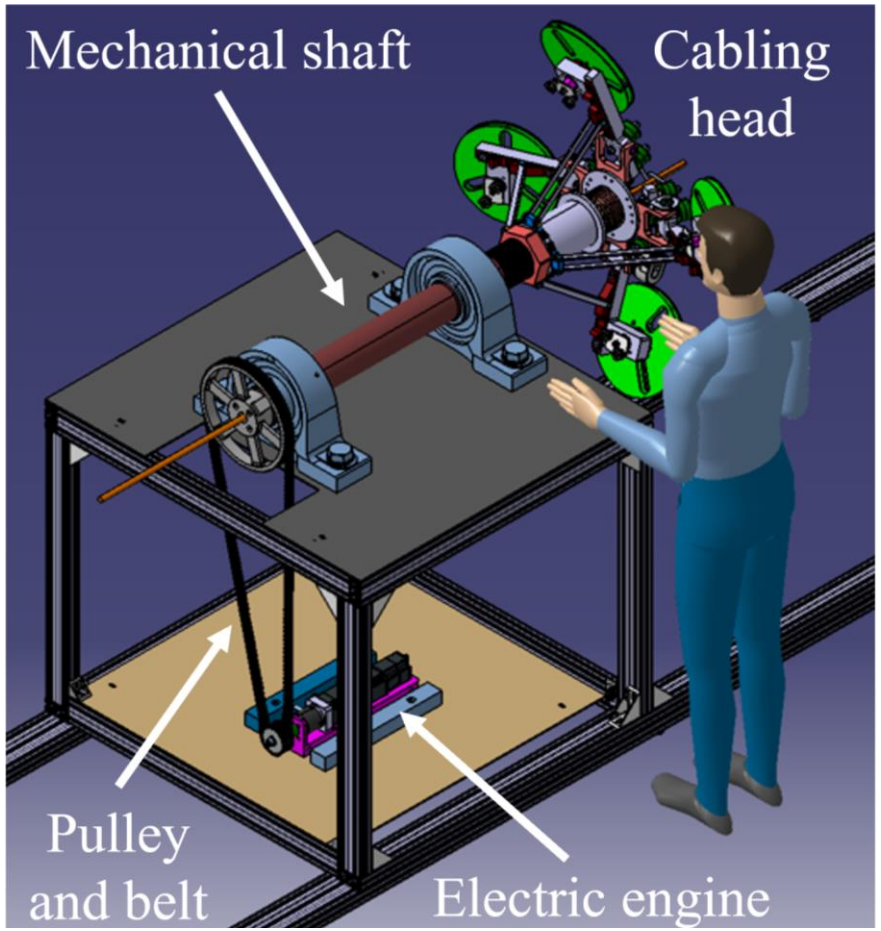
The current design is based on five modules:



The cabling head – mechanical design (1/2)

➢ The design of the **cabling head** and its **support shaft** is finalized.

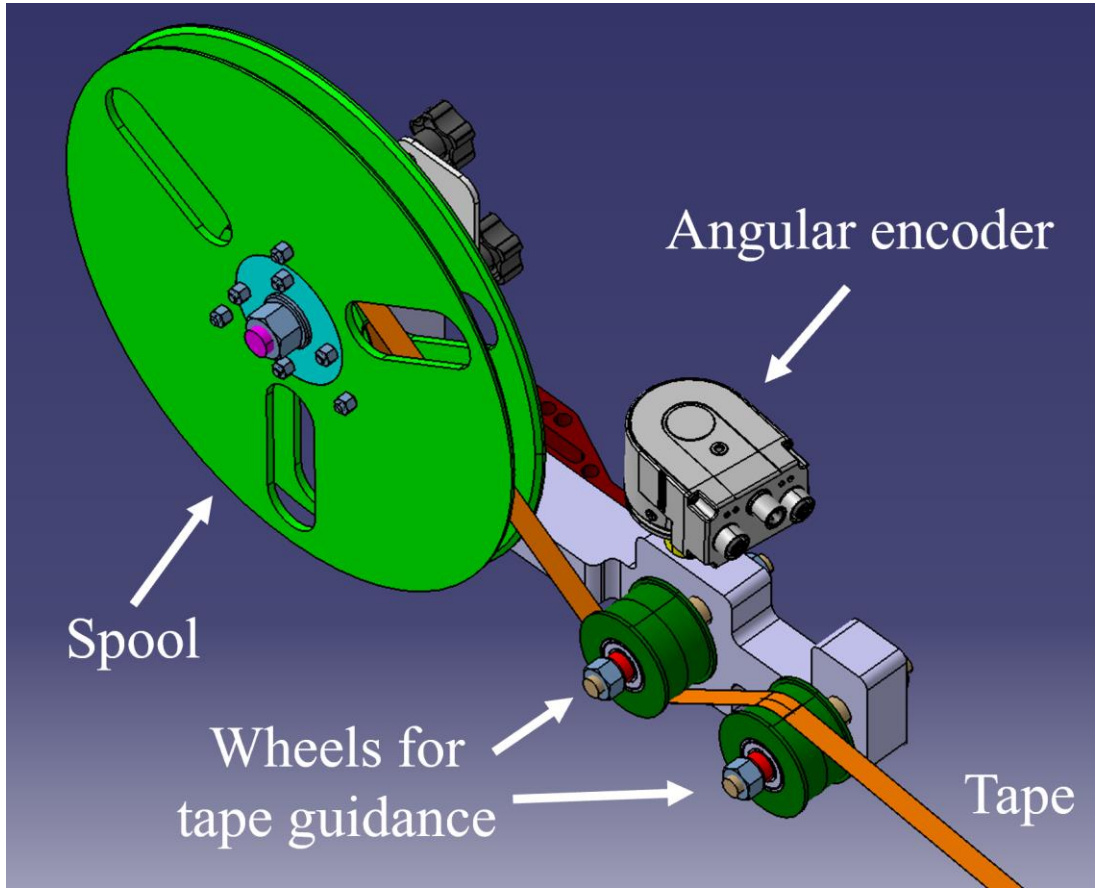


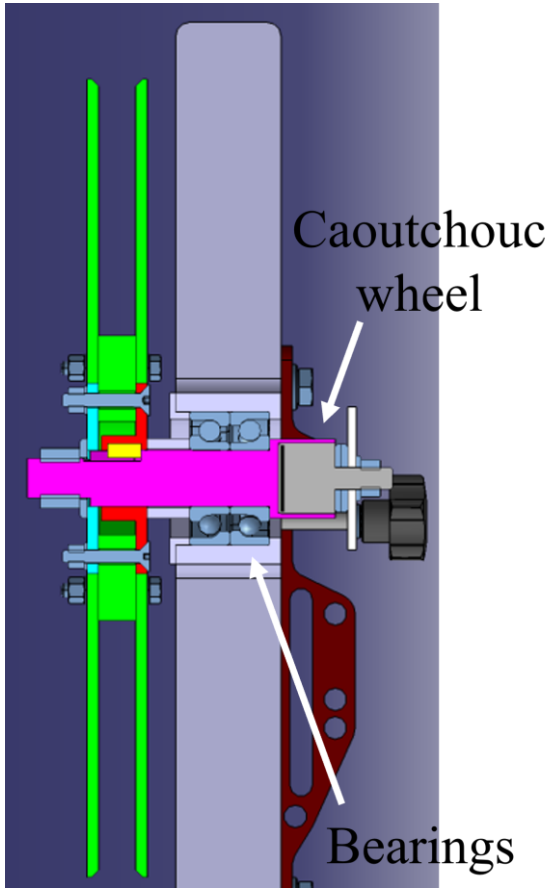


- Foreseen up to 4 tapes/layer → cable head design is with 4 arms, adjustable to 2, 3, or 4.
- Shaft outer diameter : 100 mm (!)

The cabling head – mechanical design (2/2)

➢ The design of the **cabling head** and its **support shaft** is finalized.

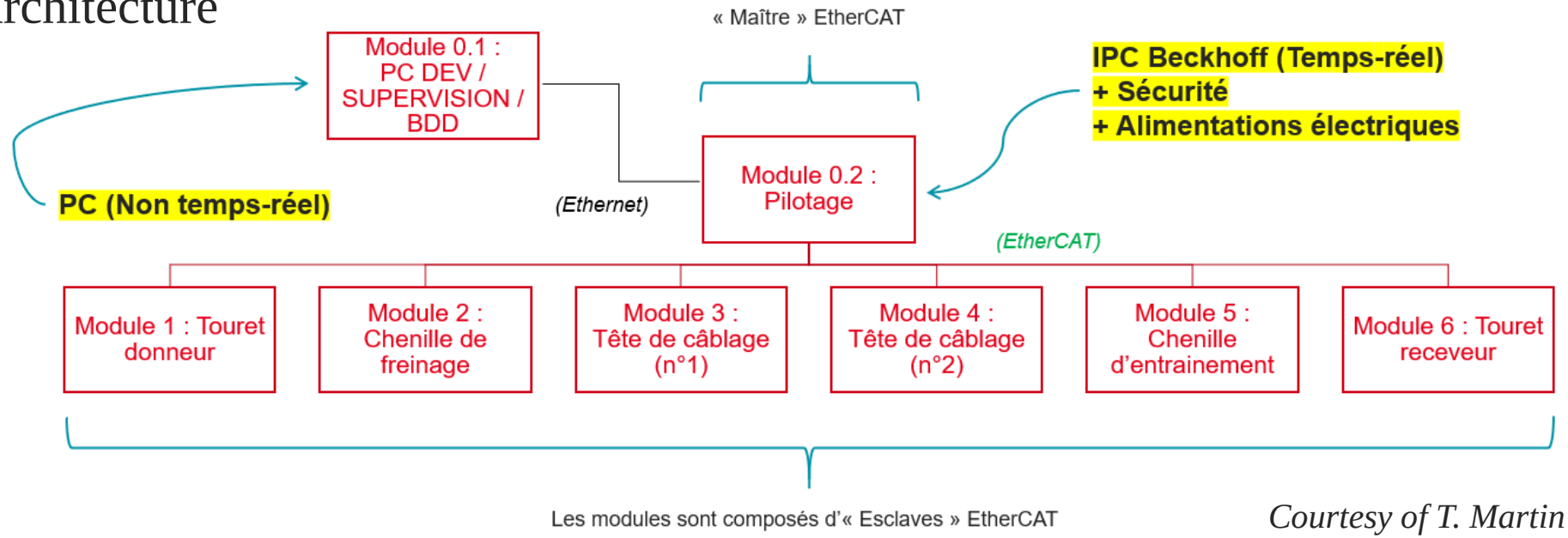




- A *passive* tape tension control system will be implemented on each arm, to ensure proper tape unwinding and deposition on the copper core.

Automation

- Global architecture



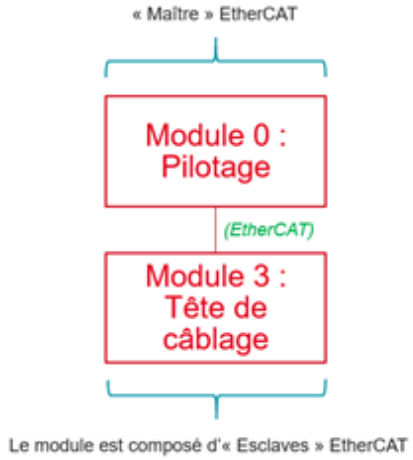
Courtesy of T. Martin

- 1st objective: **coordinate** *head rotational speed* to *core/cable linear speed*

$$\omega_{head} = \frac{2\pi}{t_p} v_{core}$$

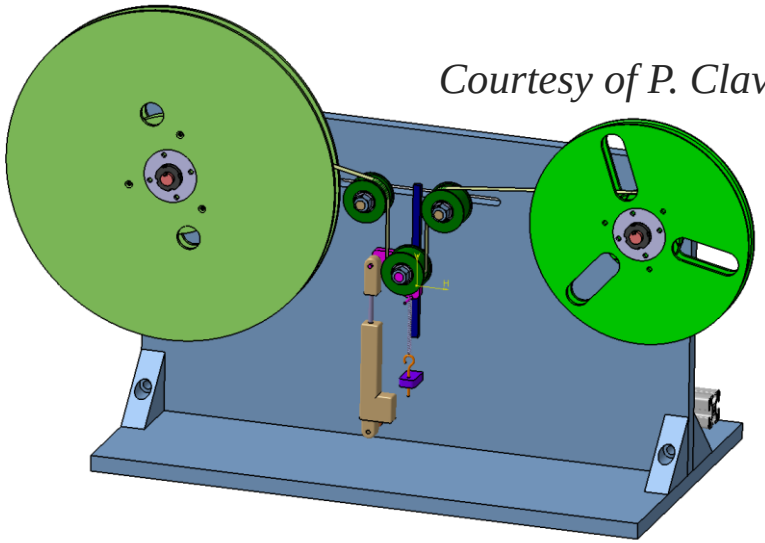
ω_{head} ⟶ given by the electric motor

v_{core} ⟶ given by the caterpillars

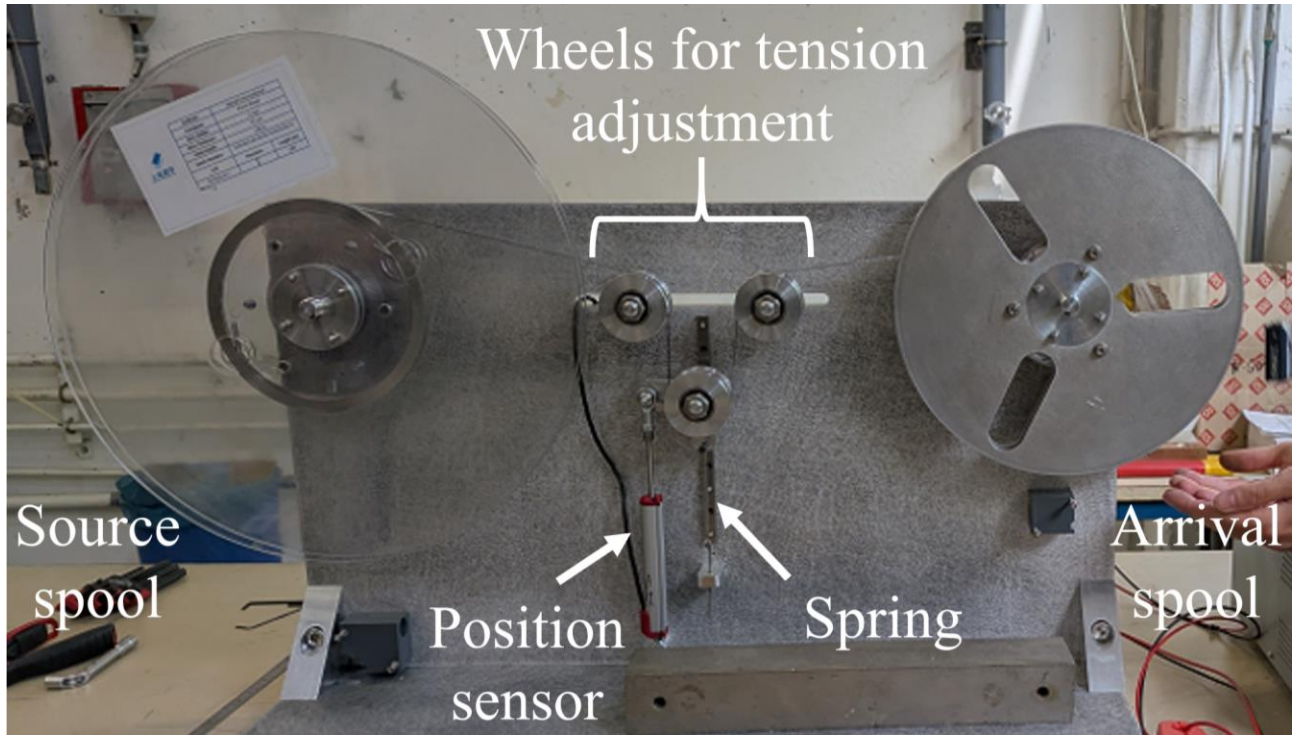


A preliminary step: the respooling machine

- Scope of the respooling machine is to *control tape tension* in the arrival spool (later used for cabling).
- It is composed of :
  - Source spool
  - Arrival spool
  - Tape tension control system (wheels, spring, position sensor)



Courtesy of P. Claverie



- The *lessons learnt* from the design and operation of the respooling machine are of paramount importance for the **cabling head design** and the **tension control system** of the cabling machine.

Modelling for tape strain state from tension and winding (1/2)

- Applied tension and winding induce strain in the tape

Analytical estimation

$$\varepsilon_{axial,t} = \frac{T/S}{E} \longrightarrow \varepsilon_{tensile} = +0.04\ \%$$

just on the Hastelloy (to simplify):

uniform across the width

- T = 20 N
- $S = w \cdot t$ = 3 mm x 50 µm
- E = 228 GPa (at 77 K) [1]

$$\varepsilon_{axial,wind,max} = -\frac{t}{d + t + 2h}\cos^2\alpha = -0.41\ \% \quad [2]$$

- t = 50 µm : REBCO distance from neutral axis
- d = 6 mm : core diameter
- h = 20 µm : electroplated copper thickness
- α = 45° : winding angle

- These values are within the axial tensile and compressive strain limits, +0.4% and -1.2% [3].

[1] V. A. Anvar *et al.*, Supercond. Sci. Techn., vol. 31, 2018. Art. No. 115006
[2] D. C. van der Laan *et al.*, Supercond. Sci. Techn., vol. 32, 2019. Art. No. 033001
[3] D. C. van der Laan and J. W. Ekin, Supercond. Sci. Techn., Appl. Phys. Lett., vol. 90, 2007. Art. no. 052506.

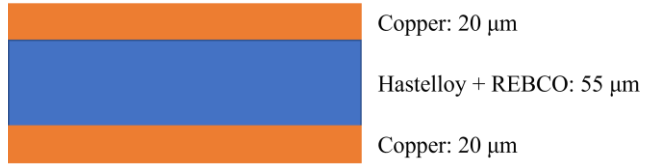
Modelling for tape strain state from tension and winding (2/2)

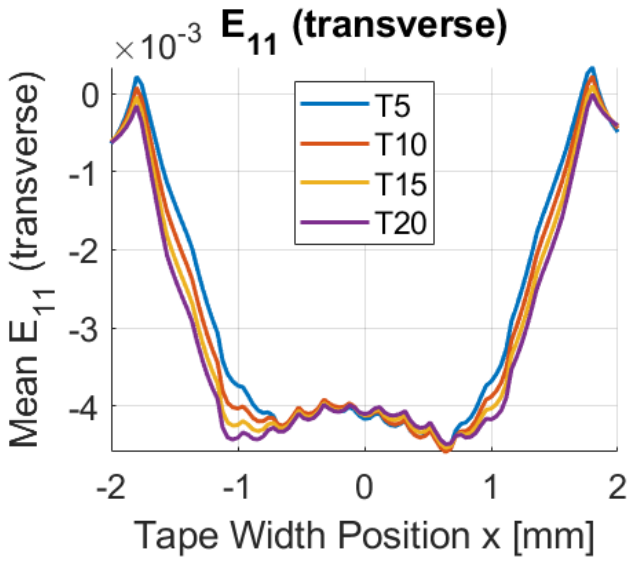
- The tape strain state was evaluated using the MULTIFIL finite-element code [4]
- 4 different cable configurations were studied

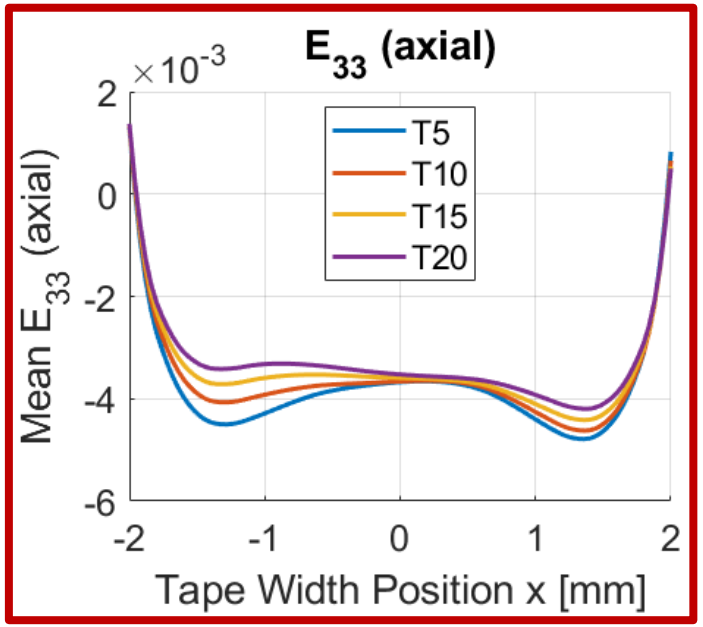
$\phi_{core} = 6$ mm

$d_{inter-tape} = 0.5$ mm

Tape width [mm]	# tapes	θ [°]	Twist-pitch [mm]
3	3	56.2	12.64
3	4	42.0	20.91
4	3	44.3	19.34
4	4	17.3	60.64







E_{33} well agrees with the analytical prediction

E_{11} also expected due to tape winding with a non-zero lay angle

[4] D. Durville, *Journal of materials science*, vol. 40, 2005.

Present status, planning, and qualification

- We have already procured several parts:
  - Arms of the cabling head and associated parts
  - Mechanical shaft
  - Bearings (ϕ_{int} = 100 mm)
  - Tape spools

- *Next steps*: installation of the *electrical engine*, procurement of the two *caterpillars*.

Planning and qualification (until 2028)

Cabling trial	Length	Qualification	Foreseen
Hastelloy tapes	1 m	Visual/Geom.	4th 2026
Low-quality tapes	1 m	LN2 tests	1st 2027
Good quality tapes	1 m	LN2 tests	2nd 2027
Good quality tapes	3 m	LN2 tests	4th 2027
Two-layers	3 m	LN2 tests	1st 2028
Up to ten layers	3 m	LN2 tests	4th 2028



Thank you for your attention

References

[1] V. A. Anvar et al, «Bending of $CORC^{®}$ cables and wires: finite element parametric study and experimetal validation», *Supercond. Sci. Techn.*, vol. 31, 2018. Art. No. 115006.

[2] D. C. van der Laan, J. D. Weiss, and D. M. McRae, « Status of $CORC^{®}$ cables and wires for use in high-field magnets and power systems a decade after their introduction», Supercond. Sci. Techn., vol. 32, 2019. Art. No. 033001.

[3] D. C. van der Laan and J. W. Ekin, “Large intrinsic effect of axial strain on the critical current of high-temperature superconductors for electric power applications”, Appl. Phys. Lett., vol. 90, 2007. Art. no. 052506.

[4] D. Durville, “Numerical simulation of entangled materials mechanical properties”, *Journal of materials science*, vol. 40, 2005.