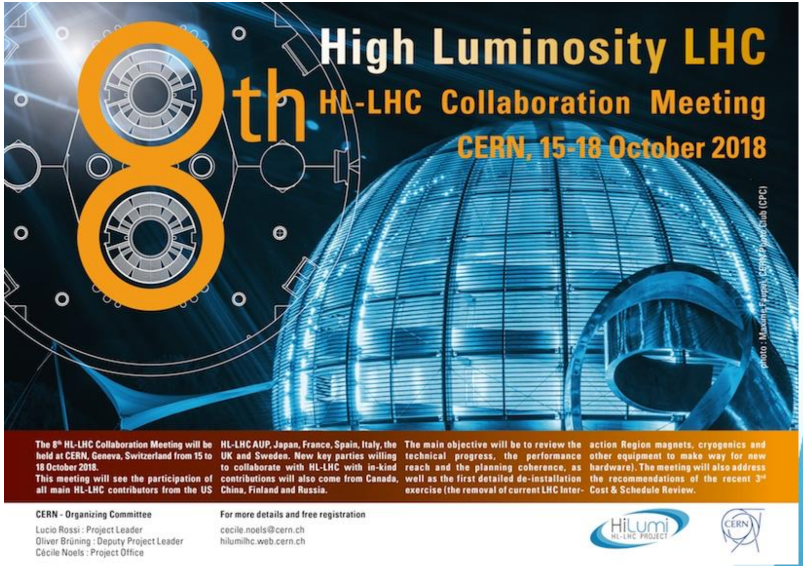

The 11T Dipole Test results, Prototyping, and Industrial Production

M. Barberan Marin, L. Bottura, B. Bordini, N. Bourcey, M. Daly, A. Devred, P. Ebermann, P. Ferracin, S. Ferradas Troitino, A. Foussat, J. Fleiter, L. Grand Clement, S. Izquierdo Bermudez, F. Lackner, C. H. Löffler, F. Mangiarotti, J.C. Perez, H. Prin, G. de Rijk, J.L. Rudeiros Fernandez, **F. Savary**, L.J. Travian, G. Vallone, G. Willering ... **and many others**

8th HL-LHC Collaboration Meeting – CERN Kjell Johnsen Auditorium – 2018.10.17

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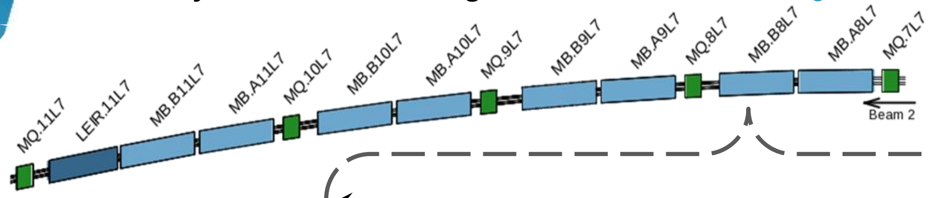
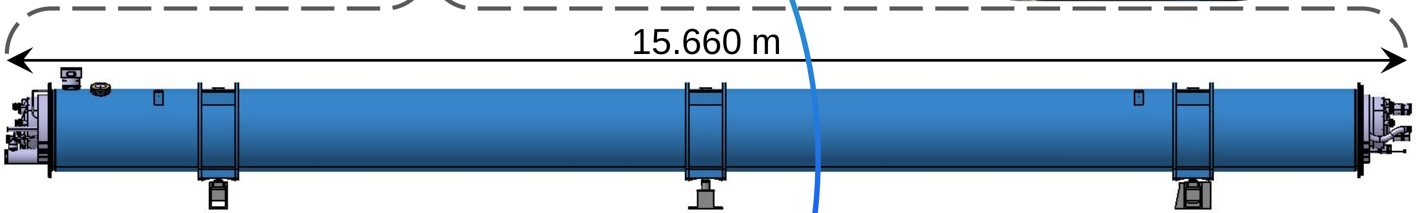
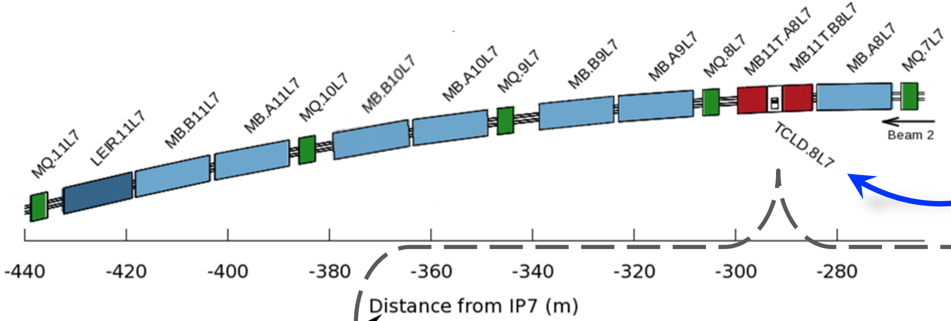
Present layout of the DS region:

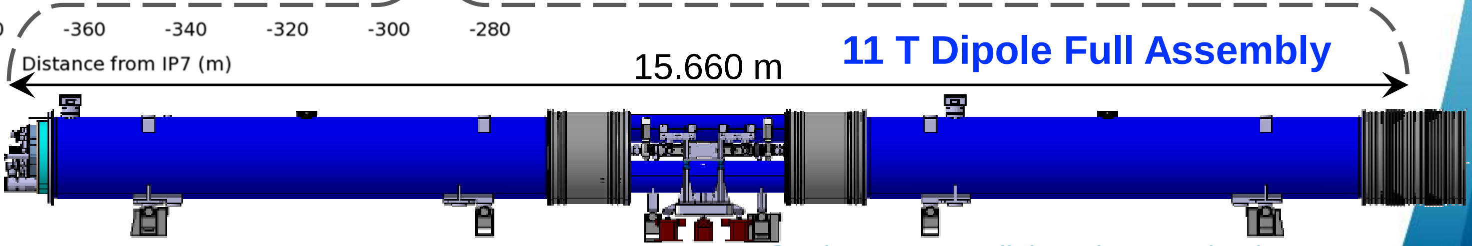




New layout with one collimator and two 11T dipoles:

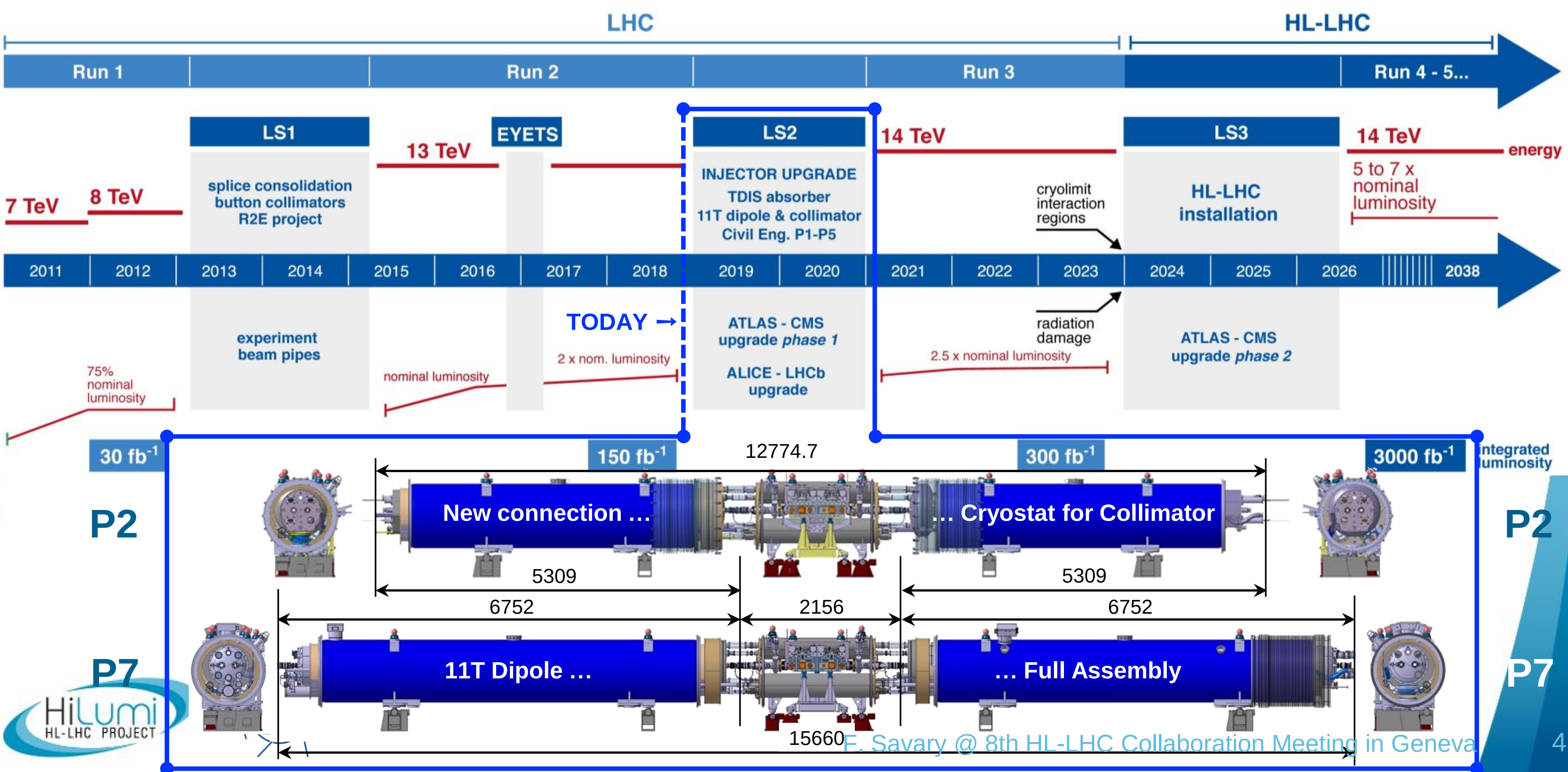


Two collimators, **one per beam, will be installed on either side of interaction point 7** (IP7) in order to absorb both proton and heavy-ion collimation losses



11 T Dipole Full Assembly

LHC / HL-LHC Plan



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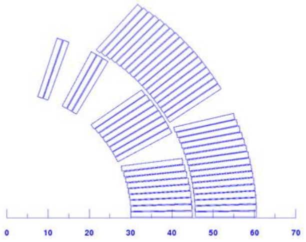
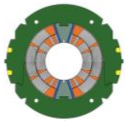
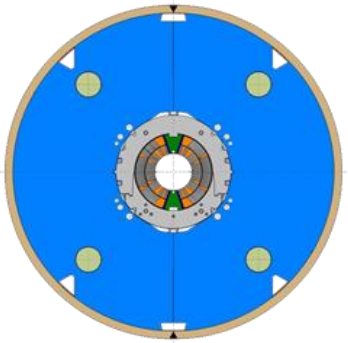
Original model programme @ CERN





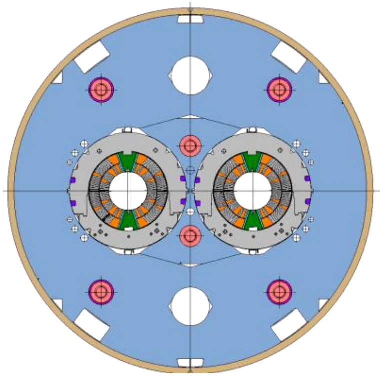
- 6 blocks
- 56 turns:
  - 22 in IL
  - 34 in OL

Single Aperture
OD 534 mm



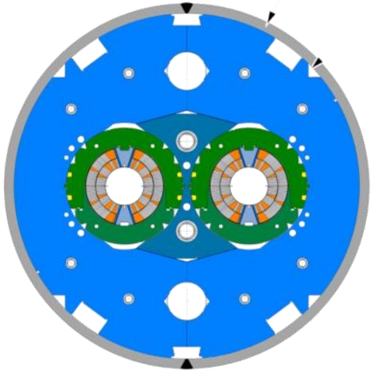
MBHSP101 Not OK
MBHSP102 OK
MBHSP103 OK
MBHSP104 Not OK
MBHSP105 Not OK
MBHSP106 OK

Two-in-One
OD 580 mm



MBHDP101 OK

Two-in-One
OD 570 mm

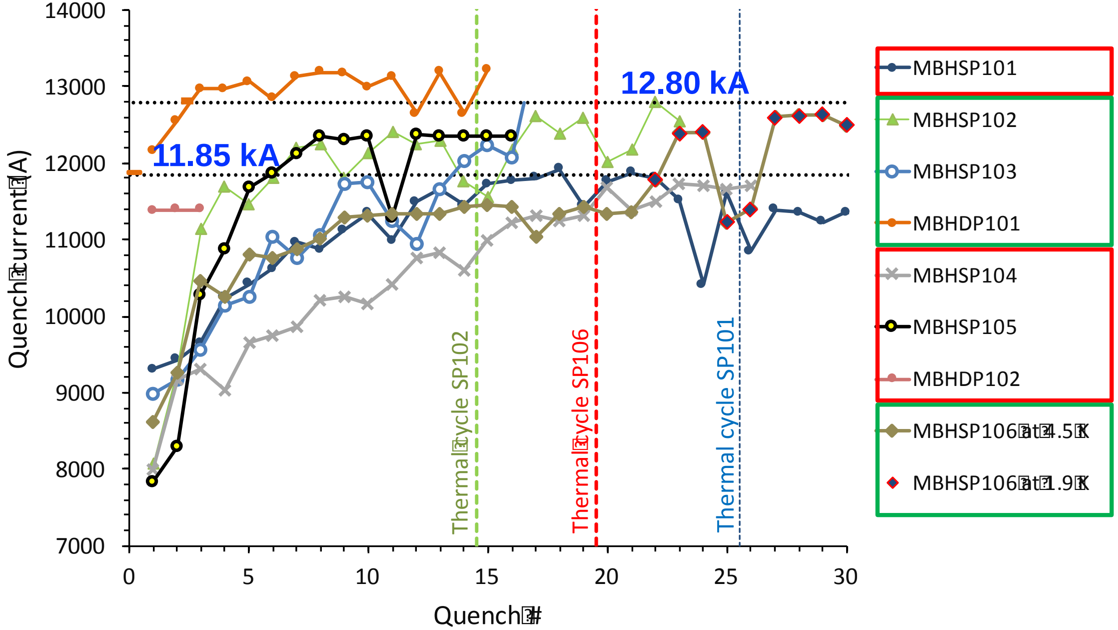


MBHDP102 Not OK

In total 12 coils were tested in 9 model assemblies

Test results of the original model programme

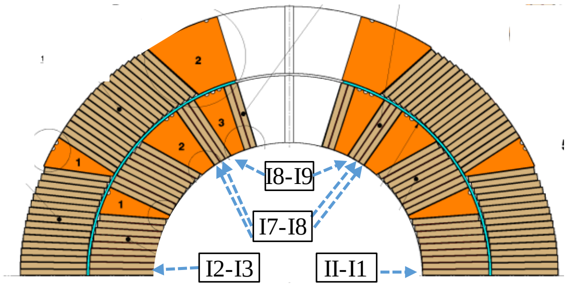
Courtesy G. Willering

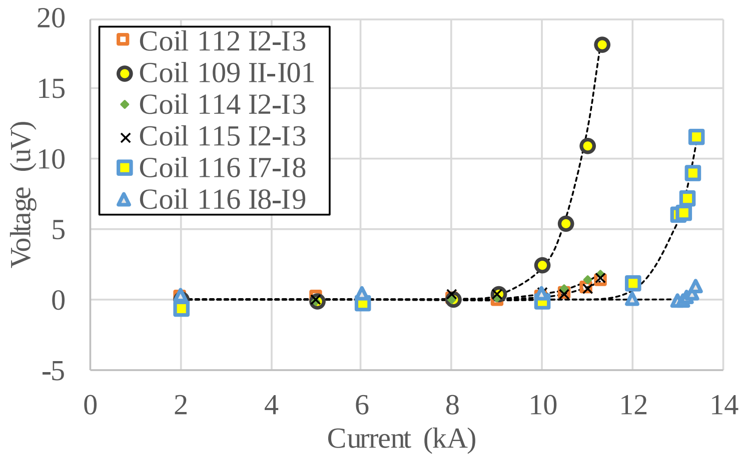


Training of short models shown at the 7th HL-LHC Collaboration meeting held in Madrid in 2017 ***+ MBHSP106***

- Variability in training of virgin coils
- Slow training of some coils linked to issues in layer jump
- **SP106 reached record of 13.47 kA (not shown on the plot)**
- The models **MBHSP104** and **MBHSP105**, **exhibit limitation** due to conductor degradation in the mid-plane (due to excessive stress)
- Re-collared with 15 MPa lower pre-stress, and put together in a two-in-one structure MBHDP102, which did not perform better

Performance limitation due to conductor degradation





- Conductor degradation as suggested for the model MBHDP101 was supported by measurements of **superconducting to normal transition** in the models MBHDP102 and MBHSP106 (very **accurate voltage measurements**!)
- These results, together with the mitigated results of SP104, SP105, and DP102, triggered the **need of additional R&D work**, which materialized within the framework of the **11T Dipole Task Force (kick-off on 10 Nov. 2017)**

Other key results

- All 24 **Nb_3Sn to Nb-Ti splices** have a resistance of 0.3 ± 0.1 nΩ
- **Magnetic field quality**: OK
- **Stable current**: No quench at flat-top current observed in multiple tests at current levels between nominal and ultimate and from 1 to 10 hours duration
- **Quench protection**: The baseline design with only Outer Layer Quench Heaters has been tested with a protection delay of 40 ms at 13.4 kA, reaching a high hot spot temperature without coil degradation
- **Memory after thermal cycle** is very good, even after recollaring of coils
- Effect of **heat load** on quench performance was studied, see presentation L. Bottura (this afternoon session on WP11)

Nb of quenches needed to reach the same current level as before the thermal cycle

Coil	Action performed during thermal cycle	Magnet	I_{max} (kA)	Number of quenches after thermal cycle
106	Re-collared	SP101 →SP102	11.8	3
106	Thermal cycle	SP102	12.5	2
106	Re-yoked	SP102 →DP101	12.8	2
108	Thermal cycle	SP102	12.5	0
108	Re-yoked	SP102 →DP101	12.8	0
109	Re-yoked	SP103 →DP101	12.8	0
111	Re-yoked	SP103 →DP101	12.8	0
116	Thermal cycle	SP106	13.0	0
117	Thermal cycle	SP106	13.0	0
120	Thermal cycle	SP107	12.85	2
121	Thermal cycle	SP107	12.85	0

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Task Force on 11T Dipole Magnet (as from Nov. 2017)

3
E-modulus on ten-stacks, and **on coils**

4
Collaring mock-ups and instrumentation

2
Role of Mica in insulation & Fiber Glass braiding on **insulation thickness**

1
Irreversible Ic degradation caused by transverse stress at RT
Allowable stress

Optimized collaring process

5
QA, **harmonization of fabrication and QC procedures** between long & short coils

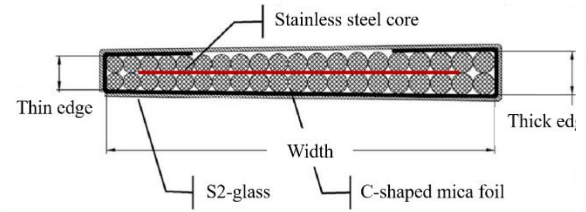
6
Fabrication of 2 magnet models with final conductor & insulation scheme, **including cold tests**

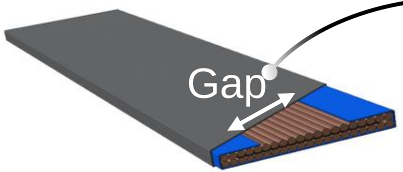
Scheduling

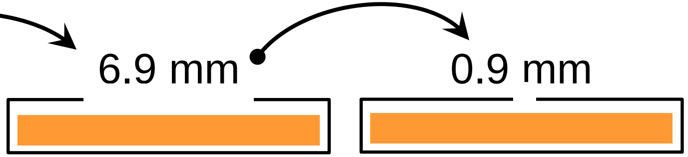
Links with series production, in particular the collaring operation

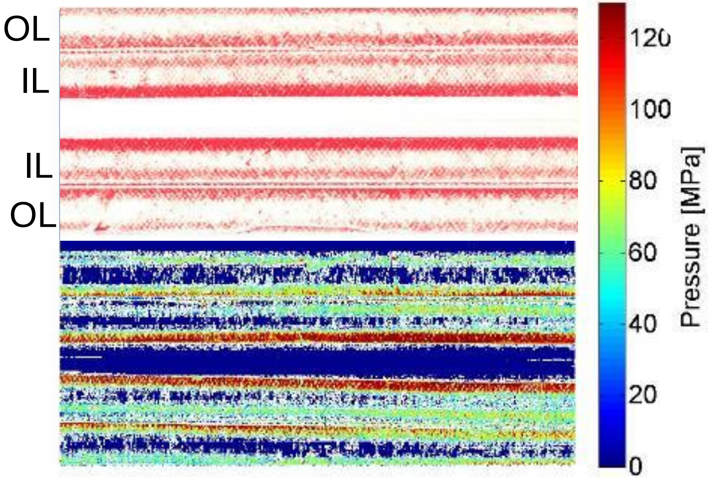
New insulation scheme

- Actually discussed and developed well before setting up the 11T dipole Task Force, triggered by systematic complications when closing the impregnation mould







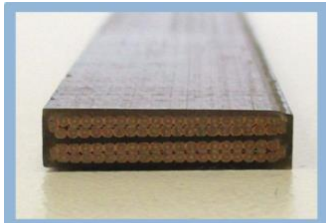


120 MPa stress gradient on the mid-plane in MBHSP105b

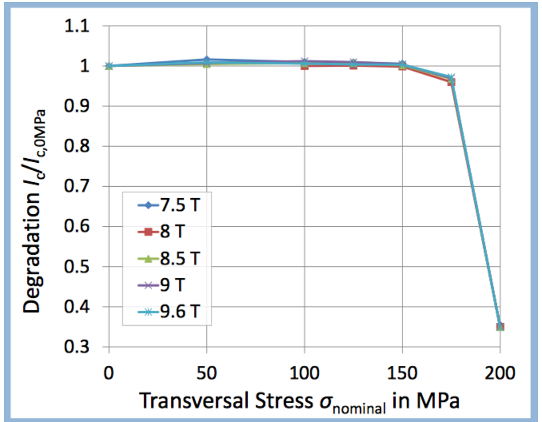

	Before Nov. 2017	After Nov. 2017
Cable width, mm	14.7	14.7
Cable thickness, mm	1.25	1.25
Mica width, mm	**25**	**31**
Gap, mm	**6.9**	**0.9**
Gap/cable width, %	**50**	**6**
Total insulation thickness at 5 MPa, μm	**135**	**100**

Courtesy S. Izquierdo Bermudez

Irreversible degradation of Nb_3Sn Rutherford cables due to transversal compression stress @ room temperature



Specimen cross section
(15.6 x 3.8) mm²



Degradation of I_c at T = 4.2 K (E_c = 3 µV m^{-1})

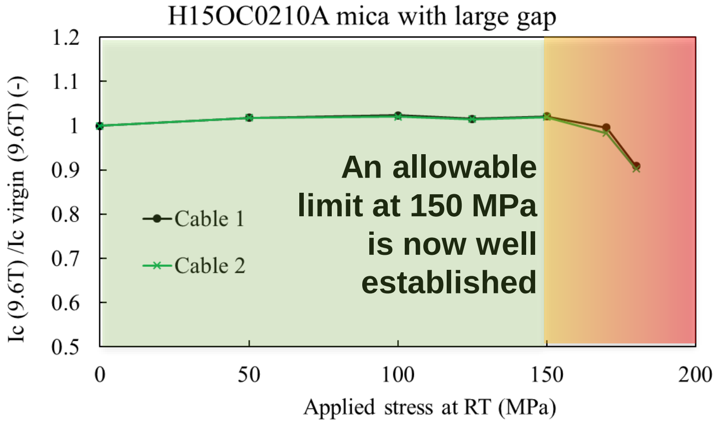
I_c measurement results at max(B_{app}) = 9.6 T and T = 4.2 K

$\sigma_{nominal}$	I_c*	$I_c/I_{c,0MPa}$	n**
MPa	kA	1	1
0	22.1	1.00	60
50	22.2	1.00	60
100	22.2	1.00	60
125	22.2	1.00	60
150	22.2	1.00	60
175	21.45	0.97	60
200	7.9	0.36	<10

* $I_c := I(E = E_c := 3\ \mu V\ m^{-1})$
** $E/E_c := (I/I_c)^n$, [10]

Courtesy P. Ebermann, J. Fleiter, and F. Lackner

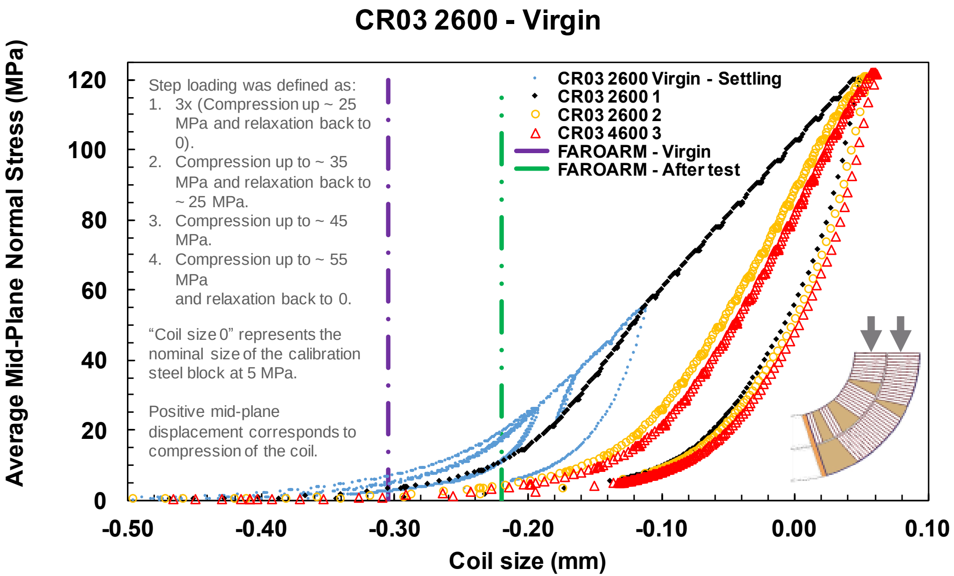
- Final cable of the series, RRP 108/127
- Mica large gap, original before Nov. 2017
- No irreversible degradation up to 150 MPa
- 2% irreversible degradation at 170 MPa
- 10% irreversible degradation at 180 MPa
- The two cables behave the same

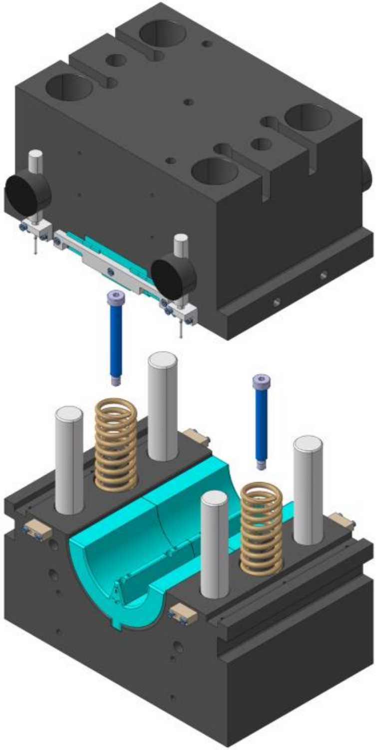


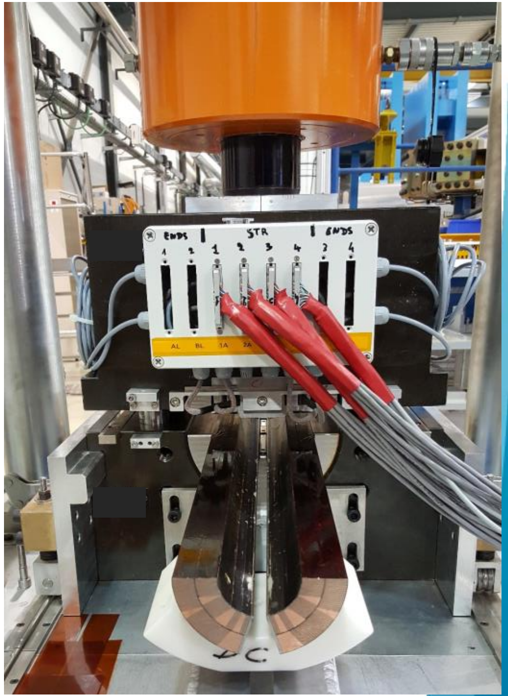
F.

Mechanical behavior of the coils

Coil stiffness measurements







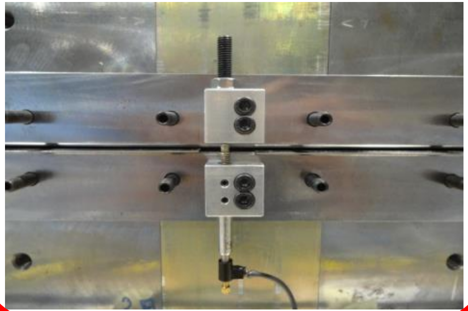
Courtesy S. Izquierdo Bermudez and J.L. Rudeiros Fernandez

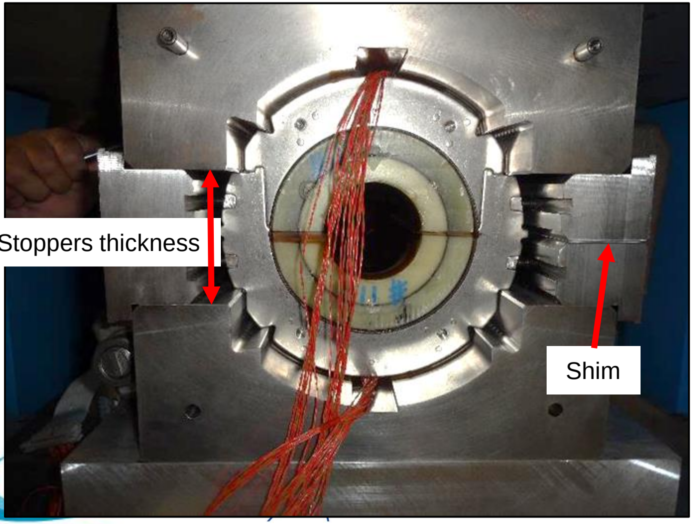
Collaring procedure refined

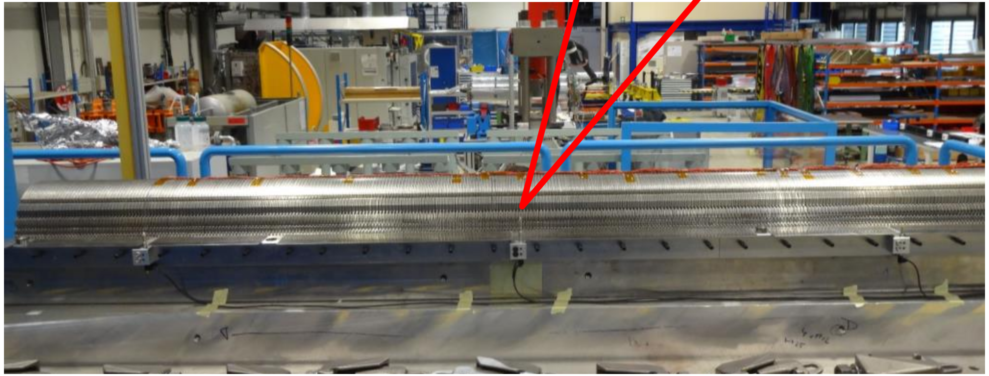
Courtesy N. Bourcey and J.C. Perez

6 LVDT sensors to control the closure of the tooling

STOPPER	SHIM	TOTAL	CLEARANCE
69.70	1	70.70	No
	0.3	70	0
	0.15	69.85	0.150



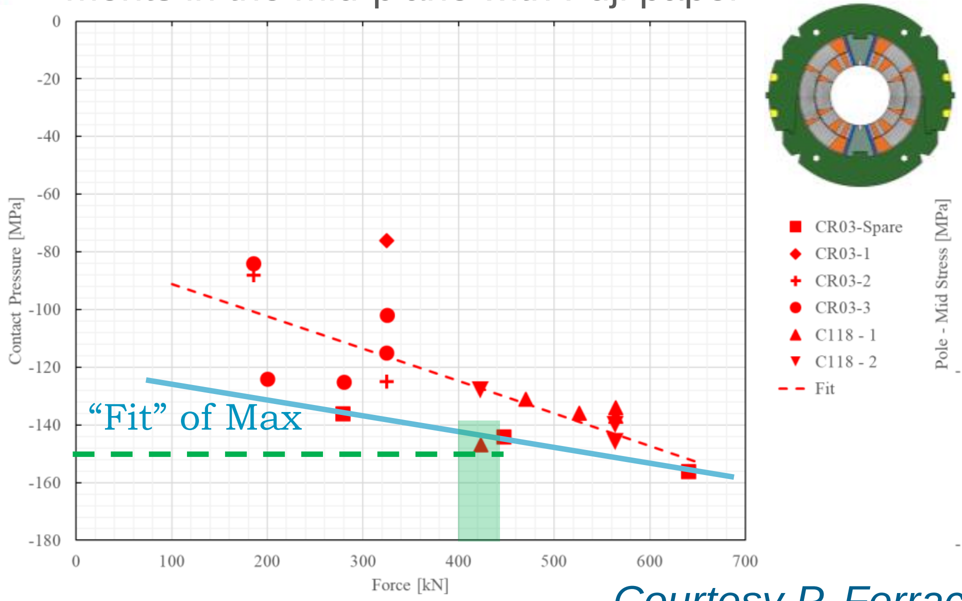




Almost **90 collaring tests** have been made on **150-mm long collaring mock-ups**

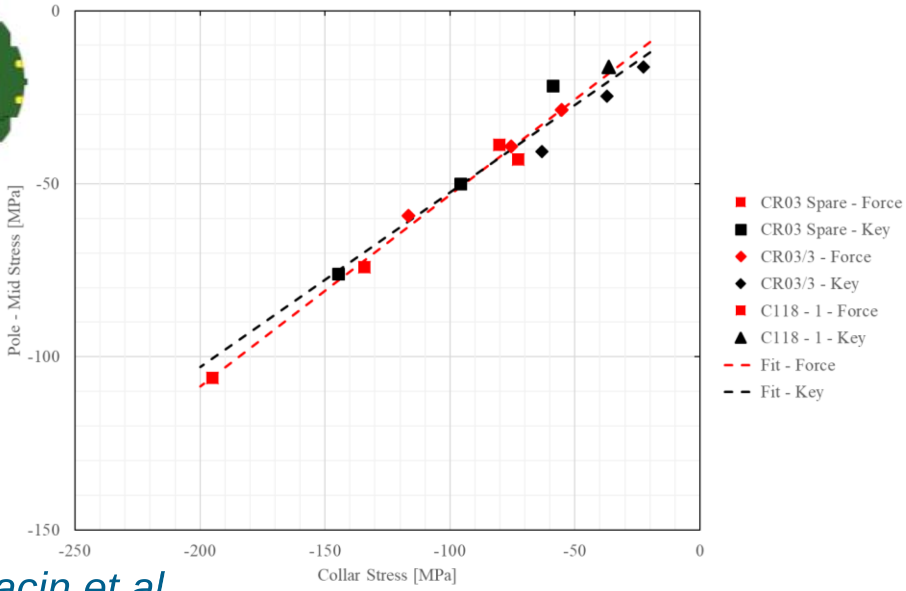
Contact pressure at mid-plane vs. collaring force

- From the 150-mm long collaring mockups, one can deduct a **maximum collaring force of 400-450 kN in order not to exceed a contact pressure of 150 MPa in the mid plane**. The plot is built with the measure-ments in the mid-plane with Fuji paper



Pole stress vs. collar nose stress

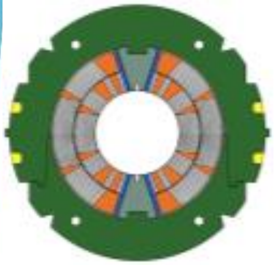
- From the 150-mm long collaring mockups, there is a **good correlation between the pole mid-stress and the collar nose stress**. So, in general, we should be able to estimate the applied pre-stress from this measurement during the collaring of the models

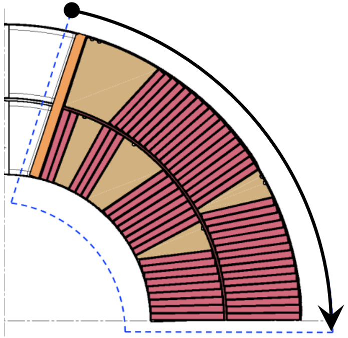


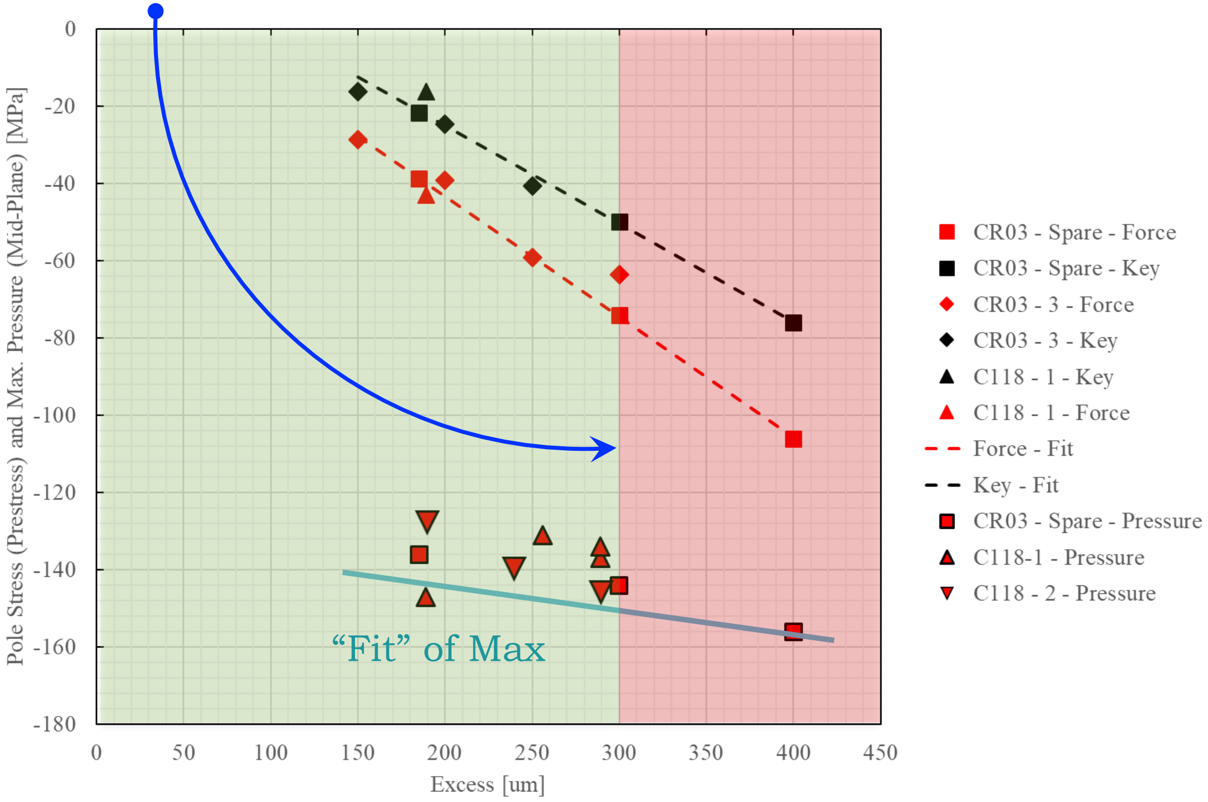
Courtesy P. Ferracin et al.

Pole stress and mid-plane stress vs coil excess

- A **maximum excess of 300 μm is retained** for the shimming plan
- This target has been applied in SP107



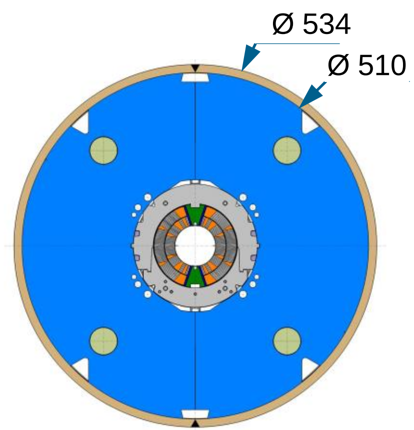




Courtesy P. Ferracin et al.

Additional models

- **New cable insulation scheme**
- **Same conductor as for the series production**
  RRP 108/127
- **SP107 and SP108**
  - **Made identical** in order to demonstrate **reproducibility of the results**, and **reliability/effectiveness of the manufacturing process**
- **S109 with coils of significantly different azimuthal size** to demonstrate that we can cope with such cases in production
- Status:
  - MBHSP107 → Tested
  - MBHSP108 → Test scheduled in March 2019
  - MBHSP109 → In construction, test scheduled in December 2018



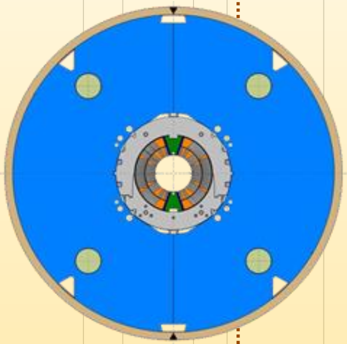
Single Aperture Structure

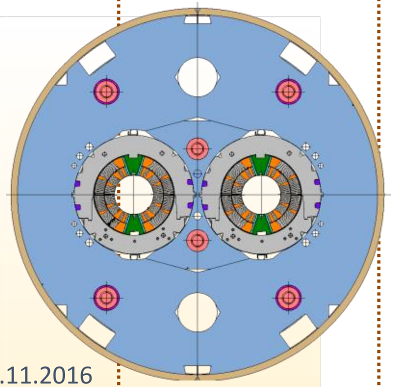
Timeline of magnet cold testing

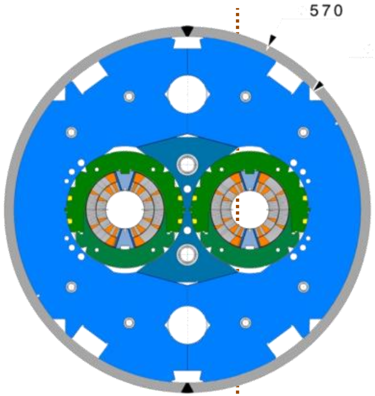
- **MBHSM101** 02.06.2014 - 26.07.2014
- **MBHSP101** X 3.11.2014 - 19.12.2014
- **MBHSP102** √ 4.5.2015 - 30.6.2015
- **MBHSP103** √ 31.8.2015 - 30.10.2015
- **MBHDP101** √ 1.12.2015 - 26.2.2016
- **MBHSP104** X 1.6.2016 - 29.7.2016
- **MBHSP105** X 1.11.2016 - 30.11.2016
- **MBHDP102** X 2.10.2017 - 31.10.2017
- **MBHSP106** X 1.12.2017 - 30.3.2018
- **MBHSP107** (series production cable/insulation scheme) √ 02.07.2018 - 03.08.2018
- **Full length prototype – LMBHB001** X 6.18.2018 - 8.3.2018
- **MBHSP109** (series production cable/insulation scheme/coils of diff. size) 03.12.2018 - 14.12.2018
- **MBHSP108** (series production cable/insulation scheme/identical to SP107) 3.4.2019 - 3.29.2019

2014 | 2015 | 2016 | 2017 | 2018 | 2019

TODAY



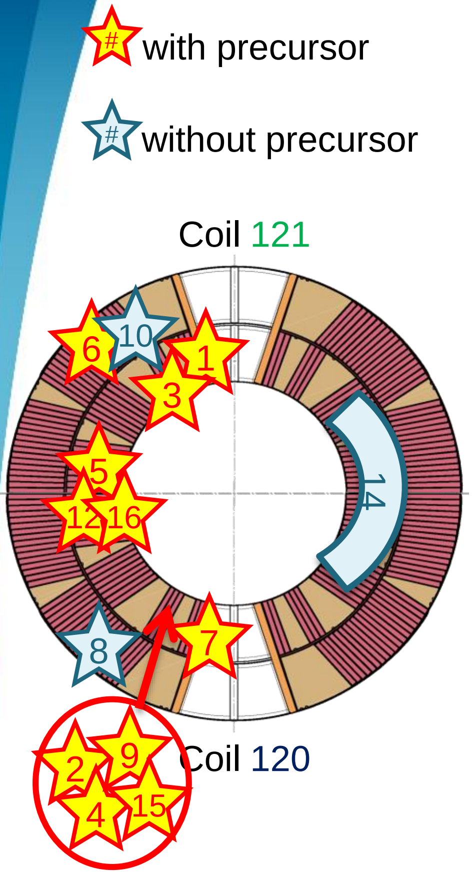


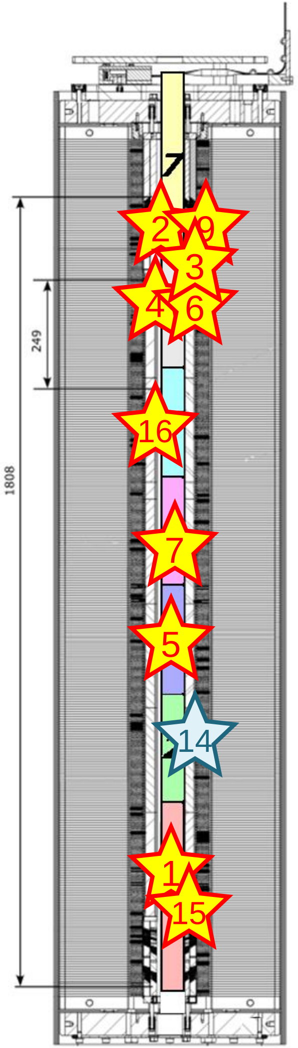


Cold tests of SP107 in SM18

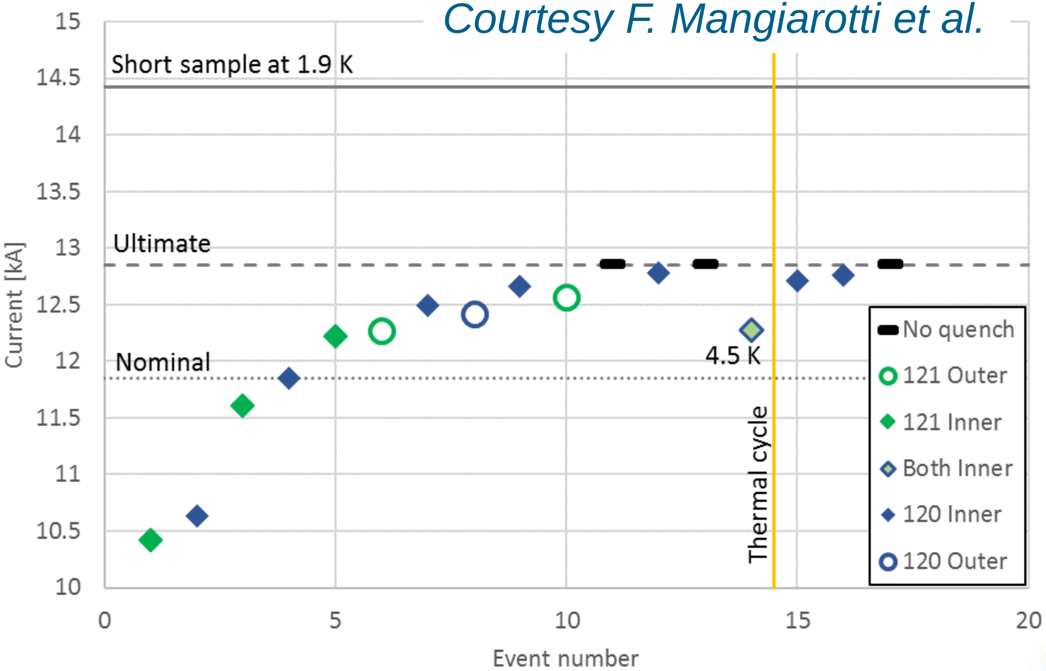
Courtesy N. Bourcey, F. Mangiarotti et al.

Training behavior of SP107





Courtesy F. Mangiarotti et al.

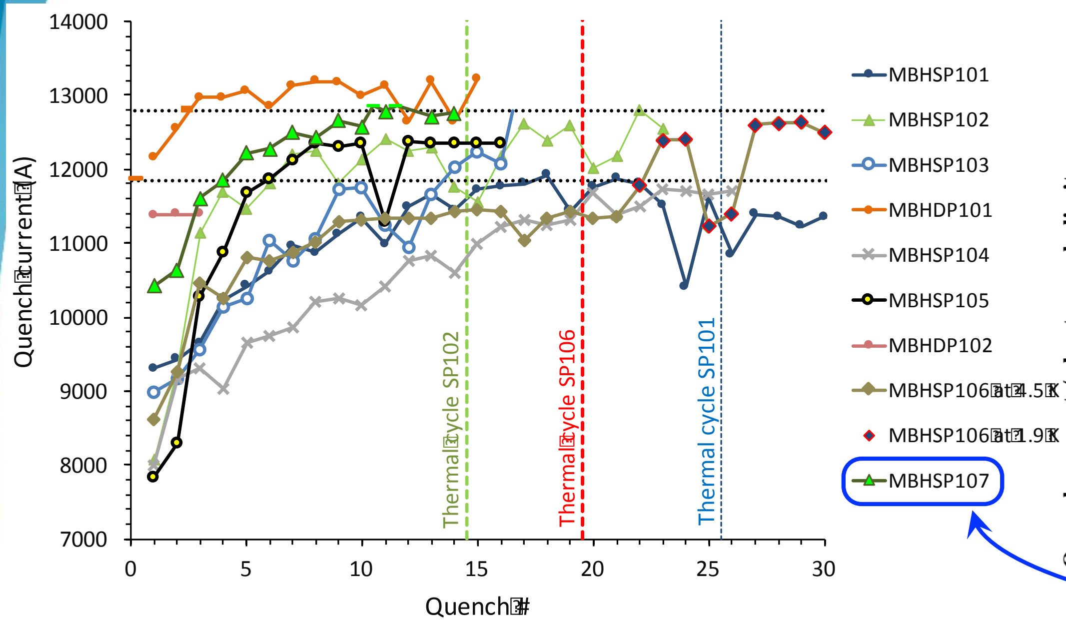


- Vibrations/precursors: in all quenches, except #8, #10 and #14
- Endurance: 2.5 h at nominal (not shown), 10 min. at ultimate
- Test at 4.5 K (94% Iss) looks more like a magnet limitation in the mid-plane (deducted from the ramp rate studies)

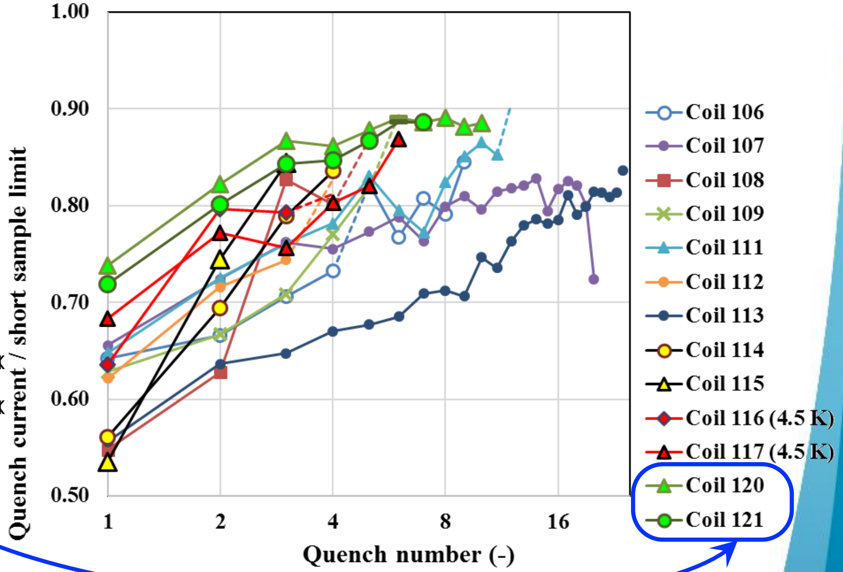
SP107 compared to the other models

Courtesy G. Willering and F. Mangiarotti et al.

Per magnet



Per coil



- Fastest training to ultimate current
- Reaching highest quench current level at 4.5 K of 12.3 kA!! (nominal is 11.85 kA at 1.9 K)
- V-I measurements show no sign of degradation @ 1.9 K
- Ramp rate studies show SP107 gets closest to the witness sample superconducting limit

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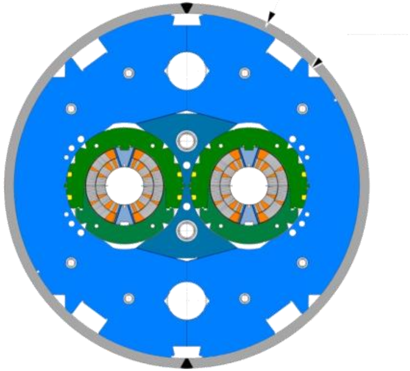
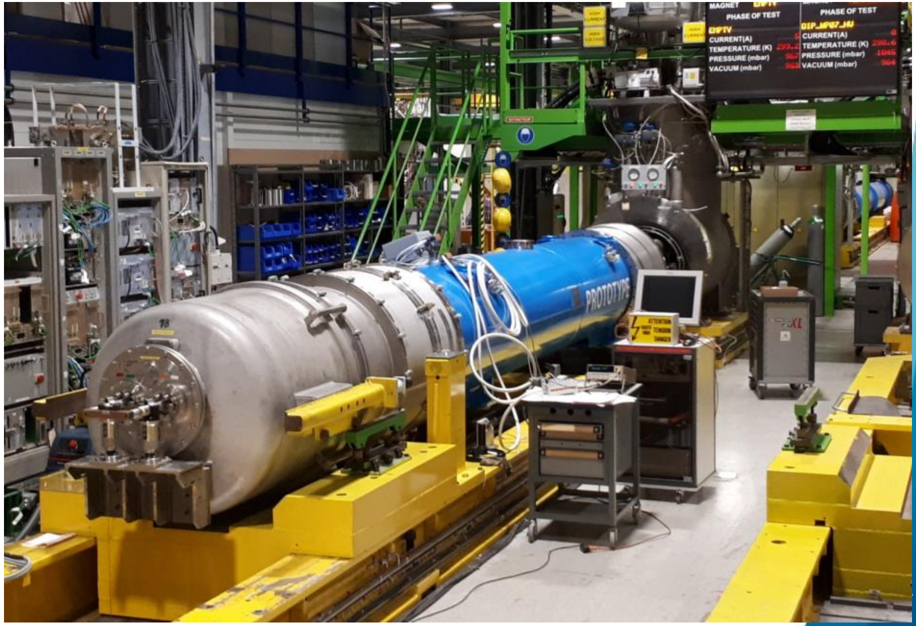
Prototype – LMBHB001

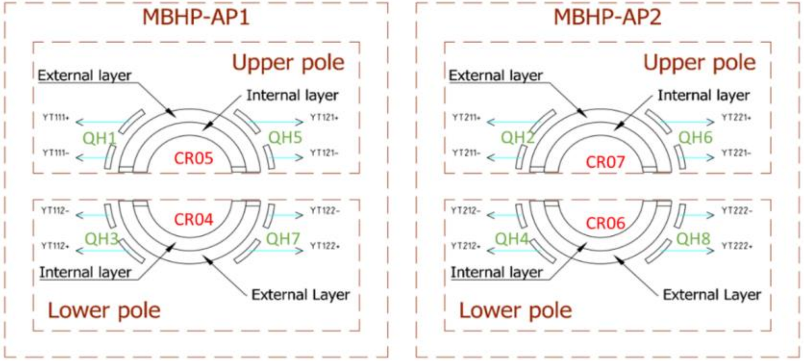
Two-in-One
OD 570 mm





Main parameters

Seen from lead end



Nominal current	11.85 kA
Ultimate current	12.85 kA
Central field at 11.85 kA	11.24 T
2D and 3 D peak field with SF at 11.85 kA	11.79 T
Differential inductance at 11.85 kA	62.75 mH
Magnetic length at 11.85 kA / 1.9 K	5.264 m

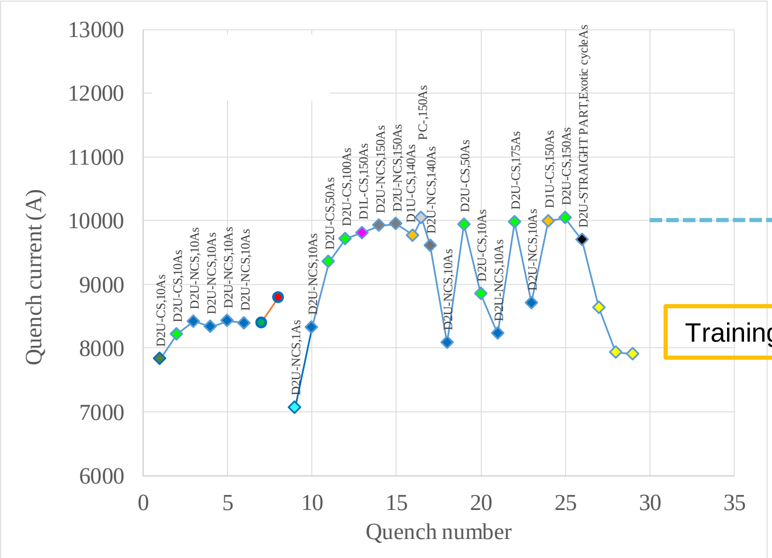
	APERTURE 1		APERTURE 2	
Coil	**CR04**	**CR05**	**CR06**	**CR07**
Strand Type	RRP 132/169 & 150/169	RRP 144/169 & 150/169	RRP 108/127	RRP 108/127
Cable ID	H15OC0194A	H15OC0196A	H15OC0209A	H15OC0210A
Cable Insulation (original, thick scheme)	S2-11Tx - Mica 80 μm	S2-11Tx - Mica 80 μm	S2-11Tx - Mica 80 μm	S2-11Tx - Mica 80 μm
R_{300K} after impregnation (mOhm)	1254	1362	1267	1252
Cu/non-Cu ratio range (average)	1.04-1.27 (1.18)	0.96-1.19 (1.06)	1.11 – 1.18 (1.14)	1.11 – 1.2 (1.15)
Expected RRR from short samples (-)	129	107	163	147
$RRR_{293K/20K}$ measured **	> 146	> 108	>212	>205
Min Short sample current (kA) at 1.9 K	14.32	15.38	15.19	15.32
Min Short sample current (kA) at 4.3 K	13.02	14.02	13.90	13.90

** Transition from superconducting to normal took about 25 minutes. A temperature gradient over the magnet is expected

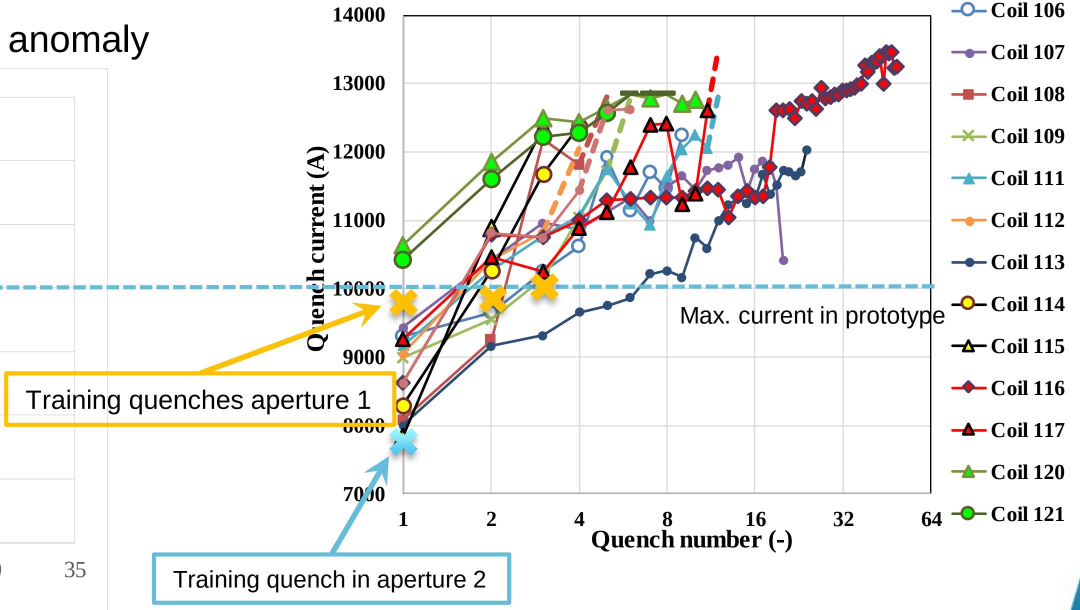
Magnet training

Courtesy G. Willering and F. Mangiarotti

- **4 quenches**: 1, 13, 16, and 24 are **training quenches**, since a large vibration precursor is seen at the start of the quench
- For all the **other quenches**, **conductor degradation** plays a substantial role
- Insulation qualified at 3.3 to 3.4 kV between coils, heaters and ground
- Quench heaters fired > 80 times, no anomaly



Tentative comparison with the model coils, to be seen with caution

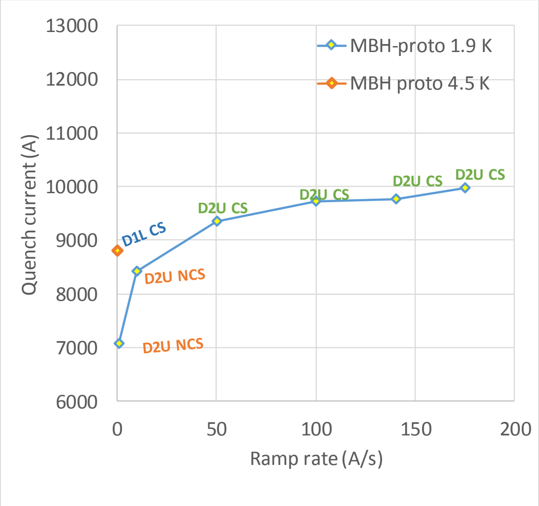


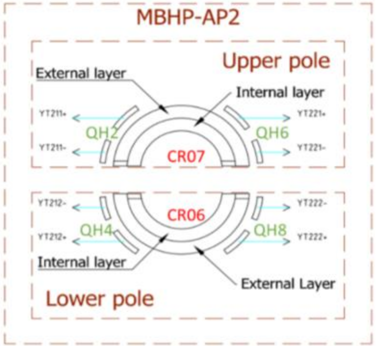
Magnet limits – 1

- The **prototype exhibits 2 clear limits**:
  - At low ramp rates, in the head of D2-Up, non-connection side
  - At higher ramp rates, in the head of D2-Up, connection side

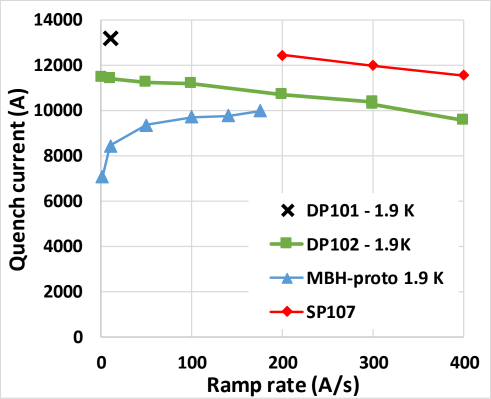
- **The model DP102 had a normal dependency on ramp rate**, but at a reduced level due to the degradation in the midplane, whereas **the prototype LMBHB001 has an inversed dependency**. This may be related to non-homogeneous defects, which are causing non-homogeneous current distributions and weird quench effects

Courtesy G. Willering





At 4.5 K a higher quench current was reached compared to 1.9 K for low ramp rates



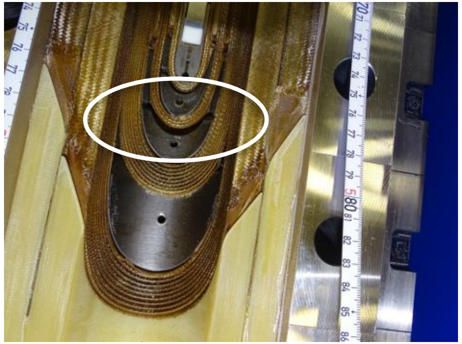
Comparison of the LMBHB001 prototype with the best performing model coils (SP107, and DP101), and the worst ones (DP102)

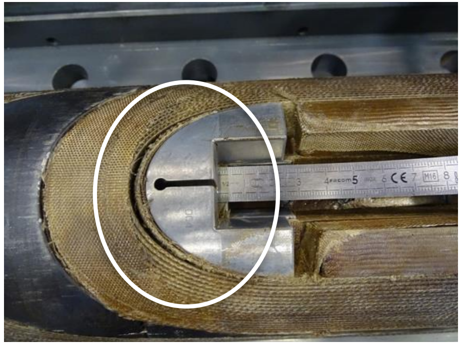
Magnet limits – 2

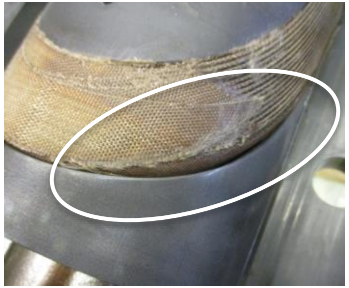
- The **prototype has clearly a bad coil, CR07**, due to **issues in the heads**
  - Very non-homogeneous damage to the coil in multiple strands, could be consistent with local incidents provoquing deterioration of the conductor during the reaction process

- Resistive voltage was also observed, like in the magnet models

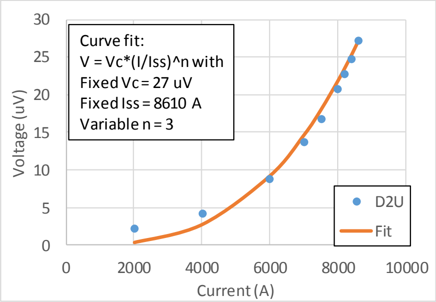
- CR07, NCS – Outer Layer
- CR07, NCS – Inner Layer



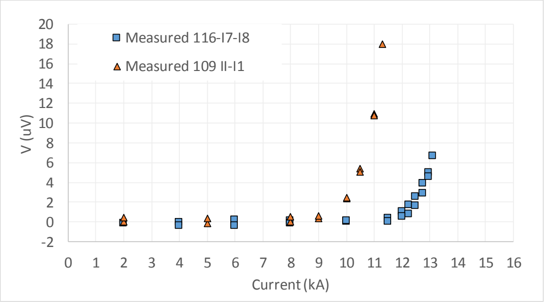




V-I signature
in the prototype



V-I signature @ midplane of coil 109
and block 3 of coil 116 (models)



Courtesy G. Willering

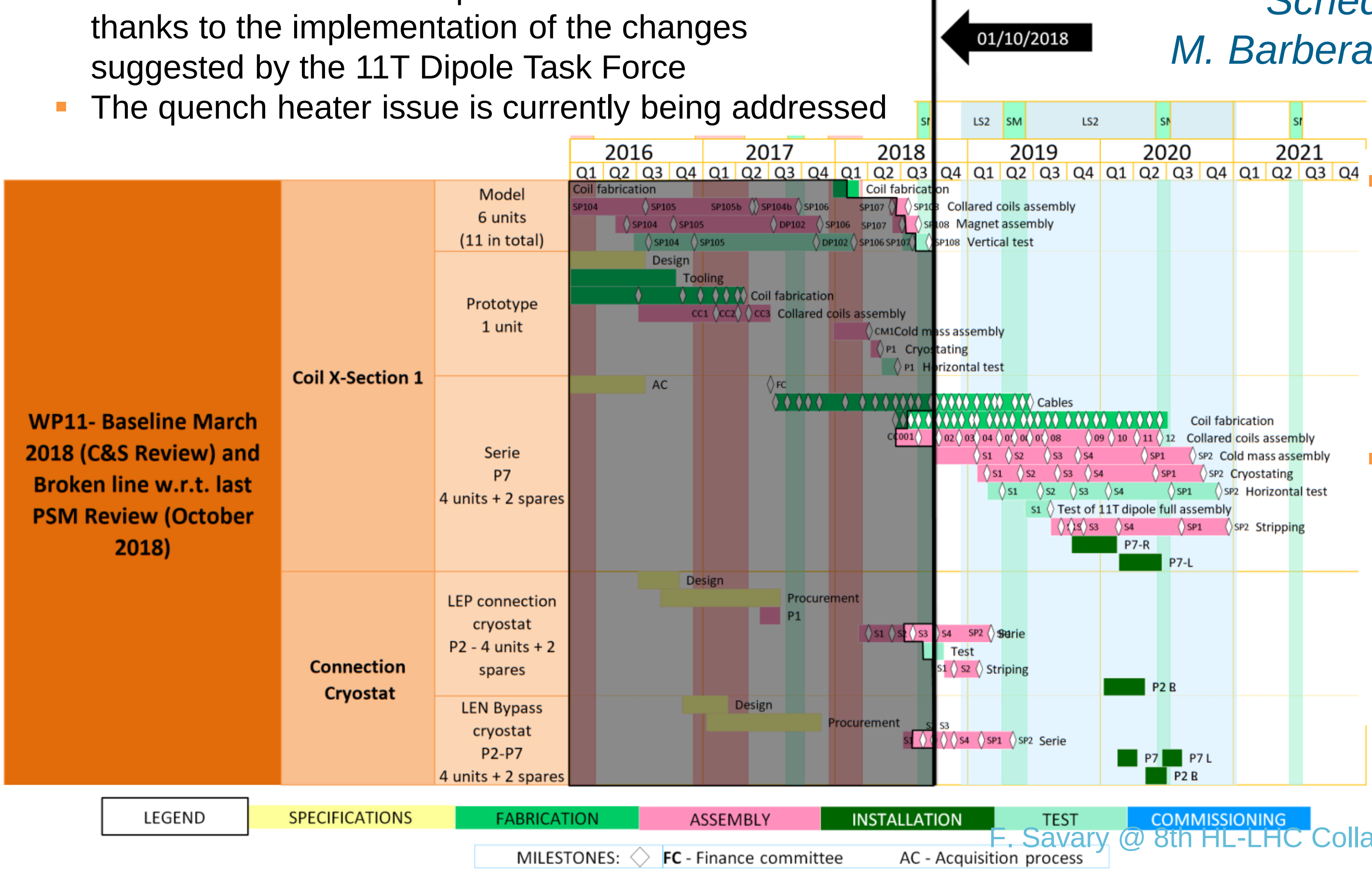
Quench heater insulation fault

QH ID	Cold Mass Assembly Virgin, on 04.04.18 Before cryostating 2.1 kV	Cold Mass Assembly Modified, on 20.08.18 After forming of IFS 1 kV	Cold Mass Assembly Modified, on 30.08.18 Before transport for cryostating -	Before destructive test On 27.09.18 25 V
YT111	All QH / all coils + Gnd 0.83 μA @ 2.1 kV - R = 2.53 GΩ @ 2.1 kV	All QH / all coils + Gnd 0.68 μA @ 1 kV - R = 1.48 GΩ @ 1 kV	All QH / all coils + Gnd 0.57 μA @ 1 kV R = 1.75 GΩ @ 1 kV Not passed @ 2.1 kV	R / Coil 1 = 5.65 MΩ
YT112				R / Coil 1 = 0.64 MΩ
YT121				R / Coil 1 = 7.38 MΩ
YT122				R / Coil 1 = 7.10 GΩ
YT211				R / Coil 2 = 1.31 MΩ
YT212				R / Coil 2 = 0.42 MΩ
YT221				R / Coil 2 = 1.25 MΩ
YT222				R / Coil 2 = 6.15 GΩ

Outcome and plan for the prototype LMBHB001

- The severe limitation in quench current will be cured thanks to the implementation of the changes suggested by the 11T Dipole Task Force
- The quench heater issue is currently being addressed

Schedule by courtesy of M. Barberan Marin and L.J. Tavian



- **Reassembly APERTURE 1 with the first CC of the series**, such that cold tests can be performed in Jan.-Feb. 2019
- **Carry out electrical tests on QH of APERTURE 2** in order to identify the cause of the weakness, and put in place a solution

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- Model programme and test results
- 11T Dipole Task Force
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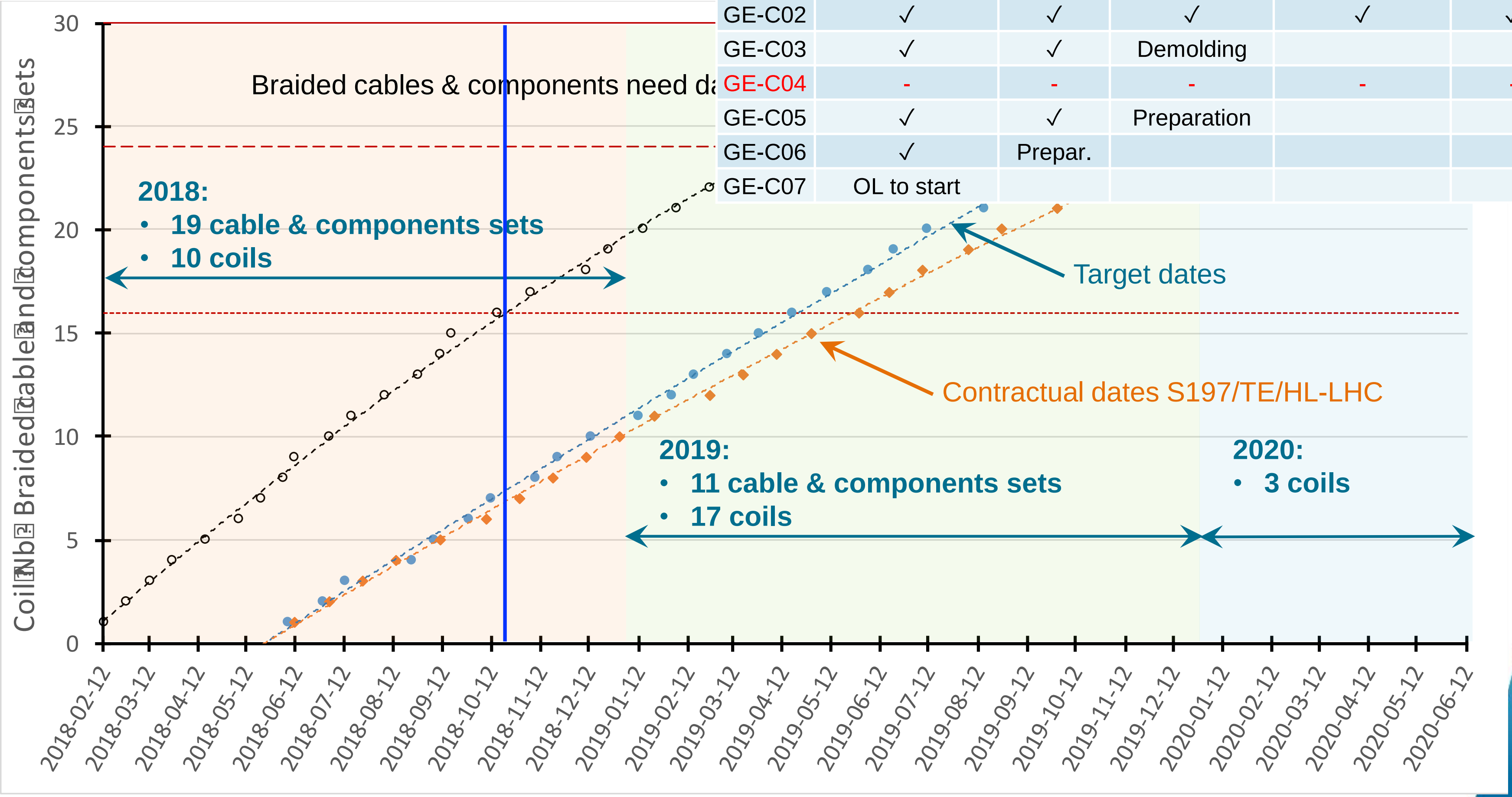
- Summary

Production of '4 + 2' 11T Dipole Cryo-Assemblies

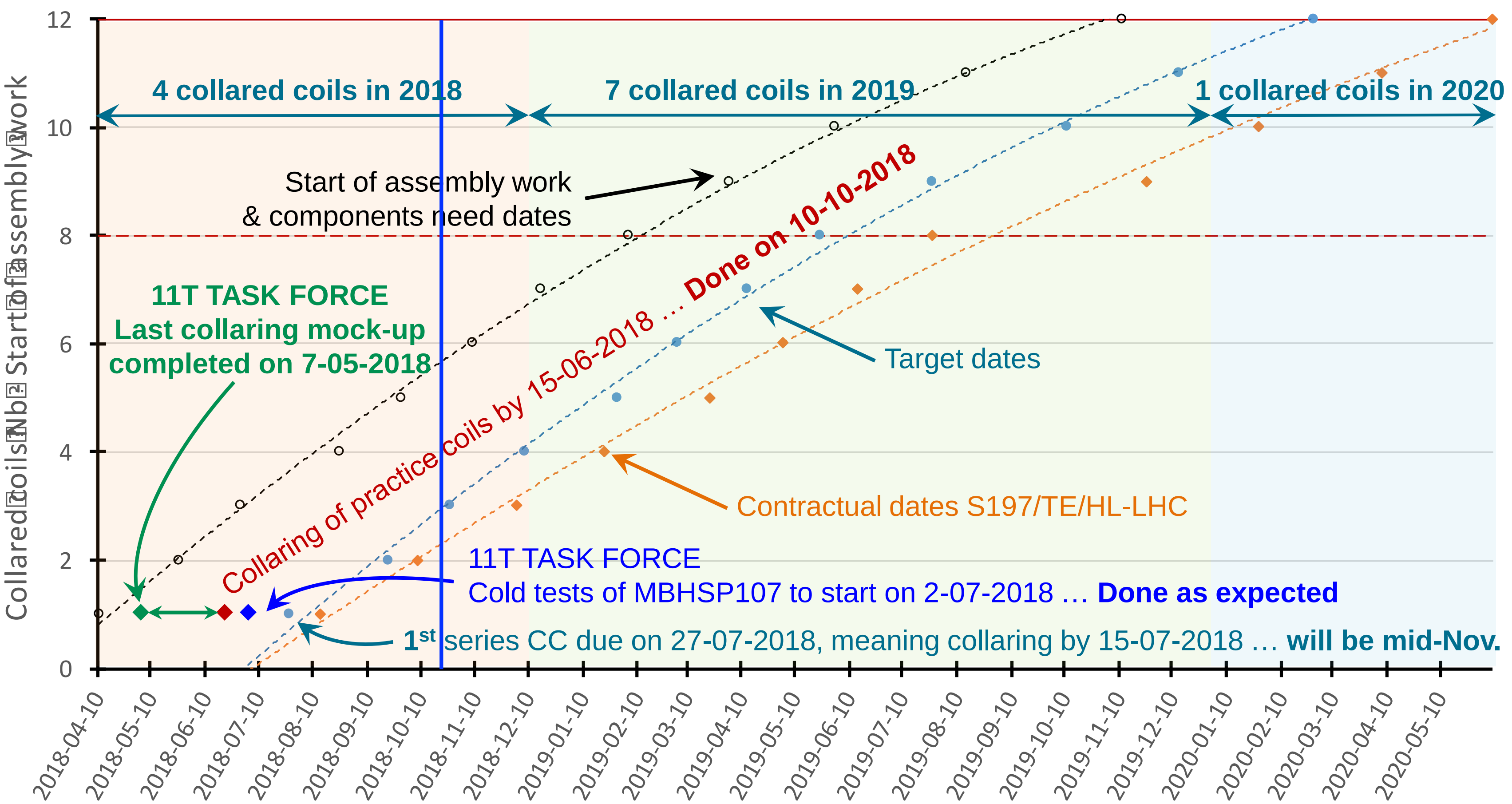
- At CERN, in the Large Magnet Facility in bldg.180
- Production of the coils and collared coils by a contractor, the company GE, formerly Alstom Belfort
  - 30 coils (16 for installation + 8 for spare magnets + 6 spare coils) and 12 collared coils (8 for installation + 4 for spare magnets)
  - Contract started in the end of 2017 with a start up phase (now a team of 16 people)
  - Status, see next slide
- Production of the magnet & cold mass assembly, cryostating, testing and preparation for installation by CERN staff + contract labour technical staff (FSU)

Coils producti

Coil ID	Wind. & Curing	Reaction	Impregnation	Electrical tests	Metrology
GE-Cu	√	√	√	√	√
GE-C01	√	√	√	√	√
GE-C02	√	√	√	√	√
GE-C03	√	√	Demolding		
GE-C04	-	-	-	-	-
GE-C05	√	√	Preparation		
GE-C06	√	Prepar.			
GE-C07	OL to start				



Collared coils production plan (12 collared coils)



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Summary

- The model programme, and a very nice combination of comprehensive and accurate measurements at cold have given us deep insight on the 11T dipole behavior
- An “aggressive” action plan materialized within the framework of the 11T dipole task force has allowed understanding better the mechanical behavior of the magnet, and the boundary conditions prevailing in terms of conductor limits, and allowable stress at the mid-plane. An improved collaring process was developed
- The prototype, even though not performing well, has provided valuable return on investment, in particular as to what regards the coil manufacturing process, and the electrical robustness of the insulation system, which needs to be improved for the quench heaters
- The series production has started. Even though the schedule is more than challenging, we can still implement the changes suggested by the 11T Dipole Task Force. There is a solid team in place to carry out the work, and all tooling needed are available

Thank you very much for your attention!