DE LA RECHERCHE À L'INDUSTRIE

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# Cable Dimensional Changes Studies at CEA

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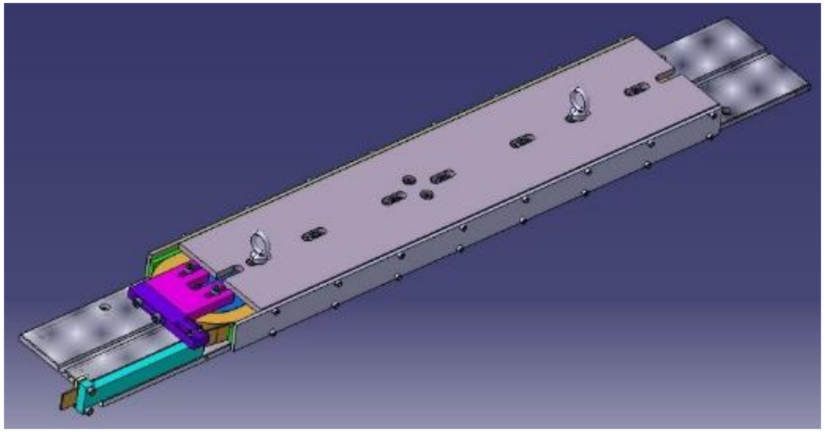


Workshop on $Nb_3Sn$ Rutherford cable characterization

for accelerator magnets

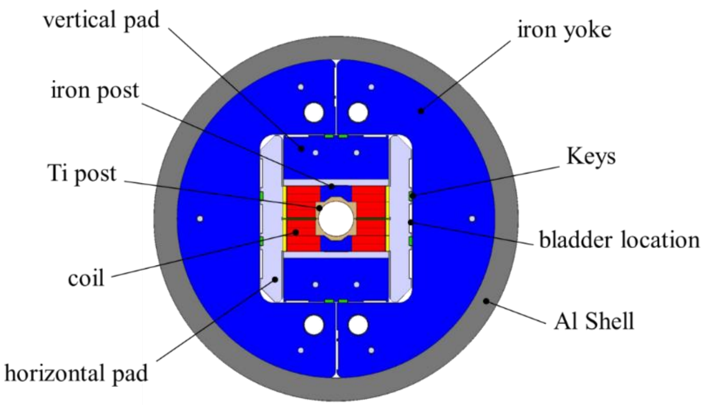
CIEMAT, Madrid – 17/11/2017

# CONTENT

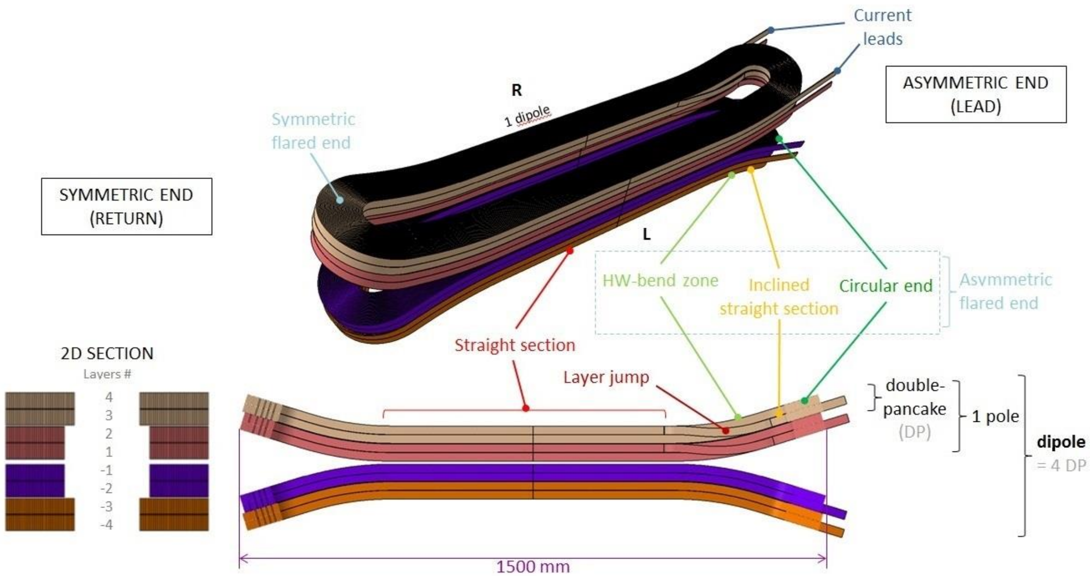
- Framework
- Cable Dimensional Changes Studies at CEA
  - Reduced scale dimensional change test setups
  - FRESCA2 experience

# FRAMEWORK

- R&D program on dimensional changes studies started during FRESCA2 design phase




FRESCA 2 dipole magnet

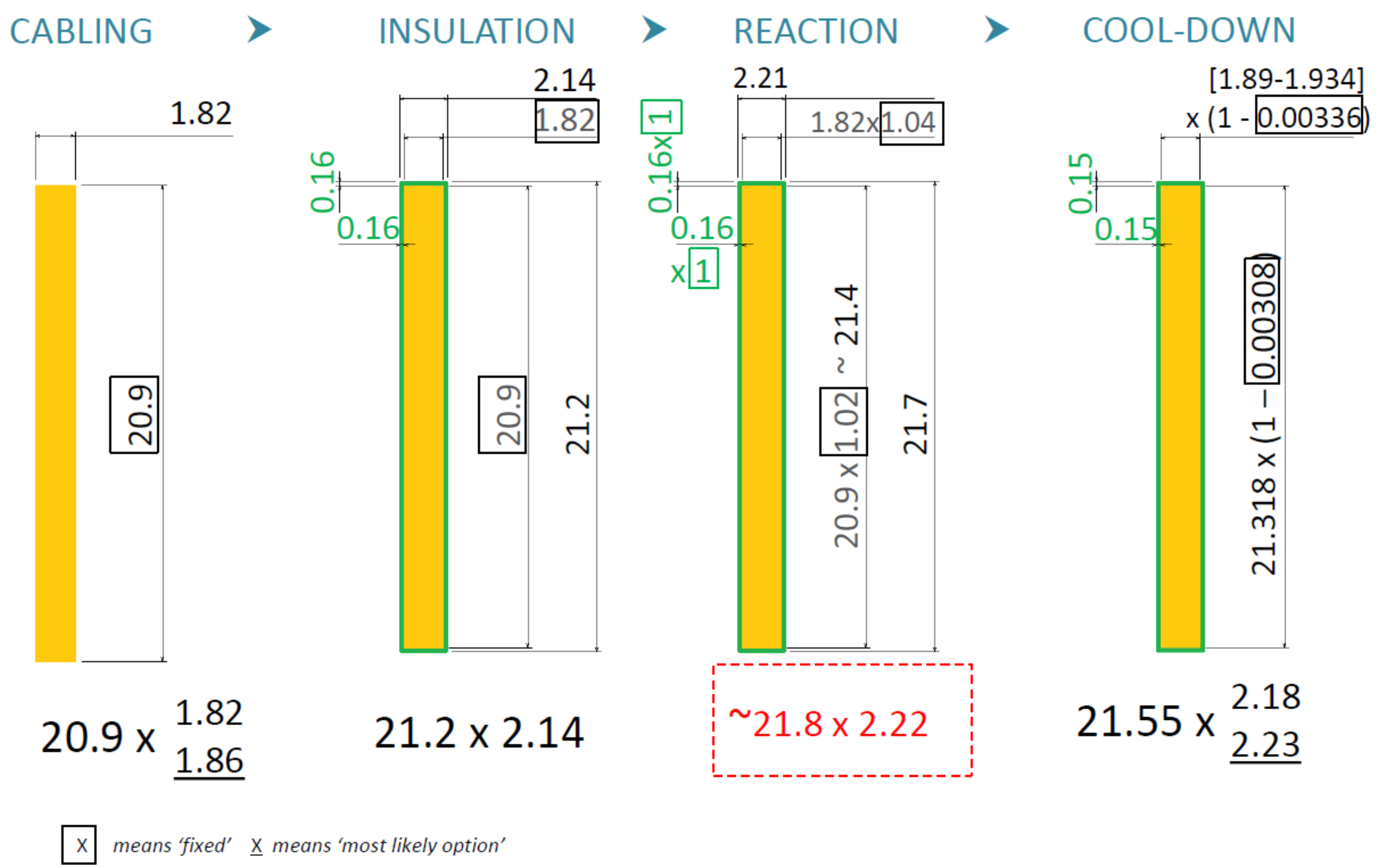



- The initial goal was to have a small test setup, able to check cable behavior during the heat treatment and give rules to be applied on the engineering design of FRESCA2 manufacturing tools

# FRESCA2 CABLE

Assumed cable behaviour: +4% in thickness

+2% in width



# DIMENSIONAL CHANGES - THICKNESS

## Test campaign on FRESCA2 PIT and RRP cables stacks

## Bare cable

RRP Cable

| TEN STACK | HT (CAVITY) | Thickness @5MPa | Thickness increase / 1.82 |
|---|---|---|---|
| SRNNN02 | no | 1.834 mm | |
| SRNTN02 | Yes (26.5%) | 1.873 mm | 2.91% |
| SRNTN03 | Yes (26.5%) | 1.872 mm | 2.86% |
| SRNTN04 | Yes (4%) | 1.877 mm | 3.13% |

PIT Cable

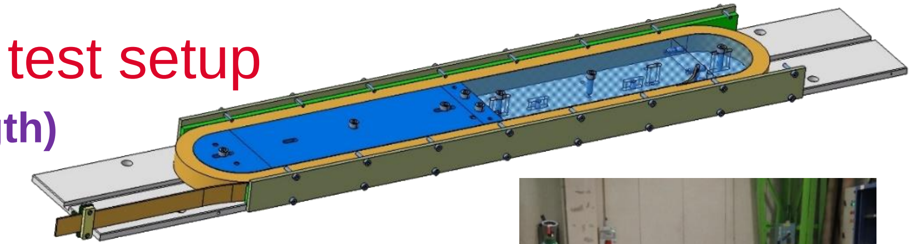
| TEN STACK | HT (CAVITY) | Thickness @5MPa | Thickness increase / 1.82 |
|---|---|---|---|
| SPNNN02 | no | 1.831 mm | |
| SPNTN02 | Yes (26.5%) | 1.889 mm | 3.79% |
| SPNTN03 | Yes (26.5%) | 1.883 mm | 3.46% |
| SPNTN04 | Yes (4%) | 1.881 mm | 3.35% |

- Stacks prepared and reacted at CEA
- Thickness measurements under 5 MPa done at CERN

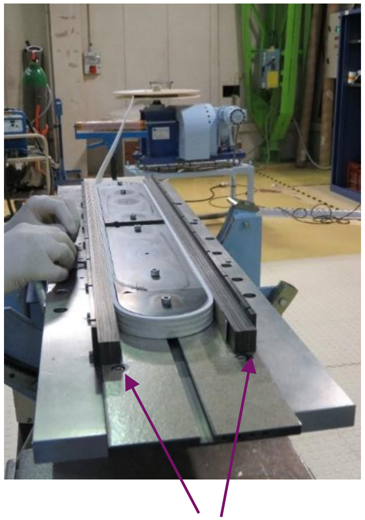
## Nominal expansion factor 4% in FRESCA2 tools design validated

# DIMENSIONAL CHANGES - LONGITUDINAL

## Reduced scale longitudinal changes test setup



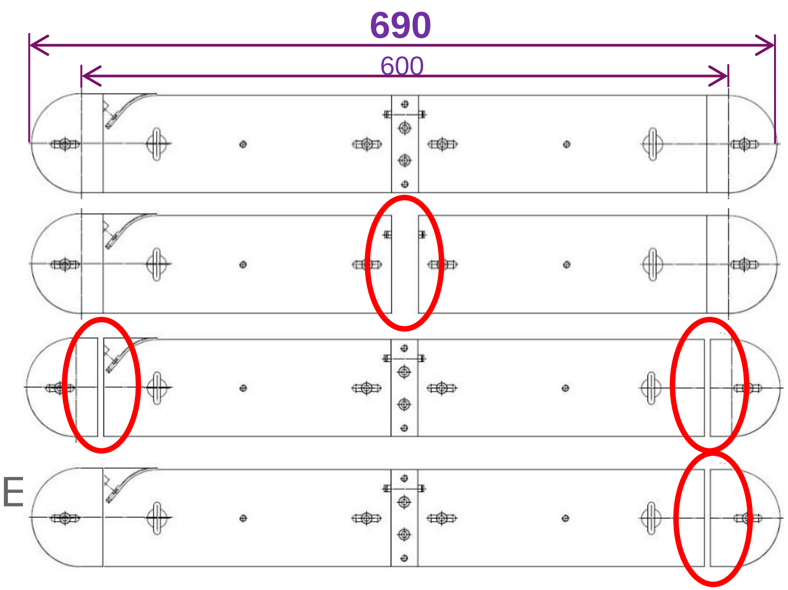
- Mandrel total length: **690 mm (reference length)**
- Straight section total length: 600 mm
- Mandrel width: 90 mm
- 3 mandrel materials : Titanium, Iron, Stailess Steel
- 1.5 turns = 2.4 m of cable



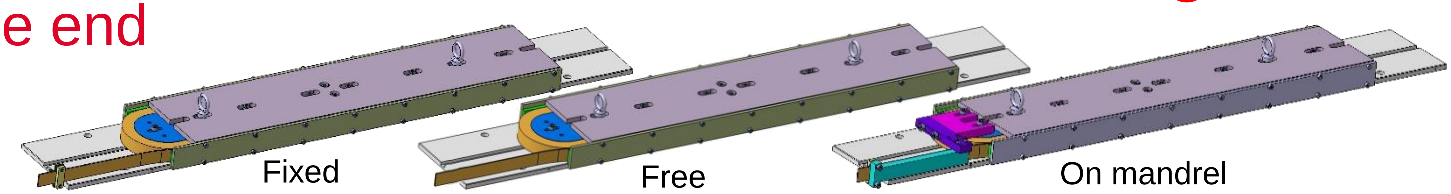
Adaptable cavity dimension

## Mandrel configurations

- Configuration 0 – C0
- Configuration 1 – C1
- Configuration 2 – C2
- Configuration 1 sym – C1 LE

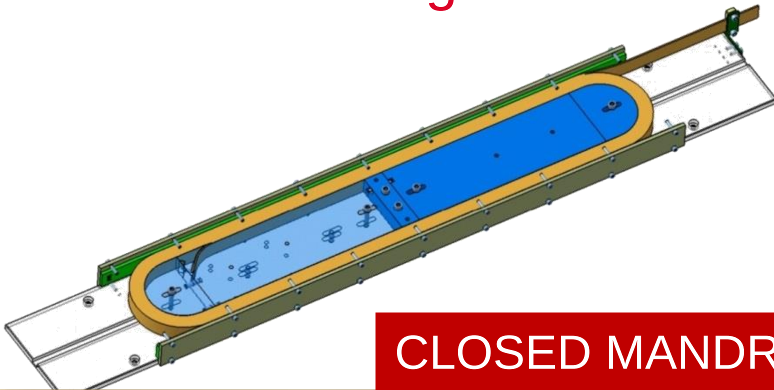



## Cable end



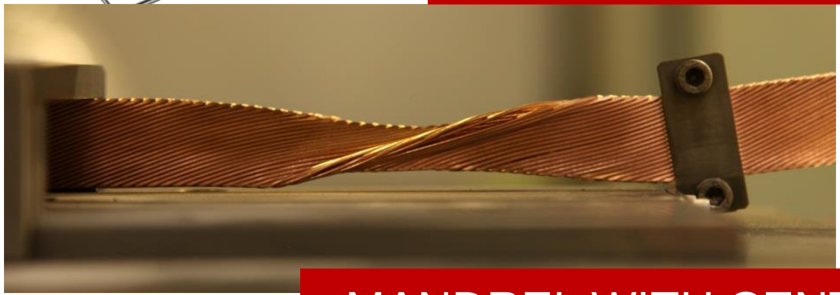
# FIRST TESTS ON BARE CABLE

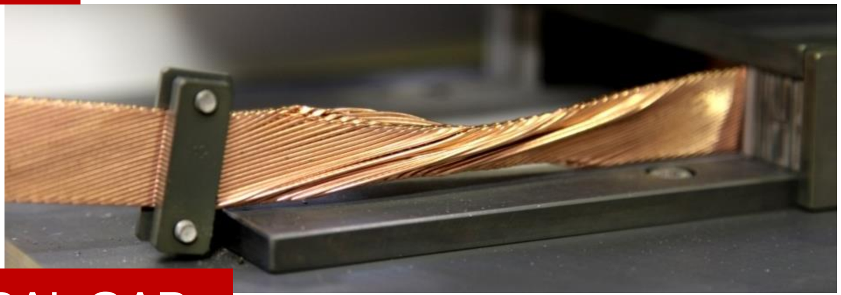
## Reduced scale longitudinal behavior tool



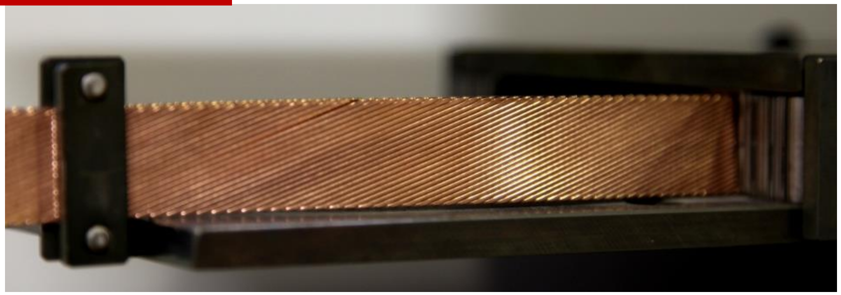
Stress witness

CLOSED MANDREL





MANDREL WITH CENTRAL GAP



# FIRST RESULTS WITH BARE PIT CABLE

## PIT Bare Cable

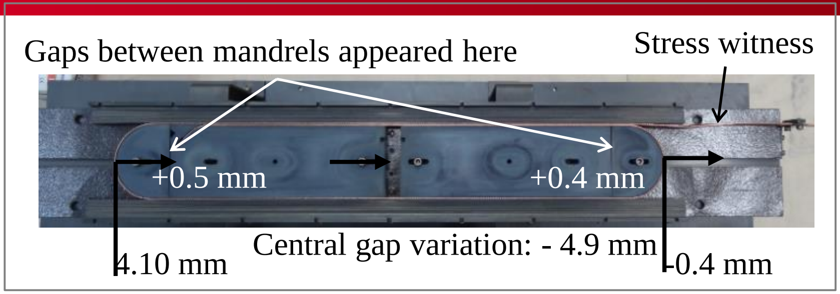
| Mandrel material | C1<br>1 central gap | Gap reduction % LSS | | C2 (*C1 LE)<br>2 head gaps *1 | Gap reduction % LSS | |
|---|---|---|---|---|---|---|
| Iron | HT1 | 5.83 mm | 0.97% | HT2 | 5.22 mm | 0.87% |
| Stainless steel | HT2 | 6.73 mm | 1.12% | HT3 | 8.02 mm | 1.34% |
| Titanium | HT2 | 5.50 mm | 0.92% | HT3 | 7.94 mm | 1.32% |

Tests on non insulated cable

Attention only on central gap reduction

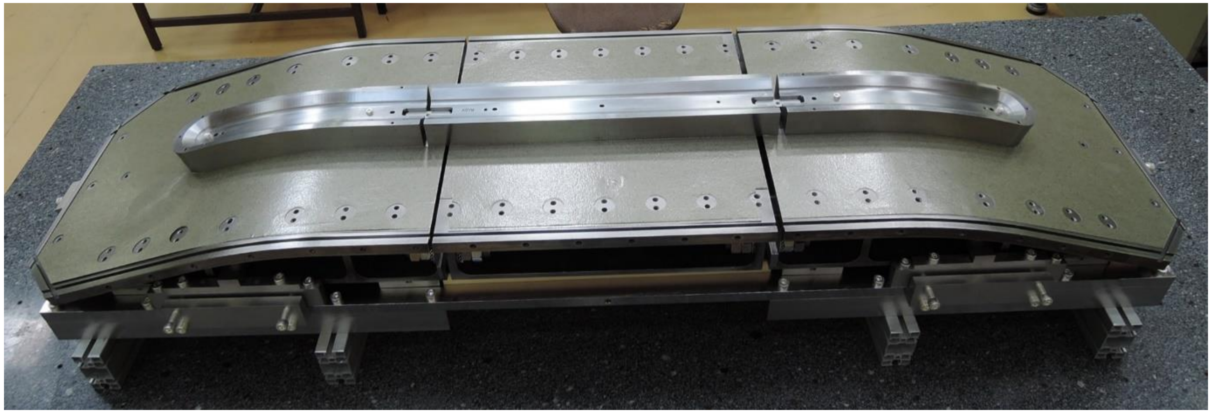
% on Straight Section

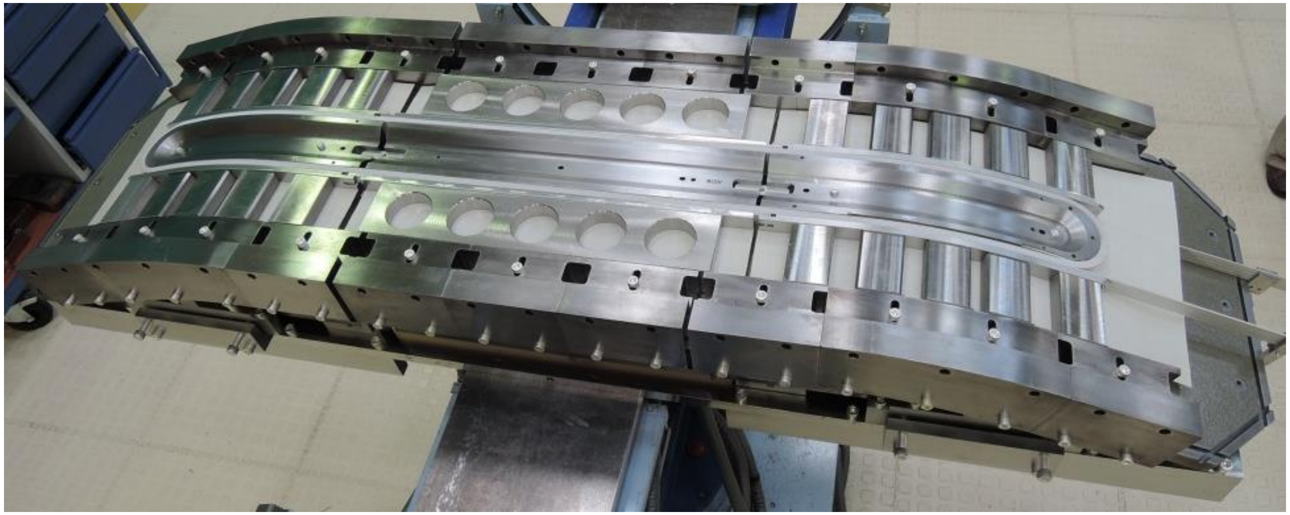
## RRP Bare Cable




| Mandrel material | C1<br>1 central gap | Gap reduction | | L SS = 600 mm<br>% L SS | L TOT = 690 mm<br>% L TOT (head to head) | L cable = 741.4 mm<br>% L cable |
|---|---|---|---|---|---|---|
| Titanium | HT5 | Central gap | 4.73 mm | 0.79% | 0.69% | 0.64% |
| | | **Total gap (central - lateral)** | **3.93 mm** | **0.66%** | **0.57%** | **0.53%** |
| | HT6 | Central gap | 4.55 mm | 0.76% | 0.66% | 0.61% |
| | | **Total gap (central - lateral)** | **3.84 mm** | **0.64%** | **0.56%** | **0.52%** |
| | HT10 | Central gap | 4.89 mm | 0.82% | 0.71% | 0.66% |
| | | **Total gap (central - lateral)** | **3.97 mm** | **0.66%** | **0.58%** | **0.54%** |

# FRESCA2 WINDING AND REACTION TOOLS MODIFICATION





# Winding / reaction tooling in 3 parts

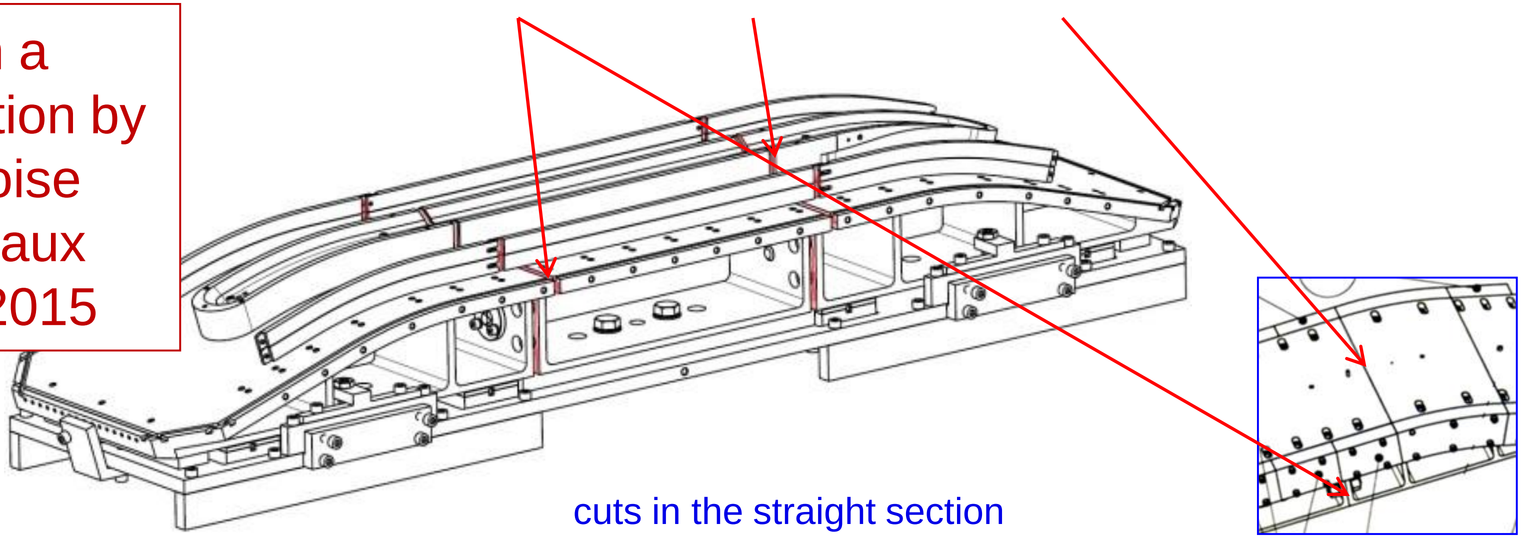
In subscale reaction tests, axial contraction = 0.5-0,7% with RRP cables (⬄ 4 – 9 mm)
0,8-1.5 % with PIT cables

To manage the length's variation of conductor during heat treatment (using tooling in one part is risky because stress induced on the $Nb_3Sn$ filaments)

➔Modified winding / reaction tooling : in 3 parts

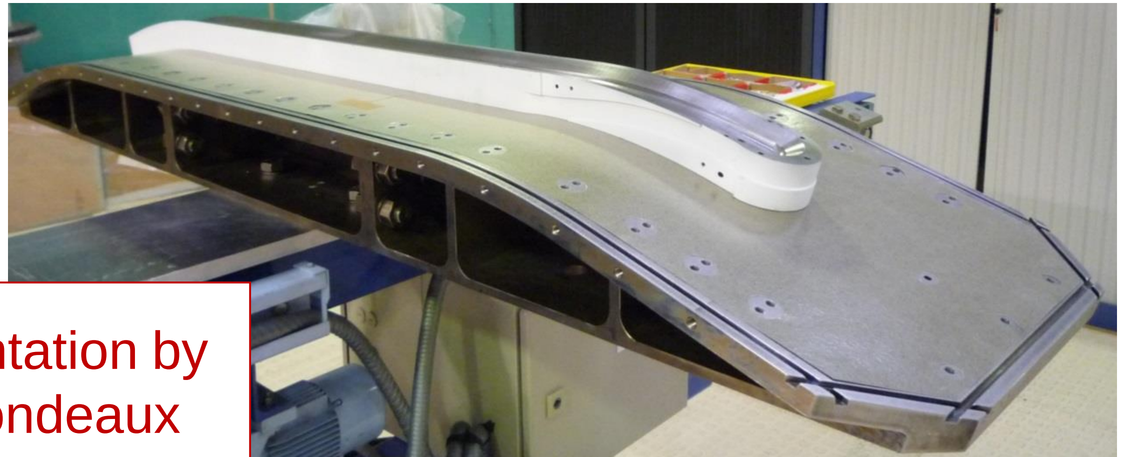
- Solution could be applied for production of longer coils
- 3 zones of cut : winding table / post and rails / reaction mould

From a presentation by Françoise Rondeaux 09/06/2015



cuts in the straight section
+ already in the existing tooling

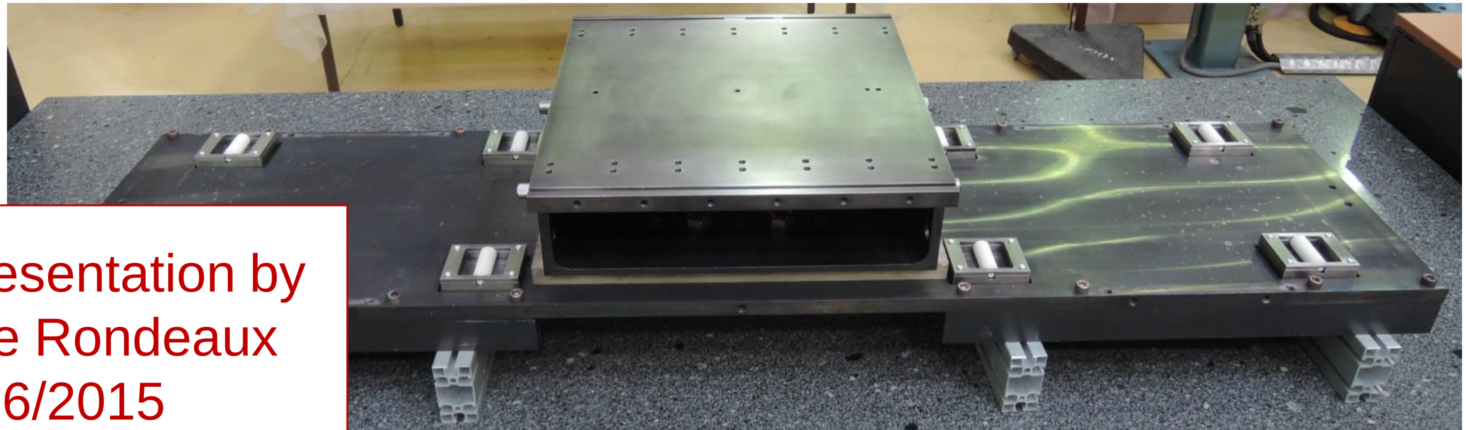
# Winding / reaction tooling in 3 parts



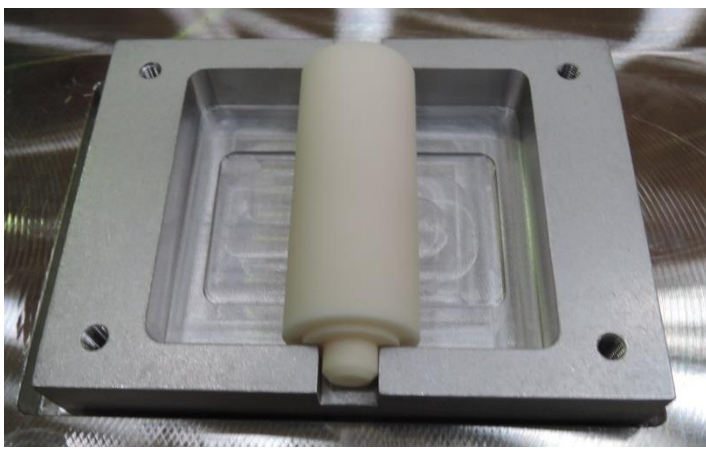
From a presentation by Françoise Rondeaux 09/06/2015

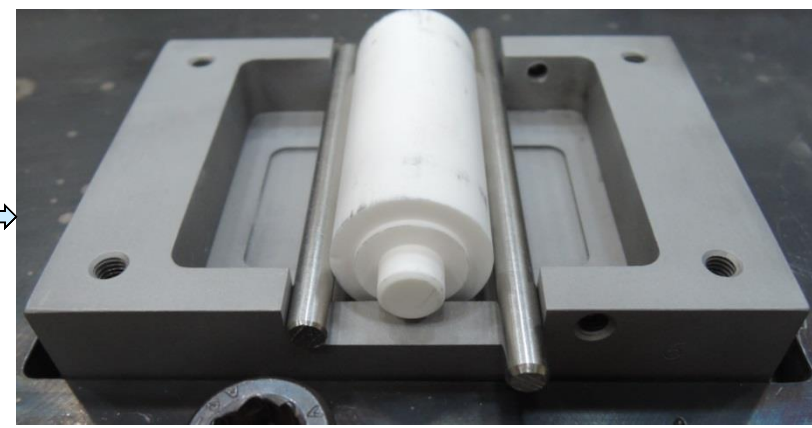

DP3402

# Support for lateral blocs of the table



From a presentation by Françoise Rondeaux 09/06/2015

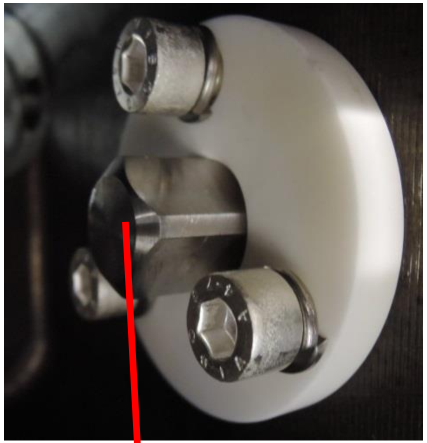




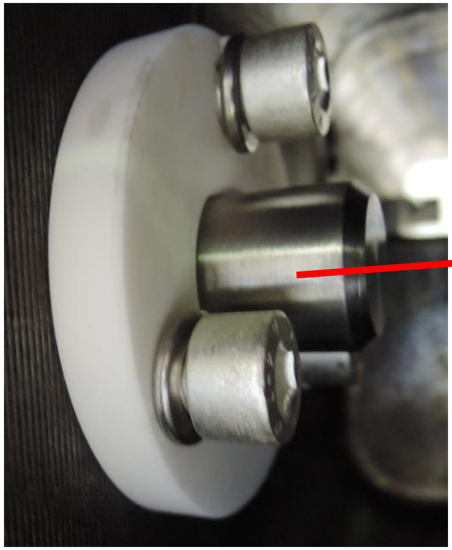
DP3402 : allow axial movement

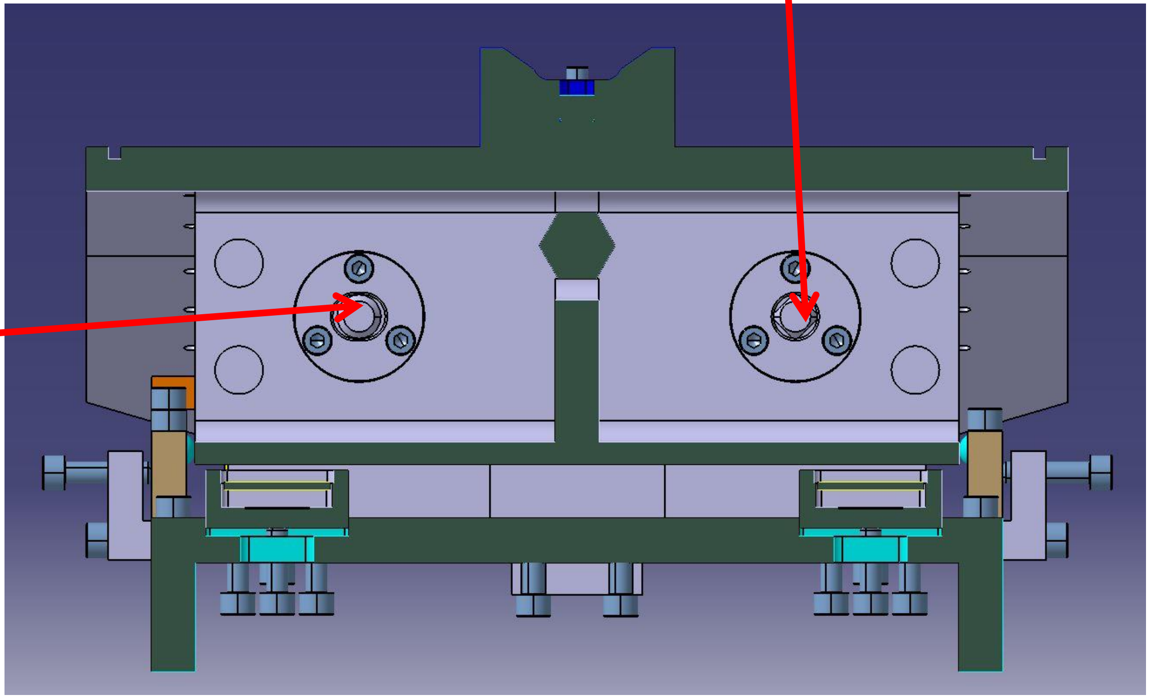
# Axial guiding

- Axial guiding : guiding rings
  - Ceramic in DR3401
  - Stainless steel in DR3402 and DP3401
  - None in DP3402

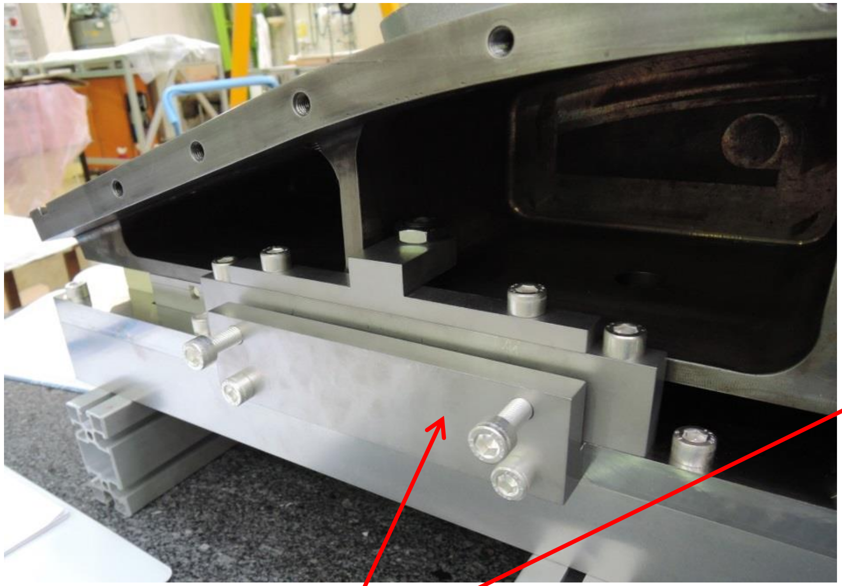


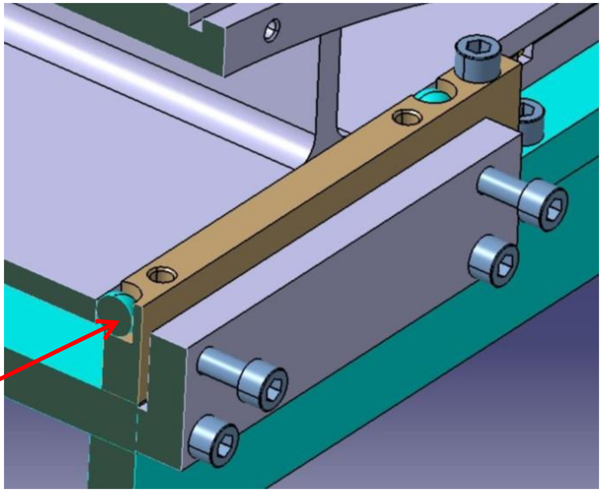
From a presentation by Françoise Rondeaux 09/06/2015





# Lateral guiding





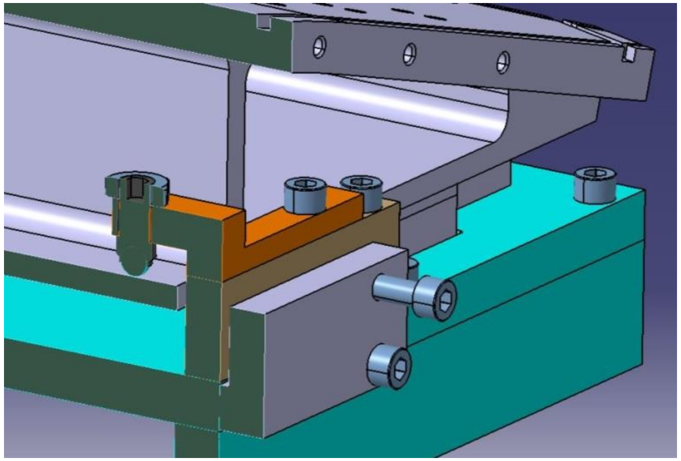
Lateral guiding system with balls (DR3401, DR3402)

➔ 2 layers of mica + 0,1 mm gap (DP3401)

➔longer guiding plates (DP3402)

From a presentation by Françoise Rondeaux 09/06/2015

# Vertical guiding

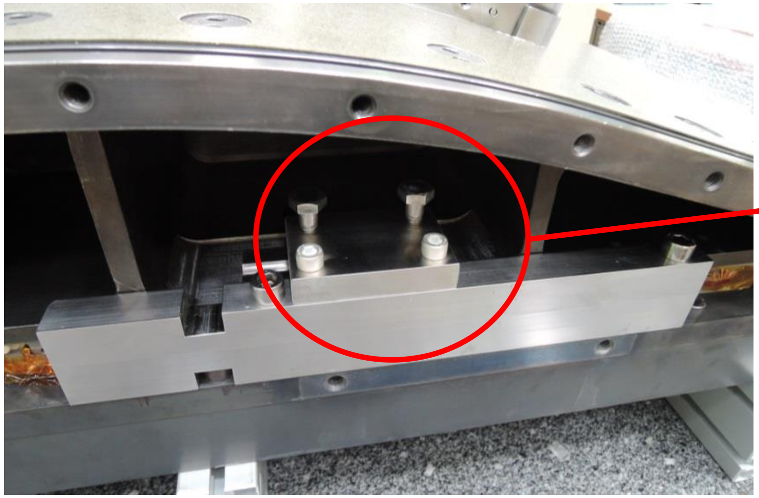


Vertical stop with ball screw (DR3401, DR3402)

➔ 2 mica sheets + 0,1 mm gap (DP3401)

➔ plate + 2 mica sheets + 0,1 mm gap (DP3402)

From a presentation by
Françoise Rondeaux
09/06/2015



# Tests

From a presentation by Françoise Rondeaux 04/09/2015

- Assembly test with CC3401 + CC1201 :
  - Small adjustment required for the posts
  - Intercoil shim preparation
- Full scale dilatation tests with cut tooling:

*(tooling modifications between tests to reduce identified frictions)*


| | Jeu initial | | Variation | | |
|---|---|---|---|---|---|
| | sym | asym | sym | asym | totale |
| **DR3401** | 9,72 | 5,93 | -1,91 | -1,36 | **-3.27** |
| **DR3402** | 1,77 | 1,2 | -0,6 | -0,4 | **-1.0** |
| **DP3401** | 2,4 | 1,6 | -1,1 | -0,5 | **-1.6** |
| **DP3402** | 2,4 | 1,62 | -0,49 (*) | 0,31(*) | **-0.18** |

(*) Sur DP3402, les jeux se sont équilibrés, ~1.9 mm de chaque côté.

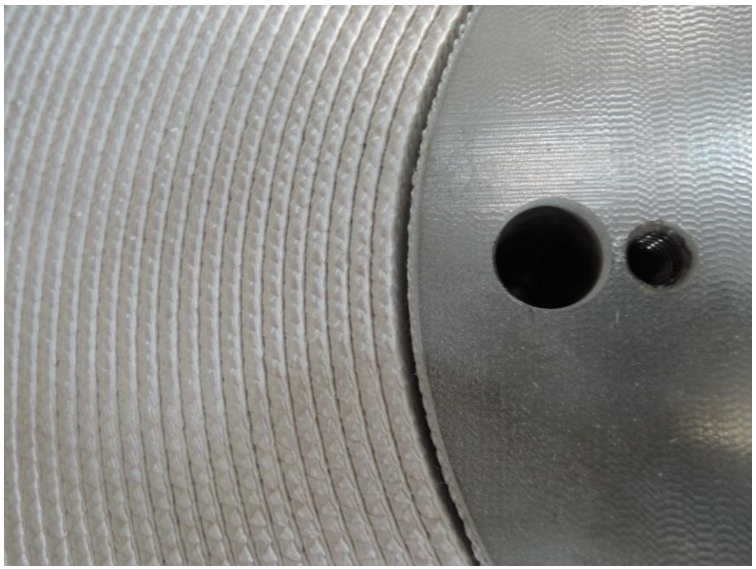
# Tests

<u>Decision for the $Nb_3Sn$ coils</u> (FRESCA2 Technical Meeting 09/06/2015):

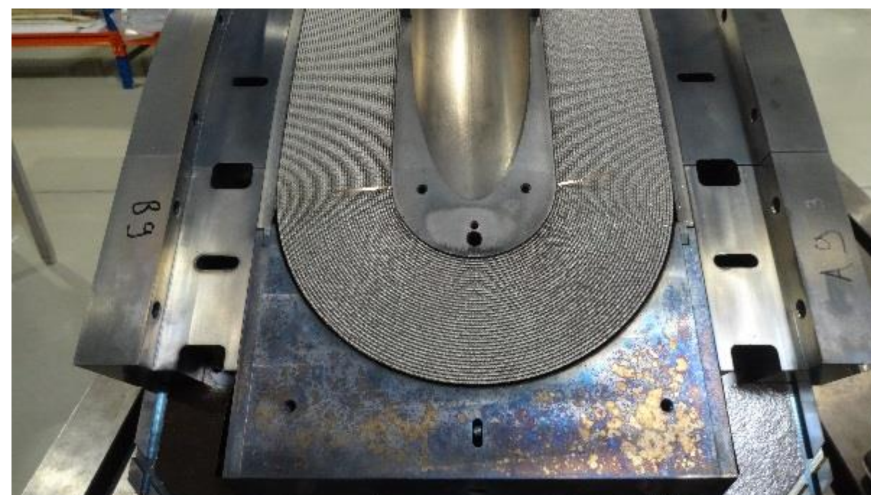
Gaps = 1 + 1 mm, closed before closing of the reaction mould

Post-coil gaps closed after reaction

From a presentation by Françoise Rondeaux 04/09/2015



After closing the gaps



# DIMENSIONAL CHANGES - LONGITUDINAL

## 20 heat treatments have been carried out during the whole campaign

- 7 HT (17 coils) on different PIT bare cables
- 5 HT (8 coils) on PIT insulated cable
- 3 HT (3 coils) on RRP bare cable
- 5 HT (8 coils) on RRP insulated cable

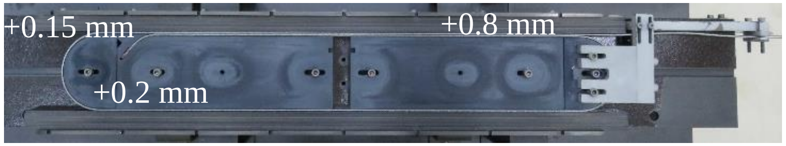
Gaps between mandrels appeared here

Stress witness


4.10 mm Central gap variation: - 4.9 mm -0.4 mm

Gaps appeared here

Stress witness




-1 mm Central gap variation: - 3.3 mm 3 mm

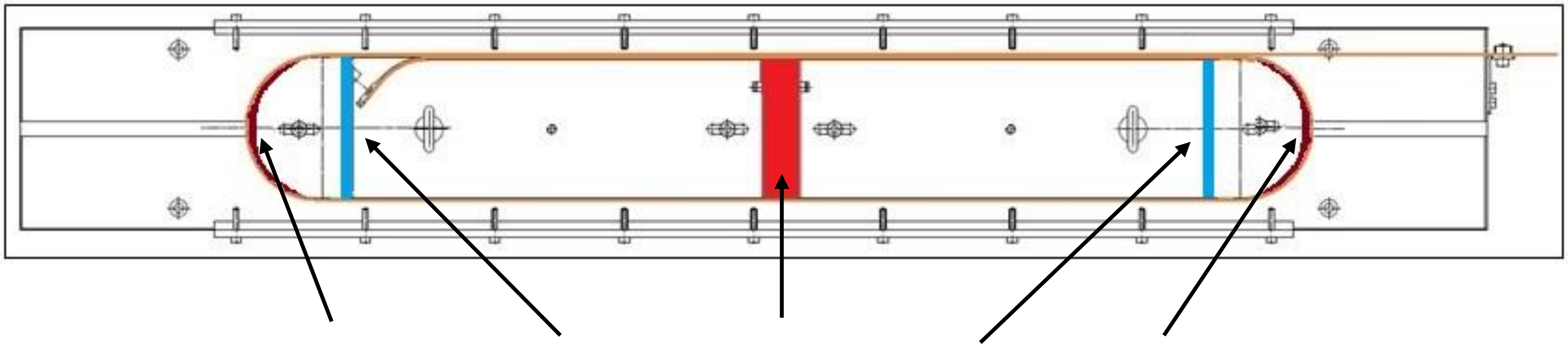
# RRP CABLE – MAIN RESULTS

| Mandrel material | C1<br>one central gap | Ends<br>Fixed/Free/on mandrel | Tatal Gap variation (central - ends) | L TOT = 690. mm<br>% L TOT |
|---|---|---|---|---|
| Titanium | Bare cable HT5 | Fixed | -4.03 mm | -0.58% |
| | Bare cable HT6 | Fixed | -3.84 mm | -0.56% |
| | Bare cable HT10 | Fixed | -4.05 mm | -0.59% |
| | Insulated cable HT11 | Fixed | -2.48 mm | -0.36% |
| | Insulated cable HT14 | on mandrel | -2.21 mm | -0.32% |
| | Insulated cable HT19 | on mandrel | -2.52 mm | -0.36% |
| | Insulated cable HT18 - **2 turns** | on mandrel | -3.10 mm | -0.45% |
| Iron | Insulated cable HT16 | on mandrel | -2.25 mm | -0.33% |
| | Insulated cable HT18 | on mandrel | -2.38 mm | -0.35% |

# PIT CABLE – MAIN RESULTS

| Mandrel material | C1<br>one central gap | Ends<br>Fixed/Free/on mandrel | Total Gap variation (central - ends) | L TOT = 690. mm<br>% L TOT |
|---|---|---|---|---|
| Titanium | Bare cable HT7 | Fixed | -4.36 mm | -0.63% |
| | Insulated HT12 | Free | -2.06 mm | -0.30% |
| | Insulated HT13 | on mandrel | -2.28 mm | -0.33% |
| | Insulated HT15 | on mandrel | -1.93 mm | -0.28% |
| | Insulated cable HT17 | on mandrel | -2.18 mm | -0.32% |
| | Insulated cable HT21 - 2 turns | on mandrel | -1.86 mm | -0.27% |
| Iron | Insulated 1.82 mm thick HT13 | on mandrel | -1.67 mm | -0.24% |
| | Insulated 1.82 mm thick HT20 | on mandrel | -1.72 mm | -0.25% |

# HT WITH STEPS 210°C / 400°C / 650°C



| TT RRP #19-1 | Conductor/mandrel RE | Ends gap RE | Central gap | Ends gap LE | Conductor/mandrel LE | Total gap (central - lateral) |
|---|---|---|---|---|---|---|
| Après palier à 210°C | < 0.04 | < 0.04 | -3.00 | < 0.04 | 0.20 | -2.82 |
| Après palier à 400°C | < 0.04 | < 0.04 | -4.75 | 0.20 | 0.40 | -4.17 |
| Après TT complet | 0.25 | < 0.04 | -4.53 | 1.78 | < 0.04 | -2.52 |

| TT PIT #22-1 | Conductor/mandrel RE | Ends gap RE | Central gap | Ends gap LE | Conductor/mandrel LE | Total gap (central - lateral) |
|---|---|---|---|---|---|---|
| Après palier à 210°C | 0.00 | < 0.04 | -2.45 | 0.04 | < 0.04 | -2.41 |
| Après palier à 400°C | 0.15 | < 0.04 | -3.40 | 0.25 | < 0.04 | -3.00 |
| Après TT complet | < 0.04 | 0.38 | -3.15 | 0.55 | 0.05 | -2.17 |

# CONCLUSIONS

- **Insulation** has an important impact on cable behavior
  - Coil length contraction 50% smaller for insulated cable
  - Final cable, final insulation must be used
- Similar behavior for **RRP and PIT cables**
  - Slightly lower contraction for PIT cable
- Similar behavior for **Titanium and Iron mandrels**
  - But Iron mandrel is softer, higher risk for errors
- Impact of **number of turns** not clear.

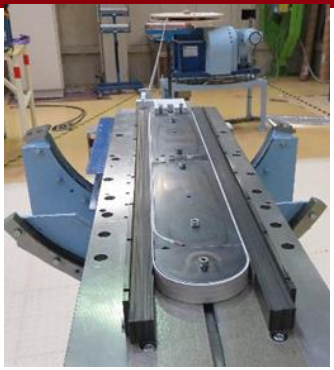
- A large part of cable contraction seems to occur in the first part of the heat treatment (up to 400°C); then the cable grows due to $Nb_3Sn$ formation.

# CONCLUSIONS

- **Standard Test procedure has been validated**
  - Titanium mandrel
  - 2 turns
  - Conductor end fixed on the end mandrel

# DIMENSIONAL CHANGES TEST CAMPAIGN

- **Measurement of the longitudinal contraction** during heat treatment of $Nb_3Sn$ cables in coil configuration
  - 2 x 4 m of insulated cable needed



- **Measurement of the cable thickness** under 5 MPa before and after heat treatment
  - 2 stacks per cable
  - 4 m of insulated cable needed

- **Measurement of the cable thickness and width** after reaction, by image analysis of a stack section after impregnation and surface polishing.
  - Image analysis at CERN