Coil manufacturing

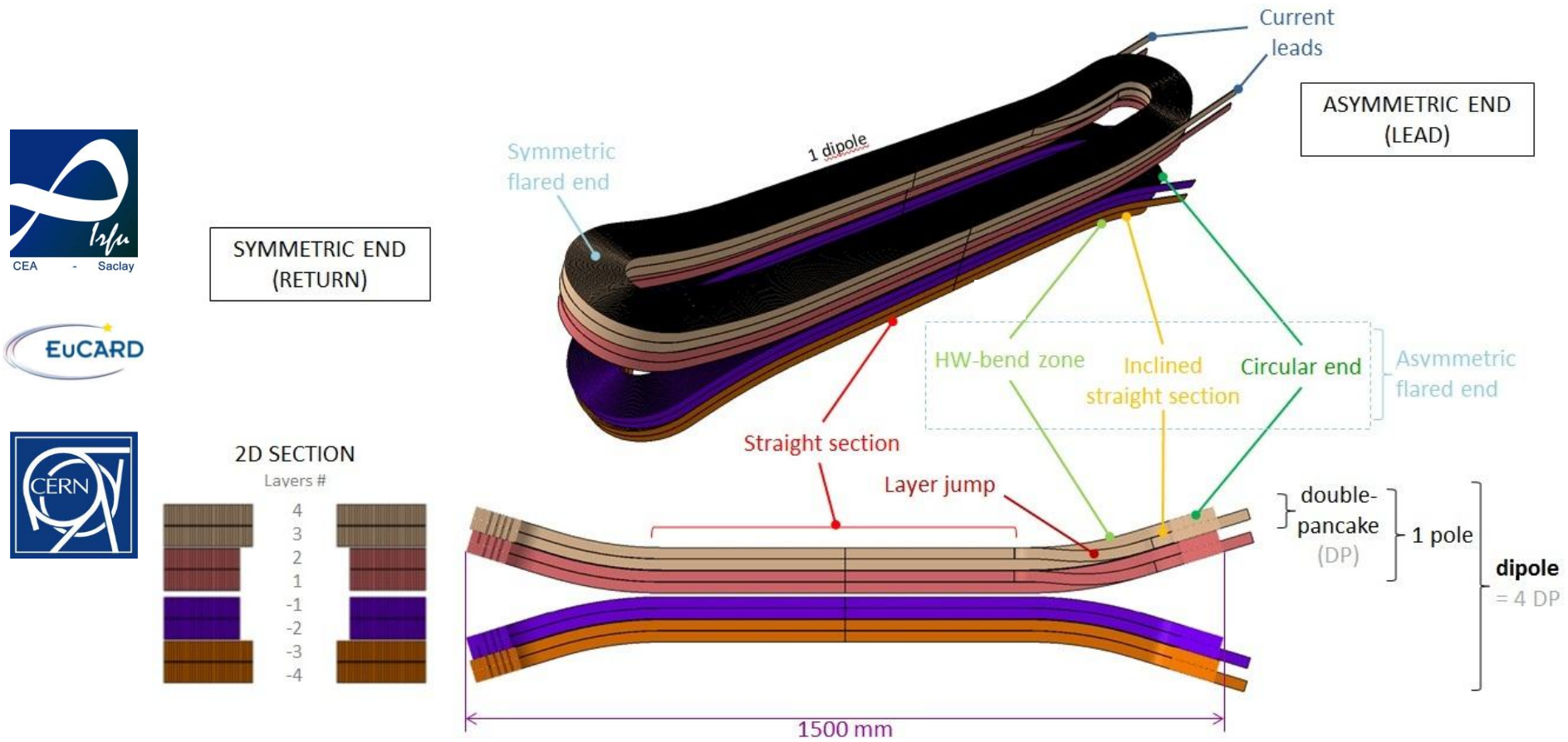
F. Rondeaux

Outline

- Coils detailed geometry
  - Overview
  - Close-up on the geometry
  - Coil 1-2 design
  - Electrical insulation configuration
- Winding tooling and process
- Reaction tooling

  Reaction process, impregnation tooling and process will be discussed by Juan Carlos
- Quality and documentation

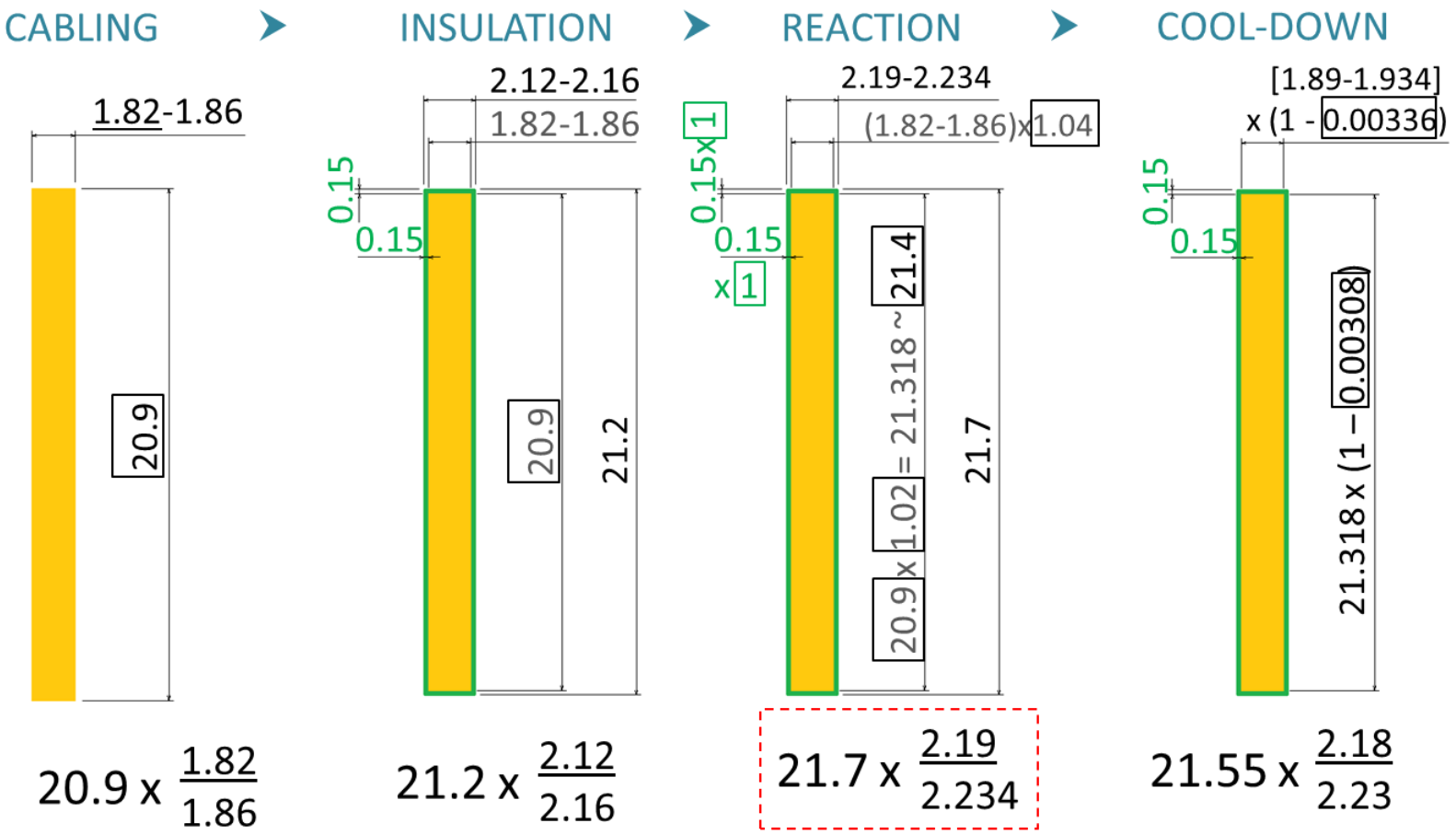
Coils detailed geometry - overview



1 color = 1 cable unit lenght (223 m / 253 m)

Cable dimensions

- Baseline section = 21.8 mm x 2.22 mm (insulated and reacted)
- Nominal thickness for insulation = 0.2 mm, braided insulation preferred



~21.8 x 2.22

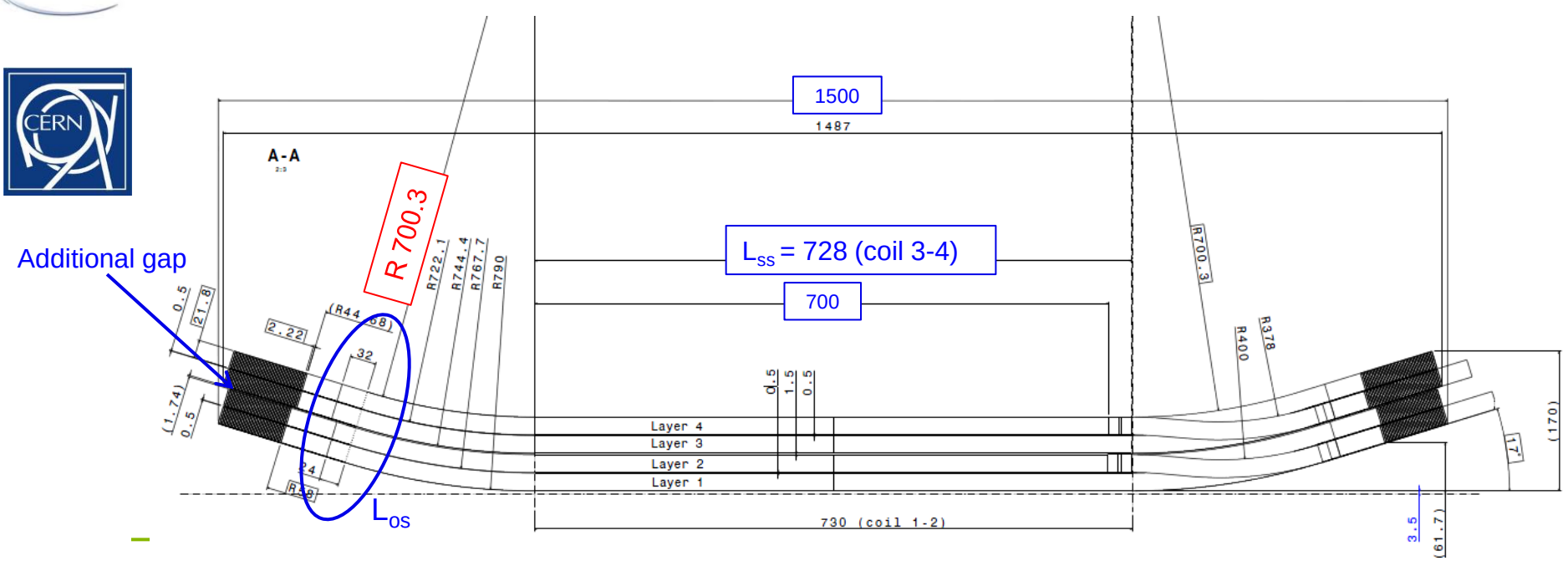
Tooling design can be done with the baseline dimensions

[X] *means 'fixed'* X *means 'most likely option'*

Coils geometry details

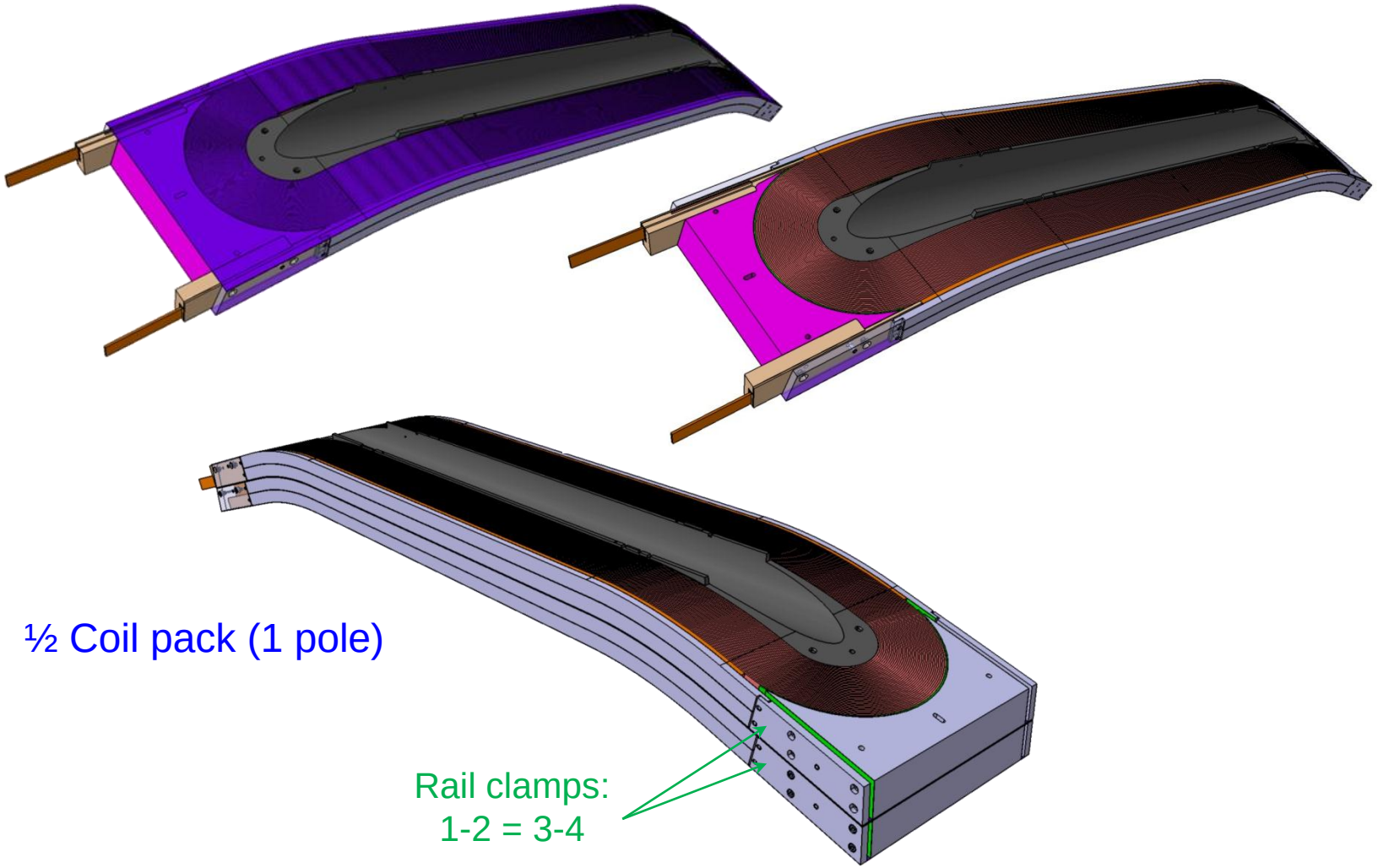
- Ramp angles : 17° - R_{HW} = 700 mm - aperture = 61.7 mm - h_{tot} = 170 mm
- Adjustments between double pancake 1-2 and 3-4 :
  - ➢ Forced contact between the coils along the straight section.
  - ➢ Avoid stress concentration around sharp edges in the ends:

    => additional gaps created along the ends (to be filled during the assembly process)
- Inter-coils insulation thickness = 1.5 mm for the instrumentation traces, leading to increase the HW radiuses for coil 1-2



Coil 1-2 design

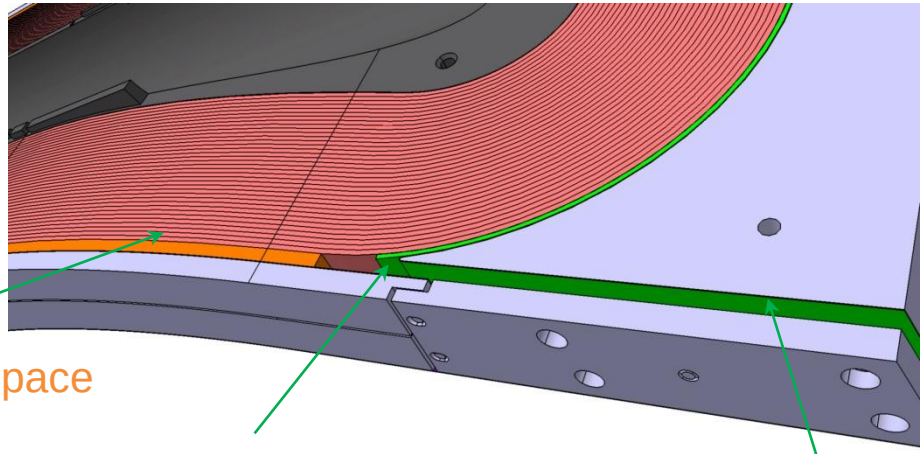
- Double pancake 1-2 with / without trace - very similar to coil 3-4



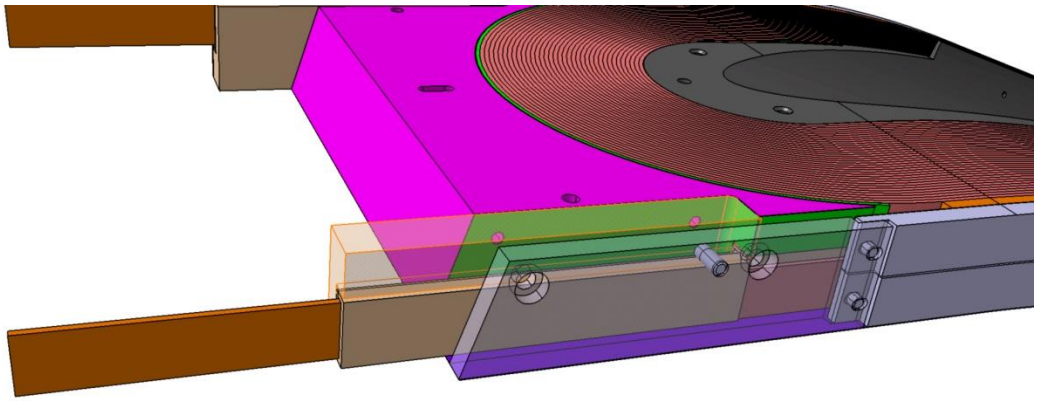
- ½ Coil pack (1 pole)

Coil 1-2 design

- Close-up (sym)

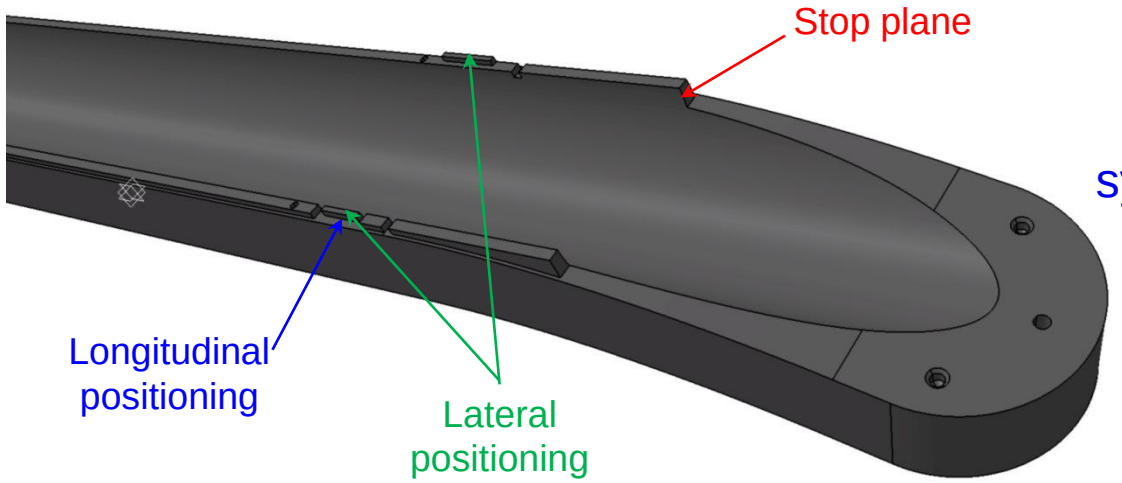


- Close-up (asym)

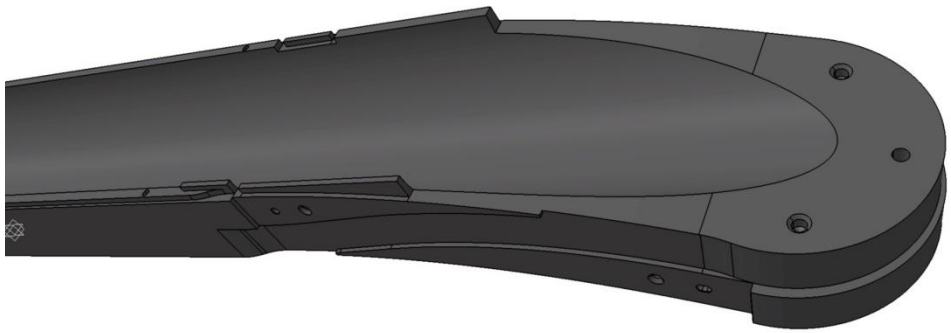


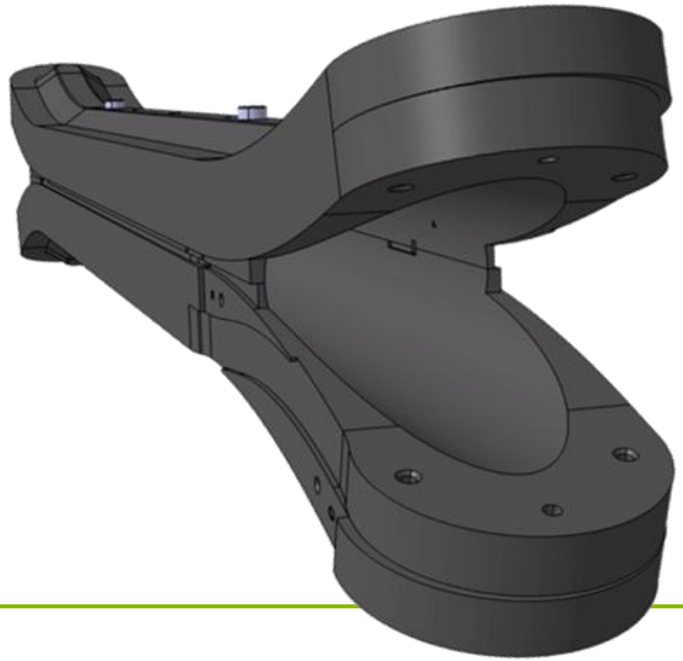
Coil 1-2 design – central post

- in Ti-6Al-4V



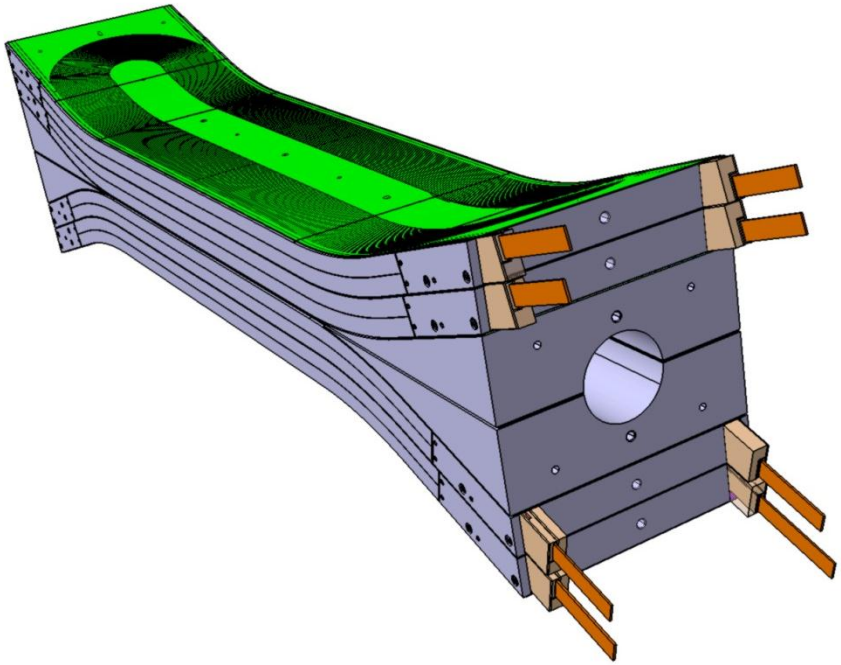
asym

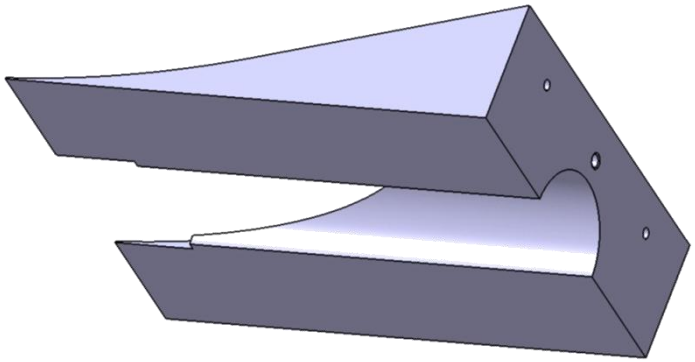


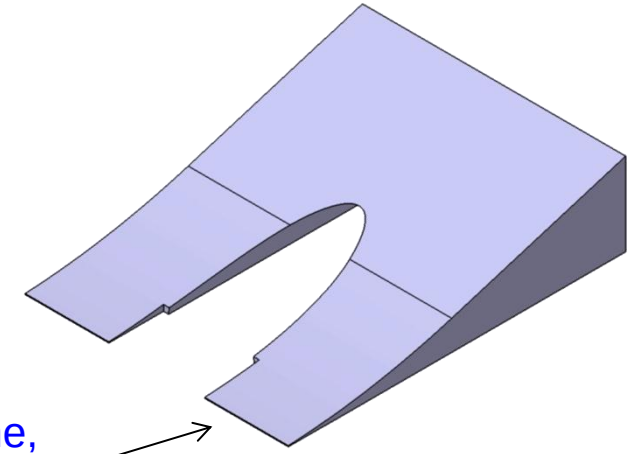


Coil 1-2 design – wedges

Reduced width in order to align it with the thinnest possible coil

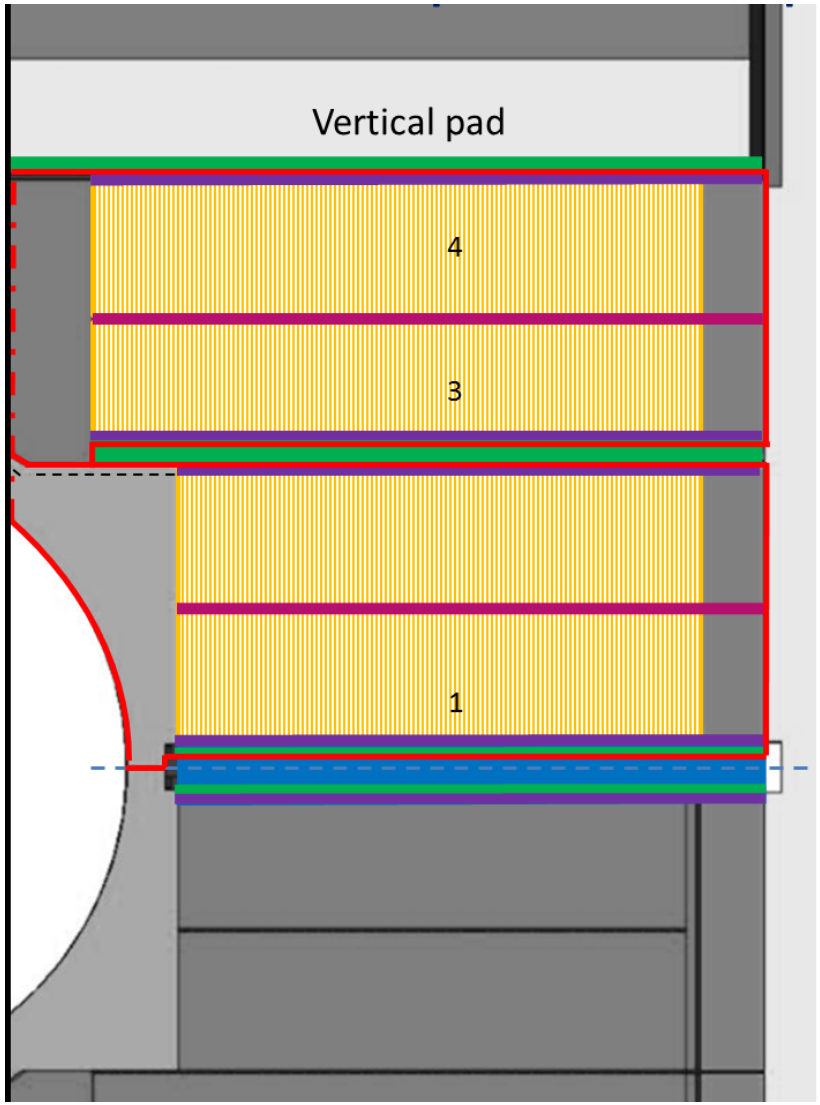






1 mm thick to avoid any sharp edge in the midplane,
in regard of midplane insulation

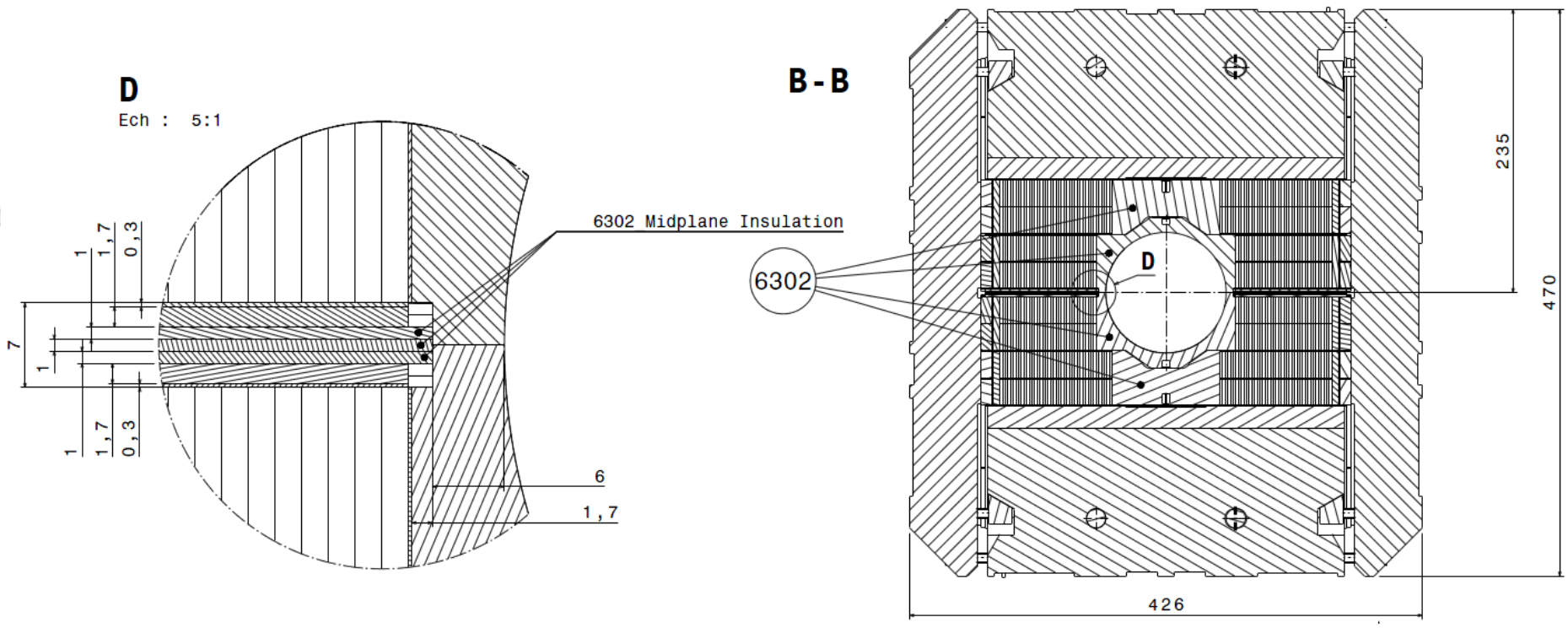
Electrical insulation configuration



Tailored insulation	0,7 mm	Fiberglass	1 mm
Insulated trace	0,3 mm	kapton/steel /fiberglass	
Interlayer insulation	0,5 mm	S2 glass	0,5 mm
Insulated trace	0,3 mm	*idem*	1,5 mm
Tailored insulation	0,9 mm	Fiberglass	
Insulated trace	0,3 mm	*idem*	
Interlayer insulation	0,5 mm	S2 glass	0,5 mm
Insulated trace	0,3 mm	*idem*	7 mm
Flared insulation	1,7 mm	Fiberglass	
Tailored flat insulation	3 mm	Fiberglass	
Flared insulation	1,7 mm	Fiberglass	
Insulated trace	0,3 mm	*idem*	

Impregnated volume

Assembled coil pack



Insulation layout : winding configuration

4 0,5 mm Fiberglass
- S2 933
- 2x 0,25 mm
- CTD binder
- Delivered by CERN
- Cut at Saclay

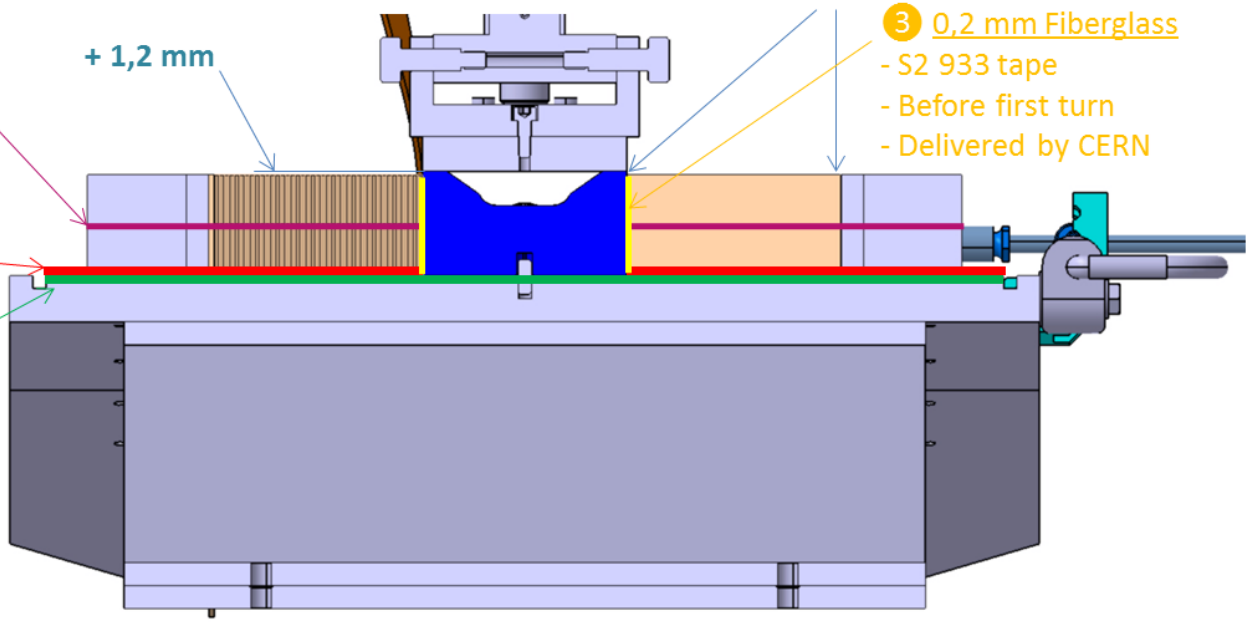
2 0,3 mm Mica
- Cut around post
- Delivered by Saclay

1 0,2 mm Mica
- All over the table
- Below the post
- Delivered by Saclay

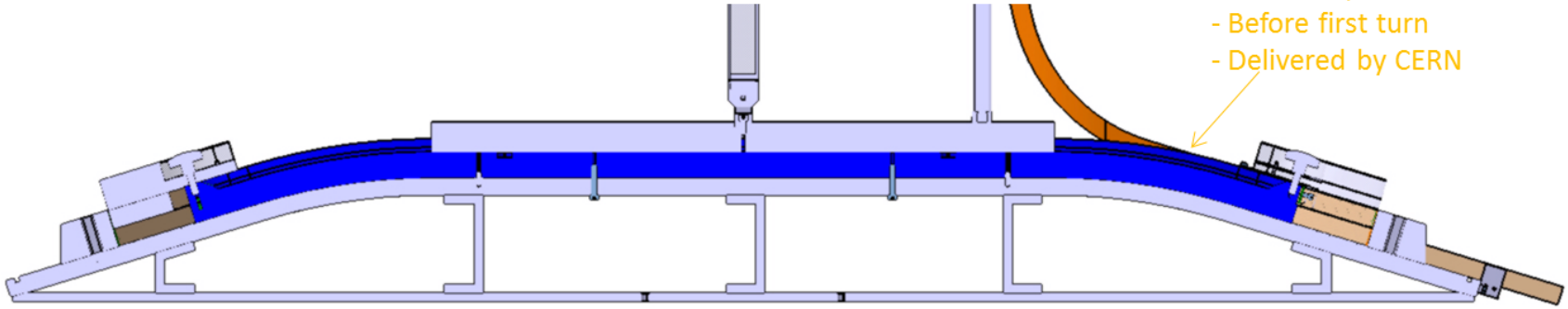
+ 1,2 mm

0 0,3 mm Al_2O_3 deposition

3 0,2 mm Fiberglass
- S2 933 tape
- Before first turn
- Delivered by CERN

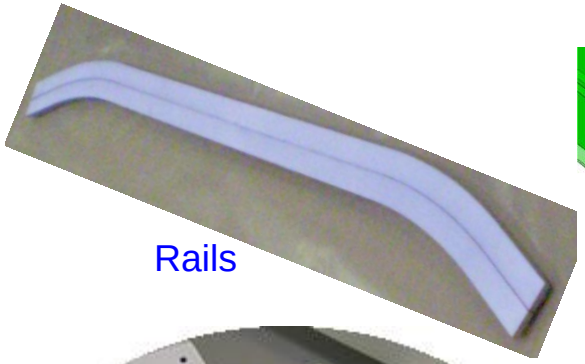


3 0,2 mm Fiberglass
- S2 933 tape
- Before first turn
- Delivered by CERN

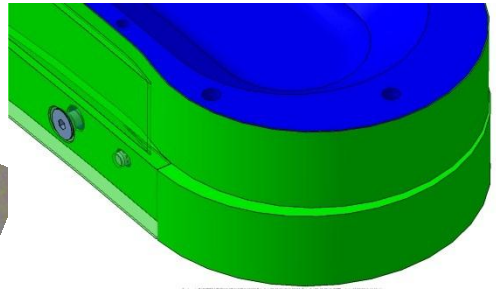


Electrical insulation

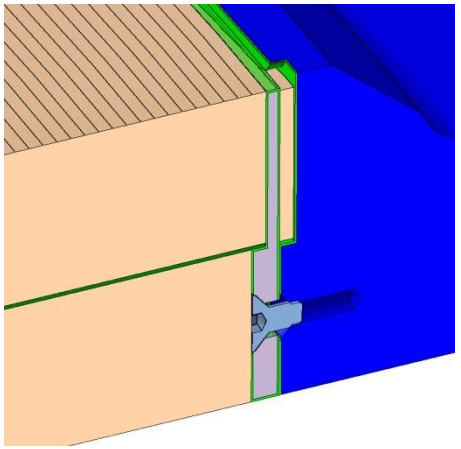
- Glass fiber impregnated with epoxy resin
  - Around cable: braided 0.15 – 0.2 mm – fiber = S2 436-66 Tex (ten-stack measurements on-going)
  - between layers: S2 933 glass fiber sheet of 0.5 mm
  - between double pancakes: 0.9 mm glass fiber with MY-750 + 0.3 mm insulated instrumentation traces (voltage taps connections + quench heaters)
- Alumina coating (0.3 mm) - some parts are partially or totally covered:



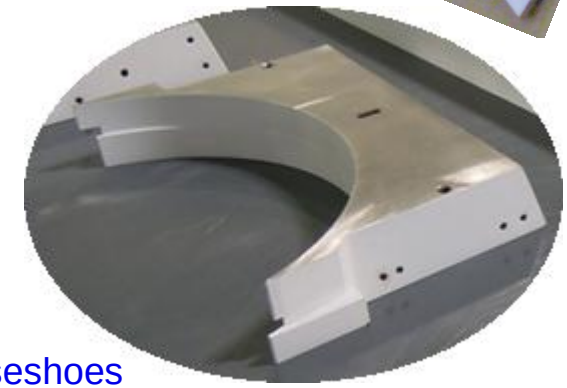
Rails



Central post

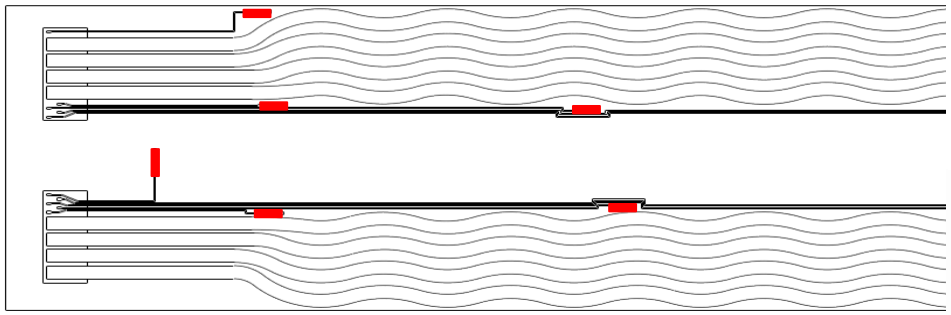


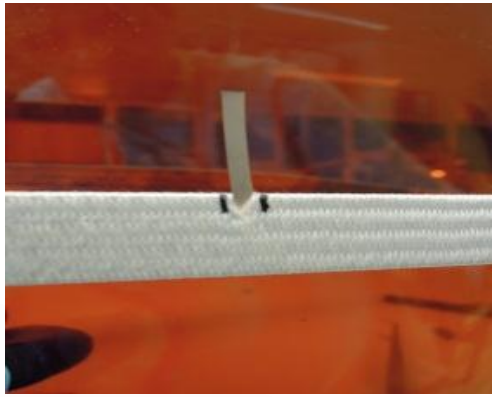
Layer jump shim

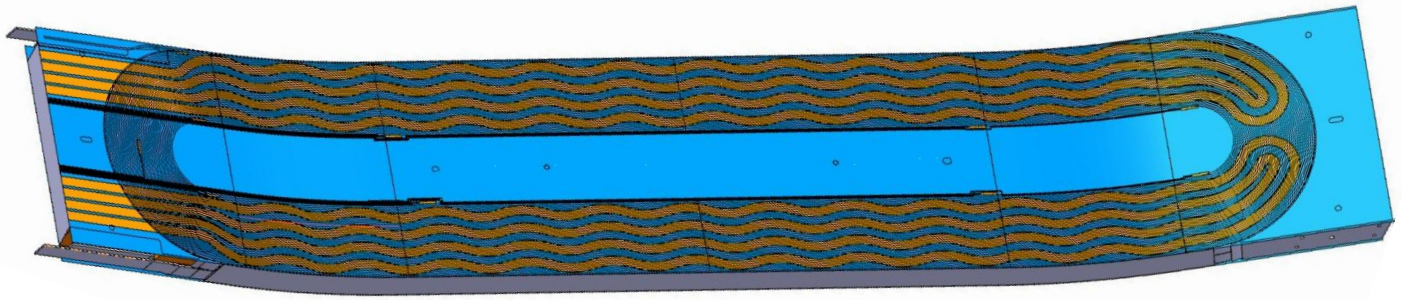


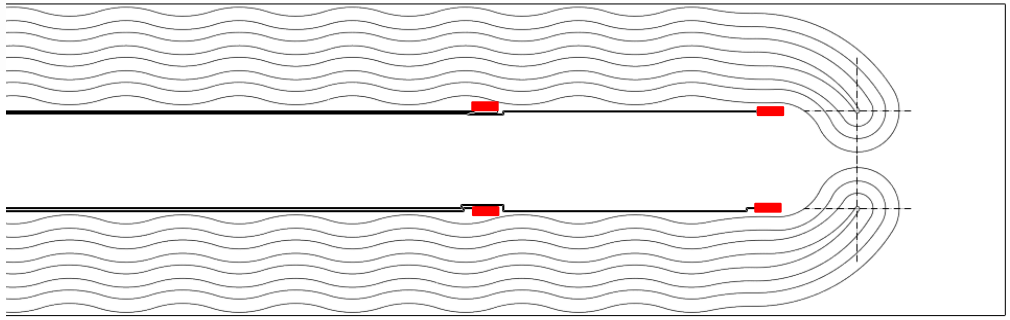
Horseshoes

Insulated traces









10 voltages tapes/layer

Design thickness = 0.3 mm :

- 50 µm Kapton
- 25 µm steel
- 0.2 mm glass fiber insulation layer

Fabrication process – main steps

- Conductor insulation
- Conductor preparation
- Winding
- Preparation for the heat treatment:
  - Assembly of the reaction mold around the wound coil
  - Transport to CERN

At Saclay

- Heat treatment
- Preparation for impregnation :
  - Nb_3Sn/NbTi splice soldering
  - Instrumentation, ground insulation and quench heaters integration
- Impregnation
- Coil assembly
- Magnet assembly

At CERN

(cf. Juan Carlos' presentation)

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At Saclay

At CERN

(cf. Juan Carlos' presentation)

Winding

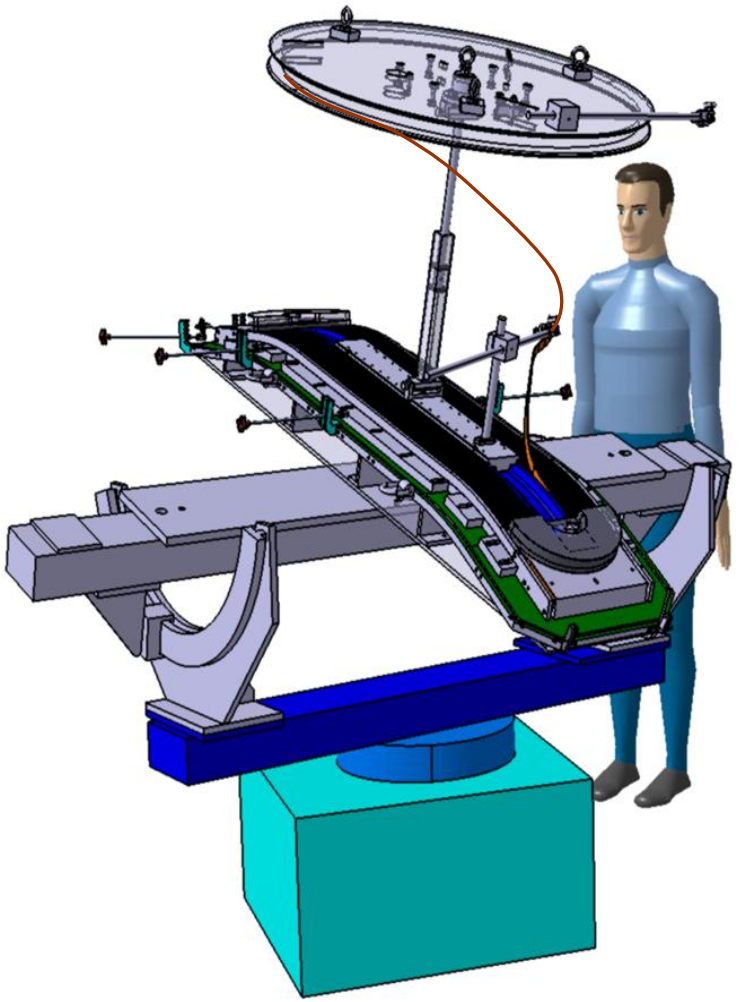
Heavy pieces are equipped for handling with a crane

Winding table: 220 kg – 1.72 m x 0.45 m

Stock spool with cable : ~ 75 kg

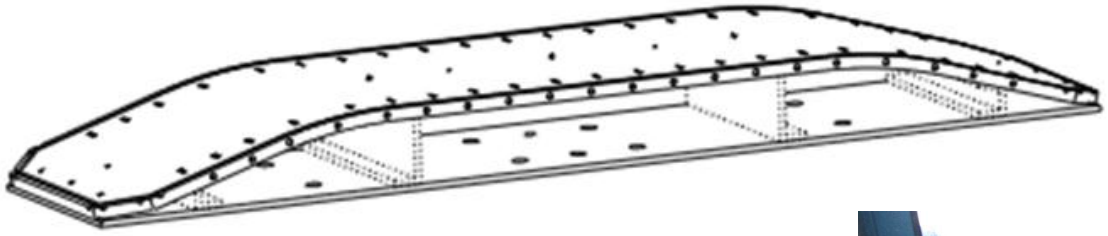
Iron post: 34 kg

Horseshoes: 8 kg



Winding table

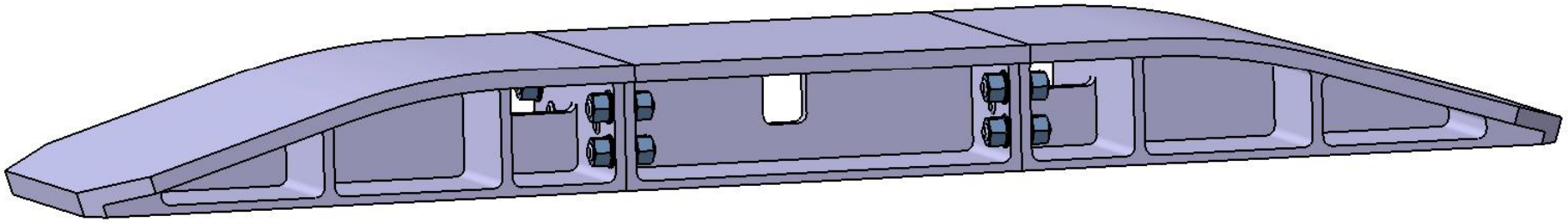
- Table made with welded plates : irreversible damage after heat treatment



➔ Machining in 3 blocks of 304L forged 3D

➔ No welding

➔ Thermal firing at 930°C



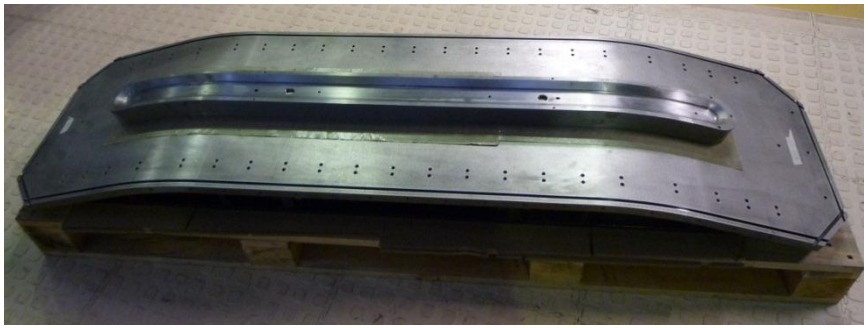


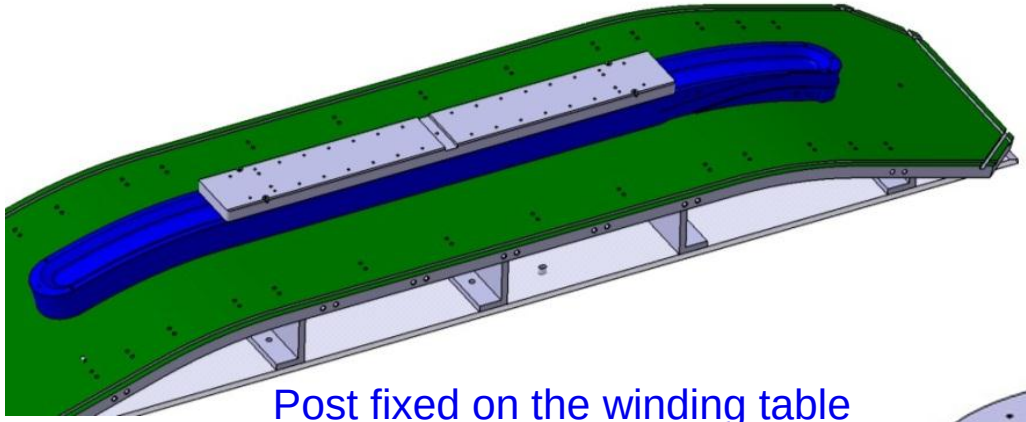
Table with post

The winding table is fixed on the winding machine - the table can be tilted to follow the geometry of the coil.

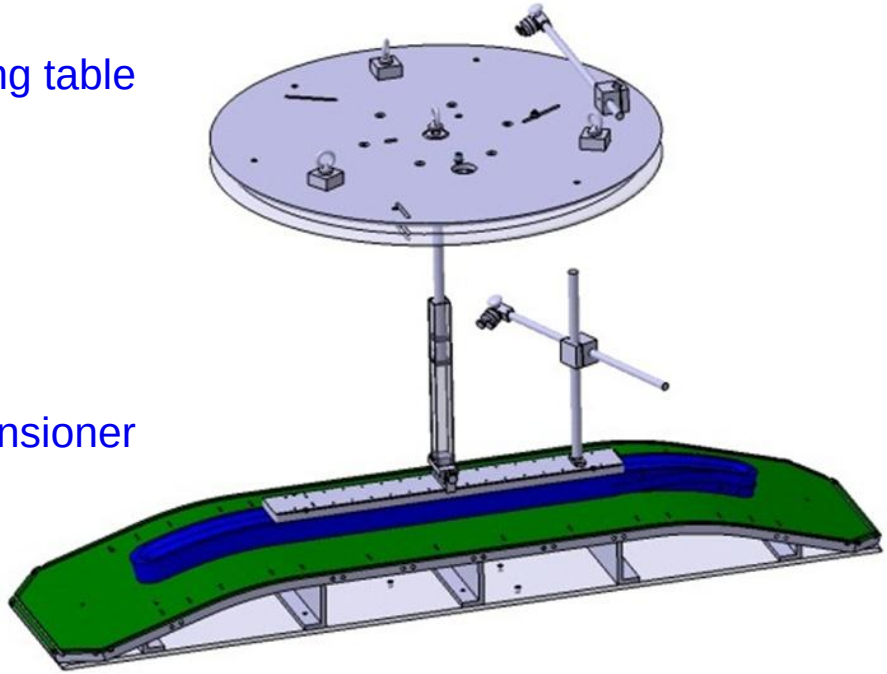
Winding process - installation

0.2 mm mica protection sheet on table

0.3 mm mica sheet around the post = Reserve for traces



Post fixed on the winding table

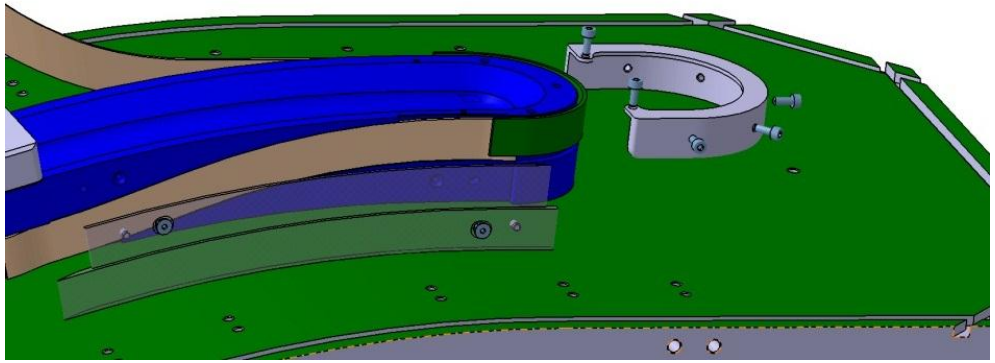


The cable is installed

layer 4 on the support spool on the tensioner

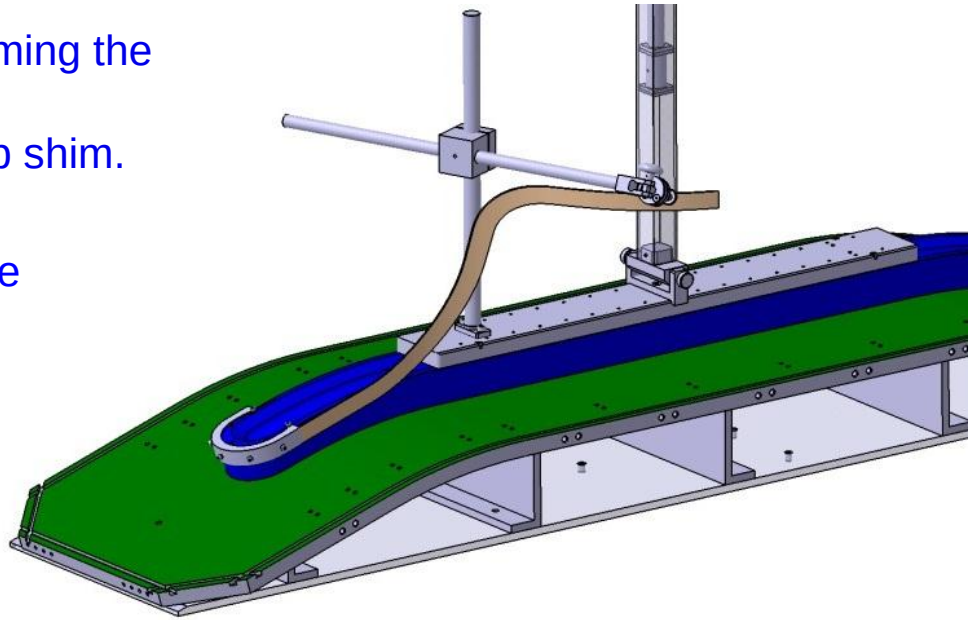
layer 3 on the stock spool

Winding layer 4



The coil winding will start by forming the layer jump.
It is protected with the layer jump shim.

The first layer is wound clockwise

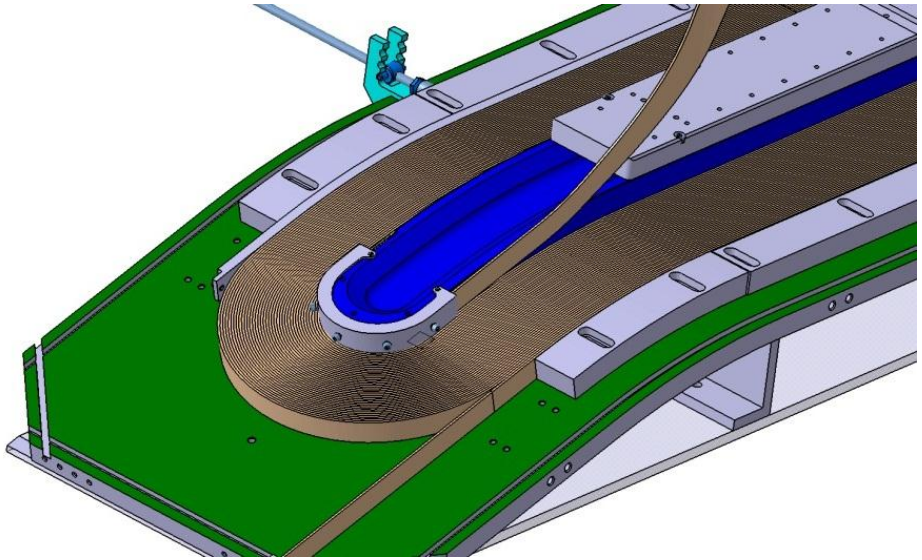


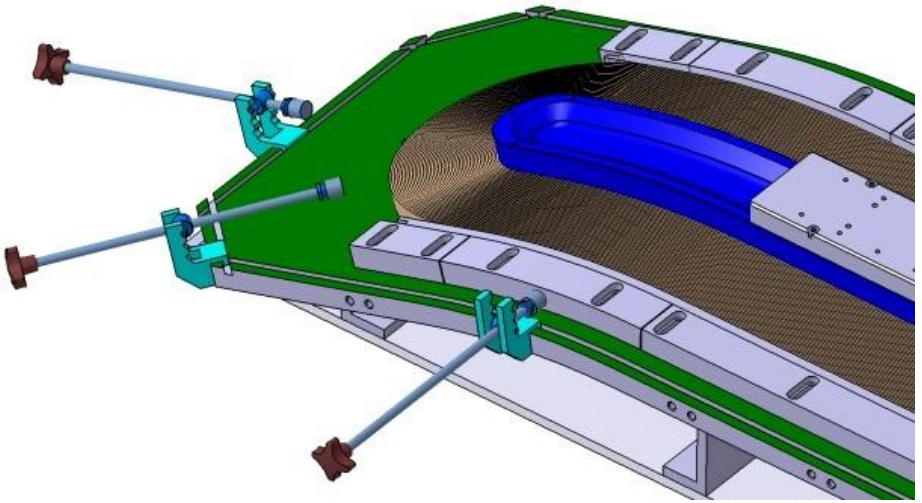
Winding layer 4

During winding, conductor turn will be maintain by lateral compression system using pressure wedges and rods.

Voltage tapes are introduced according to the instrumentation design.

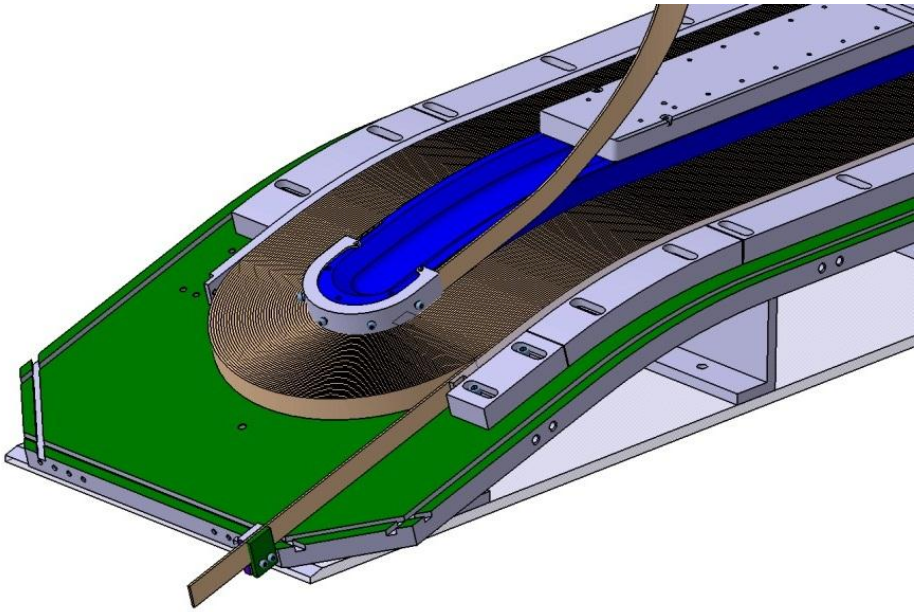
At the end of the layer 4 winding, the bottom layer is maintained through rails and pressure wedges.

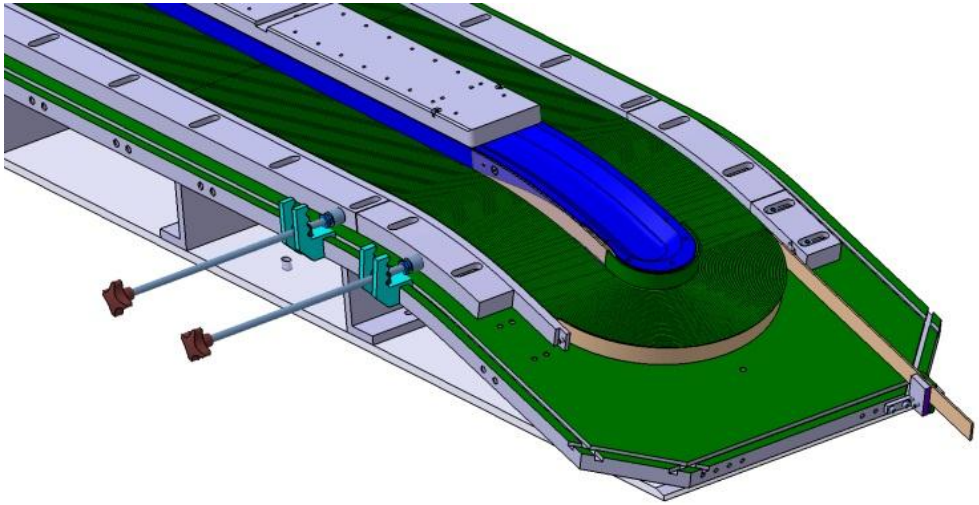




Winding layer 4

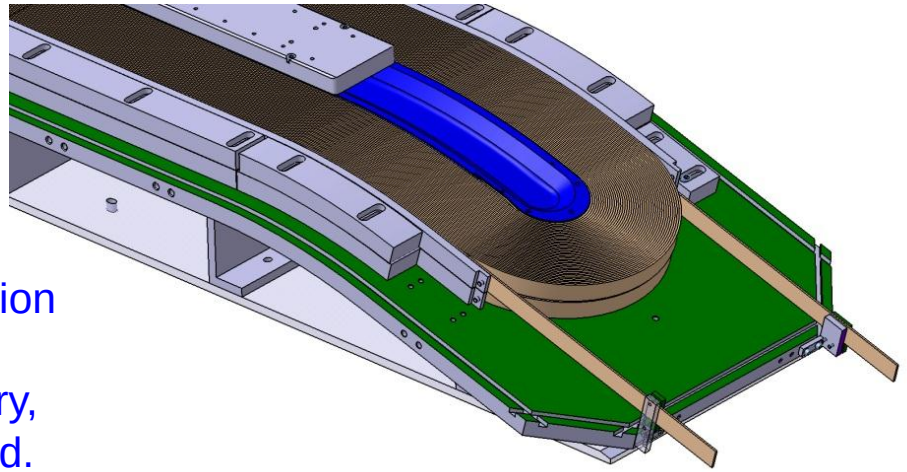
The cable is fixed and cut.





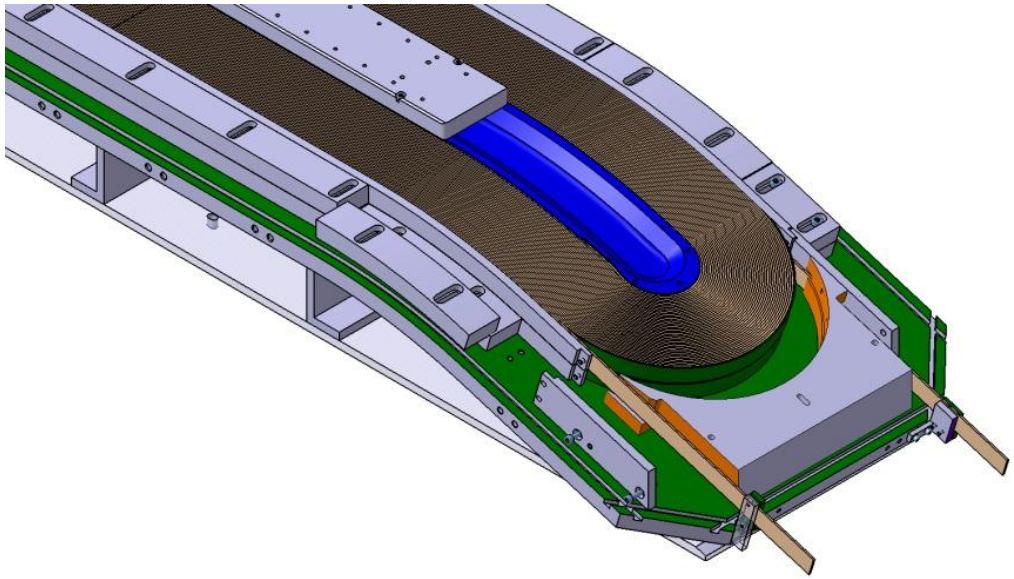
The interlayer insulation is installed and fixed.

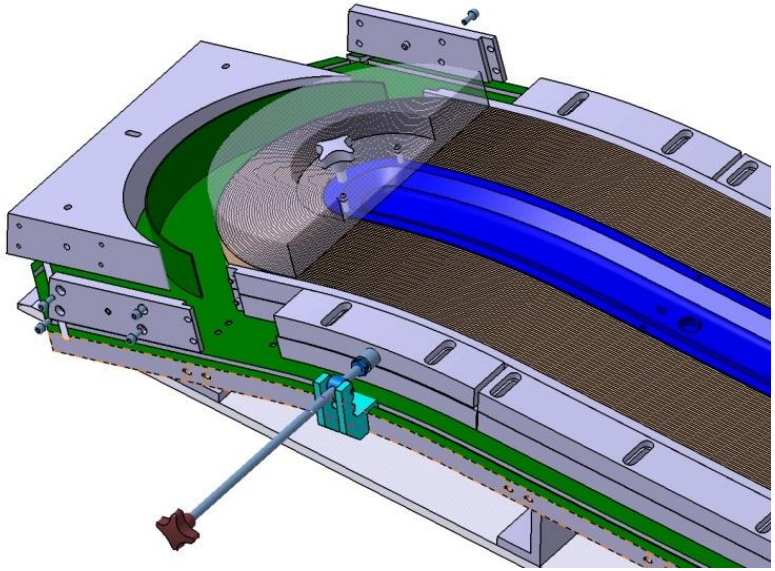
Winding layer 3



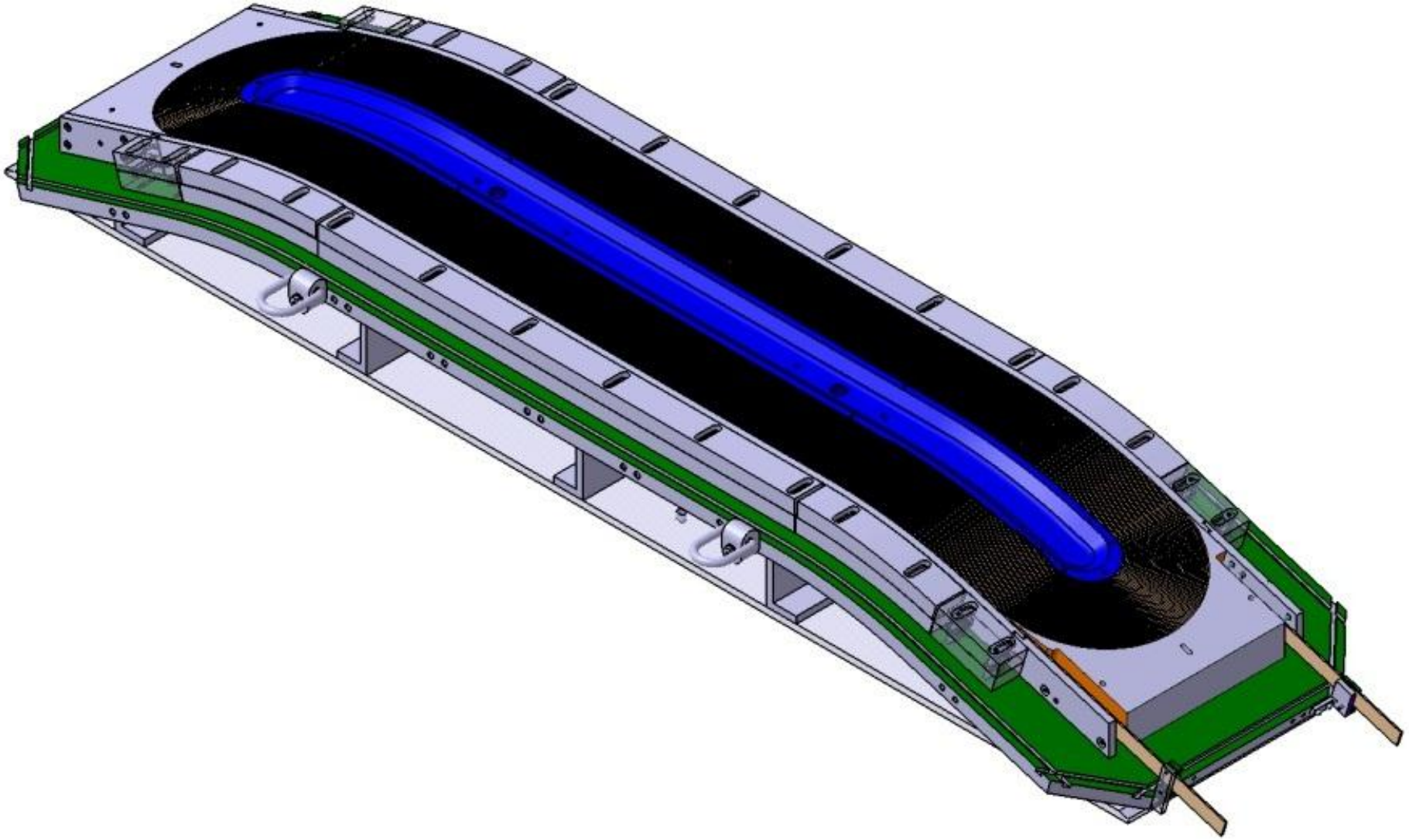
The layer 3 is wound over the insulation

Horseshoes are adjusted, if necessary, pushed in place and the rails are fixed.





Winding completed



Fabrication process – main steps

- Conductor insulation
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- **Preparation for the heat treatment:**
  - Assembly of the reaction mold around the wound coil
  - Transport to CERN
- Heat treatment
- Preparation for impregnation :
  - Nb_3Sn/NbTi splice soldering
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- Impregnation
- Coil assembly
- Magnet assembly

At Saclay

At CERN

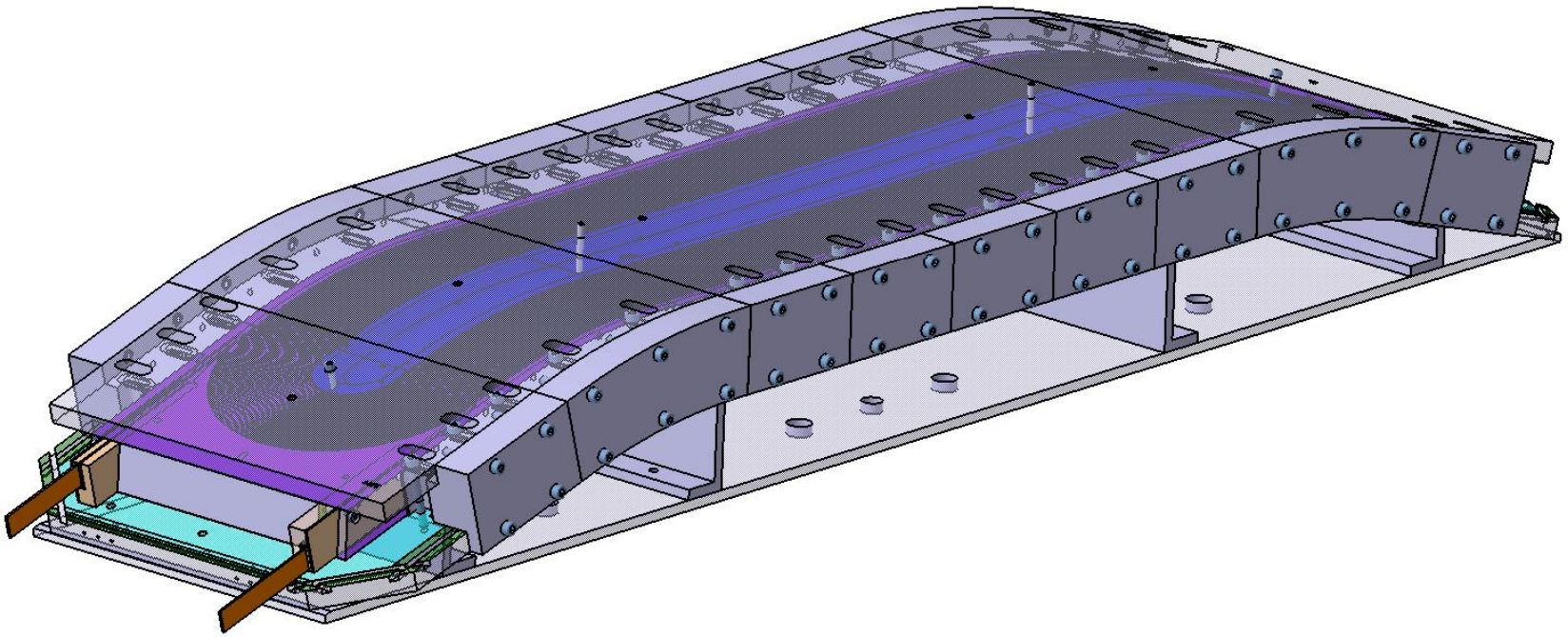
(cf. Juan Carlos' presentation)

Reaction tooling

The winding table is part of the reaction tooling.

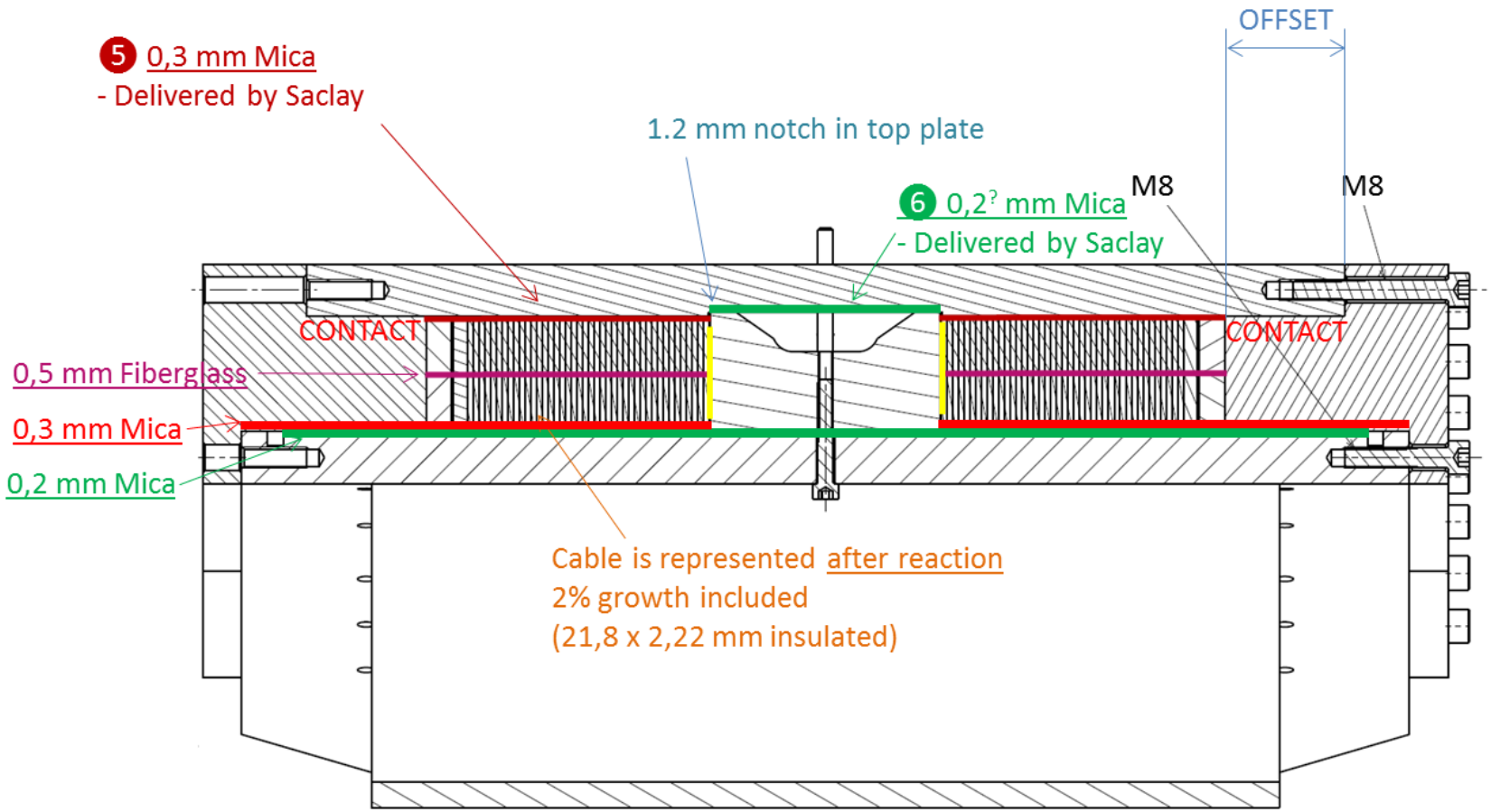
Top plates and pressure wedges are added to complete the tooling.

Segmentation of the pressure wedges to allow replacement of the compression wedges.

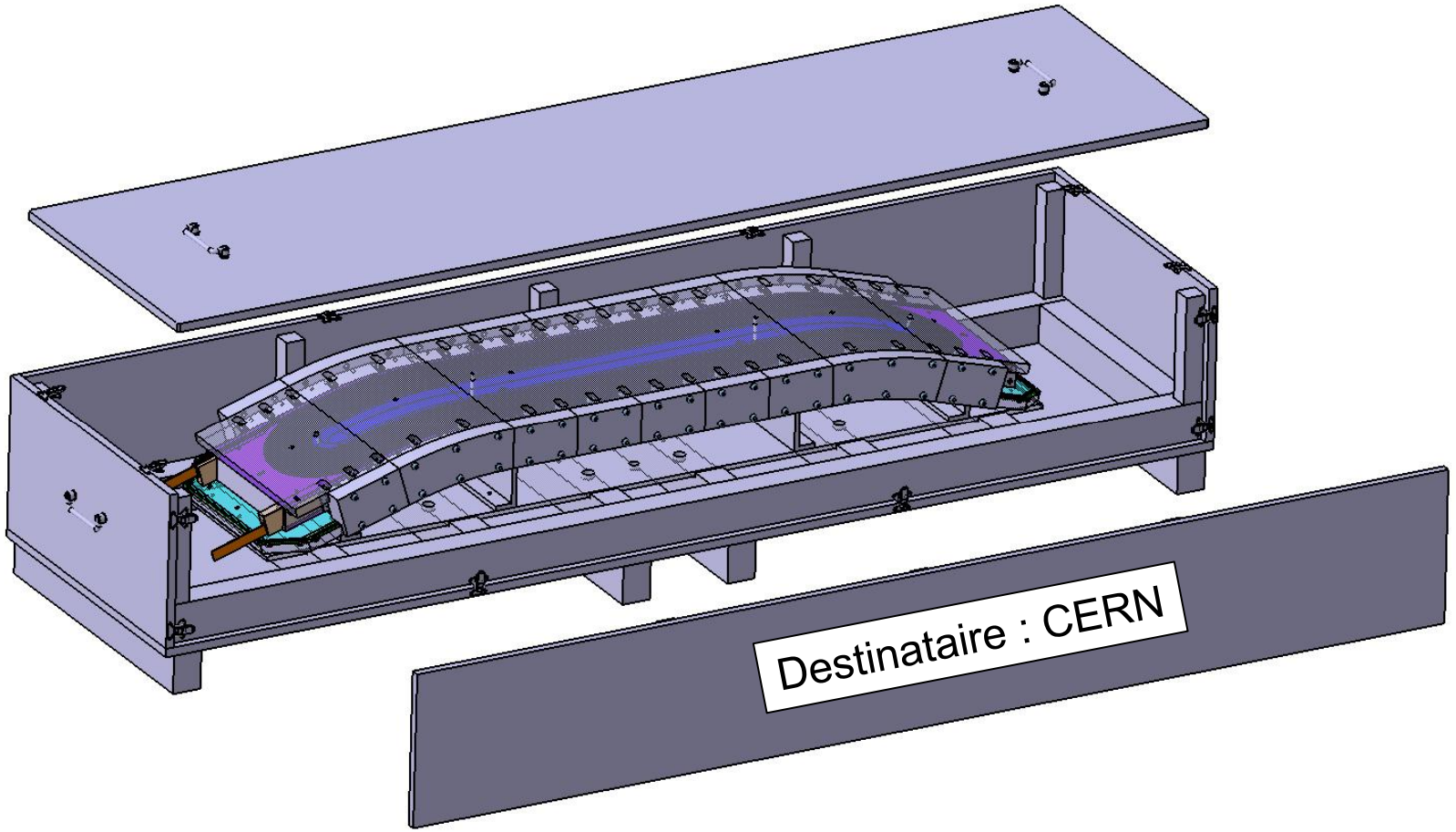


This object will be send to CERN for the reaction

Reaction tooling 3-4



Transport



Quality and documentation

- Manufacturing procedure
  - Procédure de fabrication du prototype Cu – Partie 1 : du bobinage à l'expédition au CERN- SAFIRS-00517-E
  - Procédure de fabrication du prototype Cu – Partie 2 : de la réception au CERN à l'imprégnation - SAFIRS-00579-A
- Inspection documents for cable, components and toolings:
  - Fiche de Suivi câble 270 m cuivre 1ere bobine 3-4 - SAFIRS-00643-A
  - Inventaire de réception outillage de bobinage couches 3 et 4 - SAFIRS-00540-G
  - Inventaire de réception table de bobinage couches 3 et 4 - SAFIRS-00652-B
  - Inventaire de réception rail clamp 3-4 + visserie - SAFIRS-00612-B
- Traveller to follow the manufacturing
  - Traveller bobinage CC3401 - SAFIRS-00647-A

Conclusion

- 3D models completed for coil 1-2, coil 3-4 and coil pack.
- Coil 3-4 : winding and reaction tooling received.
- Coil 1-2 :
  - winding tooling for under fabrication
  - reaction tooling call for tender in progress.
- Preparation for the winding of the first full scale prototype CC3401 in progress.

Acknowledgements

- CEA/Saclay:

  P.Contrepois, M.Devaux, M. Durante, J.J.Goc, P. Manil, J.F. Millot, A.Przybylski, J.M. Rifflet, V.Stepanov …

- CERN:

  S.Clément, P. Ferracin, J.E.Munoz Garcia, R.Gauthier, J.C.Perez, G de Rijk …

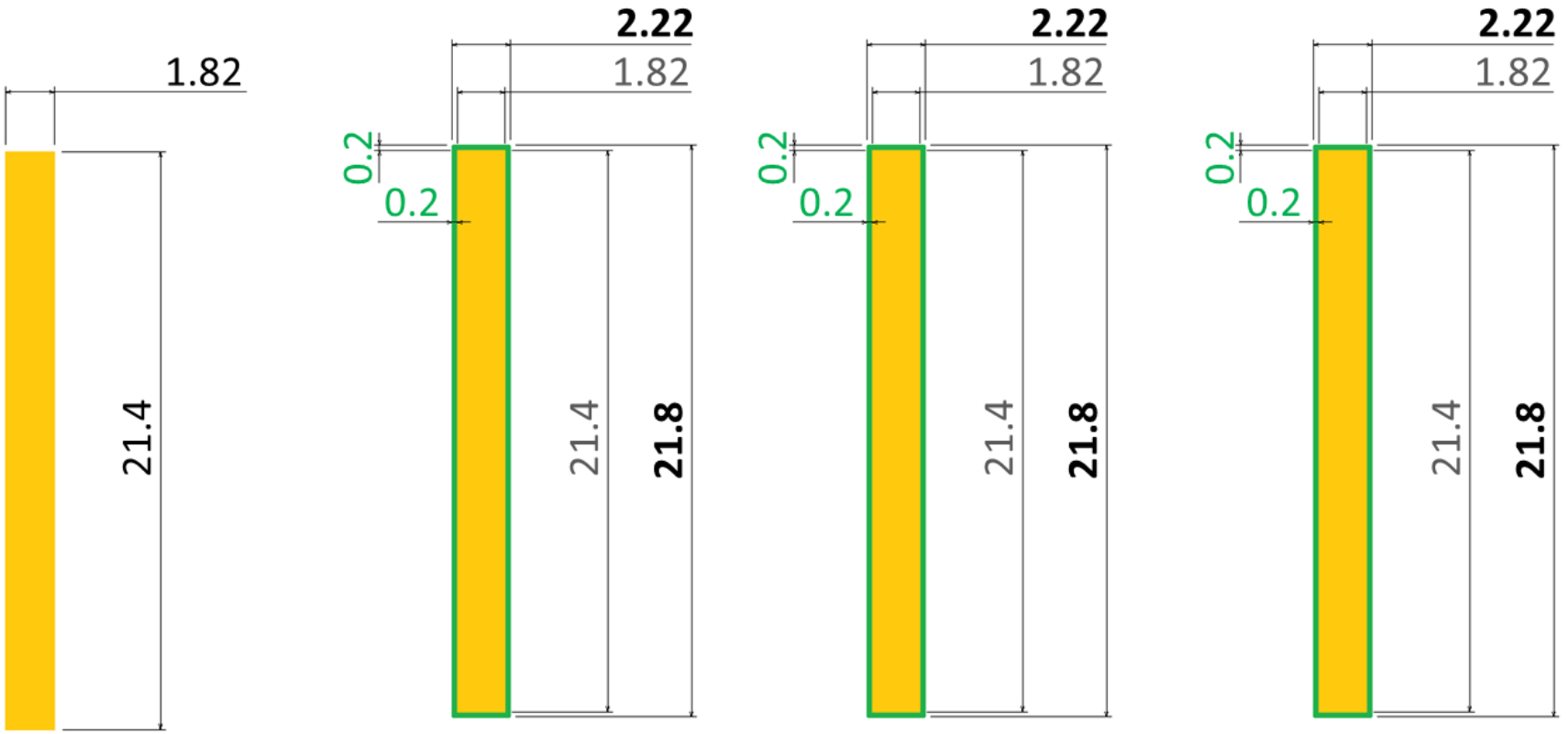
Thanks for your attention

- Réserve

1 BASELINE CABLE

- Has been used up to now in the tooling and structure design
- Dialtation during reaction & cool-down are **not** considered

CABLING ➤ INSULATION ➤ REACTION ➤ COOL-DOWN

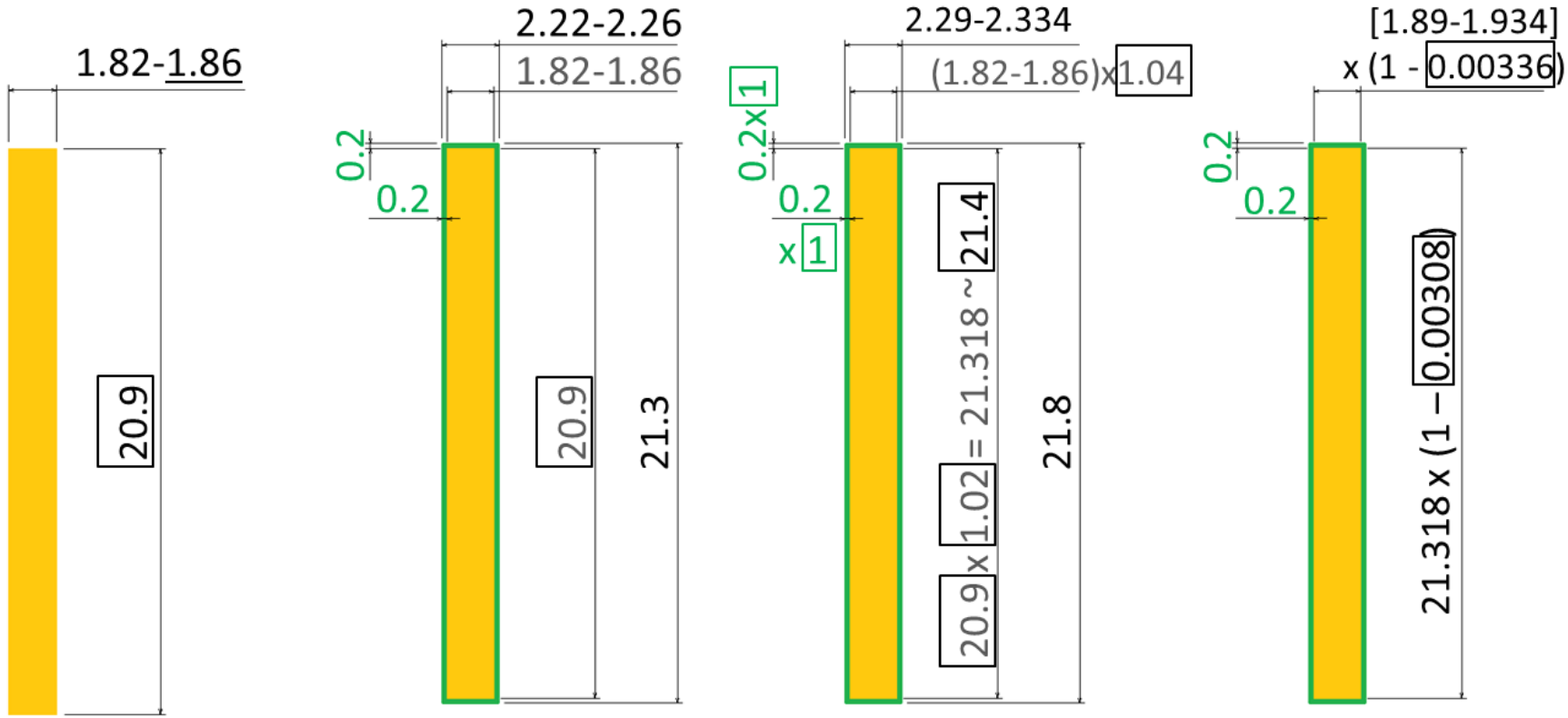


21.4 x 1.82 21.8 x 2.22 = 21.8 x 2.22 = 21.8 x 2.22

2 REAL CABLE with BASELINE INSULATION

- Initial cable width has been fixed to 20.9 mm. Cable thickness is between 1.82 and 1.86 mm (1.86 more likely)
- A RAL-type insulation is considered, with 0.2 mm per face

CABLING ➤ INSULATION ➤ REACTION ➤ COOL-DOWN



20.9 x 1.82 / 1.86

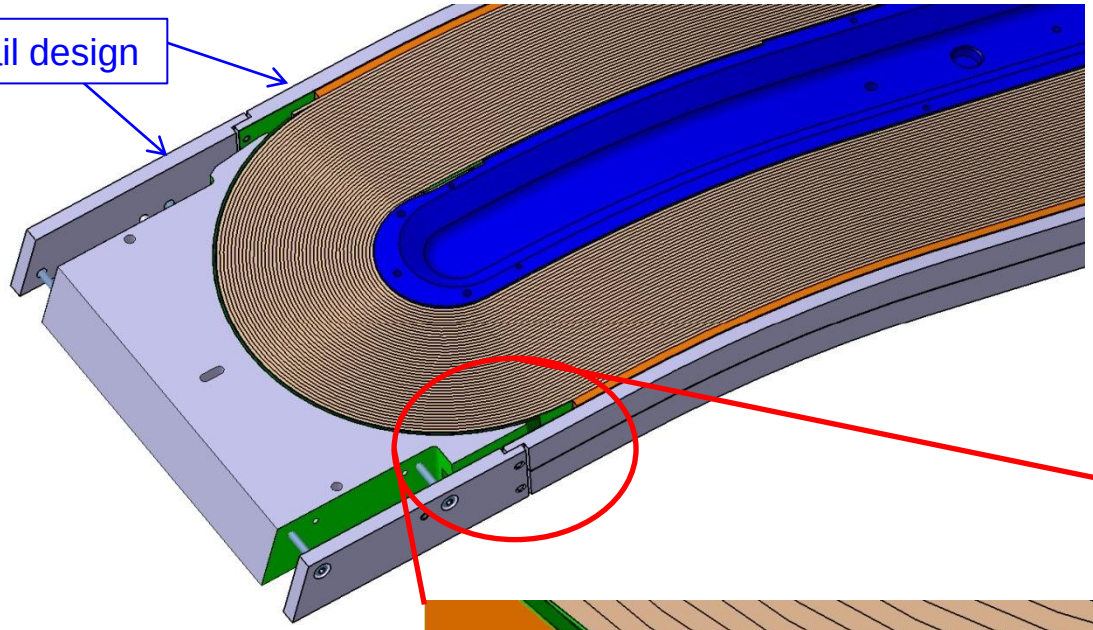
21.3 x 2.22 / 2.26

21.8 x 2.29 / 2.334

21.65 x 2.28 / 2.33

X *means 'fixed'* X *means 'most likely option'*

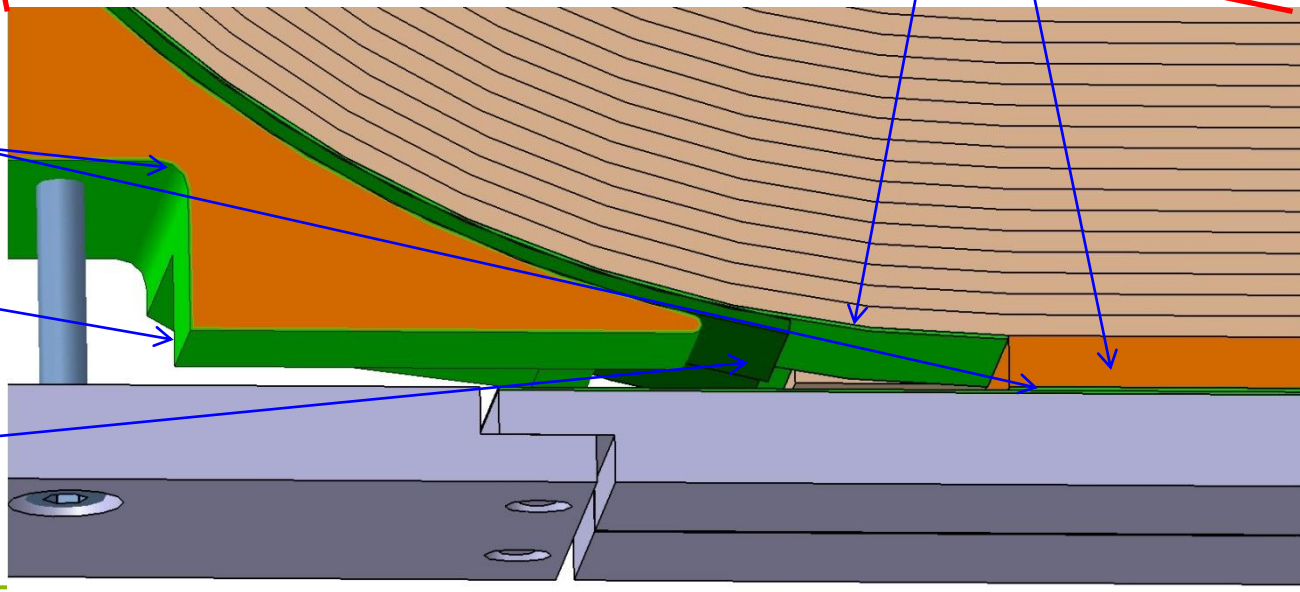
Detailed 3D model of coil 3-4



New rail design

Possibility of 2x0.2 mm steel shim ⇔ obtain continuous contact all along the side of the coil

Reserved space ⇔ max dimension of the reacted coil

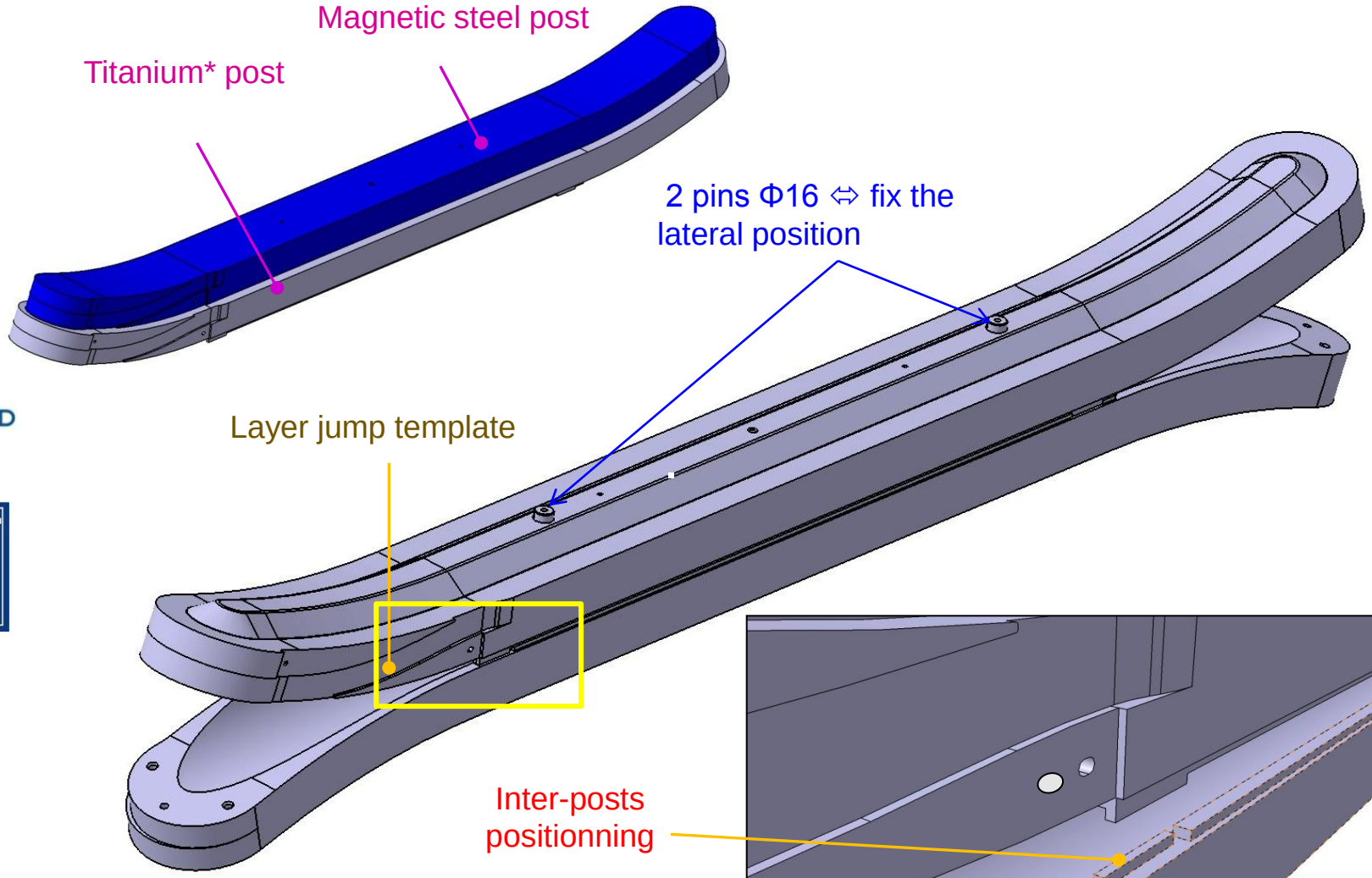


0.3 mm-thick alumina coating

Connection design

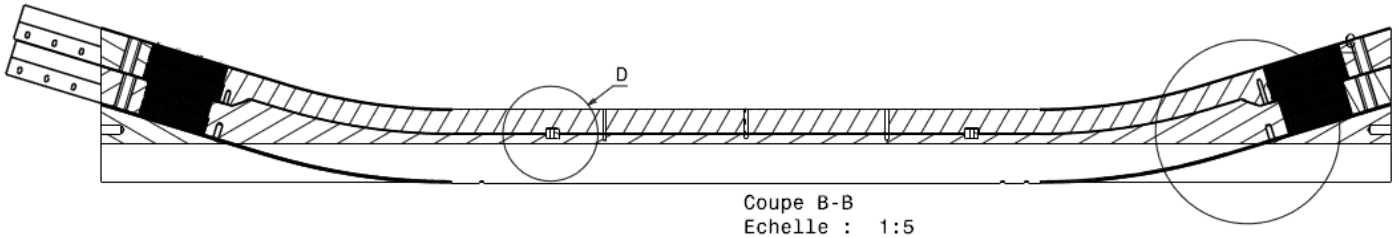
1.5 mm shim ⇔ fill the gap between coil and horseshoe (offset possible)

Posts design

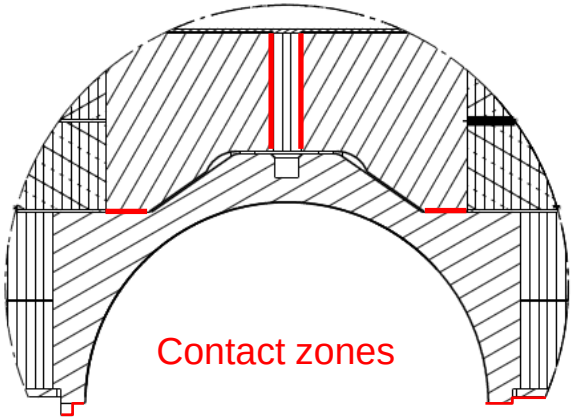


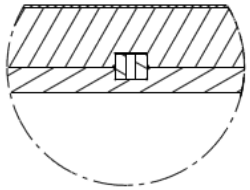
* choice maid after thermal tests

Posts design

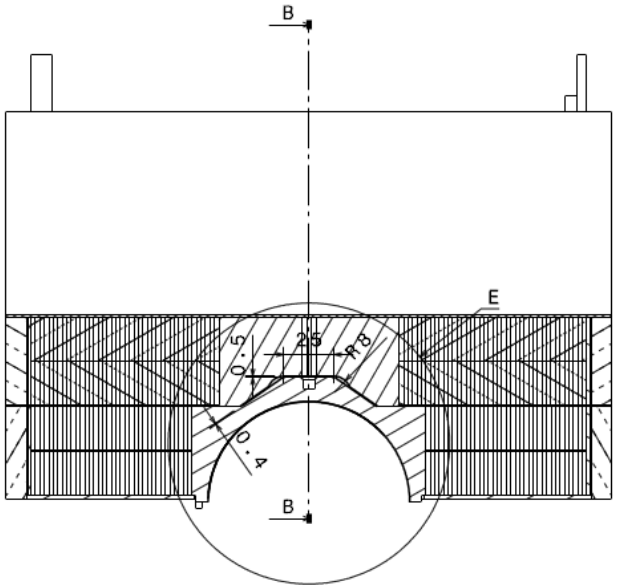


Coupe B-B
Echelle : 1:5



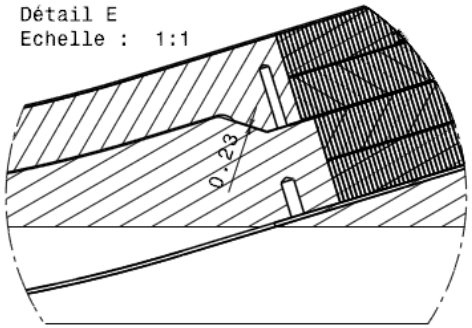


Détail D
Echelle : 1:2



Coupe A-A
Echelle : 1:2

Détail E
Echelle : 1:1

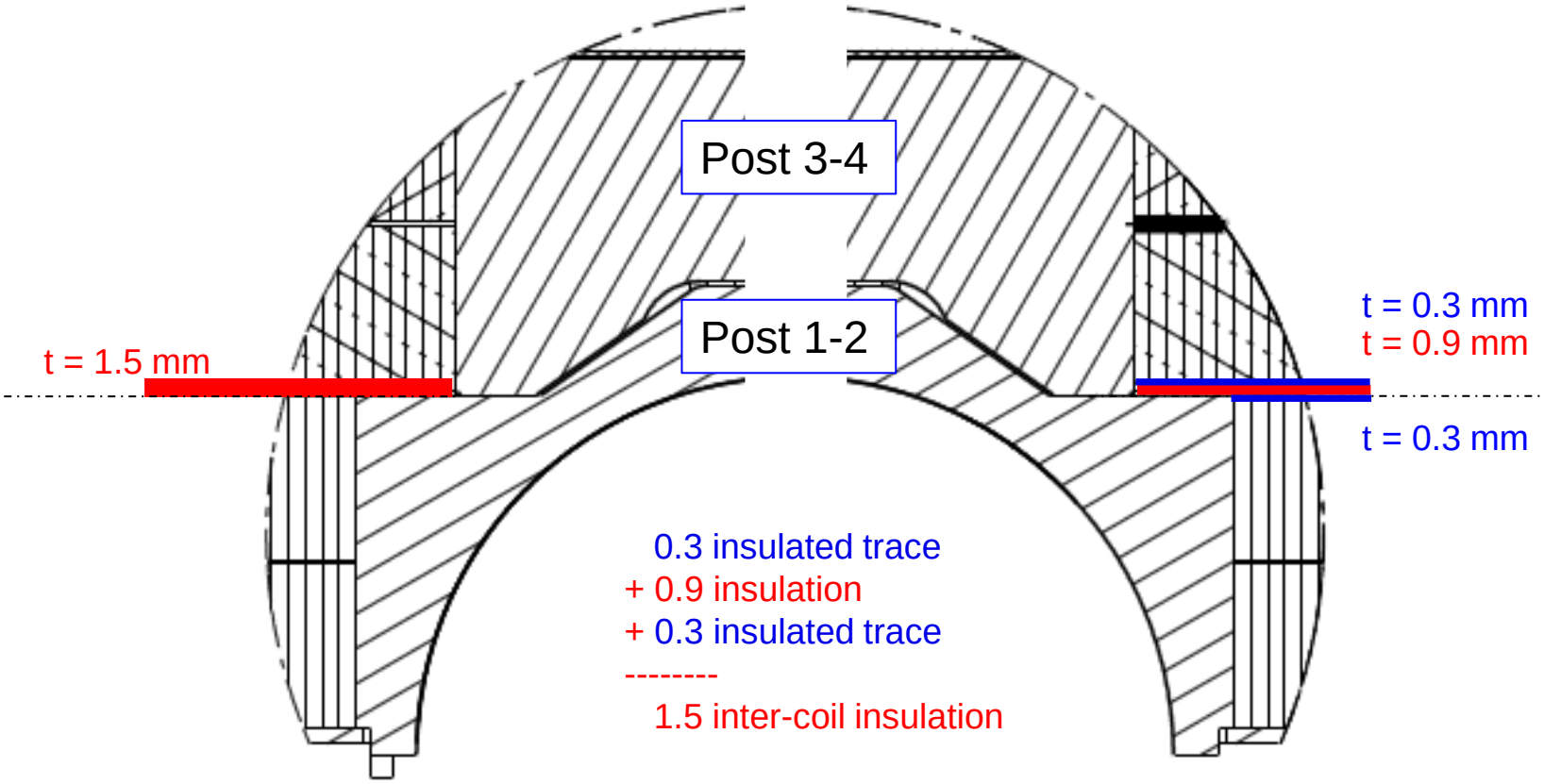


Détail C
Echelle : 1:2

Insulation between double pancakes = 1.5 mm

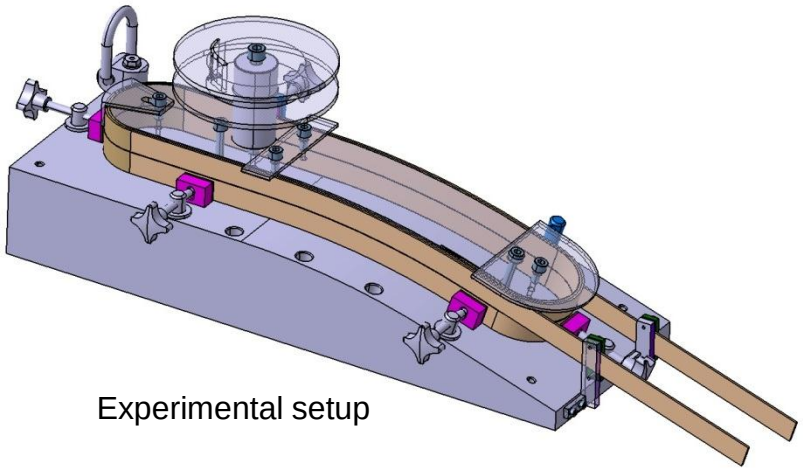
What we have today
in the prototype:

What would be:

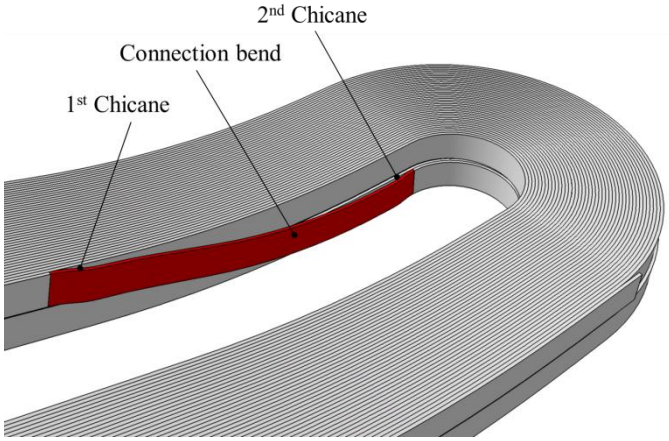


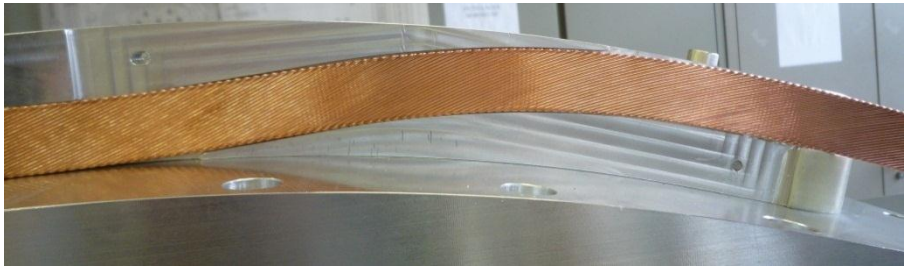
Layer jump

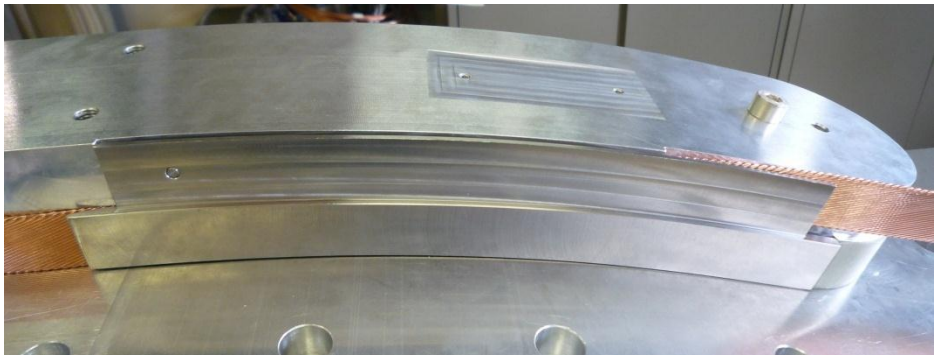
- In the HW zone, « double chicane » solution selected
- Shim easier to position and fix, ensure better protection of the jump zone
- Tests have been done:



Experimental setup



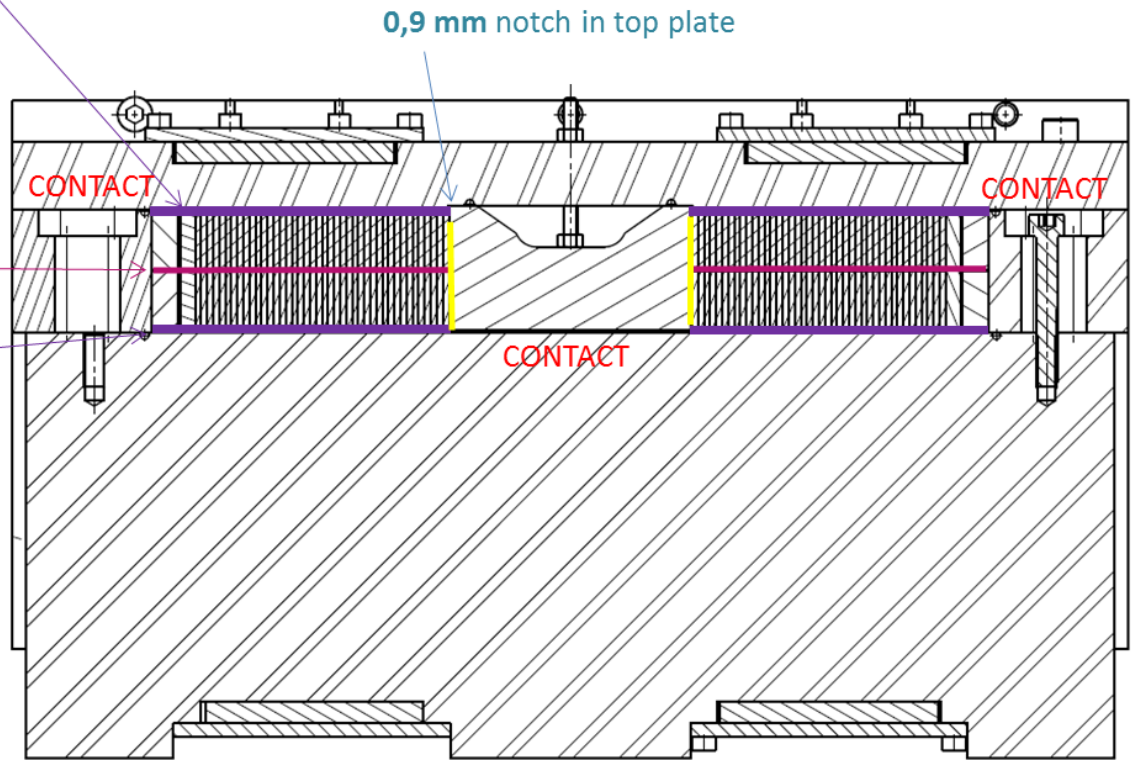




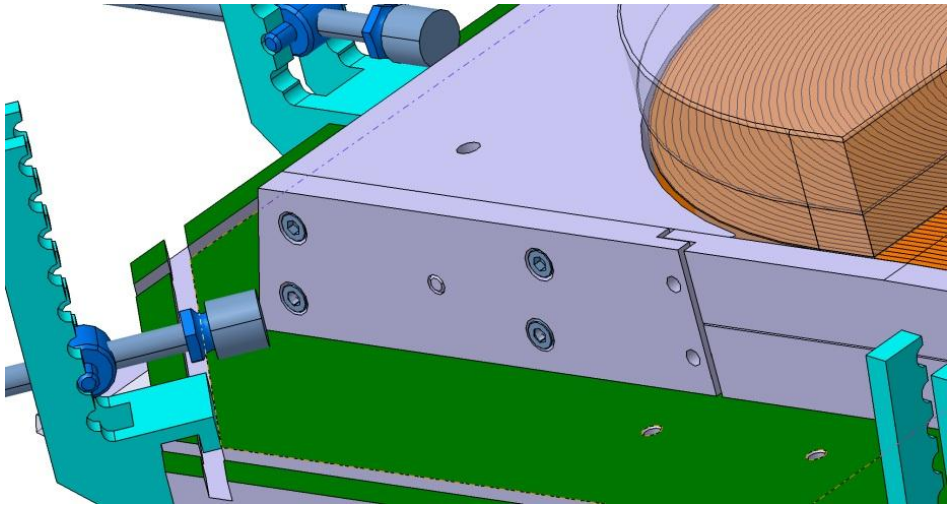
Ref : report on layer jump test SAFIRS-00373-E (2011)

Insulation : impregnation 3-4

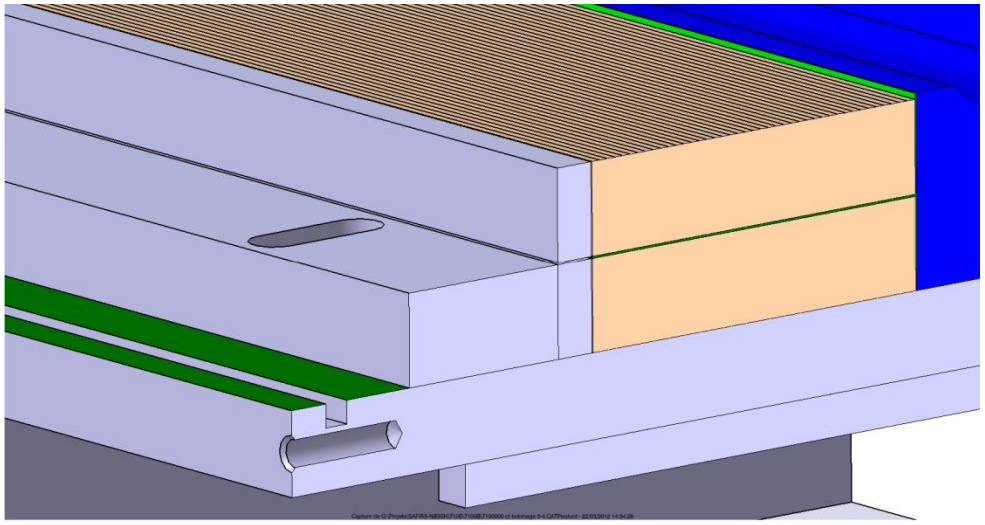
7 Insulated trace
- 0,3 mm
- Cut around the post
- Delivered by CERN



Rails geometry

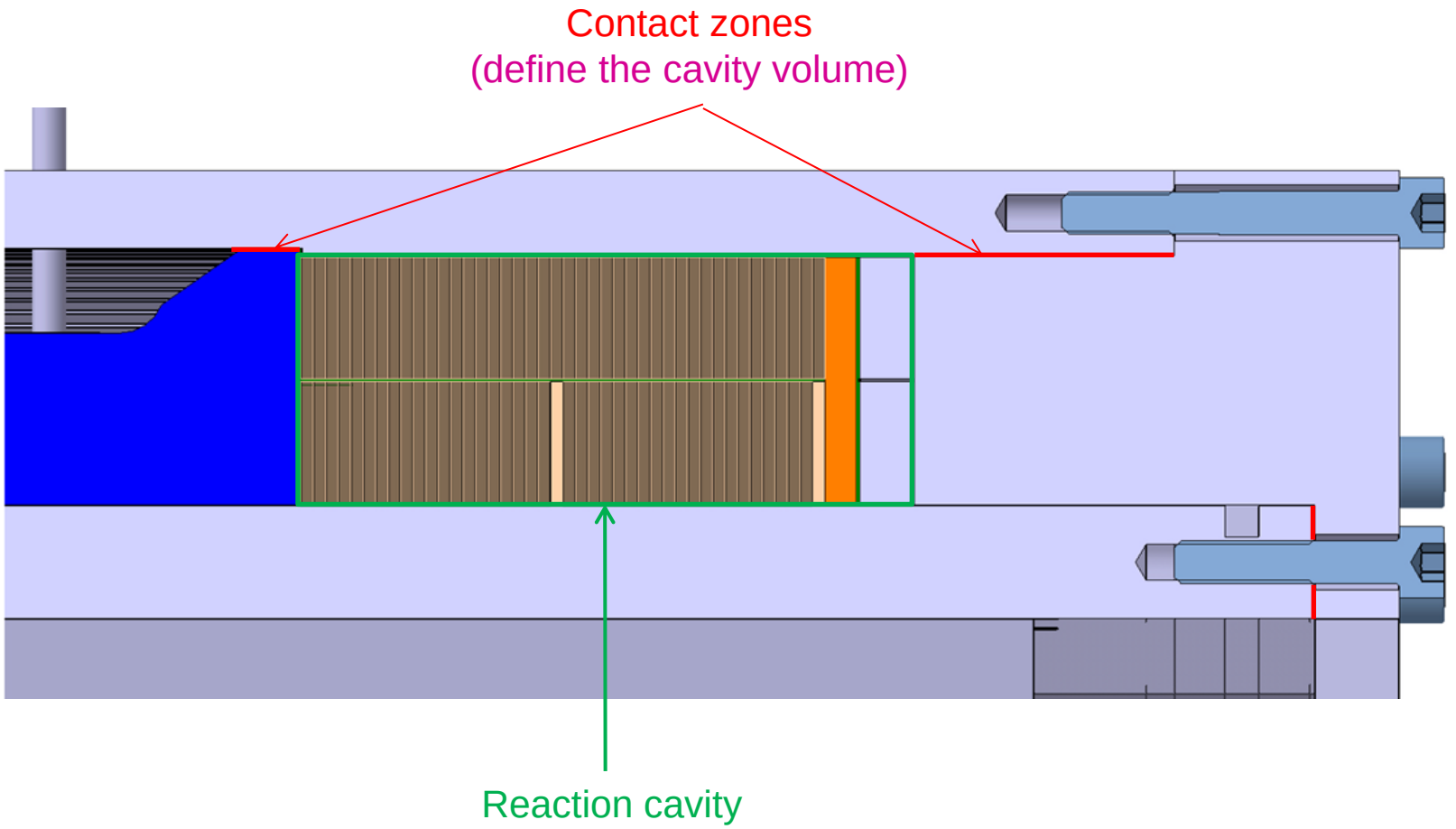


Fixation of the rails
on the horseshoes



Section of the coil

Reaction tooling



4% (respectively 2%) have been added to the dimensions with respect on bare cable thickness (respect. bare cable width).