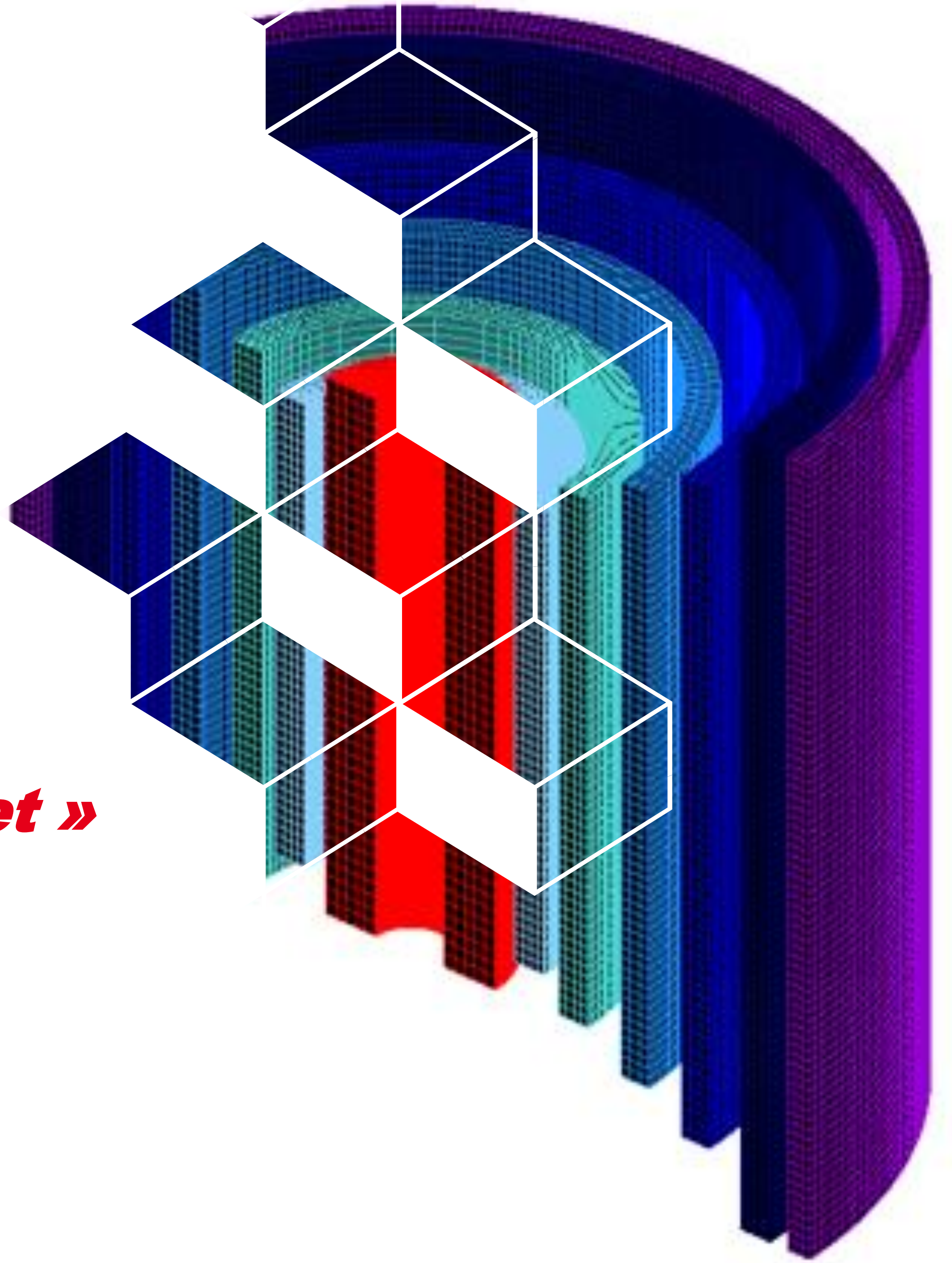
# Mechanics in UHF solenoids.

## *« The challenge of a 40 T full SC magnet »*



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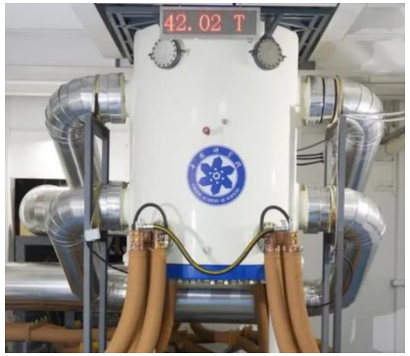
# Introduction

## High magnetic field magnet

### Full **resistive** magnet

42T (CHMFL)

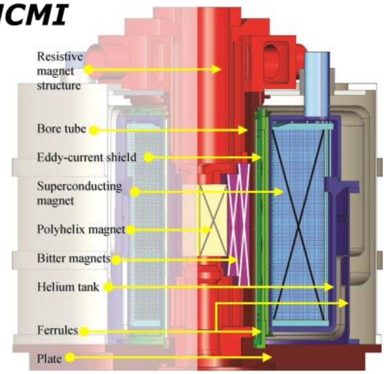



42,02T resistive magnet of the High Magnetic Field Laboratory of Hefei Institutes of Physical Science, Chinese Academy of Sciences (CHMFL) – 2017

### Hybrid **Resistive / LTS** user magnet

43T(CNRS)/ 45T (NHMFL)

LNCMI



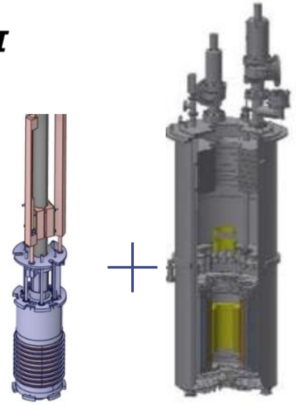

43T Hybrid magnet of the Laboratoire National des Champs Magnétiques Intenses (LNCMI-CNRS)

### Full SC **LTS/ HTS** magnet

40T (FASUM/NHMFL)

LNCMI

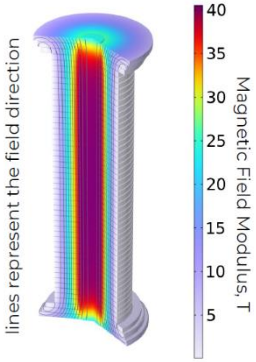
40T Full superconducting magnet FASUM - LNCMI & CEA – 2021



OXFORD INSTRUMENTS NANOSCIENCE

### Full SC **HTS** magnet

40T (Muon Collider)




International MUON Collider Collaboration

40T HTS solenoid of the MuonCollider project - 2021.

- Fundamental research
- Innovation on SC magnets
- Development of HTS materials
- Energy consumption
- …

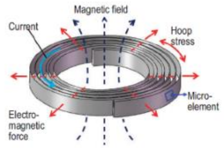
# Introduction

**High magnetic field challenge**

**Induces high Lorentz forces**

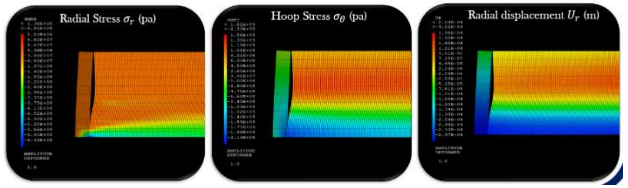
Volumic force f = jxB # B²

*At constant volume of conductor,*
**from 10 T to 40 T**
**force density increases by 16**




**With the use of HTS ReBCO material.**

Special issue of **screening currents**



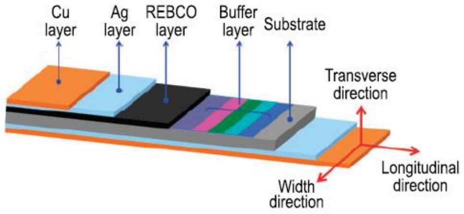

**Configuration of single or nested solenoids**

Radial force **produces a circumferential hoop stress** in the winding.
+
**Quenchs**
+
**Structural mechanics**
(radial/ axial misalignment….)

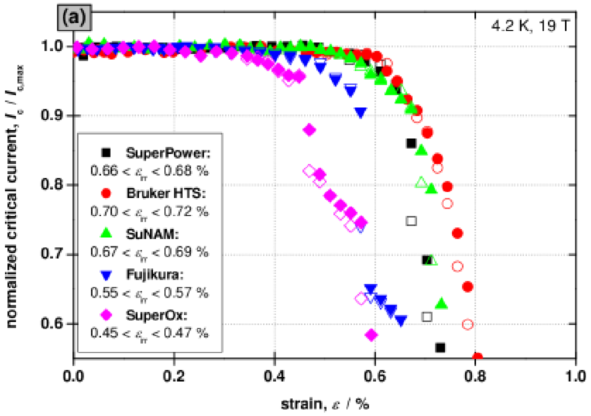
**Major issue of mechanics in UHF solenoids**

# ReBCO tapes, a sensitive material

- **Multi-layered architecture**



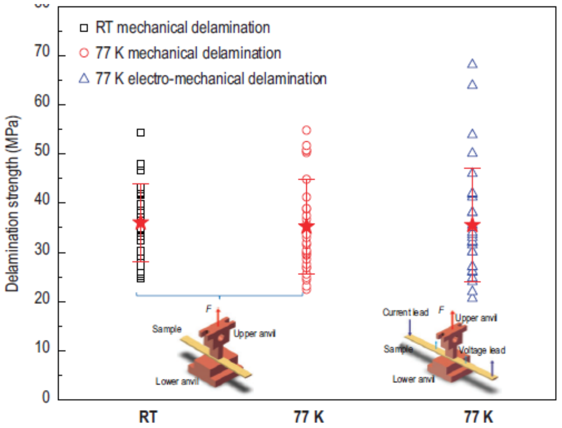

- **Longitudinal mechanical properties**
  - Reversibly degrades the critical current below an irreversible strain limit (εirr ~ 0.4 %), after which degradation becomes permanent due to ceramic layer fracturing,




Barth (2015)

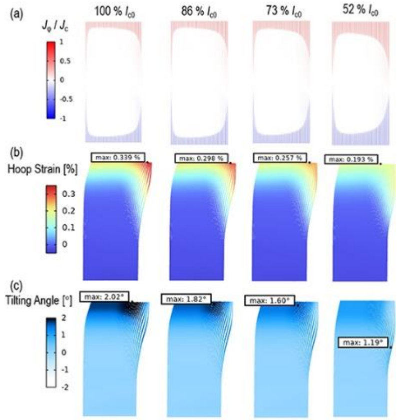
- **Transverse mechanical properties and delamination**
  - The laminated structure creates vulnerability to transverse delamination.
  - Mechanical delamination strength at 77 K ranges around 30 MPa.

Zhou (2023)




- **Fatigue and High-Cycle Loading**

- **Screening Current effects**
  - Produce significant field reduction and non-uniform field distributions.
  - Shear stresses due to strong reverse forces.
  - local overstressing and potential plastic deformation
  - Tilting effect.




Yan (2021)

# High magnetic field program at CEA

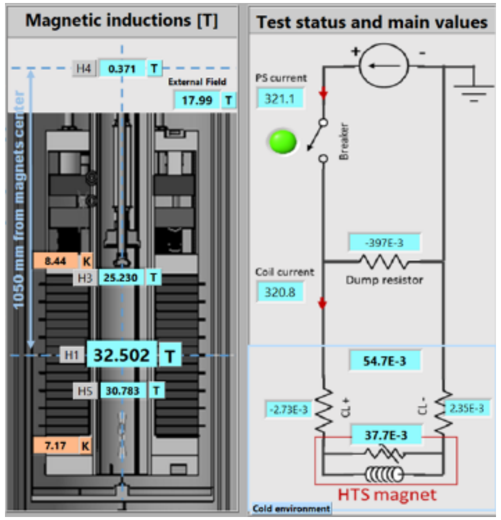
## NOUGAT 32.5 T

LNCMI

NÉEL institut

14.5 T HTS
+
18 T resistive coils

cea irfu




## SuperEMFL SC 32 T+/40 T+ 2020-2024

11 europeans partners (academic/industry), total budget 2.9 M€

**Designs of single and nested coils all sc 40 T+ magnets**

**Prototypes of nested coils.**

## FASUM 40 T 2022-2027

cea UGA Université Grenoble Alpes LNCMI

3 french partners (CEA/LNCMI-G,UGA)

Total budget 3.4 M€

**Fabrication of a 40 T all sc user magnet**

**Hybrid LTS/HTS magnet**

?

## 50 T Insert 2025-2027

Internal CEA fundings

ANR – PROJET FINANCÉ PAR L'ANR – PROJECT FUNDED BY THE ANR

# Outline

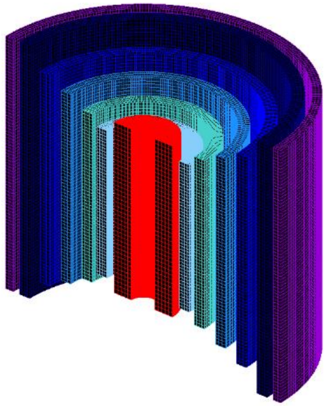
*"From 32.5T to 40T the mechanical issues of LTS / HTS hybrid magnet"*

## ■ HTS insert

- □ Single stack vs nested stack coils
- □ Mechanical modelling
- □ Screening-current issues
- □ Solutions for mechanical challenges

## ■ HTS/LTS mechanical interactions

- □ Interactions and mechanics during a quench : HTS/LTS
- □ Structural analysis of axial/lateral misalignment between HTS/LTS.
- □ Solutions for mechanical challenges

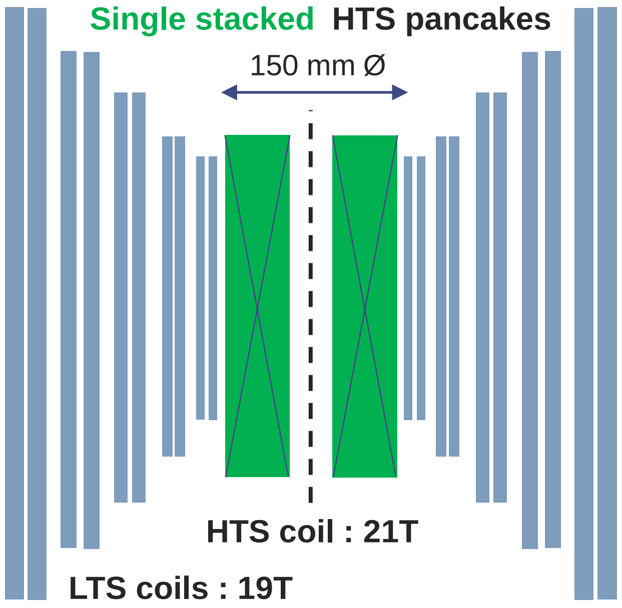


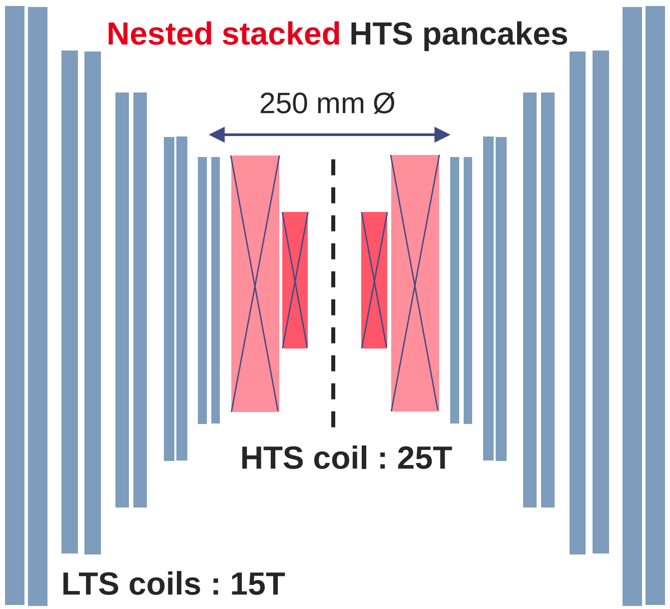
# 1. Mechanics in the HTS insert : the superEMFL and FASUM 40T projects

# The superEMFL project : Nested coil vs Single coil

"Design of 32+ and 40+ T all-superconducting user magnets & fabrication of nested coil prototypes"

- **Two main configurations due to commercial LTS outserts :** OXFORD INSTRUMENTS | NANOSCIENCE
  - ◻ LTS outsert **150 mm Ø** / **Single stacked** pancake HTS solenoid
  - ◻ LTS outsert **250 mm Ø** / **Nested stacked** pancakes HTS solenoid



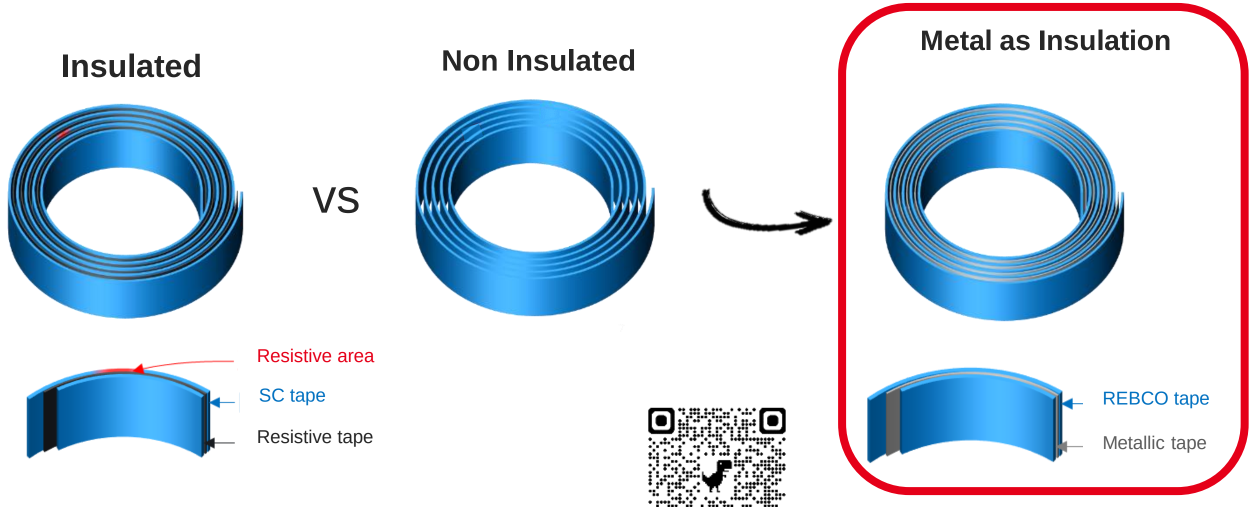

**Which choice for the FASUM 40T project ?**

◻ Best **LTS economical** configuration : **Single HTS coil**

◻ Best **HTS mechanical** configuration : **Nested HTS coil**

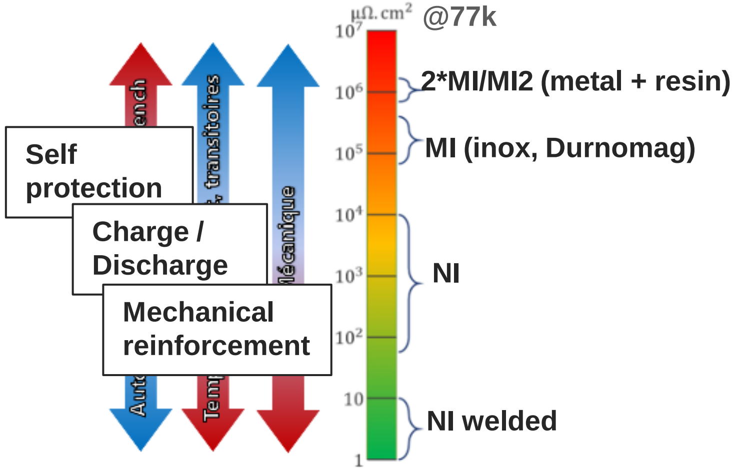
# A quick regard : the HTS pancake

## I or NI winding ?




C. Genot 2022

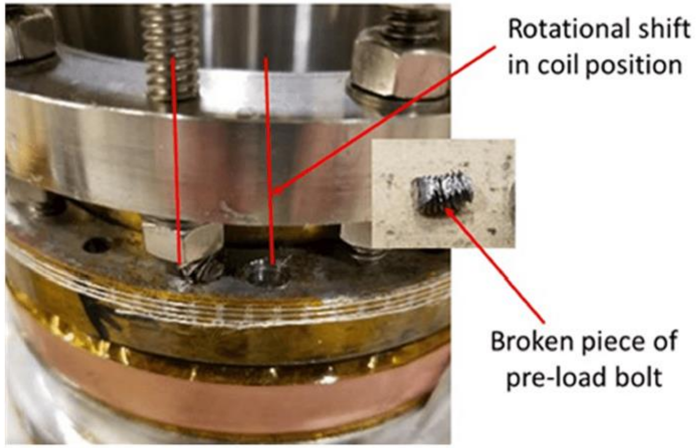
## The Rct compromise




*Courtesy P. Fazilleau - HDR defense*

- **Choice at CEA of the intermediate solution of MI technology**
  - **Mechanical reinforcement** + pre-winding & over-banding with Durnomag ® stainless steel tape
  - Good compromise with **charge/discharge time constant**
  - Good compromise with **self protection.**
- **Example of severe mechanical issue : the MIT H800 NI nested coil**
  - Mechanical damage during quench due to **strong torques due to nested coils coupling** and **radial current due to NI configuration.**
  - **Using the MI technology we are willing to avoid these particularly high mechanical issues.**

Broken preload bolt due to strong torque on coil n°1 following H800 magnet quench.




Philip. C 2019

# SuperEMFL : HTS single coil results

## Magnetic optimised designs of SuperEMFL single coil HTS insert

| | Basic Design | High Field | | High Volume |
|---|---|---|---|---|
| *Ref.* | *S1* | *S2a* | *S2b* | *S2c* |
| ***Design led by*** | Mechanics | Mechanics | Mechanics | Mechanics |
| ***Geometry*** | | | | |
| *Internal diameter (winding)* | **40 mm** | **30 mm** | **40 mm** | **50 mm** |
| *External diameter (winding+ob)* | 122.8 mm | 121.2 mm | 122.8 mm | 125.4 mm |
| *Number of double-pancakes* | 25 | 25 | 25 | 25 |
| *Turns per pancake* | 380 | 420 | 380 | 360 |
| *Total length* | 4769.3 m | 4888.6 m | 4769.3 m | 4959 m |
| ***Electrics*** | | | | |
| *SC conductor* | THEVA APC | | | |
| *Nominal current* | 293 A | 303.9 A | 308.9 A | 283.3 A |
| *Critical current* | 388.1 A | 373.1 A | 389.1 A | 398.1 A |
| *Current margin on load line* | **24.5 %** | **18.5 %** | **20.6 %** | **28.8 %** |
| ***Magnetics*** | | | | |
| *Magnetic field at center (HTS alone)* | **21 T** | **24 T** | **22 T** | **19 T** |
| *Total Magnetic field at center* | **40 T** | **43 T** | **41 T** | **38 T** |
| ***Mechanics*** | | | | |
| *Winding tension* | 100 MPa | | | |
| *Turns of over-banding* | 50 | | | |
| *Maximal hoop stress* | **655.8 MPa** | **677.9 MPa** | **707.3 MPa** | **667.2 MPa** |
| *Non-thermal deformation (winding+field)* | 0.37 % | 0.38 % | 0.39 % | 0.37 % |

**Parametric study (>10000 cases) with design criteria :**

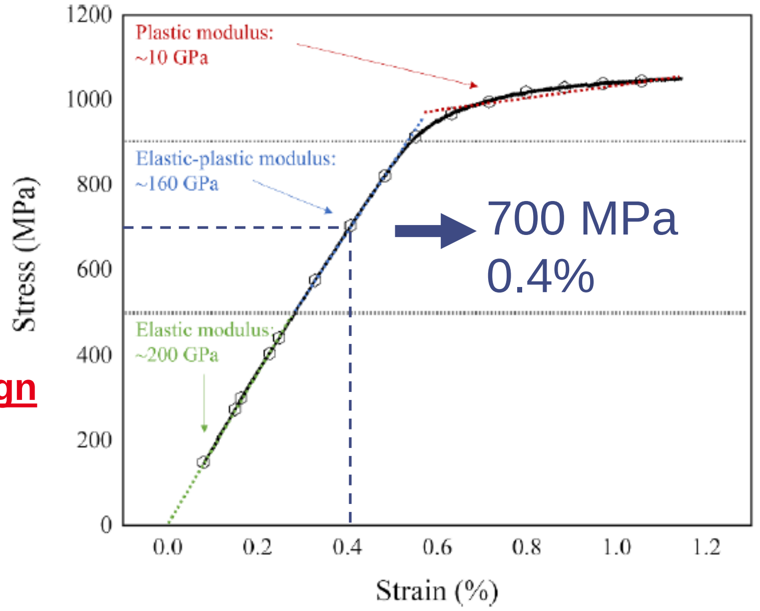
- **Current margin > 25%**
- **Max Hoop-stress < 800 MPa**
- **Max elastic Hoop-strain < 0.4%**

## Conclusion of the study :

- Easy to fabricate
- High mechanical stress level due to high number of turns
- Possible loss of contact issue due to high number of turns
- Not possible to achieve 40T in a 50mm Ø

**Elastic-plastic model of the REBCO coated conductor.**

Bang 2024



# SuperEMFL : HTS nested coil results

## Magnetic optimised designs of SuperEMFL nested pancake coil

| Name | Basic design | | Low-stress design | High-Field Design | High-volume Design |
|---|---|---|---|---|---|
| *Ref.* | N1a | N1b | N2 | N3 | N4 |
| ***Design led by*** | | | Mechanics | | |
| ***Geometry*** | | | | | |
| *Unit length* | < 200 m | < 100 m | < 200 m | < 200 m | < 200 m |
| *Internal diameter (winding)* | **50 mm** | **50 mm** | **50 mm** | **50 mm** | **70 mm** |
| *External diameter (windings+ob)* | 213.2 mm | 167 mm | 215.8 mm | 215.8 m | 214.8 mm |
| *Gap between HTS1 and HTS2* | 15 mm | 15 mm | 10 mm | 10 mm | 10 mm |
| *Number of double-pancakes HTS1* | 21 | 24 | 23 | 25 | 24 |
| *Turns per pancake HTS1* | 360 | 330 | 520 | 520 | 460 |
| *Number of double-pancakes HTS2* | 22 | 25 | 24 | 25 | 25 |
| *Turns per pancake HTS2* | 260 | 70 | 160 | 160 | 120 |
| *Maximal unit length* | 200 m | 100 m | 200 m | 200 m | 200 m |
| *Total length* | 10 744 m | 5934.8 m | 12 051 m | 13 470 m | 11 961 m |
| ***Electrics*** | | | | | |
| *SC conductor* | | | THEVA APC | | |
| *Nominal current* | 231.2 A | 339.7 A | 208.8 A | 238.3 A | 239.1 A |
| *Critical current* | 342.6 A | 406.1 A | 326.6 A | 324.2 A | 348.1 A |
| *Current margin on load line* | **32.5 %** | **16.4 %** | **36.1 %** | **26.5 %** | **33.3 %** |
| ***Magnetics*** | | | | | |
| *Magnetic field at center (HTS alone)* | **25 T** | **25 T** | **25 T** | **29 T** | **25 T** |
| *Total magnetic field (HTS+LTS)* | **40 T** | **40 T** | **40 T** | **44 T** | **40 T** |
| ***Mechanics*** | | | | | |
| *Winding tension* | | | 100 MPa | | |
| *Turns of over-bending* | | | 50 | | |
| *Maximal hoop stress HTS1* | **410.2 MPa** | **692.8 MPa** | **496.1 MPa** | **614.6 MPa** | **659.2 MPa** |
| *Non-thermal deformation (winding+field) HTS1* | 0.25 % | 0.38 % | 0.29 % | 0.35 % | 0.37 % |
| *Maximal hoop stress HTS2* | **749.6 MPa** | **705.1 MPa** | **616.2 MPa** | **722.8 MPa** | **693.1 MPa** |
| *Non-thermal deformation (winding+field) HTS2* | 0.41 % | 0.39 % | 0.34 % | 0.40 % | 0.38 % |

*Courtesy of SuperEMFL design report of 32+T and 40+T nested coil HTS inserts*

→ Low stress design

## Conclusion of the study :

- Reduced of stress level : because of less number of turns better transfer of radial mechanical loads.
- Reduction of contact loss due to reduced number of turns per pancakes
- High magnetic coupling between coils.
- Need larger LTS internal diameter : 250 mm Ø

→ 50% more expensive.

## Choice for the FASUM 40T project :

- Best **HTS technical** configuration : **Nested coil**
  LTS (15T – 150 mm Ø ) / HTS (25T – 50 mm Ø)
- Best **LTS economical** configuration : **Single coil**
  LTS (19T – 140 mm Ø) / HTS (21T - 40 mm Ø )

***"Even though the Nested coil configuration can not be used for the FASUM project we are investigating nested coils dynamics with SuperEMFL prototypes…should be tested in the coming months."***

# FASUM 40 T : HTS single coil mechanical calculation

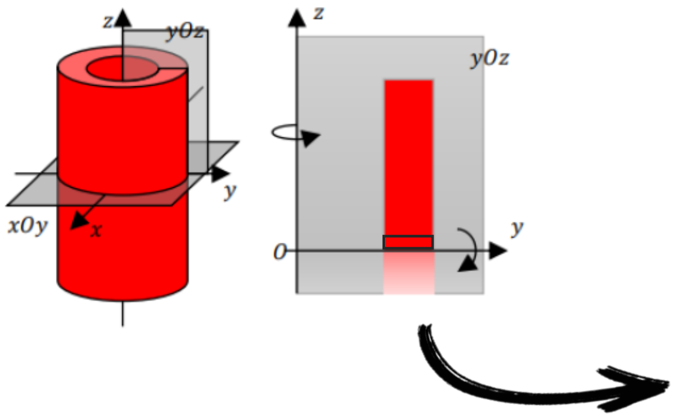
## Choice of a single pancake design

| | Basic Design |
|---|---|
| *Ref.* | *S1* |
| ***Design led by*** | Mechanics |
| ***Geometry*** | |
| *Internal diameter (winding)* | **40 mm** |
| *External diameter (winding+ob)* | 122.8 mm |
| *Number of double-pancakes* | 25 |
| *Turns per pancake* | 380 |
| *Total length* | 4769.3 m |
| ***Electrics*** | |
| *SC conductor* | |
| *Nominal current* | 293 A |
| *Critical current* | 388.1 A |
| *Current margin on load line* | **24.5 %** |
| ***Magnetics*** | |
| *Magnetic field at center (HTS alone)* | **21 T** |
| *Total Magnetic field at center* | **40 T** |
| ***Mechanics*** | |
| *Winding tension* | |
| *Turns of over-banding* | |
| *Maximal hoop stress* | 655.8 MPa |
| *Non-thermal deformation (winding+field)* | 0.37 % |

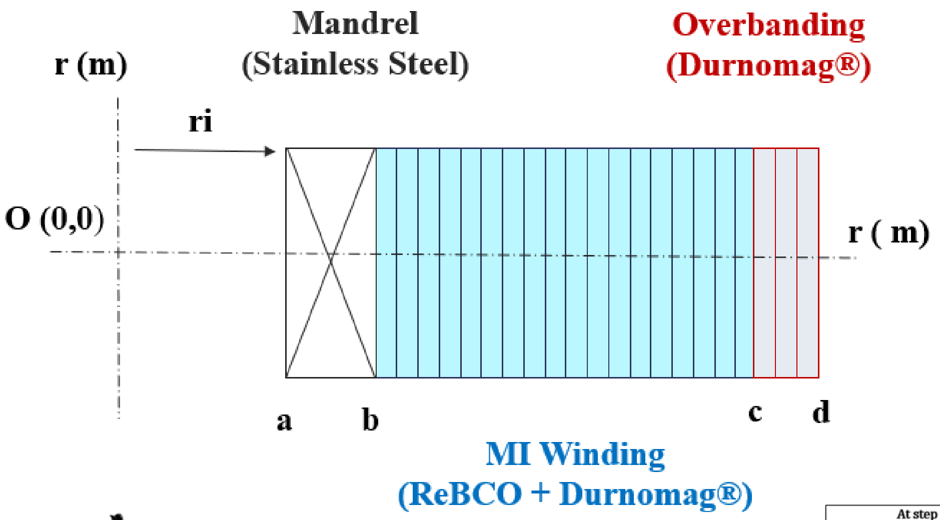
*SuperEMFL design report of 32+T and 40+T single coil HTS inserts*

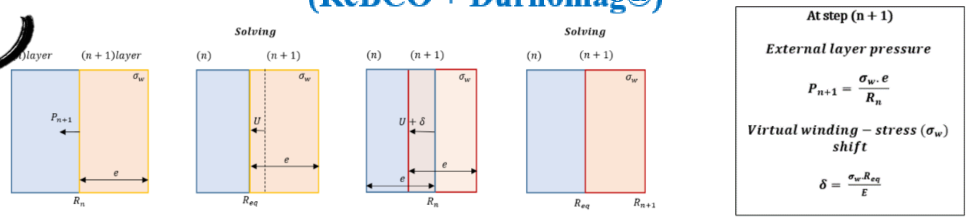
T. de Chabannes - 2024

## 2D pancake axisymmetric model

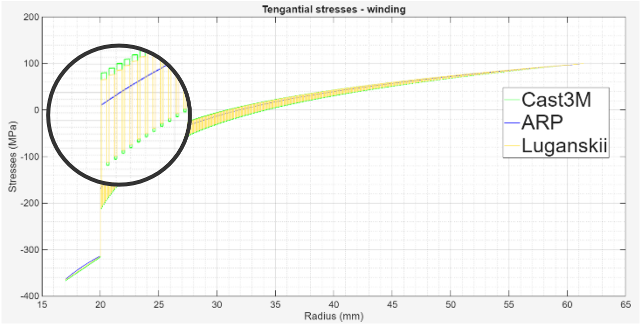



## Meshing the co-winding with pre-tension




Pre-tensioned meshing



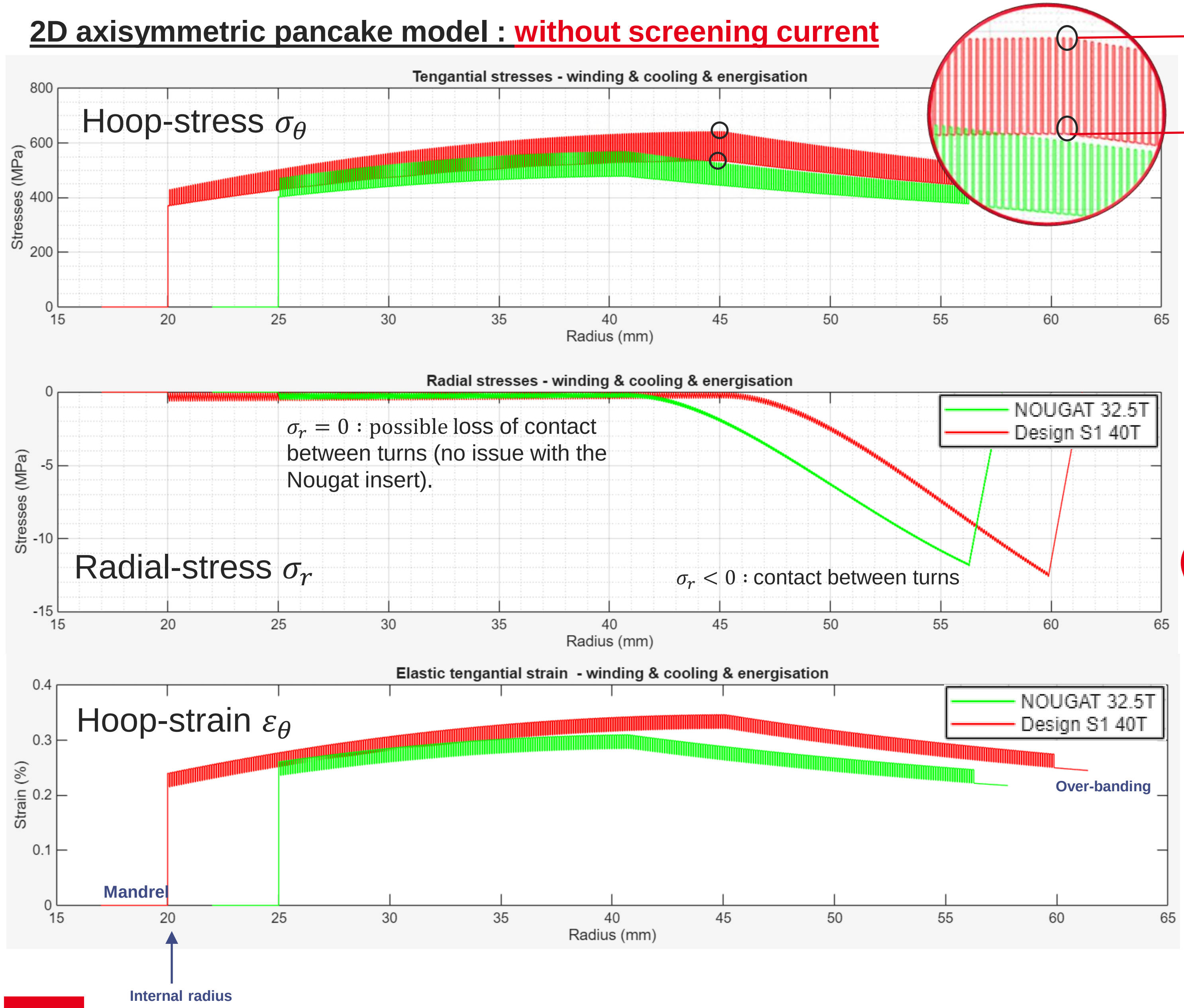

## CEA in house mechanical FEM

### 3 loadings

- Winding with pre-tension
- Cooling at 4K
- Lorentz force density due to energizing and external field (uniform or screening current density)

# FASUM 40 T : single coil mechanical calculation

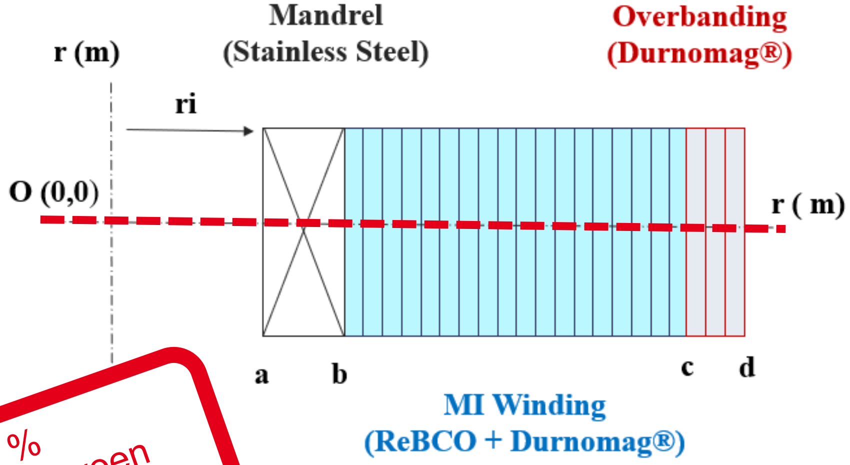
## 2D axisymmetric pancake model : without screening current




**Co-winding Durnomag**
max Hoop-stress : 655 MPa

**ReBCO tape**
max Hoop-stress : 534 MPa

## Mid-plane pancake analysis



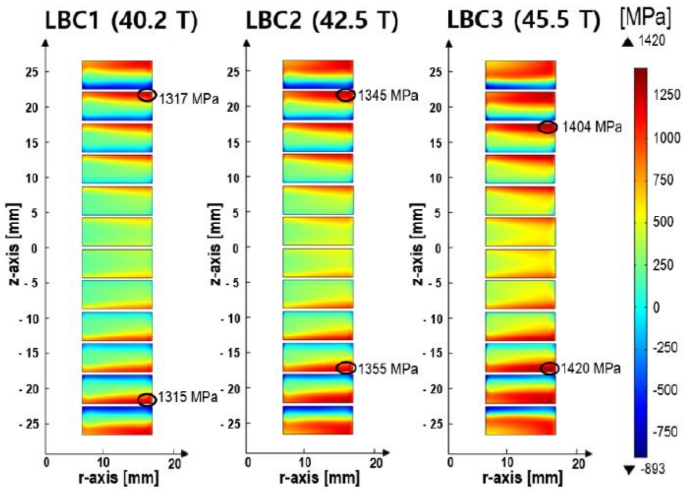

A gap of 15 % (100 Mpa) between 32.5T and 40T designs.

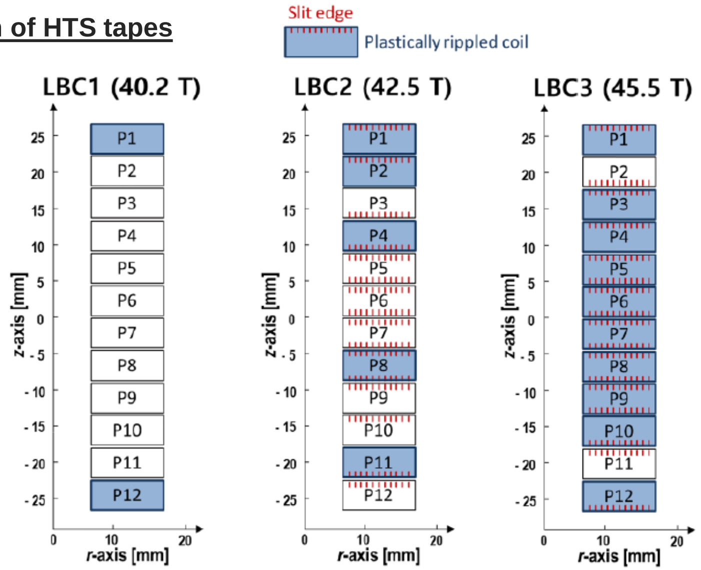
| | | Nougat 32.5 T | Deign S1 40T |
|---|---|---|---|
| Nb turns [-] | [-] | 290 | 360 |
| Nominal current | [A] | 318 | 293 |
| External field | [T] | 18 | 19 |
| Over-banding turns | [-] | 50 | 50 |
| Max hoop-stress | [MPa] | 569 | 655 |
| Max elastic hoop-strain | [%] | 0.31 | 0.36 |
| $\sigma_r$ = 0 | [-] | yes | yes |

# Special case : the screening current issue

- **Strong mechanical issues**
  - **High current density** area with reverse directions
  - Strong & localised **opposite induced Lorentz forces**
  - High tensile & compressive **hoop stresses and shear stress effect**
  - Mechanical and magnetic degradation : **Ic decrease & local plastic behavior**
- **The particular case of the Little Big Coil 45T+ NHMFL**
  - **SC induced hoop-stress > 1 GPa**

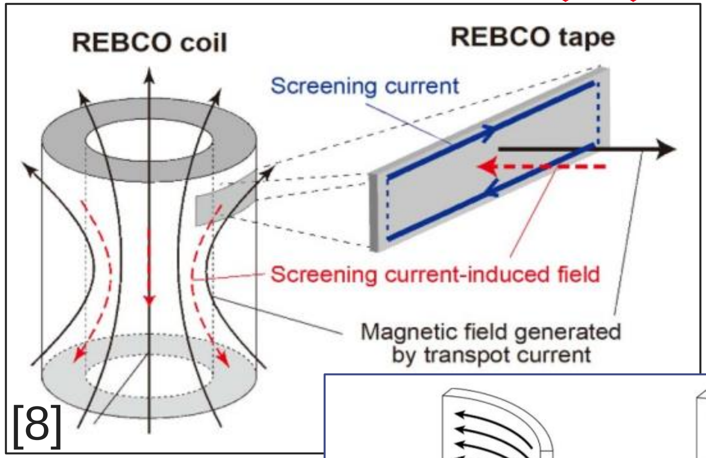
Hoop stress with SC calculation inducing plastification of HTS tapes

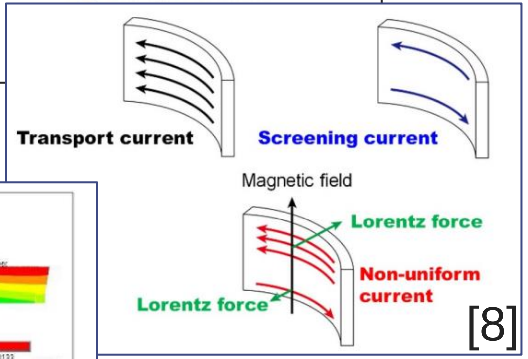


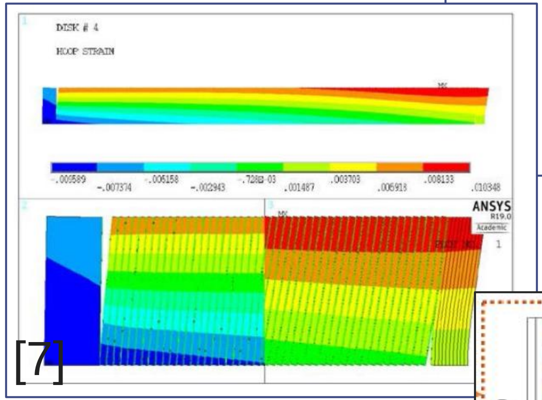




Xinbo Hu 2020

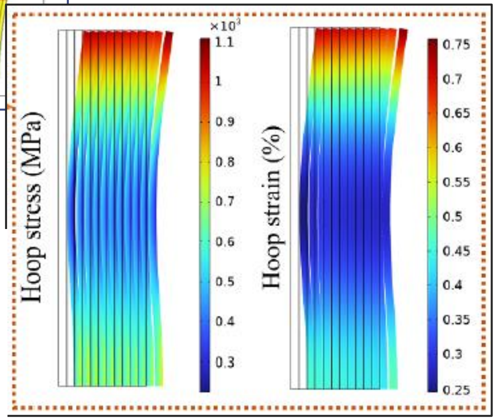
Unwound tape with plastified edge.



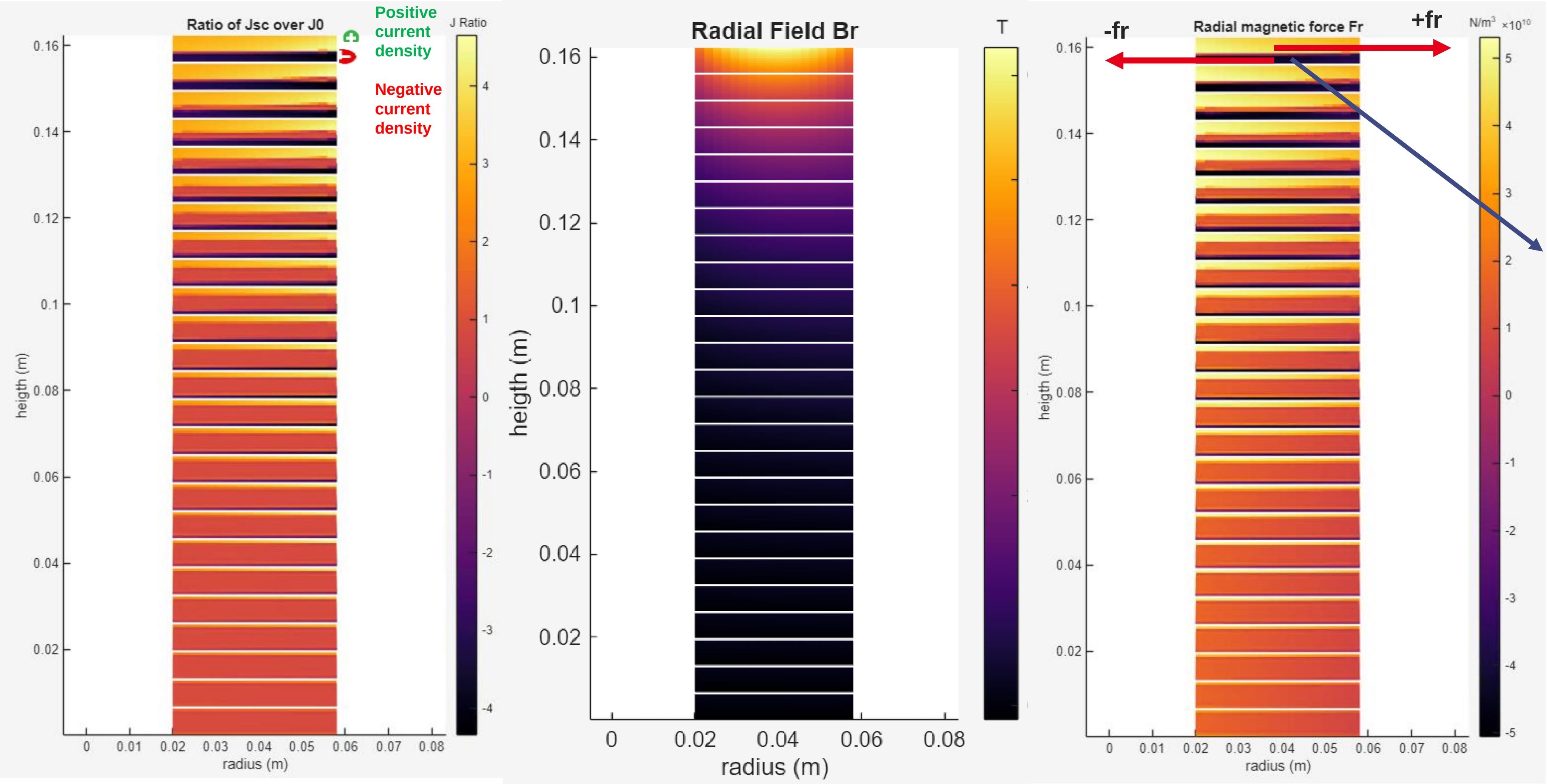




Bang 2024



# FASUM 40 T : calculation of screening current

- **A-V formulation** code (In house 2D axisymmetric model) to achieve the **SC distribution**
  - Results of SC distribution within the Design_S1 40T




Opposite forces.

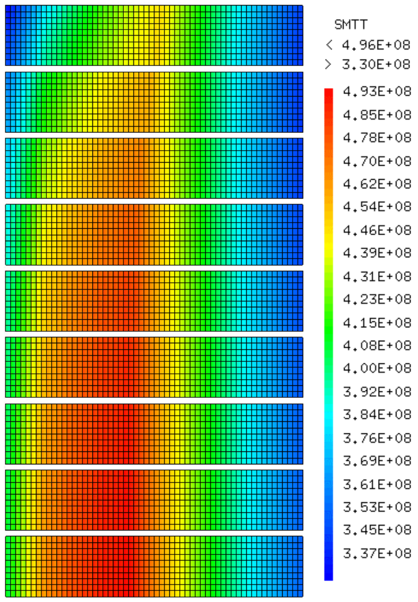
| | Simulation data | |
|---|---|---|
| Current slope | 1 | $[A.s^{-1}]$ |
| Uniform current density | 651 | $[A.mm^{-2}]$ |
| Nominal current | 293 | $[A]$ |
| Copper matrix (rrr) | 100 | $[V.m^{-1}]$ |
| Power law n index | 31 | |
| Power law voltage criteria | 0.0001 | |
| Ic fit | THEVA APC | |
| External field | 19 | $[T]$ |

G. Dilasser 2022

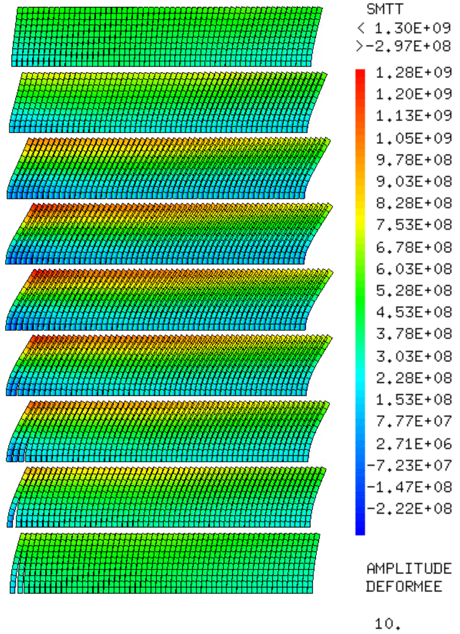
# FASUM 40 T : calculation of screening current stresses & strains

## Comparative mechanical study with **homogenised** co-wound tapes :

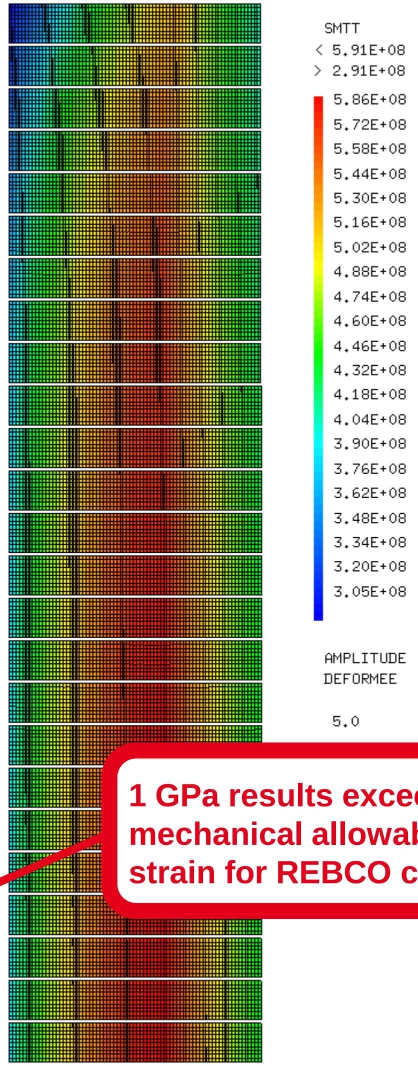
**Hoop-stress Nougat 32.5T**
**Uniform current density**



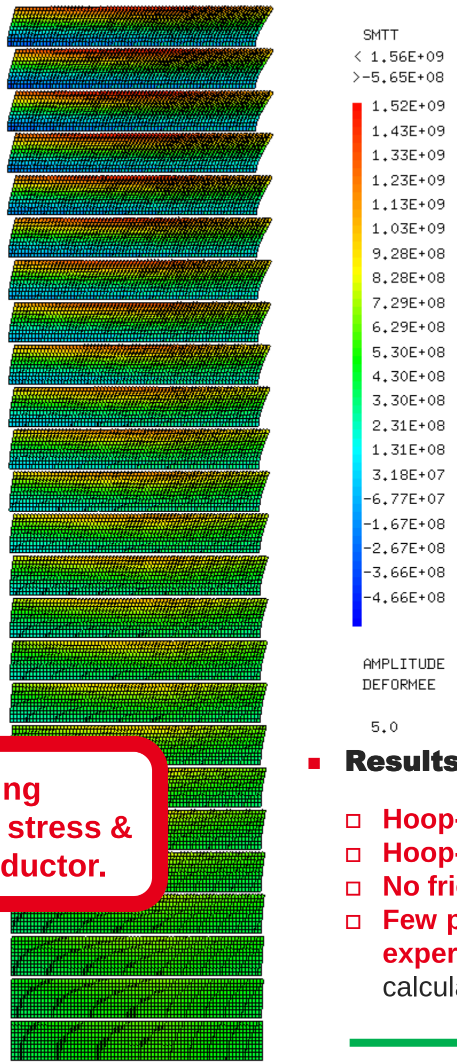

**Hoop-stress Nougat 32.5T**
**Screening current density**



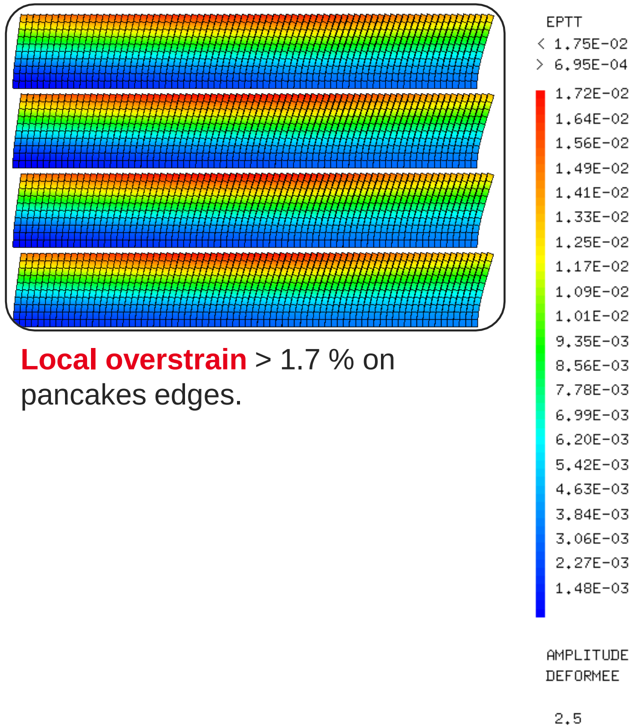

**Hoop-stress Design_S1 40T**
**Uniform current density**




**Hoop-stress Design_S1 40T**
**Screening current density**




**Focus on elastic hoop-strain for the 4 top pancakes.**




**Local overstrain** > 1.7 % on pancakes edges.

| | | Nougat 32.5 T | Design_S1 40T |
|---|---|---|---|
| Max hoop-stress @ J0 | [MPa] | 496 | 591 |
| Max elastic hoop-strain @ J0 | [%] | 0.285 | 0.55 |
| Max hoop-stress @ JSC | [MPa] | 1280 | 1560 |
| Max elastic hoop-strain @ JSC | [%] | 1.51 | 1.44 |

**1 GPa results exceeding mechanical allowable stress & strain for REBCO conductor.**

- **Results exceeding mechanical strengh**
  - **Hoop-stress > 1GPa** exceeding REBCO elastic behavior
  - **Hoop-stress >0.4 %** starting Ic degradation
  - **No friction and axial pressure** taken into account
  - **Few plastic behavior observed with the Nougat 32.5T experimentation** in spite of the 1300 MPa predicted by calculation.

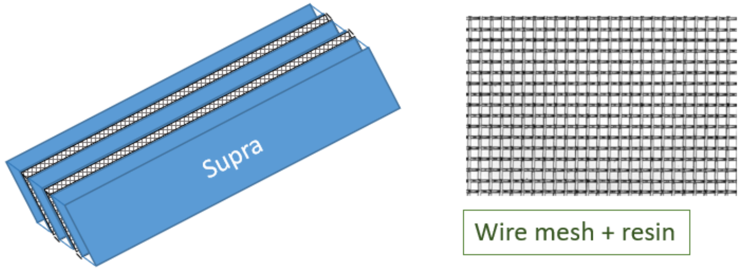
→ **Need further studies**

# Keys : for mechanical issues in the HTS insert

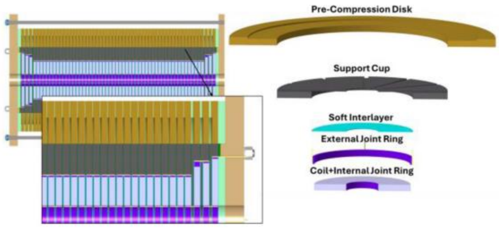
- **Conclusions & discussion of FASUM single coil mechanical analysis**
  - For the FASUM 40T the **Single coil HTS insert** configuration have been chosen for its **economical reason.** Although the nested coil configuration shows interesting mechanical perfomances.
  - Mechanical results on the FASUM 40T single coil design_S1 with uniform current density show high but **reasonable stress** and strain level, **below 0.4%**.
  - **Screening current analysis** shows **very high stress and strain level** exceeding ReBCO allowable stress. These results **needs further study** especially with the taking into account of **the friction between pancakes due to axial pressure**.
  - The issue of **contact loss** observed in the mechanical study may occur due to high number of turns of the FASUM design_S1 and **need to be further studied** as  it is not a concern in the Nougat 32.5T experiment.

- **Solutions for the high stress level :**
  - **High pre-winding** tension (MI technology) + strong **over banding**
  - **Pre-compression ring** : [Muon Collider] bladders or frets are difficult with the FASUM configuration : no space for reinforcement
  - **MI2 impregnation** [CEA Patent] consist in MI + impregnation (wax, resin) = self-protection + mechanical reinforcement
  - **NI + Soldering/Partial soldering** : [Muon Collider] & [Tokamak NRJ]

- **Solutions for the screening current effect :**
  - ReBCO tape **striation**
  - Reduction of REBCO **tape width**
  - Low ramping **time constant** or current overshoot
  - Adjusting **a/b plane** direction with **field orientation**
  - **Vortex-shaking**




**MI2 CEA Patent - 2025**
**Courtesy of F.Rondeaux P.Fazilleau T.Lecrevisse**




**Muon Collider 40T magnet compression ring**

C. Accetura 2025

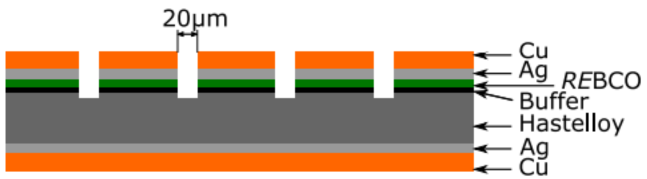



Fig. 1. Cross-sectional diagram of the superconducting striated tape with five filaments after cutting the edges.

A. Godfrin 2017

# 2. Mechanical issues with HTS/LTS interactions : FASUM 40T project.

# FASUM 40 T : mechanical issues with HTS/LTS interactions

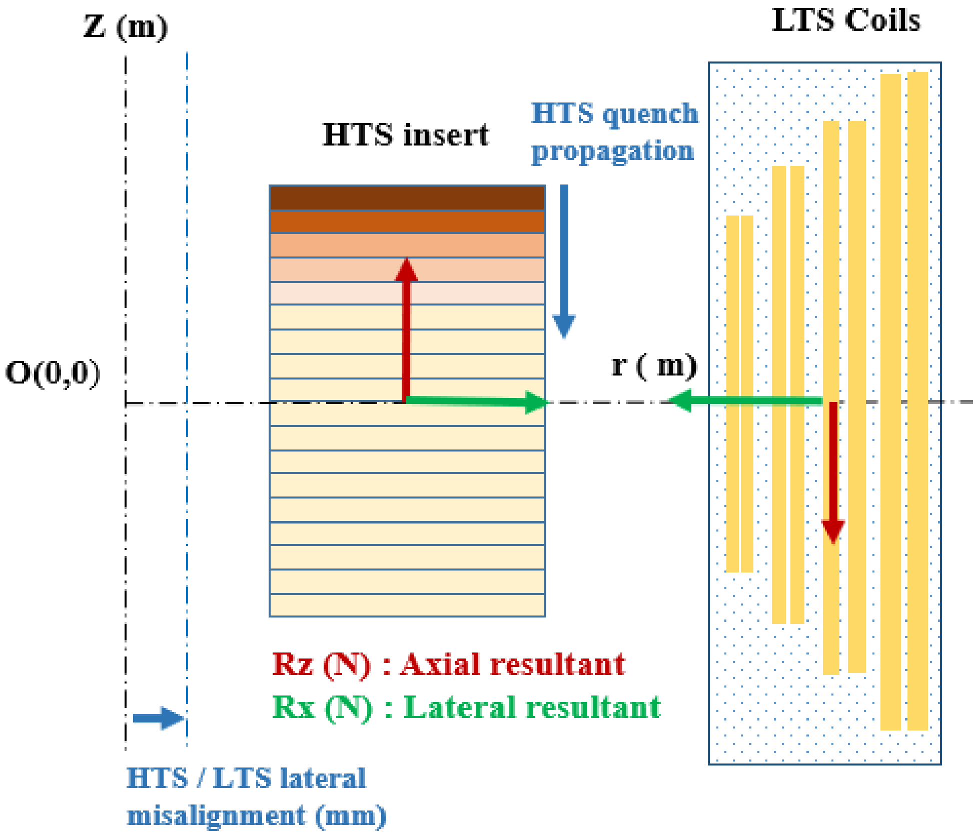
## Problematic & issues

***Magnetic interactions*** *between HTS insert and LTS outsert.*
***Strong resultant forces induced****, to manage : axial & lateral*
***No Torque issues with MI technology*** *: conclusions of the superEMFL study.*

**Two main issues to tackle :**

- **Quench** of the HTS insert / LTS outsert
- **Lateral / axial misalignment** of the HTS insert within the LTS outsert

Mechanical resultants due to magnetic interactions between HTS and LTS coils.

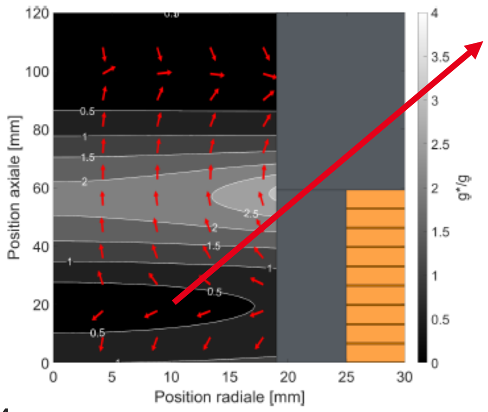


# FASUM 40 T : mechanical issues of HTS/LTS interactions

- **Quench of the HTS insert**
  - **Asymmetrical quench of the HTS pancakes**. Ignition starting at the top intern of the solenoid.
  - Impact of the **magneto-gravitational forces** due to helium diamagnetism.
  - Progressive **quench of the HTS pancakes** induce an strong **axial resultant**.

- **Calculation of the axial resultant in the case of the HTS asymmetrical quench**

2D magnetogravitational resultants mapping on top of the Nougat HTS insert.

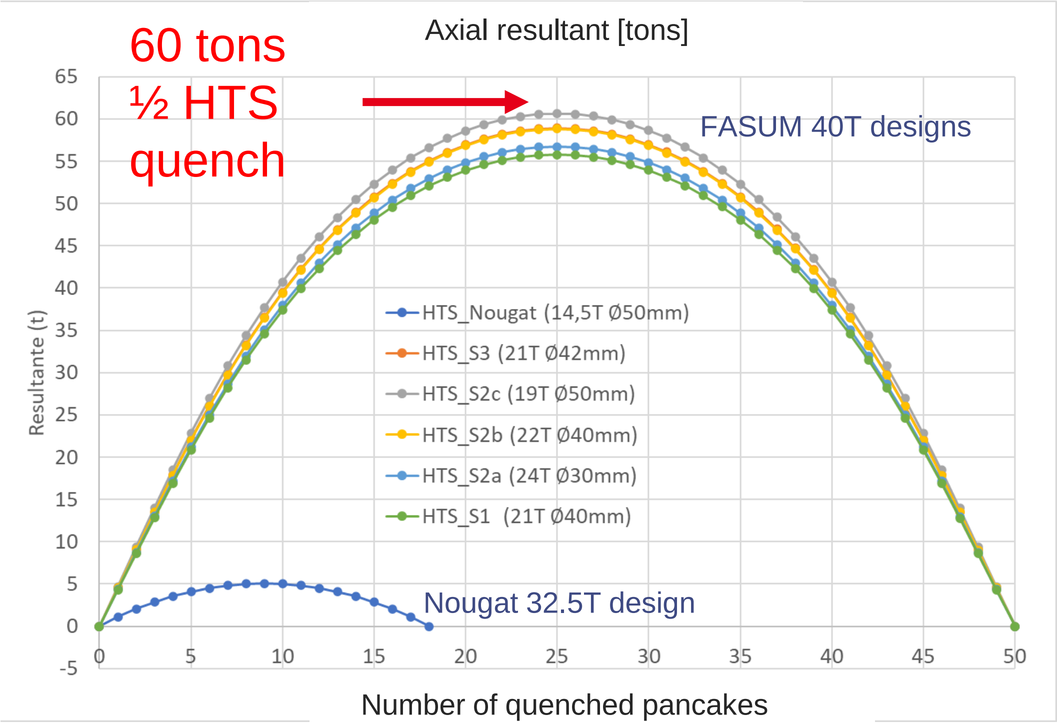


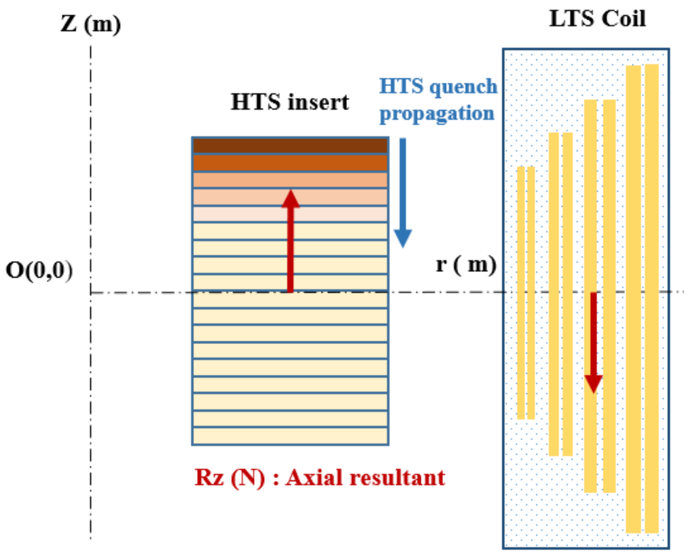

Trapped helium bubbles area. Local degradation of the cooling performances.

S. Bagnis 2023

E. Pardo 2024

**Axial resultant due to increasing number of quenched pancakes.**




- **High axial resultant**
  - **Calculated theoretical value of 60 tons** in the worst case (half of the HTS quench) but **mitigated with quench numerical modelisation : taken as 25 tons.**
  - Need to **reinforce axially the LTS outsert**.
  - Need to **design a fixing device** between HTS insert and LTS base plate.

# FASUM 40 T : mechanical issues of HTS/LTS interactions

- **LTS outsert quench**
  - **Symmetrical quench of the LTS coil with respect to the median plan.**
  - No mechanical issue on the HTS insert, no axial resultant except in the case of a THEVA APC REBCO tape due to the tilting angle of the a-b plane.

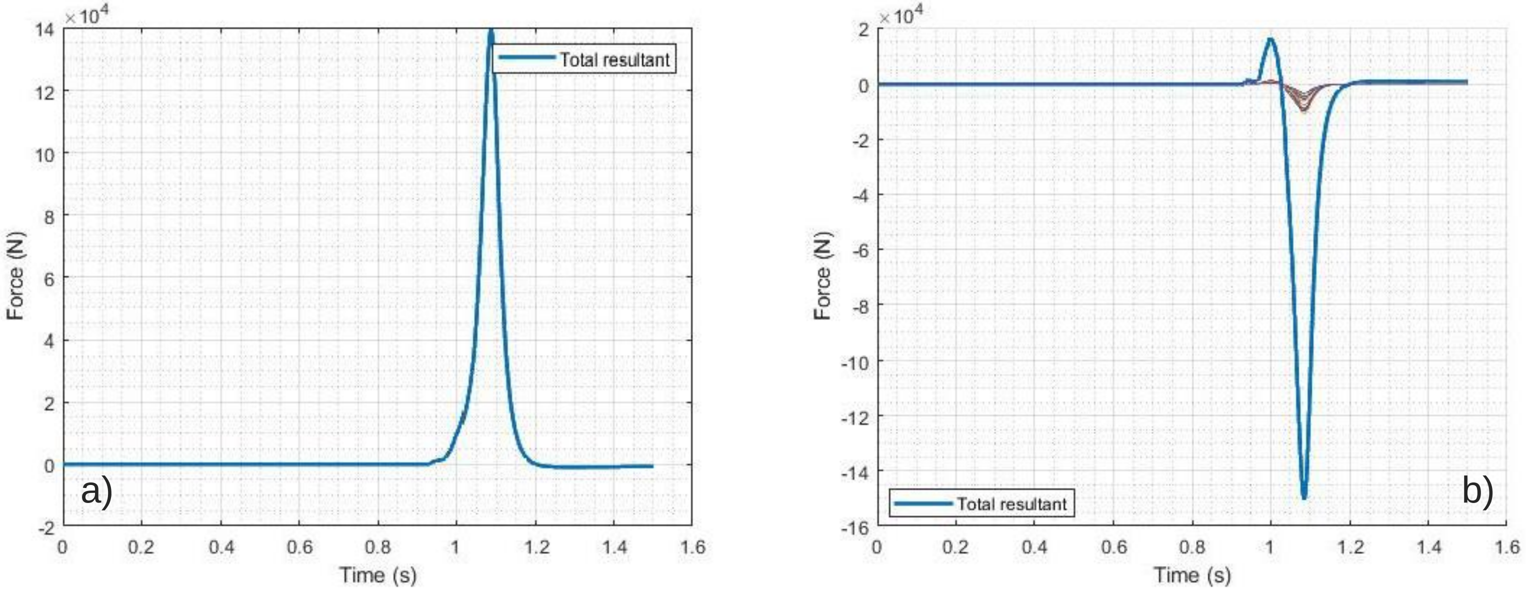
**Results of superEMFL** - axial resultants due to HTS/LTS quench event

| | | NOUGAT IN 19 T | 32 T BASIC DESIGN | S1 40 T DESIGN |
|---|---|---|---|---|
| QUENCH IGNITION IN HTS PART | Axial force/pancake | 58 kN | 120 kN | 160 kN |
| | Total axial resultant | | | 2 |
| QUENCH IGNITION IN LTS PART | Axial force/pancake | 80 kN | 130 kN | 280 kN |
| | Total axial resultant | 0 N | 20 kN[4] | 140 kN[4] |

THEVA APC conductor : axial resultant > 20 KN

SuperPower conductor : axial resultant = 0 KN

**Results of superEMFL** – Axial resultant generated in the HTS (a) and the LTS (b) parts during LTS quench event.

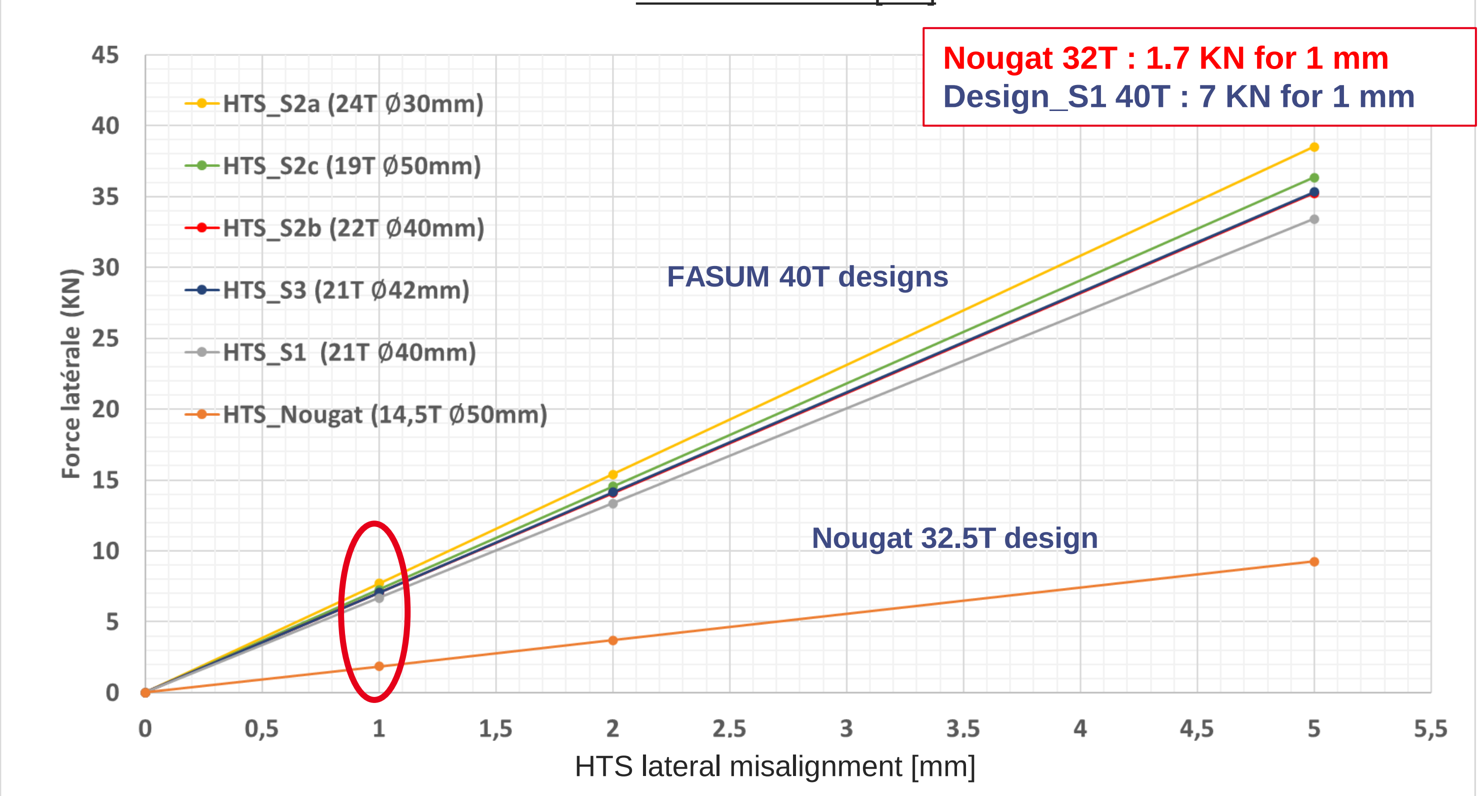


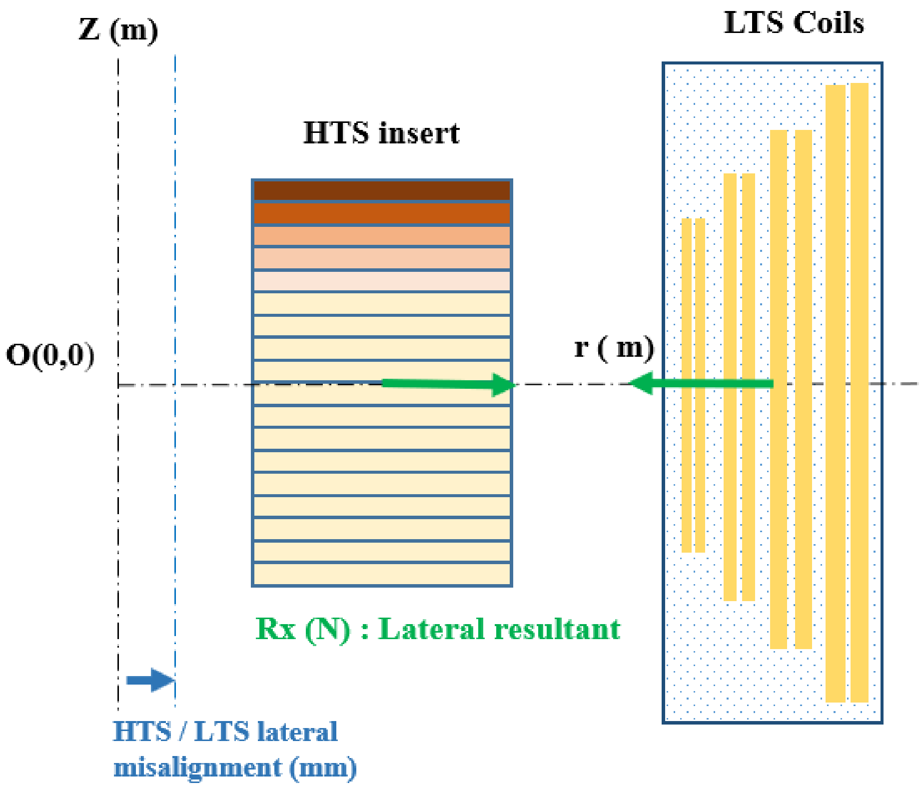

- **Special issue THEVA APC**
  - Axial resultant of 14 tons in case of the LTS quench due to THEVA APC a-b plane 30° angle.
  - For future HTS insert this issue is **managed with a tape orientation adjustement** in order to have no axial resultant.

# FASUM 40 T : mechanical issues of HTS/LTS interactions

- **HTS insert axial misalignment**
  - HTS axial misalignment induces auto-centring forces transferred to the HTS/LTS fixing device.
- **HTS insert lateral misalignment**
  - Lateral misalignement is a **severe issue of the FASUM project** currently. Hard to reinforce laterally the LTS coils which can resist only a limited lateral resultant value. **Quasi not allowable** with the FASUM design_S1 insert with **1 mm** lateral misalignment.

LTS max allowable lateral resultant for < 1 mm lateral misalignment.



## Keys for mechanical issues with the HTS/ LTS interactions

- **Conclusions of HTS/LTS mechanical interaction study**

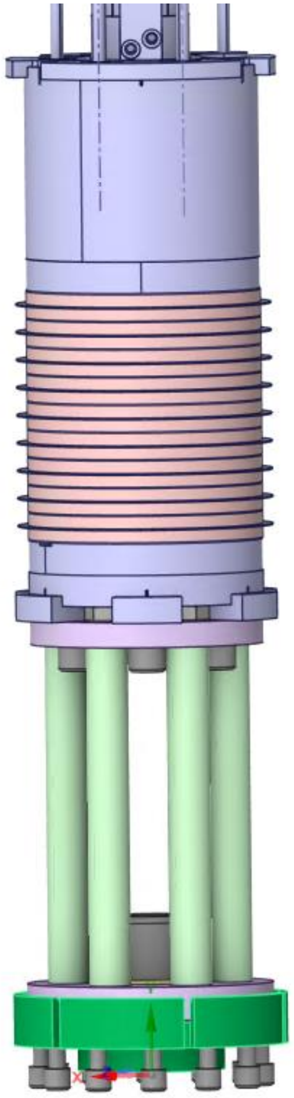
  - Issue of the **HTS insert quench** inducing **25 tons axial resultant.**
  - Issue of the **HTS lateral misalignment** inducing **7 KN lateral resultant** bearly acceptable for the LTS coils.

- **Technical solutions to HTS/LTS mechanical interactions**

  - LTS outsert **axial & lateral reinforcement** : coil support and bore tube
  - HTS/LTS **fixing device** to resist the axial resultant of 25 tons.
  - HTS geometrical positioning : imposing a **maximum of +/-1mm lateral misalignment** during testing experiment.
  - Progressive experimental **testing with increasing number of DP** :

*"Current testing of the Nougat 14.5T insert in Dresden HZDR with a 18T LTS outsert delivered by Oxford Instrument : reaching 28,2T last week."*

*X. Chaud & J. Song – LNCMI*



Conceptual design of the HTS/LTS fixing device to prevent from lateral/axial resultant.

# Conclusion

- **Issues with mechanics in UHF : particular case of hybrid LTS/HTS magnet**

  ◻ **High increase of stress & strain level** : **allowable results with uniform current density** :
  Hoop stress < 800 MPa & Elastic Hoop-strain < 0.4%

  ◻ **Screening current local over stress & strain : exceeding material mechanical properties** :
  Hoop stress < 1 GPa & Elastic Hoop-strain >1%

  ◻ **HTS/LTS mechanical interactions** : **axial/lateral resultants** not allowable for the LTS magnet.

- **Technological implications & perspectives**

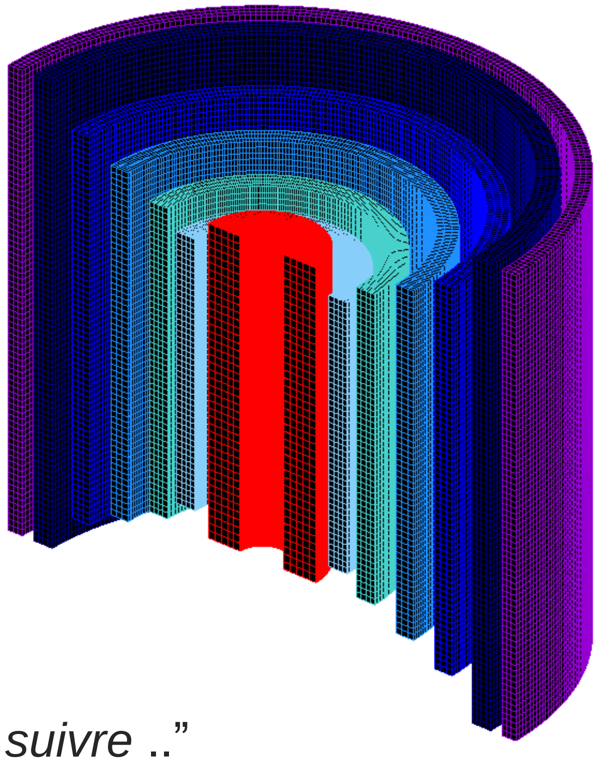
  ◻ **Needs for** a **HTS insert design** managing the high stress and strain level with technical solutions :
  MI2, pre-winding, over-banding, tape striation ..

  ◻ **Needs for LTS reinforcement specifications** : axial / lateral

  ◻ **Needs for HTS/LTS fixing device**

  ◻ **Needs for** further **mechanical numerical studies and modelling**:
  - Loss of contact between turns
  - Introducing the friction and axial pressure
  - Elastic-plastic behavior due to screening current over-stress

  ◻ **Needs for specific testing procedures** to mitigate the mechanical issues & validate reinforcement solutions :
  progressive DP testing, over-shooting, vortex shaking, misalignment.



*“Affaire à suivre ..”*