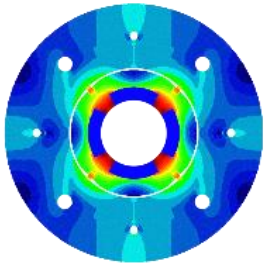
DE LA RECHERCHE À L'INDUSTRIE



MQYYM

HiLumi HL-LHC PROJECT

TE-MSC Seminar

Design, manufacturing and test of the MQYYM magnet

Damien Simon for the MQYYM team

6TH MAY 2021

www.cea.fr

ACKNOLEDGEMENTS

CEA core team: Hélène Felice, Damien Simon, Simon Perraud, Romain Godon, Ricardo Correia-Machado

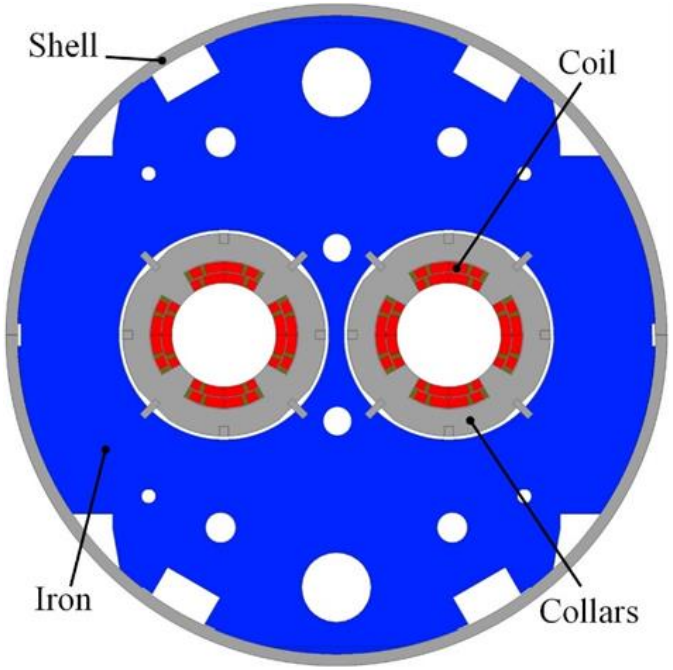
CEA design team:, Jean-Michel Rifflet, Michel Segreti, Patrick Graffin, Gilles Minier, Hubert Neyrial, Edouard Pepinter, Sébastien Somson

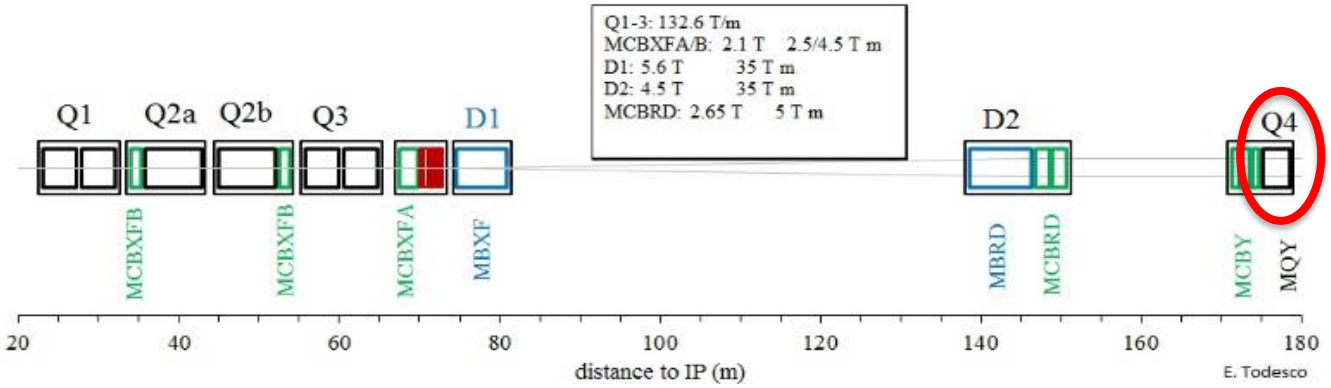
CEA test team: Jean-Marc Gheller, Denis Bouziat, Frédéric Molinie, Philipe de Antoni, Vadim Stepanov, Quentin Guihard, Bertrand Hervieu, Arnaud Madur, Johan Relland, Nicolas Commaux, Pascal Godon

CERN: Juan Carlos Perez, Nicolas Bourcey, Michael Guinchard, Salvador Ferradas Troitino, Sohrab Emami Naini, Sylvain Mugnier, Pierre Antoine Contat, Hugues Dupont, Pietro Antonio Rizzo, Arnaud Foussat, Lucio Fiscarelli, Carlos Petrone, Matthias Bonora, Ezio Todesco.

THE MQYY QUADRUPOLE OPTION IN HL-LHC

Characteristics	MQY	MQYY
Aperture diameter	70 mm	**90 mm**
Inter beam distance	194 mm	**194 mm**
Magnetic length	3,4 m	**3,67 m**
Gradient	160 T/m	**120 T/m**
Current	3610 A	**4590 A**
Peak field at nominal current	6,1 T	**6,4 T**
Load line margin	23%	**23%**
Temperature	4,5 K	**1,9 K**
Mechanical structure	**Self supported collars**	

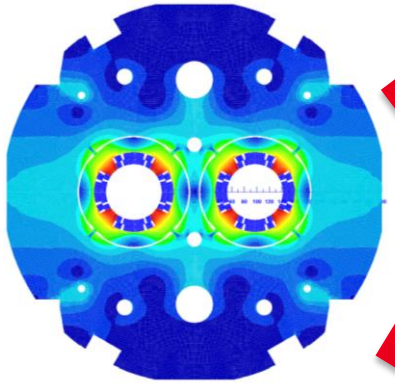




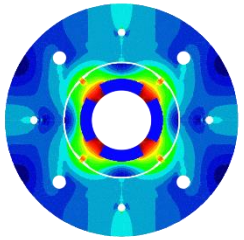
Removed from baseline in 2016

Decision to continue the R&D on large aperture NbTi quadrupole as an option for HL-LHC

OVERVIEW OF MQYY ACTIVITY

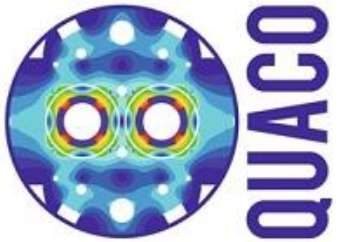


HL-LHC
MQYY magnet



MQYYM

- **Single aperture short model of 1.320 m long**
- Operating current : 4550 A (23% margin)
- NbTi cable with kapton insulation
- Yoke outer diameter 360 mm



QUACO

- 2 full length prototypes

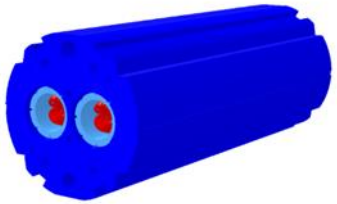
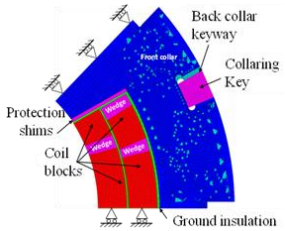
PHASE 1	PHASE 2	PHASE 3
Concept. Design	Engineering design	MQYYP Manufacturing

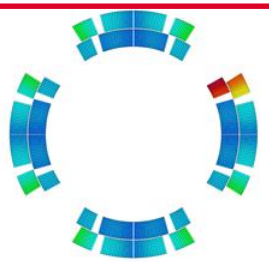
ELYTT ENERGY

SIGMAPHI ACCELERATOR TECHNOLOGIES

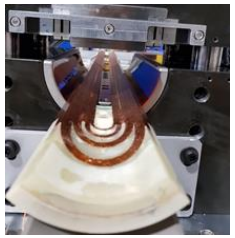
TALK OVERVIEW

DESIGN

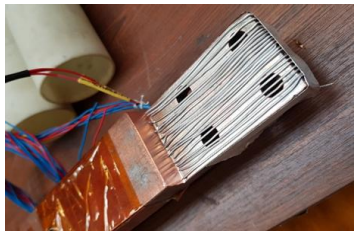




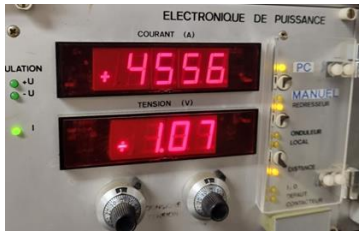


MANUFACTURING

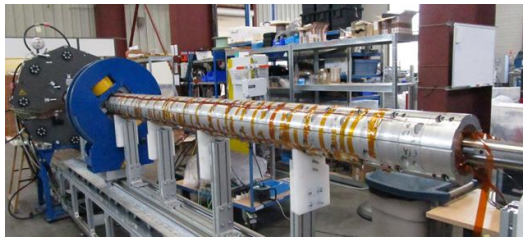



COLD TEST





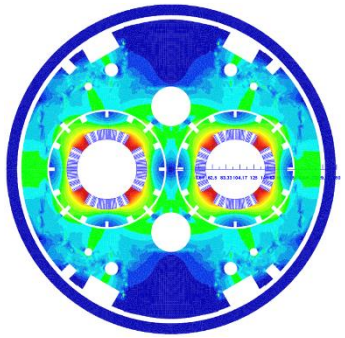
TOWARD QUACO




MAIN GOAL OF THE SEMINAR

- Report on the MQYYM project results
- Report on the lessons learned during all the steps of the project from the design decision to the manufacturing difficulties

MAGNETIC DESIGN



[1] M. Segreti et al, "A Nb-Ti 90 mm Double-Aperture Quadrupole for the High Luminosity LHC Upgrade"

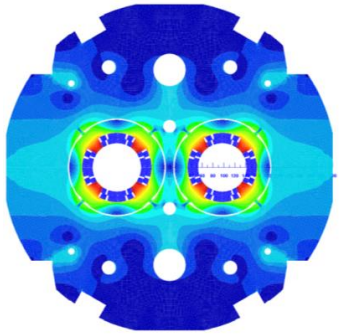
From 2011 to 2015

- Design study (2011-2013)
- Single layer coil
- LHC MB outer layer cable (15 mm wide)

Reasons

- Use available cable
- CEA considerable experience with this cable for the MQ

Characteristics MQYY one layer	
Aperture	90 mm
Nominal Gradient	115 T/m
Magnetic length at 1,9 K	3.8 m
1st design Nominal Current	15650 A
Peak Field	6.1 T
Margin on the loadline	20 %
Differential inducance	2 x 2.9 mH
Cable type	MQ (MB outer layer)



[2] H. Felice et al, "Development of MQYY: A 90-mm NbTi Double Aperture Quadrupole Magnet for HL-LHC"

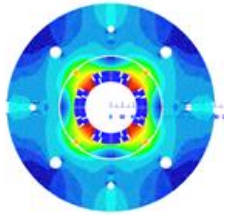
September 2015:

- Two layer coil
- LHC MQM cable (8.8 mm wide)

Reasons

- Saving on power converters and links
- Reduce operational current

Characteristics MQYY two layers	
Aperture	90 mm
Nominal Gradient	120 T/m
Magnetic length at 1,9 K	3,7 m
MQYY Nominal Current	4590 A
Peak field	6.4 T
Margin on the loadline	23 %
Differential inductance	2 x 37.7 mH
Cable type	MQM



[3] D. Simon et al, "Mechanical Analysis and Assembly of MQYYM: A 90 mm NbTi Quadrupole Magnet Option for HL-LHC"

September 2015:

- Single aperture short model to be manufactured and test by CEA

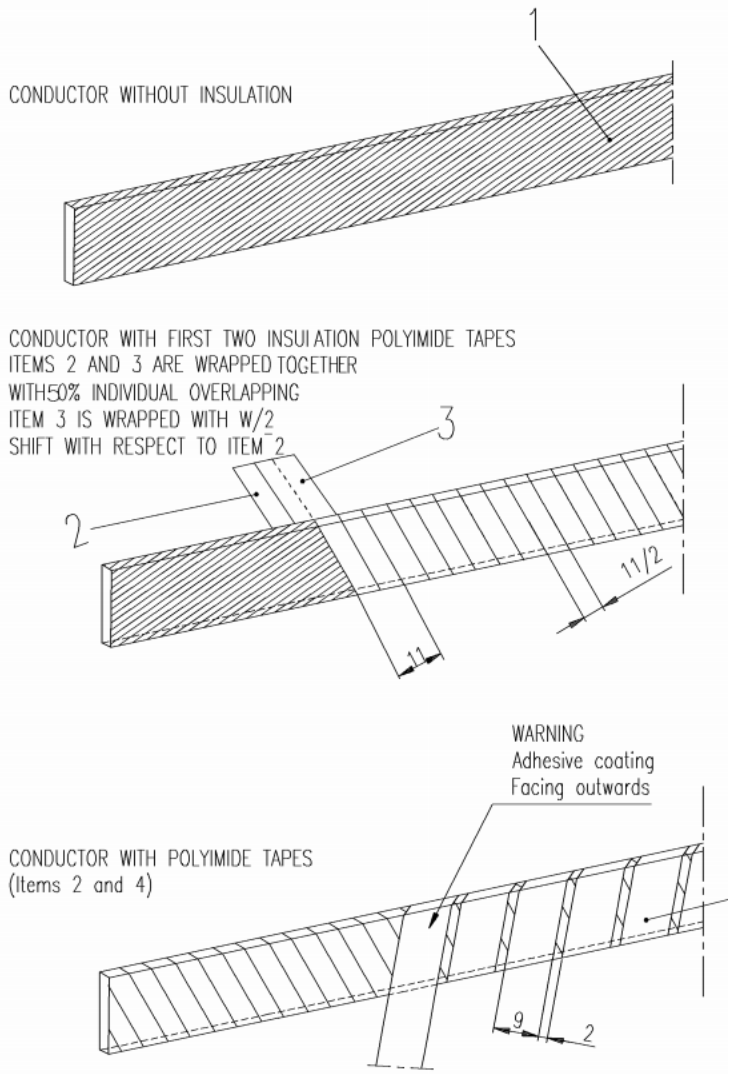
Reasons

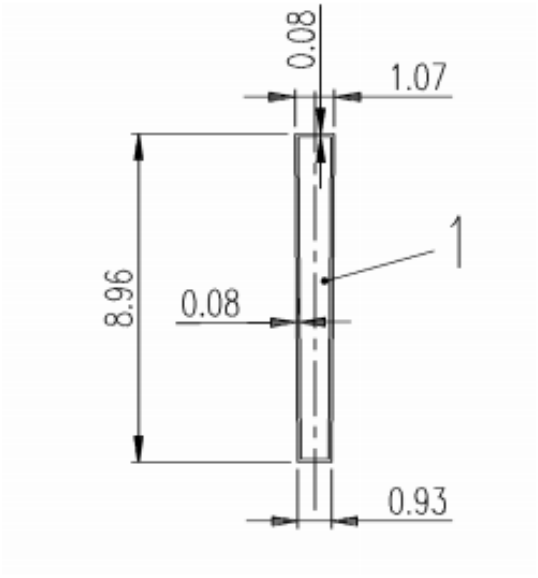
- Prove the feasability
- Train a new team

Characteristics MQYYM	
Aperture	90 mm
Nominal Gradient	120 T/m
Magnetic length at 1,9 K	1.2 m
MQYYM Nominal Current	4550 A
Peak field	6.4 T
Margin on the loadline	23 %
Differential inductance	12.4 mH
Cable type	MQM

CABLE AND INSULATION

MQM CABLE





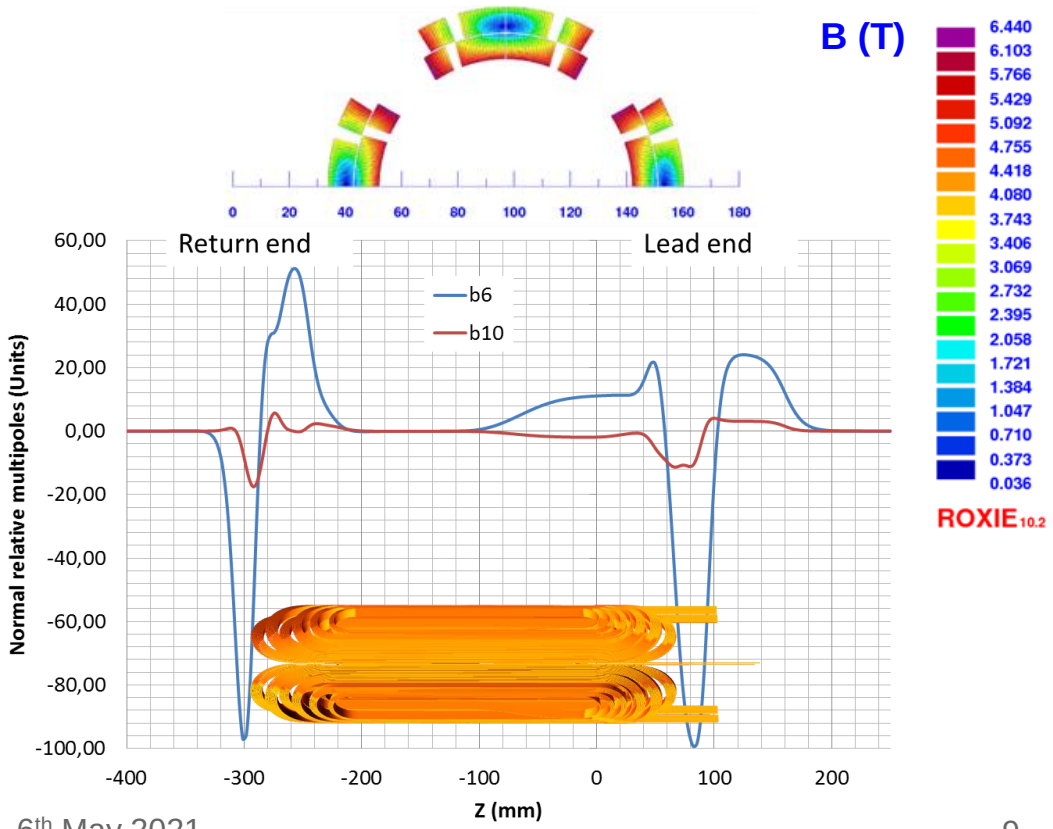
4	Polyimide film	0.055x9 with adhesive on the outside
		(220 LCI)
3	Polyimide film	0.025x11
		(100 HN)
2	Polyimide film	0.025x11
		(100 HN)
1	NbTi in Cu-matrix	

Conductor Parameter	
Bare cable width	8.8 mm
Bare cable thin/thick edge	0.77/0.91 mm
Insulation thickness at 50 MPa	0.080 mm
Strand diameter	0.48 mm
Number of strands	36
Cu/Superconductor ratio	1.75 ± 0.05
RRR on extracted strand meas/spec	250/80
Measured strand Ic at 1.9 K and 8 T	189 A

MAGNETIC DESIGN

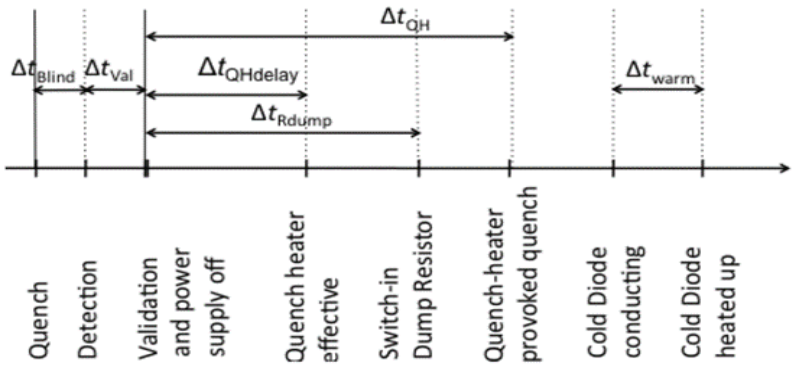
- All the harmonics have been optimized to be bellow the units including during the imbalance phase
- The coil ends have been optimized to minimize the integrated b_6 and b_{10} along the length of the magnet

Computed Multipole Components in units								
	I (kA)	b_1	b_3	b_4	b_5	b_6	b_{10}	b_{14}
MQYY 0% imbalance								
Left	4.59	-0.44	-0.17	0.09	0.07	0.00	-0.01	1.32
Right	4.59	0.44	0.17	0.09	-0.07	0.00	-0.01	1.32
MQYY 50% imbalance								
Left	4.59	-0.84	-0.56	0.08	-0.02	-0.02	0.00	1.32
Right	2.29	-0.78	0.34	0.38	-0.09	-0.70	0.01	1.32
MQYYM single aperture								
	4.55	0.00	0.00	-0.01	0.00	-0.01	-0.01	1.32



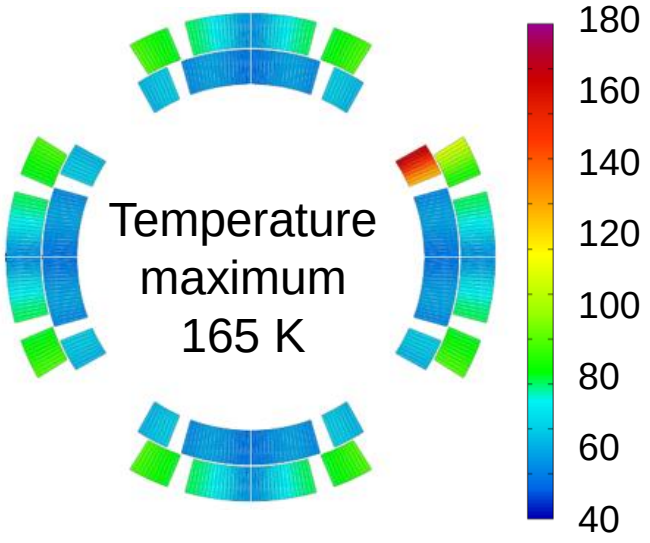
PROTECTION

Inputs protection	
$V_{threshold}$	0,1 V
$T_{detection}$	10 ms
$T_{validation}$	10 ms
$T_{PHvalidation}$	10 ms
QH delay	~ 20 ms
Dump MQYYM	0,1 Ω



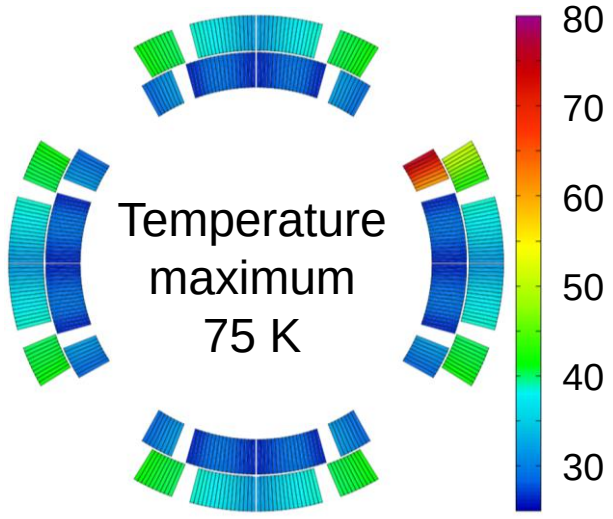
MQYY

- No dump resistor
- Protection heater
- Hotspot estimated with Roxie at 165 K and voltage to ground at 200 V

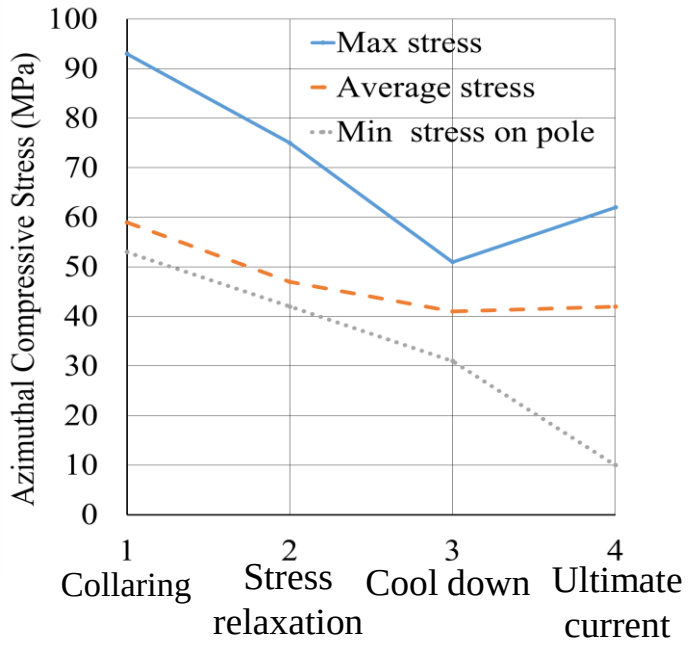


MQYYM

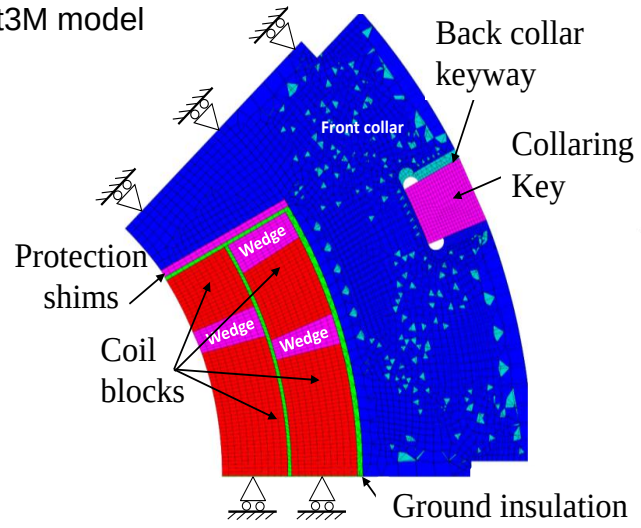
- Dump resistor at 0.1 Ω
- Protection heater
- Hotspot estimated with Roxie at 75 K and voltage to ground at 455 V

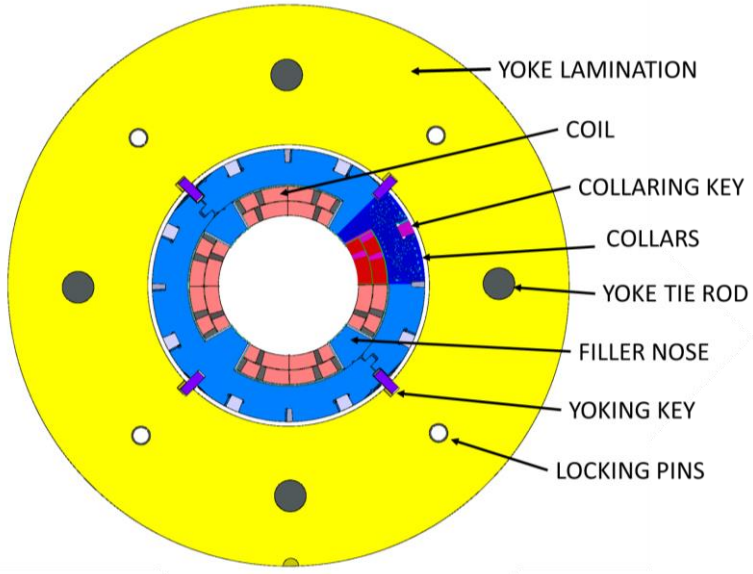


MECHANICAL DESIGN



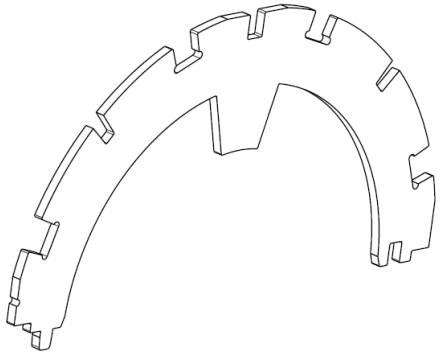
Cast3M model





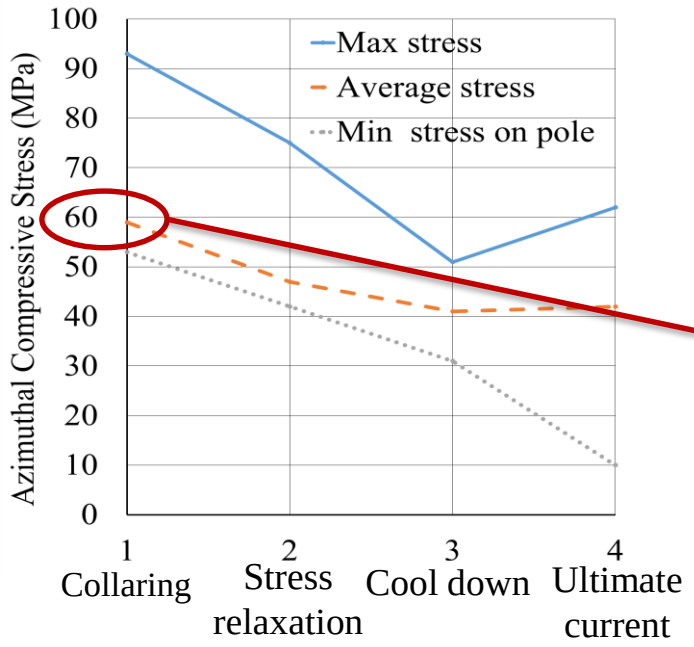
Design Material Properties	
Coils rigidity at warm [4]	5,4 GPa
Coils rigidity at cold [5]	7,9 GPa
Coil thermal contraction [5]	5 mm/m

Self supported structure with 3 mm thick stainless steal collars

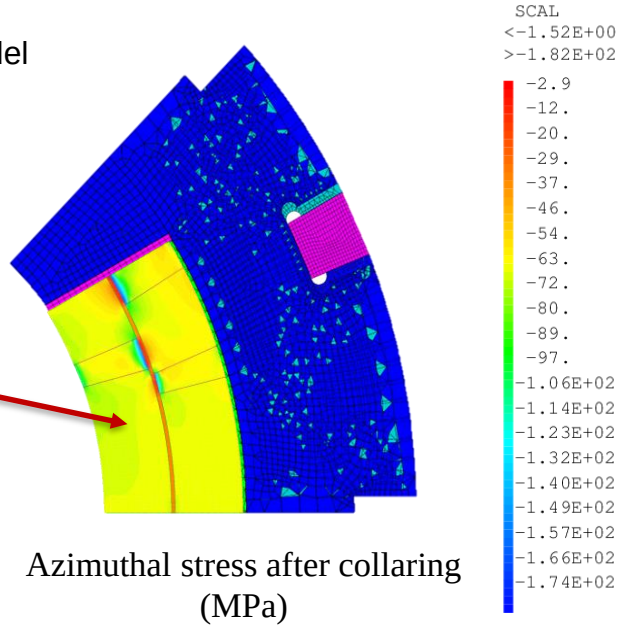


[4] J. Lucas et al., Internal report on MQMC2 coil rigidity measurements
[5] M. Segreti et al, Internal value used for the MQ FEA simulation

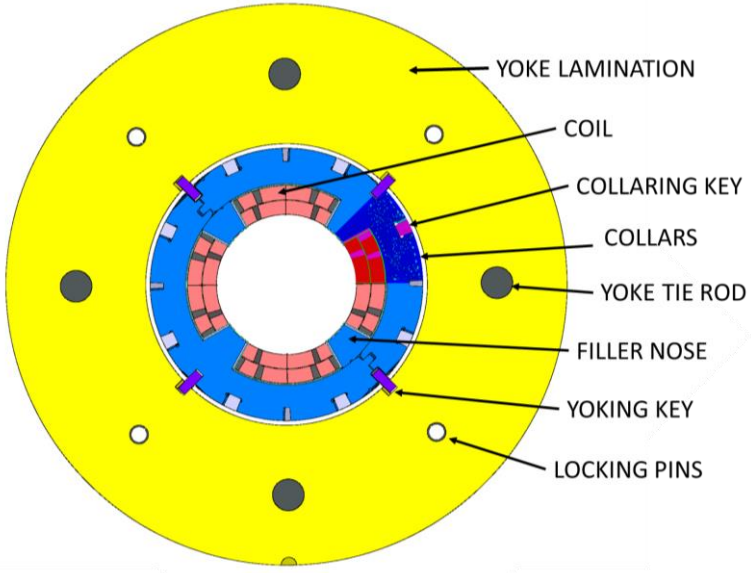
PRE-STRESS REQUIREMENTS



Cast3M model



Azimuthal stress after collaring (MPa)



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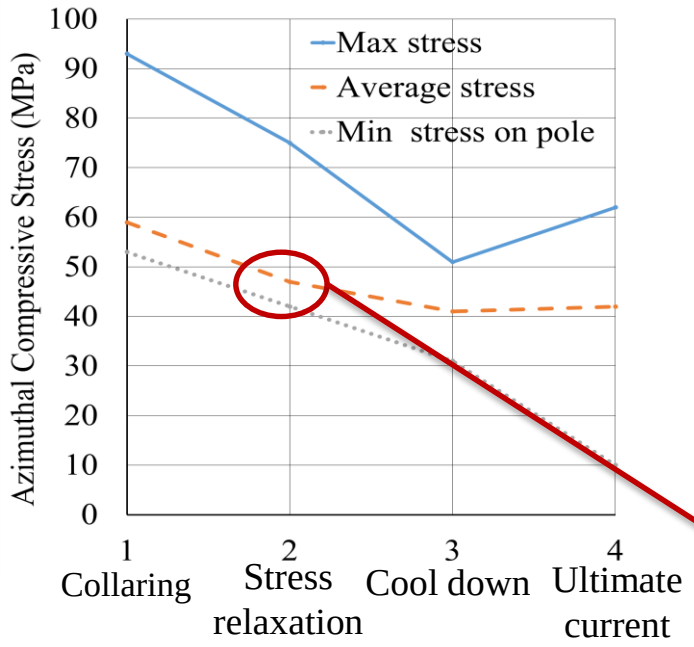
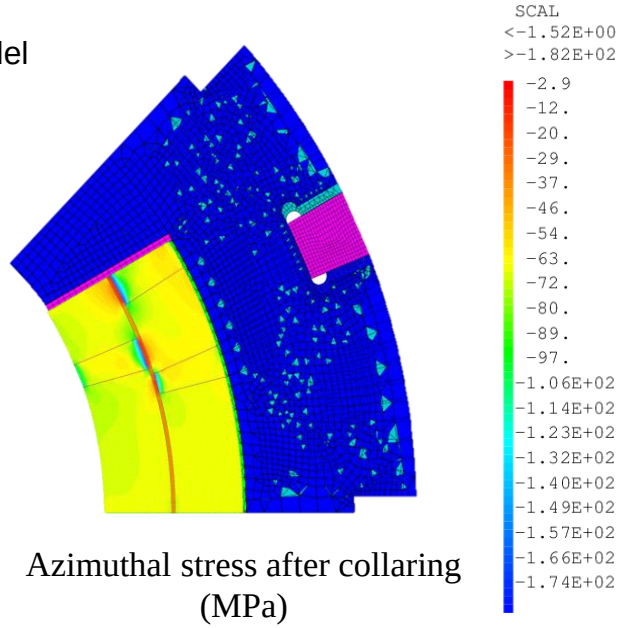
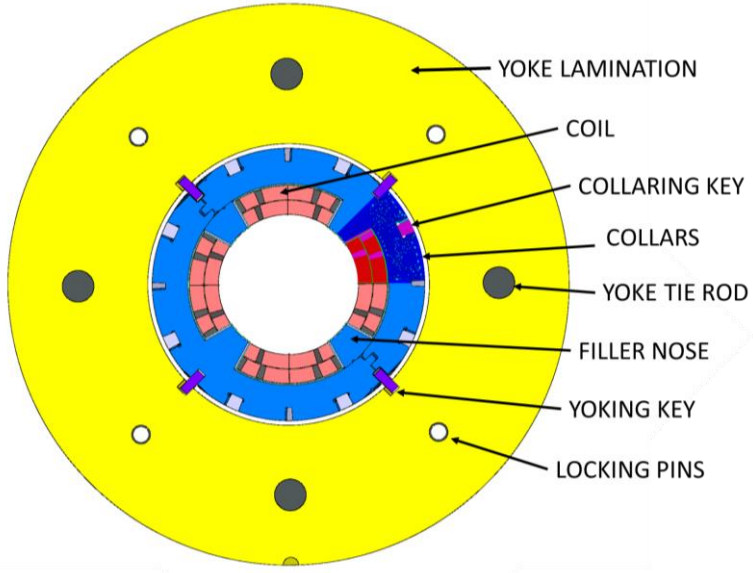


Cast3M model



Azimuthal stress after collaring (MPa)



Design Material Properties	
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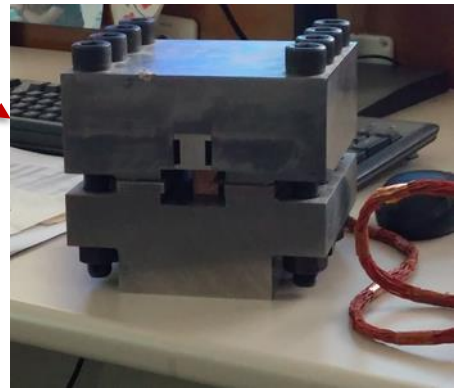
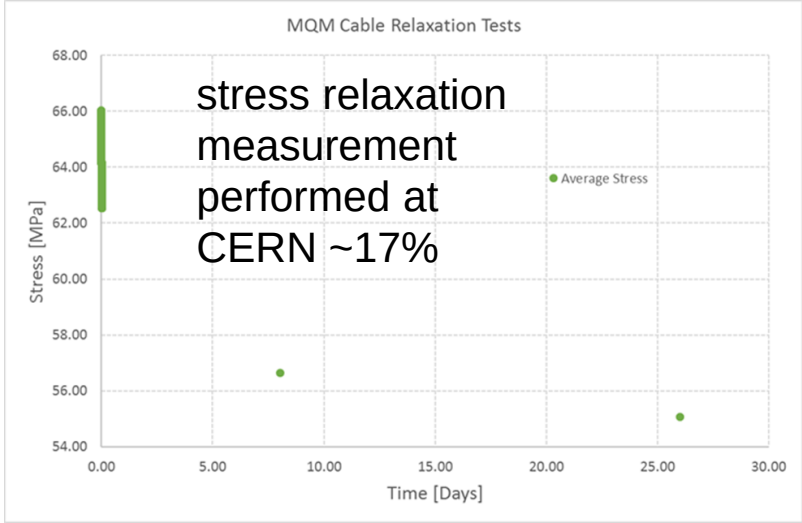


Courtesy Michael Guinchard (CERN)



[4] J. Lucas et al., Internal report on MQMC2 coil rigidity measurements
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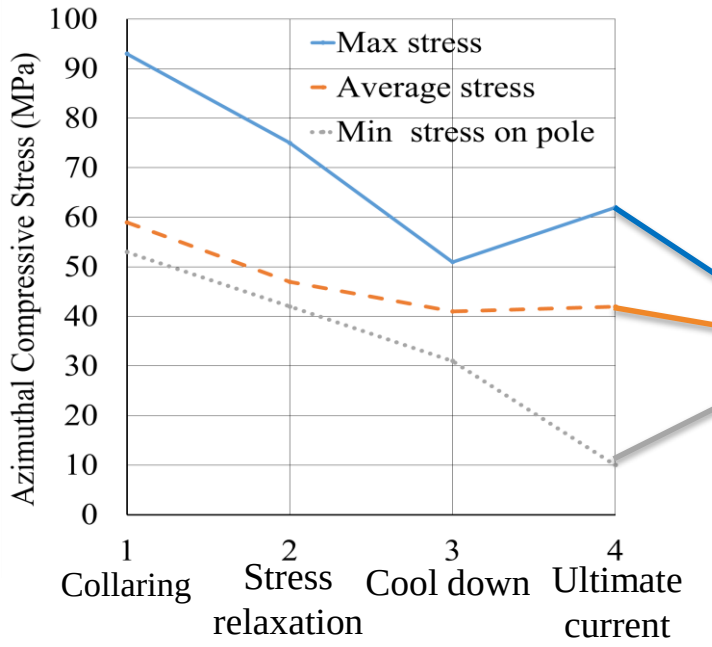
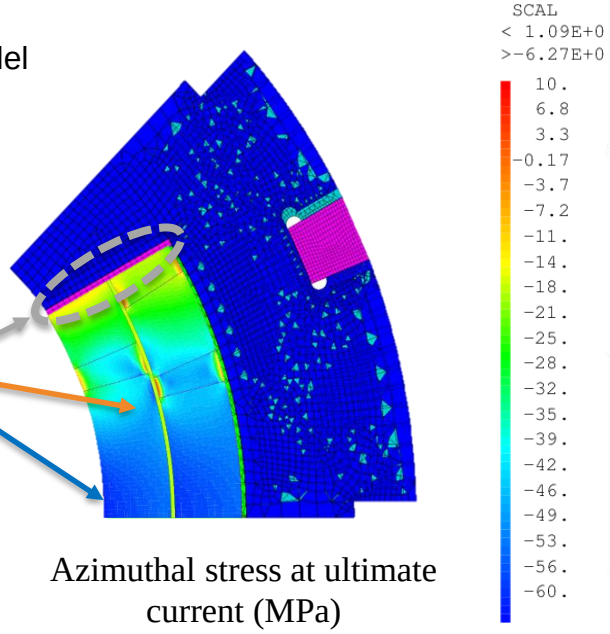
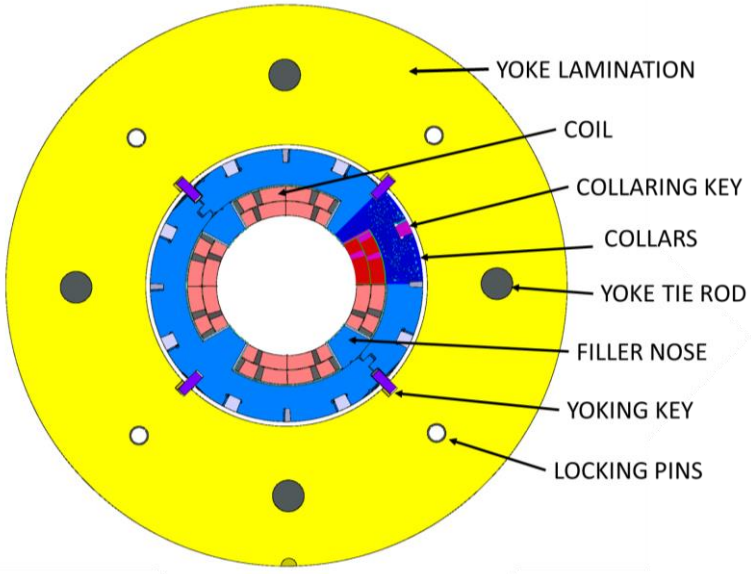
PRE-STRESS REQUIREMENTS



Cast3M model



Azimuthal stress at ultimate current (MPa)



Design Material Properties	
Coils rigidity at warm [4]	5,4 GPa
Coils rigidity at cold [5]	7,9 GPa
Coil thermal contraction [5]	5 mm/m

Azimuthal stress after collaring:

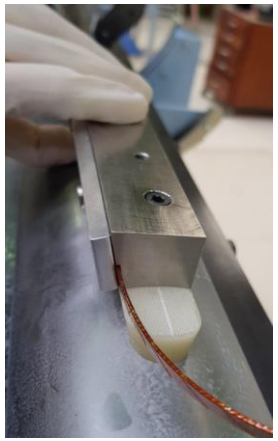
60 MPa for a minimum compression of **10 MPa** on the pole during energization at ultimate current

Lower than **150 MPa** to not damage the insulation [6]

[4] J. Lucas et al., Internal report on MQMC2 coil rigidity measurements
[5] M. Segreti et al, Internal value used for the MQ FEA simulation
[6] Technical Specification of the superconducting cables for the LHC MQM and MQY quadrupoles, LHC Project Document

10 COILS FABRICATED AT CEA

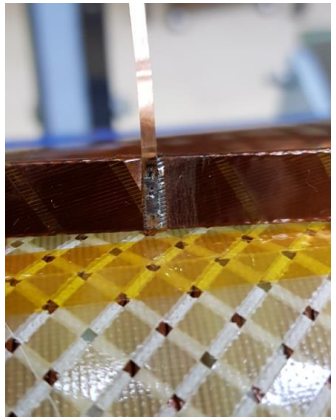
Layer jump positioning

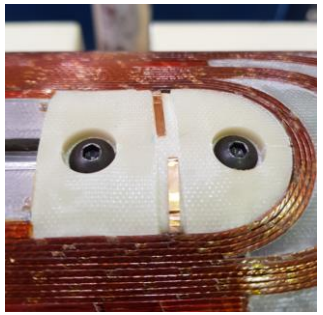


Winding of the inner layer

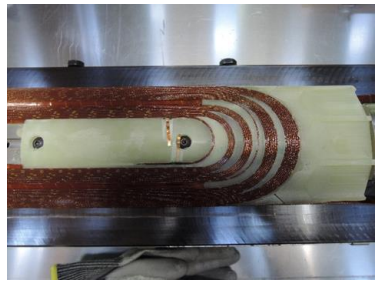
Polymérisation of the inner layer

Vtap soldering

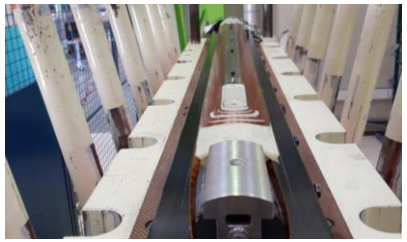


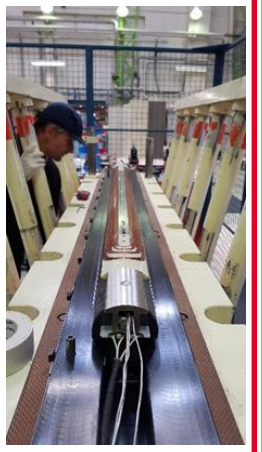


Winding of the outer layer



Polymérisation of the outer layer



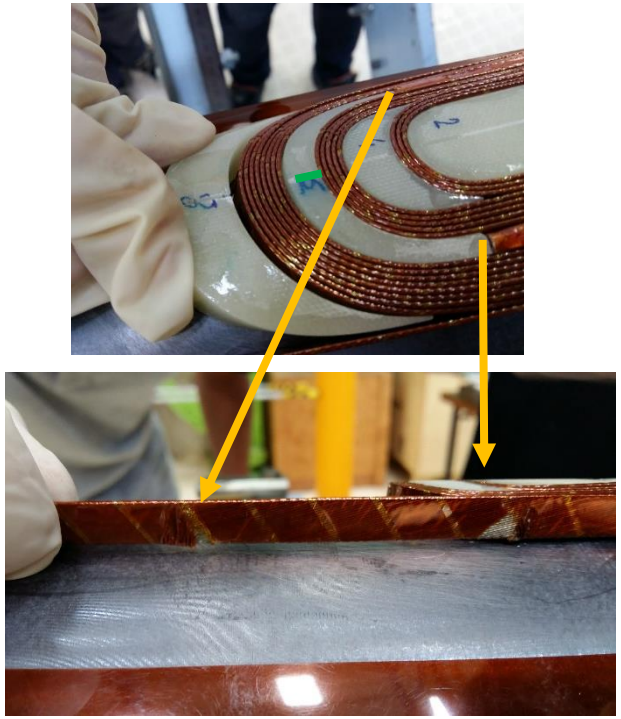


Electrical test and shipping

COIL FABRICATION LESSONS LEARNED

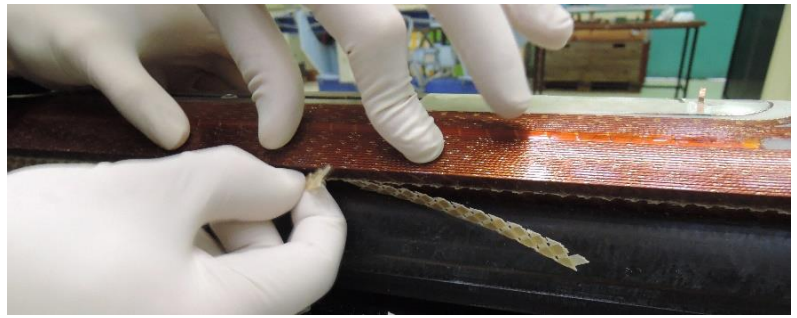
COIL 1

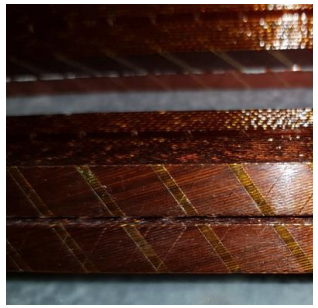
Slit in some of the spacers to give them flexibility, filled with G10 pieces before polymerization

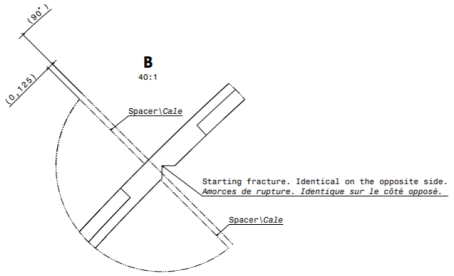


COIL 5

Damage of the interlayer insulation after fabrication during the cuting of the insulation

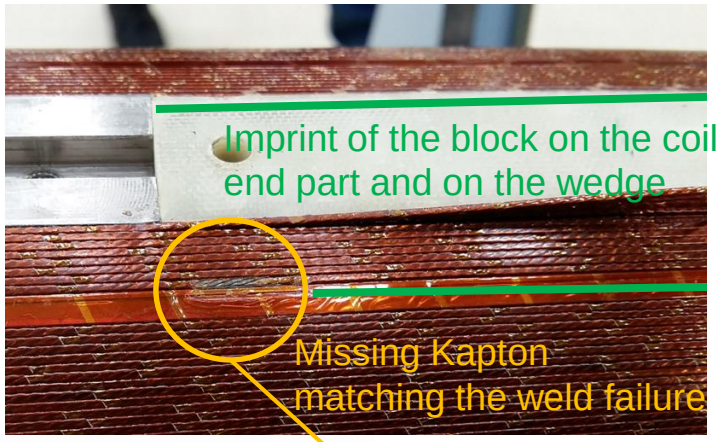


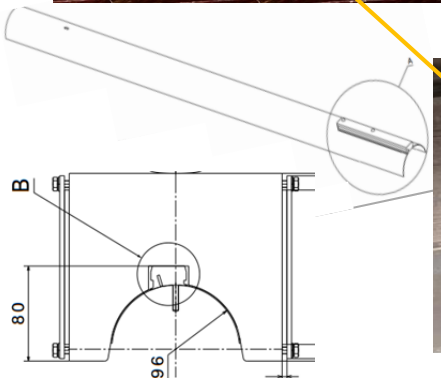


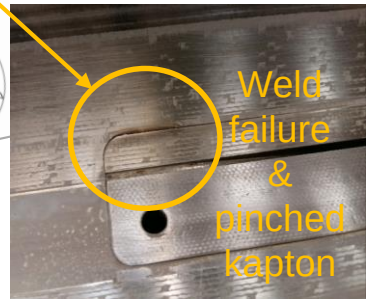


COIL 7

Issue on insulation encountered after the IL curing sheet removal:







COIL FABRICATION LESSONS LEARNED

COIL 1

Slit in some of the spacers to give them flexibility, filled with G10 pieces before polymerization

COIL 5

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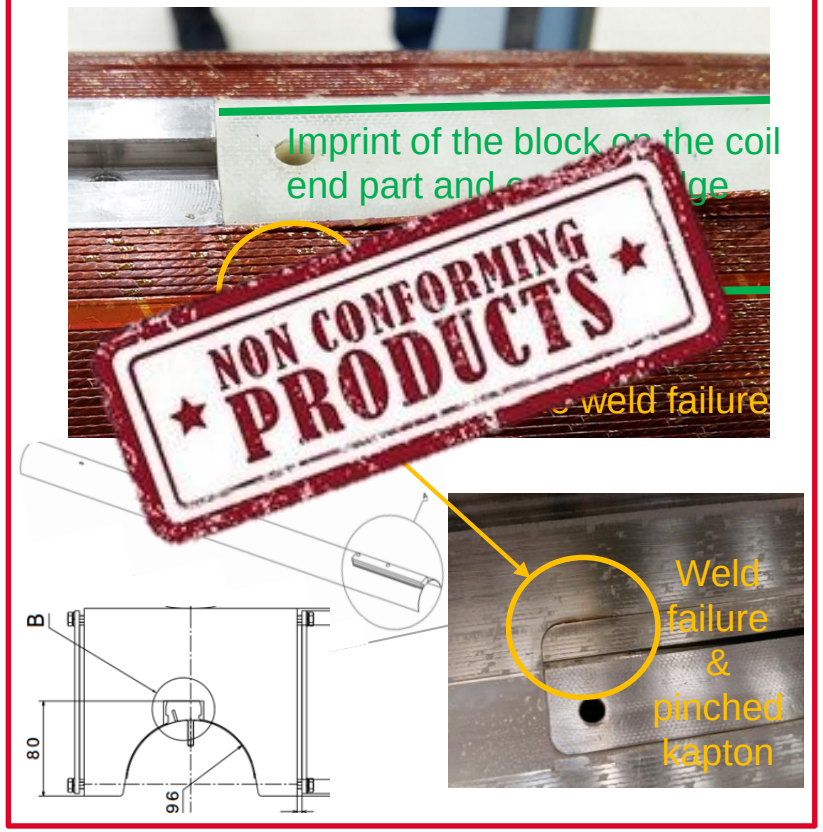
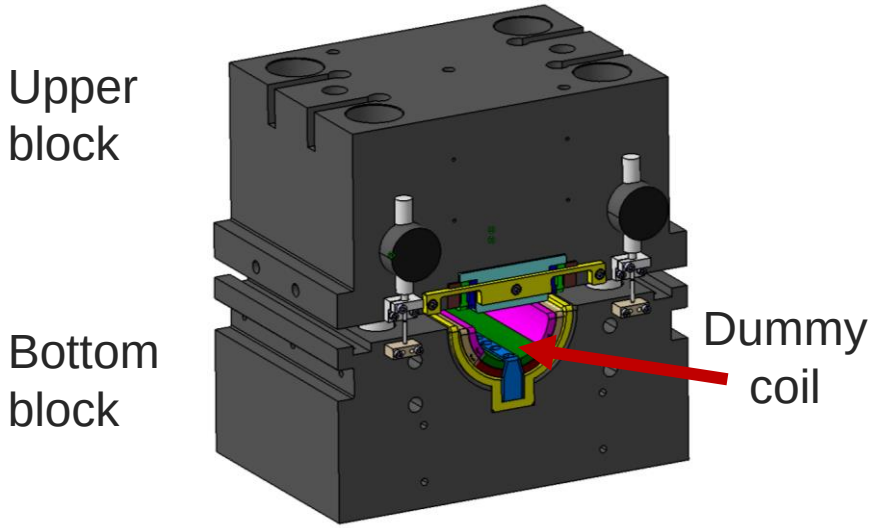
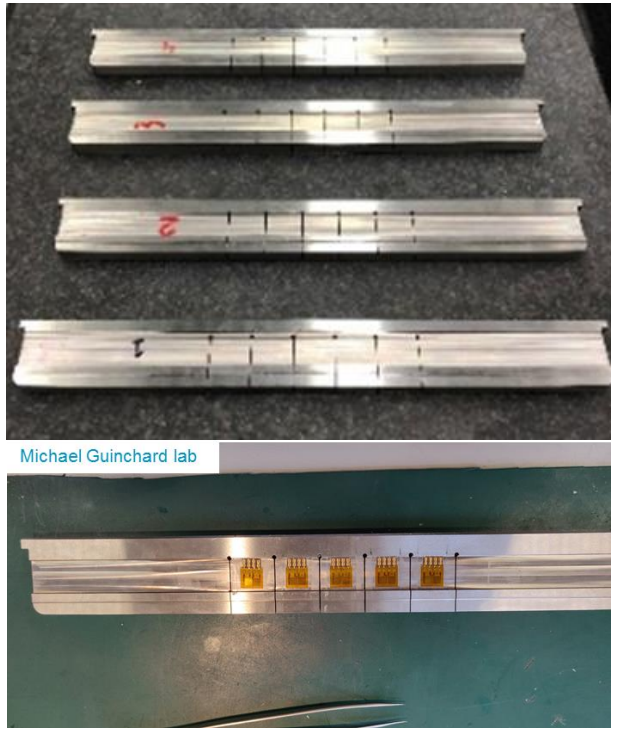
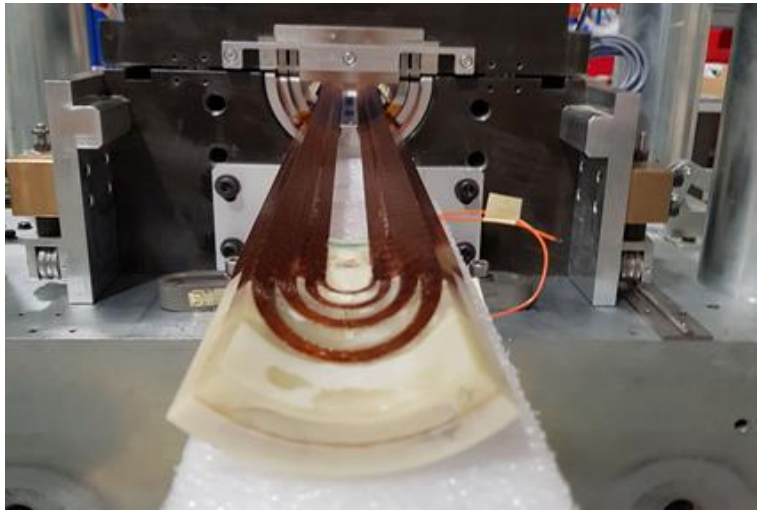


COIL MECHANICAL MEASUREMENTS

- Check the coils size to adjust the coils preload after collaring (at CERN)
- General Procedure [7][8]:
  - Define the coil nominal size (using the stainless steel dummy coils)
  - Press the coil on the E modulus press until the nominal coil size





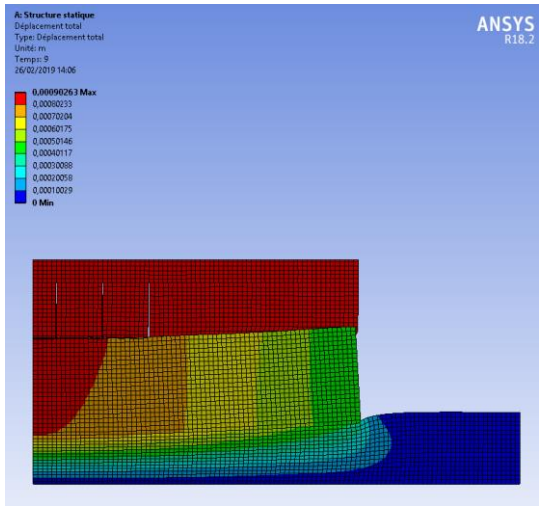


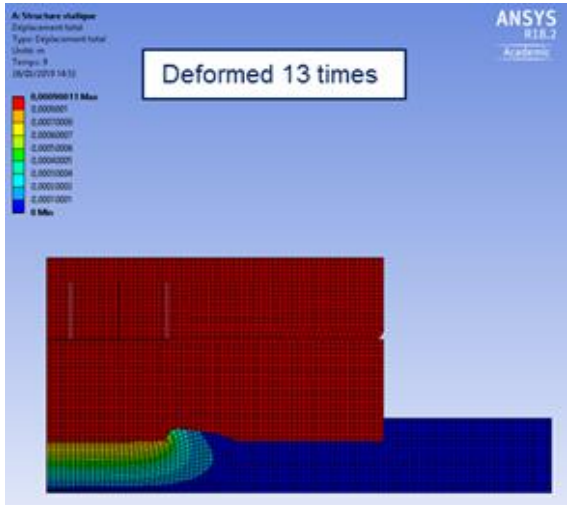
E-modulus press in CERN 927

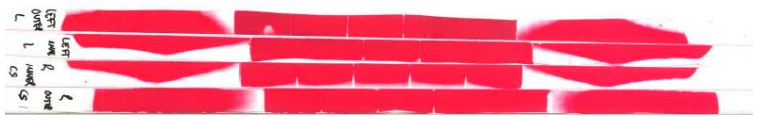
[7] G.A. Kirby et al, “Engineering design and manufacturing challenges for a wide-aperture superconducting quadrupole magnet”
[8] J.L Rudeiros et al, “Mechanical characterization of Nb3Sn impregnated coils – Compression properties”

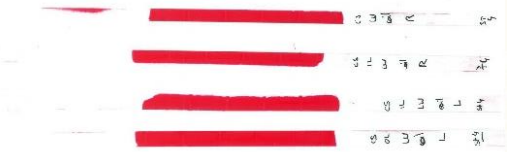
COIL MECHANICAL MEASUREMENTS

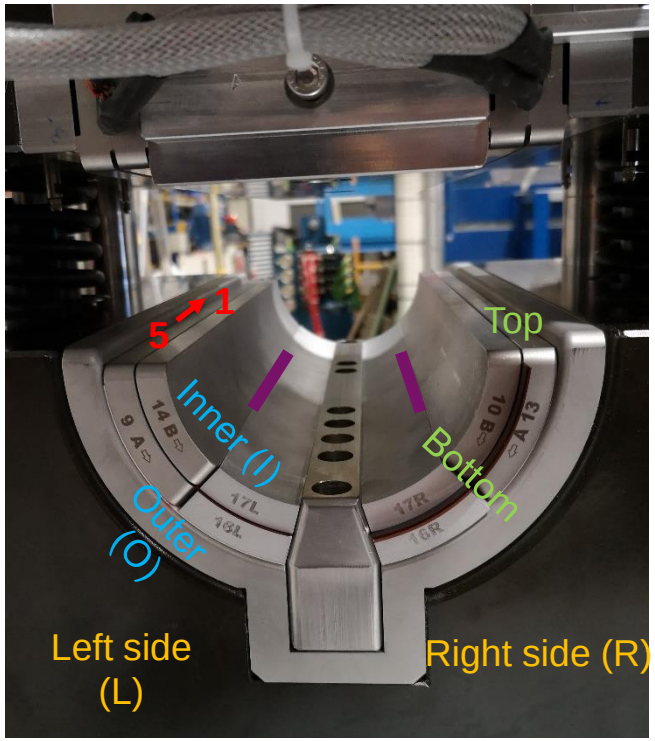
- Both model and Fuji observation show a longer contact zone than expected (due to softness of the coil)
- Thick shims to explore collaring stress for the practice coils
- Real coils tested at lower stress to check consistency and to avoid insulation damage



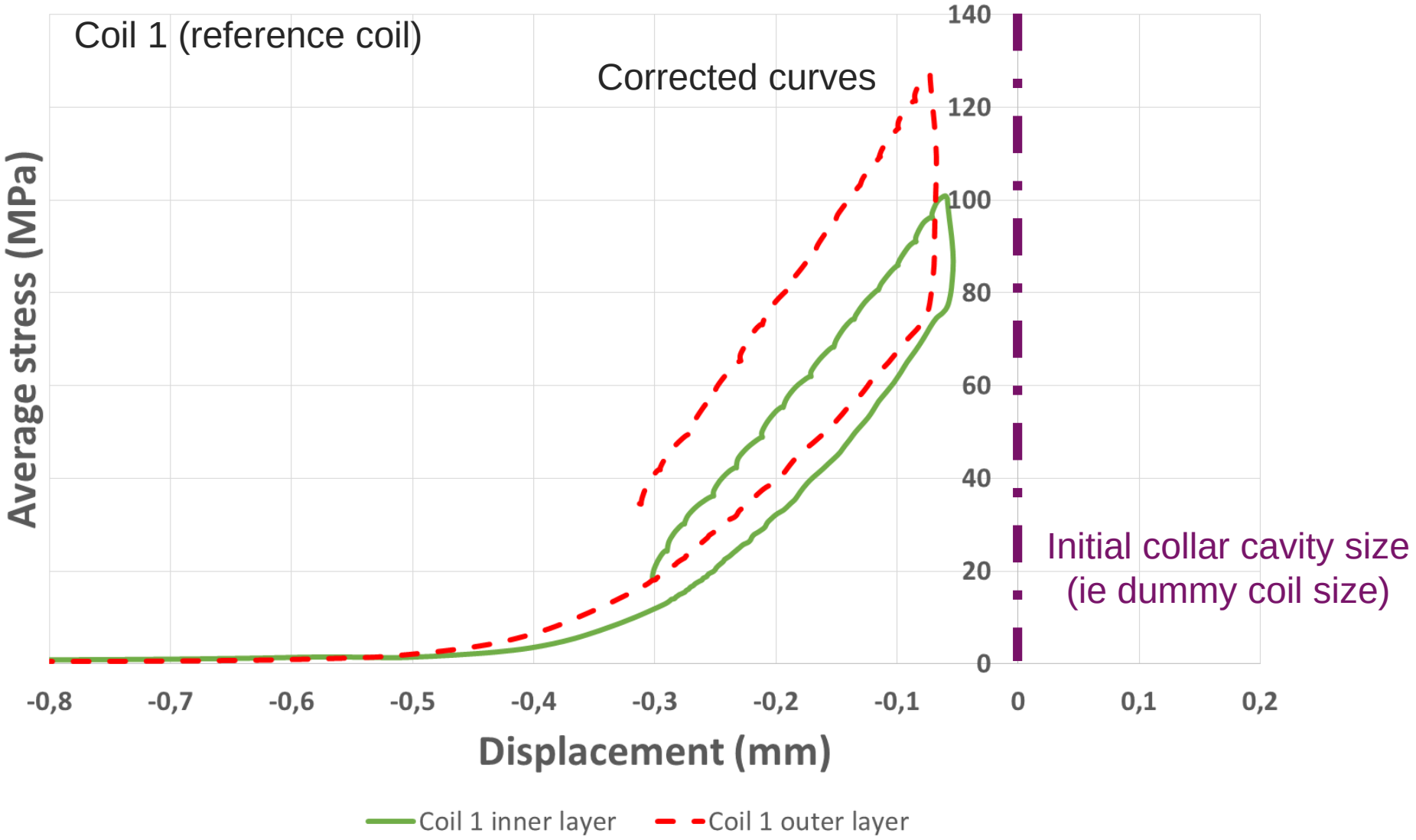




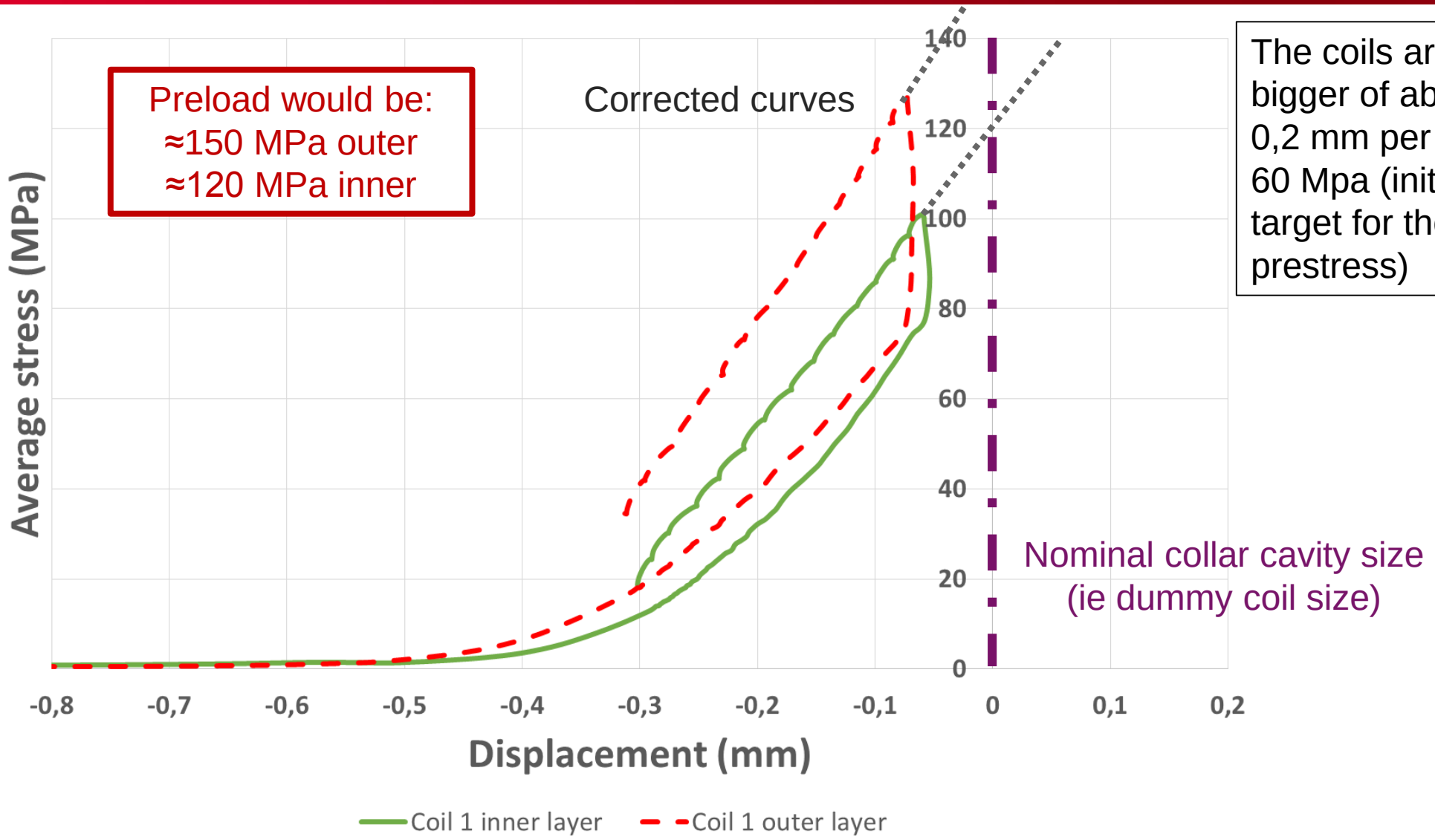




COIL MECHANICAL MEASUREMENTS



COIL MECHANICAL MEASUREMENTS



The coils are bigger of about 0,2 mm per legs at 60 Mpa (initial target for the prestress)

COIL MECHANICAL MEASUREMENTS

Fabrication error:

Azimuthal:

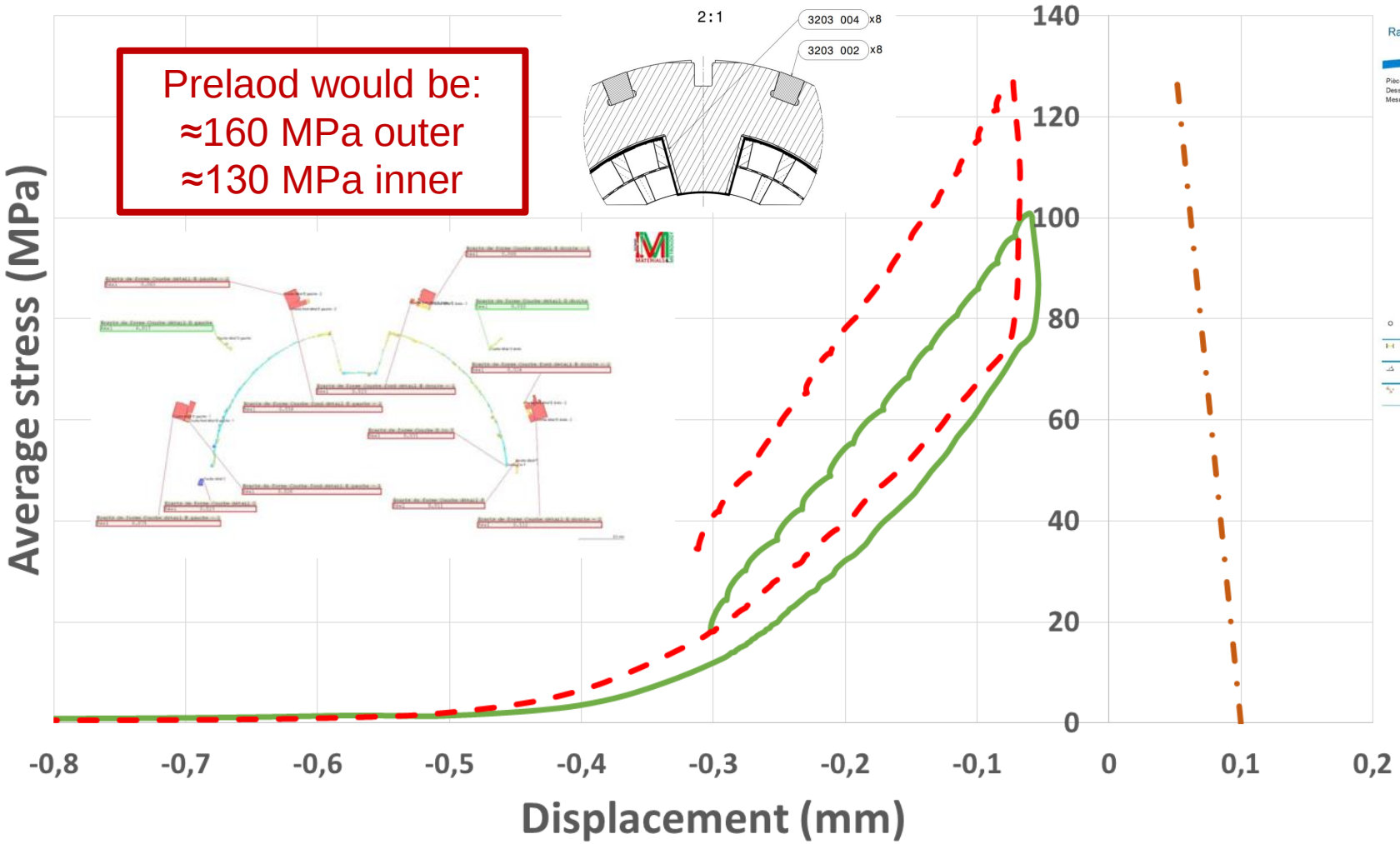
- Keys: +20 µm
- Collars nose: -10 µm
- Collars slot for keys: +70 µm
- Protection sheets: -20 µm

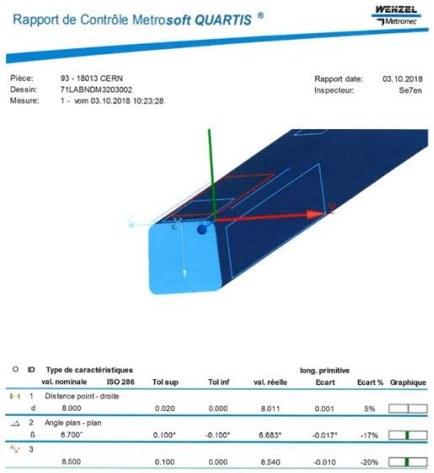
Radial:

- Collaring Shoe: +20 µm
- QH: +40 µm

Total azimuthal: Cavity smaller by +100 µm

Prelaod would be:
≈160 MPa outer
≈130 MPa inner





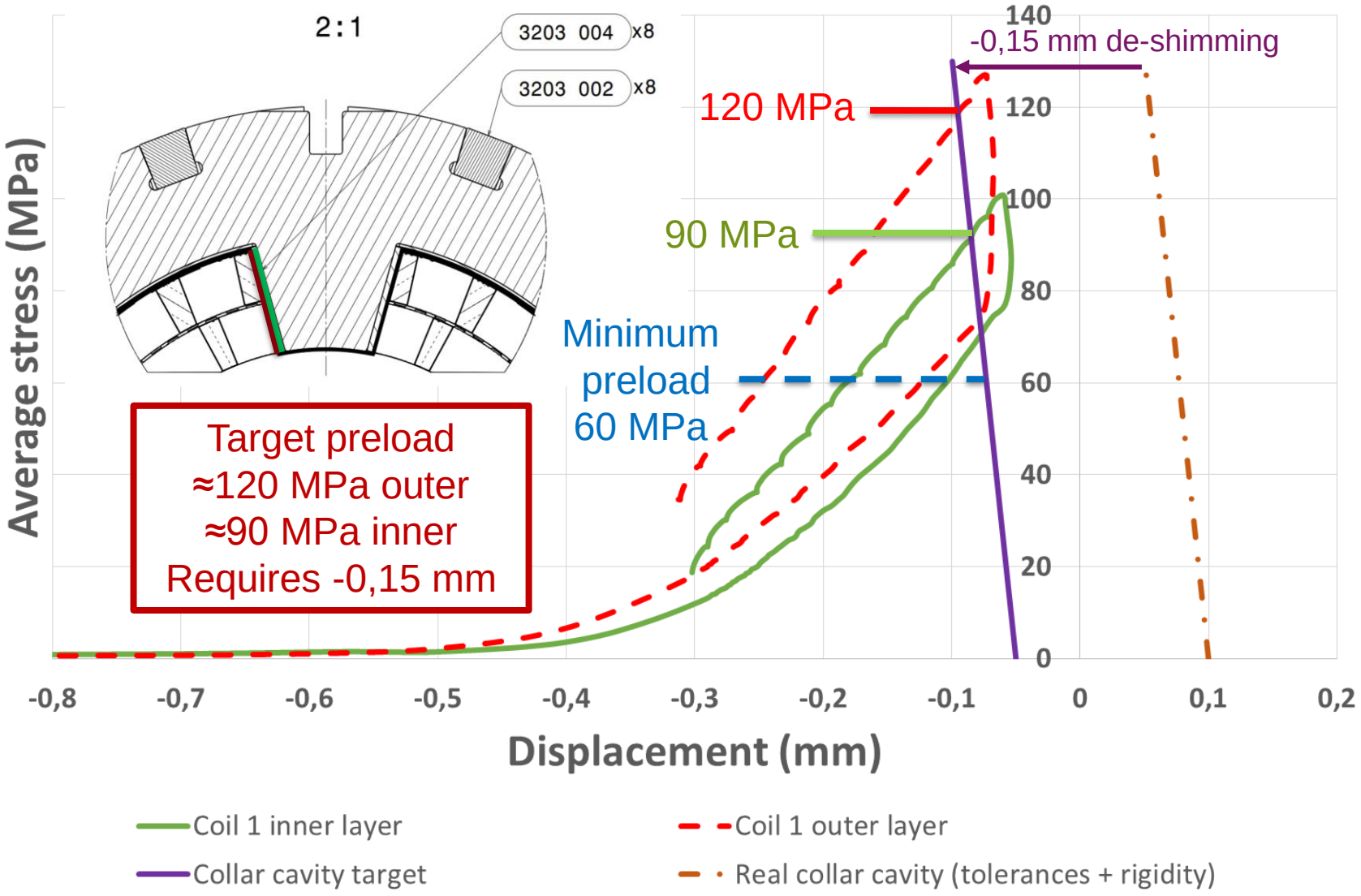
Unfavorable components tolerance build-up increase the stress in the coils
=> Need for a mitigation plan

Coil 1 inner layer — Coil 1 outer layer — Real collar cavity (tolerances + rigidity)

COIL MECHANICAL MEASUREMENTS

De-Shimming plan proposal by acting on protection sheet to decrease the prestress range to 90 to 120 Mpa

Replace the 316 LN **1 mm** thick azimuthal protective plate by 304 L **0,6 mm** thick plate with **0.2 mm** or **0.3 mm** kapton shim

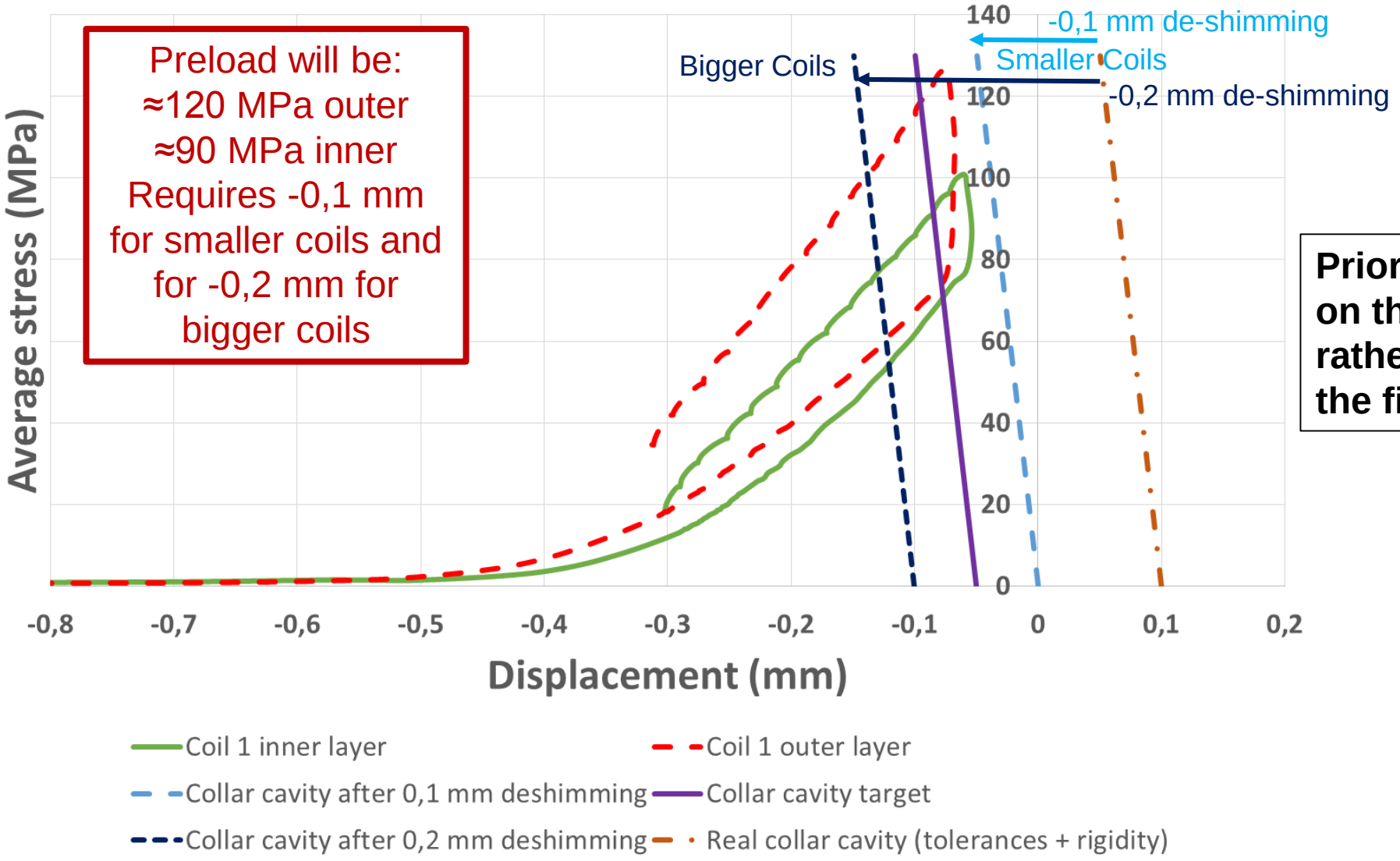


COIL MECHANICAL MEASUREMENTS

All the coils behave similarly

The dispersion between the coils is 0,1 mm

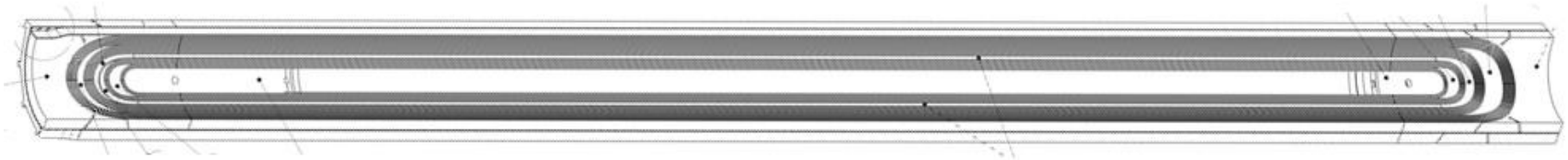
Preload will be:
≈120 MPa outer
≈90 MPa inner
Requires -0,1 mm for smaller coils and for -0,2 mm for bigger coils

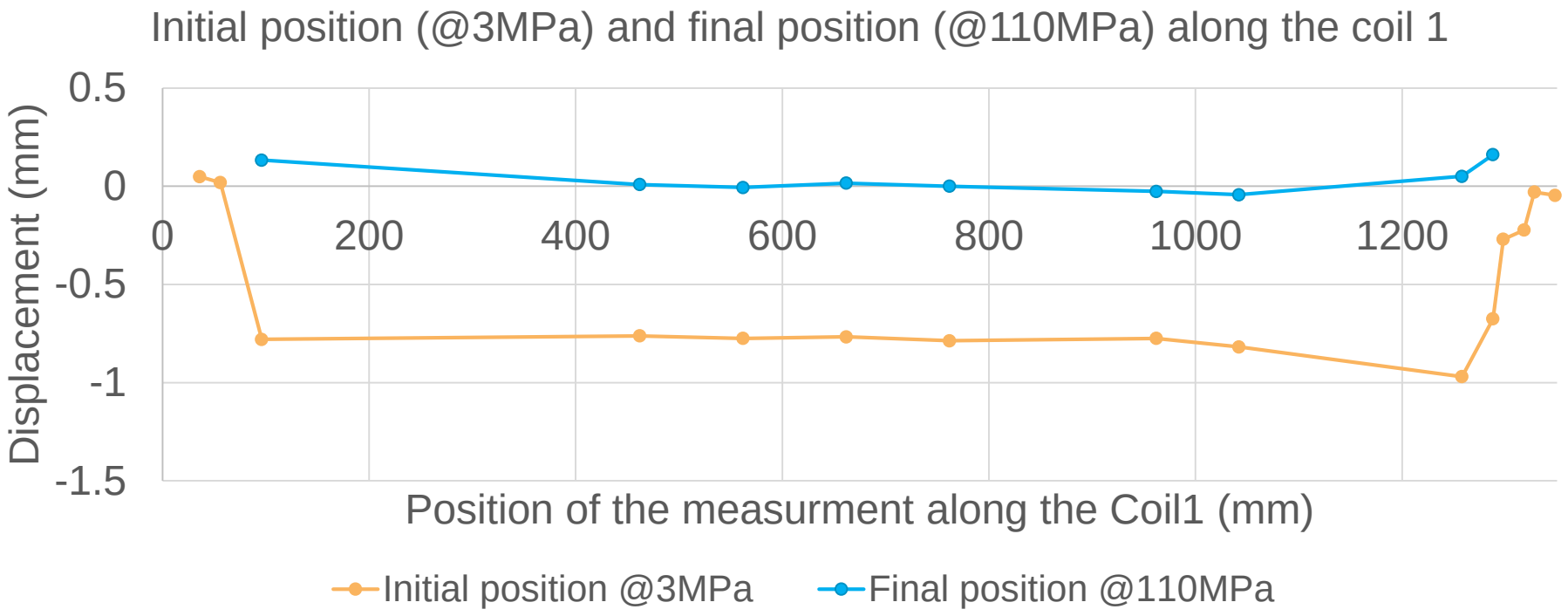


Priority placed on the prestress rather than on the field quality

COIL MECHANICAL MEASUREMENTS

Initial decision to not shim the ends





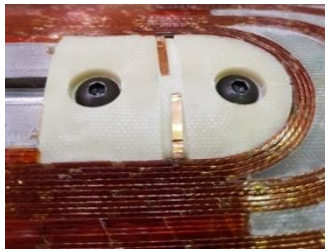
COIL MEASUREMENTS LESSONS LEARNED

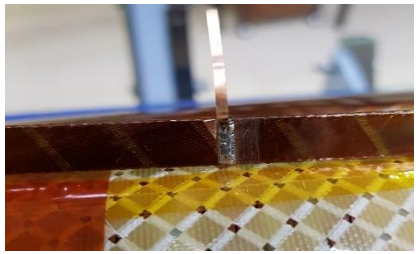
- The calibration of the E-modulus press is a long and painstaking process which need very precise parts
- The coil mechanical measurement has been done too late in the project
- Ideally to be done after the polymerization of the practice coil to adjust the polymerization cavity
- For a first model accept to degrade field quality to insure a proper prestress

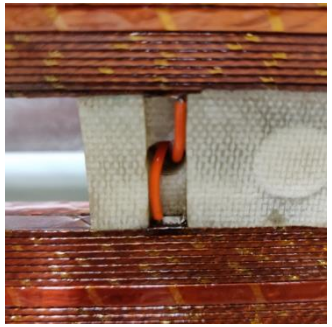
INSTRUMENTATION

Voltage taps

- Two different type of voltage taps (wire for the inner layer and copper flag for the outer layer)
- **First time that a magnet non-impregnated used PH and Vtaps with trace**

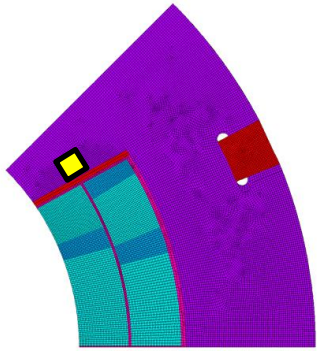


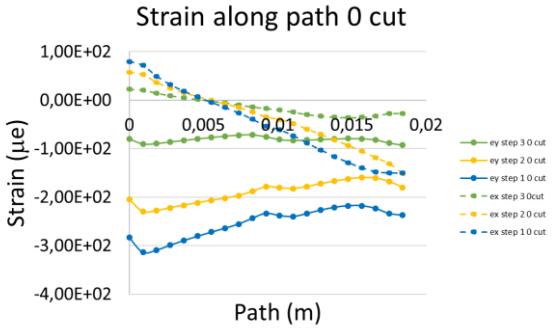


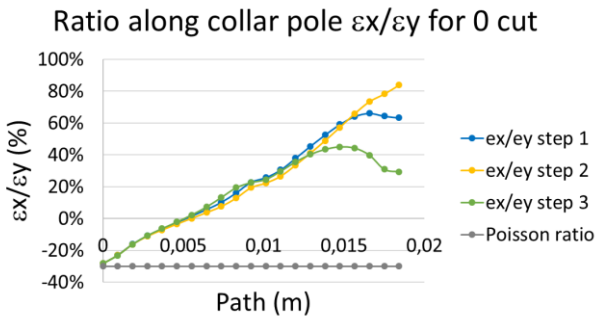


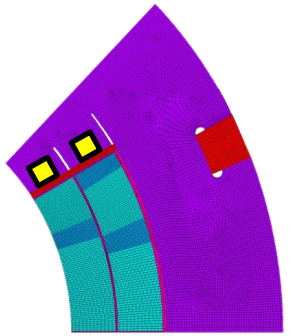
Strain gauges

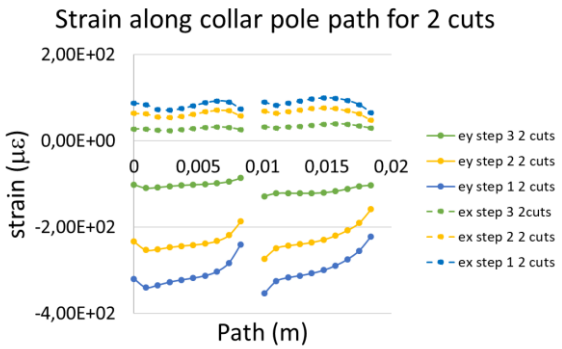
- Cancelation of the radial stress on the collar nose ie to have a ratio of -0,3 between the radial and azimuthal strain by adding wire cut

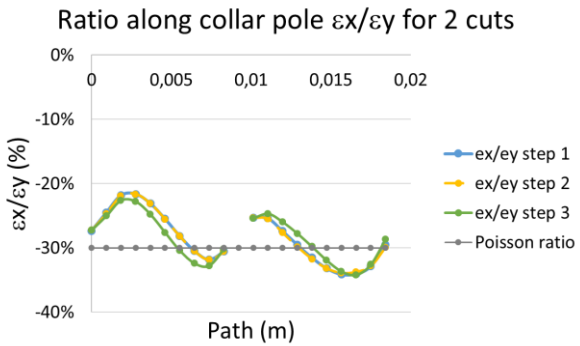












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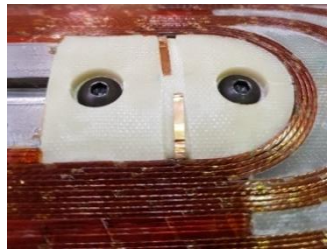
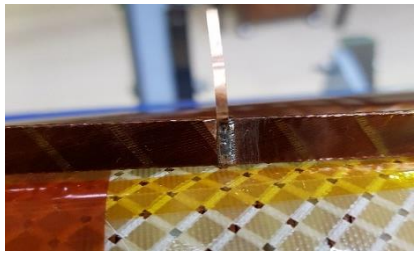
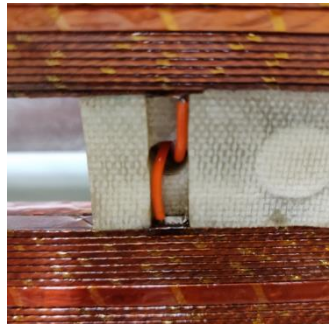
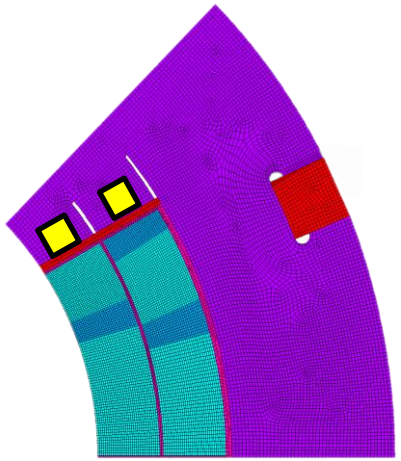


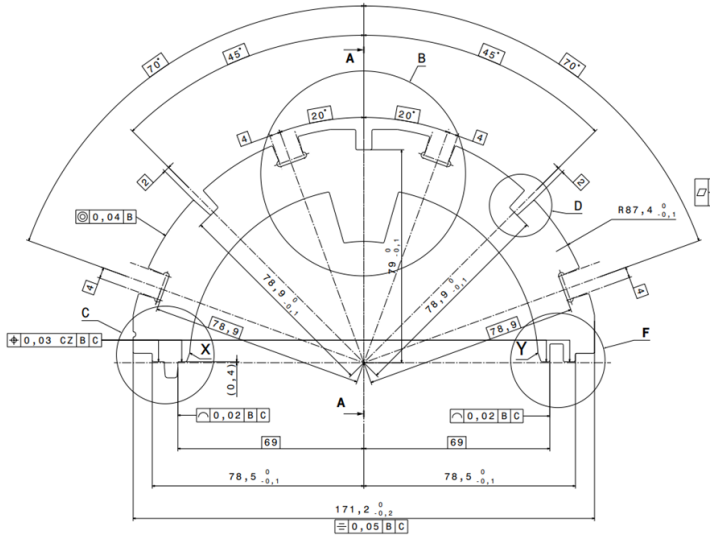


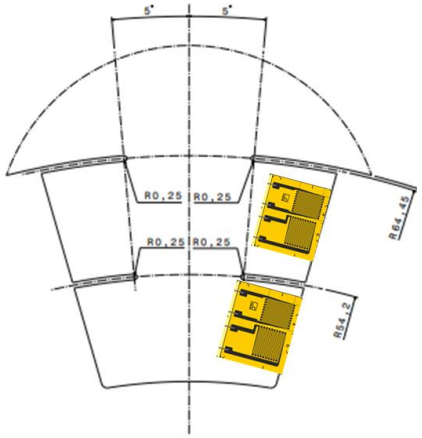


Strain gauges

- Cancelation of the radial stress on the collar nose ie to have a ratio of -0,3 between the radial and azimuthal strain by adding wire cut
- Cancelation of the collar nose bending by gluing strain gauges on the top and on the bottom of the collar nose
- Compensation of the thermal contraction by using bi-axial strain gauges







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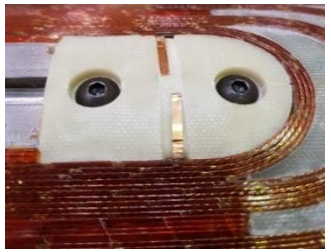

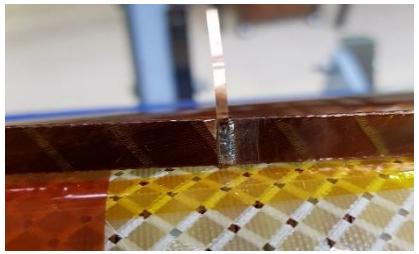

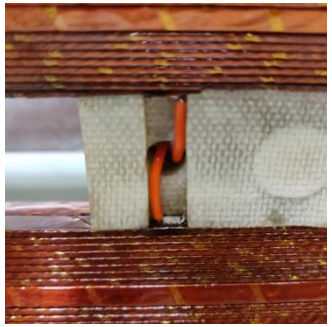

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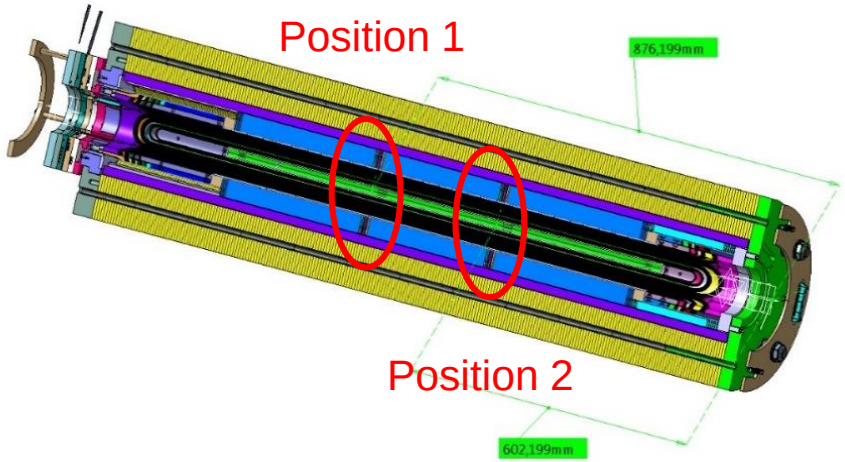
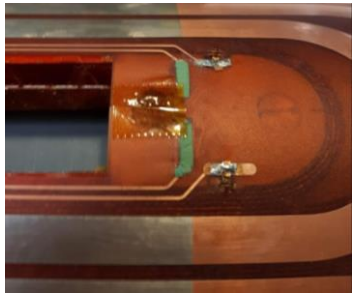
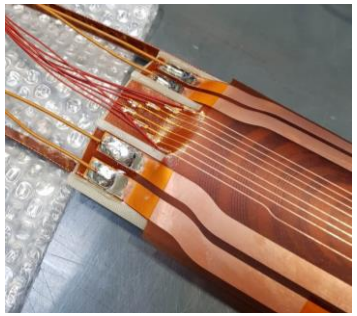
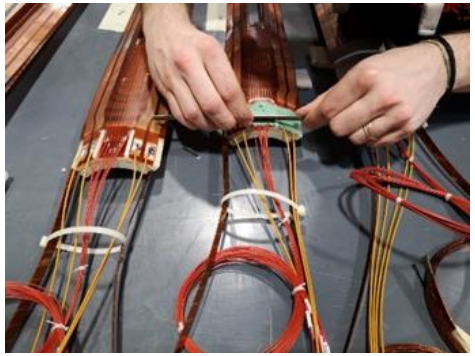


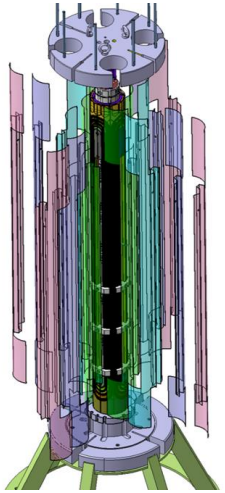
ASSEMBLY

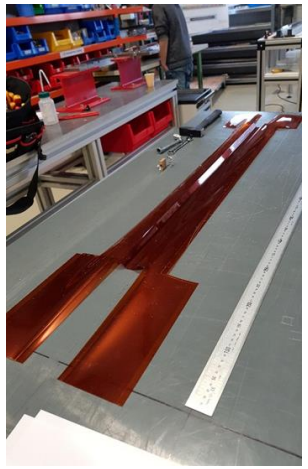
Coil instrumentation

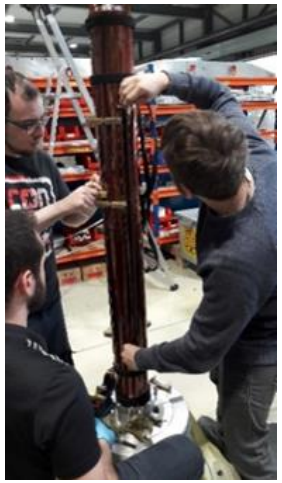


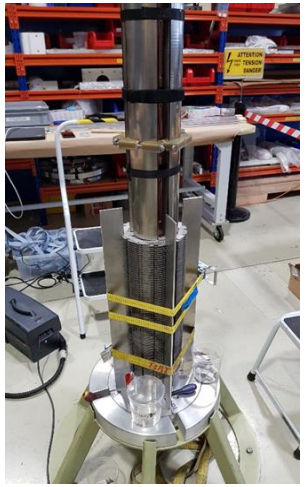
Ground plane insulation forming



Coils assembly and half-collars stacking

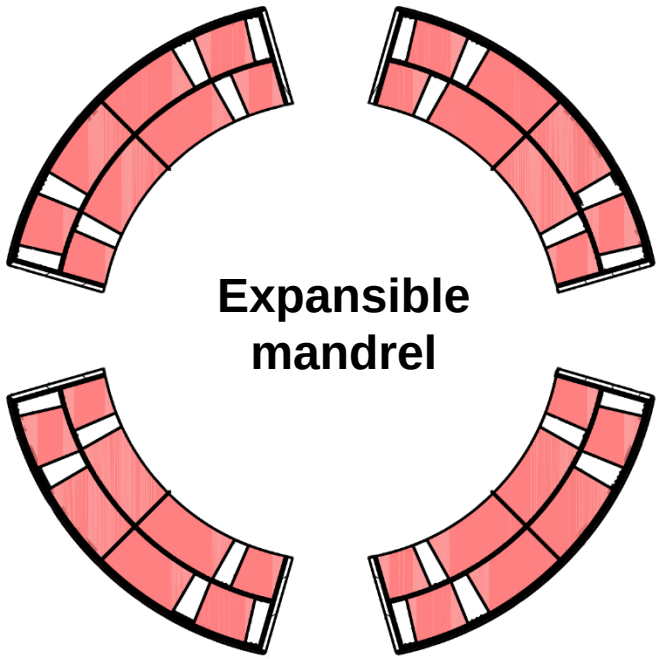



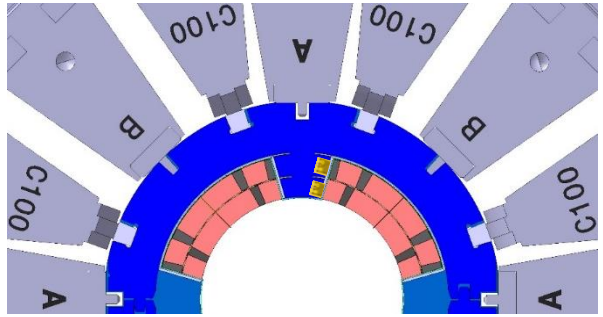


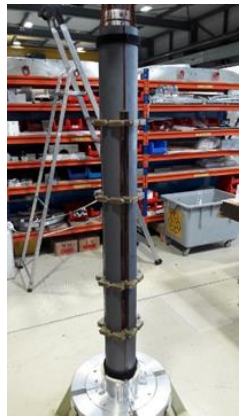
Electrical test


VERTICAL COLLARING PROCESS

- Collaring press with 16 jacks (4 jacks A, 4 jacks B and 8 jacks C for the collaring keys)
- Step 1: « Massaging » of the aperture by activing jack A in order to position correctly the collars
- Step 2: Activation of the jack A to open the key slot
- Step 3: Activation of the jack B to avoid the ovalization of the collar
- Step 4: Activation of the jack C to insert the collaring keys and limit the stress overshoot during collaring







Vertical press in CERN 927

VERTICAL COLLARING PROCESS

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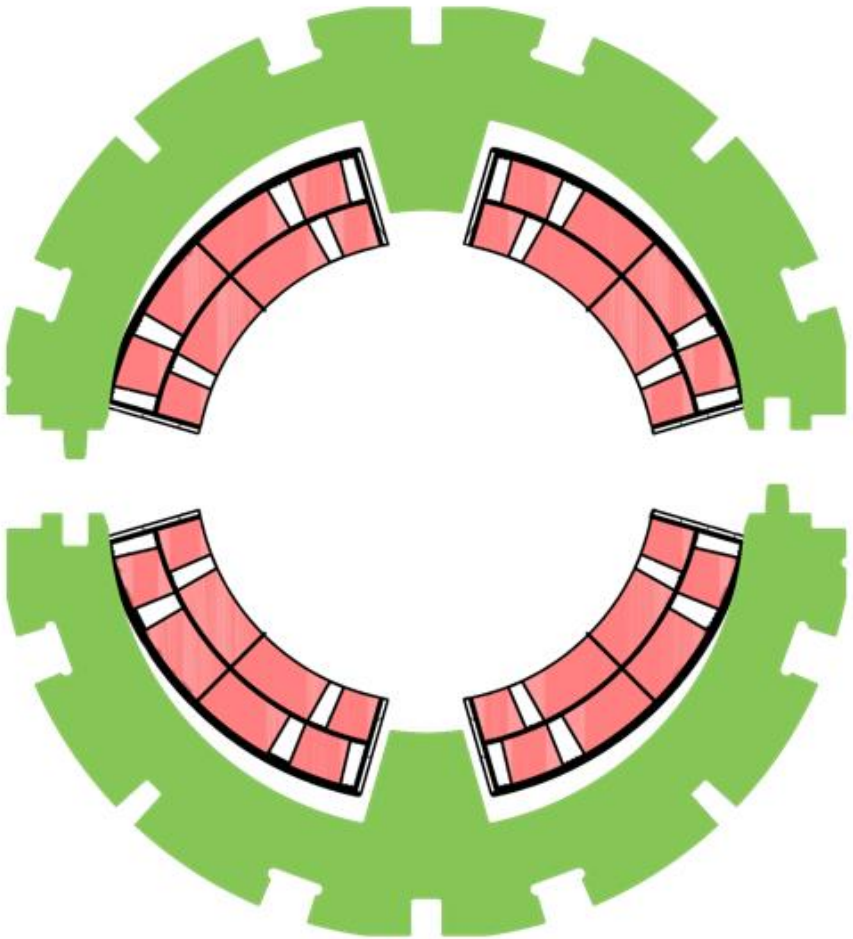

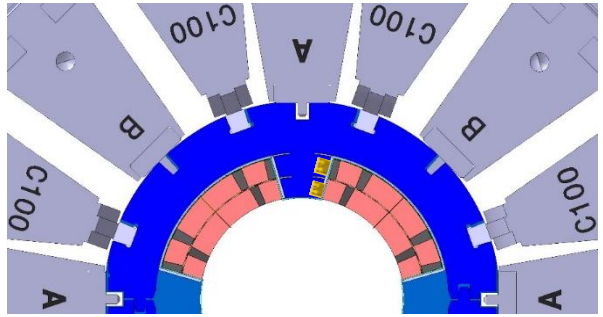

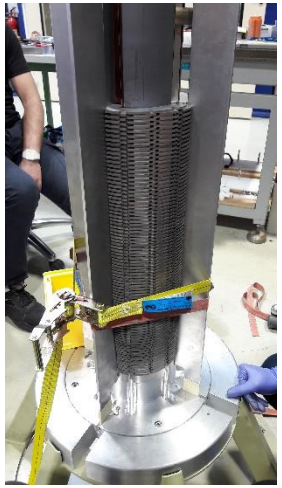

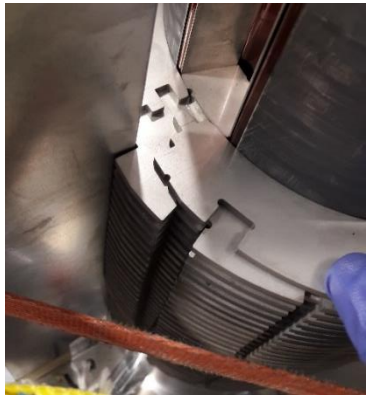

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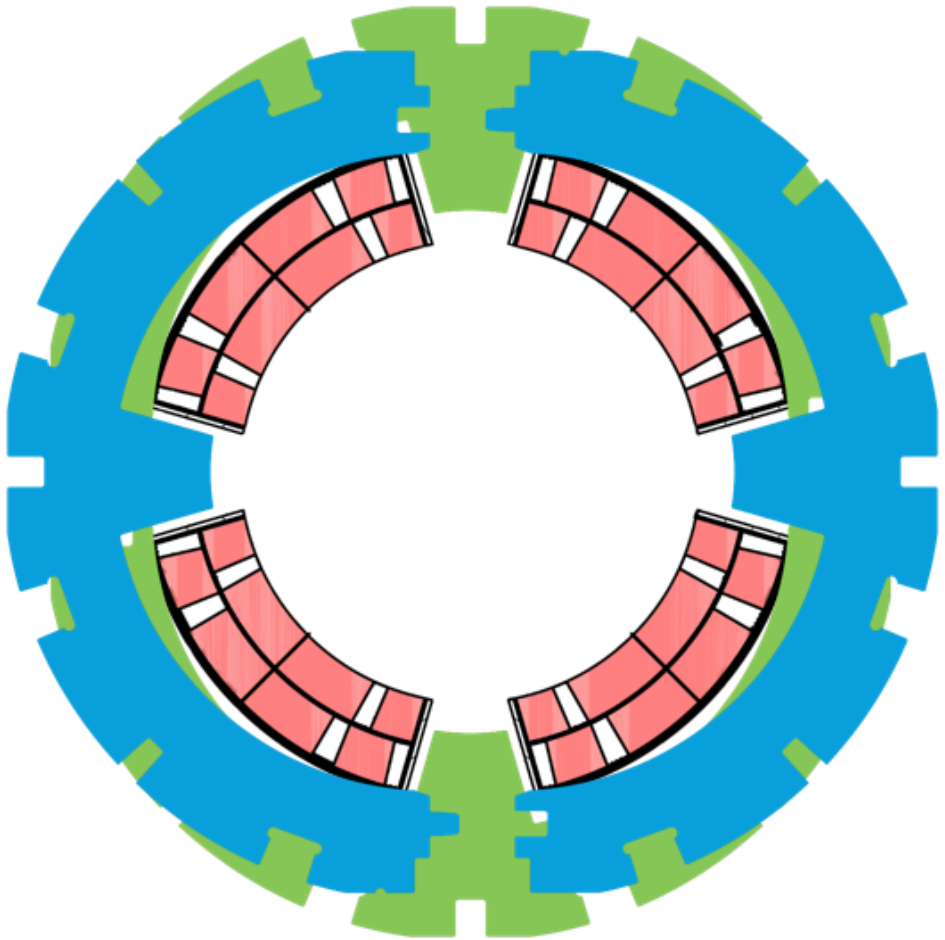

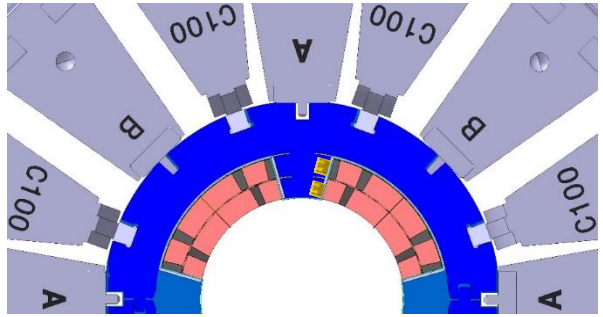

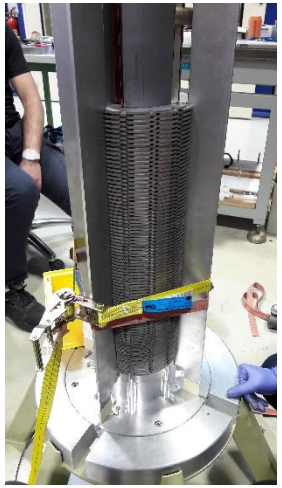

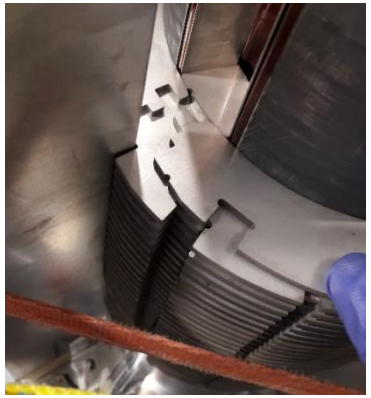

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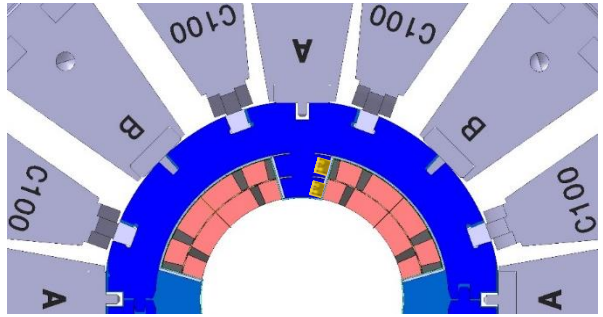

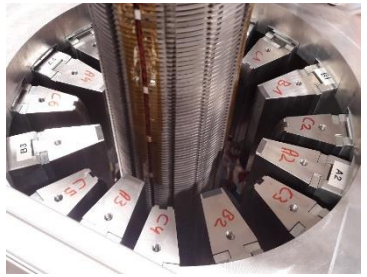

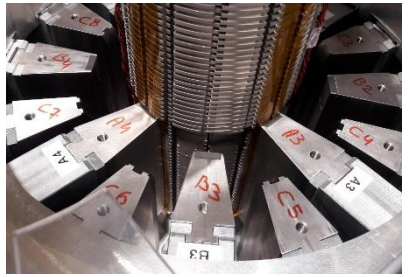

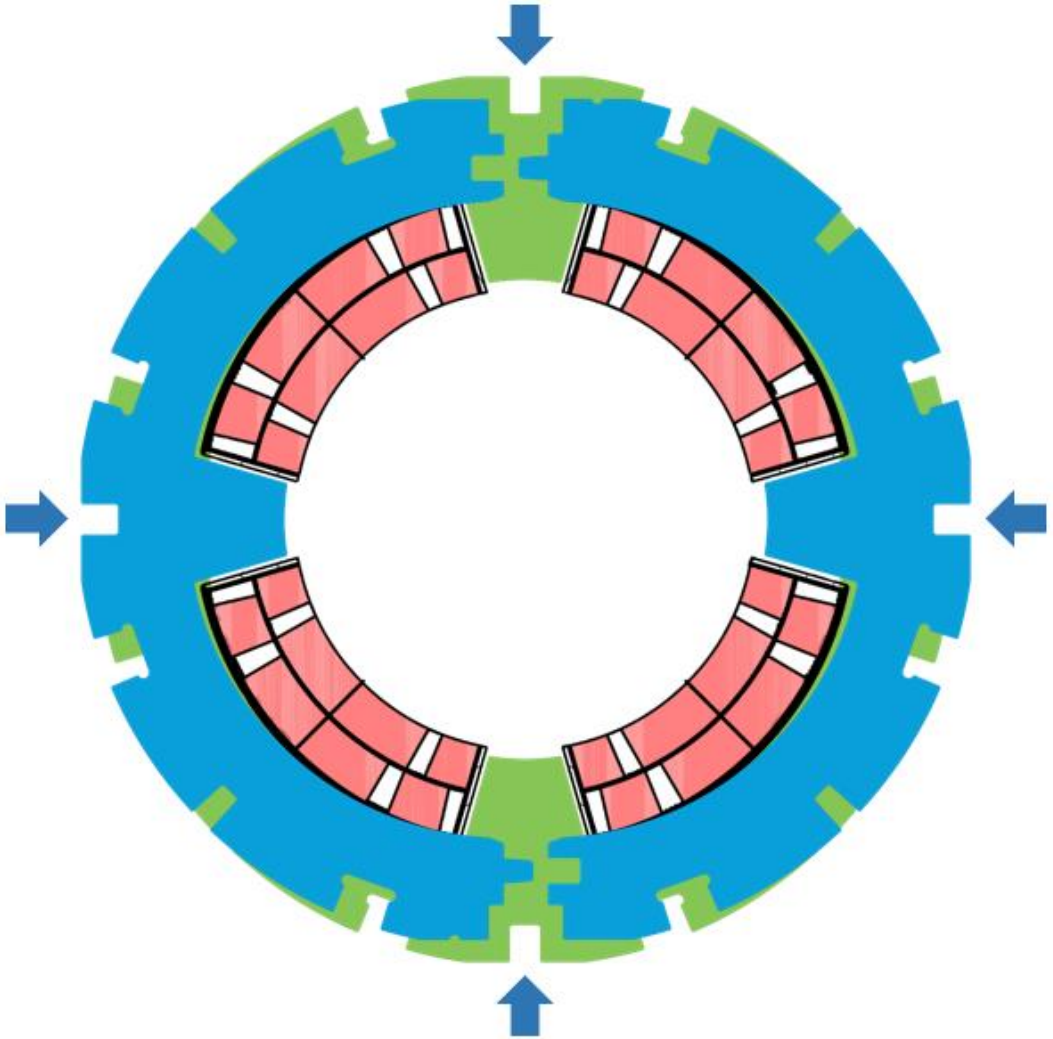

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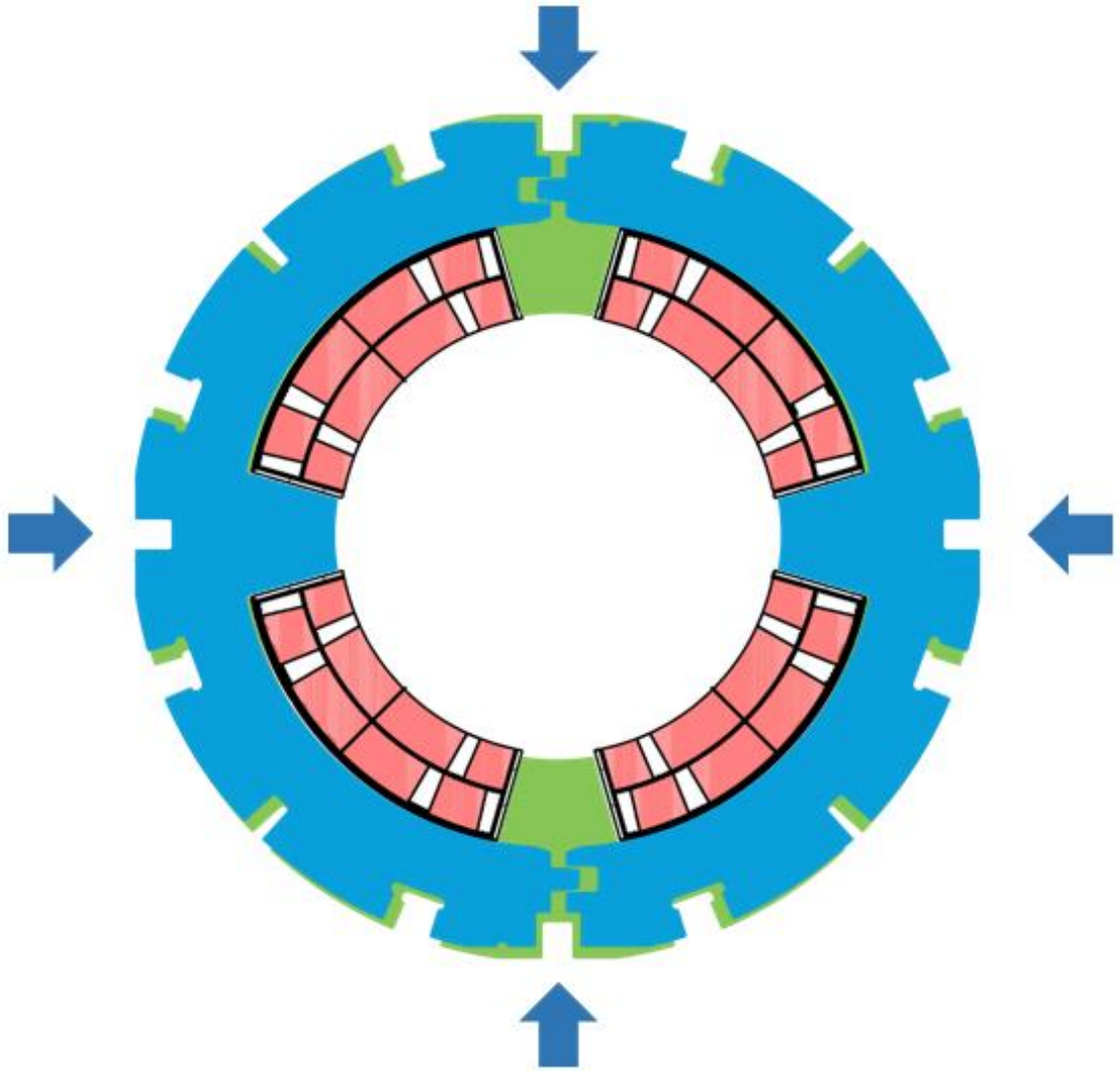

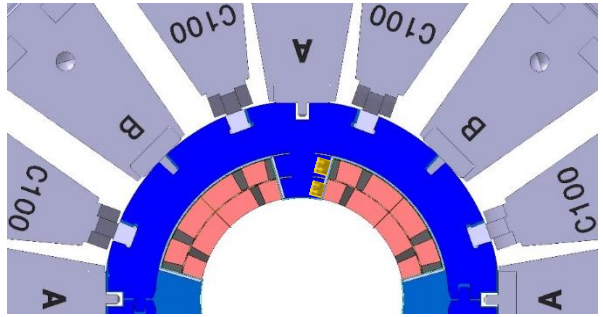

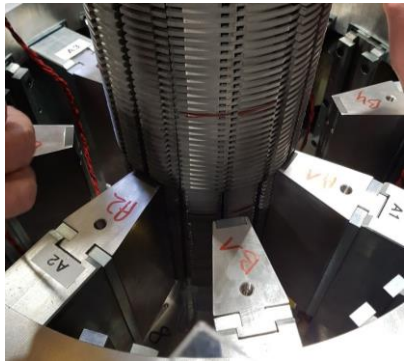

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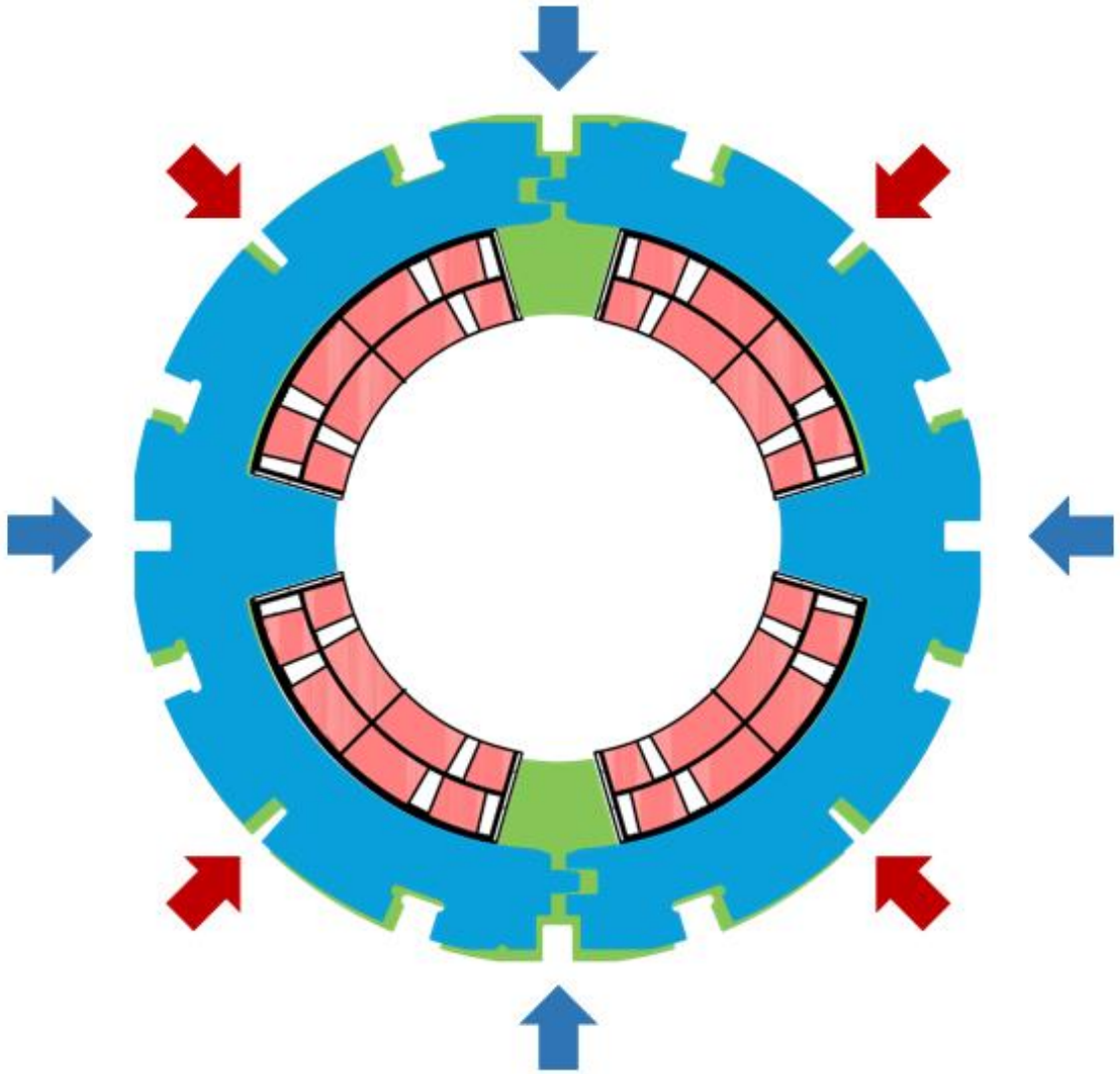

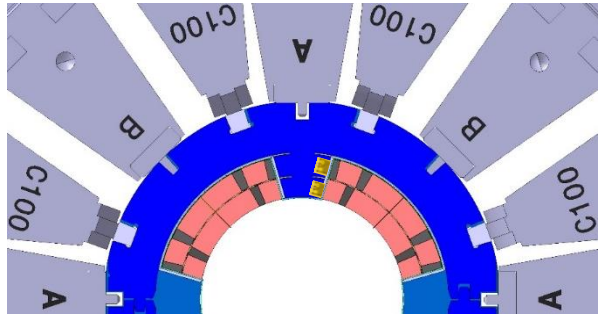

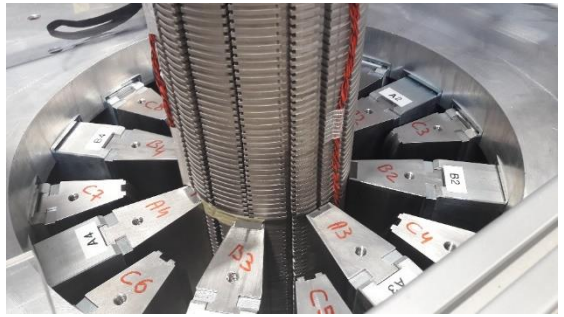

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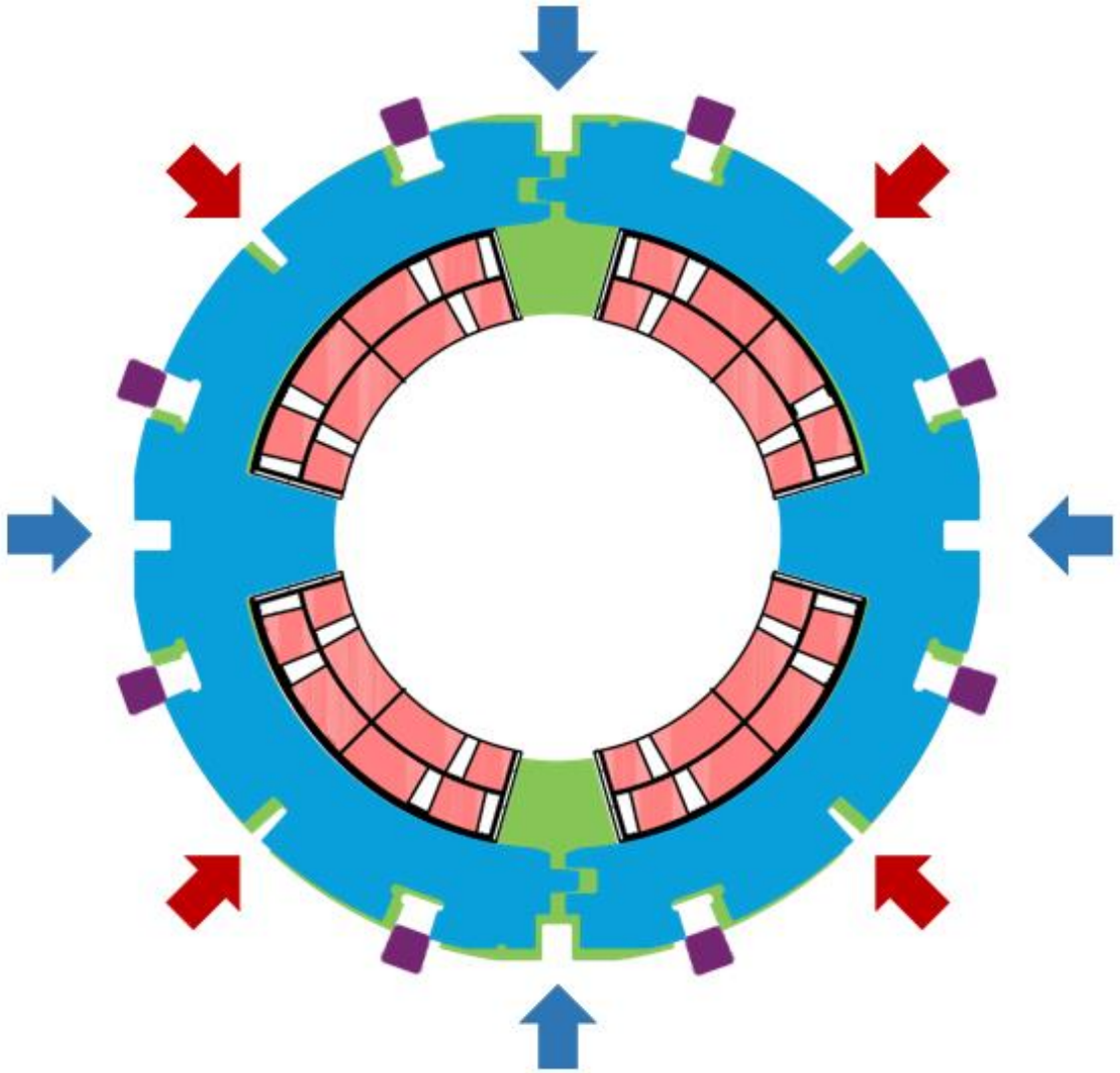

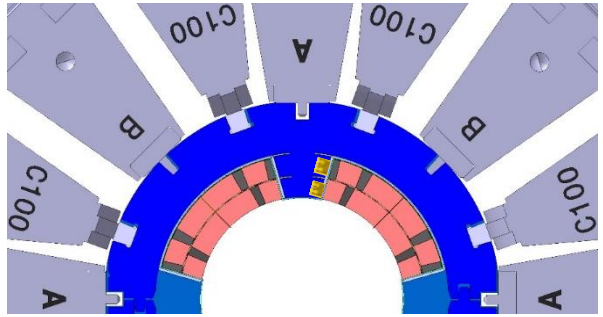

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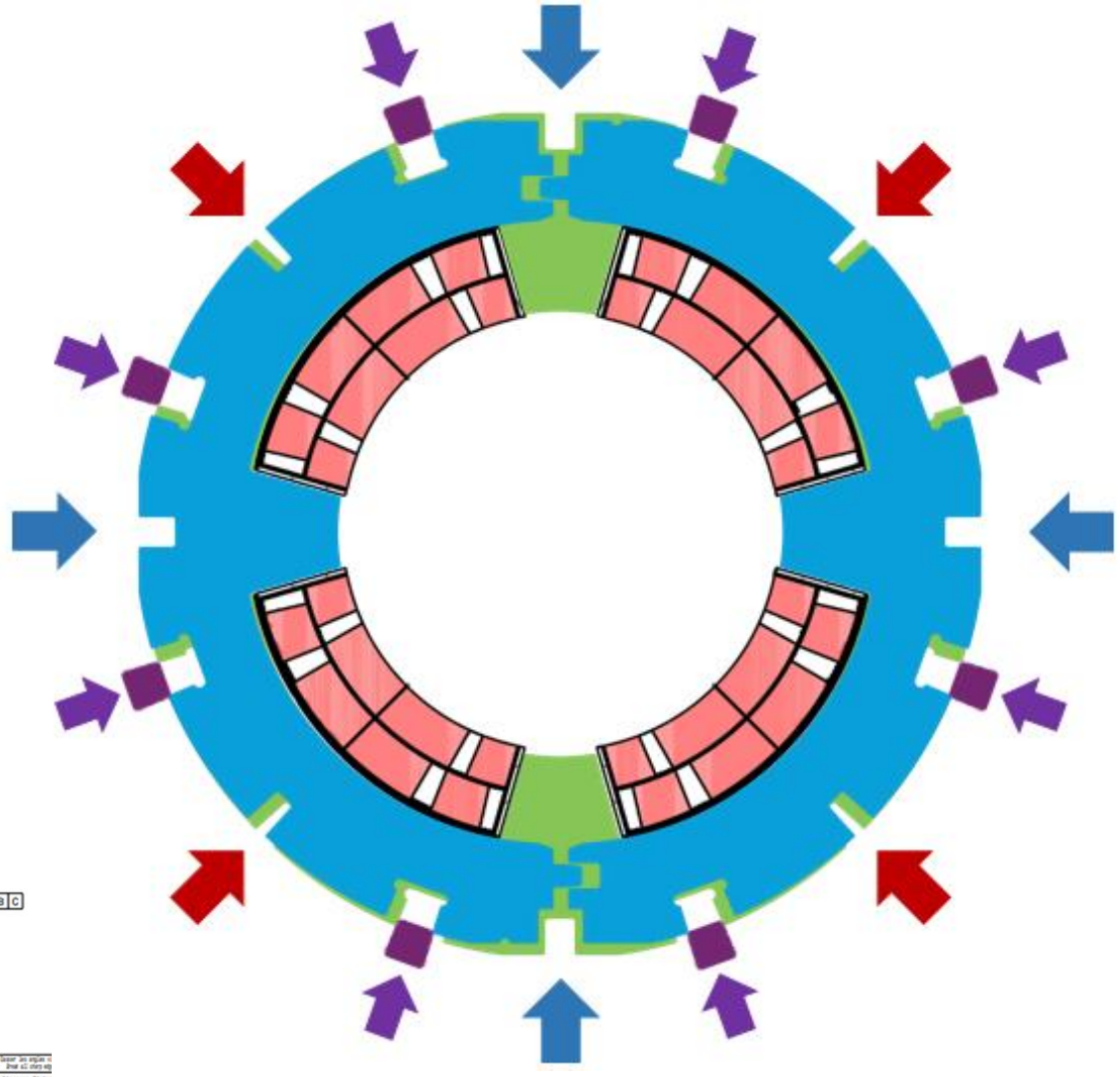

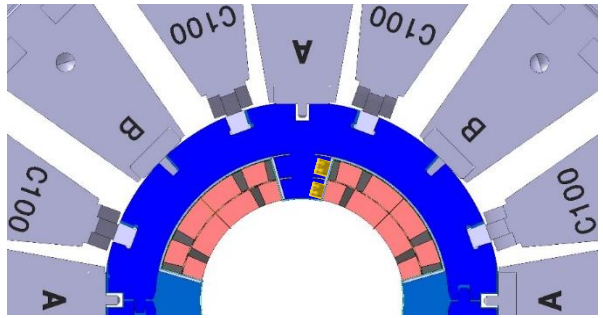

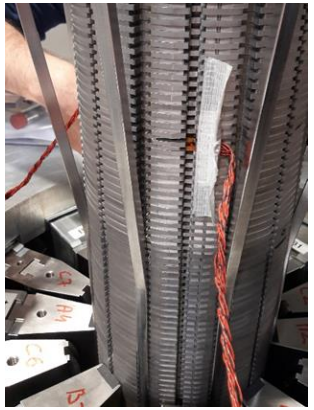

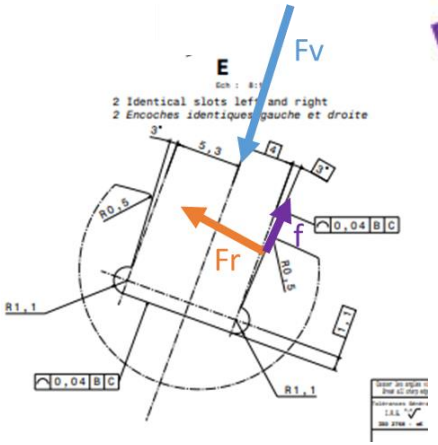

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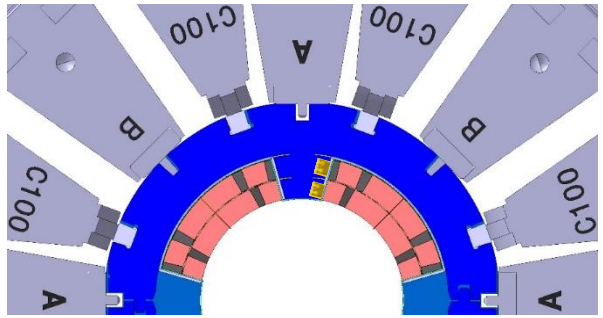

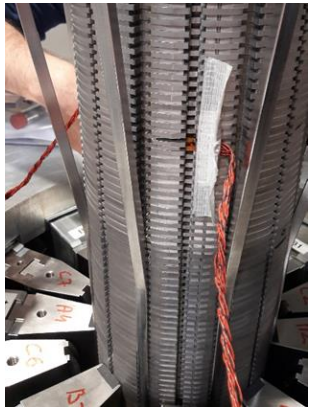

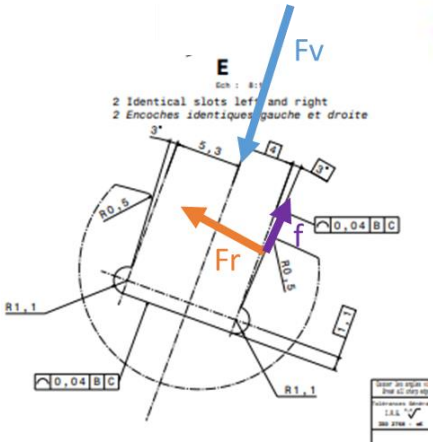

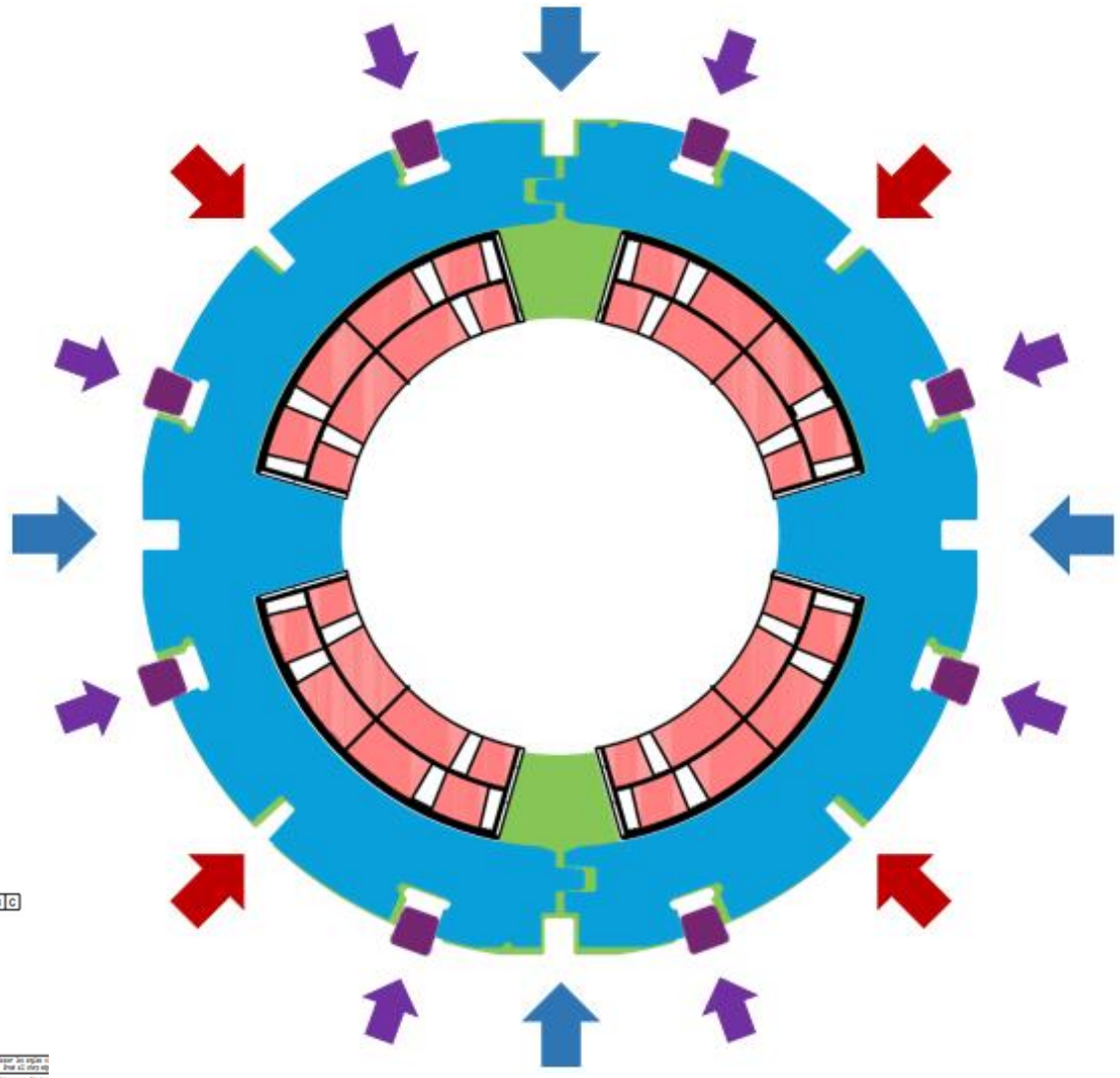

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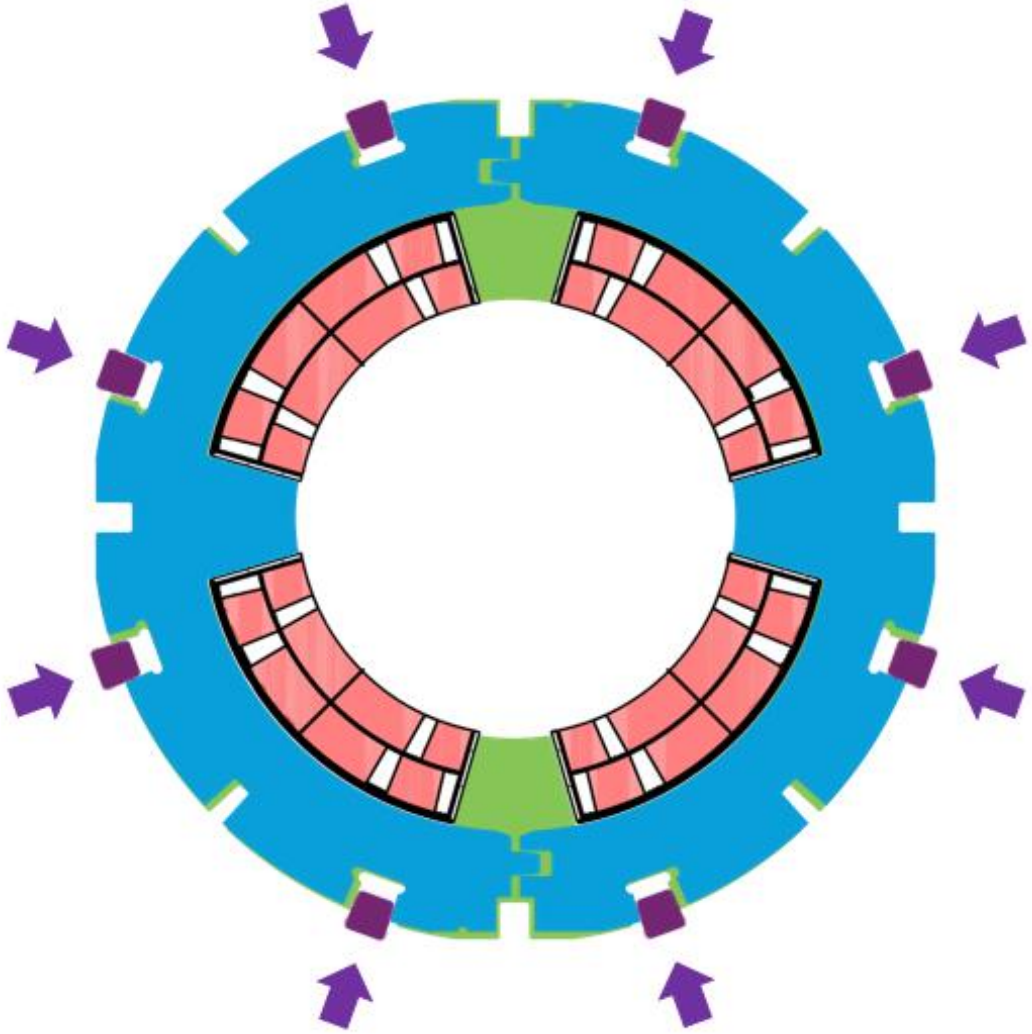

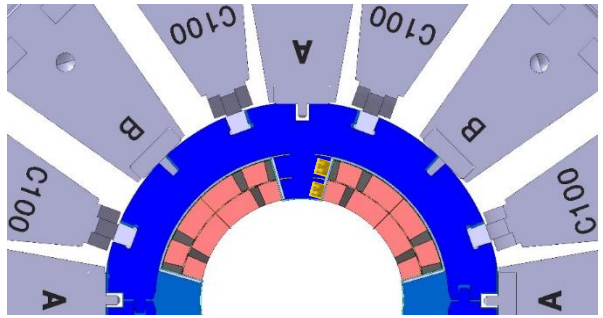

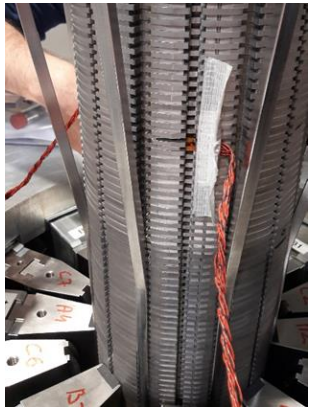

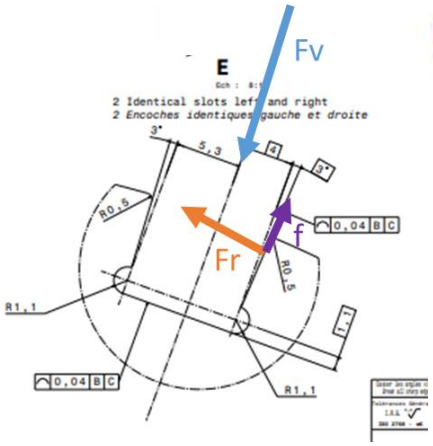

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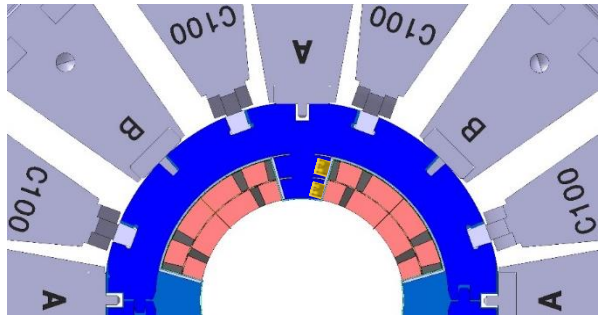
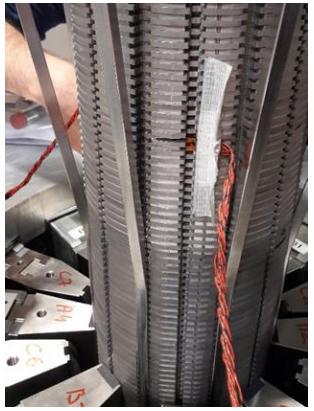
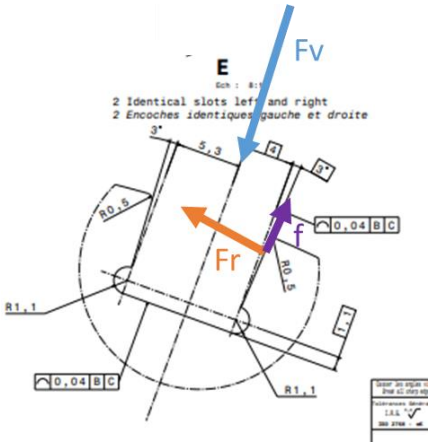
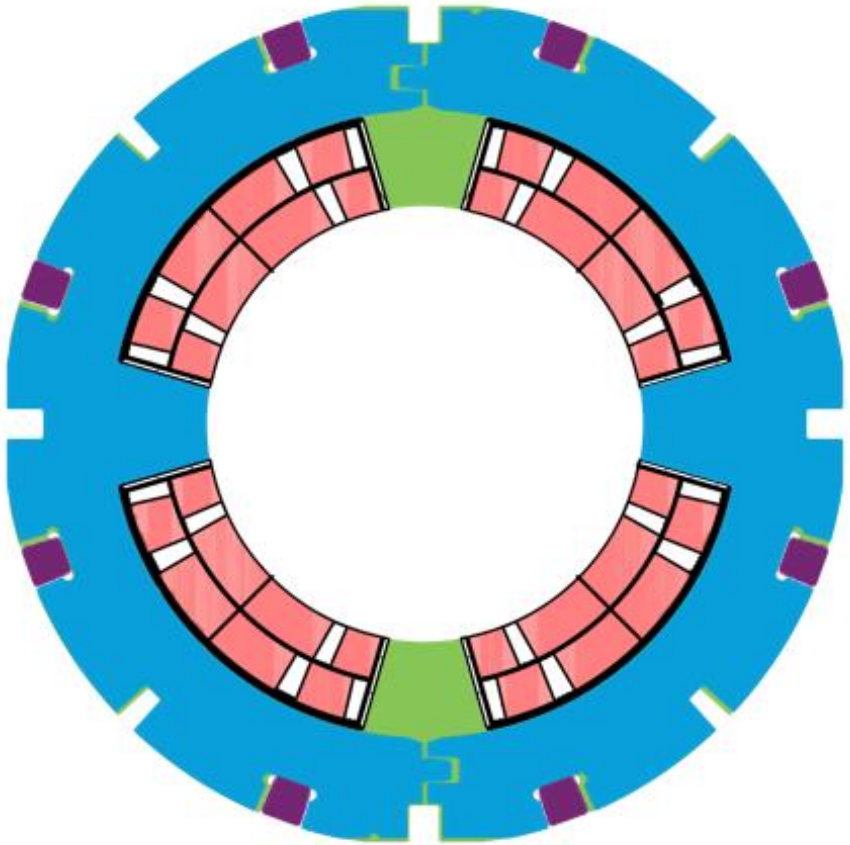




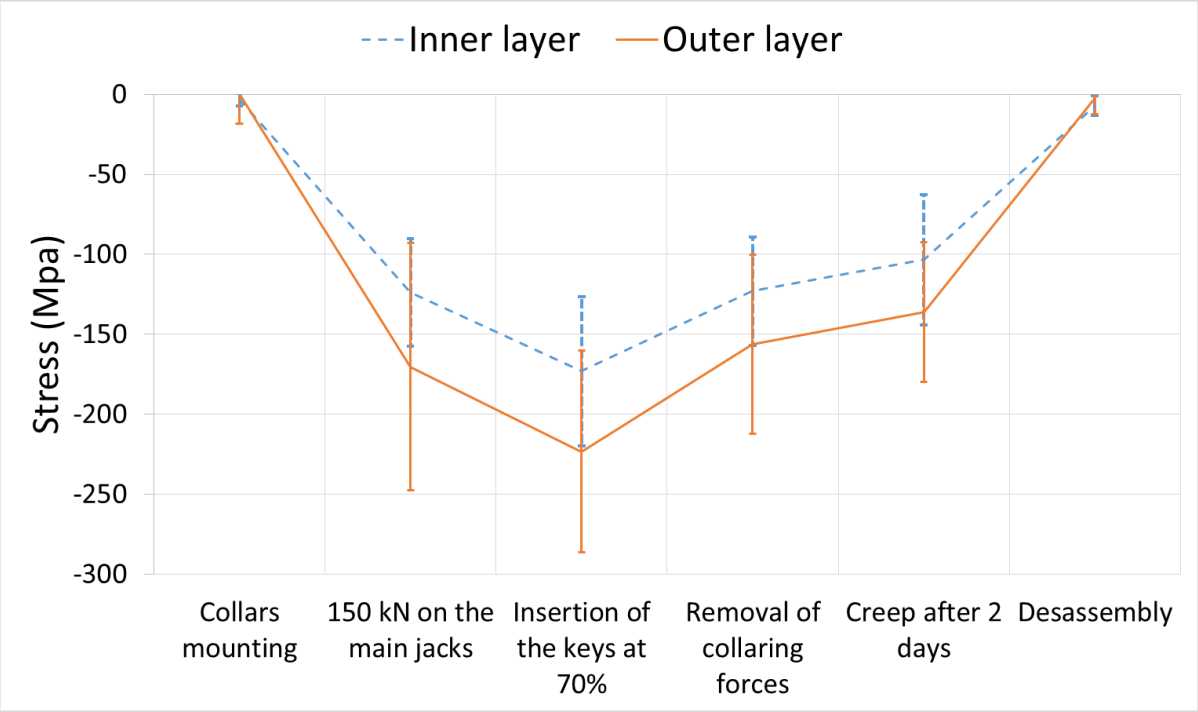




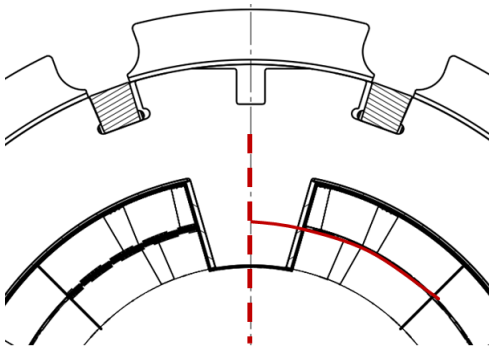
Vertical press in CERN 927

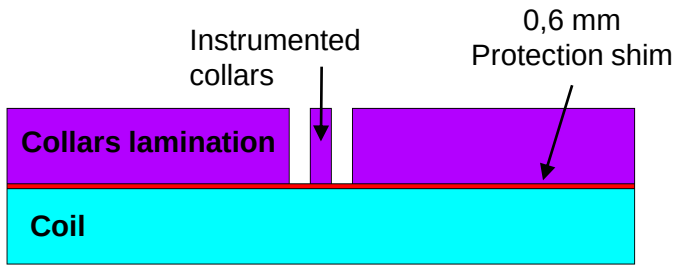
FIRST COLLARING

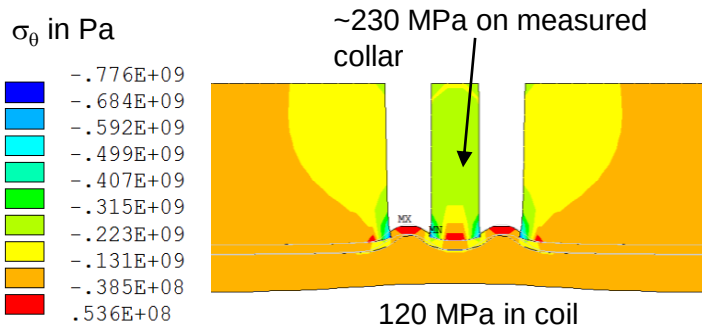
- Massaging + Insertion of the keys at 70%
- Factor 2 between the strain read in the collars and the one expected due to the lack of collar nose



Stress in the collars measured by the strain gages







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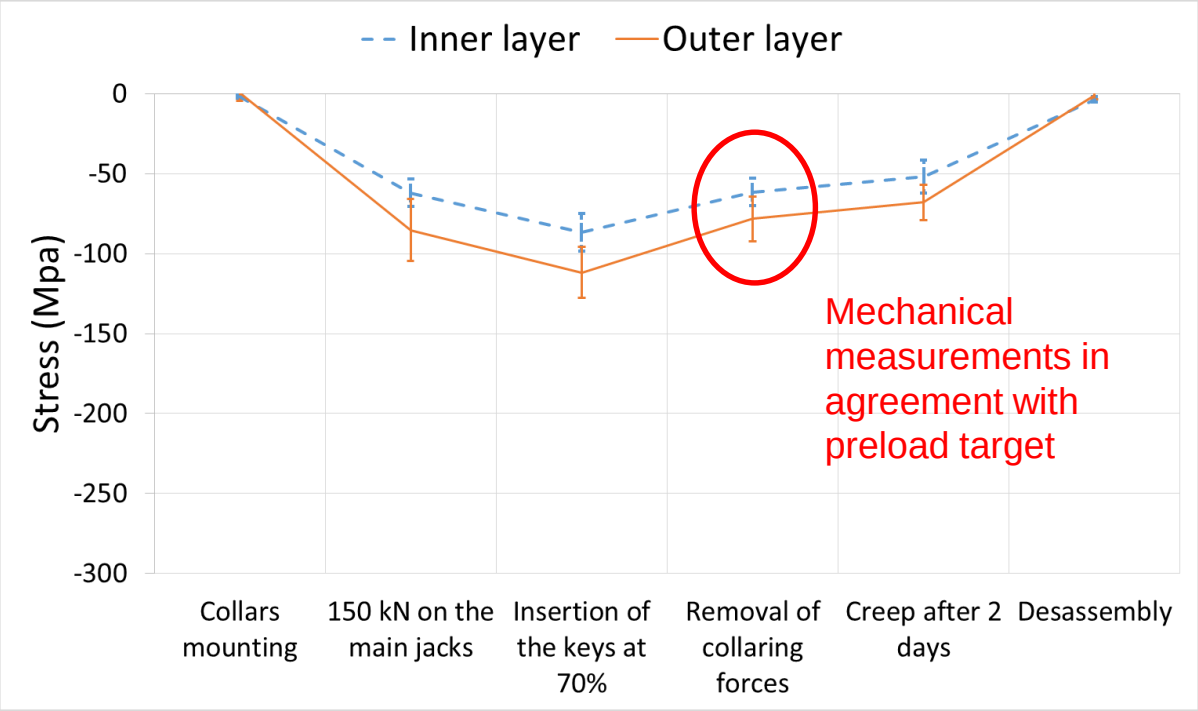
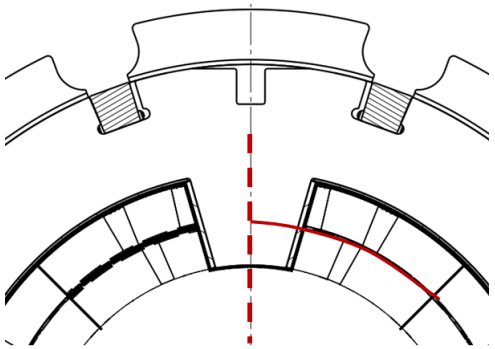
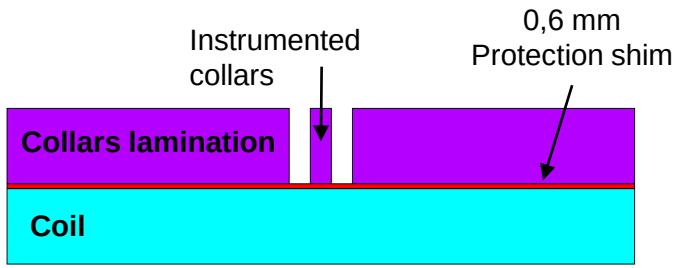
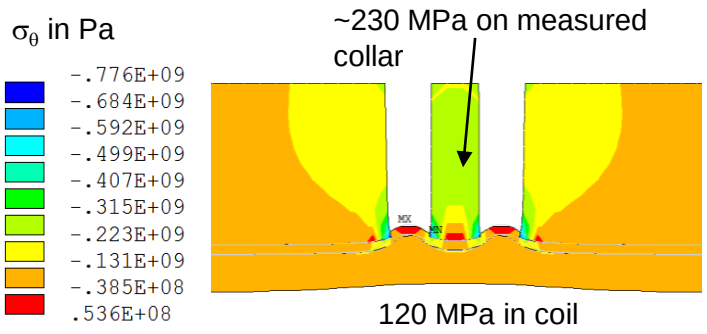


Stress in the coil (2 time less than the stress measured in the collar)

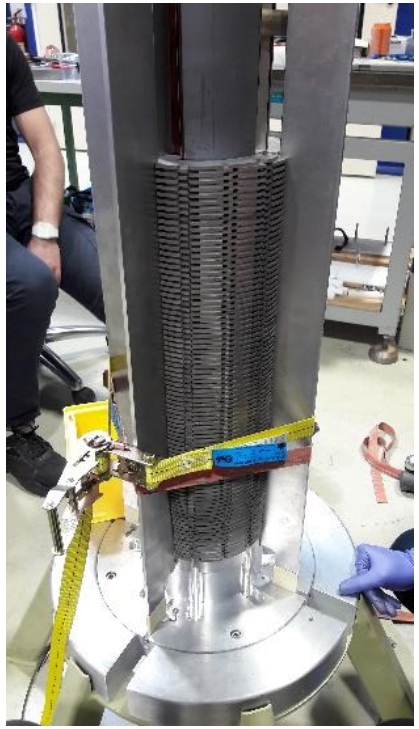


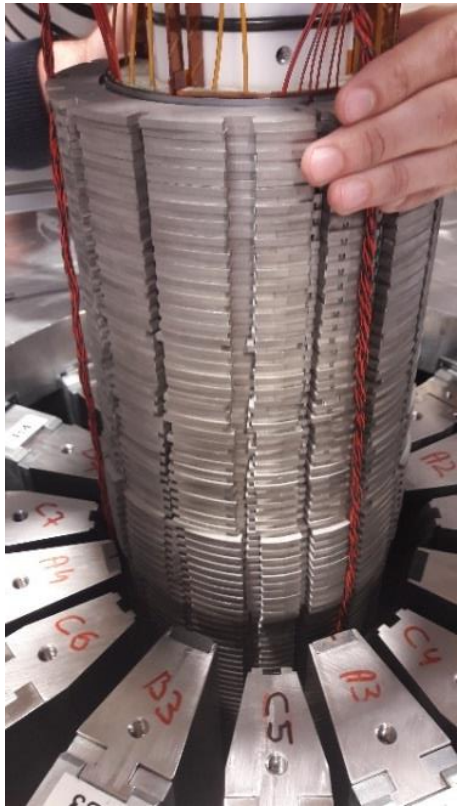




FIRST COLLARING

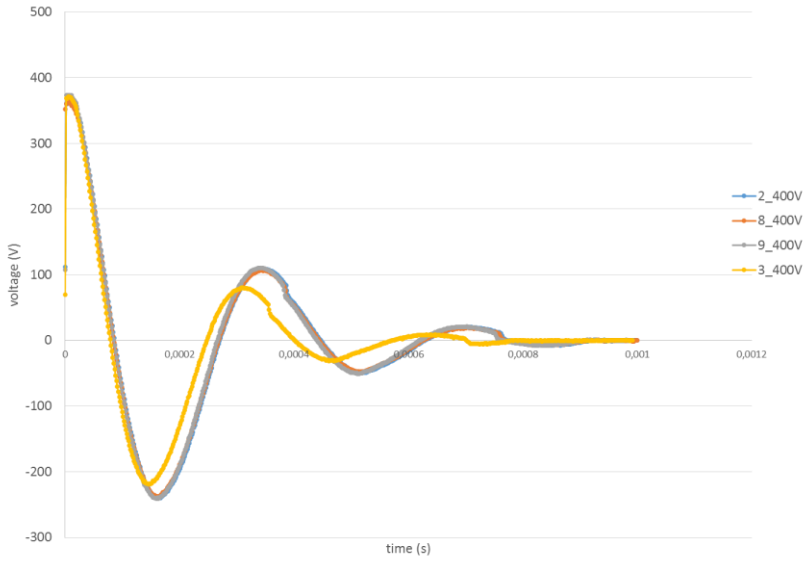
- Misalignment of the collars over the coil ends
- Bigger forces used on the jacks over the coil ends to compensate misalignment => Coils end overloaded

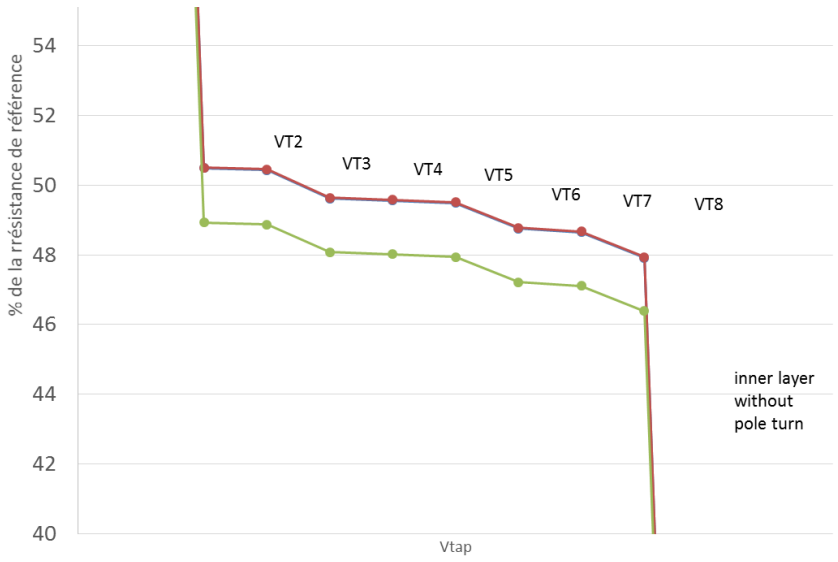


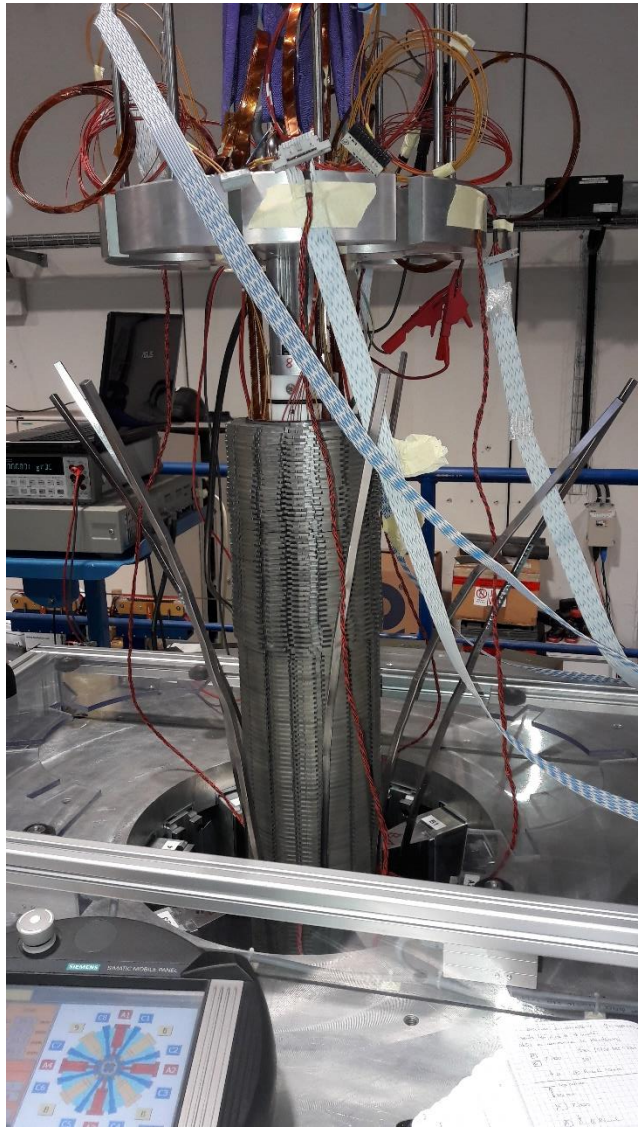


FIRST COLLARING

- Electrical tests after the collaring at 70%: **Turn to turn short circuit detected => decision to decollar**
- Short disappears after decollaring of the LE

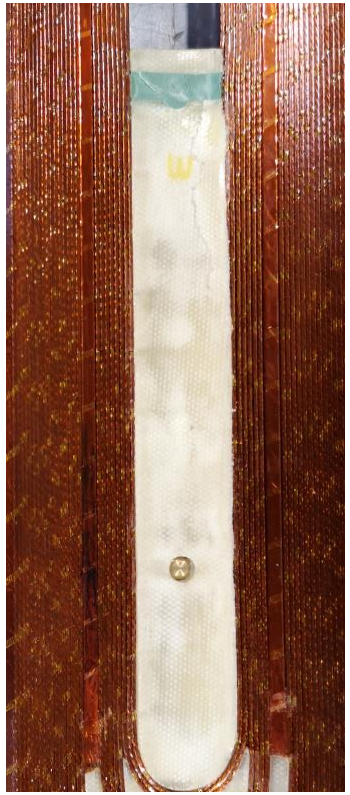


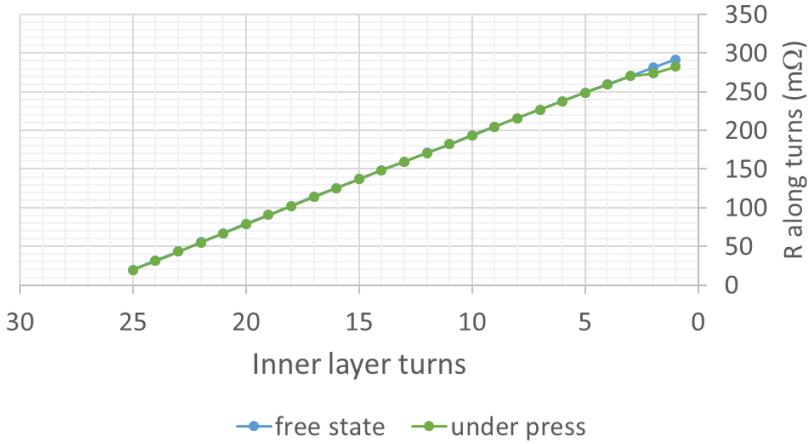




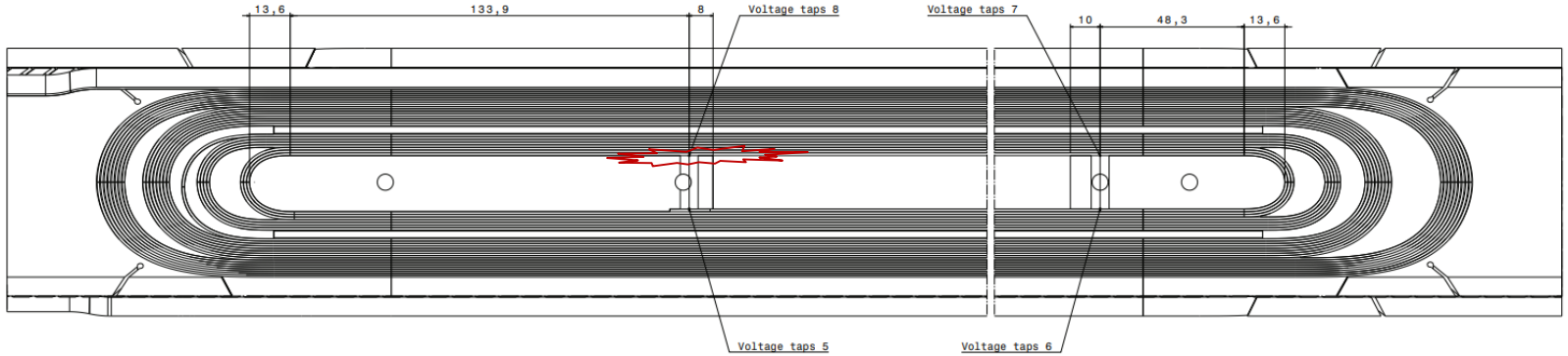
SHORT LOCALIZATION

- Localization of the short circuit reproduce with the E modulus press suspected to be between the pole turn and second turn
- Crack starts observed in G10 coils ends after polymerisation and worst after collaring



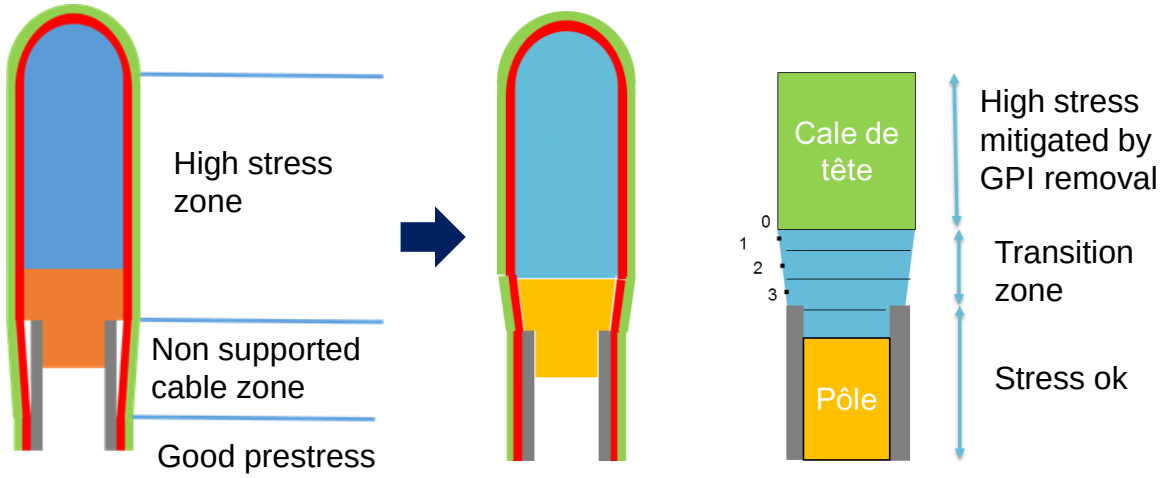


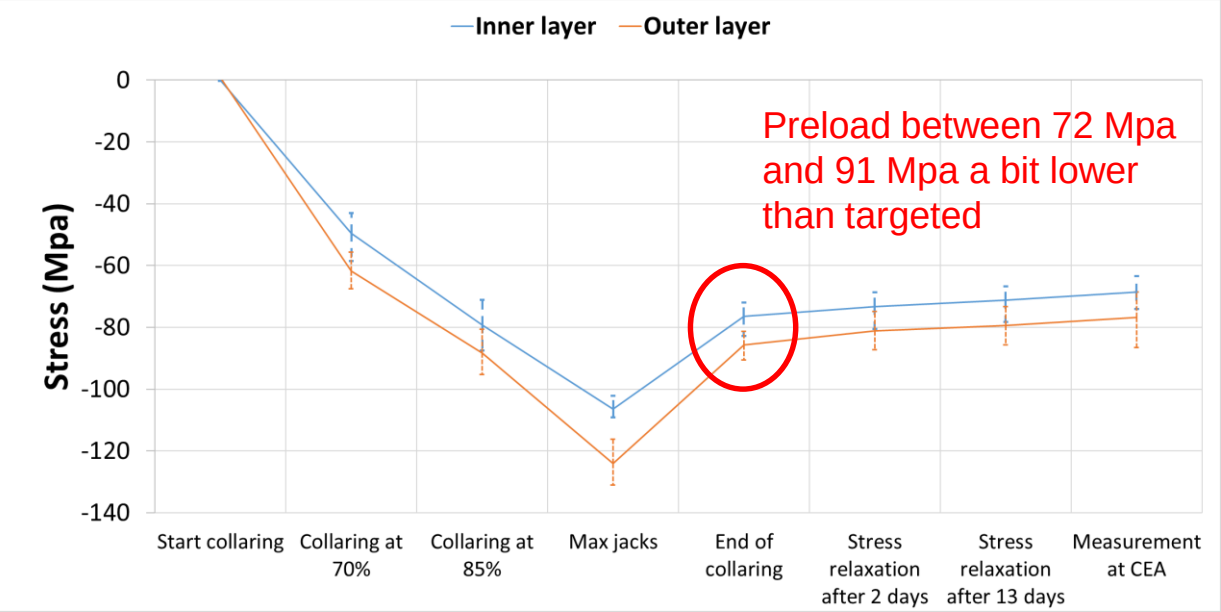
Coil 3 exhibits Reproduction of the short on the E modulus press Shear plane and cracks appear

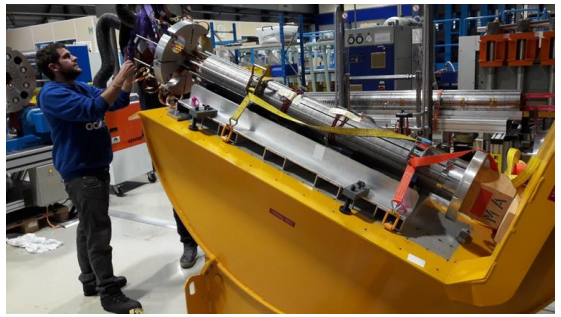


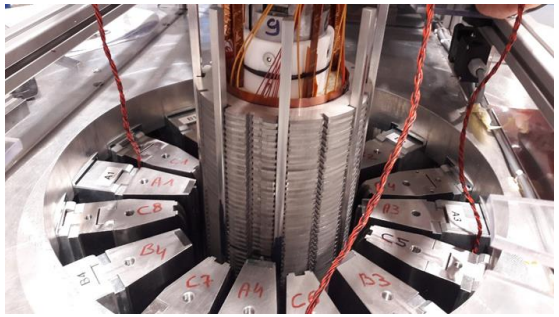
SECOND COLLARING

- Replacement of the coil with a short by a spare coil => New shimming plan
- Creation of a slope in the « stair » part
- Removal of some ground plane insulation in the ends to homogenize the stress
- Special tools manufactured to align the collars in the heads
- Collaring perform with success with good level of stress



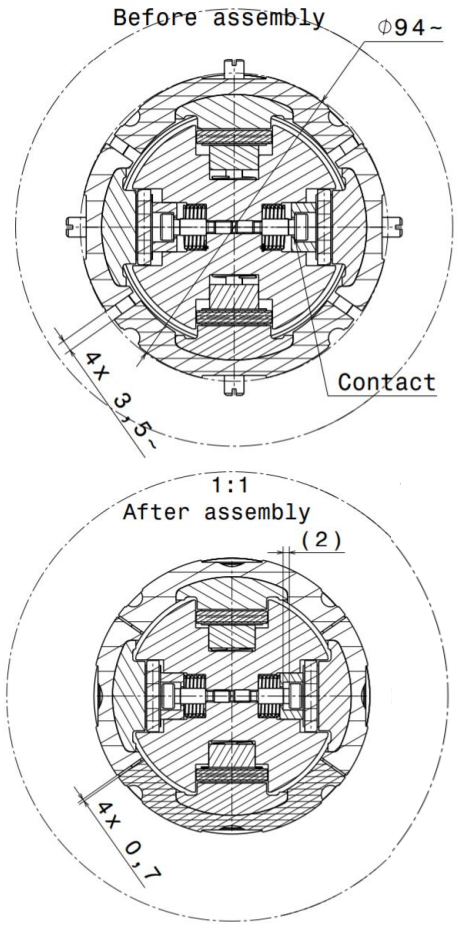




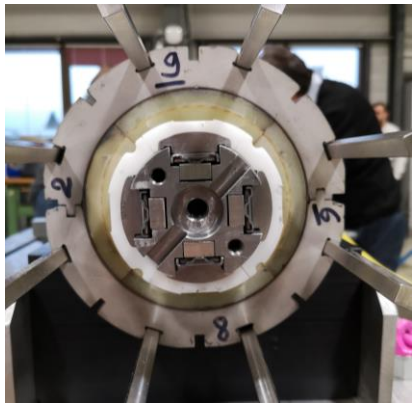


MANDREL EXTRACTION

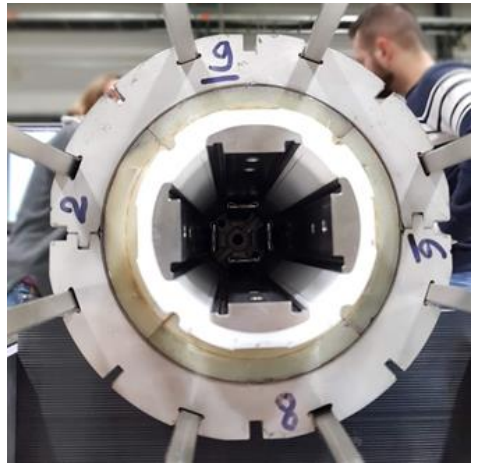
DESIGN

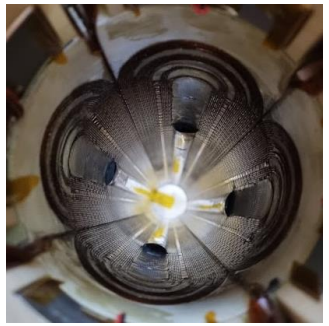


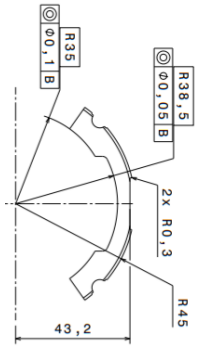
CENTRAL PART REMOVAL



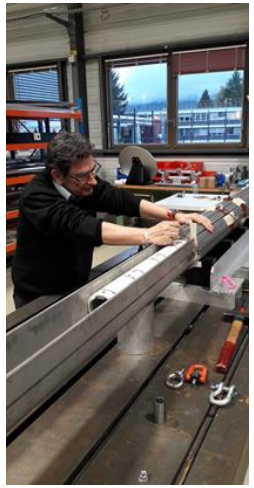
BEGINNING OF THE TROUBLE

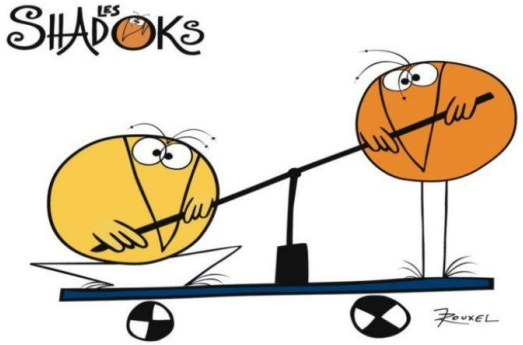






SOLUTION AND FINAL MANDREL REMOVAL





MANDREL EXTRACTION

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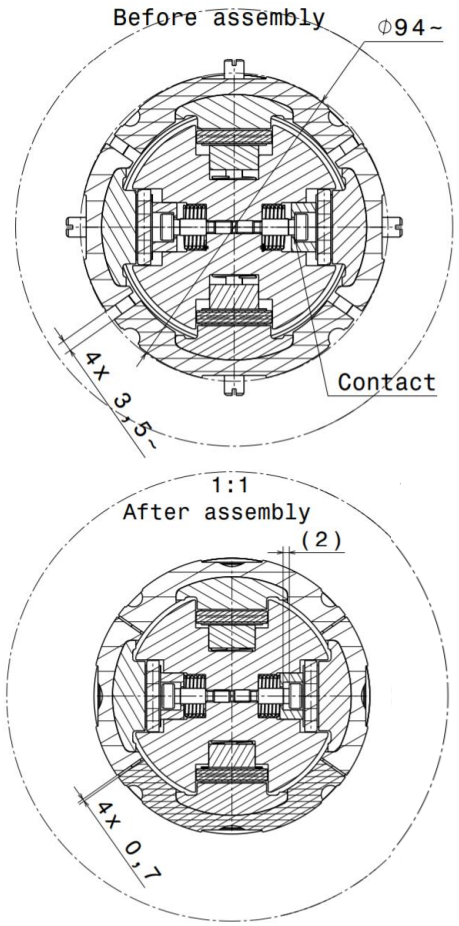
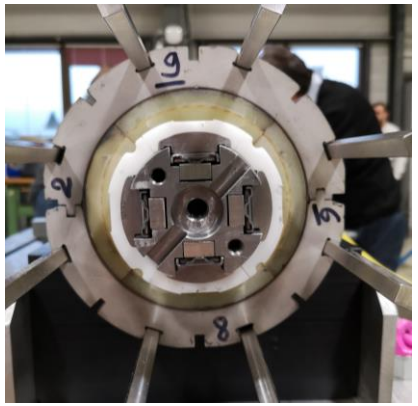
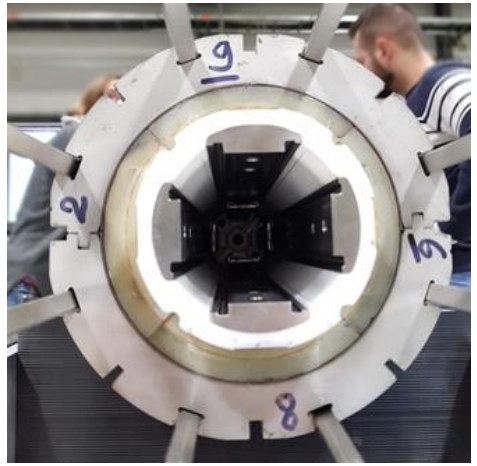
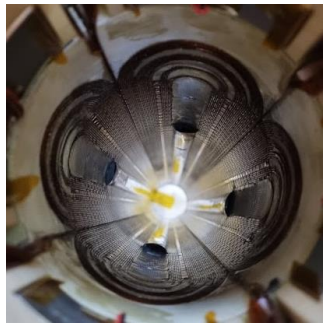


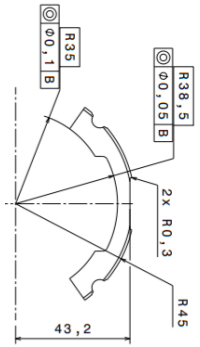
CENTRAL PART REMOVAL



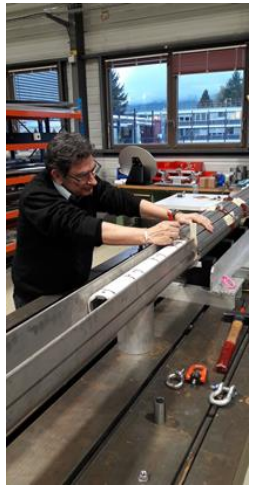
BEGINNING OF THE TROUBLE

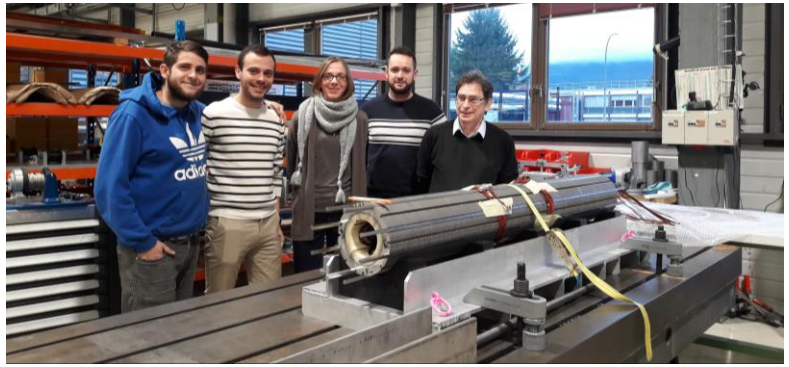






SOLUTION AND FINAL MANDREL REMOVAL



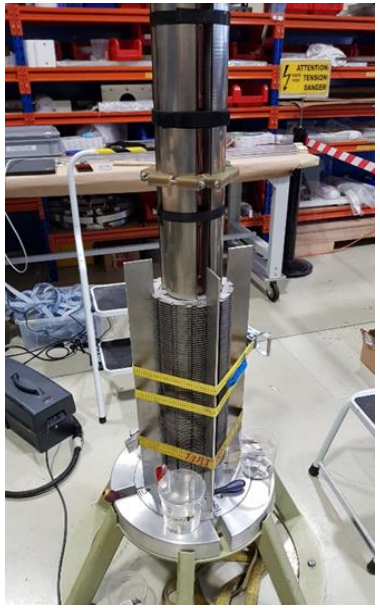


COLLARING LESSONS LEARNED

- The bars for the alignment of the collar should be very rigid, as long as the magnet ad be kept during the collaring

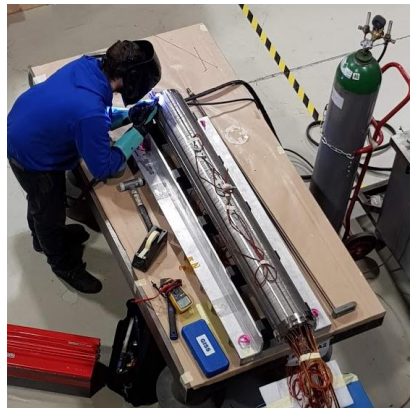
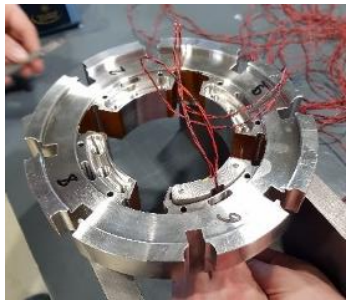
- The shimming should be homogenous all over the magnet, avoid step and brutal change of preload: particular attention should be paid when shimming is at the pole

- Do not hesitate to make small mock-ups

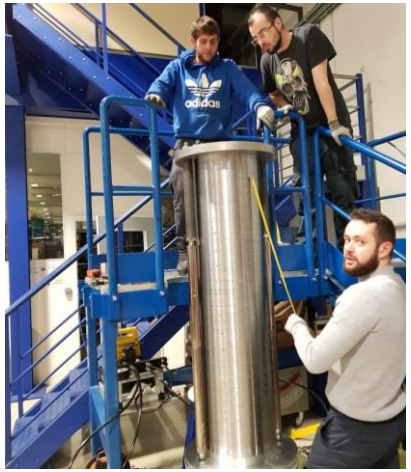
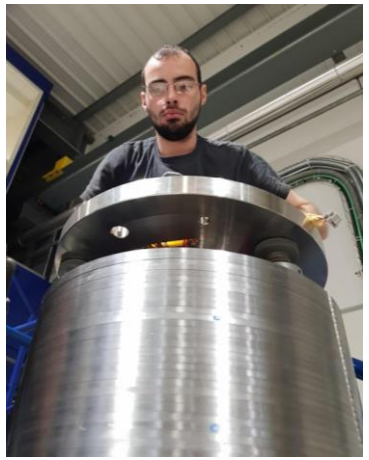


YOKING & CONNECTION

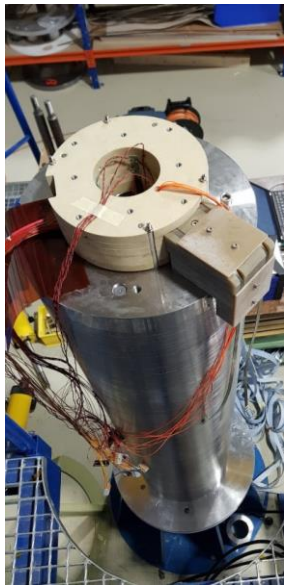
End flange welding

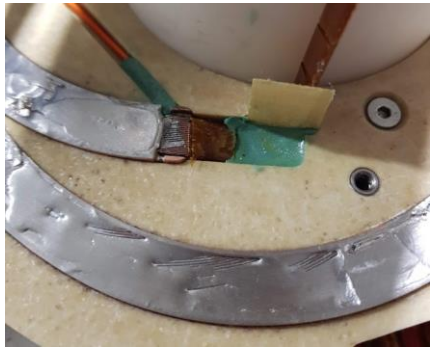




Yoking


Connection box

Activities carried out at CERN (927) by the CEA team with the support of the 927 team

Video of the assembly: http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast.php?t=fait_marquant&id_ast=4900

MQYYM TEST AT CEA

- The MQYYM magnet arrived at CEA in January 2020 after a warm magnetic measurements campaign on the 927 magnetic test bench
- Preparation of the cryogenic test
- COVID 19 lock down
- Preparation restart end of may 2020

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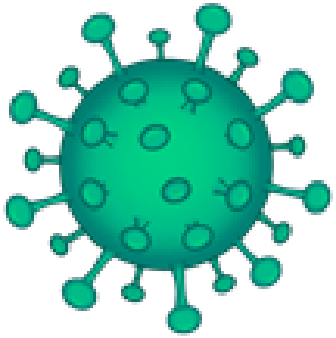

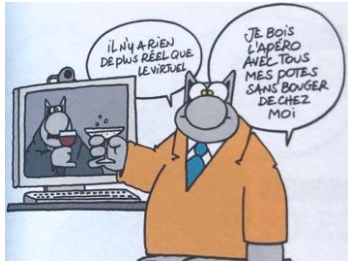

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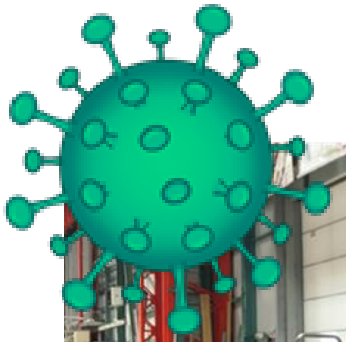
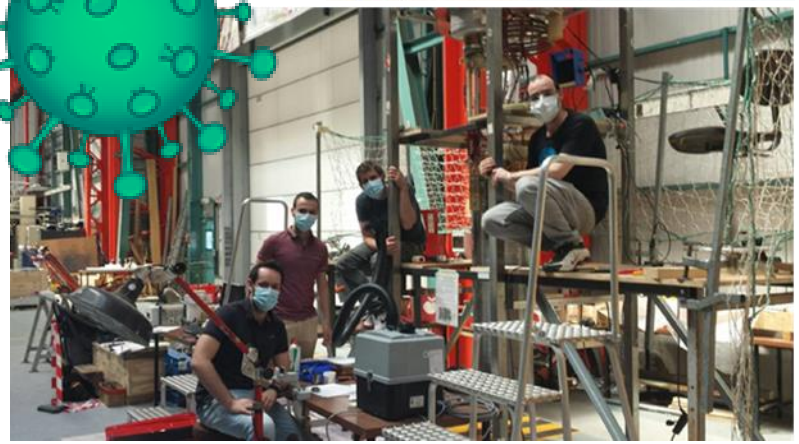
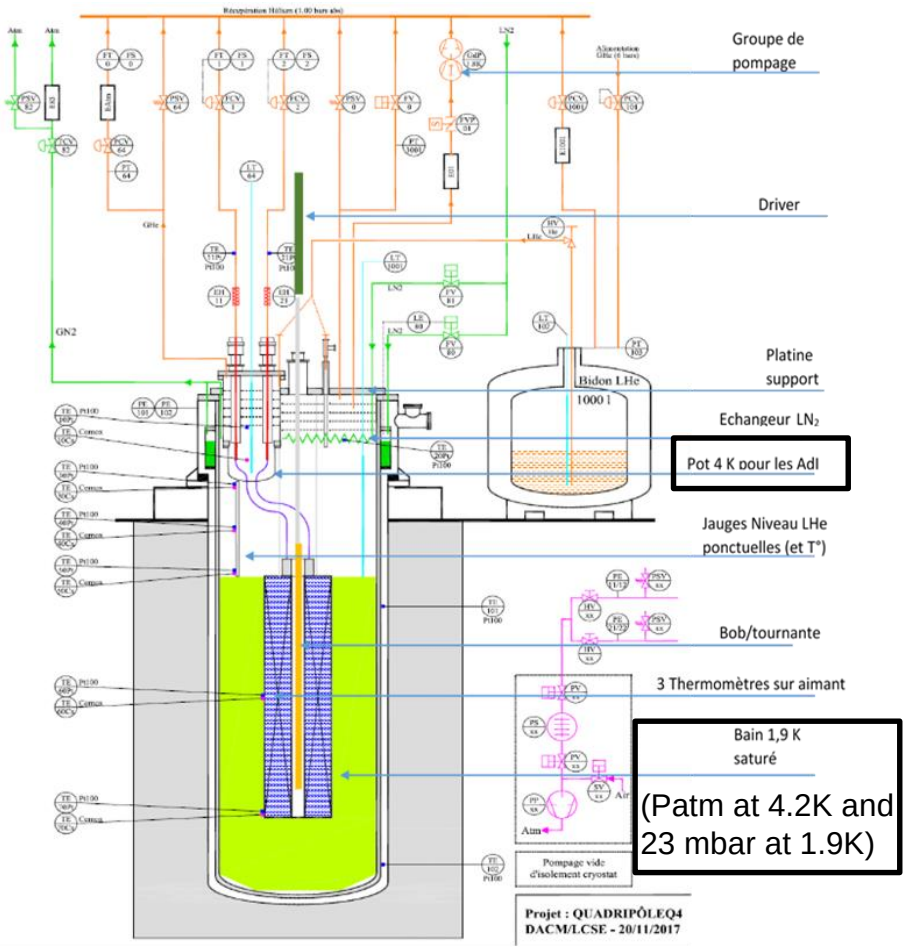




MQYYM TEST STATION

TEST STATION AT CEA…



Synoptique station test MQYYM

… WITH A LOT OF CERN MATERIAL AND SUPPORT

- Magnetic measurement system coming from CERN
- Mechanical measurement system coming from CERN too

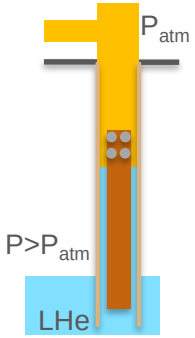
Strong support from CERN teams on remote

FIRST COOL DOWN

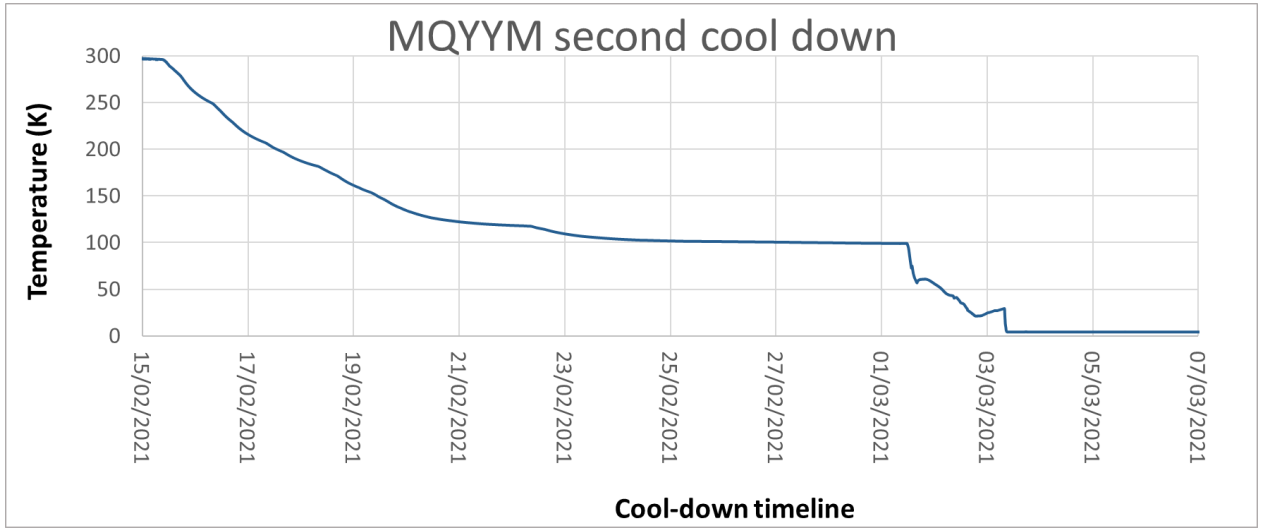
Busbar become resistive at 1295 A

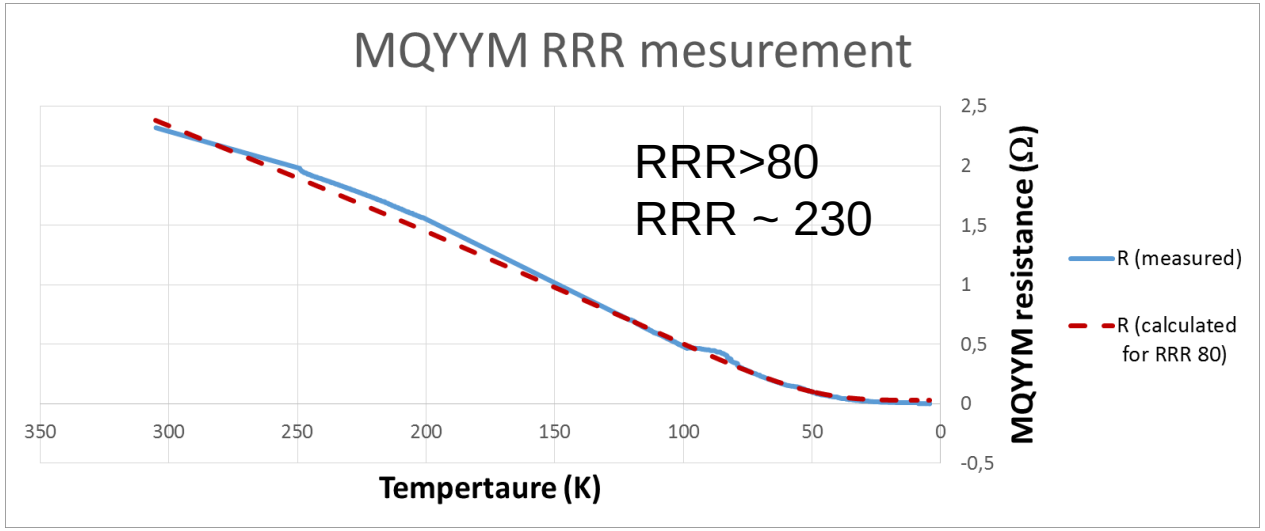
Simplification

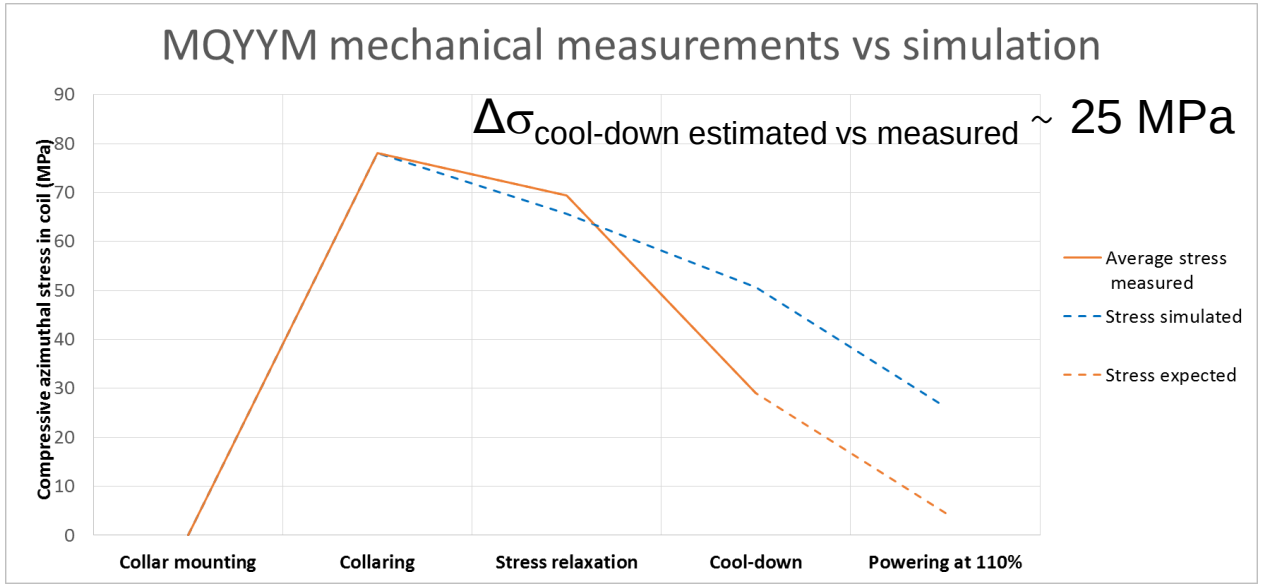
Decision to warm up the magnet and postpone the 1.9K test

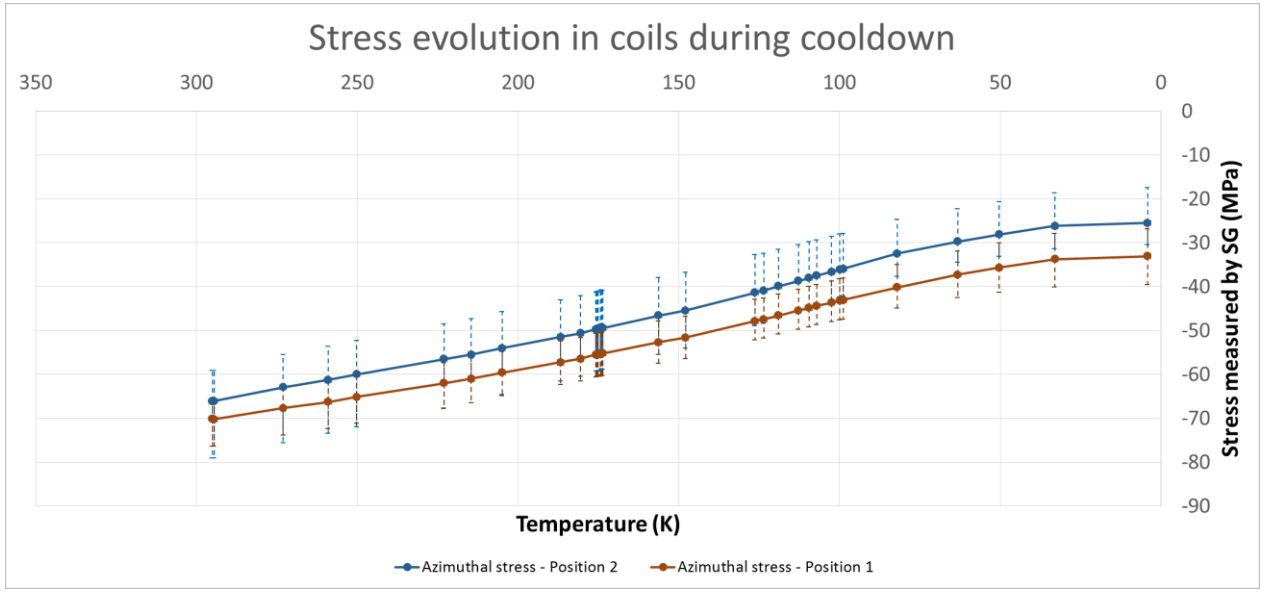


SECOND COOL-DOWN

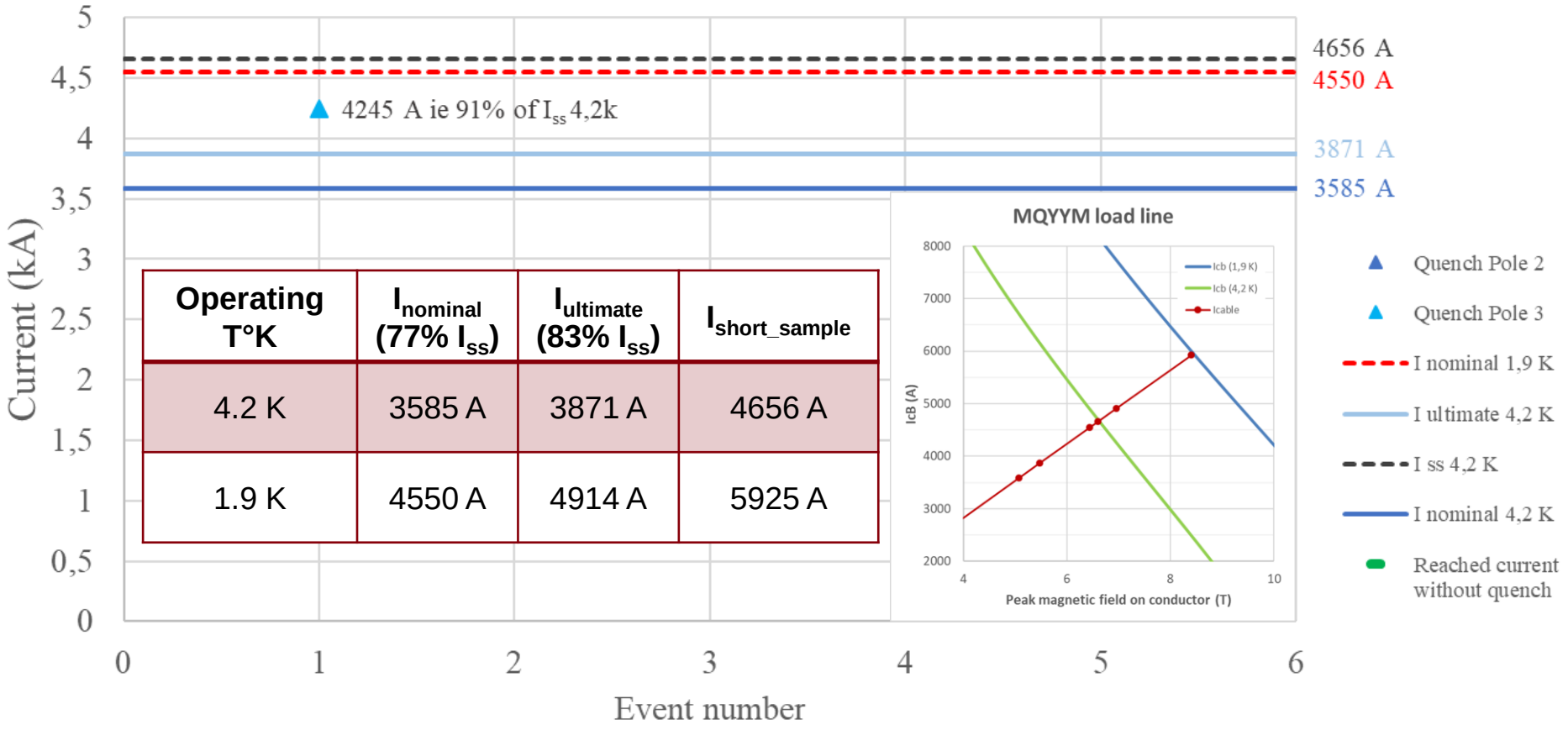








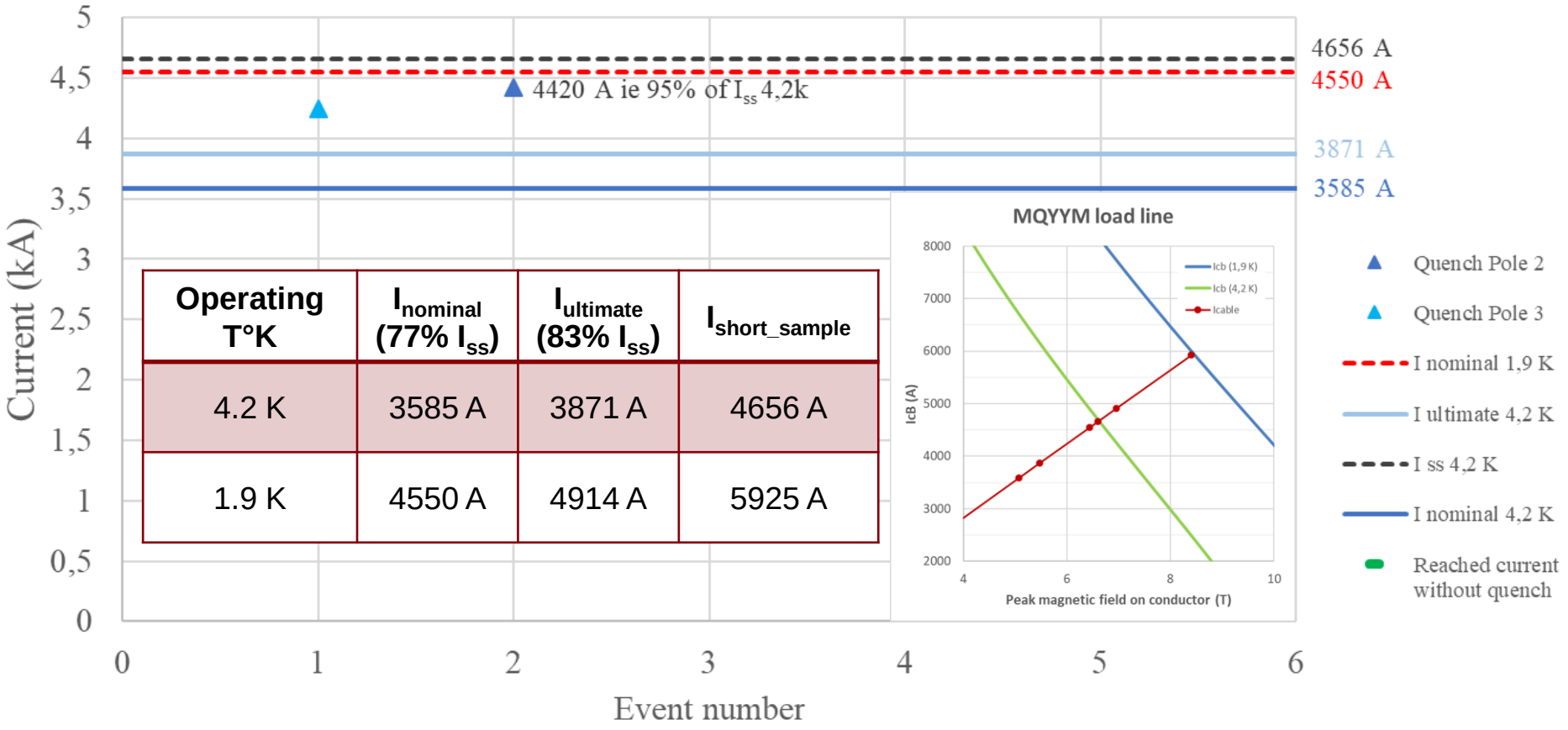
TRAINING AT 4,2 K



Operating T°K	$I_{nominal}$ (77% I_{ss})	$I_{ultimate}$ (83% I_{ss})	I_{short_sample}
4.2 K	3585 A	3871 A	4656 A
1.9 K	4550 A	4914 A	5925 A

Test at CEA

TRAINING AT 4,2 K



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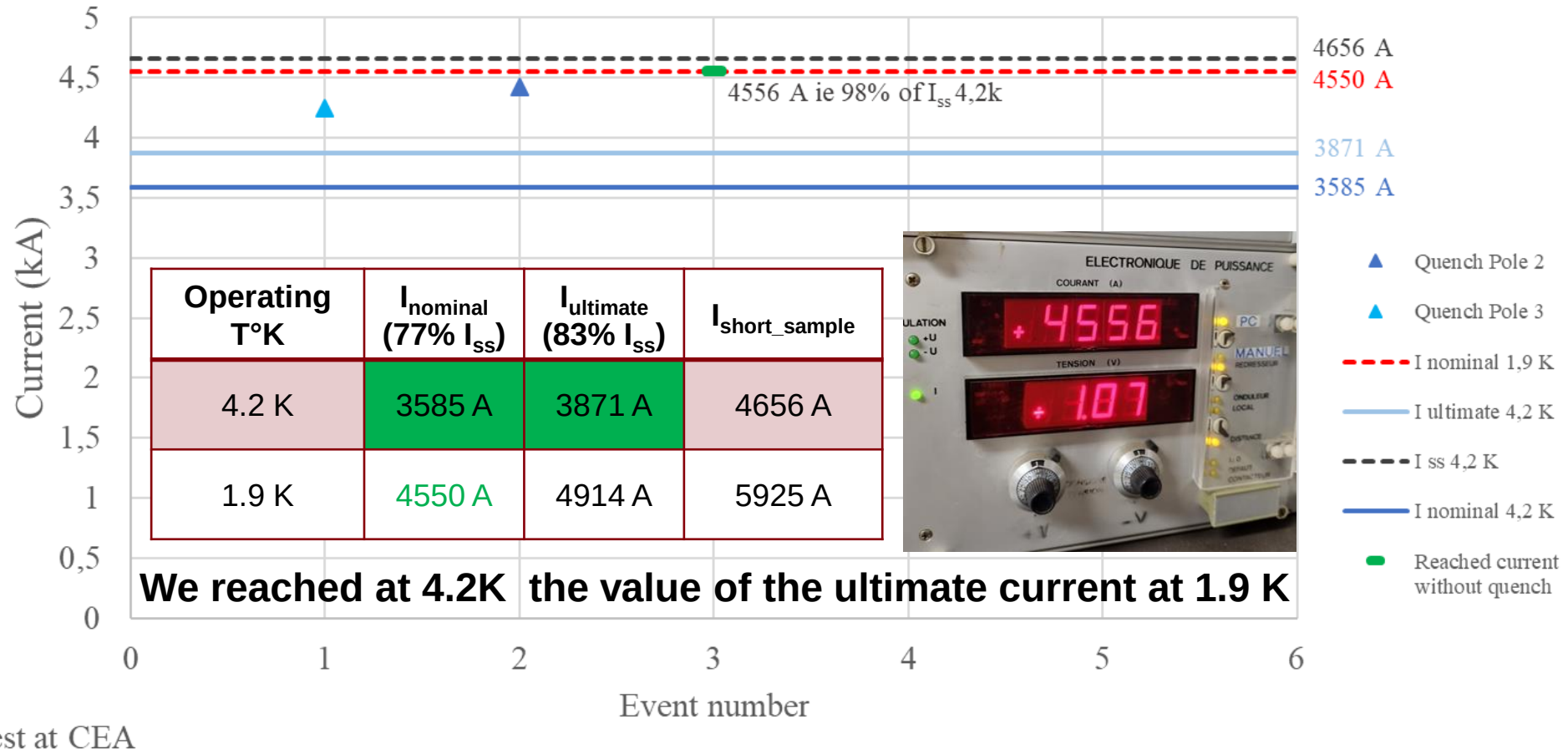

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4.2 K	3585 A	3871 A	4656 A
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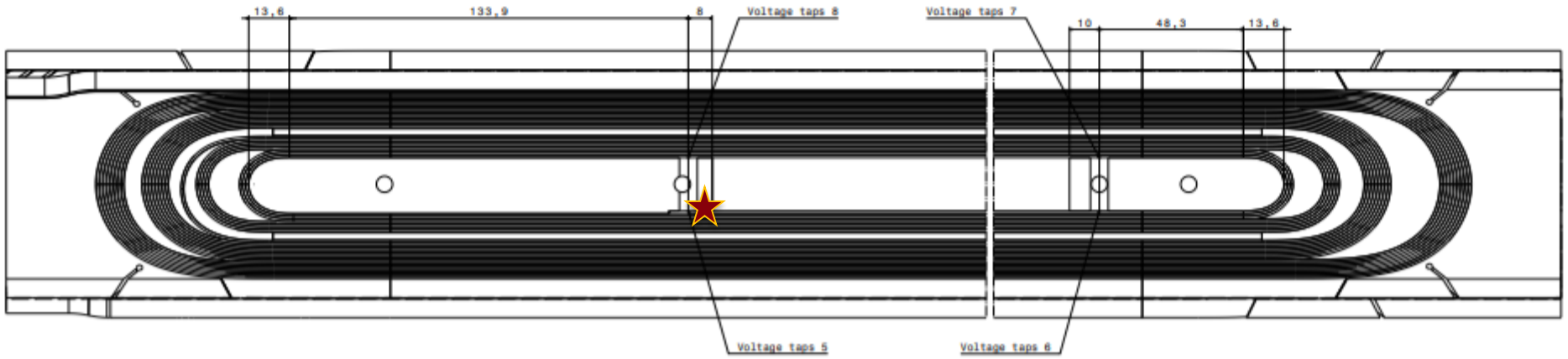
We reached at 4.2K the value of the ultimate current at 1.9 K

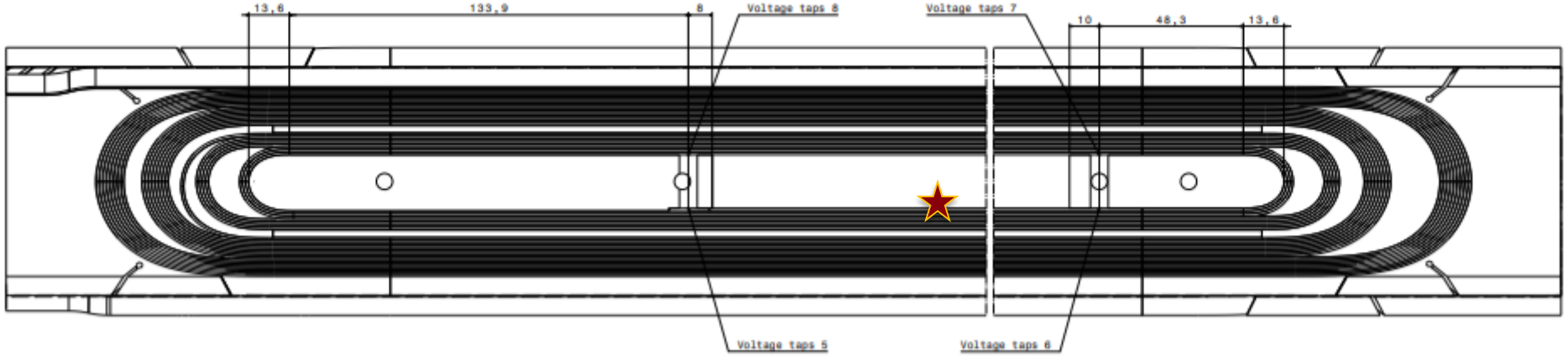
Test at CEA

TRAINING AT 4,2 K

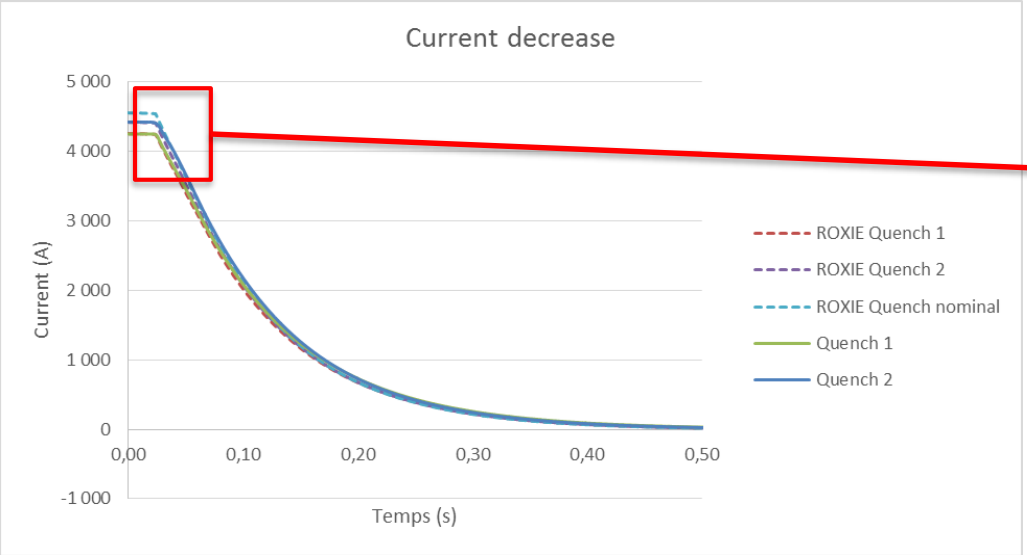
- Quench n°1: Pole 3 ie coil 6 localized on the inner layer, first turn at the level of the layer jump:

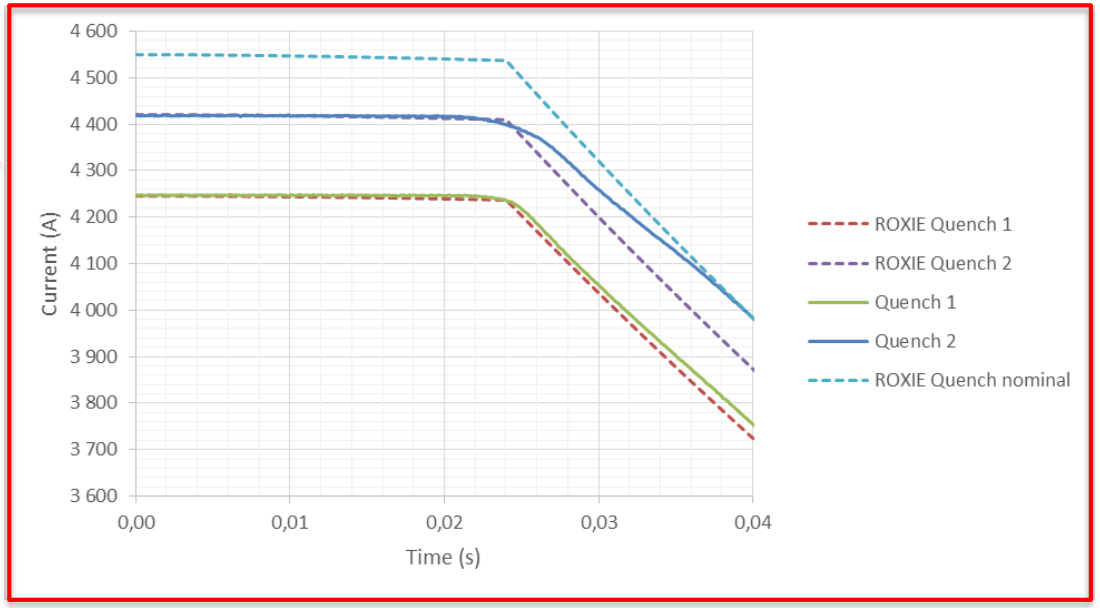


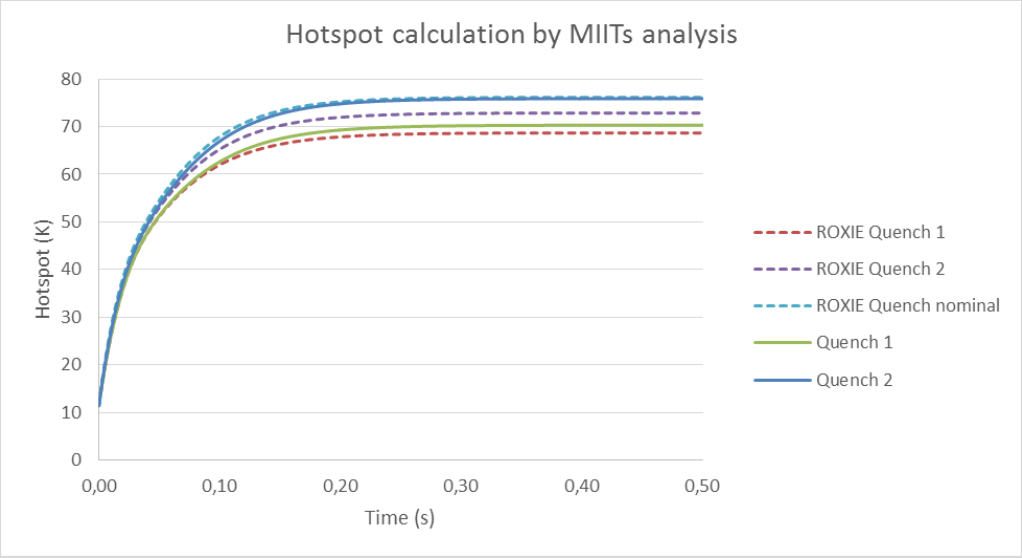
- Quench n°2: Pole 2 ie coil 8 localized on the inner layer, first turn few cm before the layer jump:



PROTECTION







Hotspot estimated at 76 K for nominal current with a MIITs analysis apply to the decay current simulated by Roxie

MIITs analysis with measured current decay

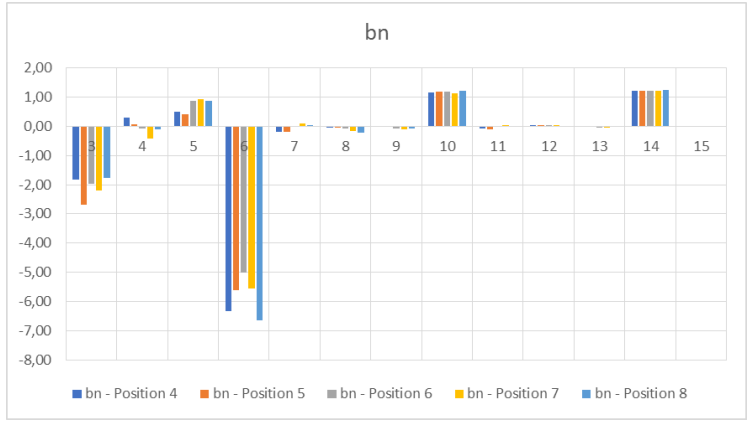
- 70 K for 4245 A
- 76 K for 4420 A

WARM MAGNETIC MEASUREMENT

AT CERN 927

- Horizontal translation (scanning probe)
- Radius probe = 30 mm
- Tangential probe
- WMM performed before and after yoking

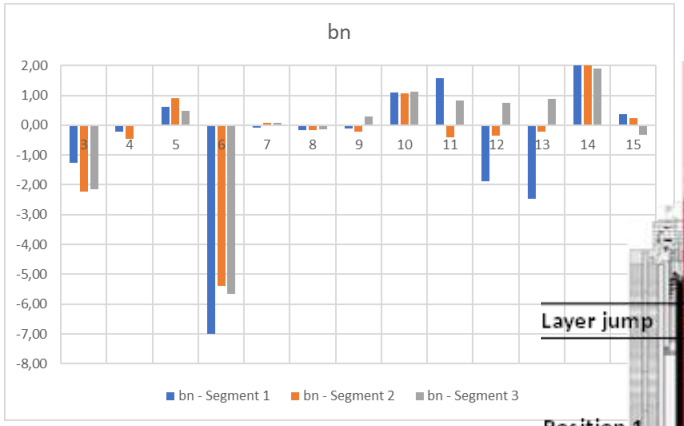
Warm magnetic measurements in units after yoking

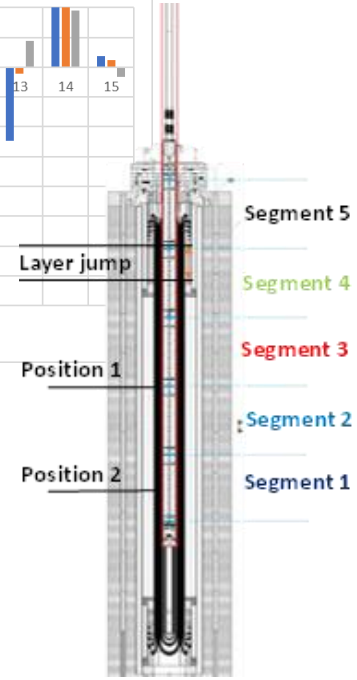


AT CEA

- Vertical measurements (5 segments)
- Radius probe = 23.5 mm
- Radial probe
- WMM performed before and after pit insertion

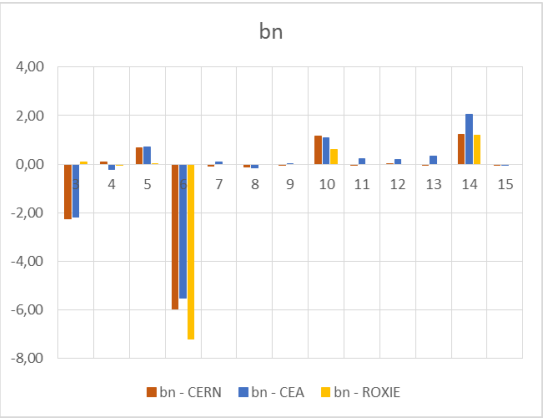
Warm magnetic measurements in units in CEA cryostat

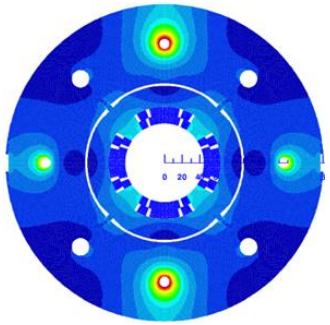




COMPARISON

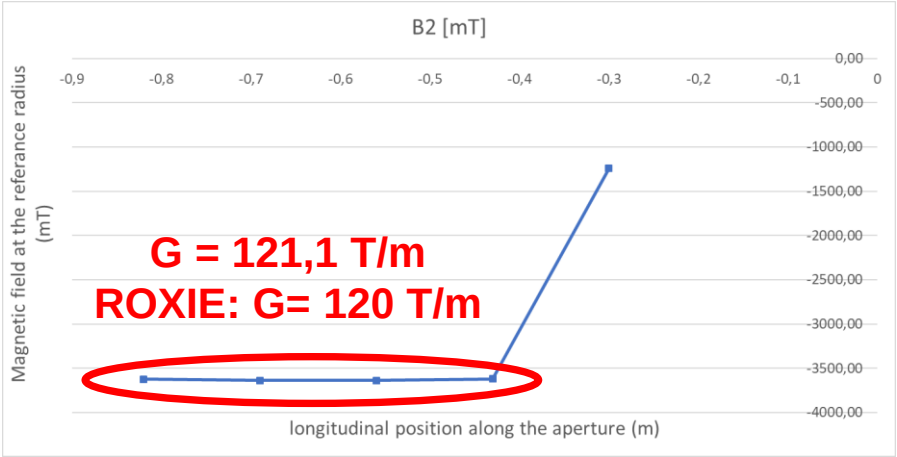
- Good correlation between the WMM performed at CEA and at CERN with ROXIE simulation

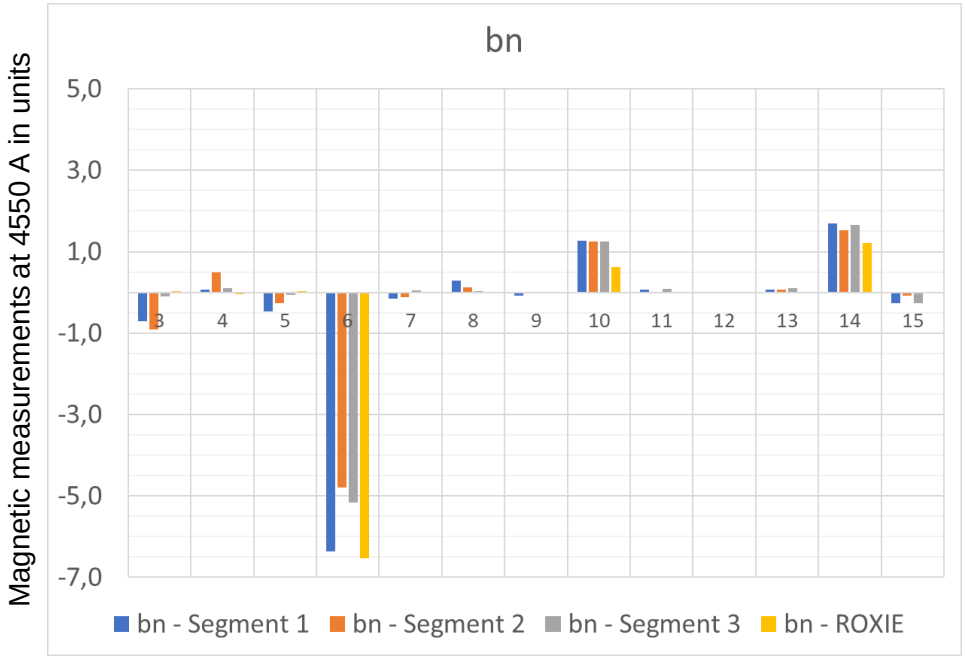


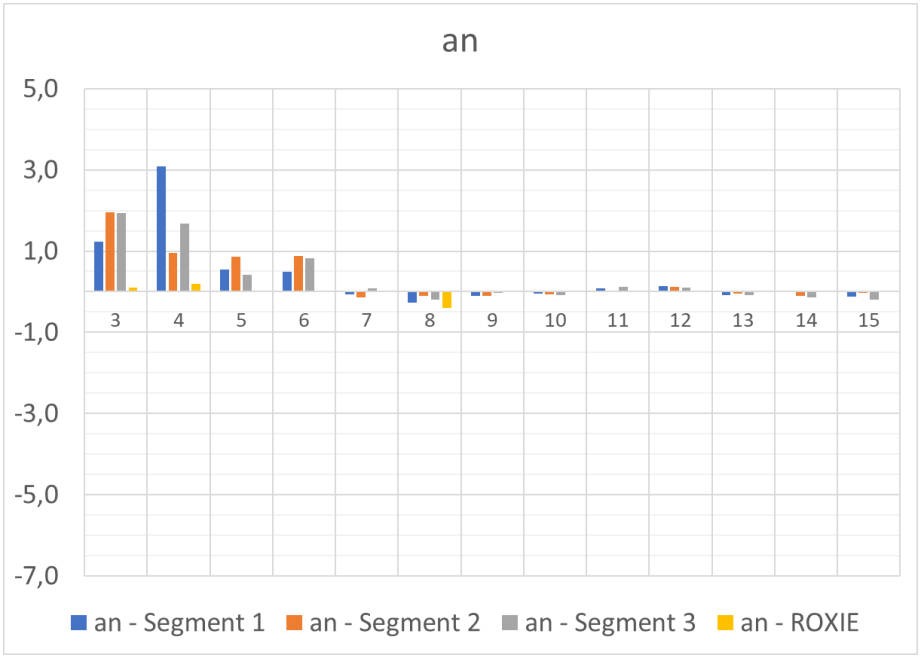


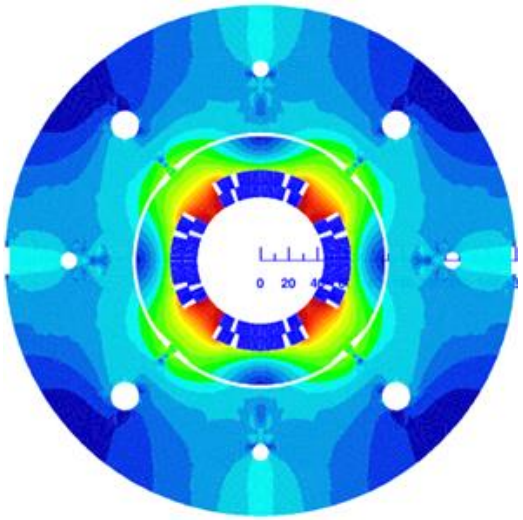
COLD MAGNETIC MEASUREMENTS

- The comparison between the magnetic measurements and the ROXIE simulation is still **<u>ongoing</u>**
- Rather good agreement for the b_n



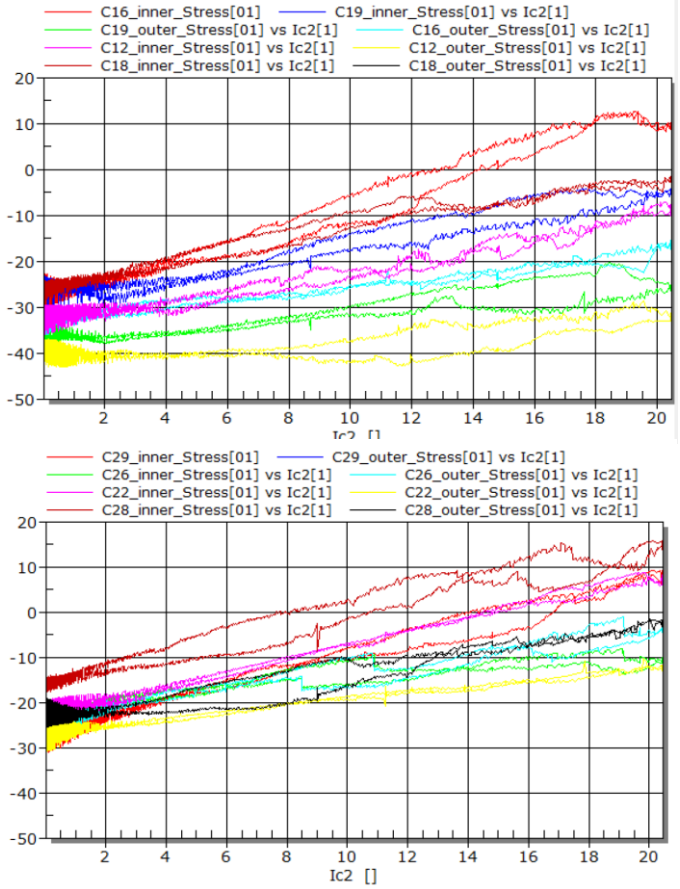


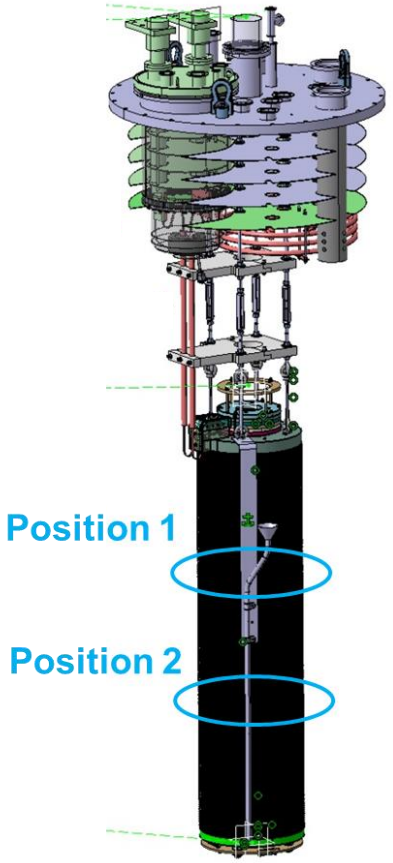




MECHANICAL MEASUREMENTS

- Greater loss of preload than expected during cool-down

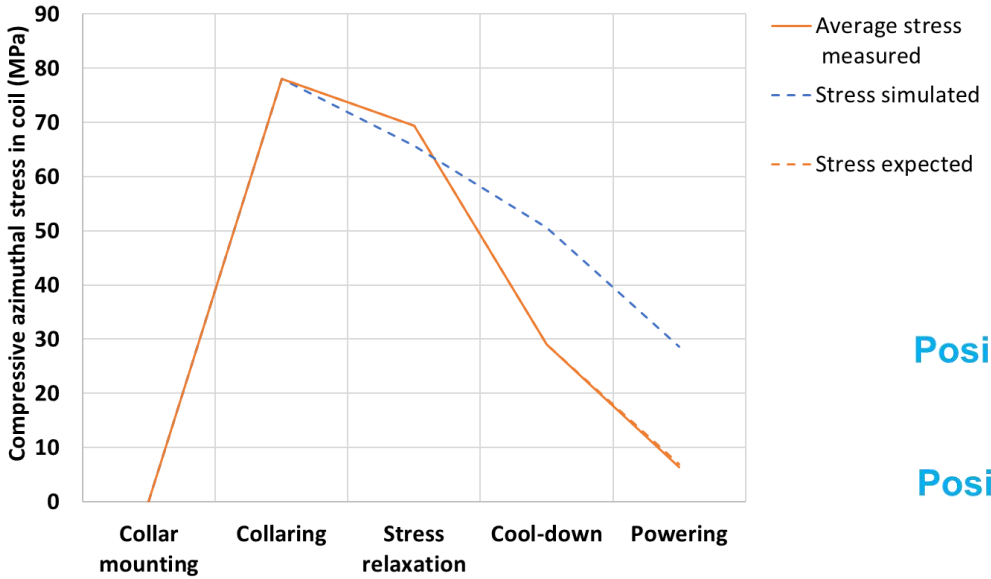


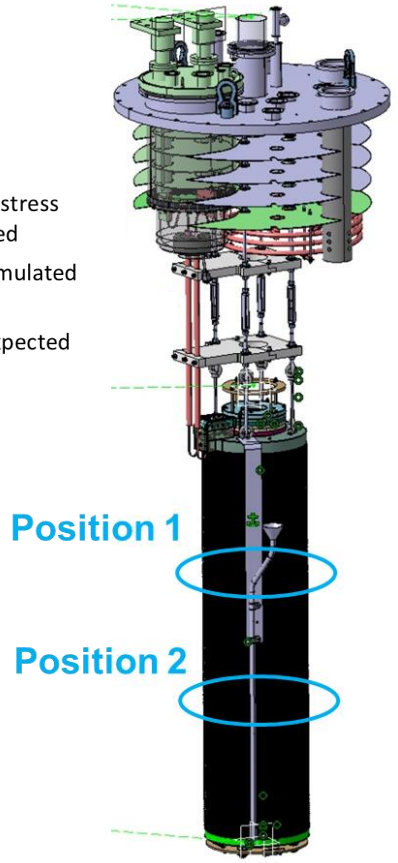


MECHANICAL MEASUREMENTS

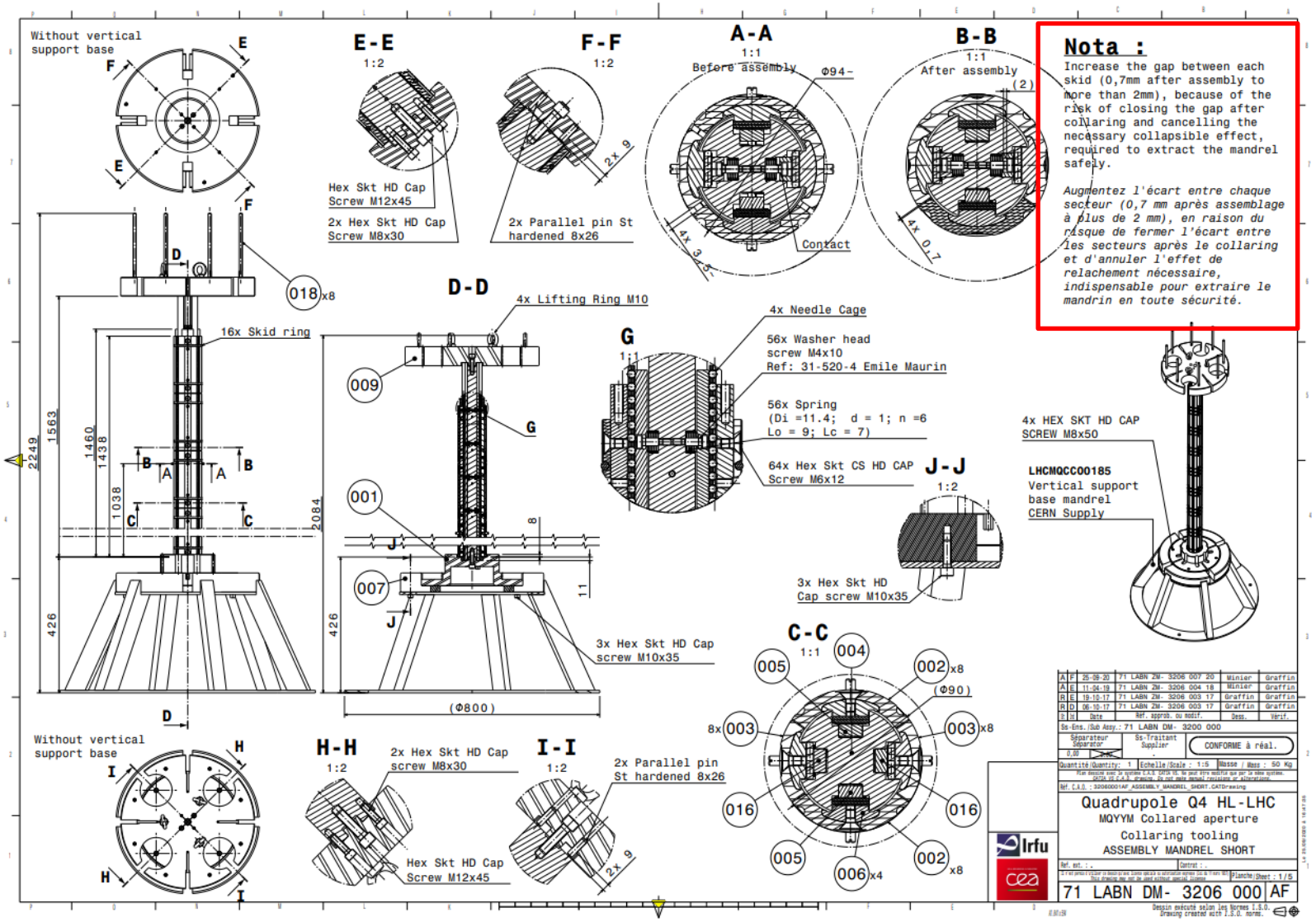
- Greater loss of preload than expected during cool-down
- Pre-stress loss slope during current rise in accordance with simulations

MQYYM mechanical measurements vs simulation





DOCUMENTATION



Annotation of the as built drawings that were problematic during assembly

Soon on EDMS

TOWARDS PROTOTYPES (QUACO)

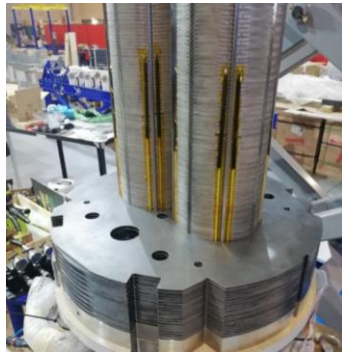
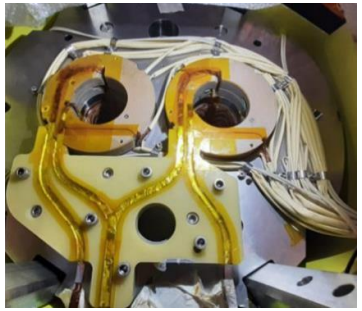
- The two magnets will be at CERN for warm magnetic measurements in June





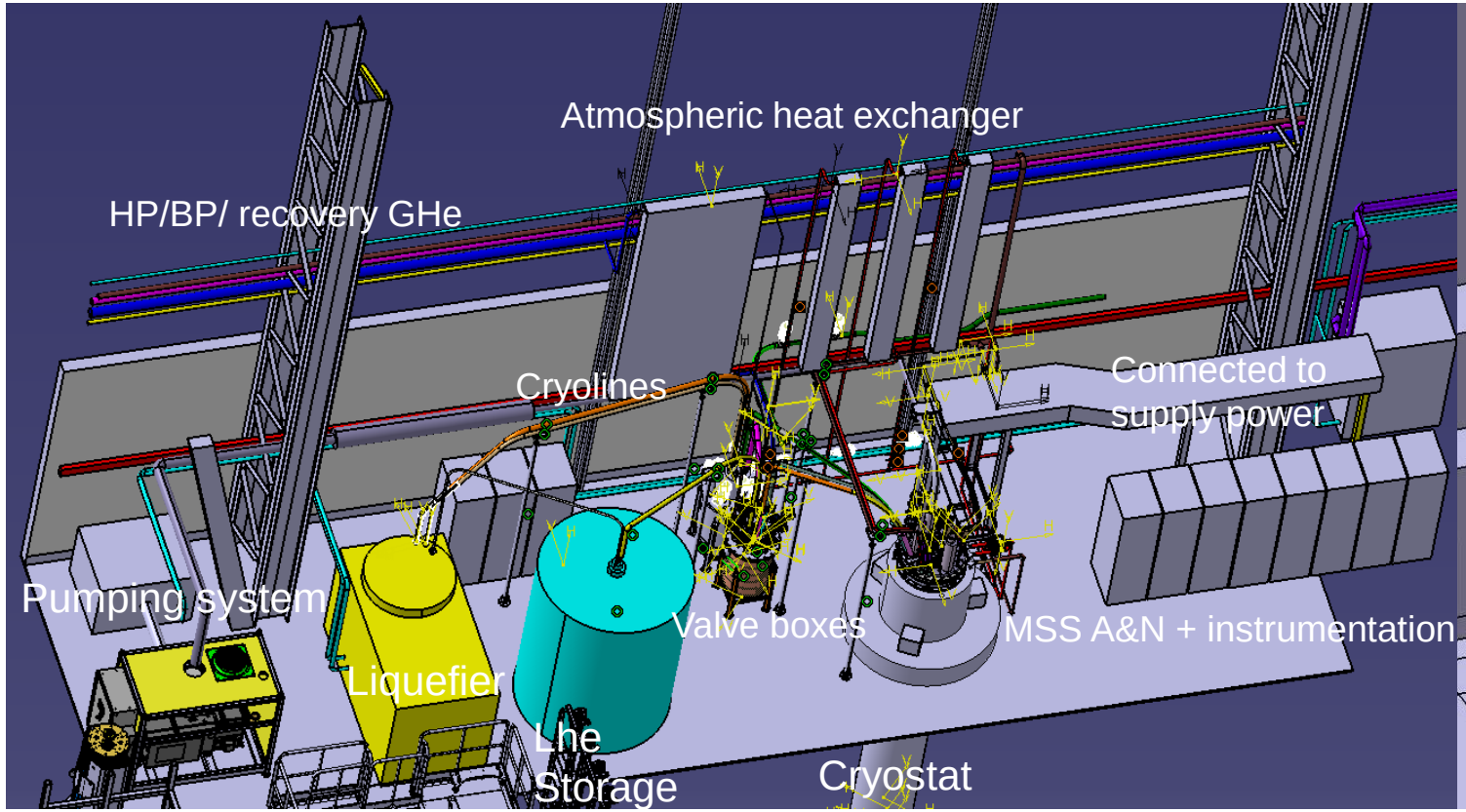


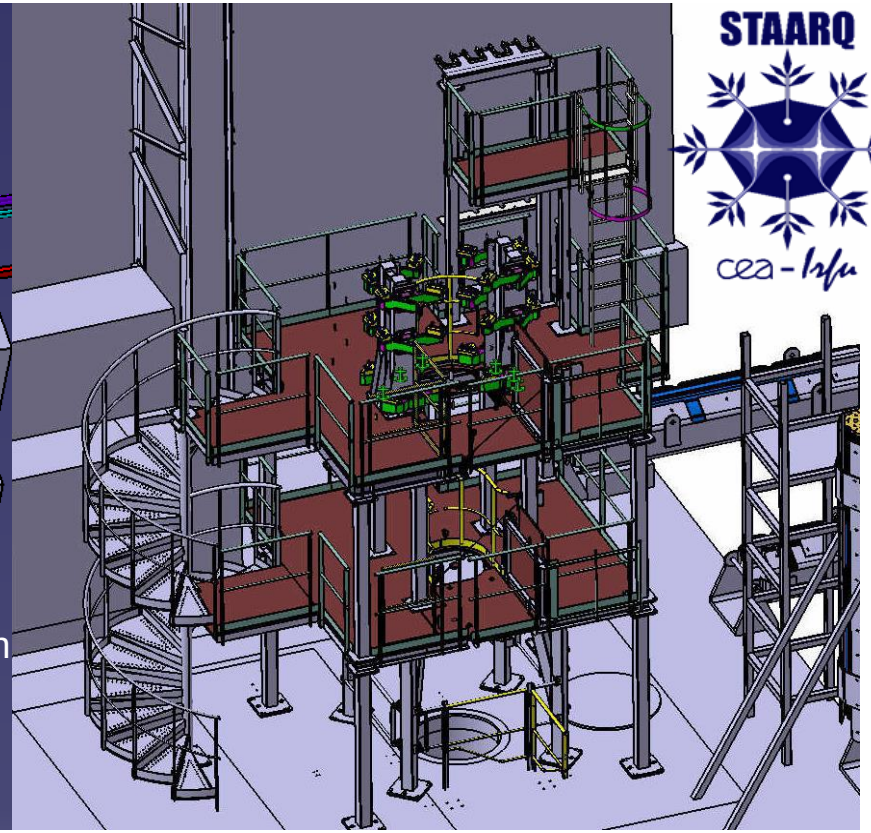



STAARQ

- Fully new station with lambda plate under construction at CEA-Saclay
- Improved acquisition and protection system
- Test of the MQYYM and QUACO magnet plan at 1.9 K in 2022





CONCLUSION

- Mechanical assembly validated however some improvements on polymerisation cavity size and initial stress level could be done
- The larger loss of prestress during cool-down still needs to be investigated
- The protection behaviour is conform to design
- Magnetic measurement in agreement with simulation accounting for shimming plan
- The manufacturing and test process have been consolidated at CEA
- **98% of Iss reached at 4,2 K after two quenches, 1.9K results expected in 2022**

LESSONS LEARNED

- The 10 coils were truly needed for the short model
  - 2 practice coils
  - 2 coils with non conformities
  - 1 coil with inter-turn short circuit during collaring
- Some small adjustments on the assembly tooling would be necessary to redo this magnet
- Designing and building a new NbTi quadrupole with a new team is not straight forward
- **Success only possible thanks to the strong collaboration between CERN and CEA**

THANK FOR YOUR ATTENTION

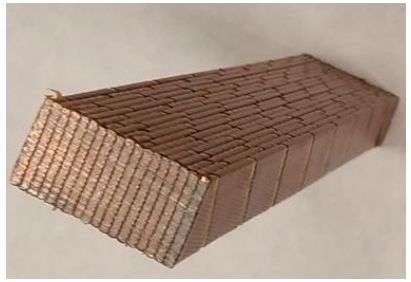
BACK-UP SLIDE

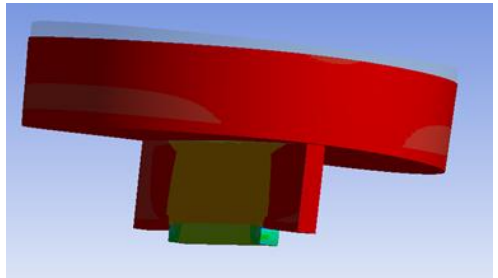
CABLE AND INSULATION

STACKS MEASUREMENTS AT CEA

- Technical data on MQM cable not fully recovered
- Rigidity measured ~8 Gpa after correction
- Tentative to define the polymerization cavity size
- The set-up used for the stacks measurement did not allow us to measure accurately the insulation size under load for different polymerization cavity size => lead to overestimate the curing cavity size

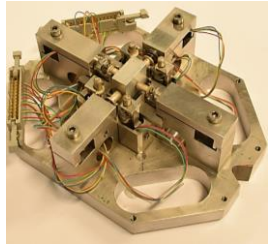
Coil bigger than required

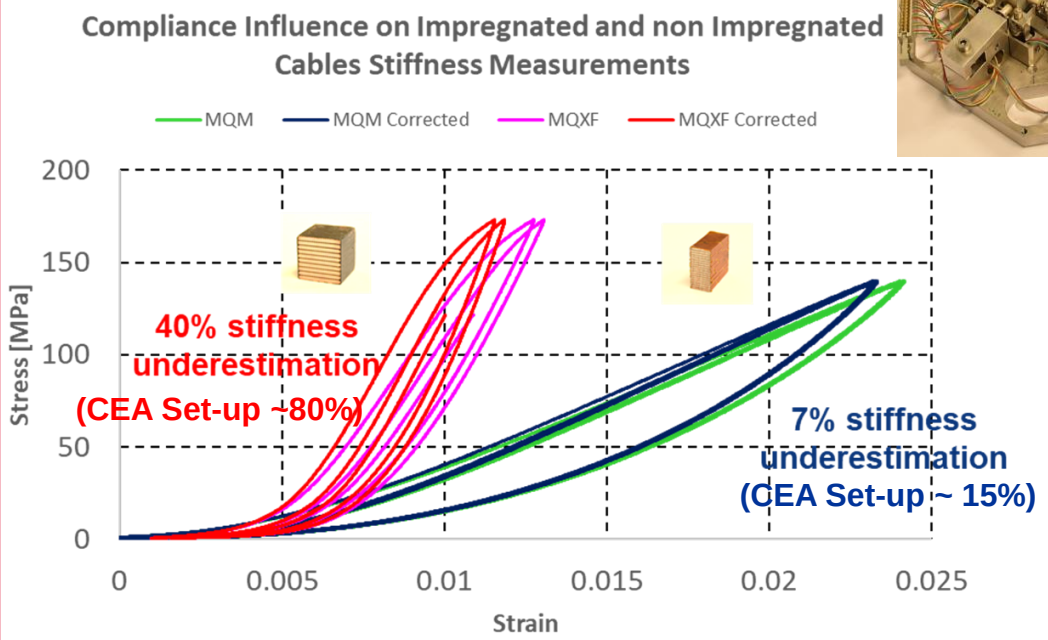




RIGIDITY CROSS CHECK AT CERN

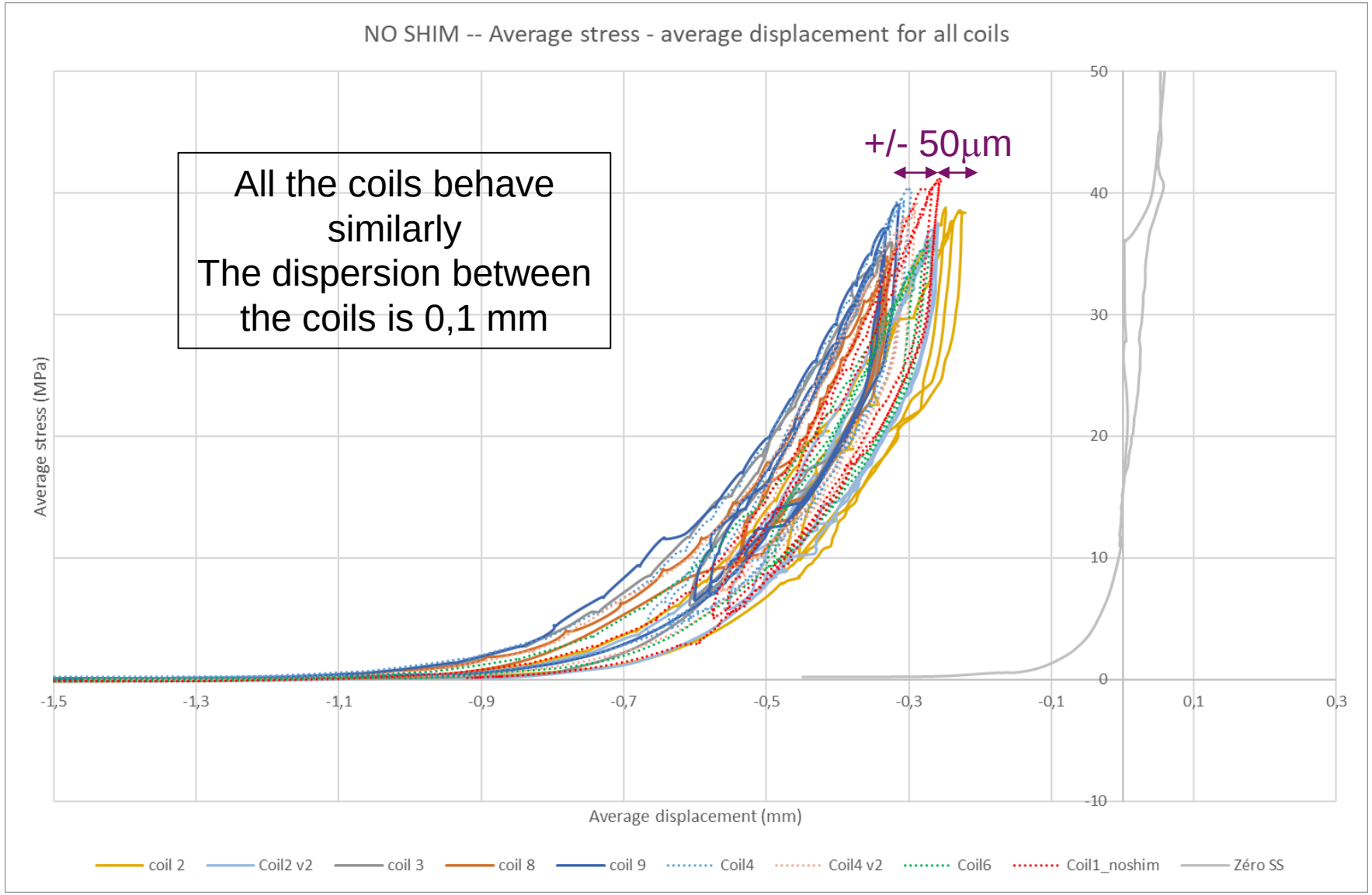
- Rigidity set-up more reliable confirm CEA measurements on coils rigidity
- Measurement campaign during coil manufacturing





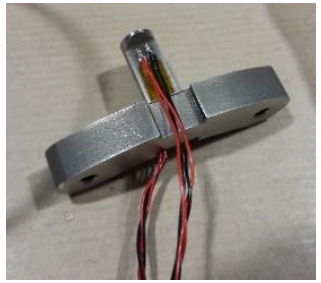
Courtesy Michael Guinchard (CERN)

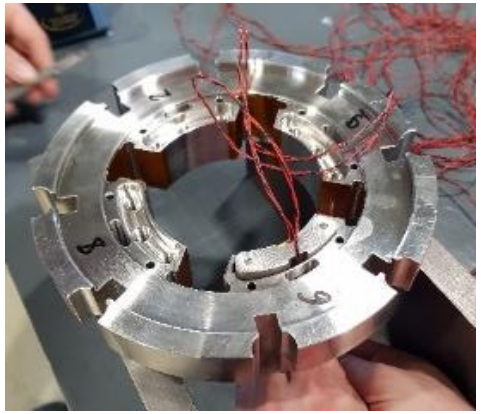
COIL DIMENSIONAL DISPERSION



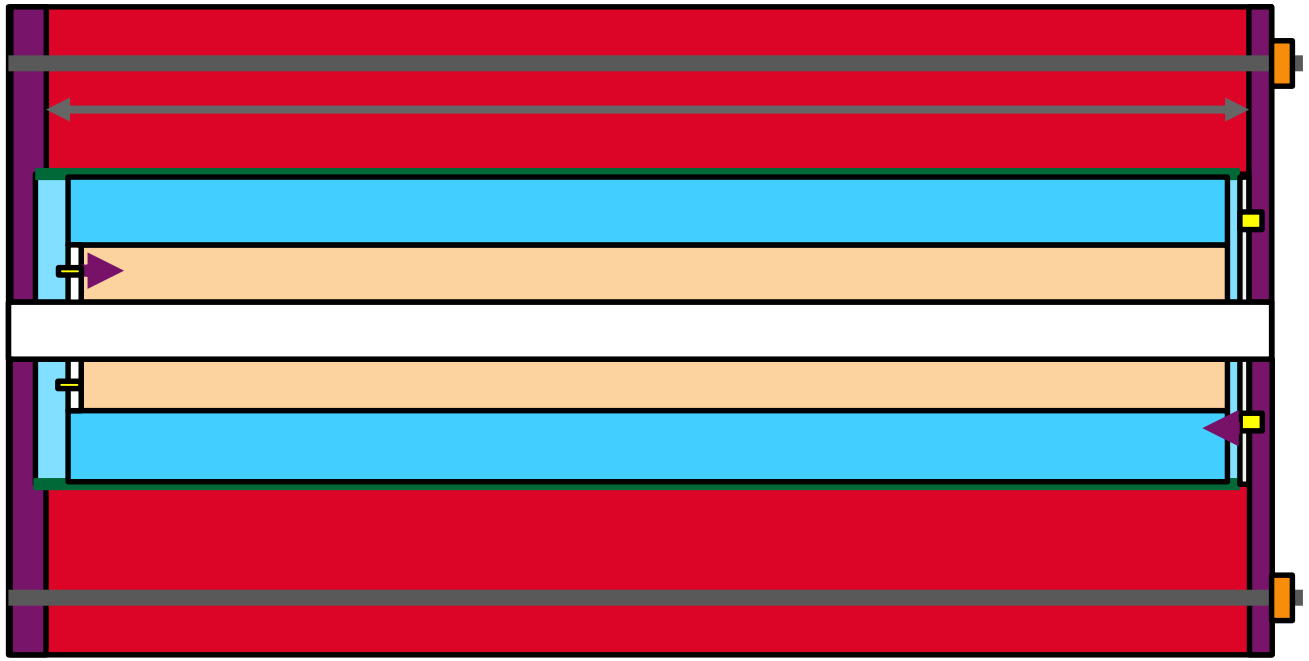
All the coils behave similarly
The dispersion between the coils is 0,1 mm

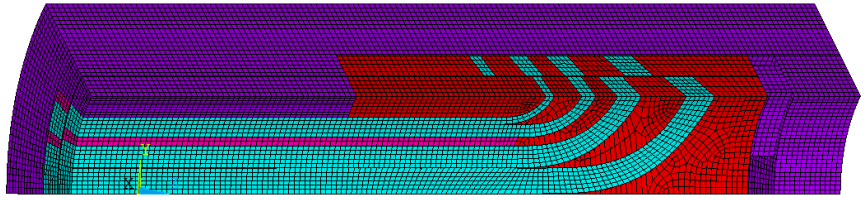
AXIAL PRELOAD

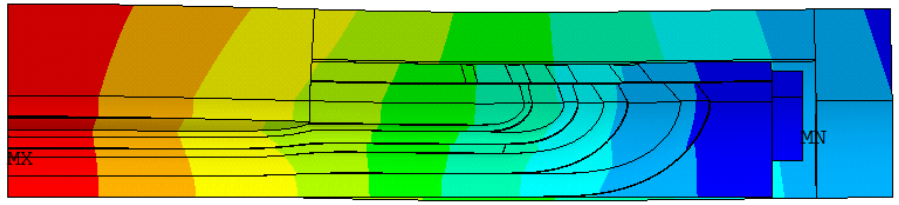




Initial design







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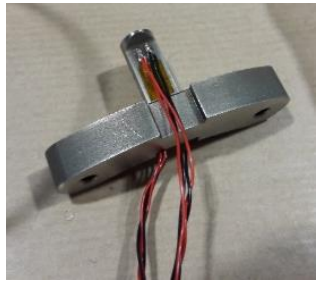
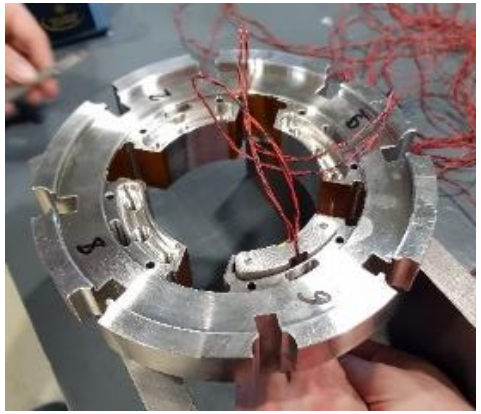
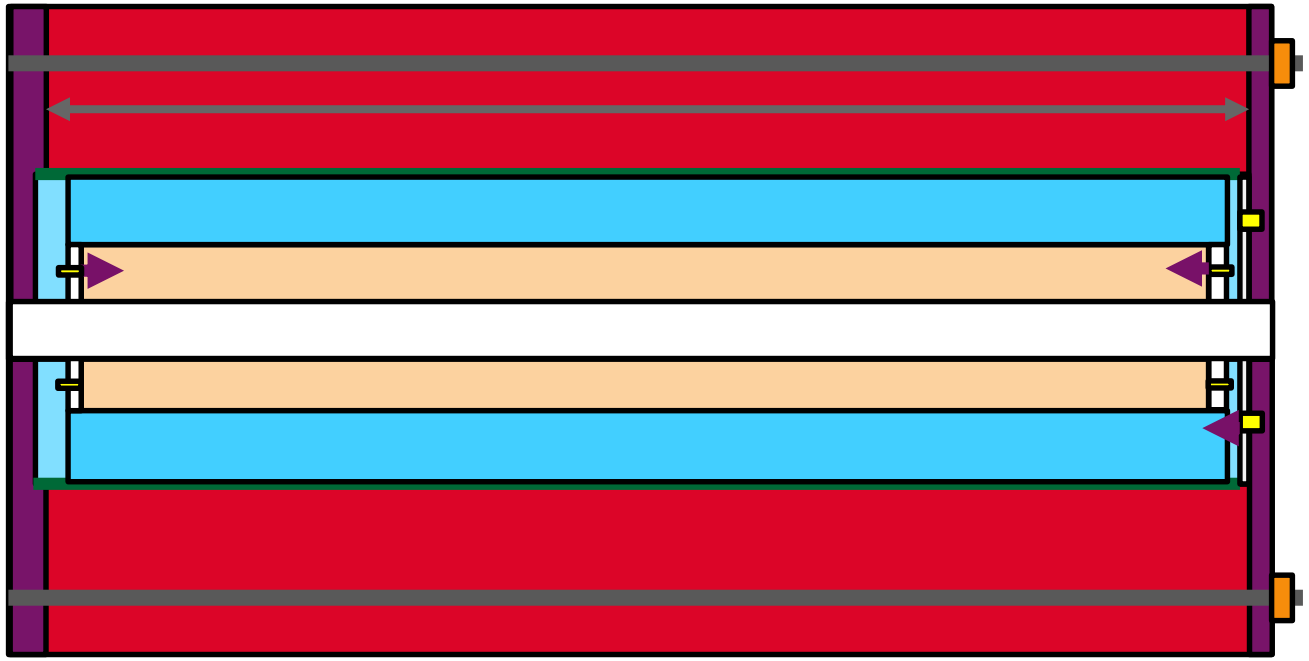
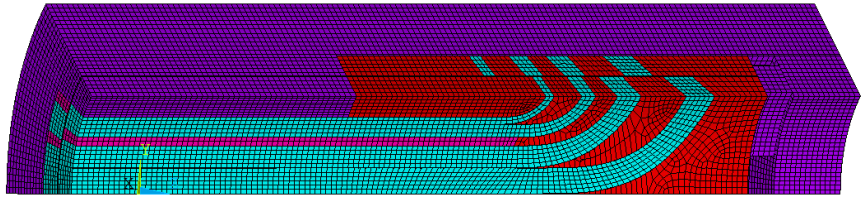
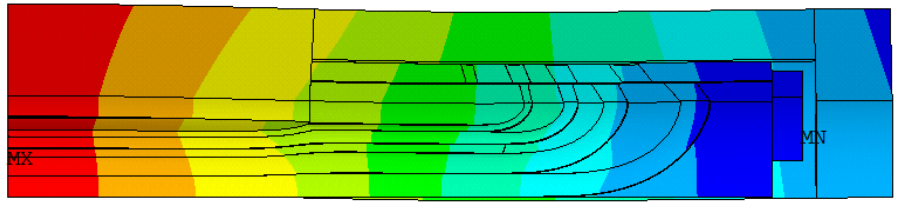




Final design

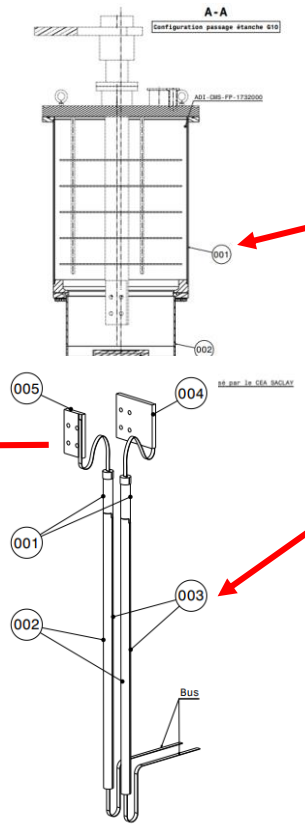


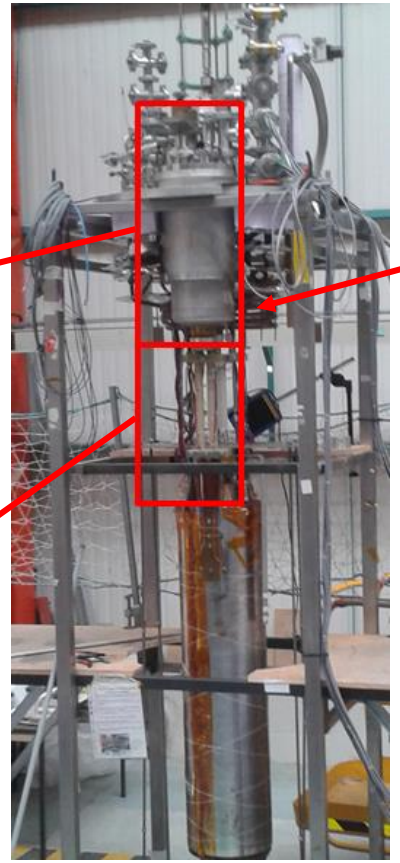


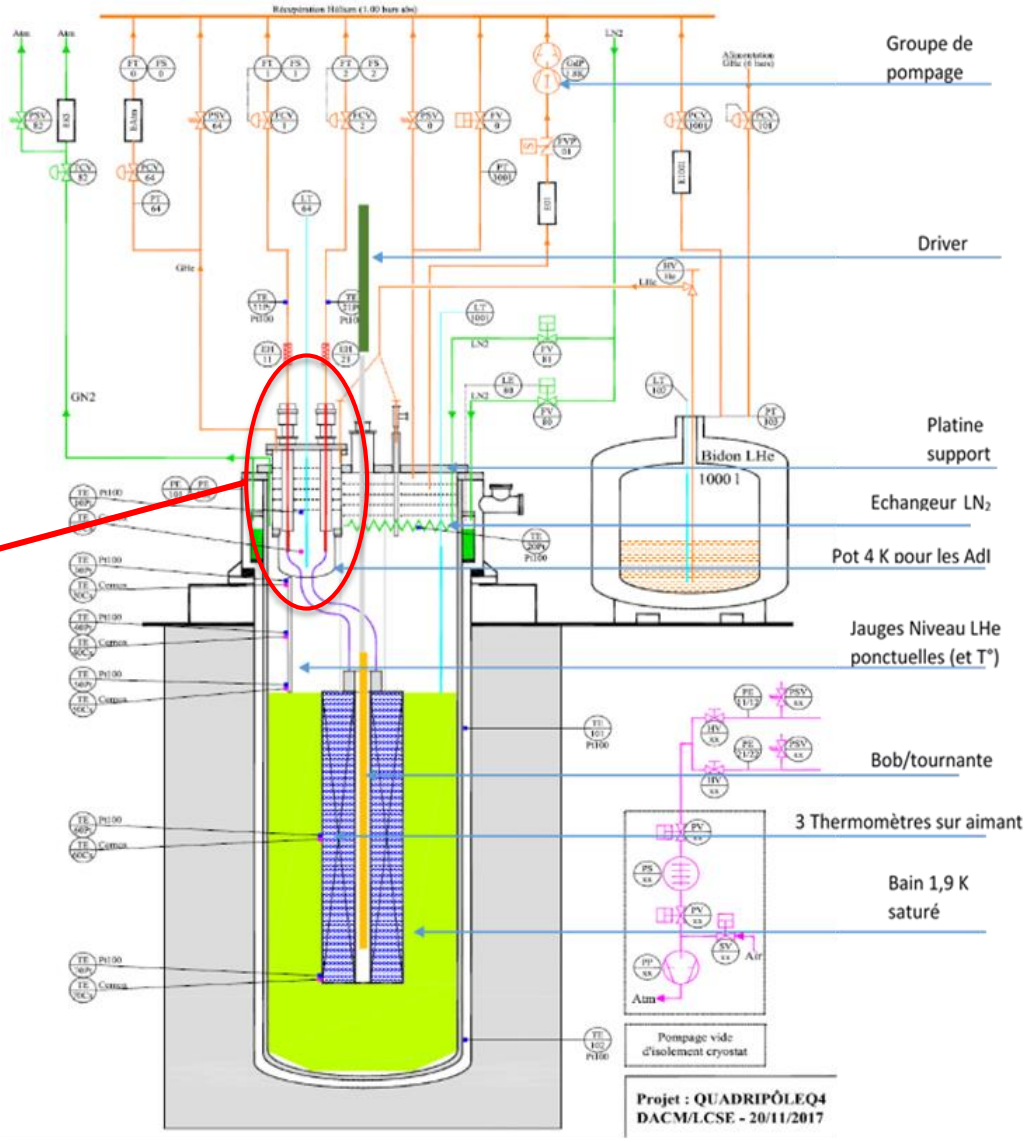


4 K POT

- Vertical station with saturated Helium bath (Patm at 4.2K and 23 mbar at 1.9K)
- 4 K pot to reach the 1,9 K
- ADI AMI copper



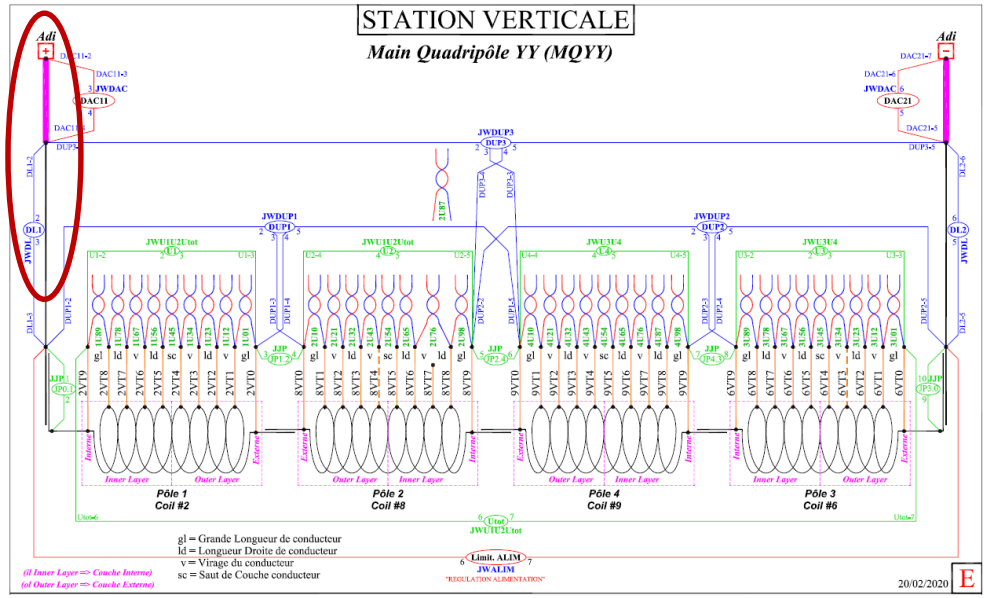


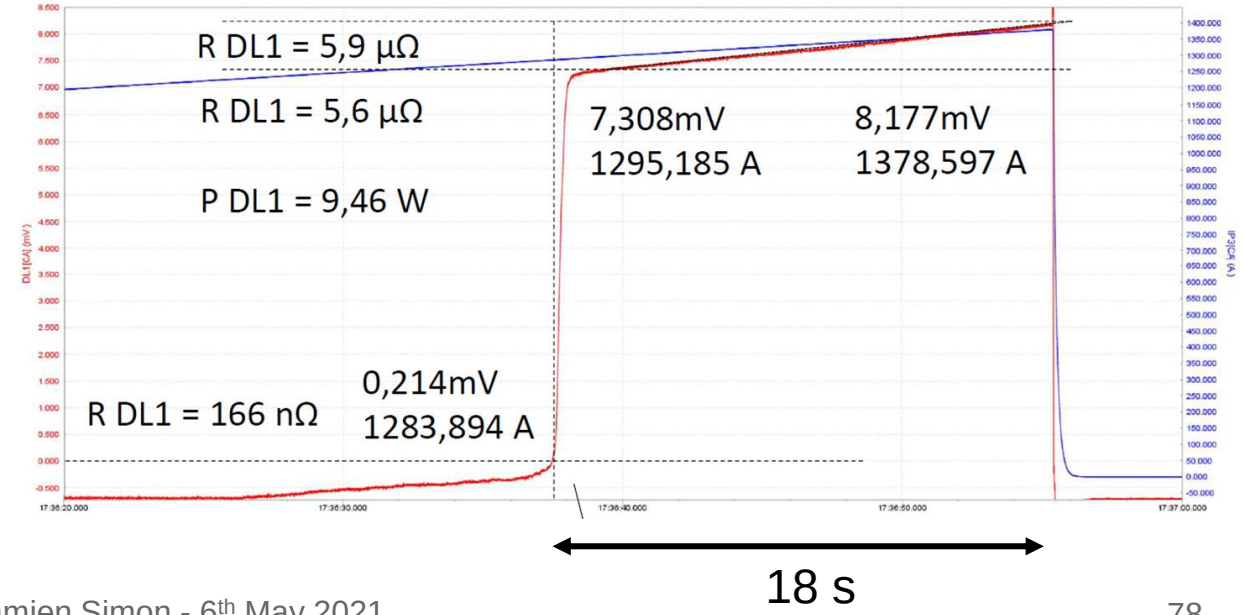


Synoptique station test MQYYM

FIRST POWERING TO QUENCH

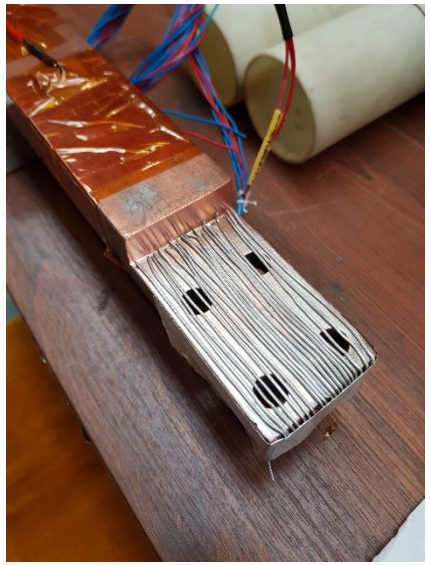
- Busbar become resistive at 1295 A reached threshold at 1378 A => discharge triggered
- Power dissipated ~9W (not measurable on the 4K pot He bath)
- 5,6 mW => 4,5 m bus resistance (RRR=40) and 12 cm cable resistance
- Decision to warm up the magnet to diagnose and repair the busbar area

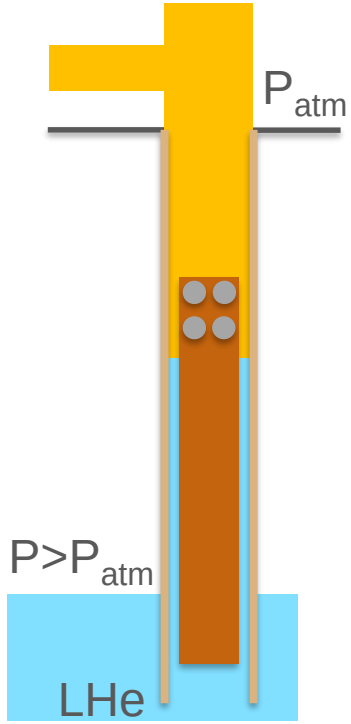




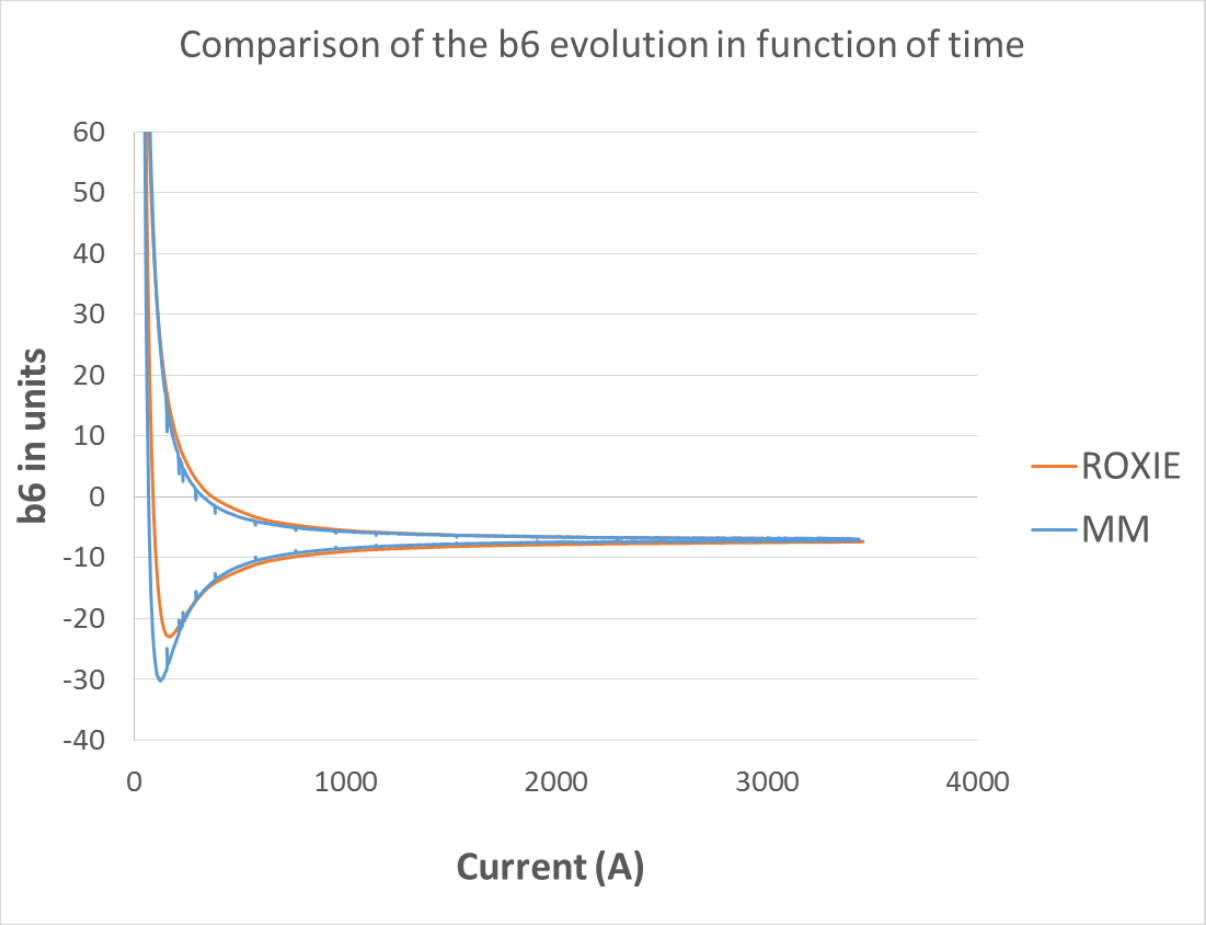
BUSBAR CHANGE AND NEW STRATEGY

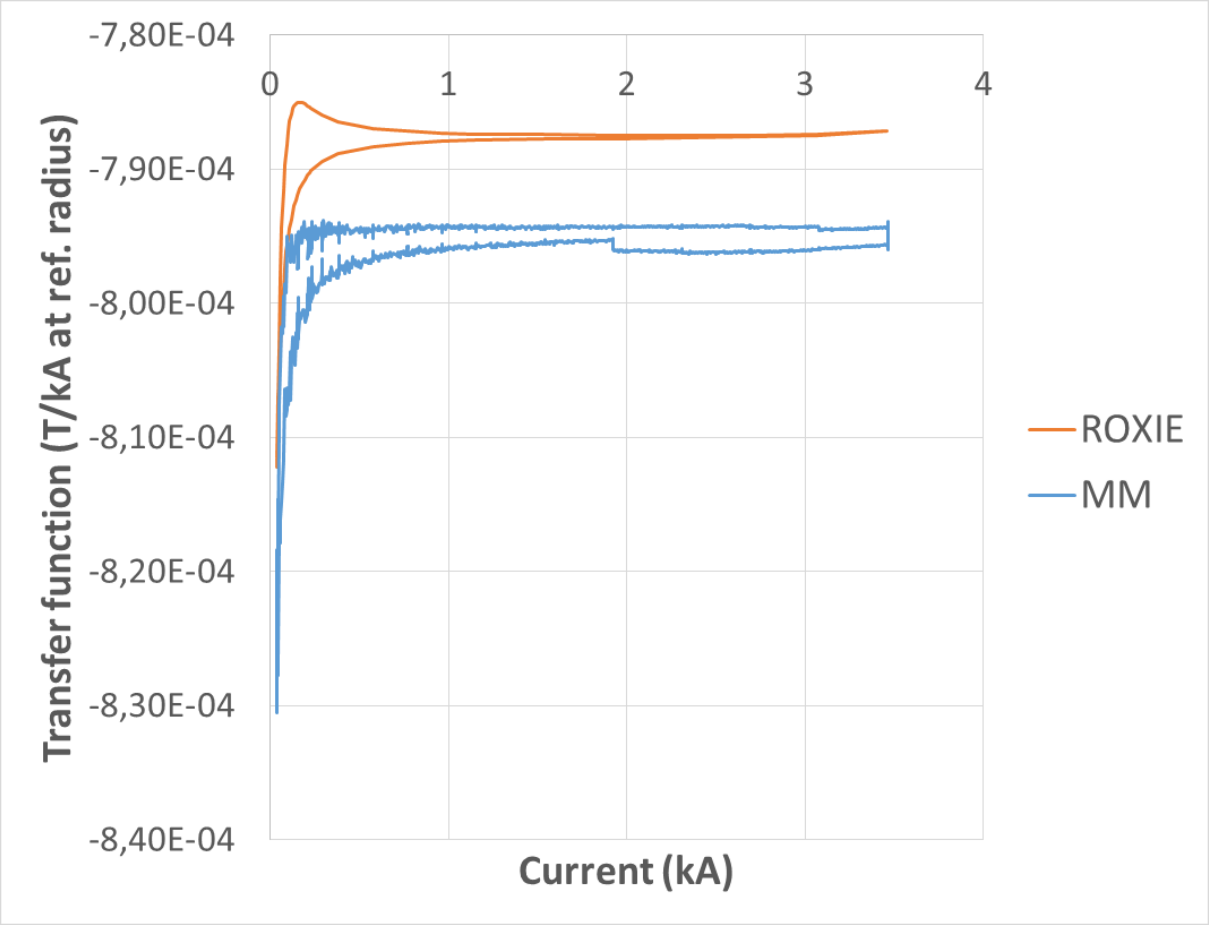
- Simplification of the test station design by removing the 4K pot
- Same test plan without the 1,9 K training (the 1,9 K test will be done later on the STAARQ station)
- New busbar already used on an other project with CMS cable
- Instrumentation reinforce on each busbar (2 thermal sensors, 12 new Vtaps per busbar) + Improvement of the busbar cool-down



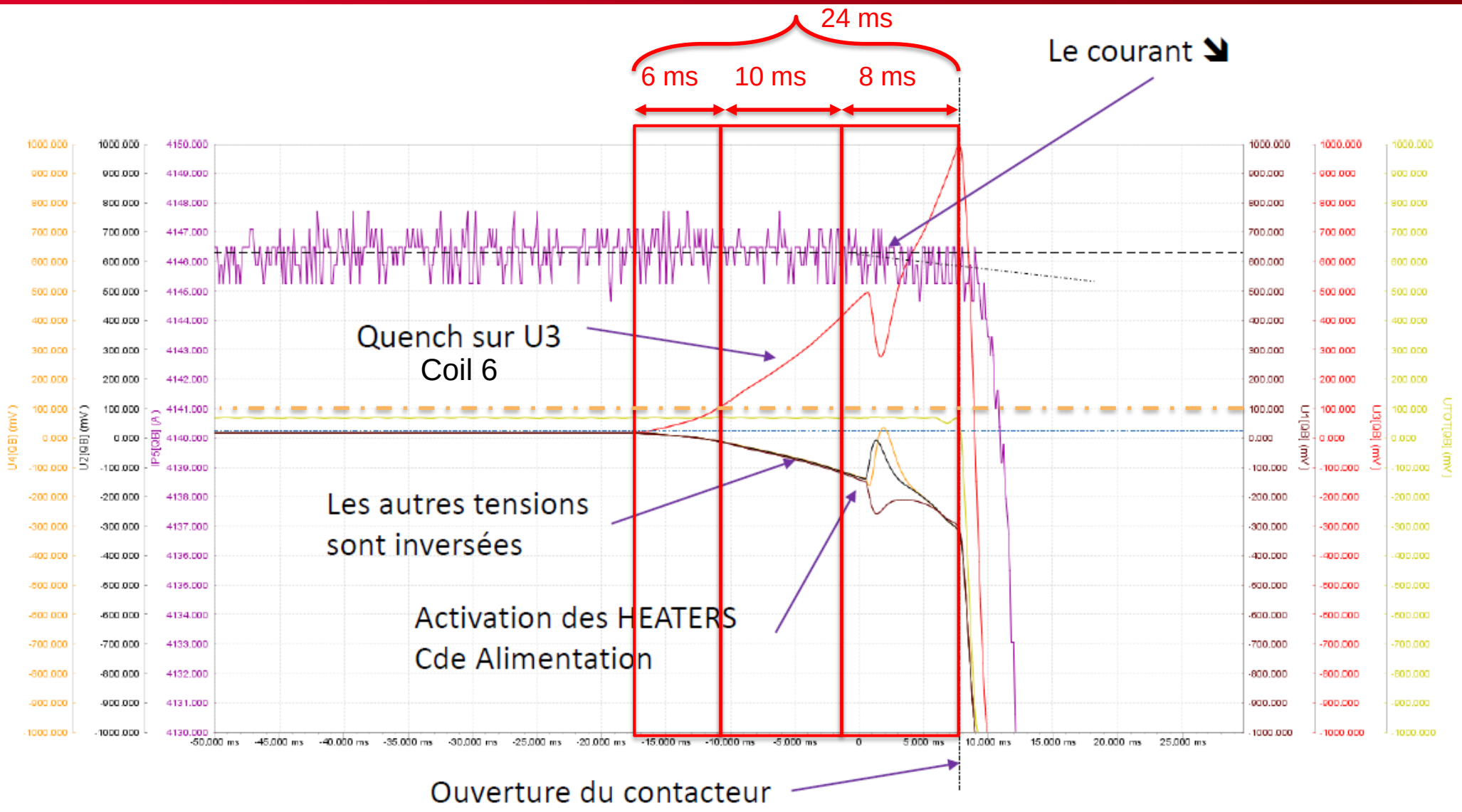


MAGNETIC MEASUREMENTS





TRAINING AT 4.2 K



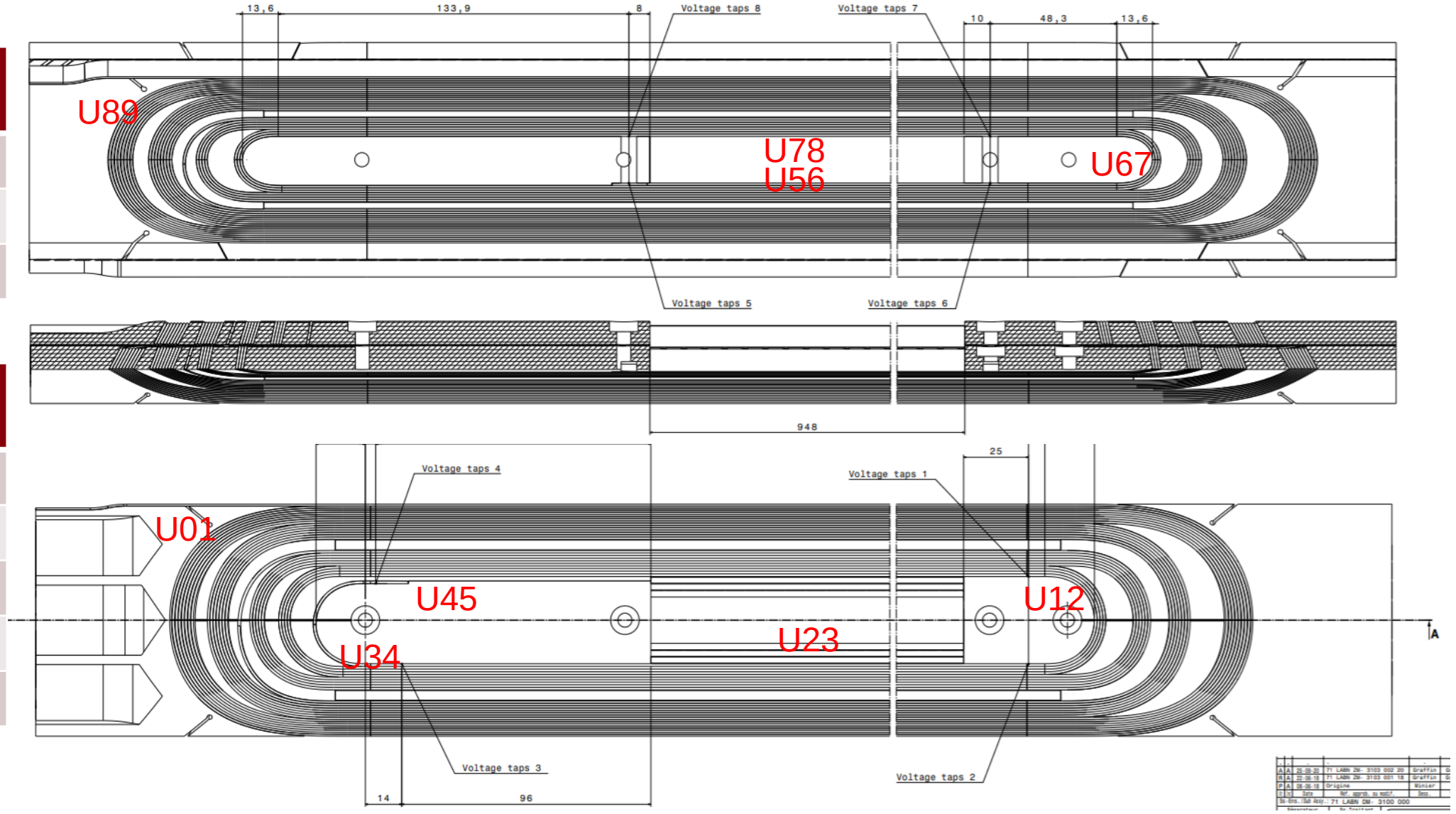
QUENCH PROPAGATION

Quench propagation n°1		
t = 0 ms	U56	U45
t = 5 ms	U23	U34
t = 16 ms	U67	

Propagation velocity ~ 60 m/s

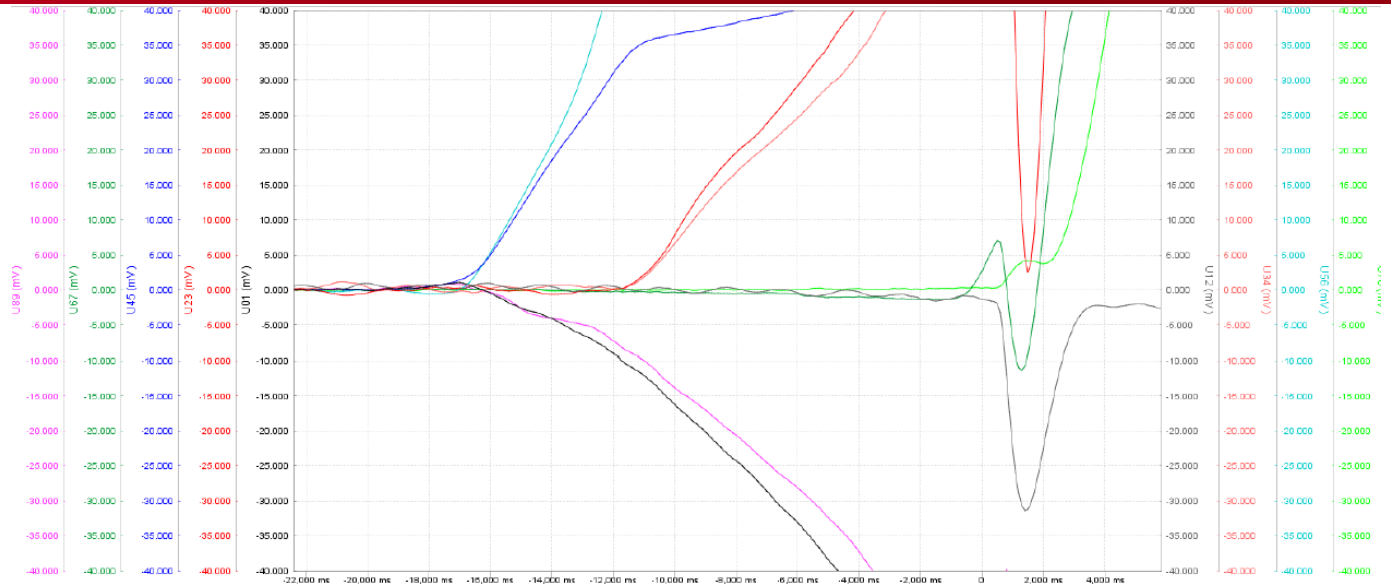
Quench propagation n°2		
t = 0 ms	U65	
t = 1 ms	U45	U34
t = 7 ms	U32	
t = 8 ms	U98	
t = 14 ms	U76	

Propagation velocity ~ 65 m/s

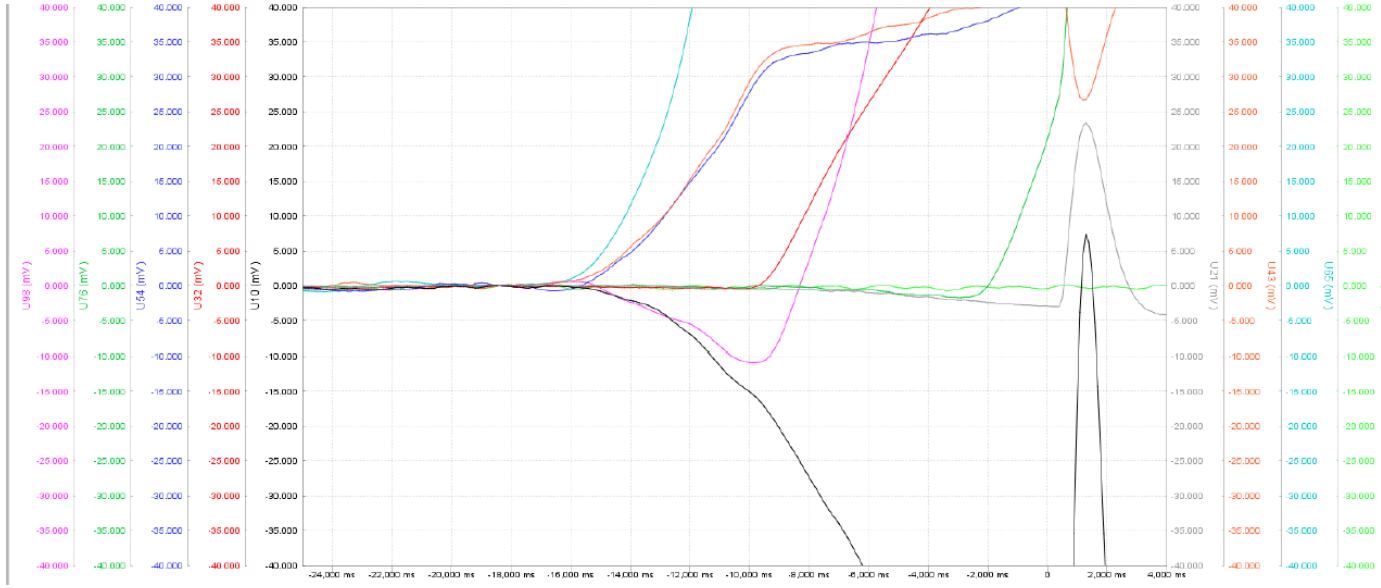


QUENCH PROPAGATION

QUENCH N°1

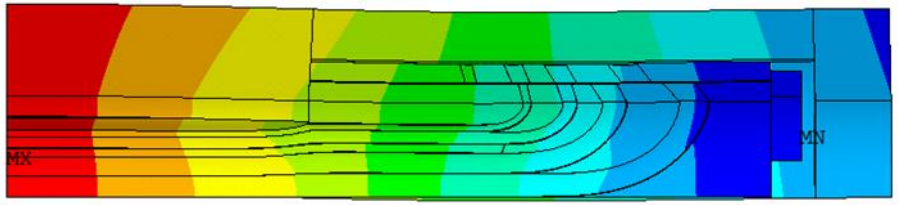


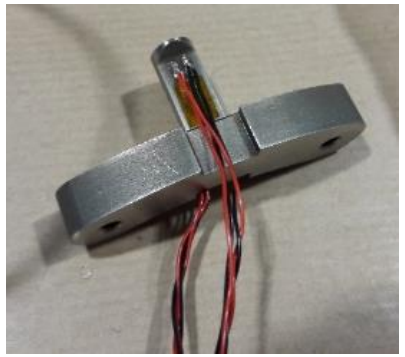
QUENCH N°2

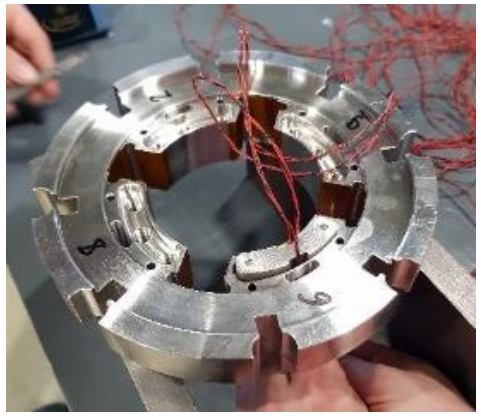


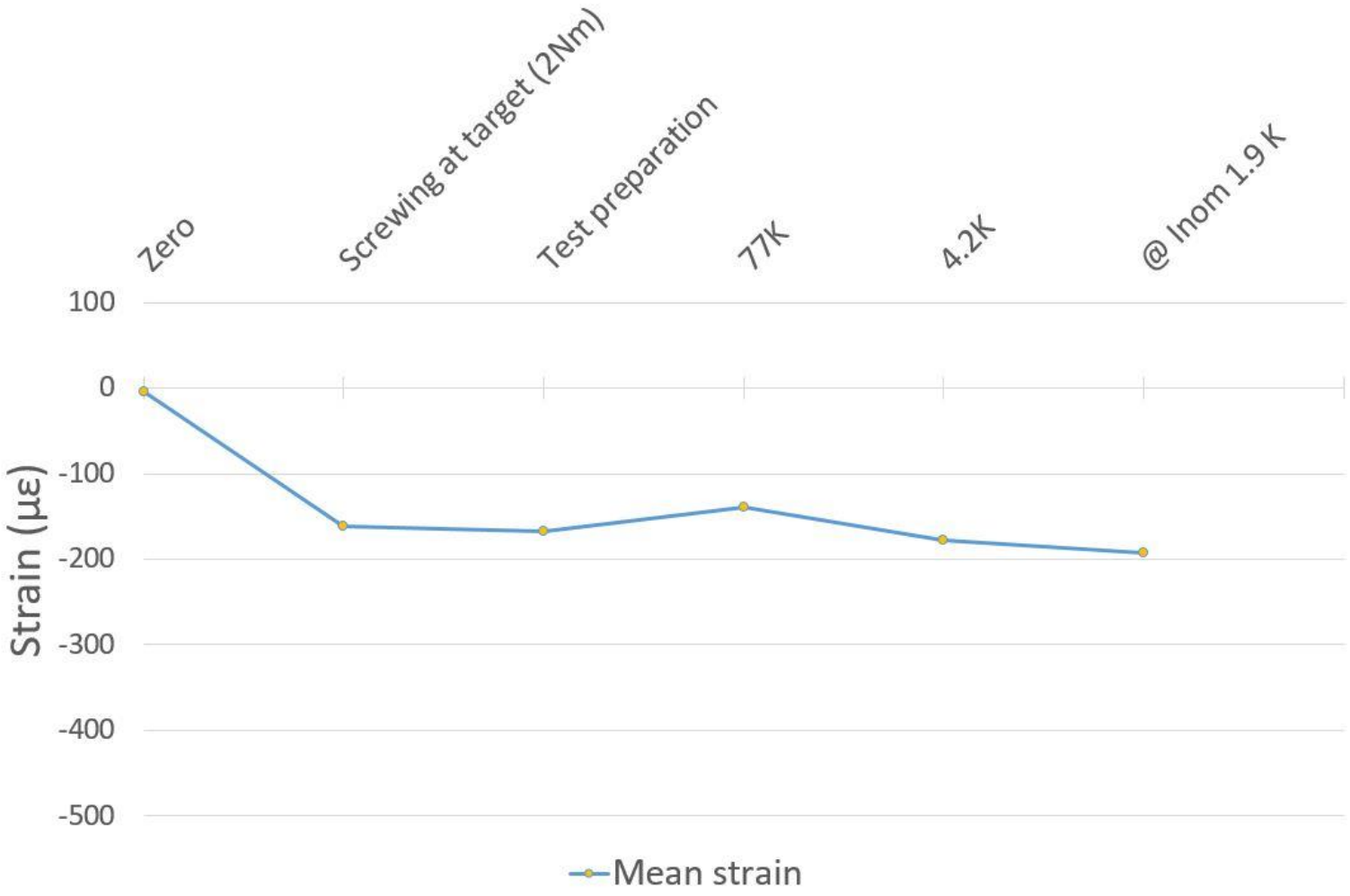
AXIAL PRELOAD

- Bullets average strain at the different steps of the project
- The heads are all the time preloaded









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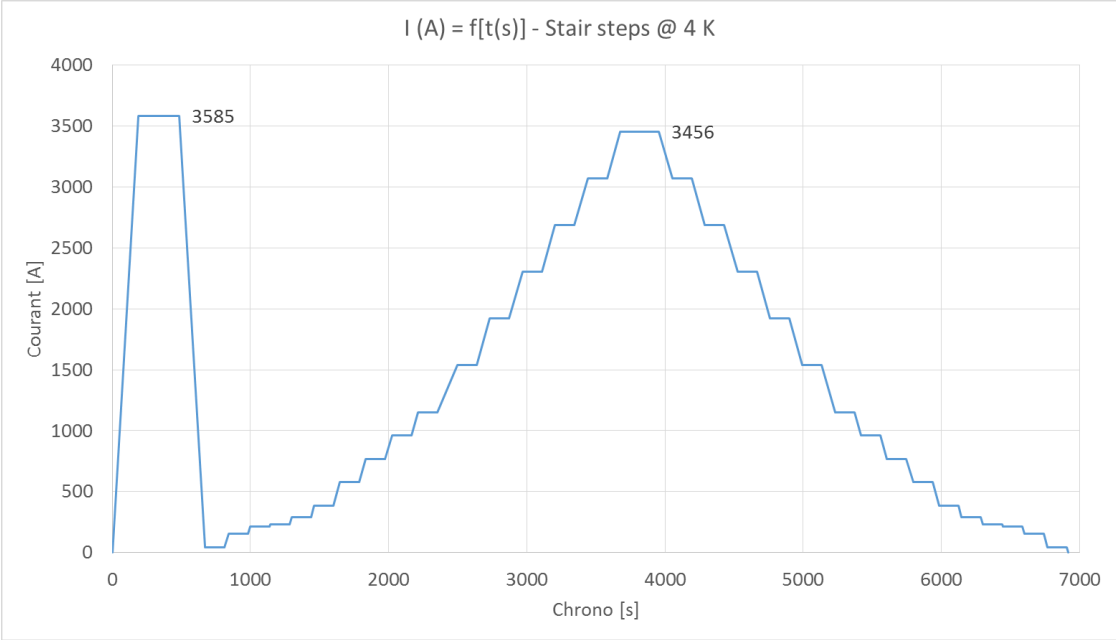

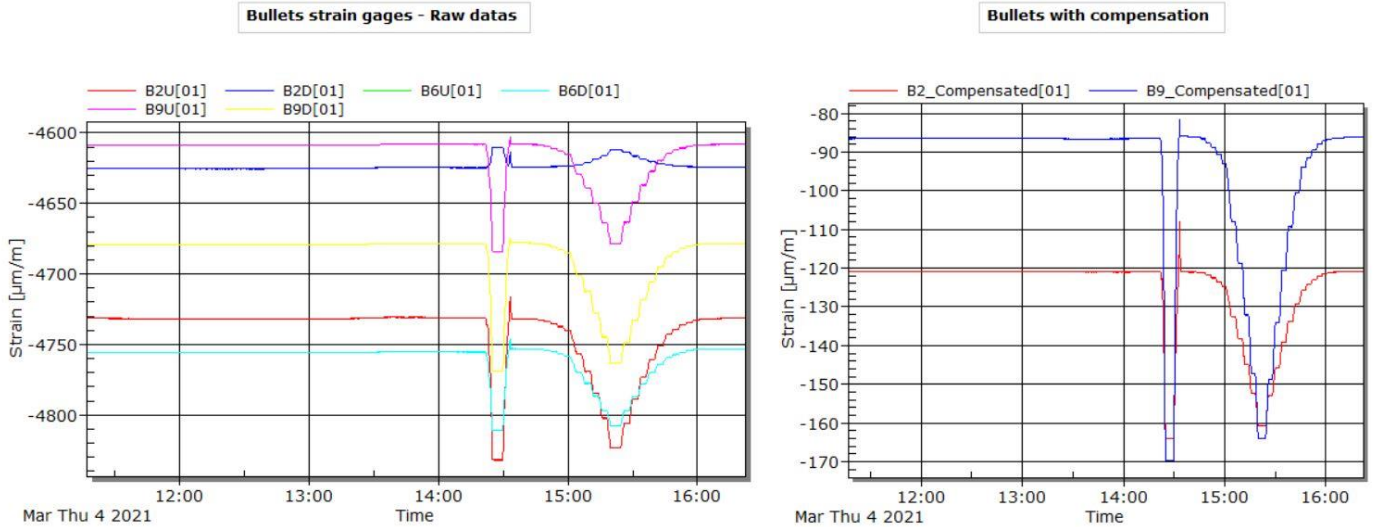

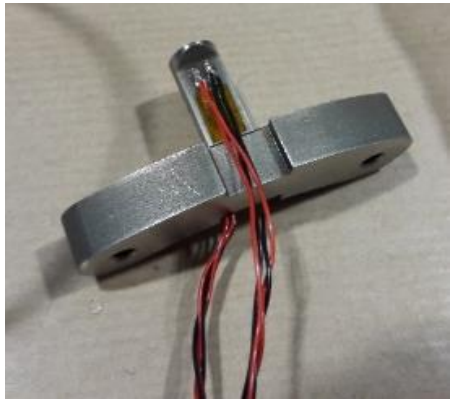

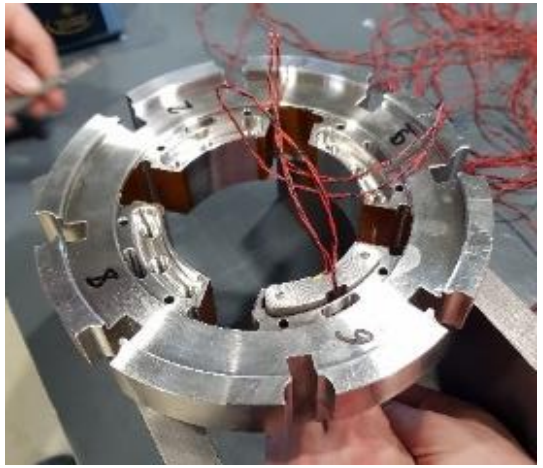

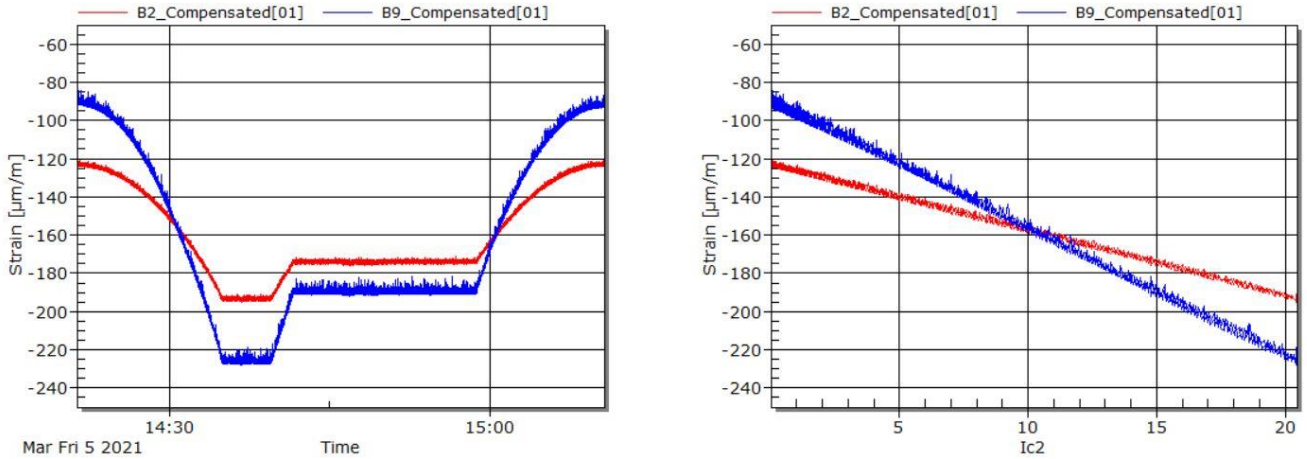

Commissariat à l'énergie atomique et aux énergies alternatives
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