HiLumi
HL-LHC PROJECT

Status and Test Results of the 11T Magnets

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G. Willering, **and actually many others**

CERN

10th HL-LHC Collaboration Meeting, CERN, https://indico.cern.ch/event/937797/, 2020-10-06

Outlook

- Plan
- Magnet performance tests results
- Quench heaters
- Spikes
- Thermal gradients
- Status
- Concluding remarks

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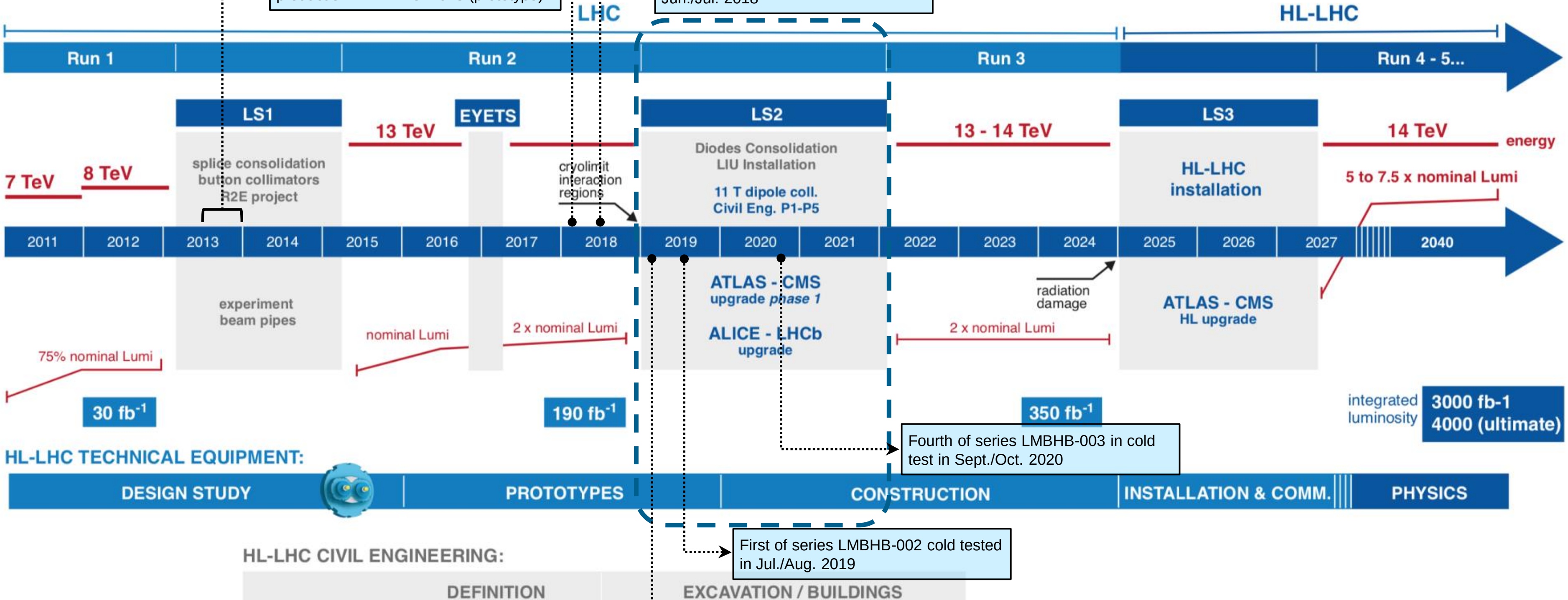
LHC / HL-LHC Plan

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



Fourth of series LMBHB-003 in cold test in Sept./Oct. 2020

First of series LMBHB-002 cold tested in Jul./Aug. 2019

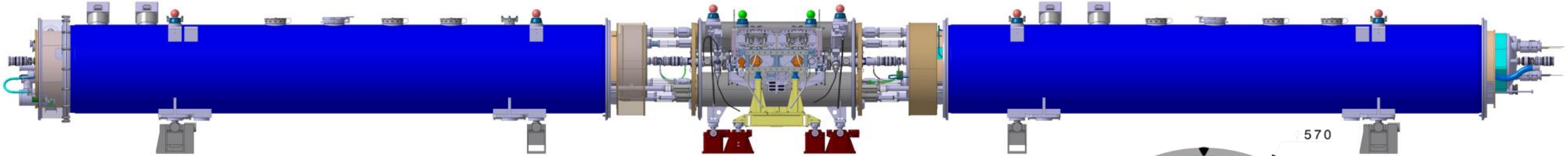
Hybrid LMBHP-001 cold tested in Feb./Mar. 2019

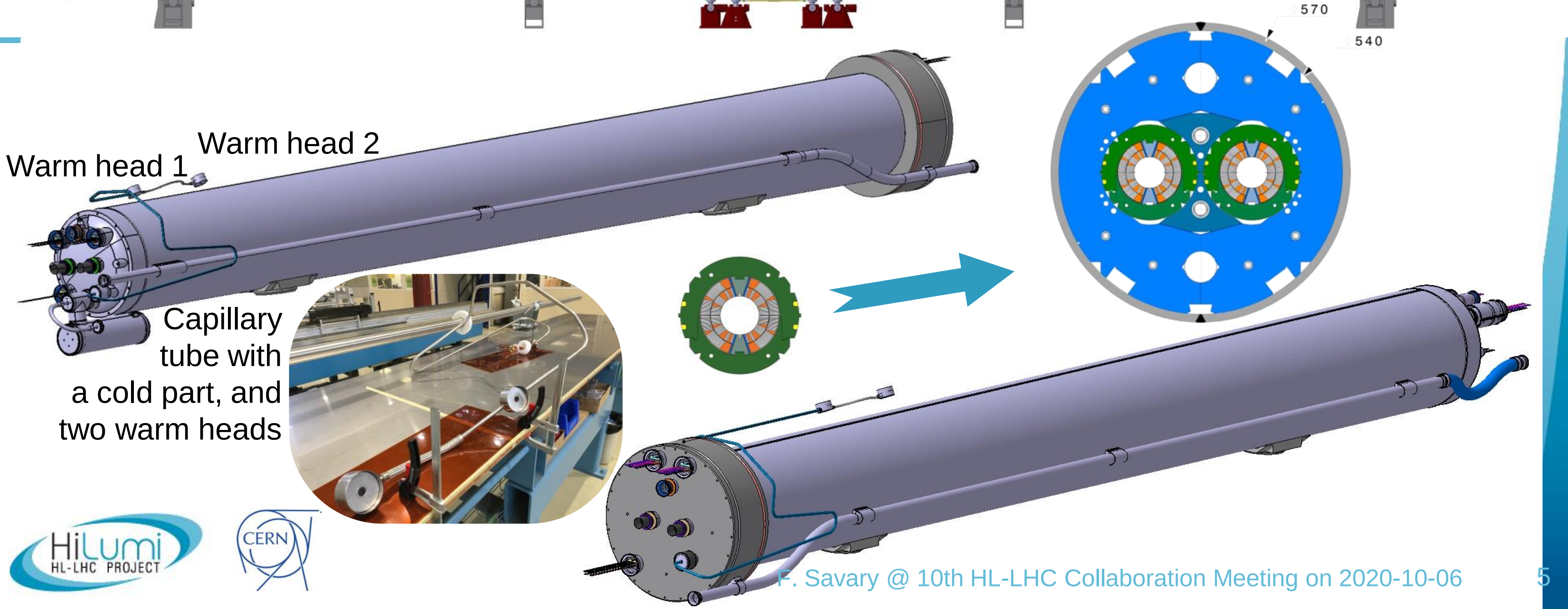
The 11T Dipole Full-Assembly

LBH_**A** (type A)

By-pass cryostat with collimator

LBH_**B** (type B)





Warm head 2

Warm head 1

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: LMBH**A**001			
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

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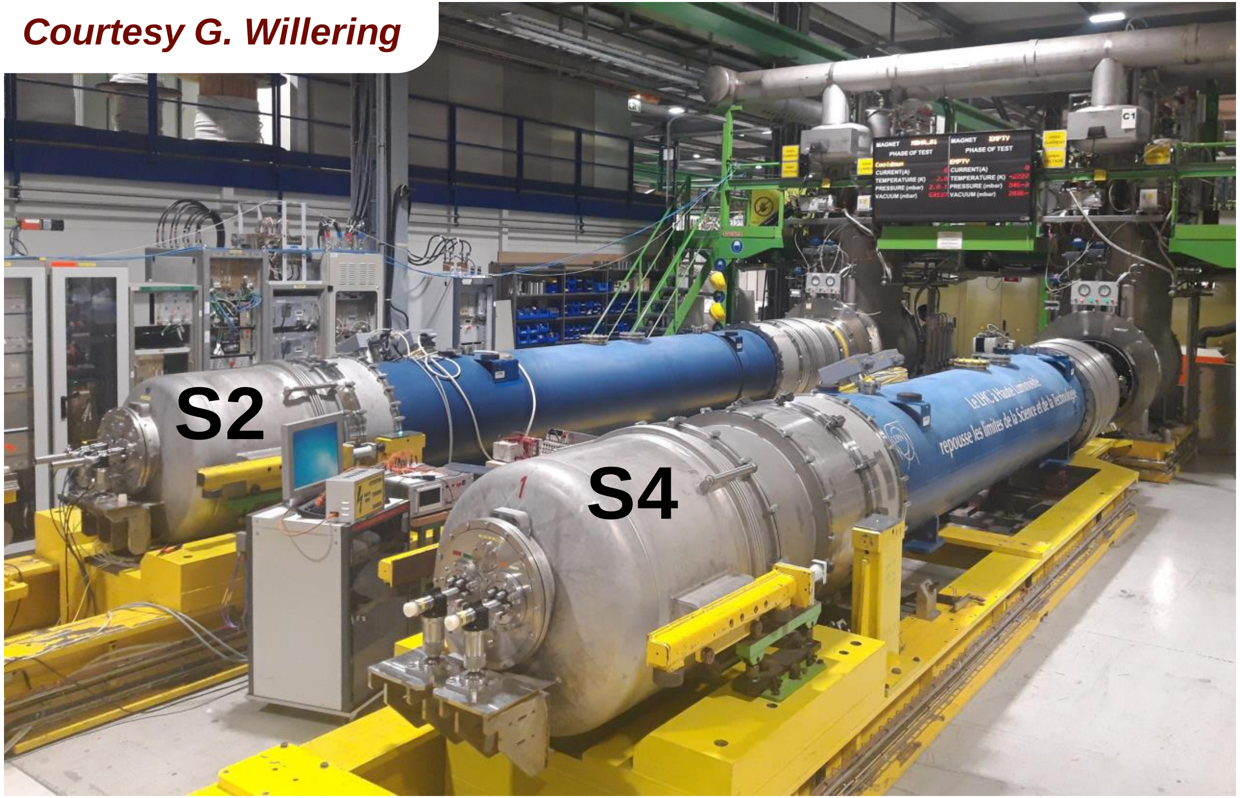
S2 and S4 on test in SM18 – Picture taken on 2020-02-20

Courtesy G. Willering

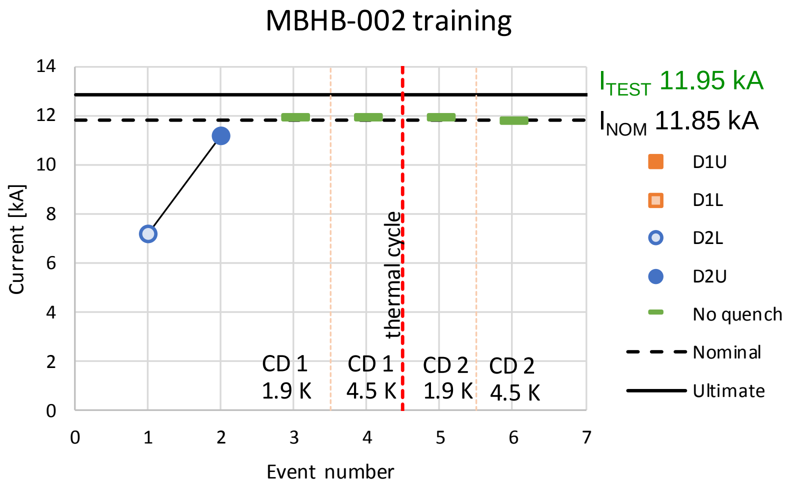


S2 ready for CD2

S1 (LMBHB002) – Powering tests results

Courtesy G. Willering et al. – See also A. Devred et al. @ https://indico.cern.ch/event/806637/

Decision management document EDMS 2213035 (Sept. 2019): Qualification of the 11T magnets as **suitable for installation in the LHC if they can be powered stably at a current of 11950 A** (i.e. nominal design current for beam energy of 7 TeV plus 100 A operating margin as required for HWC)



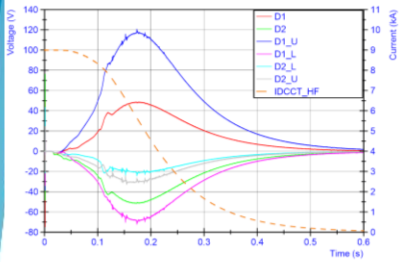
T (K)	Imax (kA)	Iss (kA)	% Iss
1.9	11.95	15.0	**80**
4.5	11.95	13.5	**88**
1.9	12.85 **(not performed)**	15.0	**86**

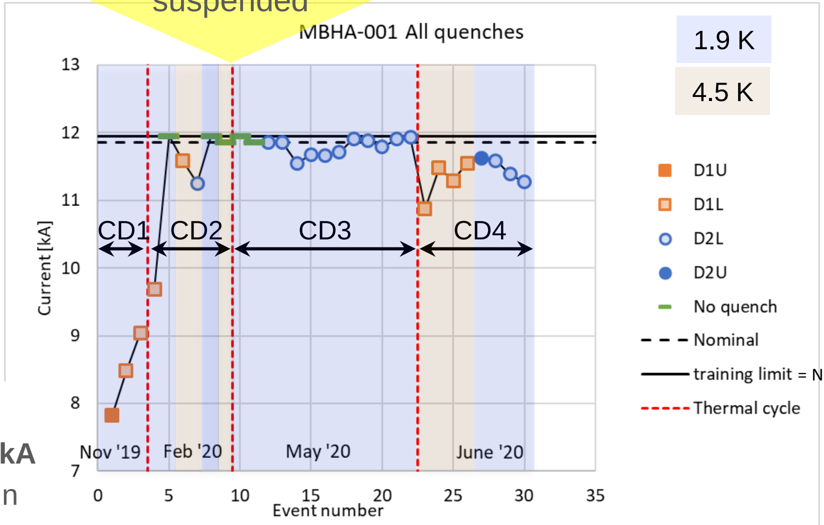
- **Virgin training with only 2 quenches (in Ap2) to 11.95 kA**, one in each coil. The first one at rather low current (not uncommon in models too)
- After thermal cycle, no quench up to 11.95 kA, **good memory**
- After the two quenches at the initial training, **no additional quench** recorded throughout all subsequent powering tests, at all ramp rates, and temperatures (1.9 K and 4.5 K)
- The magnet reached nominal current at 4.5 K, indicating a temperature margin > 2.6 K
- The magnet has been subject to **330 electro-magnetic cycles**, and **4 holding current tests** for a total of 20.5 hours (of which one plateau of 12 hours)

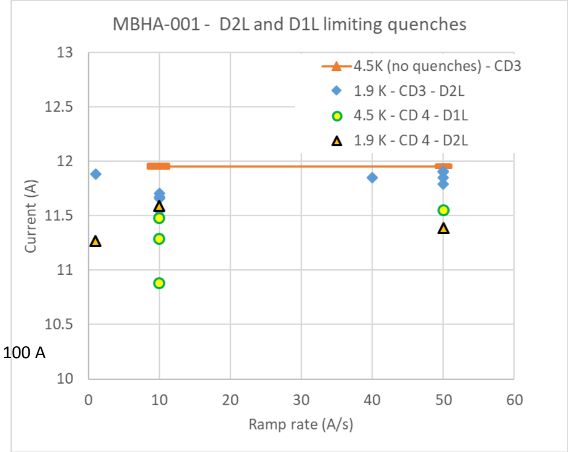
S2 (LMBHA-001) – Powering tests results

Lock-down Covid-19
Cold tests
suspended

Courtesy G. Willering et al.







Cool down 1 and 2:

- ✓ **Four quenches to 11.95 kA**
- ✓ The **magnet** is **OK**, no sign of degradation
- ✓ **12-hour holding current test at 11.85 kA**
- ✓ **Spikes on V-signals**, originally attibuted to an intermittent short between D1 & D2 in the capillary tube

Cool down 3:

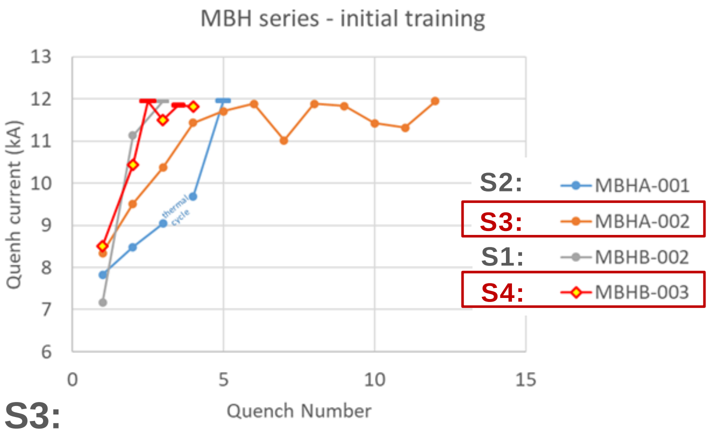
- ✓ **No quench in the beginning up to 11.95 kA, then 4-hour holding current test at 11.85 kA w/o quench**
- ✓ Instability as from 2nd week of testing in coil D2L @ 1.9 K
- ✓ V-I measurements show degradation in coil D2L
- ✓ **120 electromagnetic cycles** (3 series of 10, 30, and 80) between 5 kA and 11.85 kA **without degradation** (checked on V-I measurements)
- ✓ **No quench at 4.5 K**

Cool down 4:

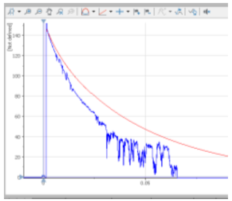
- ✓ At 4.5 K, quench limit in coil D1L
- ✓ At 1.9 K, quench limit in coil D2L, like during CD3
- ✓ V-I measurements show conductor degradation in both D1L and D2L

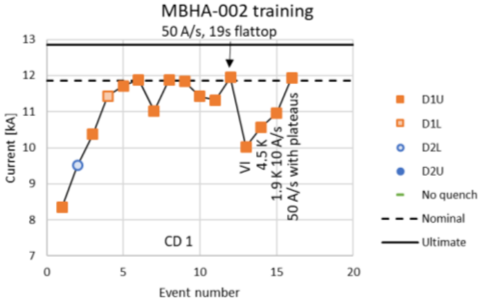
S3 & S4 (LMBHA&B-002&3) – Powering tests results

Courtesy G. Willering et al.



- **S3:**
- Did not reach the target current of 11.95 kA (nominal + 100 A) at nominal ramp rate of 10/s
- Quench Heater YT-212 failed in open loop





- **S4:**
- **2 training quenches to nominal** (Q1 @ 8.5 kA and Q2 @ 10.4 kA) both in Ap1, Coil-Up, Head CS
- Ramp to 11.95 kA (nom. + 100 A), 2’ stable, then 11.85 kA, 1h stable
- Q3 @ 11.5 kA in Ap1, with precursor (training), Coil-Down, towards head NCS, during VI-splice cycle. Quench Heater YT-221 failed in open loop. We suspect at the same location as for S3 (QH to pin connector jointing), as indicated by reflectometry tests. **This is a major NCR, which is putting in question the qualification of the magnet for installation**
- Q4 @ 11.84 kA in Ap1, with precursor (training), Coil-Up, towards head NCS, during 50 A/s ramp rate. A second 50 A/s ramp up was OK without quench
- At 4.5 K, the magnet reached nominal current without quench
- The **12h holding current test at nominal current was successful, and without quench**
- Splices OK (max. 0.6 nOhm for 3 splices combined), and VI measurements (1.9 K and 4.5 K) do not show degradation
- The thermal cycle was done between 25 September and 2 October

Powering test – Overview on coil degradation

Courtesy G. Willering et al.

Magnet	Cryo process	First sign of degradation	Aperture / Coil	Quench location Straight / Head	Note
MBHB-001 Prototype	ΔT not specified Fast cool down, like for LHC MBs	CD1	▪ D2U (CR2)	▪ Head, CS	
MBHP Hybrid assembly (1 aperture)	ΔT not specified Fast cool down and warm up, like for LHC MBs	CD2	▪ D1U (C02)	▪ Head, CS	▪ Magnet OK at CD1, up to: ✓ 12.85 kA at 1.9 K ✓ 12.6 kA at 4.5 K
S1-MBHB-002	ΔT = 30 K [90 K – 300 K] ΔT = 80 K [4 K – 90 K]	None	-	-	-
S2-MBHA-001 CD1 and CD2	ΔT = 30 K [90 K – 300 K] ΔT = 80 K [4 K – 90 K]	None	-	-	▪ CD 1: no V-I data above 9 kA ▪ CD 2: no degradation up to 11.95 kA at 1.9 K and 4.5 K

S2-MBHA-001
CD3
	ΔT = 30 K [90 K – 300 K]
	ΔT = 80 K [4 K – 90 K]
		CD3	▪ D2L (C09)
			▪ D1L (C13)
				▪ Head, CS
				▪ Head, CS, small degradation noticable
					▪ For **3 series coils out of 14**, loss of performance after TC
					▪ Investigations are ongoing as to the possible causes:
					  ▪ Thermo-mechanical
					  ▪ CDWU
					▪ And the possible effects:
					  ▪ Type and location of the damage

S2-MBHA-001 CD4	ΔT = 30 K [90 K – 300 K] ΔT = 80 K [4 K – 90 K]	CD4	▪ D2L (C09) ▪ D1L (C13)	▪ Head, CS (same as CD3) ▪ Head, CS (further, strong degradation)	
S3-MBHA-002	ΔT = 30 K [90 K – 300 K] ΔT = 80 K [4 K – 90 K]	CD1	▪ D1U (C15)	▪ Head, NCS	

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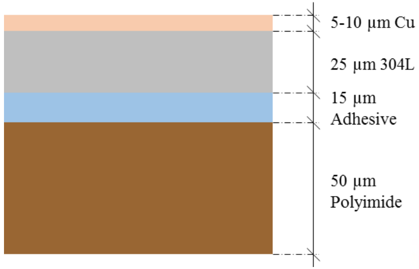
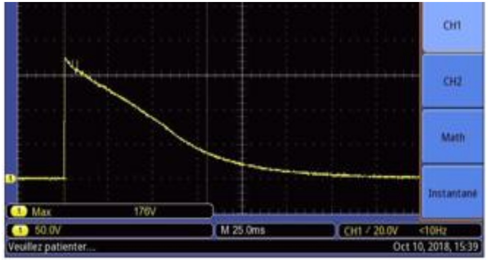
Background on QHs



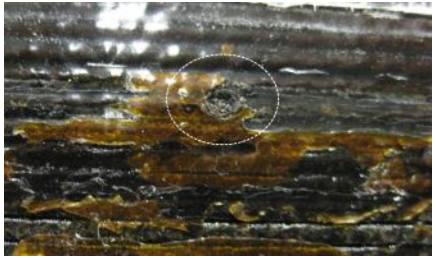
- The **prototype** LMBHB-001 did not reach the performance target (Jul. 18)
  - Limited to circa 10 kA, one coil limiting the performance (D2-Up, coil CR07)
  - Decision to disconnect D2, in order pursue the cold tests with only D1 powered
- Upon completion of the cold mass reconstruction, the electrical tests revealed **dielectric strength issues** with a systematic breakdown at circa 2.1 KV between the QH circuits and the coils, resulting in reduced electrical insulation, well below 1GΩ

Short after successive
C bank discharges in CR06

Last discharge before burn through



Short detail after peeling test

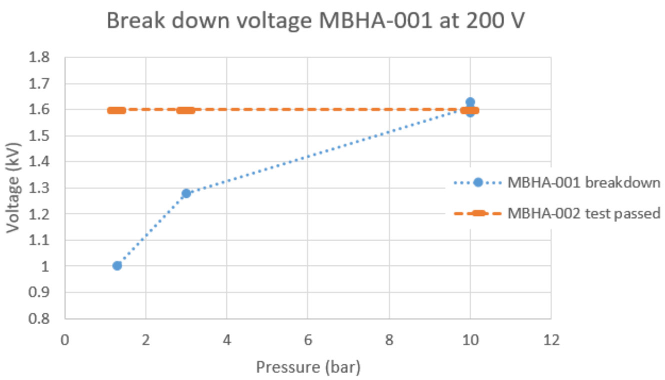


- After a review held on 2019-01-11, it was decided to change for external QHs
- External QHs were used as from the magnet S3
- **Additional HV tests** were specified as follows: In GHe, [200K, 10bar, 1.6kV], [200K, 3bar, 1.6kV], and [200K, 1.3bar, 1.6kV] in order **to make sure the magnet would survive the different operation and test conditions (including quench)**

An overview of the HV tests at 200 K in GHe

QH	S2-MBHA001 Impregnated QHs			S3-MBHA002 External QHs			Coil
	10 bar	3 bar	1.3 bar	10 bar	3 bar	1.3 bar	
YT111	Lost during lifted V test			🟩 ≈ 1.6 kV	🟩 ≈ 1.6 kV	🟩 ≈ 1.6 kV	D1Up
YT112	🟩 ≈ 1.6 kV	🟥 ≈ 1.3 kV		🟩 1 kV	🟩 1 kV		D1Lo
YT121	🟥 ≈ 1.6 kV			🟩 ≈ 1.6 kV	🟩 ≈ 1.6 kV	🟩 ≈ 1.6 kV	D1Up
YT122	🟩 ≈ 1.6 kV		🟥 ≈ 1 kV	🟩 1 kV	🟩 1 kV		D1Lo
YT211				🟩 1 kV	🟩 1 kV		D2Up
YT212	🟥 ≈ 1.6 kV						D2Lo
YT221				🟩 1 kV	🟩 1 kV		D2Up
YT222	🟥 ≈ 1.6 kV			🟩 1 kV	🟩 1 kV		D2Lo

Red box means breakdown

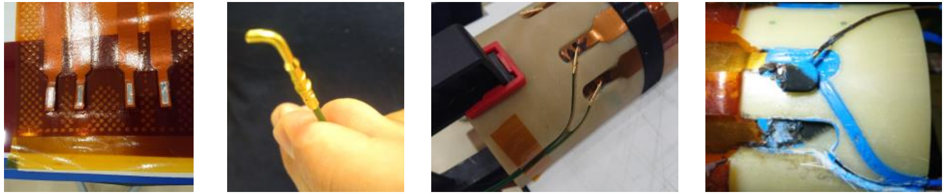


Courtesy G. Willering et al.

- **Coils equipped with external QHs pass the test successfully**, not those equipped with impregnated QHs
- **It has also been shown** recently (August 2020) on the last model MBHDP-201 (PIT conductor), equipped with external QHs, **that the QH to coil insulation system can withstand the expected dielectric strength of 10kV**, at RT, after the coils have been exposed to helium during cold tests

QH trace to wire jointing issue

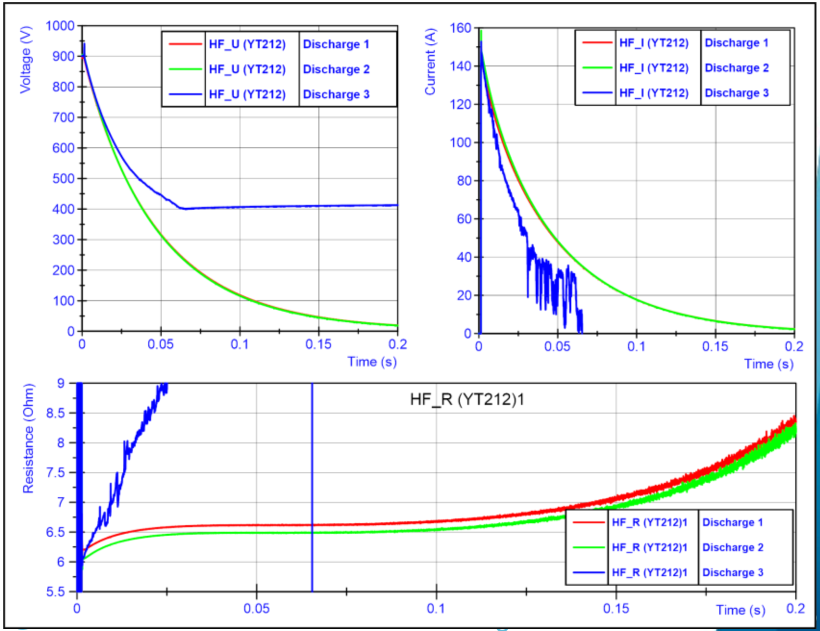
- Two QH failures have occurred, one in the magnet S3 (Jan. 20), and one in S4 (currently in test)
- So far, none of the 40 connections of the coils equipped with impregnated QHs (10 series coils) has shown any issue, and 2 out of 32 connections of the coils equipped with external (8 series coils) QHs have failed in open loop



- Work is ongoing in order (1) to consolidate the current procedure (use of a soldering jig) and QA/QC, or (2) to devise an other jointing concept (direct soldering wire to trace, or use of a flat connector), also with the soldering jig and consolidated QA/QC

- In parallel, tests on representative samples are ongoing, as follows
  - Discharges tests @ RT (endurance, limit), with thermography
  - Micro-tomography and metallography (size, interface between the parts, i.e. quality of the soldered joint)

- Case of the magnet **S3**, coil **C14**, **D2-Lo**
  - At RT, in production, 4 discharge tests are made, 1 after collaring, 3 during CM construction (400 V, 80 A)
  - Failure at 3rd discharge during reception tests at cold prior to powering (900 V, 150 A)
  - No sign of degradation during the first 2 discharge tests



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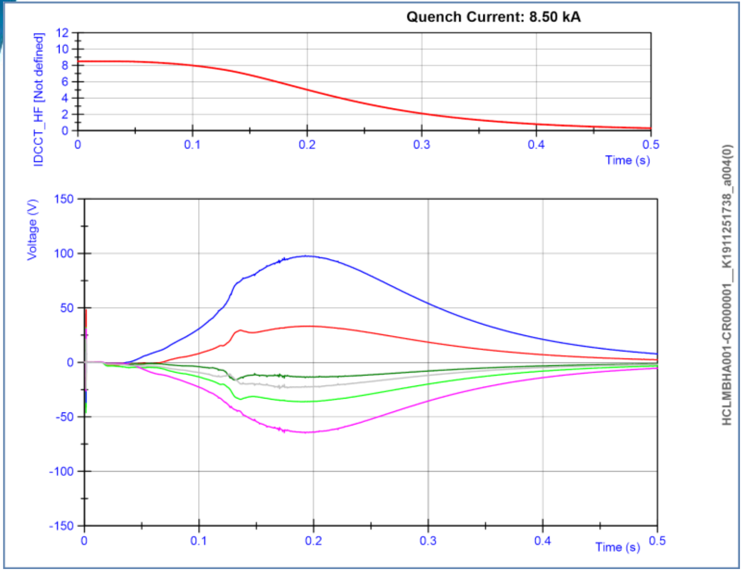
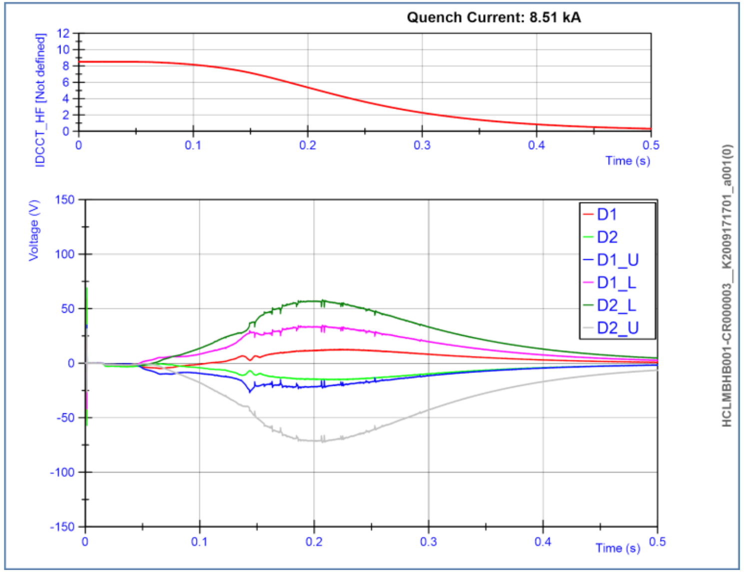


SPIKES



S2 – MBHA-001, quench at 8.5 kA

S4 – MBHB-003, quench at 8.5 kA

- Spikes appear on the voltage signals following a quench, during the current decay
- **S2 was subject to > 40 discharges** (provoked quenches) in different conditions in order to understand their origin. An **Electrical Conformity Assessment Panel** was put in place in the middle of April for the installation of the S2
- Spikes are **also present in S4 – MBHB-003**, and other 11T dipole magnets to a certain extent (also in some short models)
- The spikes are **most likely related to changes in magnetization, or differences in quench propagation velocity**. This feature still needs to be understood and explained!
- Given this, **we are convinced that we can rule out the idea of an intermittent short between the two apertures**, as originally thought, for which there was a demand to carry out electrical tests in specific conditions (“lifted voltage”). One shall review whether these special tests are still needed, as there isn’t any electrical weakness (tbc by ECAP)

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CD-WU tests and thermo-mechanical analysis

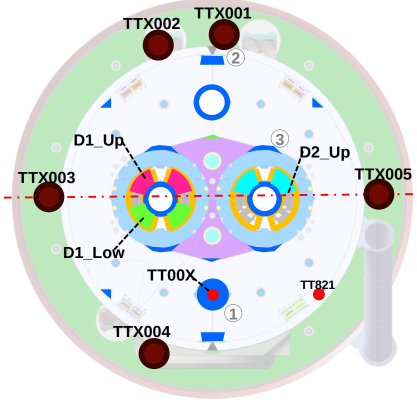
- **Determine**, both experimentally and by FE-modeling, the **temperature mapping** (in both the time-domain and the space-domain, in radial and longitudinal directions) **inside the cold mass** of the cryo-magnet, **down to the coils**, during transients and nominal operation
- **Determine the associated stress distribution** (at macroscopic level) resulting from the differential thermal contraction/expansion due to material properties and/or thermal transients
- Identify features, cryogenic parameters, which may impact on the temperature distribution in the cold mass
- The **magnet S2 was used** for the CD-WU tests. A max. delta T of 30 K was imposed, like for the CD-WU conditions, which have become standard as from the cold tests of the magnet S1-LMBHB002 (previously of the order of 200 K)
- The **mass flow rate of helium gas was changed with values comprised between 30 and 50 g/s** (usually, 60 g/s) for the range 300 K – 80 K in order to understand better the thermo-mechanical behavior of the magnet, and for benchmarking the FE Modeling

Connection to CFB & Magnet instrumentation

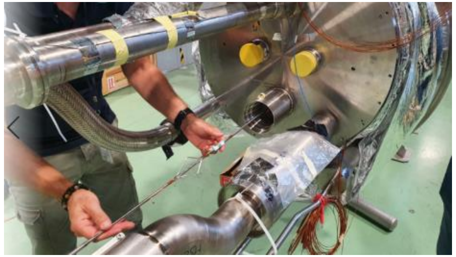
Courtesy Y. Leclercq et al.

- Connection to CFB:
  - 1 x inlet + 1 x outlet
  - Cryo control from T GHe_{OUT} – T GHe_{IN}
  - Inlet mass flow rate measured
- Monitored temperatures:
  - Gas T-gradient in **Channel 1** (**6 x Cernox**)
  - Outer **CM envelope** (**15 x PT100**)
  - Coils average temperature (indirect via V-taps)
  - Nb-Ti/Nb-Ti & Nb-Ti/Nb_3Sn splices (indirect via V-taps)

Sensors / coils locations in section view
5 positions for T-sensors in each of the 3 sections



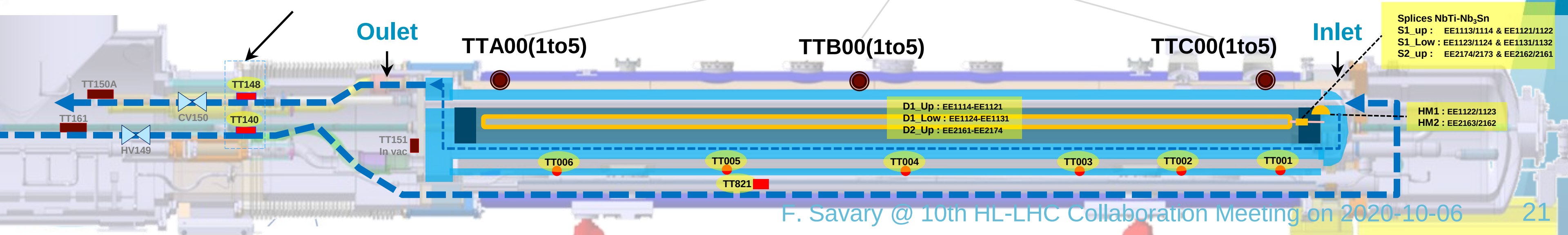
*Installation of **PT100 on outside surface of CM shells***



*Insertion of **TT00X in channel 1***

Inlet / Oulet T-sensors used for CFB control

S2 instrumentation layout on bench C2



Splices NbTi-Nb_3Sn
S1_up : EE1113/1114 & EE1121/1122
S1_Low : EE1123/1124 & EE1131/1132
S2_up : EE2174/2173 & EE2162/2161

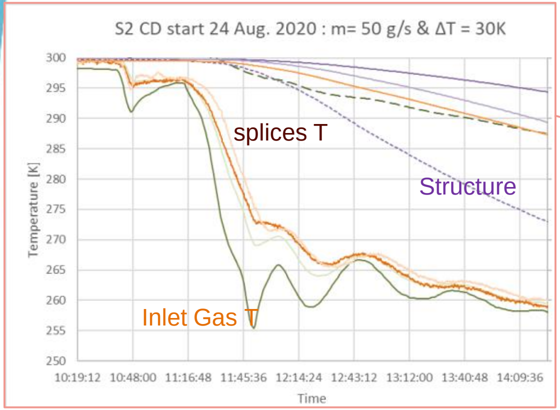
D1_Up : EE1114-EE1121
D1_Low : EE1124-EE1131
D2_Up : EE2161-EE2174

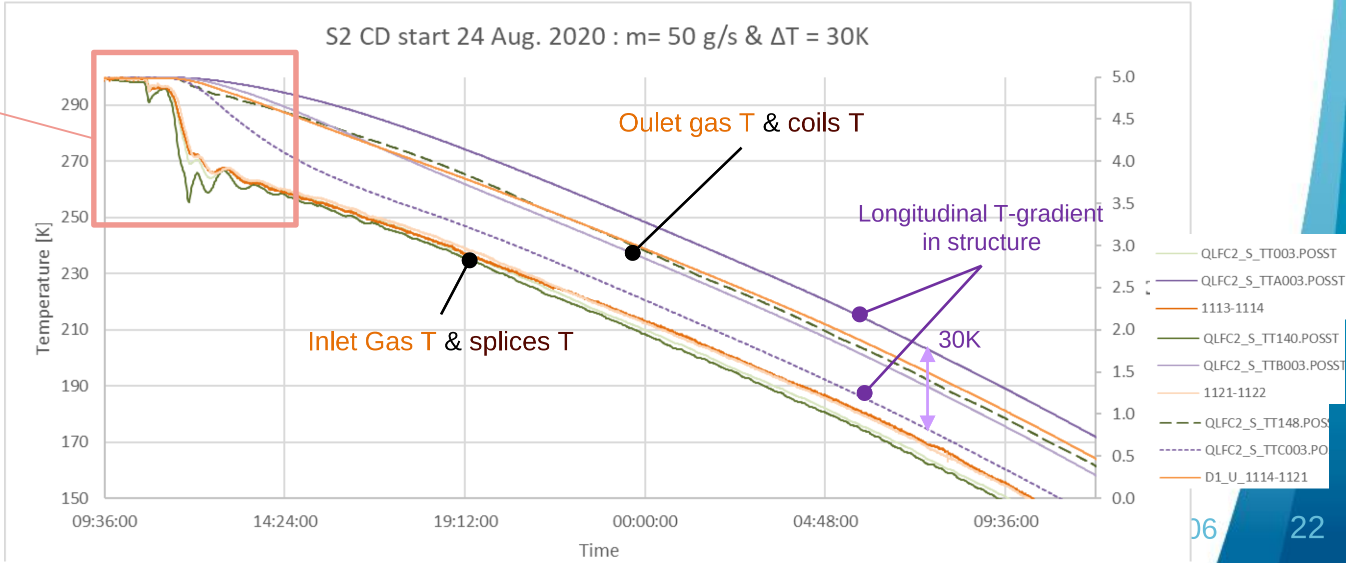
HM1 : EE1122/1123
HM2 : EE2163/2162

General observations 300-80K range @ 50 g/s

- At the start of the transient
  - Similar temperature decrease @ 1K/min for GHe$_{IN}$ & splices
  - Structure and coils temperature smoothly cool down @ 5 K/h
- Steady conditions
  - T GHe$_{IN}$ ≈ T Splices
  - Constant longitudinal T-gradient in structure
  - T GHe$_{OUT}$ < Max (T$_{STRUCTURE}$)

Courtesy Y. Leclercq et al.





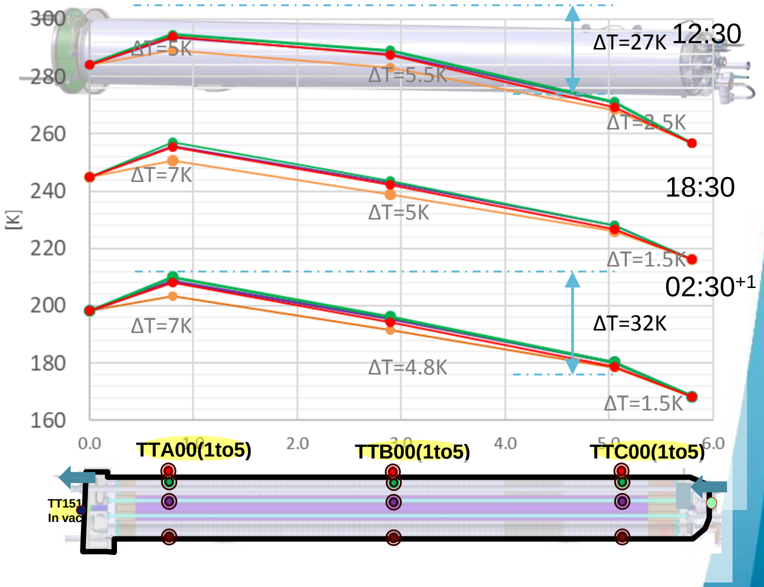
Outer structure T-mapping in 300K-80K range

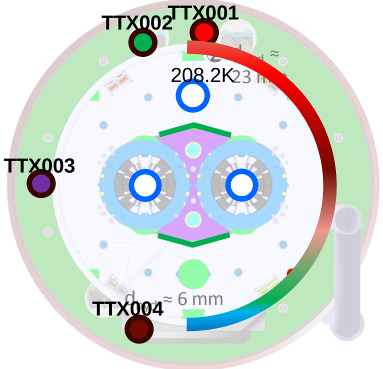
Courtesy Y. Leclercq et al.

- Radial ΔT:
  - Asymmetric flow distribution ➔ vertical ΔT in structure
  - Radial ΔT increases from injection to outlet
- Longitudinal ΔT
  - Rather constant, about 30 K
- Influence of mass flow (50 g/s & 30 g/s)
  - Limited on longitudinal ΔT (same gas T-gradient)
  - Longer cooling time ➔ more time for radial diffusion ➔ radial ΔT reduction

T_{out}-T_{in} = 30K = constant	**50 g/s**	**30 g/s**
Max Radial ΔT inject. Side TTCOO	≈ 2K	≈ 2K
Max Radial ΔT non inject. side TTAOO	≈ 7K	≈ 4K
Max longitudinal at T_{in}=250 K	27 K	27 K
Max longitudinal at T_{in}=150 K	32 K	30 K

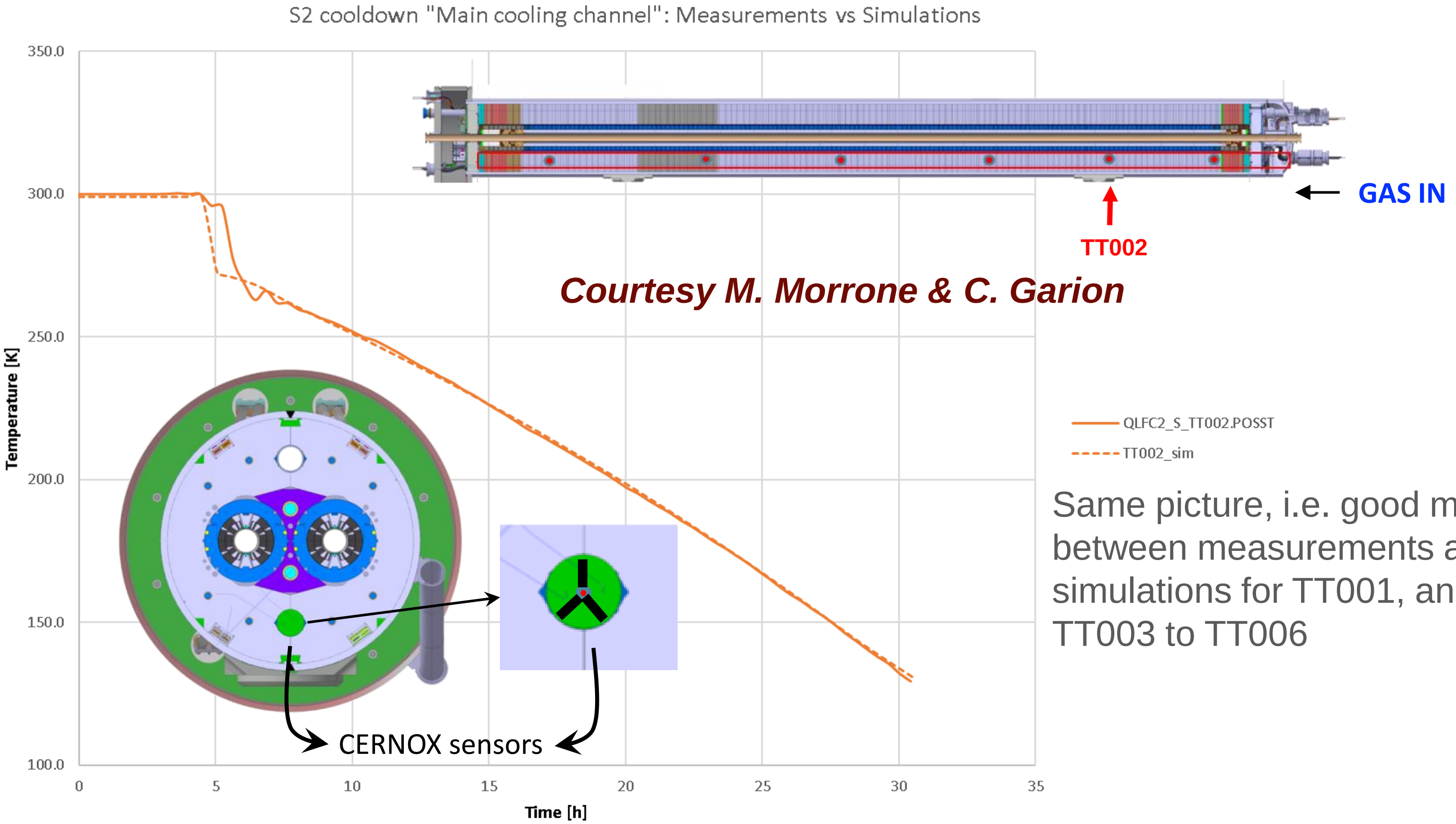
Outer envelope temperature profile along the 6-m long magnet 50g/s DT=30K
Note: locally T_{wall}-$T_{gas\ in\ ch1}$ = 10, 15, 20 K for resp. TTA, TTB, TTC





Radial position of the PT100 sensors & qualitative T-distribution on the envelope

Multi-physics model – CFD thermal benchmark (Main Channel)

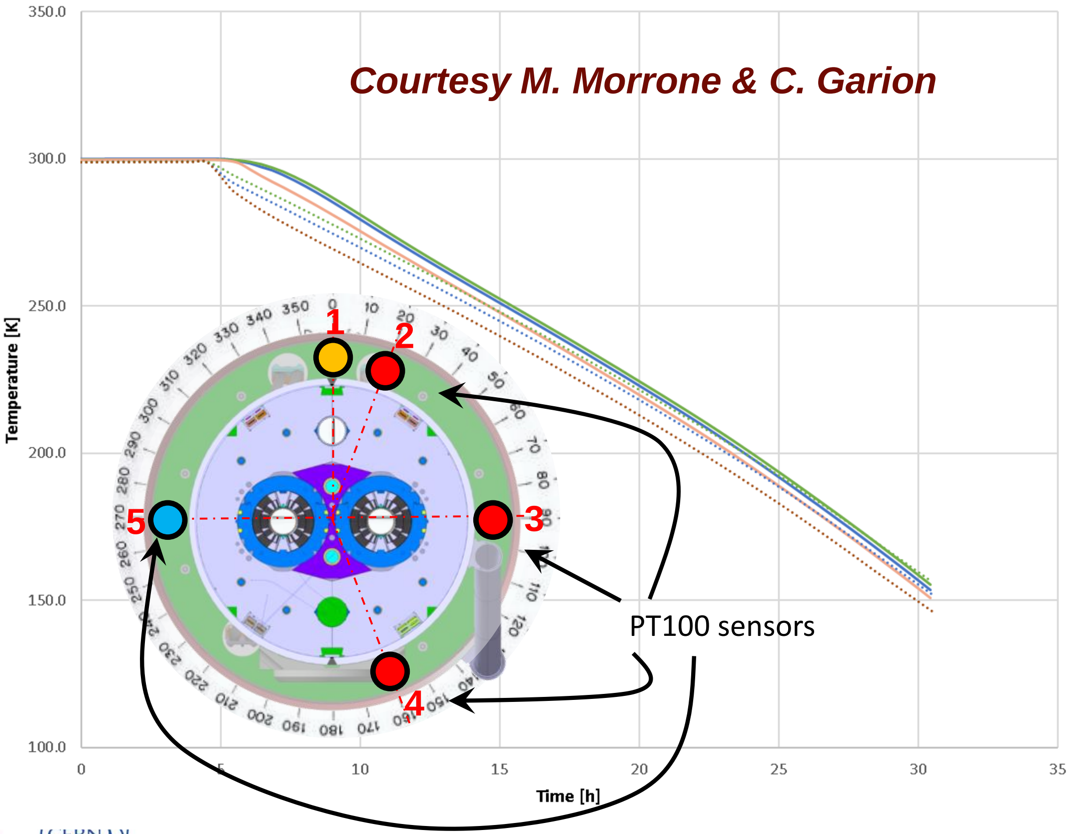


Courtesy M. Morrone & C. Garion

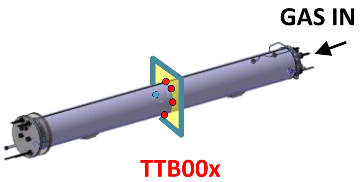
Same picture, i.e. good match between measurements and simulations for TT001, and TT003 to TT006

Multiphysics model – CFD thermal benchmark (on the shell)

S2 Cooldown "Shell of the Magnet": Measurements vs Simulations



Courtesy M. Morrone & C. Garion



Section B

Same picture, i.e. good match between measurements and simulations for the other sections A and C

Preliminary conclusions

- Heat transfer gas-to-CM is by convective heat exchange in parallel channels
- **In the 80 to 300K range, the measurements show ∆T in the outer structure up to 7K in the radial direction, and 30K in the longitudinal direction**
- Within 30-50 g/s range, the CFB mass flow rate has:
  - Limited influence on the longitudinal ∆T (gas and structure)
  - Visible influence on the radial ∆T (structure)
- **Splices Nb-Ti to Nb_3Sn follow closely the inlet gas temperature**, likely due to thermal conduction through busbars. At start, local ∆T between splices and surrounding structure may be over 20K
- Work is still in progress in terms of analysis but the data is likely to confirm the presented conclusions
- The part **thermal analysis of the CFD model** has been benchmarked against the temperature measurements
  - The **maximum difference in temperature between the measurements and simulations is below 3% for the main cooling channel and 9 % for the other cooling channels**
  - The temperature output/map of the CFD-thermal model will be used for the mechanical analysis during cool-down in a time dependent study (work in progress)

Outlook

- Plan
- Magnet performance tests results
- Quench heaters
- Spikes
- Thermal gradients
- Status
- Concluding remarks

11T status Oct. 2020
Schematic view

Magnets equipped with external QH

S4: LMBH**B**003

D1-CC09 | D2-CC08

UP C20 | LO C21 | UP C17 | LO C19

S5: LMBH**A**003

D1-CC10 | D2-CC11

UP C23 | LO C22 | UP C25 | LO C24

1st pair of magnets

S6: LMBH**B**004

CC12 | CC13

C26 | C28 | C29 | C31

S7: LMBH**A**004

CC14 | CC15

C32 | C33 | C34 | C35

2nd pair of magnets

Magnets equipped with impregnated QH

S1→Spare
LMBH**B**002

D1-CC02 | D2-CC03

UP C05 | LO C01 | UP C07 | LO C06

Spare magnet

11T status Oct. 2020 – Coils, Collared Cs, Magnets

Magnet	Collared Coils	Coils	CD-WP	Note
P1 – Hybrid assembly	D1: CC01	Cup-02 and Clo-03	Fast	
	D2: CC02 (from prototype)	Cup-05 and Clo-04 (proto)		• NOT OK, C03 is the limiting coil
S1 – Type B (tested)	D1: CC02	Cup-05 and Clo-01	ΔT_{MAX} 30K	• Qualified for installation, re-testing under consideration
	D2: CC03	Cup-07 and Clo-06		
S2 – Type A (tested)	D1: CC05	Cup-12 and Clo-13	ΔT_{MAX} 30K	• First time spikes are “noticed”, and analyzed • NOT OK, C09 and CC13 are the limiting coils
	D2: CC04	Cup-08 and Clo-09		
S3 – Type A (tested)	D1: CC07	Cup-15 and Clo-16	ΔT_{MAX} 30K	• NOT OK, C15 is the limiting coil • QH trace to wire jointing failure in C14 • C10, C14, and C16 could possibly be re-used
	D2: CC06	Cup-10 and Clo-14		
S4 – Type B (test in progress)	D1: CC09	Cup-20 and Clo-21	ΔT_{MAX} 30K	• Cold test in progress • QH trace to wire jointing failure in C17
	D2: CC08	Cup-17 and Clo-19		
S5 – Type A (cryostating started)	D1: CC10	Cup-23 and Clo-22	ΔT_{MAX} 30K	• Cryostating in progress
	D2: CC11	Cup-25 and Clo-24		
S6 – Type B (coils in production)	D1: CC12	Cup-26 and Clo-28	ΔT_{MAX} 30K	• Collared coils and coils distribution in the cross-section is provisional
	D2: CC13	Cup-29 and Clo-31		
S7 – Type A (replacement of S3)	D1: CC14	Cup-32 and Clo-33	ΔT_{MAX} 30K	• Collared coils and coils distribution in the cross-section is provisional
	D2: CC15	Cup-34 and Clo-35		
		C4		• Lost in production
		C11		• Lost in production
		C18		• Lost in production
		C27		• Lost in production
		C29		• NC during production – most likely OK
		C30		• NC during production – conductor degradation suspected, tests on Fresca needed, quarantined

S5 left 180 this afternoon to go to SMI2 for cryostating

Courtesy T. Bampton and H. Prin

Cold mass of S5 shown in bldg. 180 on 2020-10-01 (left), and on 2020-09-28 (right)

- It will move to SM18 less than three weeks after cryostating, i.e. it should be in SM18 in the 1st week of November

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Concluding remarks

- There are very good results in terms of magnet training
    - Out of 4 series magnets, 3 went to target, 11.95 kA (nom. + 100 A), after only 2-4 quenches during the initial training
- S1 was the first series magnet to be tested. It passed all the qualification tests defined at the time. The readiness for installation is under assessment
    - It did not quench anymore after the first 2 training quenches (memory after thermal cycle, EM cycles, holding current tests, …)
- The magnet S2 was good till the end of CD2
    - Two coils have shown clear degradation during CD3 and CD4. The cause of these degradations still needs to be understood
    - An extensive campaign of discharge tests was conducted (>40 additional discharges) in order to understand the spikes
- The magnet S3 did not reach the target from the start, i.e. CD1, with a coil limiting the performance
- The magnet S4 is performing well. The test campaign is currently ongoing with the 2nd CD
- The QH trace to wire jointing needs to be reviewed following two failures in the magnets S3 and S4
    - These failures have occurred on the coils equipped with external QHs only. Although the jointing concept is the same as for the impregnated QHs, the conditions of execution of the soldering operation are different (more difficult), and this might play a role
    - Work has been initiated (1) to characterize the joints made in S3, S4 and S5, and (2) to implement a consolidated solution for the magnets S6 and S7
- Work has been done in order to improve the CD-WU conditions by limiting the ΔT to 30 K in the temperature range [300K-80K]
    - The tests carried out recently on S2 are reassuring, showing limited radial/longitudinal gradients in the magnet
    - We still need (1) to complete the thermo-mechanical analysis, (2) to study what happens in the lower T range [80K-2K], and (3) to study what could happen during quenches (natural, and provoked like during the discharge tests)
- The spikes observed on the voltage signals after quench seem to be a systematic feature
    - These are not due to any electrical insulation weakness, and should not be an issue for operation
- Overall, nice results, even if there are still a few points to sort out!

Thank you for your attention