11T Summary

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11th HL-LHC Collaboration Meeting, CERN, https://indico.cern.ch/event/1079026/, 2021-10-19

Outlook

- Introduction
- Main activities part of Phase 1
  - QA/QC
  - Coil visual inspection
  - Tolerance analysis
  - Tomography and metallography
  - 3D thermo-mechanical modelling
- Link between findings and cold test results
- Hybrid magnet design and plan for Phase 2
- Concluding remarks

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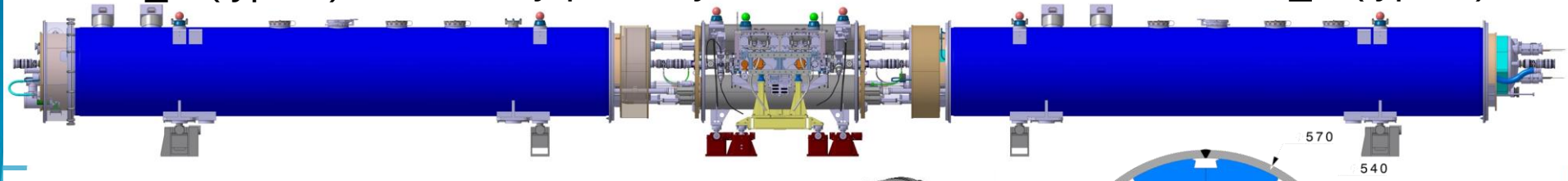
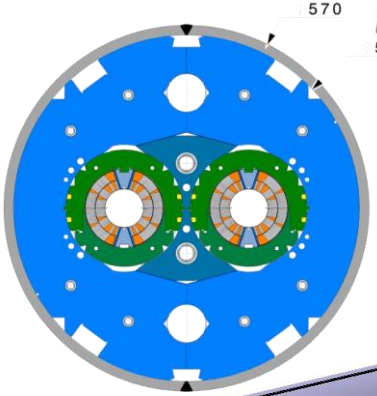
The 11T Dipole Full-Assembly

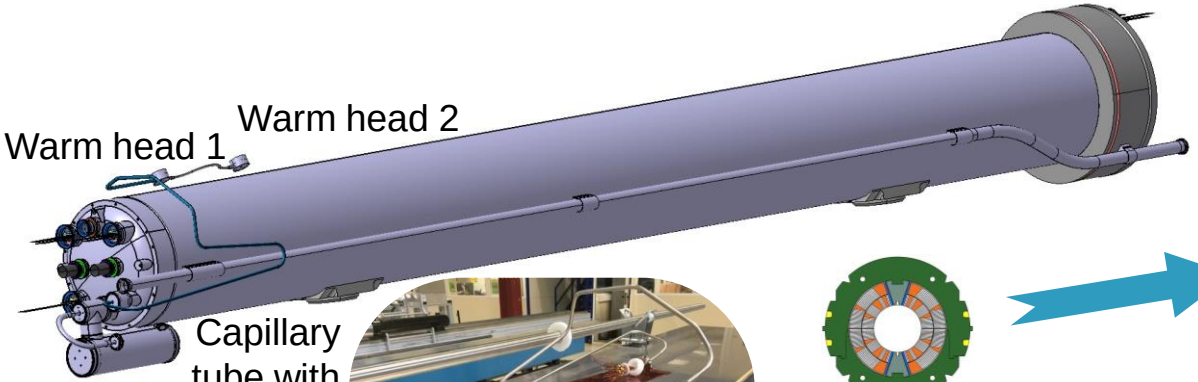
LBH_**A** (type A) By-pass cryostat with collimator LBH_**B** (type B)



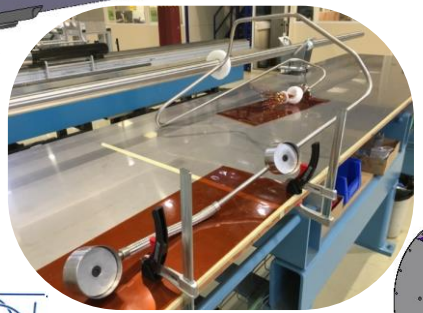


Warm head 1

Warm head 2



Capillary tube with a cold part, and two warm heads



11T dipole plan – 2019
Schematic view

Magnets equipped with impregnated QH

Magnets equipped with external QH

S1: LMBH**B**002			
D1-CC02		D2-CC03	
UP C05	LO C01	UP C07	LO C06

S2: LMBHA001			
D1-CC05		D2-CC04	
UP C12	LO C13	UP C08	LO C09

1st pair of magnets

S3: LMBH**A**002			
D1-CC07		D2-CC06	
UP C15	LO C16	UP C10	LO C14

S4: LMBH**B**003			
D1-CC09		D2-CC08	
UP C20	LO C21	UP C17	LO C19

2nd pair of magnets

S5: LMBH**A**003			
D1-CC10		D2-CC11	
UP C23	LO C22	UP C25	LO C24

S6: LMBH**B**004			
CC12		CC13	
C26	C27	C28	C29

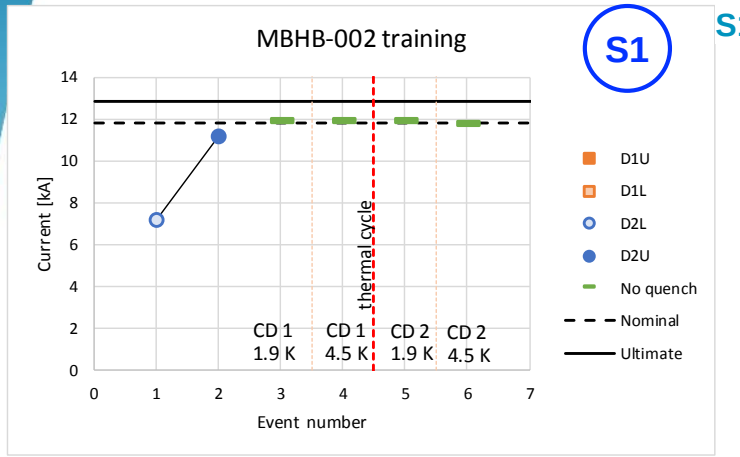
Spare magnets

A YEAR AGO

Courtesy T. Bampton and H. Prin

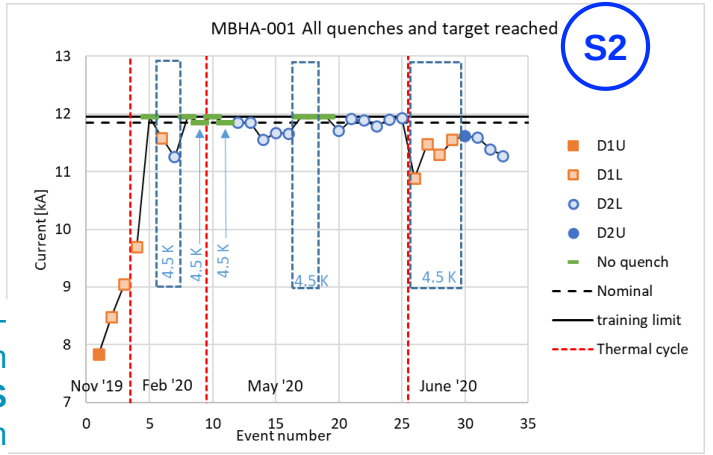
- *Cold mass of **S5** was completed in Bldg.180 on 2020-10-01*
- *Cryo-magnet **S4** was in test in Bldg. SM18, a first run was done with 2 quenches before reaching nominal, a detraining quench and a QH failure, a successful 12-h holding current test at nominal current, and another quench just below nominal.*
  V-I signals were clean, i.e. no degradation. We had started a thermal cycle

Overview of the cold tests results

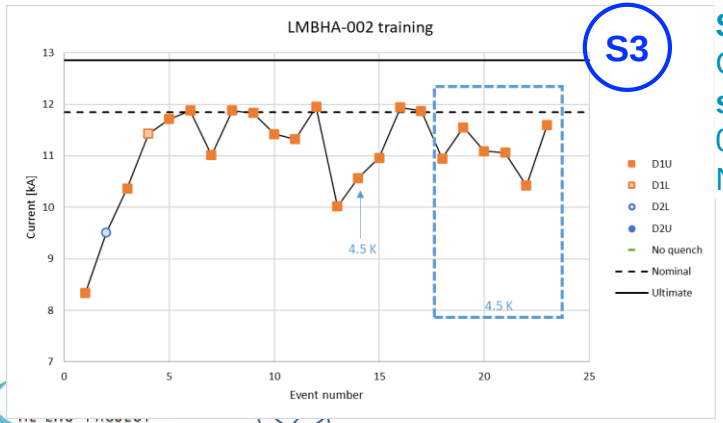


S1: golden magnet?

Courtesy G. Willering



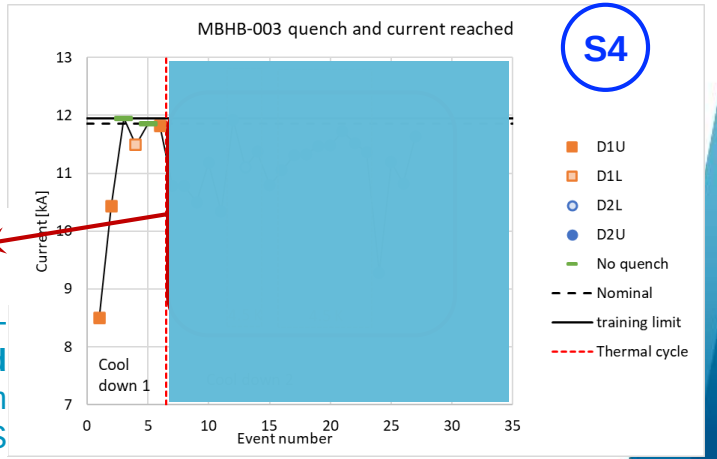
S2: degradation in D1L-GE13 and D2L-GE09, in both cases in **head CS** pole turn



S3: degradation in D1U-GE15, **head NCS and straight part** between 0.5 and 1.1 m from head NCS

TRIGGERED A HOLD POINT

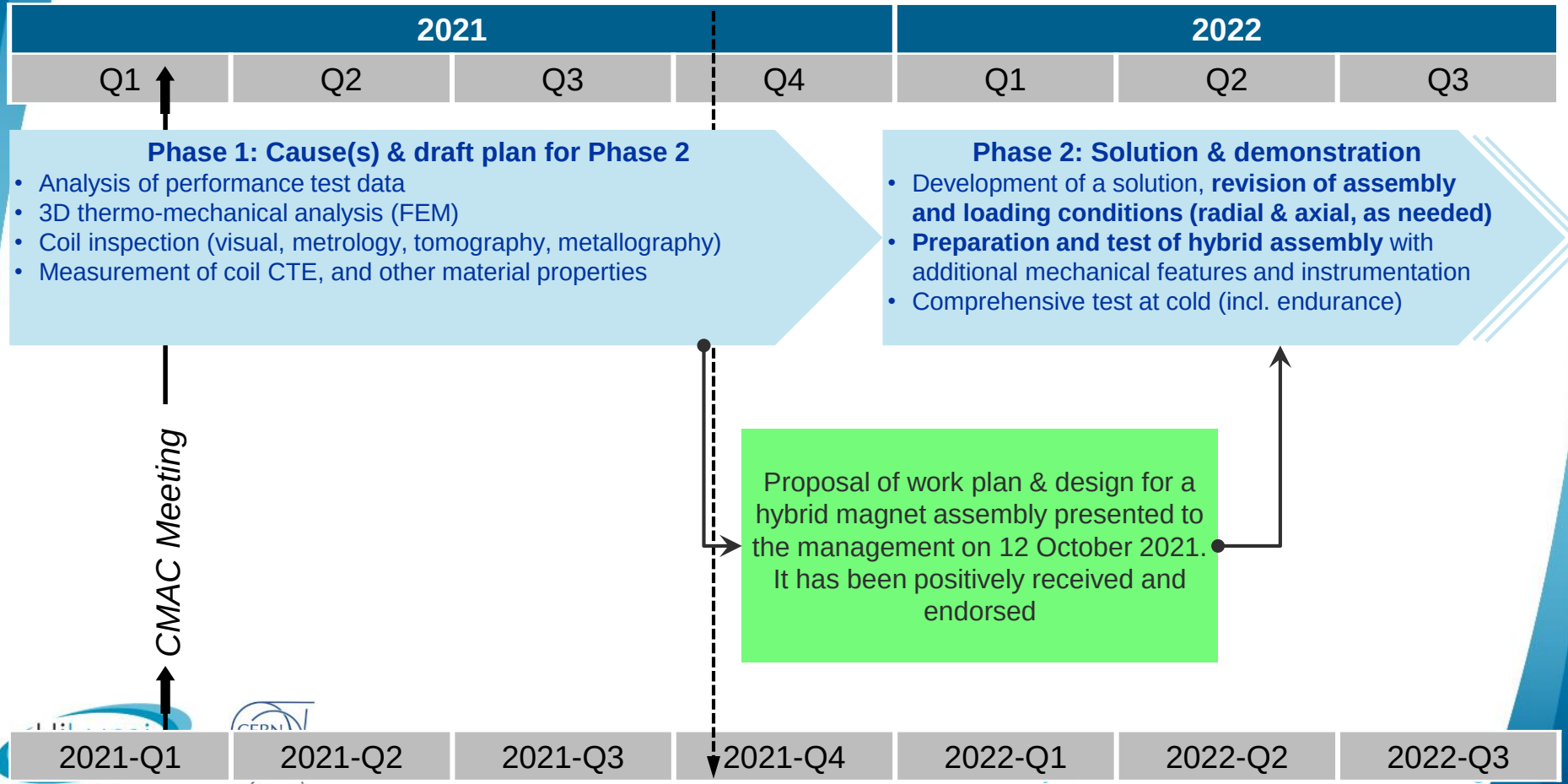
S4: degradation in D2U-GE17, **head CS and straight part** @ 1.4 m from head CS



Next steps

- It has been **decided** during a meeting of the Accelerator Sector Management Board held on 30 November 2020, after presentation of a strategy proposal:
  - **Not to install any 11T unit during LS2 and to carry out investigations to determine the root cause(s) of the performance degradation**
  - Subsequent steps to be then agreed upon following the outcome of this first post-mortem analysis
- A HL-LHC **Decision Management report** was issued along these lines on 10 January 2021
- A **special meeting of the CMAC** (CERN Machine Advisory Committee) was held on 1st March 2021 upon request of the CERN Scientific Policy Committee:
  - To **review the 11T magnet programme**
  - A series of talks were given to explain the status, on-going actions and strategic plan for the 11T dipole
- A new 11T Task Force was set up in late March (kick-off meeting on 24 March 2021) to execute Phase 1 of the plan

Timeline & decision milestones



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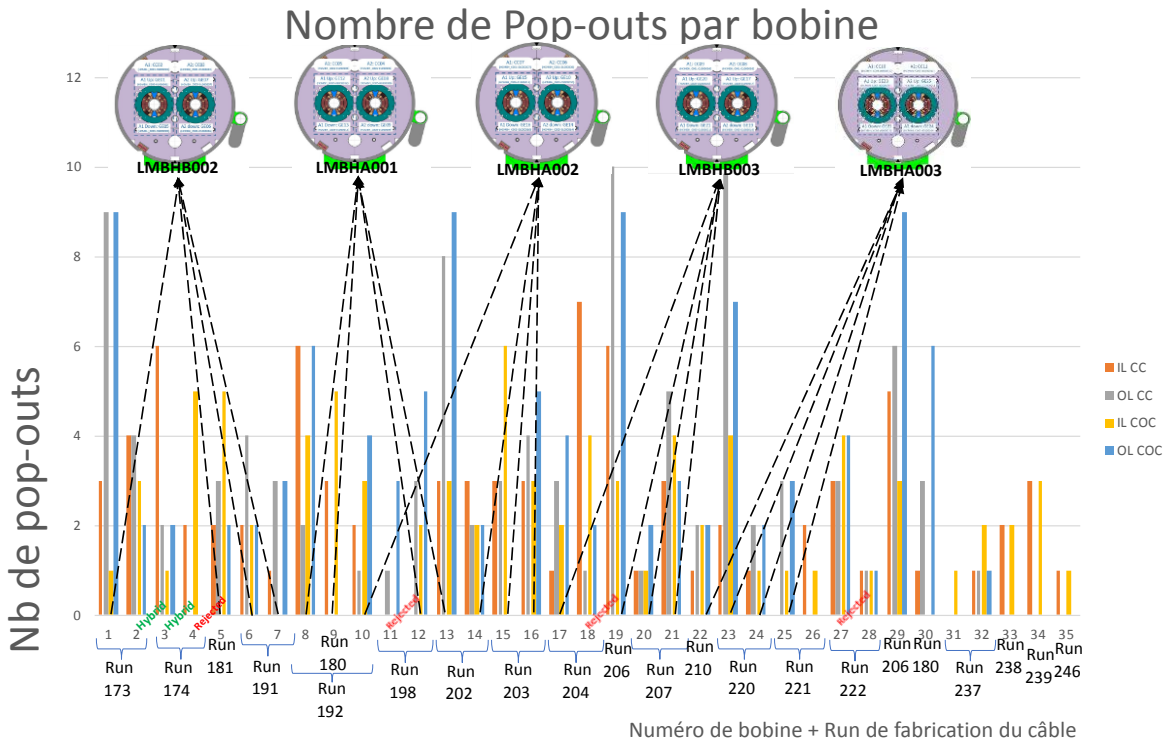
Overall status on QA/QC

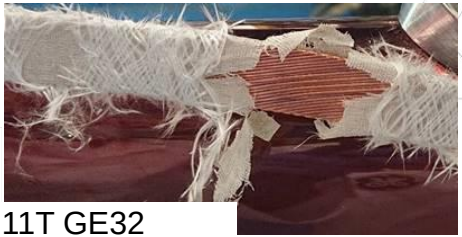
- Review QA/QC of the 11T dipole program, identify weaknesses and propose changes and/or mitigation solutions
- The main manufacturing steps were reviewed, i.e. winding, curing, reaction and splicing, impregnation and collaring
- Statistics on some data

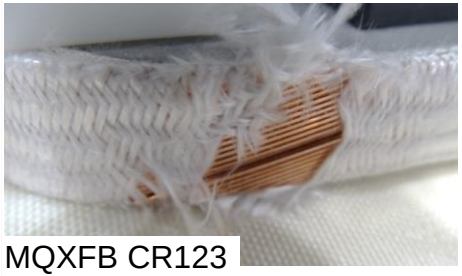
Example: winding pop-outs

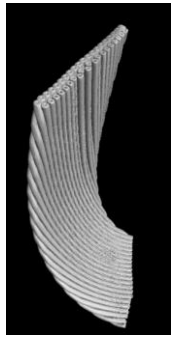
Courtesy R. Principe et al.

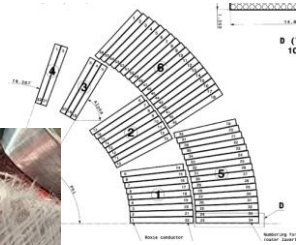
- Pop-out: the strand is misaligned, moving off its nominal position during winding (cable instability)




11T GE32


MQXFB CR123





	Inner L. 22 turns	Outer L. 34 turns	Total 56 turns
CS	61	82	143
NCS	64	88	152

Nr pop-outs follows same ratio as Nr turns IL vs OL

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List of coils inspected

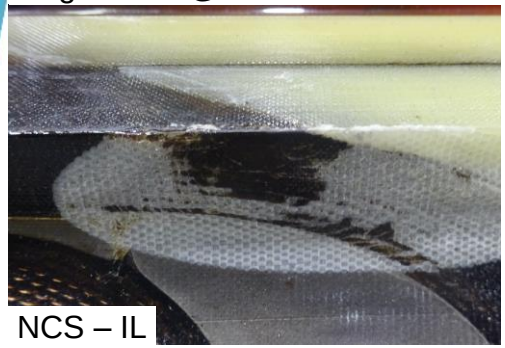
Magnet	Coil #	Note	Status
11T short model SP105	114	Good performance coil	Done
11T short model SP105	115	Limiting coil	Done
11T short model SP109	119	Midplane quenches	Done
11T short model SP109	123	Midplane quenches	Done
11T full-length magnet S2-CC04	GE08	Good performance coil	Done
11T full-length magnet S2-CC04	GE09	Limiting coil, coil head CS already cut for CT/metallography	Not done because cut for CT first
11T full-length magnet S2-CC05	GE12	Good performance coil	Done
11T full-length magnet S2-CC04	GE13	Limiting coil, coil head CS to be cut for CT/metallography	Done
11T full-length magnet S3-CC07	GE16	Good performance coil	Done
11T full-length magnet S4-CC08	GE17	Limiting coil	Done
-	GE18	Virgin, rejected for major NCR	Done
11T full-length magnet S4-CC08	GE19	Good performance coil	Done
-	GE34	Virgin, as produced	Done
-	GE35	Virgin, as produced	Done

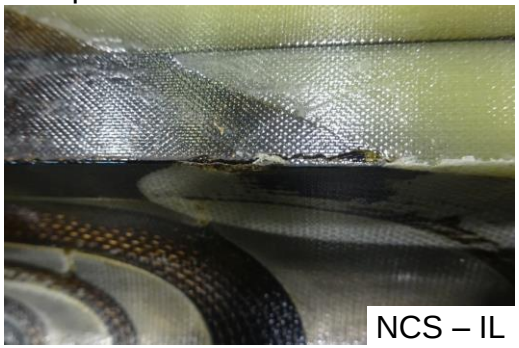
Pictures from inner/outer on all length

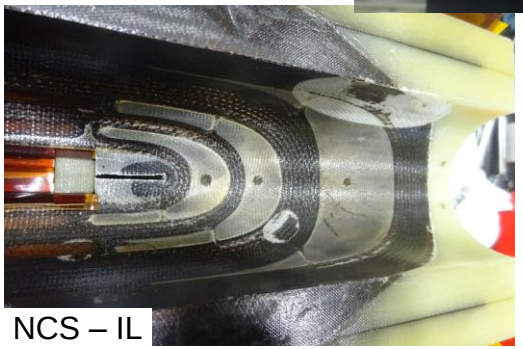
- Magnet S4 dismounted, CC08, coil **GE17** limiting the performance in S4

Courtesy R. Principe et al.

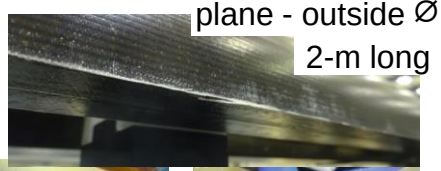
Large crack @ intersection of ID with midplane observed for the 1st time


NCS – IL

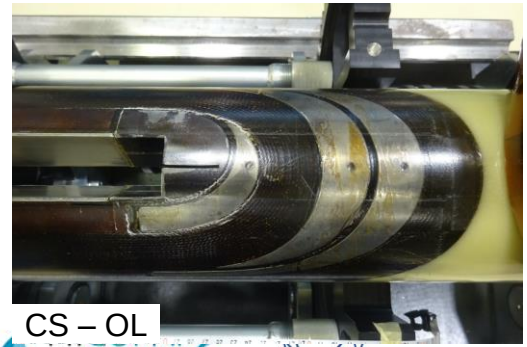

NCS – IL


NCS – IL

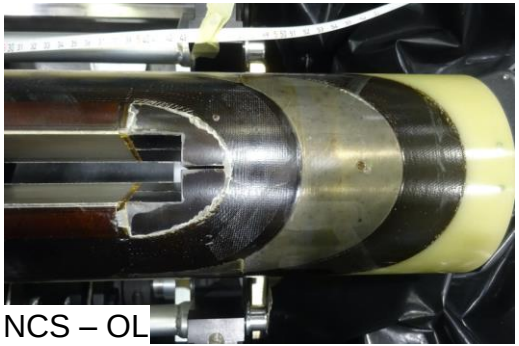
Intersection mid-plane - outside Ø 2-m long




NCS – IL


CS – OL


CS – OL


NCS – OL


NCS – OL

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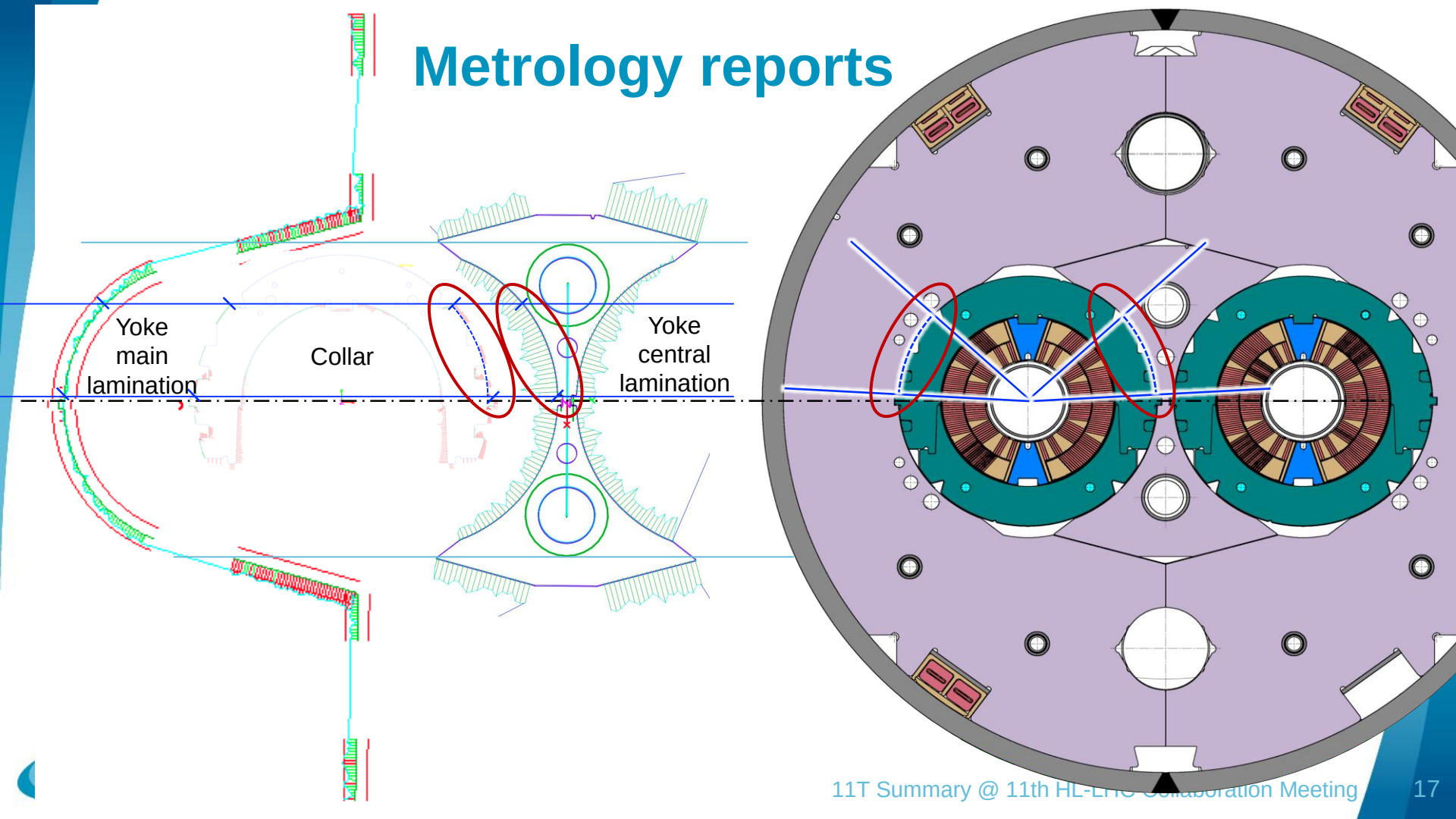
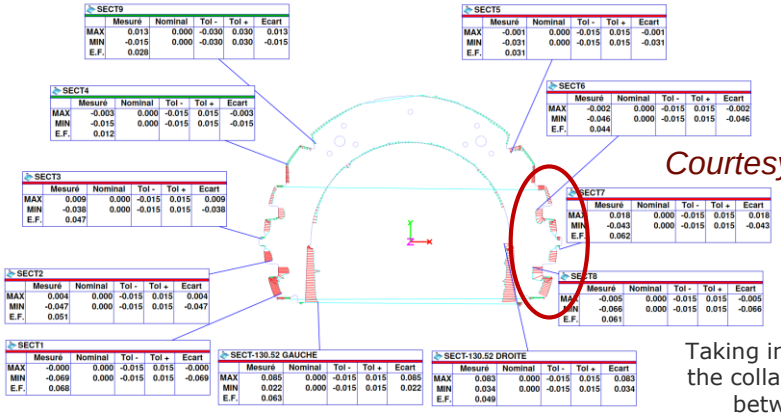
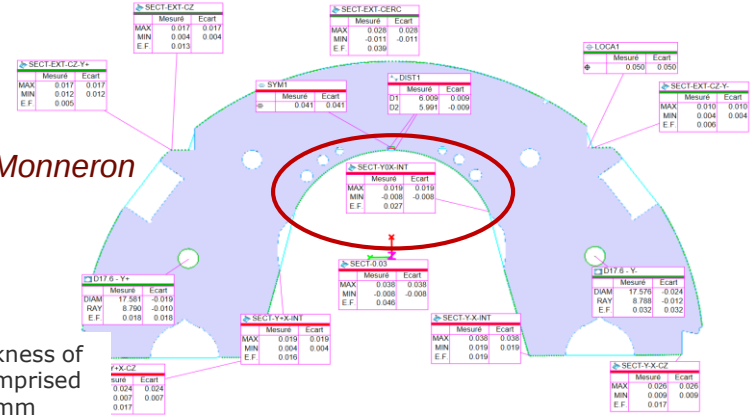
Metrology reports



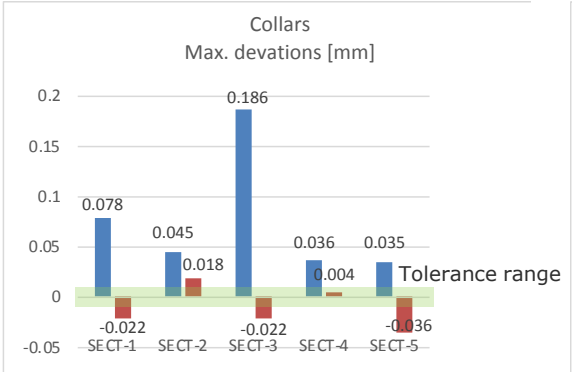
Example: interface with main lamination

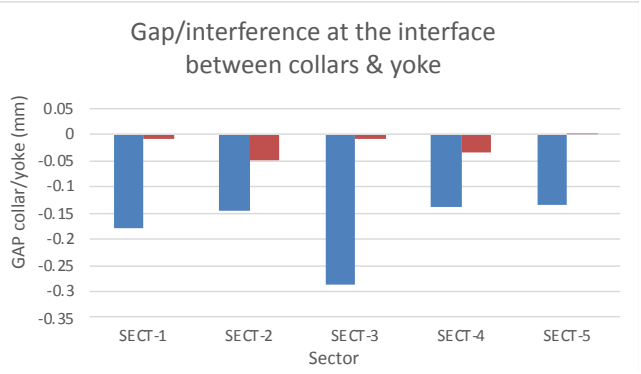


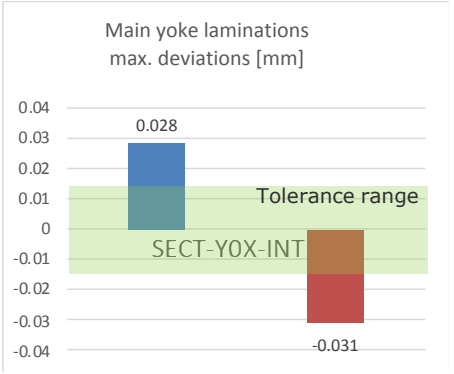
Courtesy B. Bulat, K. Monneron



Taking in account the thickness of the collar to yoke shim comprised between 0.46 & 0.47 mm







Work in progress – Need to take account of the actual size of the collared coils assembly and inject the results of the analysis in the FEA model

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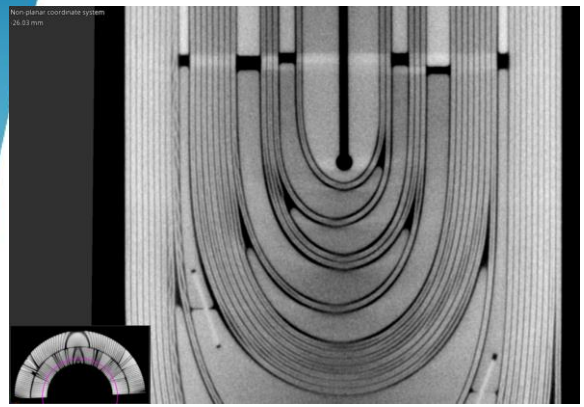
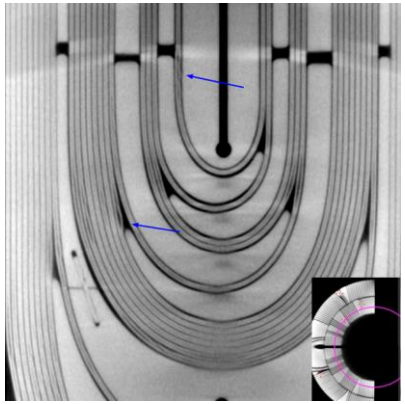
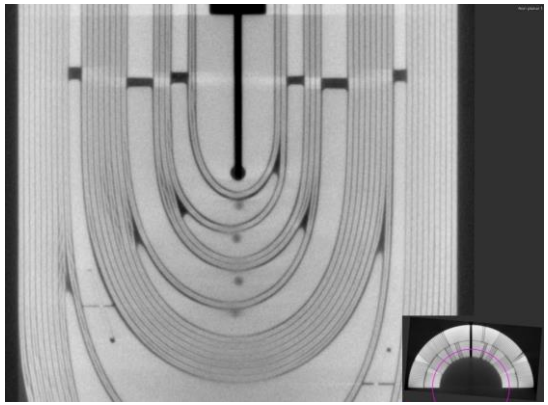
C122 – Model coil made by CERN
Virgin – Not used/tested



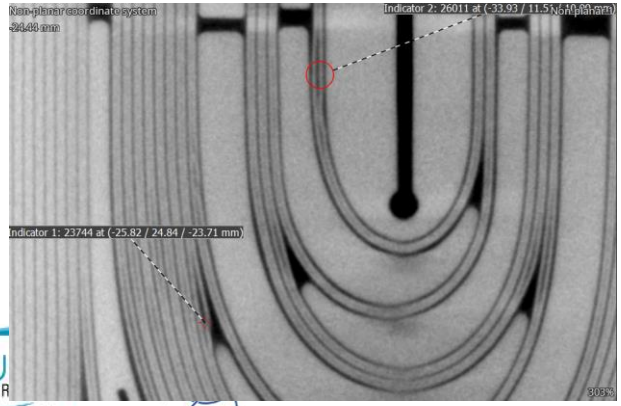
GE02 – Series production coil
Limiting coil in hybrid prototype



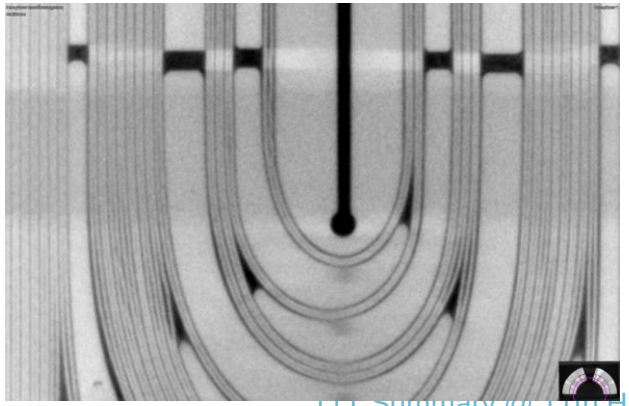
GE09 – Series production coil
Limiting coil in S2



GE11 – Series production coil
Virgin – Not used/tested



GE27 – Series production coil
Wound & cured – Not used/tested



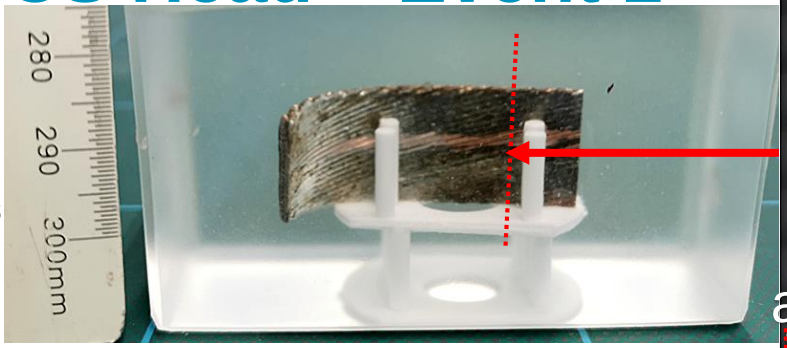
Events/imperfections are **remarkably reproducible!**

Courtesy S. Sgobba et al.

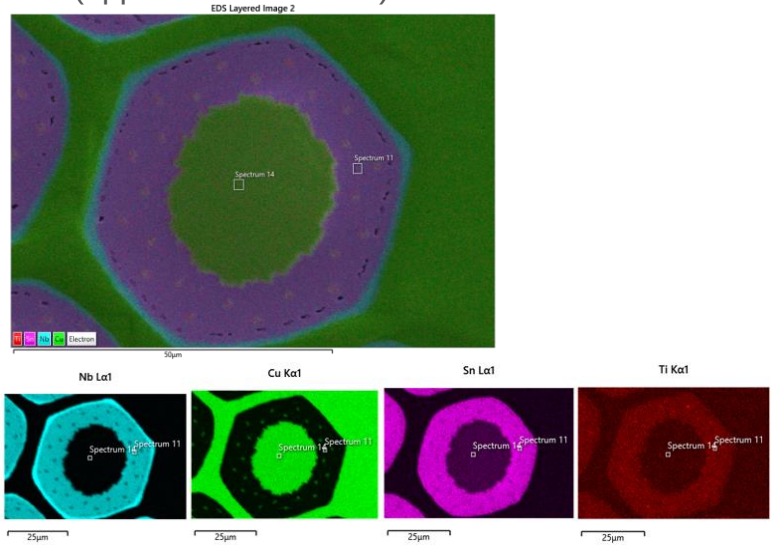
Metallography GE02 CS Head – Event 1

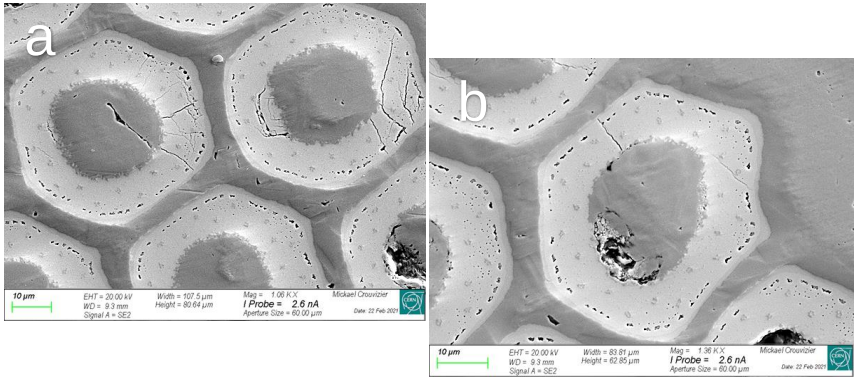
Cable of interest detailed examination shows:

- The **presence of angular and radial cracks at indicated plane** (a few SC impacted from pop-out and other strands of the cable)
- SEM-EDS confirmed that phases in presence in sub-elements composing the SC are the one expected after reaction
- **Pop-out/pop-in strands are embedded in resin** (some porosities are observed)
- **Copper** composing the strands is **in annealed state** (approx. 55-60 HV0.1)



Filaments (belonging to different strands) are affected by cracks in the SC phase



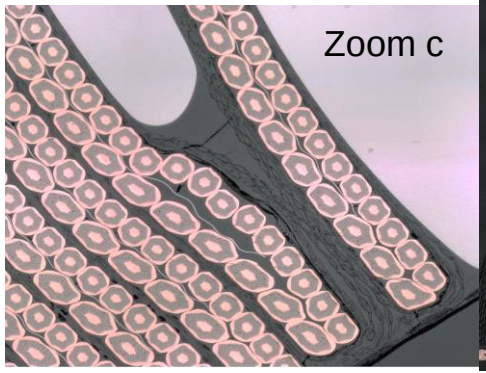


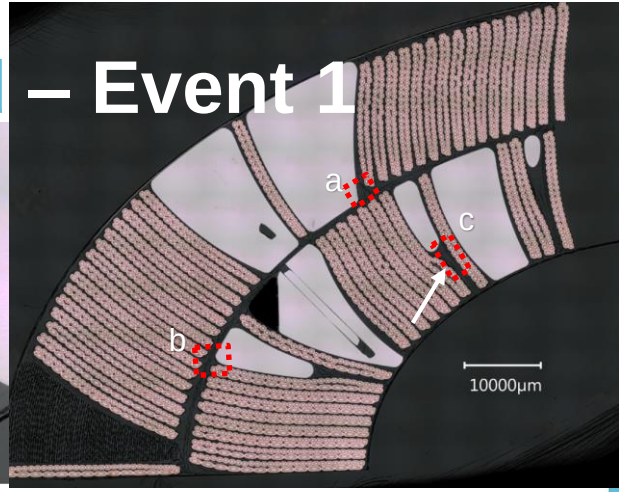
Courtesy S. Sgobba et al.

Metallography GE02 CS Head – Event 1

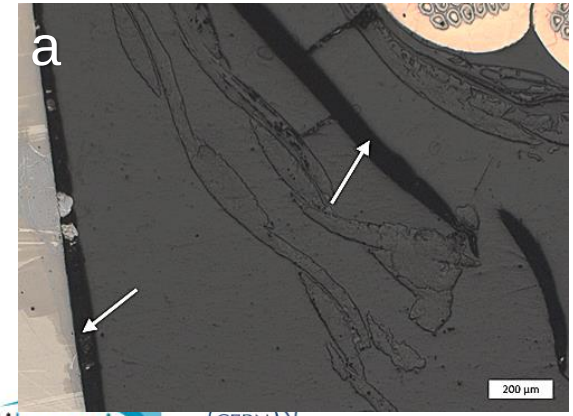
Examination of event at angular cut shows:

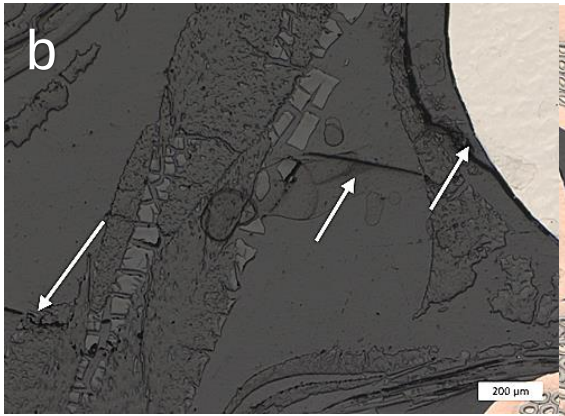
- The pop-out strands are embedded in resin (some porosities are observed)
- **SC appear free from cracks**
- **Cracks in insulation and porosities can be observed, especially at the vicinity of spacers and pop-out strands where bonding appears poor**
- Copper composing the strands is in annealed state (approx. 55-60 HV0.1)

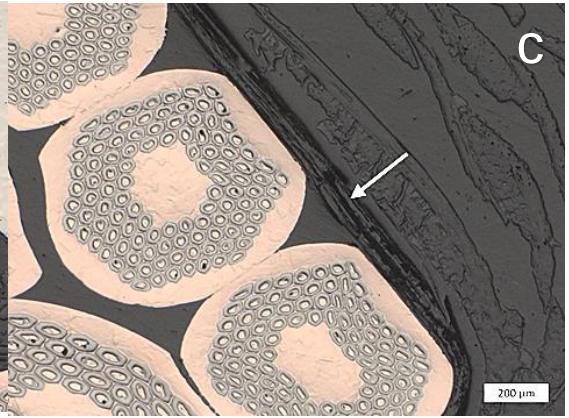




Courtesy S. Sgobba et al.

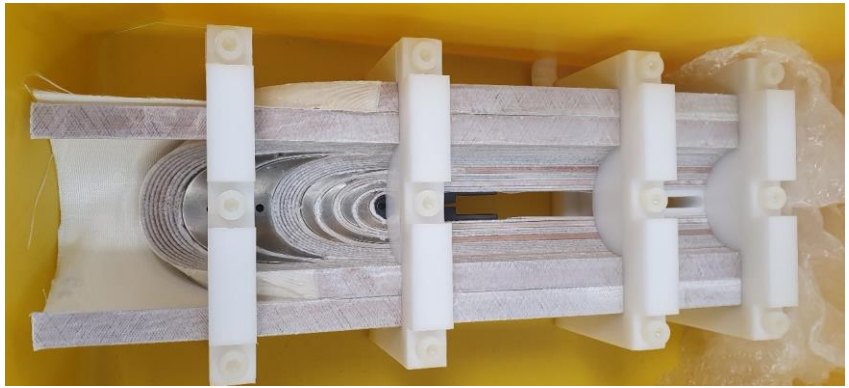


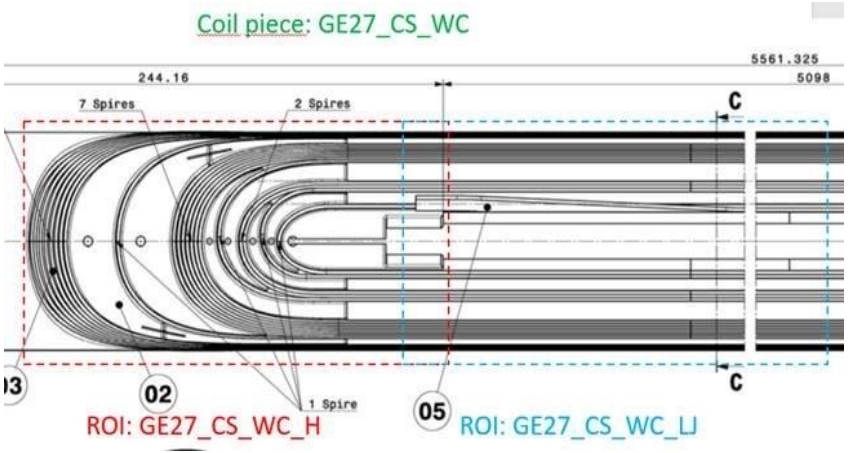




Coil GE27 – CS (rejected in production)
Wound & cured (not reacted/impregnated)

- Connection Side
  - Head (Region Of Interest in red)
  - Layer Jump (Region Of Interest in blue)

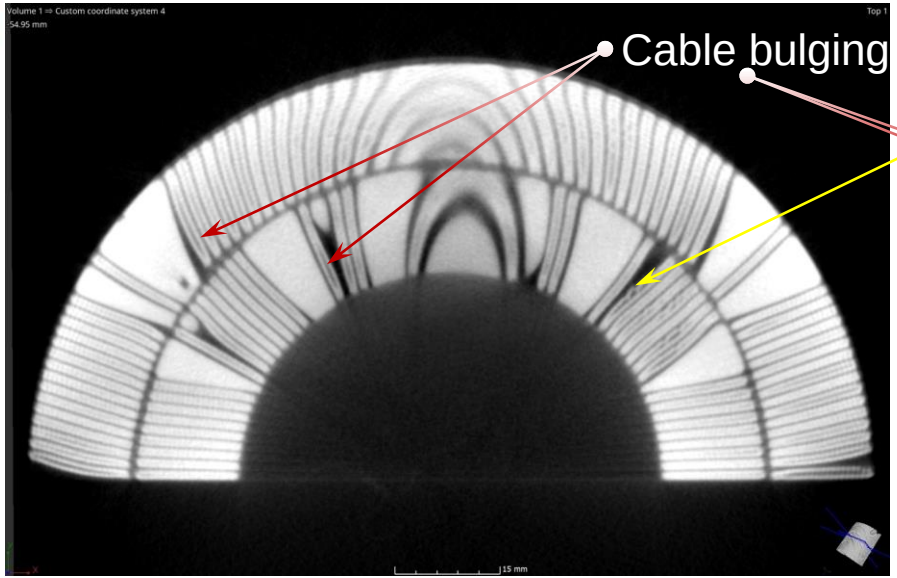




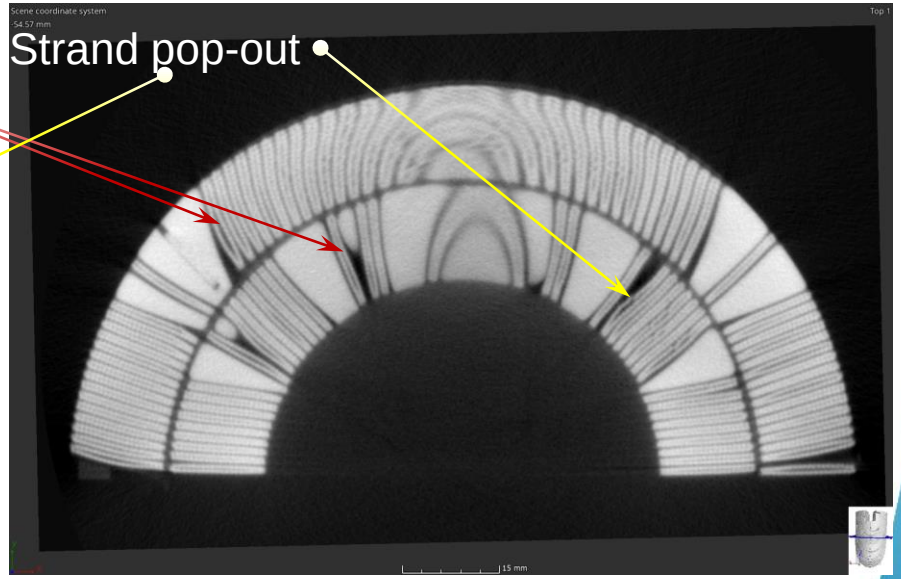
Courtesy S. Sgobba et al.

Tomography – Cross-section in coil head

GE02 – CS (limiting coil)
First full-length 11T tested (hybrid P.)

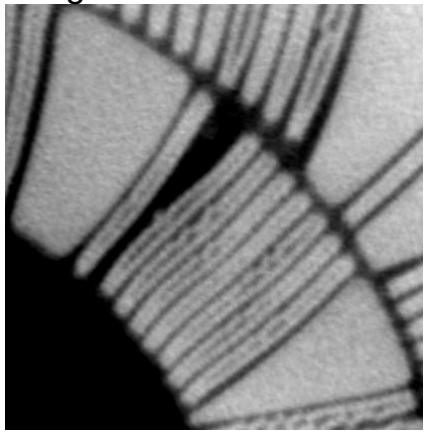


GE27 – CS (rejected in production)
Coil wound & cured – Not reacted

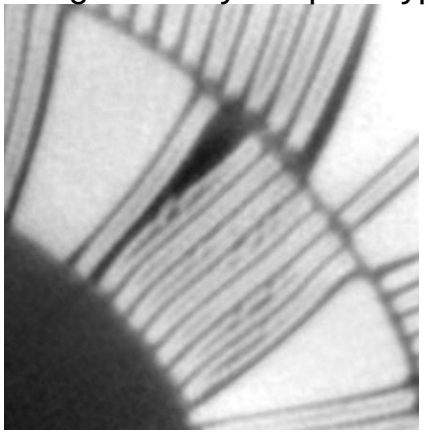


The defects are **already present** in the coil **after winding** (cable bulging, strand pop-out)

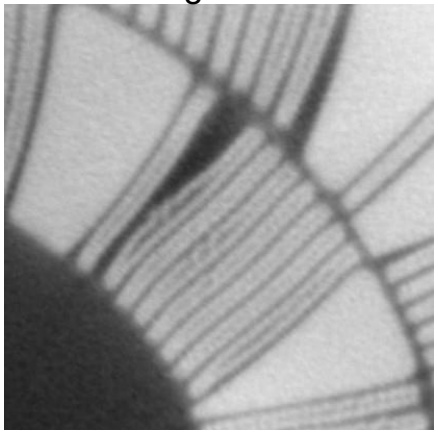
C122 – Model coil made by CERN
Virgin – Not used/tested



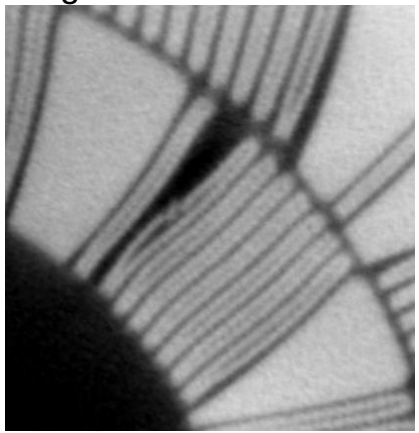
GE02 – Series production coil
Limiting coil in hybrid prototype



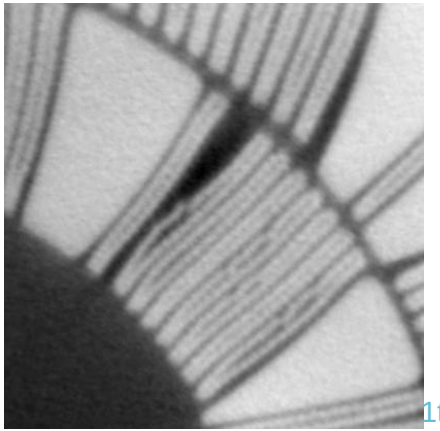
GE09 – Series production coil
Limiting coil in S2



GE11 – Series production coil
Virgin – Not used/tested



GE27 – Series production coil
Wound & cured – Not used/tested



Events/imperfections are
remarkably reproducible!

Courtesy S. Sgobba et al.

Outlook

- Introduction
- Main activities part of Phase 1
  - QA/QC
  - Coil visual inspection
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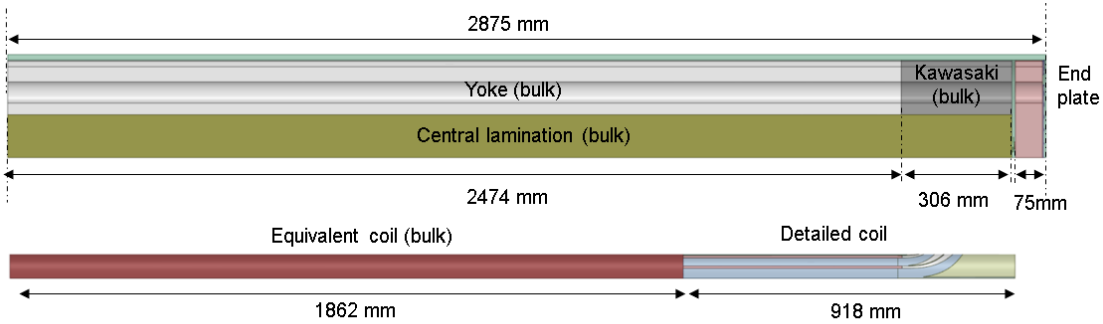
- Concluding remarks

3D thermo-mechanical model

- **Steady state** analysis of the **mechanical behaviour of the 11T magnet** (cold mass assembly, full-length, two-in-one) at cryogenic temperature, 4.2 K
- Model

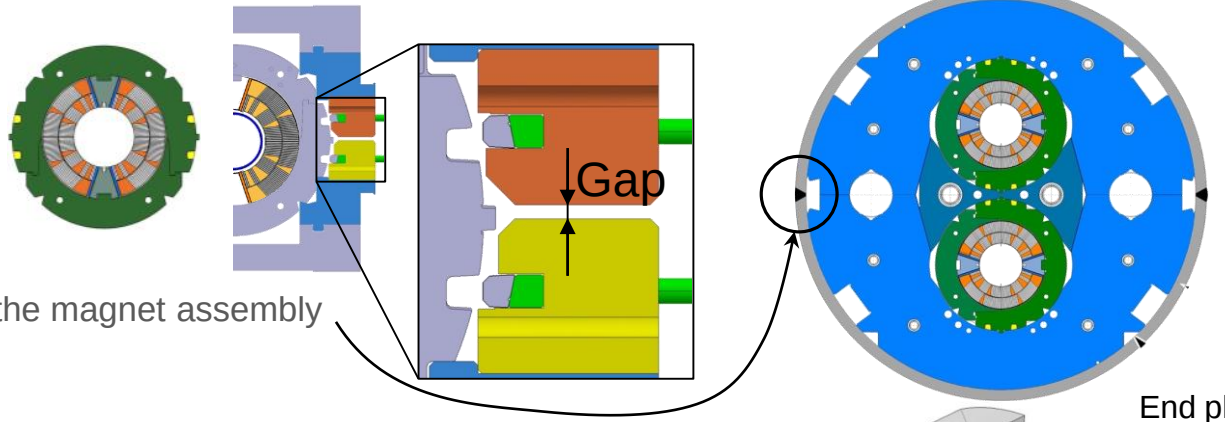


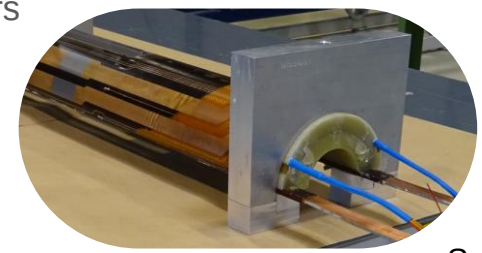
- Material properties
  - Linear elastic behaviour
  - Thermally induced strain is taken into account
  - Transverse isotropic model for yoke and collars. Laminated structure taken into account
  - Orthotropic model used for both the cable and the saddles made of G11
  - Some properties were (re)measured recently, e.g. mechanical properties of cable ten-stacks and G11 saddles, CTE of G11 saddles and full coil (short model coil) … samples cut from real parts

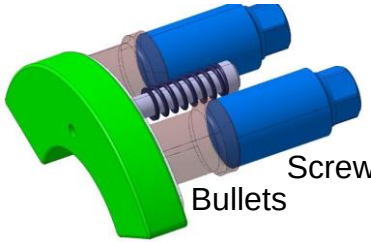
Courtesy C. Garion & M. Morrone

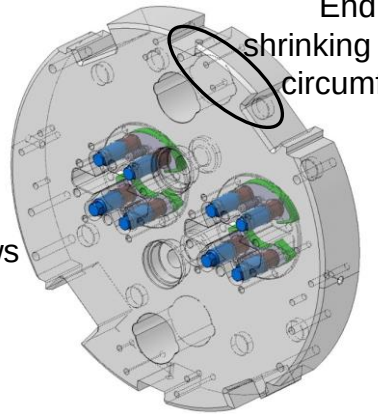
Load steps

1. **Collaring**
   a. Load the coils
   b. Lock with keys
2. Shell welding
   a. Weld the shells on the magnet assembly
3. Bullet loading
   a. Lock the coil in longitudinal direction by means of bullets and load spreading pushers
4. **Cool-down**
   a. RT to 4.2 K
5. **Powering**
   a. To nominal conditions 11850 + 100 A



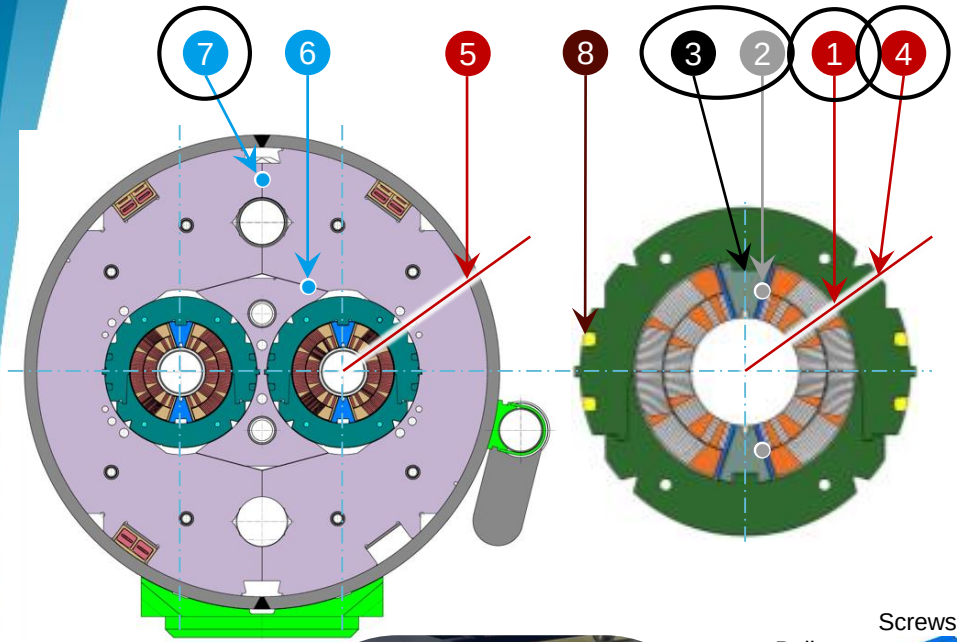




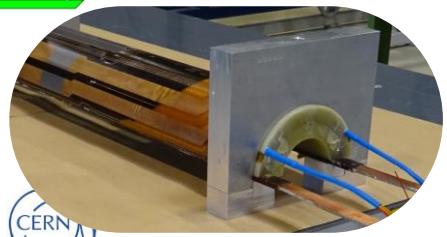


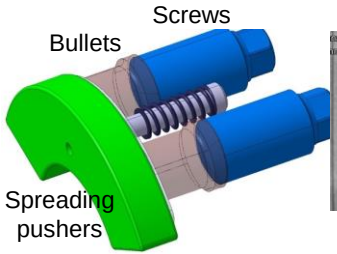
Detailed report on “3D mechanical behavior of the 11T cold mass at cryogenic temperature” see EDMS No 2643402, C. Garion, J. Harray, M. Morrone, F. Santagelo

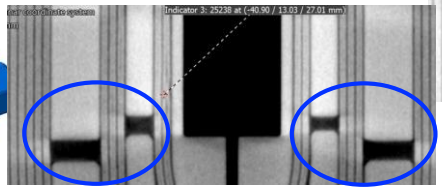
Critical locations / interfaces under scrutiny

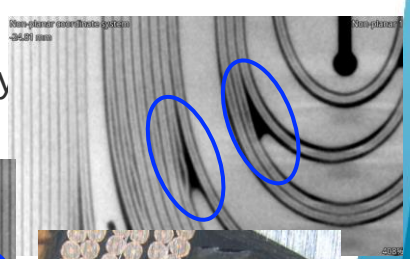


1. Coil OD – QH – GI – Collaring shoe – Collar ID
2. Coil azymuthal excess – GI – **Pole shim** – Ti-pole
3. **Ti-pole** – Top shim – Collar nose
4. Collared coil / collar OD – **Collar-Yoke shim** – Yoke
5. Yoke – Shell
6. Central yoke – Yoke
7. ½-Yoke left – ½-Yoke right
8. Collaring keys – Keyway
9. **Bullet – Coil** through load spreading pushers (axial direction)
10. **Resin-rich areas** (revealed by tomography)





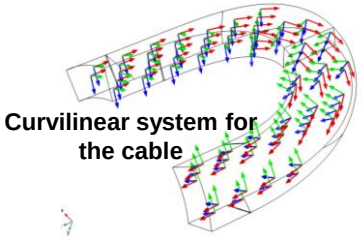




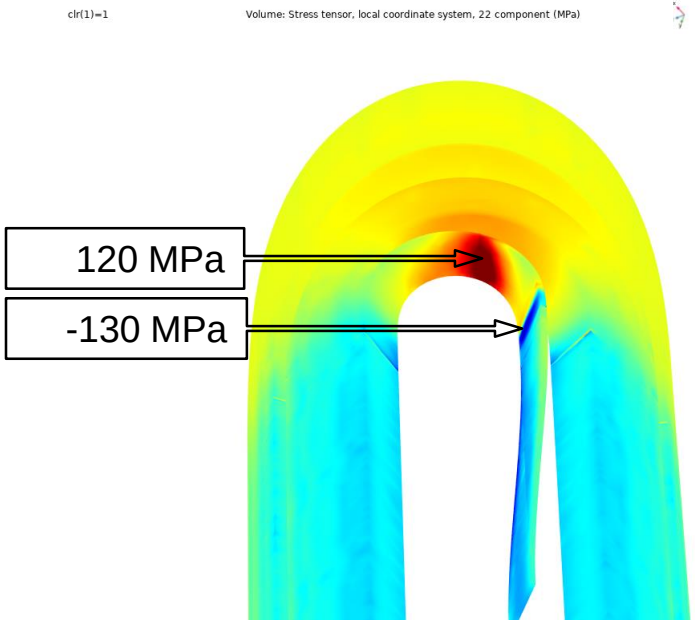
Step “collaring” – Azimuthal stress in outer L.

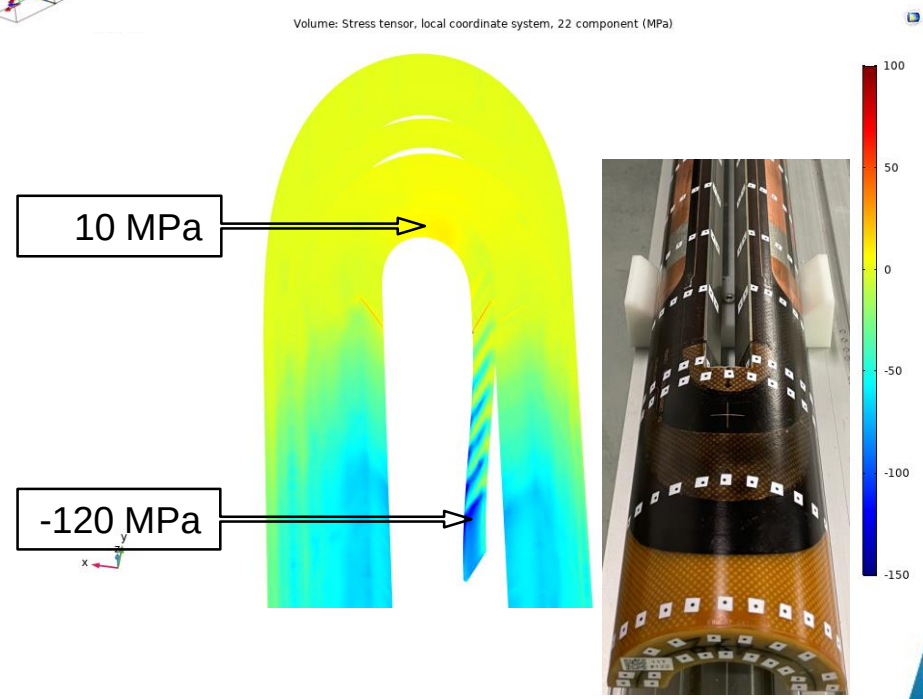
Nominal case – series production

Courtesy C. Garion & M. Morrone



Phase 2 hybrid 11T
Stainless steel pole and graded pole shim

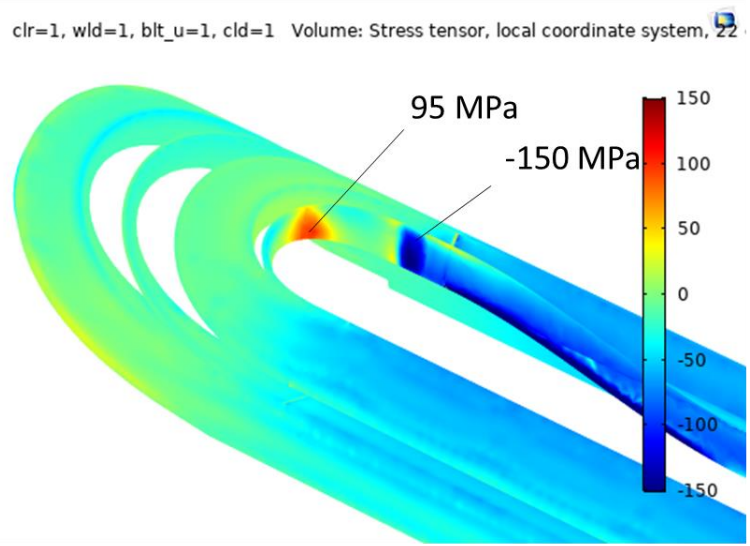




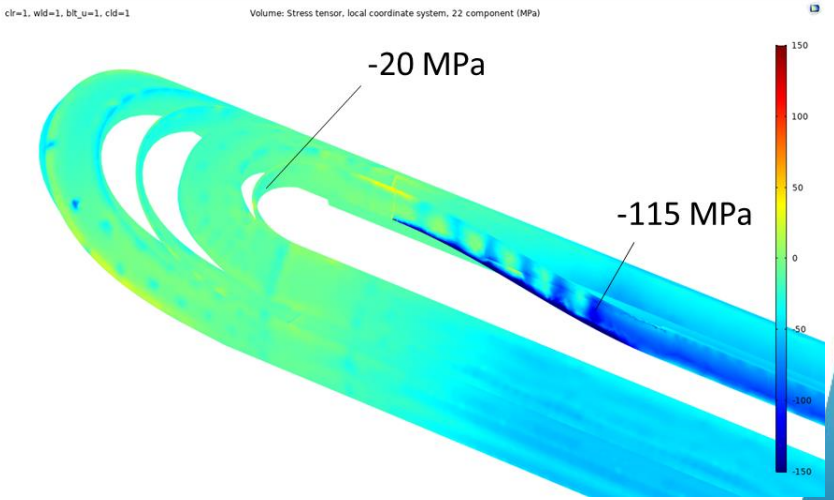
Step “cool-down” – Azimuthal stress in outer L.

Nominal case – series production

Courtesy C. Garion & M. Morrone



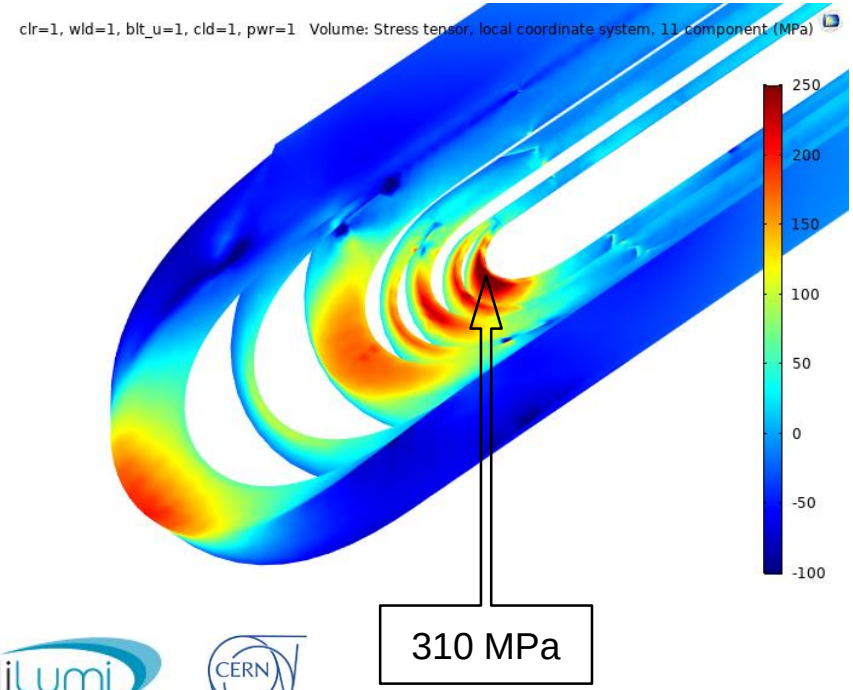
Phase 2 hybrid 11T
Stainless steel pole and graded pole shim



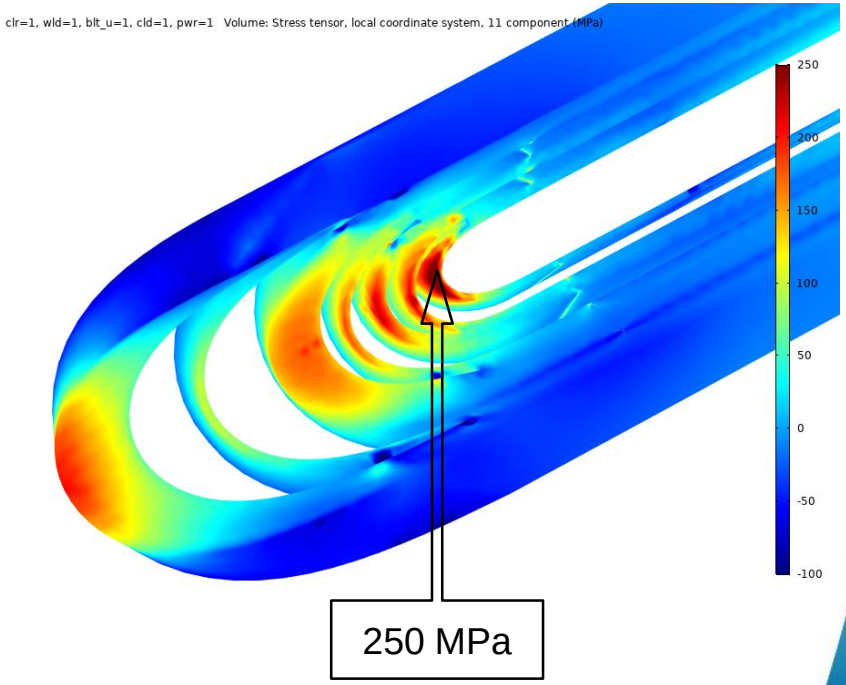
Step “powering” – Axial stress in inner L.

Nominal case – series production

Courtesy C. Garion & M. Morrone

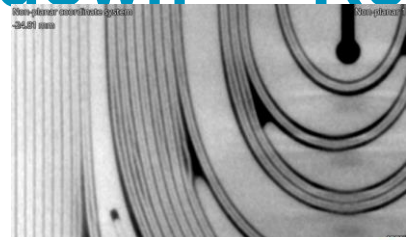


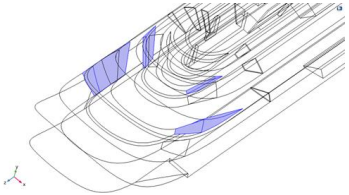
Phase 2 hybrid 11T
Stainless steel pole and graded pole shim



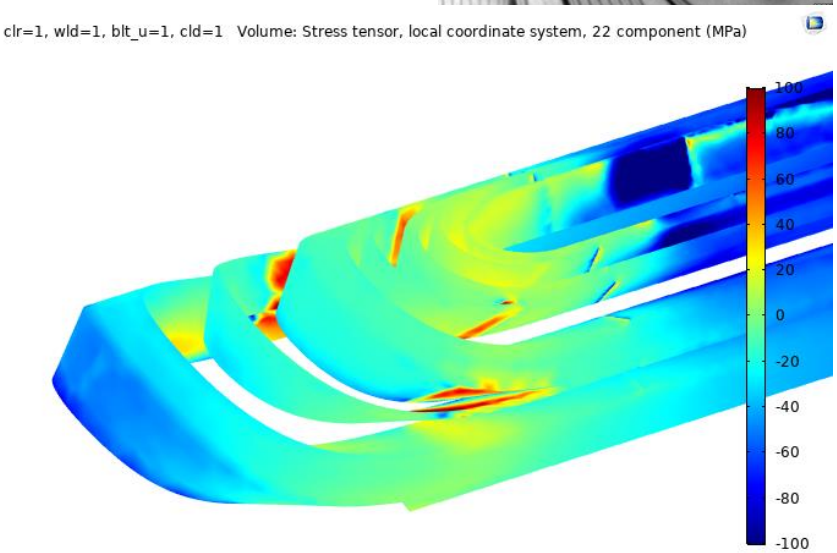
Step “cool-down” – Resin-rich areas – Inner L.

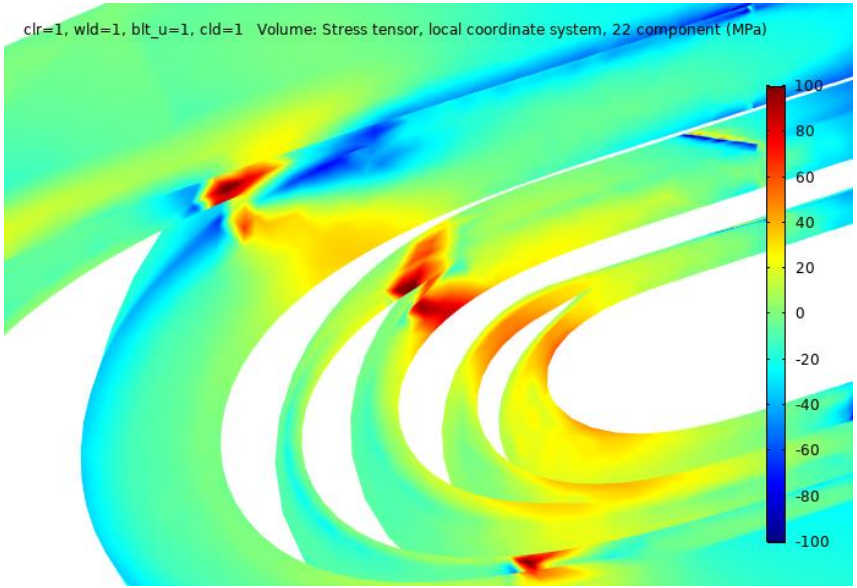
Nominal case
Azimuthal stress
View from the top





Nominal case
Azimuthal stress
View from the bottom





Courtesy C. Garion & M. Morrone

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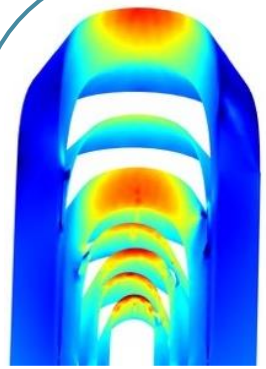
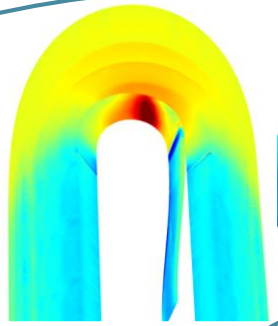
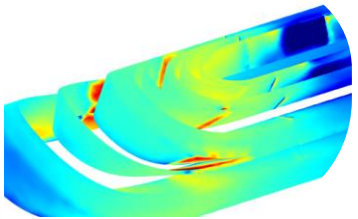
S3: degradation in D1U-GE15, **head NCS** and straight part between 0.5 and 1.1 m from head NCS

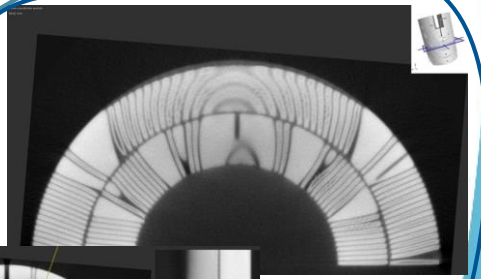
S2: degradation in D1L-GE13 and D2L-GE09, in both cases in **head CS** pole turn

S4: degradation in D2U-GE17, **head CS** and straight part @ 1.4 m from head CS

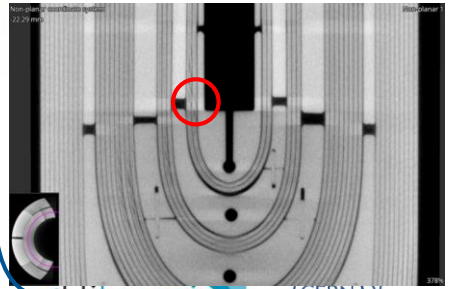


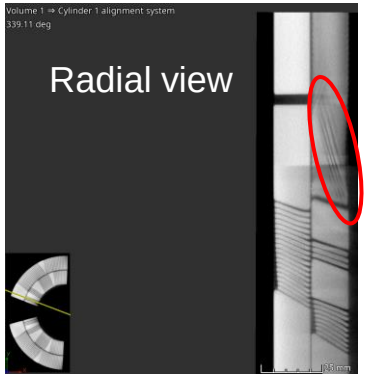




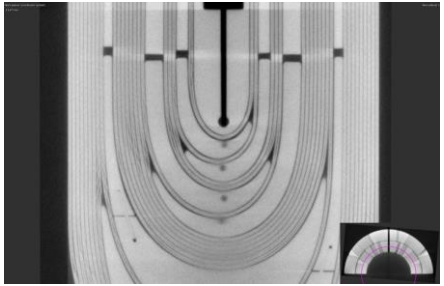


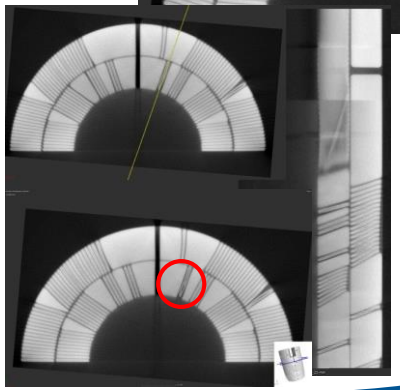
GE15 – Inner L. Head NCS
Unrolled view





GE09 – Inner L. Head CS
Unrolled view





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Guidelines to define the strategy for phase 2

- Act on the mechanical structure
- Requirements specified for the production maintained on the straight part (max. 300-micron excess)
- Hold the coil head in the 3 directions (radial, azimuthal and longitudinal) such that
  - Reduce peak stresses as much as possible at any stage of the magnet construction, during cool-down and operation
  - The cable / wire should ideally be loaded in a perfectly isostatic way (of, course this is not possible but this is to get an idea of the direction we need to go)
- We know that there are issues internal to the coil but these cannot be addressed without manufacturing new coils. This is outside of the scope of work of the ongoing task force / recovery plan

11T Hybrid magnet specification

- Coils
  - **All new/virgin coils**, 4 of the 8 last coils of the series production (GE26, 28, 29, 31, 32, 33, 34, 35)
  - External QHs with revised connection (direct soldering of wire on QH circuit, implemented on reworked CC06)
- Aperture 1: series production parts and recipe, except:
  - **Thickness of pole shims to be reduced progressively towards the coil head**, length of the transition before the coil heads to be optimized
  - **Thickness of collared coil to yoke shim to be adjusted** based on the global kinematic of the magnet structure and on the actual size of the CC assembly (yoke gap closed after shell welding and to remain closed after cool-down in order to avoid loss of preload on the coils)
  - **Stronger riveting of the collar packs** (see mock-up tests in Bldg.927 with A. Bertarelli/F. Lackner et al.)
  - Integration of **axial preloading system to be revised** (eliminate risk of misalignment/detachment between the load spreading pushers and the coil head)
  - **Replace the Ti poles by stainless steel poles**
  - **Replace the 0.5-mm thick stainless steel coil protection sheet by 2 x 0.3-mm thick Cu-Be coil protection sheets** to (1) reinforce the protection of the coil (from the laminated structure of the collars) and (2) facilitate relative (small) movements between the coil and the collars during cool down
- Aperture 2: as Aperture 1 with the following additional change
  - **Introduction of a rigid cage in order to hold better the coil head**, and in particular to reduce stresses (1) in the critical coil-block (avoid detachment) and (2) in the resin-rich areas
- The magnet end plate will necessitate modifications for the integration of the revised axial loading system
- Electrical connections of the 2 apertures to allow independent powering
- Comprehensive mechanical instrumentation

Short model prior to build the full-length hybrid

- Validate the 3D FEA model
- Validate the mechanical instrumentation plan for the full-length hybrid
- The model can be tested at cold conditions, even it is made for only mechanical purpose (no expectations as to the current level we could reach during powering)
- Two-in-one, one aperture equipped with the cage, follow specification applicable to the full-length hybrid, including independent powering of the 2 apertures

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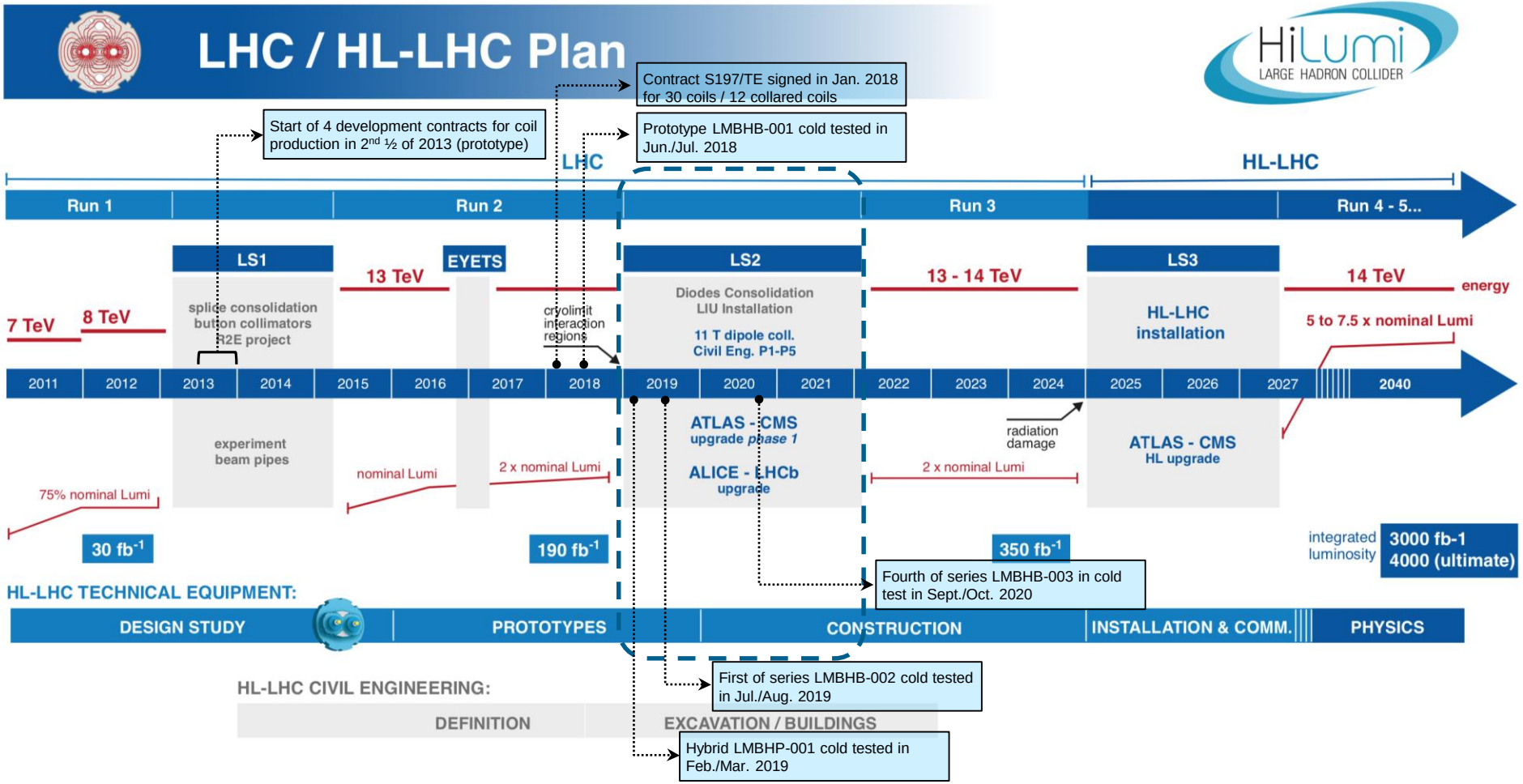
Concluding remarks

- Overall very good progess of the New Task Force activities
- Tomography inspection is providing an amazing insight of the cable status in the coil. It has been essential for localizing defects internal to the coil
- Root cause of the performance degradation is most likely a combination of (1) imperfections internal to the coil and (2) excessive stress concentration in the coil heads
- Which one of the two issues is most detrimental is not easy to say today
- Imperfections internal to the coil cannot be repaired
- Further optimisation of the mechanical structure and possibly the integration of a cage around the coil heads can surely improve the magnet robustness and this is what motivates the construction of a hybrid magnet as described

Thank you for your attention


LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
Contract S197/TE signed in Jan. 2018 for 30 coils / 12 collared coils
Start of 4 development contracts for coil production in 2nd ½ of 2013 (prototype)
Prototype LMBHB-001 cold tested in Jun./Jul. 2018
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13 - 14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
11 T dipole coll.
Civil Eng. P1-P5
HL-LHC
installation
5 to 7.5 x nominal Lumi
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
350 fb-1
integrated
luminosity
3000 fb-1
4000 (ultimate)
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
Fourth of series LMBHB-003 in cold test in Sept./Oct. 2020
First of series LMBHB-002 cold tested in Jul./Aug. 2019
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION / BUILDINGS
Hybrid LMBHP-001 cold tested in Feb./Mar. 2019

New Task Force Work Breakdown Structure

1. Sub-working Team 1:
   a. Complete the **3D Thermo-mechanical modelling of the 11T** cold masses, short and long models, and highlight the positions of excessive thermo-mechanical and electromagnetic stresses
   b. Complete the **3D thermo-mechanical modelling of the QXF** cold mass and highlight the positions of excessive thermo-mechanical and electromagnetic stresses
2. Sub-working Team 2:
   a. Review the **QA-QC of the 11-T & QXF programs**, report identified weaknesses and propose changes and/or mitigation solutions
3. Sub-working Team 3:
   a. Review the **electrical QA-QC of the 11-T program**, report identified weaknesses and propose changes and/or mitigation solutions
4. Sub-working Team 4:
   a. Review the **mechanical tolerances** and **assembly procedures** for 11T
   b. In light of the recent observations and diagnostics, review the implementation of the recommendations of the Task Force set up in November 2017

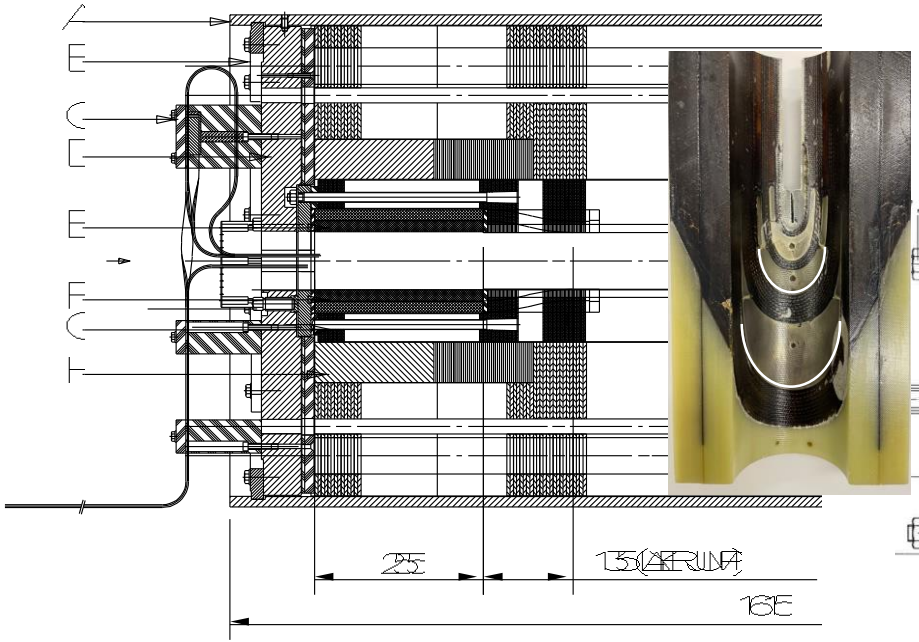
New Task Force Work Breakdown Structure

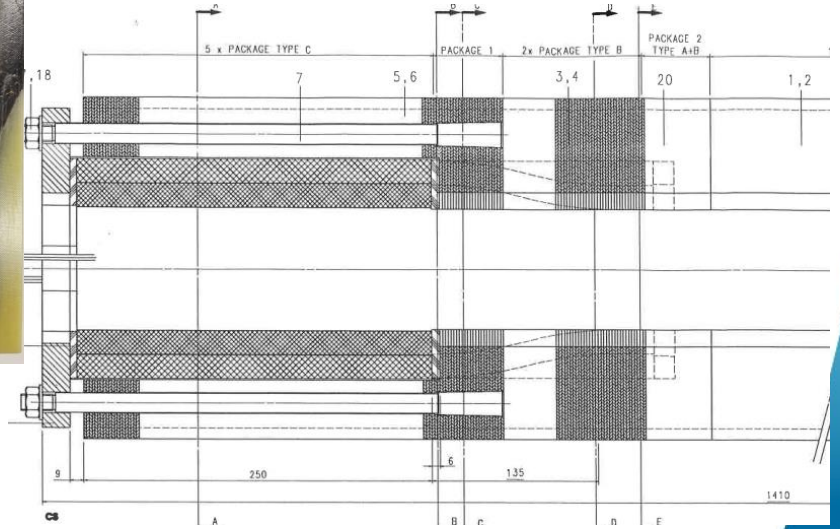
5. Sub-working Team 5 mandate:
   a. Carry out **visual inspection of coils, and collared coils / magnets**, for both 11T and QXF short & long magnets. Implement all necessary visual inspections to identify anomalies, degradations, unexpected mechanical configurations or behaviours
6. Sub-working Team 6 mandate:
   a. Carry out **visual inspection of cold masses** for both 11T and QXF. Implement all necessary visual inspections to identify anomalies, degradations, unexpected mechanical configurations or behaviours
7. Sub-working Team 7 mandate:
   a. Carry out **tomography of coils and metallurgical inspection in corresponding cuts**
   b. Implement all necessary tomography and section cuts investigations as indicated by the other sub-working teams. Including material behaviours such as the resin cracks
8. Sub-working Team 8 mandate:
   a. Review the **potential relevance of any of the above-mentioned investigations on the QXF** configuration and manufacturing program

A cage to hold the coil head

- Avoid lack of support / detachment of the first turn of a coil block under the electromagnetic forces
- A “cage” can be build around the coil head in order to mitigate this effect (prevent deformation/relative movements in the axial direction). The comcept was used in the FRESCA and MFSIC magnets

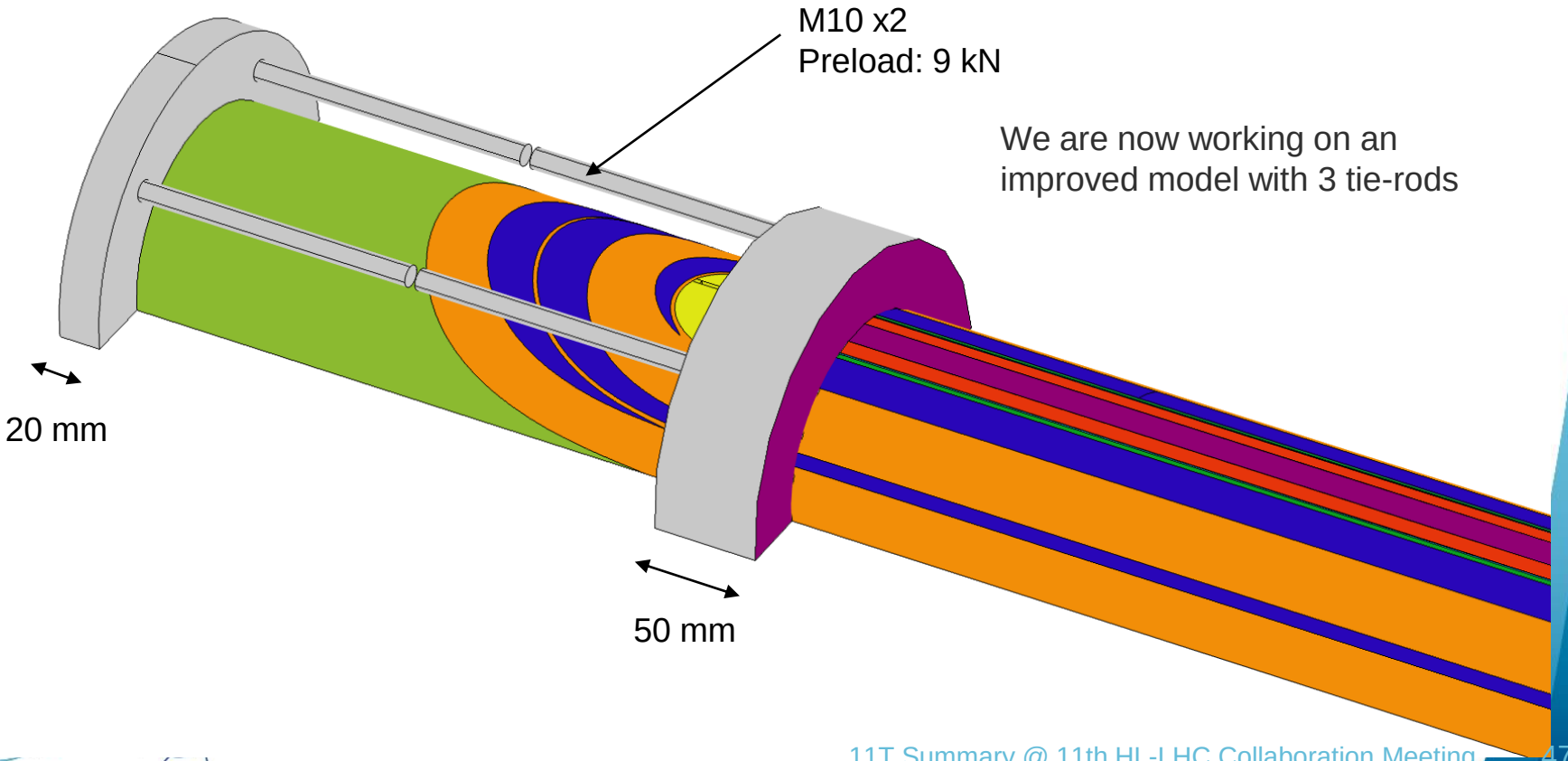
Courtesy G. Spigo





The cage, as implemented in the FEA model

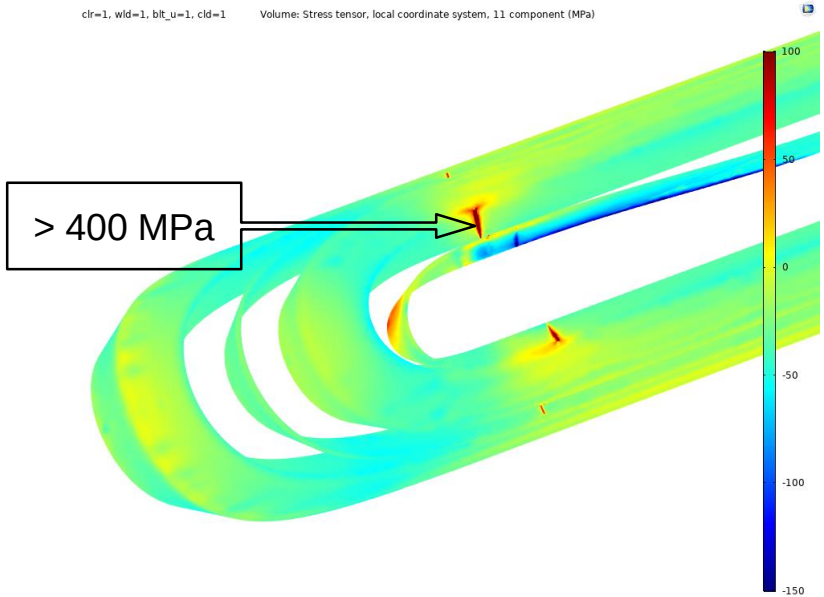
Courtesy C. Garion & M. Morrone



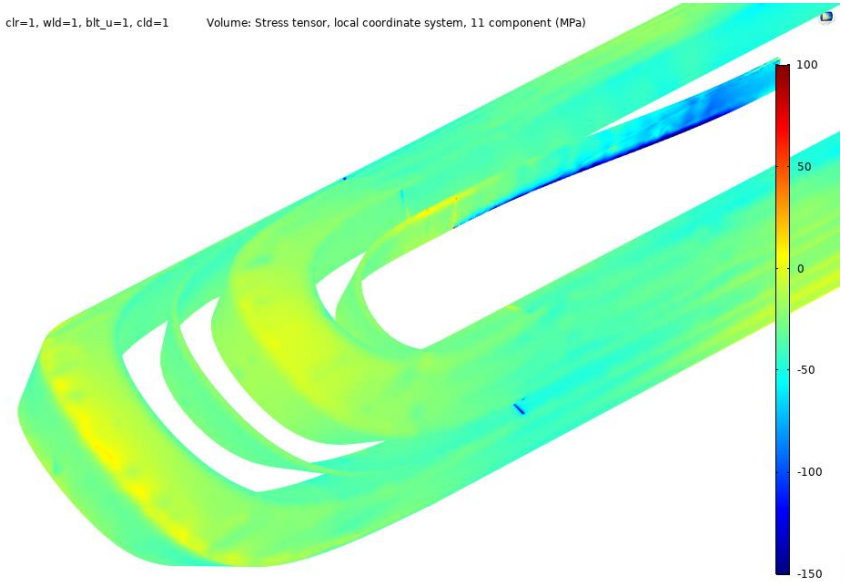
Step “cool-down” – Axial stress in outer L.

Nominal case – series production

Courtesy C. Garion & M. Morrone



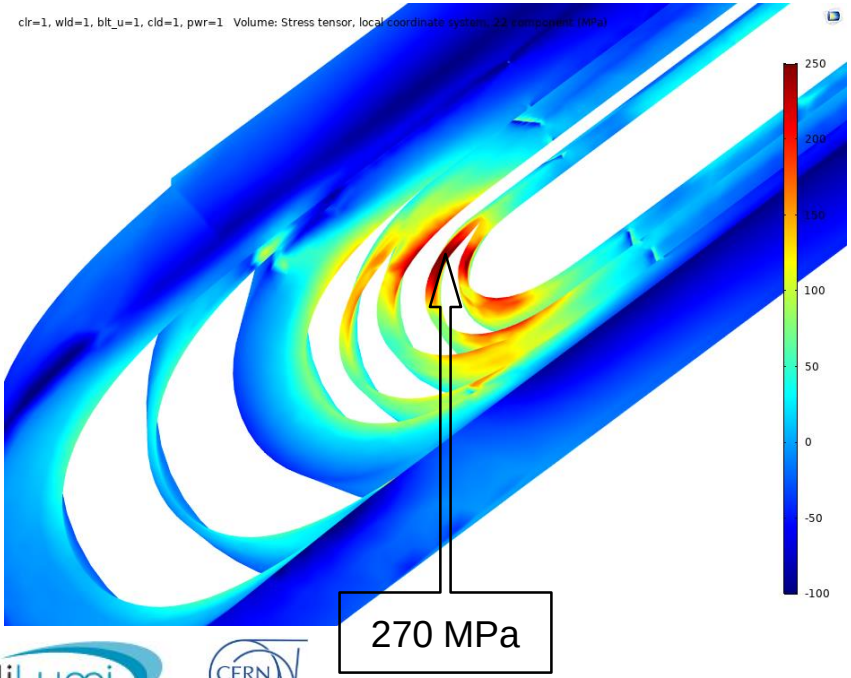
Phase 2 hybrid 11T
Stainless steel pole and graded pole shim



Step “powering” – Azimuthal stress in inner L.

Nominal case – series production

Courtesy C. Garion & M. Morrone



Phase 2 hybrid 11T
Stainless steel pole and graded pole shim