Update on 11 T Activities

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CERN/TE-MSC Group

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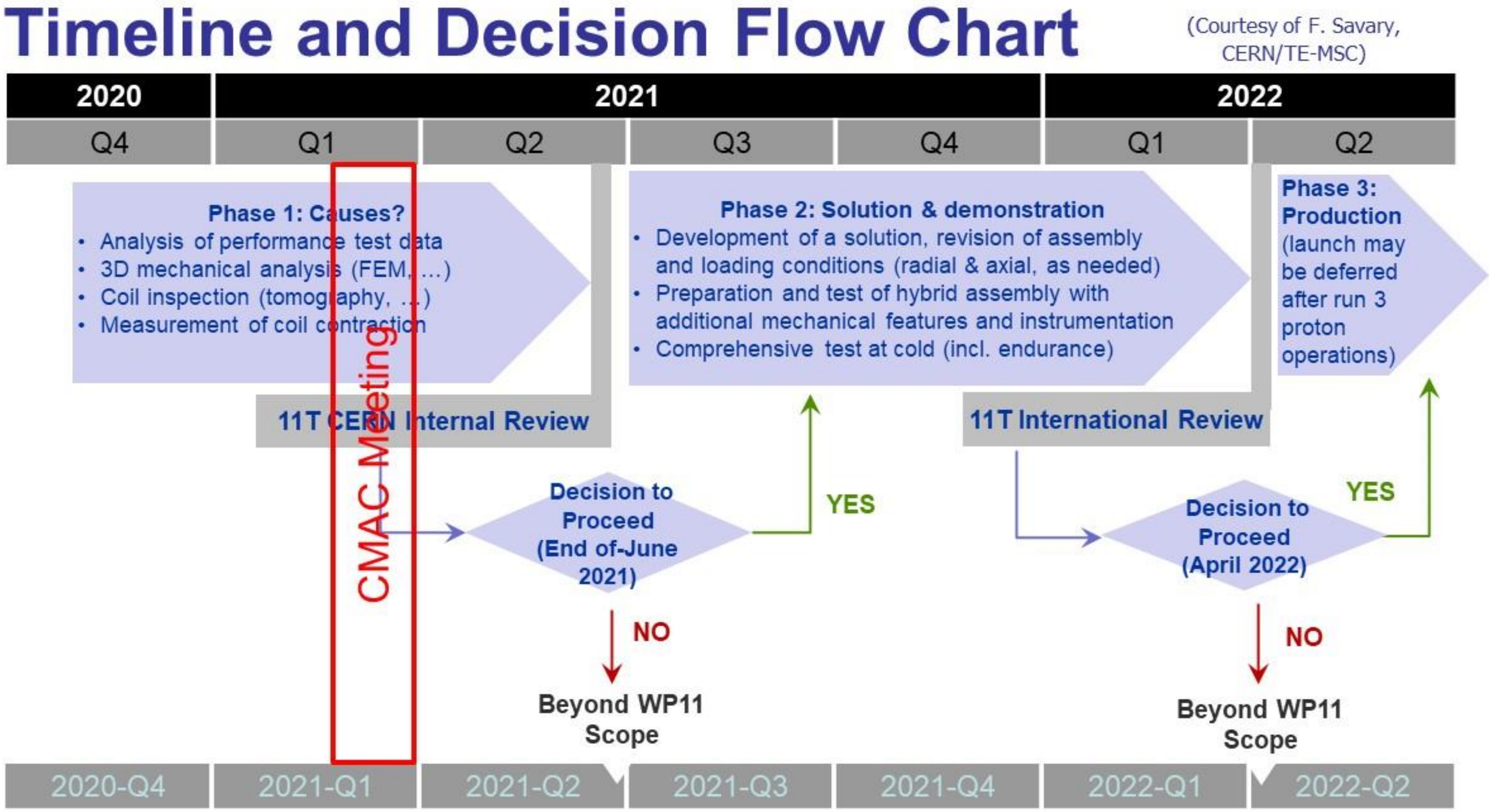
Content

Introduction (1/2)



Initial Strategy for 11 T Project

Following the decision not to install 11-T dipole magnets during LS2, **a 3-Phase strategy** was developed and agreed by management in Q4 2020.

The strategy was reviewed by **C-MAC** on 11 March 2021.

Introduction (2)

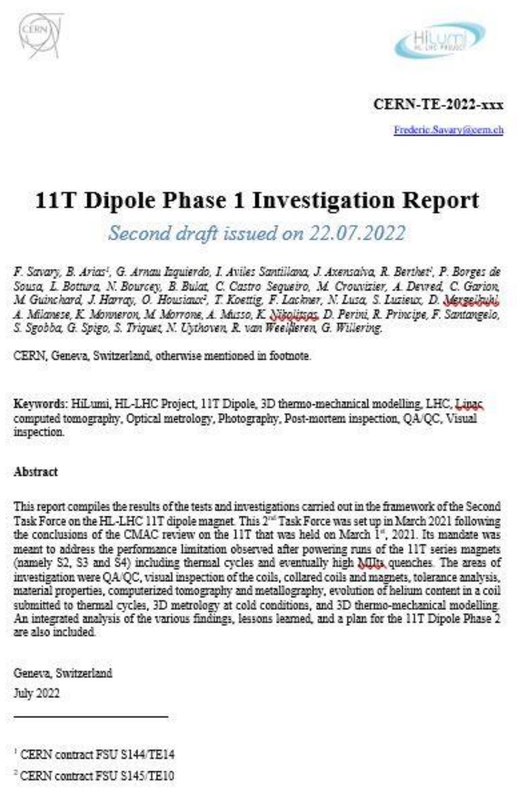
A **(2^{nd}) 11 T Task Force** was set up by TE DH at the end of March 2021 with two main aims
– to consolidate the **on-going investigations** of the performance limitations of short and long 11 T dipole magnets **(Phase 1);**
– to propose **mitigation measures** to be implemented on one full-length, twin-aperture dipole magnet prototype **(Phase 2).**

Two groups of issues were investigated by the Task Force
– issues **internal to the coils;**
– issues components/assembly procedures **external to the coils.**

Issues internal to the coils can not be addressed without manufacturing new coils; this is **outside of the scope** of the ongoing Task Force/recovery plan.

Phase 2 proposal addresses a number of issues identified on components external to the coils; it was presented and endorsed by management on **11 October 2021.**

A **comprehensive report,** edited by F. Savary, on the findings of the 2^{nd} Task Force has been completed on **31 July 2022;** now under peer review.



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11T Dipole Phase 1 Investigation Report

Second draft issued on 22.07.2022

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CERN, Geneva, Switzerland, otherwise mentioned in footnote.

Keywords: HiLumi, HL-LHC Project, 11T Dipole, 3D thermo-mechanical modelling, LHC, Linac computed tomography, Optical metrology, Photography, Post-mortem inspection, QA/QC, Visual inspection.

Abstract

This report compiles the results of the tests and investigations carried out in the framework of the Second Task Force on the HL-LHC 11T dipole magnet. This 2^{nd} Task Force was set up in March 2021 following the conclusions of the CMAC review on the 11T that was held on March 1^{st}, 2021. Its mandate was meant to address the performance limitation observed after powering runs of the 11T series magnets (namely S2, S3 and S4) including thermal cycles and eventually high MIIts quenches. The areas of investigation were QA/QC, visual inspection of the coils, collared coils and magnets, tolerance analysis, material properties, computerized tomography and metallography, evolution of helium content in a coil submitted to thermal cycles, 3D metrology at cold conditions, and 3D thermo-mechanical modelling. An integrated analysis of the various findings, lessons learned, and a plan for the 11T Dipole Phase 2 are also included.

Geneva, Switzerland

July 2022

[1] CERN contract FSU S144/TE14

[2] CERN contract FSU S145/TE10

Issues and Proposed Mitigation Measures (1/2)

Identified issues were essentially
— **high peak stre**sses in coil ends;
— non-optimum **coil end support** and axial loading;
— non-optimum support of surrounding **laminated structure in magnet ends;**
— some of the problems appeared after **a sequence of powering and thermal cycles;**
— some **non-conformities in magnet ends** were found upon disassembly and subsequent tomographic/metallographic inspections.

Although the internal coil problems cannot be fixed, it was assessed that **sufficient improvements** could be made to the coil and magnet/cold mass assemblies to justify the assembly and test of a **full-length, twin-aperture prototype**;

It was also decided to qualify new design/assembly features on a **re-assembled short model magnet,** before proceeding with the prototype.

The model and the prototype will feature
— **reduced peak stresses** in coil ends;
— **improved coil end support** and axial loading;
— **improved support of surrounding laminated structure** in magnet ends.

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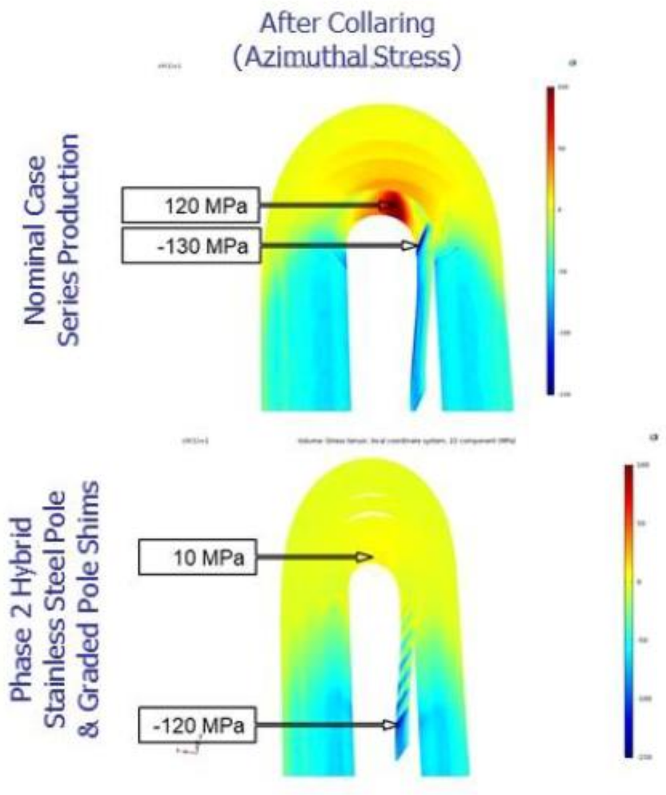
Issues and Proposed Mitigation Measures (2/2)

An **extensive campaign of FEM computations** and a thorough analysis of the results were carried out.



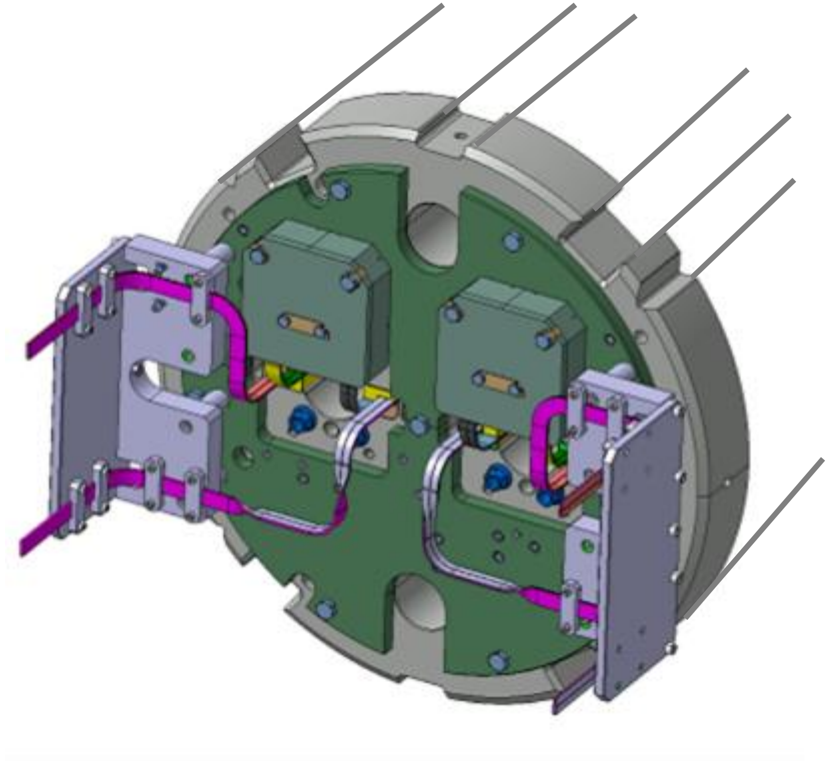
Courtesy of C. Garion and M. Morrone
(CERN/TE-VSC Group)

- The plots on left show that replacing **titanium poles** (mounted on the coils after manufacturing completion) by **austenitic stainless steel poles** enable a significant reduction of the stresses in the coil first turns.
- Additional engineering considerations suggest that
  - Stress concentrations in the transition from the straight part to the ends can be smoothened by **tapered shims** (such shims were foreseen in initial design, but not implemented)**;**
  - **A coil protection sheet in two layers** can help the correct settling of the coils inside the collar cavity;
  - The use of an **end cage system** may limit the relative displacements of the coil first turns with respect to the pole key (as successfully implemented in MFISC and FRESCA);
  - Suitable **mechanical instrumentation** (*e.g.*, bullet gauges) to be implemented for behaviour and FE model validation.

Implementation Plan (1/2)

Two independently-powered apertures

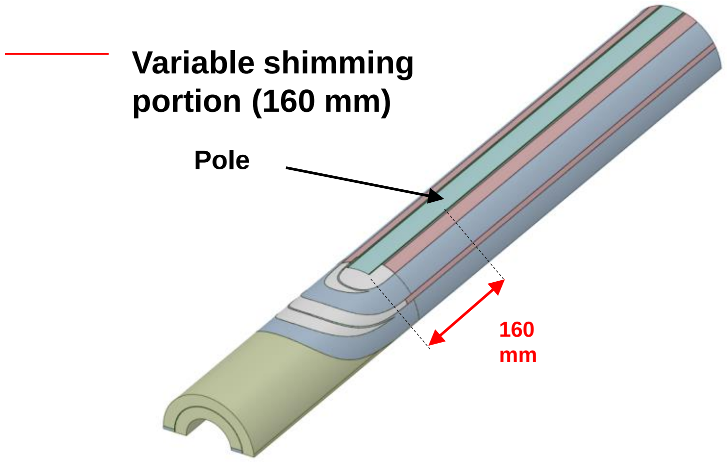
- Implement **“conservative” improvements** in one aperture and test a more **“innovative” solution** on the other aperture;
- Validate new features on a short, twin-and-independently-powered-aperture **model magnet** with **4 re-used coils** (no virgin coils available);
- Implement new features on full-length, twin-and-independently-powered-aperture **prototype with 4 virgin coils from series production** (to limit uncertainty on state of coils).



Implementation Plan (2/2)

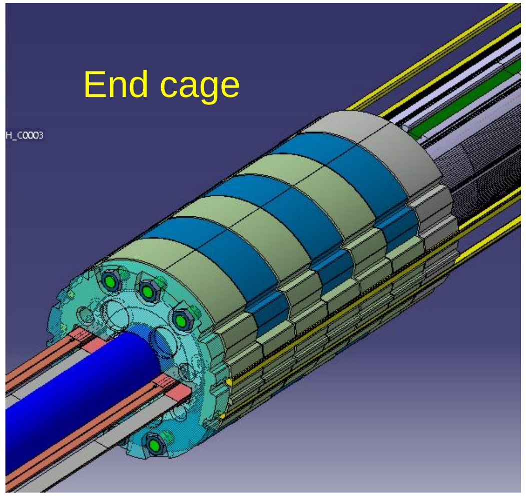
Aperture 1

- Austenitic stainless steel poles instead of titanium
- Tapered shims over coil ends
- Two-layers coil protection sheet



Aperture 2

- Austenitic stainless steel poles instead of titanium
- Tapered shims over coil ends
- Two-layer coil protection sheet
- End cage (see next slide)



Courtesy of T. Sahner (CERN/EN-MME Group)

Both short model and full-length magnets will be heavily instrumented with systematic comparison with FEM model at each stage of assembly and test.

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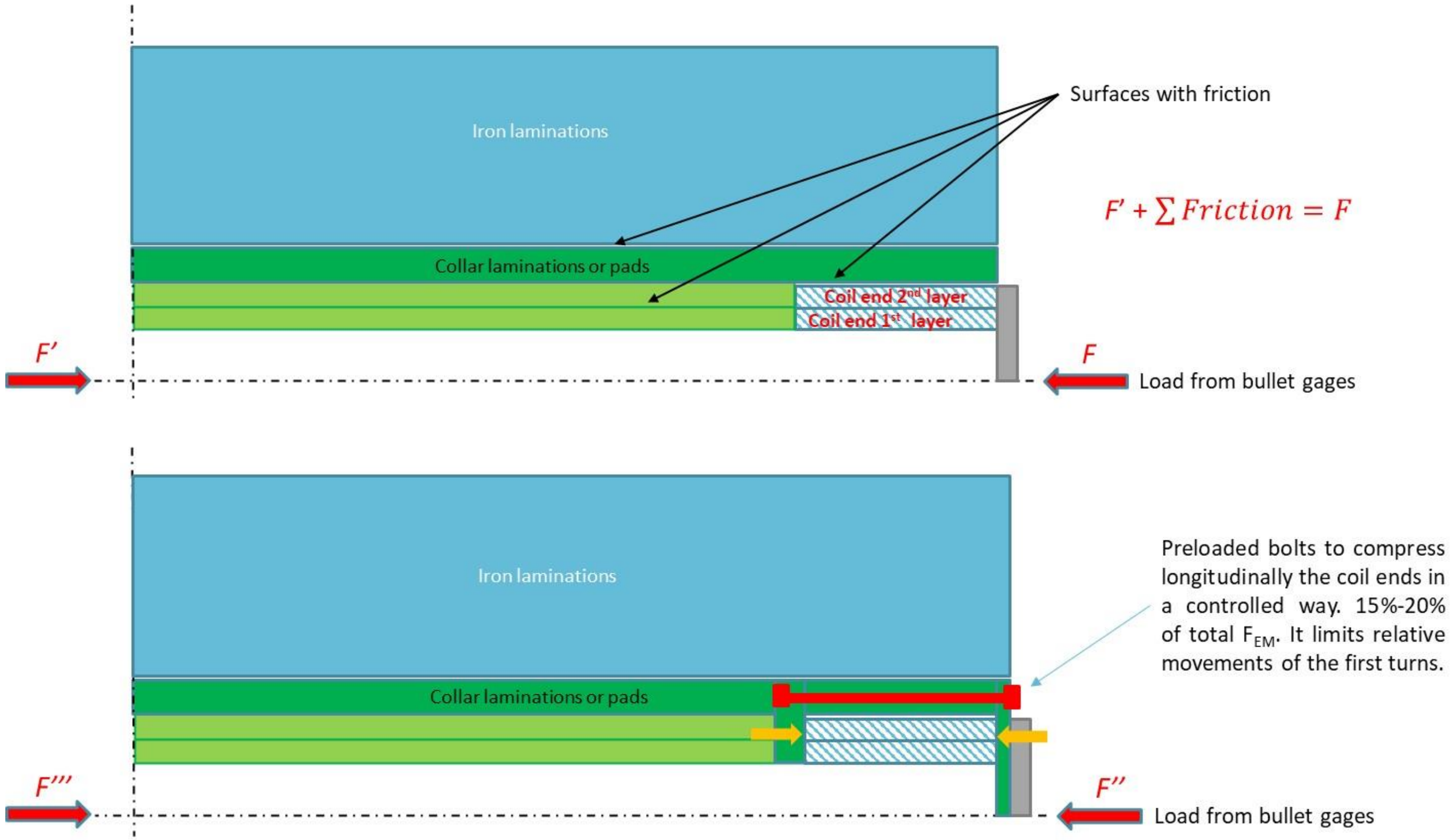
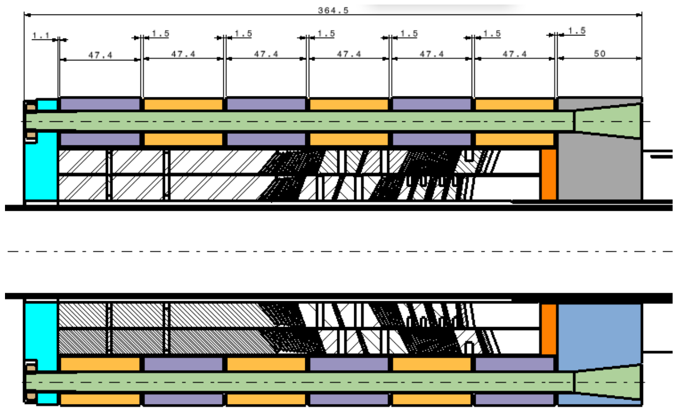
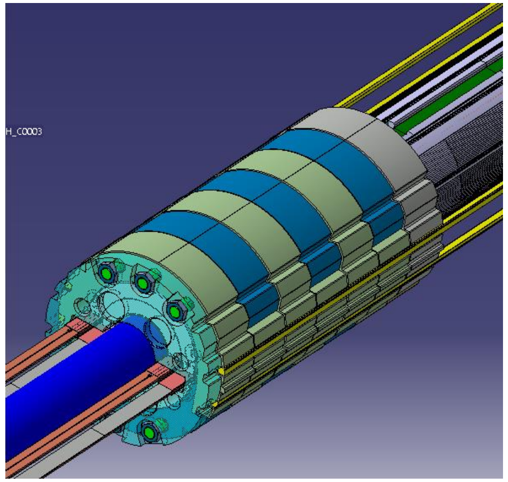
End Cage Concept

Aim: to limit **relative movement (detachment) of first coil block** with respect to pole key (a concern that was also addressed, albeit in a different manner, in MQXF).



Courtesy of G. Spigo
(formerly CERN/EP)





End cage was implemented successfully in Fresca and MFISC short model magnets in the late 1990s; these two models were among the best performing Nb–Ti dipole magnets ever built.

Assembly Procedures

- **Collaring: standard procedures,** as used during production (but with collaring shoe in 2 layers and tapered shims in the transition region).

- **Cold mass assembly**
  - Adjustment of **shims between collars and yoke** to ensure tight fit (feature not exploited before).
  - **Treatment of ends** as explained before.
  - **Instrumented bullet gauges** (implemented on short model magnets but never on a long one).

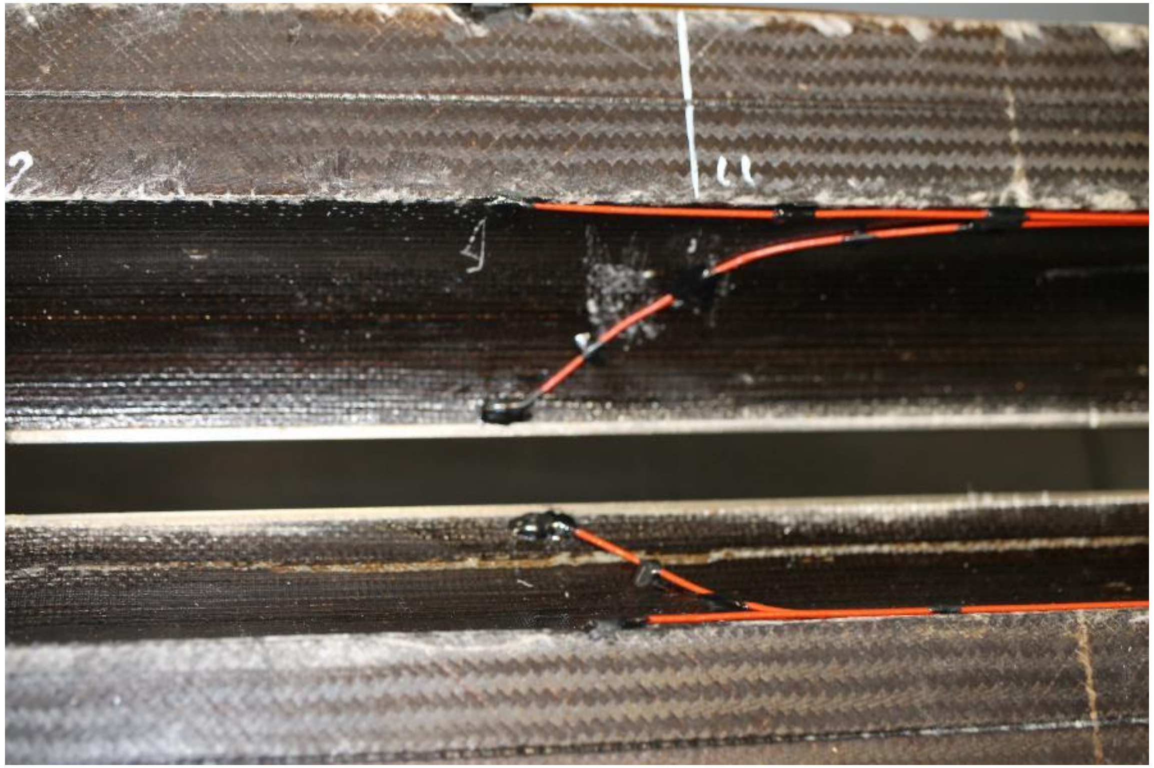
Choice of Coils (1/2)

- The choice of coils for the short model magnet prove **problematic,** because of **known issues or degradations** (see Table).
- After careful consideration, it was decided to use **coils 108 and 214 for Aperture 1** ("conservative") and **coils 212 and 213 for Aperture 2** ("innovative").
- Coils 212, 213 and 214 are the last wound coils of the series and have **PIT cables.**
- Coil 108 is among the oldest **RRP coil** produced; visual inspection revealed several surface cracks in the resin and damages of the cable insulation in the coil midplane, which were **repaired.**
- The short model magnet is meant as a **mechanical model,** to validate new coil end support concepts, and **may not achieve performance requirements.**

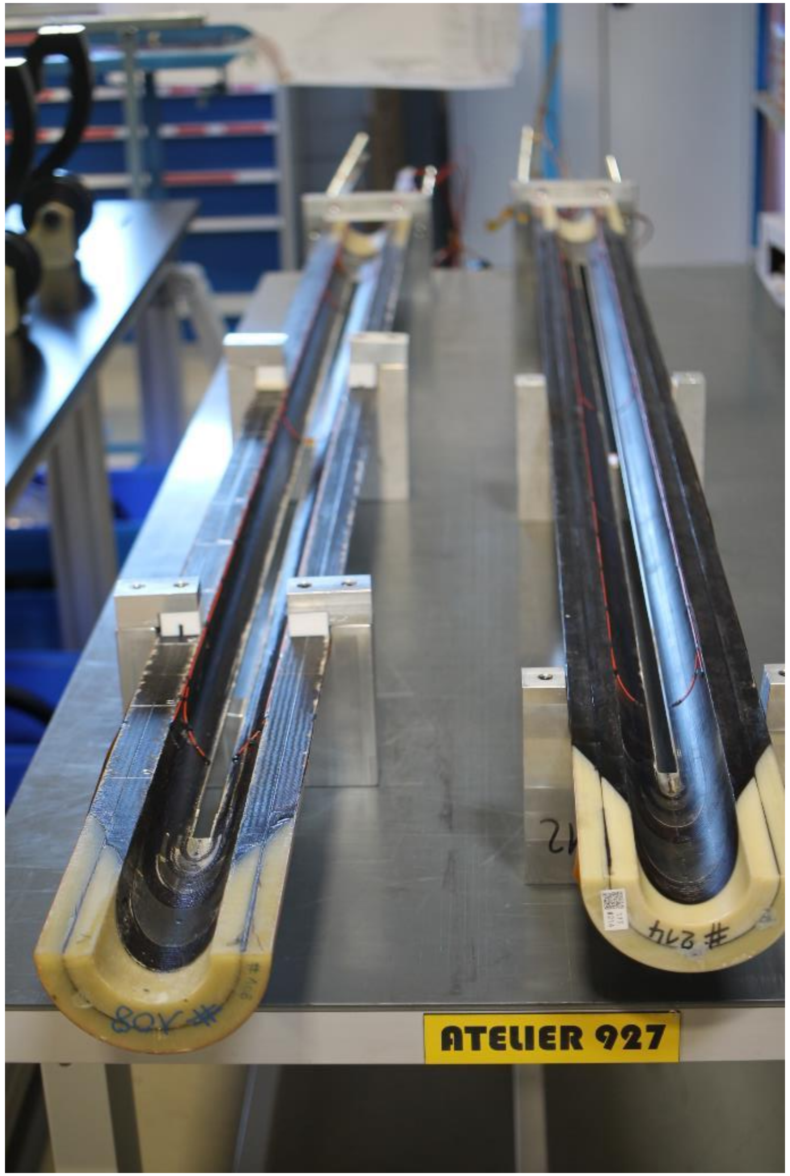
Coil 105	MBHSM101	* Very first coil tested, not considered in the discussion	
Coil 106	MBHSP101 MBHSP102 MBHDP101	* Good performance in SP101, SP102, and DP101	C106 is a supposedly good performing coil Cracks in the resin - after decollaring
Coil 107	MBHSP101	* Cut, limiting coil in SP101	
Coil 108	MBHSP102 MBHDP101	* Good performance in SP102 and DP101	C108 is a supposedly good performing coil Cracks in the resin - after decollaring
Coil 109	MBHSP103 MBHDP101 MBHDP102 (ap SP104b)	* Good performance in SP103 * Good performance in DP101 * DP102 did not perform well	C109 showed V-I signals
Coil 111	MBHSP103 MBHDP101	* Good performance in SP103 and DP101	C111 was damaged during transport - storage
Coil 112	MBHSP104 MBHDP102 (ap SP104b)	* SP104 and DP102 did not perform well	C112 showed V-I signals
Coil 113	MBHSP104	* Cut, limiting coil in SP104	
Coil 114	MBHSP105 MBHDP102 (ap SP105b)	* SP105 and DP102 did not perform well * Electrical non-conformity / QH to coil insulation breakdown	C114 showed V-I signals It has seen high stresses in SP105
Coil 115	MBHSP105 MBHDP102 (ap SP105b)	* SP105 and DP102 did not perform well * Electrical non-conformity / QH to coil insulation breakdown	C115 showed V-I signals C115 is the limiting coil in SP105
Coil 116	MBHSP106	* In CC SP106	C116 showed V-I signals
Coil 117	MBHSP106	* In CC SP106	C117 could be damaged
Coil 118	collaring mock up	* Cut (size issue)	
Coil 119	MBHSP109	* Issue with the coil size - azymuthal	C119 had midplane quenches
Coil 120	MBHSP107	* SP107 is "the" reference model, not to be dismounted	
Coil 121	MBHSP107	* SP107 is "the" reference model, not to be dismounted	
Coil 122		* Metrology at cold * Tomography * Metallography	
Coil 123	MBHSP109	Doubts about electrical integrity	C123 had midplane quenches
Coil 110	Test coil		
Coil 201	Test coil		
Coil 210	MBHSP201	Distructive electrical tests on quench heaters	300 µm excess - nominal prestress
Coil 211	MBHSP201	Distructive electrical tests on quench heaters	300 µm excess - nominal prestress
Coil 212	MBHSP202		150 µm excess - low prestress
Coil 213	MBHSP202		150 µm excess - low prestress
Coil 214	-	Spare coil - never used	

The long prototype will rely on virgin coils and will be the proper vehicle to assess performances.

Choice of Coils (2/2)



Repaired voltage taps on coil 108



Coils 108 and 214

Collaring Trial on Aperture 1 of Short Model Magnet (1/2)

- A first collaring trial was carried out on Aperture 1 of the short model magnet in early September 2022, by a **joint TE-MSC-SMT/LMF team** to ensure continuity.

- Coils 108 and 214 have been assembled introducing **FUJI paper layers** at the coil/pole interface and in the coil midplane **to check stress distribution;** some layers of ground insulation were removed to compensate for the extra thicknesses.

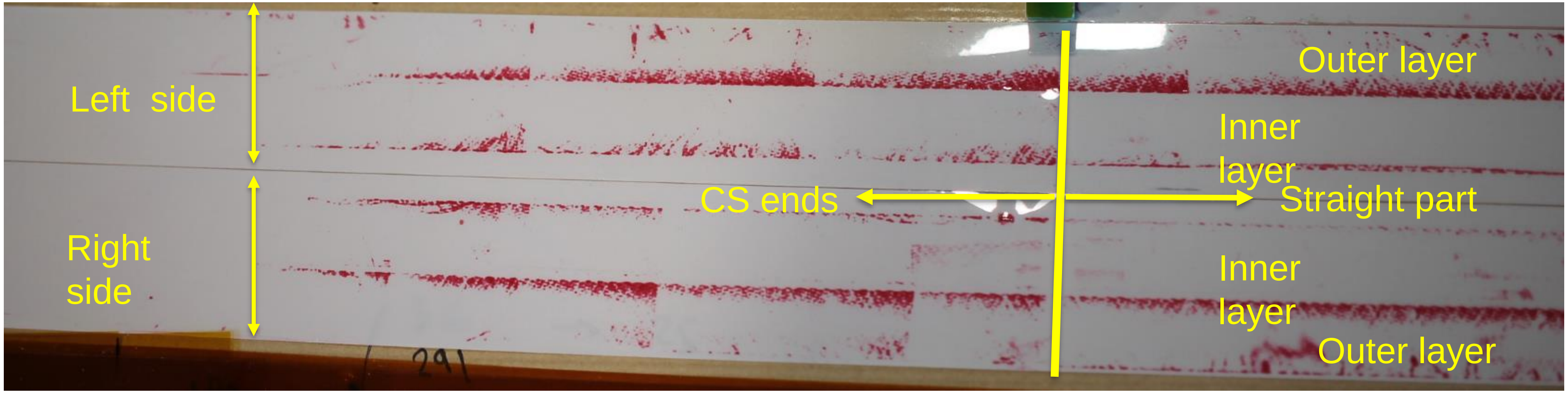
- Collar packs **instrumented with strain gages** were implemented at three axial locations: one in the centre and two close to the ends; the strain gages allow to monitor the average compression in the coils.

- Some pressure was applied via the collaring press, but the press was stopped well before key insertion **to keep the coil pre-compression bellow 50-60 MPa maximum,** which was deemed enough to assess suitability of shimming plan.

Instrumented Collar Pack

Joint TE-MSC-SMT/LMF Team

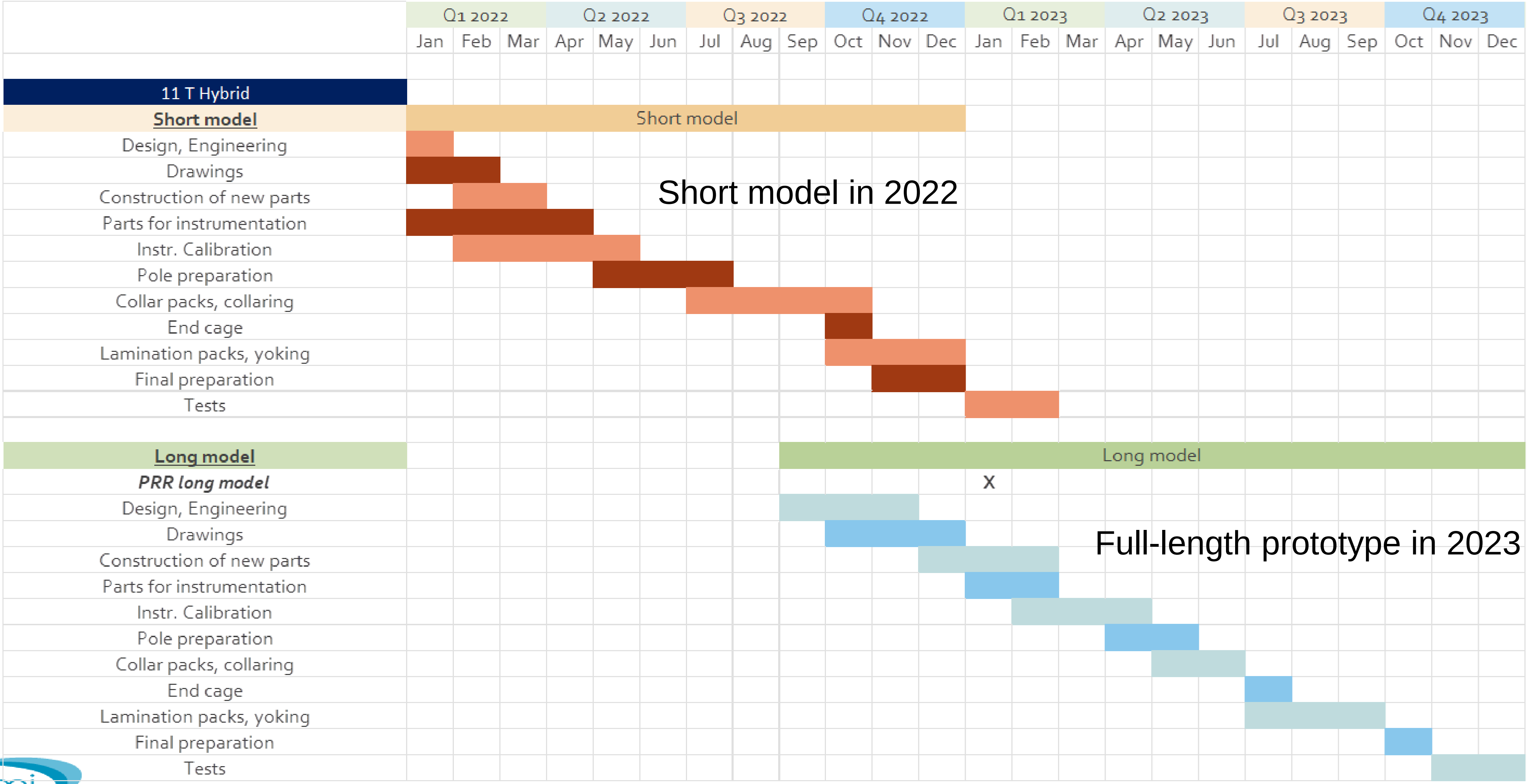
Collaring Trial on Aperture 1 of Short Model Magnet (2/2)



Coil Midplane FUJI Paper

- After disassembly, FUJI paper analysis showed
  - a **smooth transition** between straight part, transition region, and ends;
  - a decrease of compression between beginning of coil ends and last part of end saddle;
  - less compression in NCS (not showed here) with respect to CS, which can be easily corrected.
- However, in absolute value, the recorded prestress was **higher than expected** and the pressure increase had to be stopped earlier than foreseen; the coil aperture seems 0.2 mm larger in diameter with respect to measurements.
- Issue is under investigation and **a second collaring trial** will be carried out.

Schedule



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Conclusion

Phase 1 of Strategy is completed and documented; Phase 2 is underway.

Design of new components for short model magnet is completed; fabrication of new components for short model magnet is almost finished; other 'old' components are available.

Design of new components for full-length prototype has started.

Assembly of short model magnet is carried out by a joint team between B927 and B180 to ensure continuity.

Presently in early phase of short model magnet collaring; work is proceeding cautiously to ensure full control and understanding of what is being done.

Of course, the results of these activities are directly relevant for HFM (12 T robust dipole) and the main actors in TE-MSC-SMT are the same for both projects.