Status of the 11 T Dipole and CERN Magnet Program Beyond HiLumi

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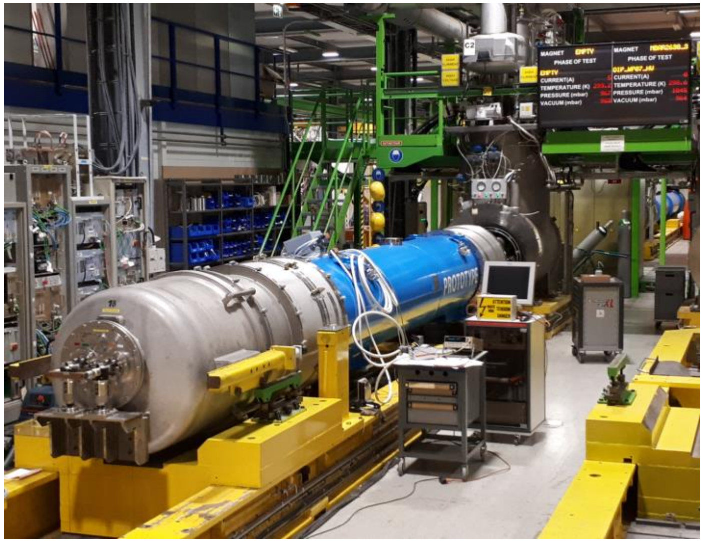
CERN

Technology Department

Magnets, Superconductors & Cryostats Group



Test of 1st Series 11 T Dipole Magnet @SM18

Acknowledgements

- to Lucio Rossi, who initiated the project in 2010 and set up the first collaboration with Fermilab;
- to Fermilab (in particular, G. Apollinari and A. Zlobin), who launched the initial R&D on 11 T dipole magnet between 2010 and 2015;
- to M. Karppinen, who led the CERN efforts from 2010 to 2014;
- to F. Savary, who resiliently manages WP11 since April 2014;
- to the 11 T Task Force, set up in November 2017, that pulled together transverse competences across the TE-MSC Group.

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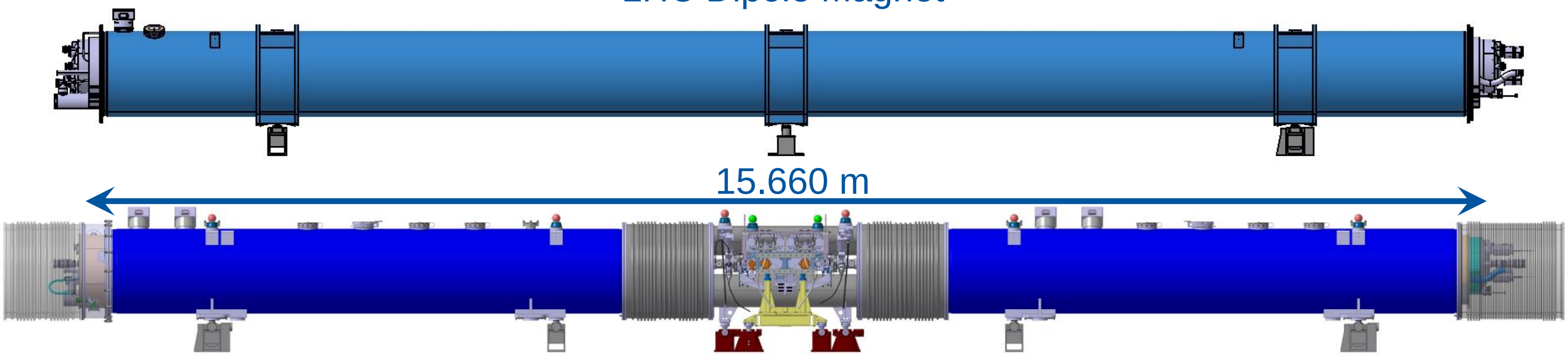
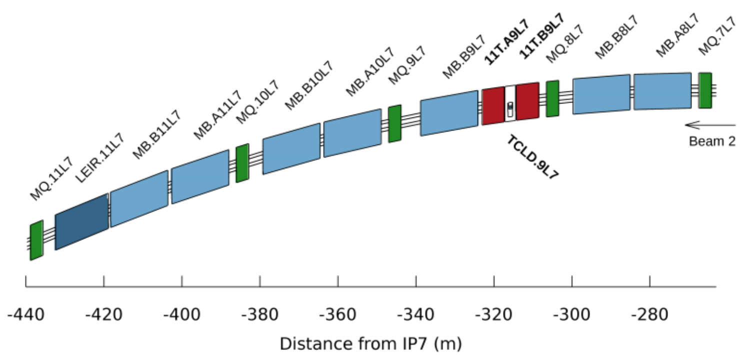
Purpose of HL-LHC WP11



- Replace in two cells of the dispersion suppressor regions of LHC one 8.33 T, 14.3-m-long LHC dipole magnet by two 11.2 T, 5.3-m-long dipole magnets delivering the same integrated field (119 T.m at 11.85 kA), so as to free space in the middle for the integration of additional collimators.



Implementation of 11 T dipole magnets in LHC magnet cell

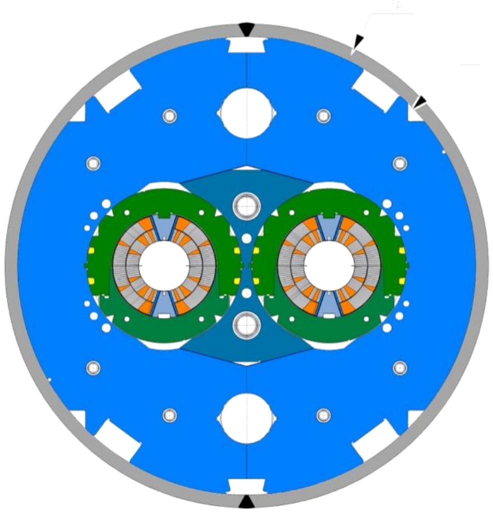
(Courtesy of F. Savary, CERN)

11 T Dipole Magnet Parameters

- One of the strong constraints on the 11 T dipole magnet is that it needed to be designed so as to fit within an existing LHC magnet cell.
- This imposed both geometrical and operational constraints as the magnet is connected in series with existing LHC magnets (if started from scratch, the design would have been different).

Salient parameters
of 11 T dipole magnet

Aperture @RT	60 mm
Distance between apertures @1.9 K	194 mm
Nominal current @7 Tev	11.85 kA
Central field @nominal	11.23 T
Conductor peak field @nominal	11.8 T
Magnetic Length at 1.9 K	5.307 m
Stored energy @nominal (2 apert.)	0.896 MJ/m
Forces per quadrant (x/y)	6.23/3.15 MN/m
# coil layers	2
# turns per layer (inner/outer)	22/34
Cold mass outer diameter @RT	570 mm

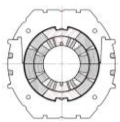


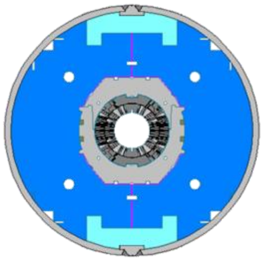
X-sectional View
of 11 T dipole magnet

(Courtesy of F. Savary and S. Izquierdo Bermudez, CERN)

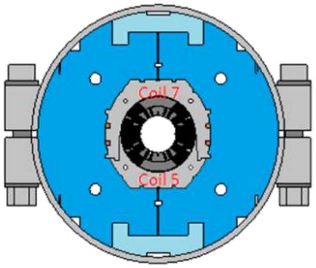
From Demo Models to Final Magnets

Integrated pole concept @ FNAL

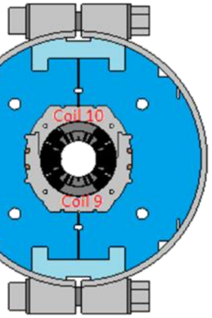




MBHSP01



MBHSP02



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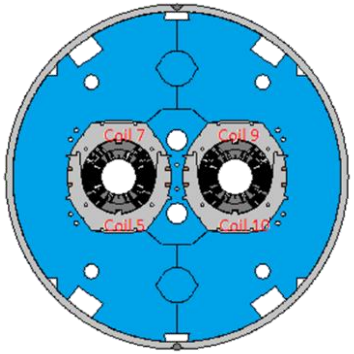
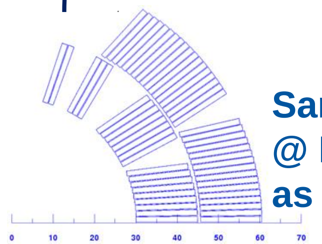
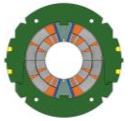


MBHDP01

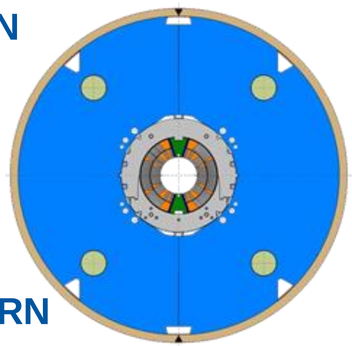


6 blocks – 56 turns

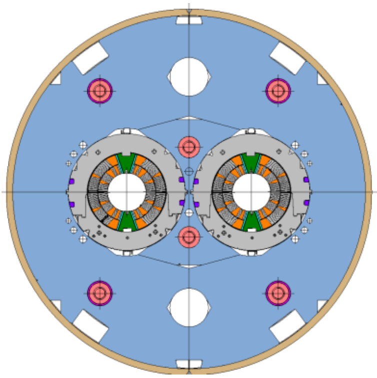
Same coil design @ FNAL and CERN as starting point



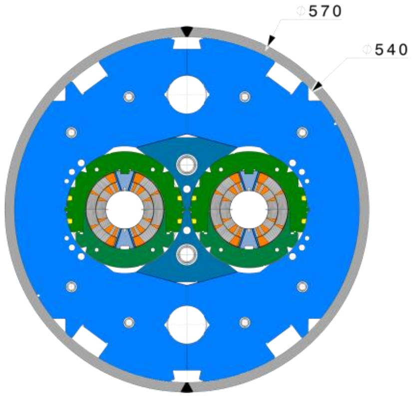
Removable pole concept @ CERN



MBHSP101-9 [RRP]



MBHDP101 [RRP]

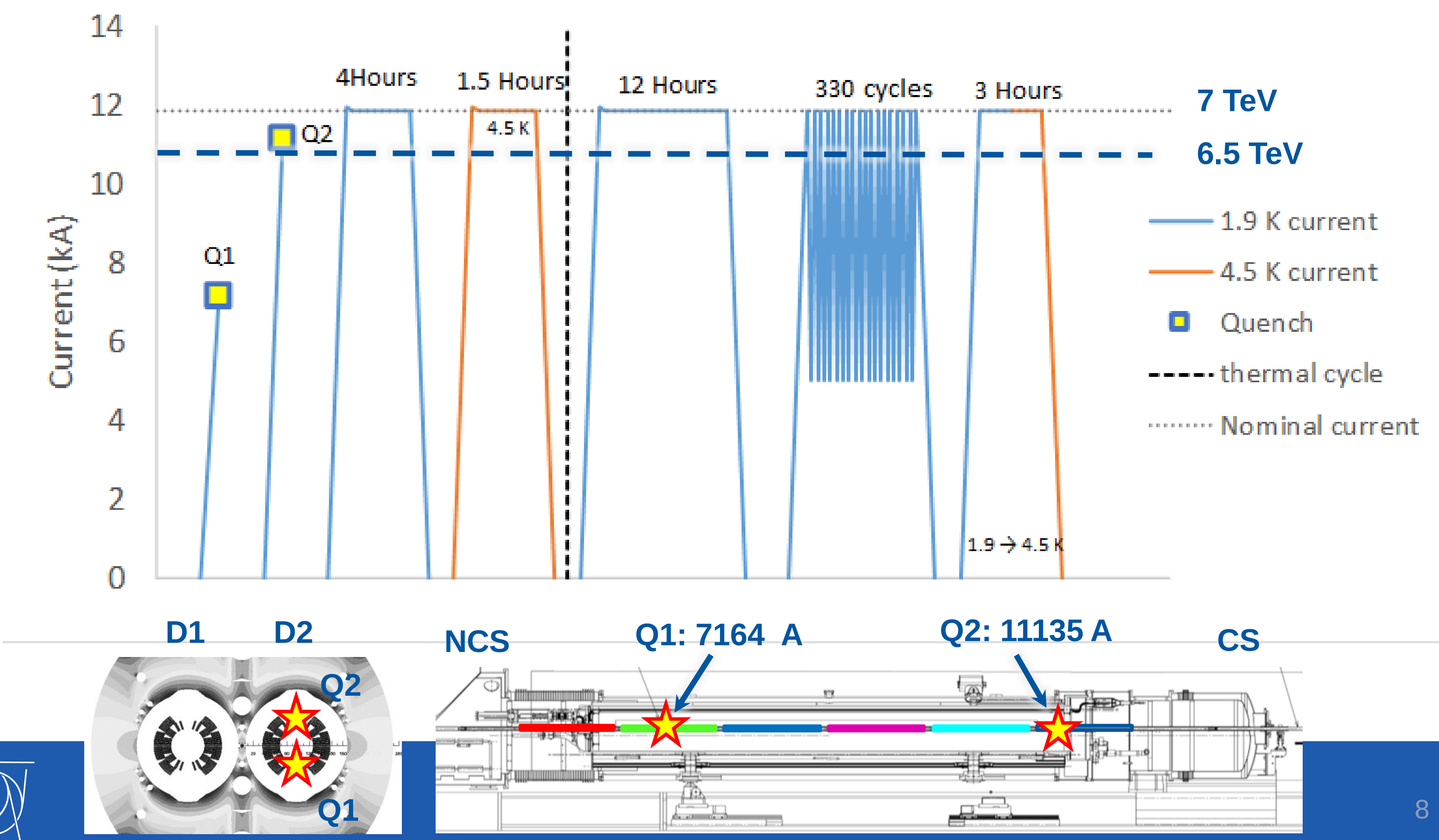


MBHDP102 [RRP]
MBHDP201 [PIT]
LMBHP001 [RRP]
LMBHB00x [RRP]

LMBHB002 Test History

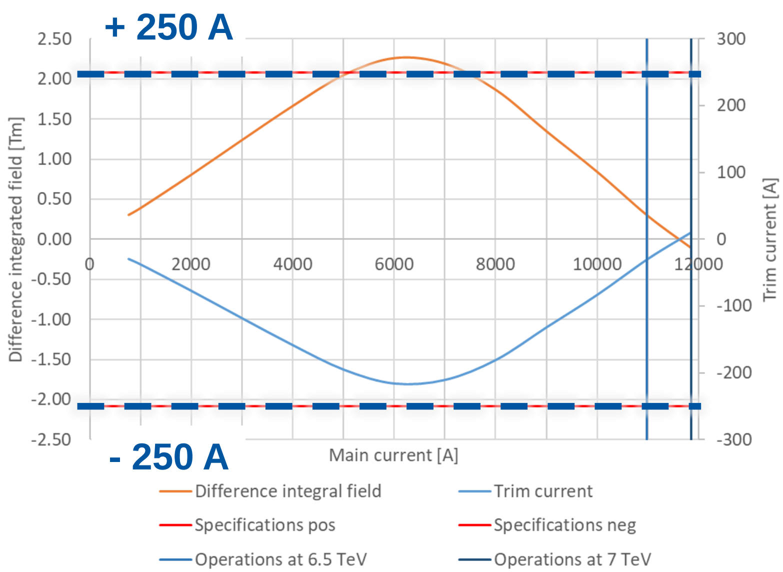
(Courtesy of G. Willering, CERN)

- LMBHB002 is the first full-length, twin-aperture 11 T dipole magnet, ready for tunnel installation.



LMBHB002 Field Quality

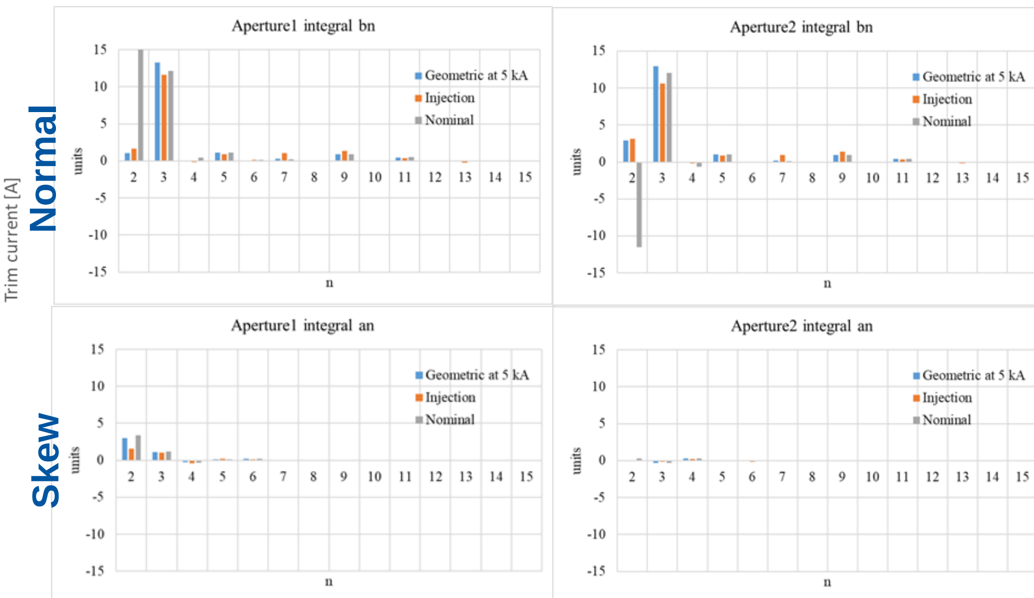
Transfer Function



Trim current in 11 T dipole circuit to match LHC dipole transfer function (based on average of integral field measurements for the 2 apertures)

Geometric Multipoles (@17 mm)

Aperture 1 | Aperture 2

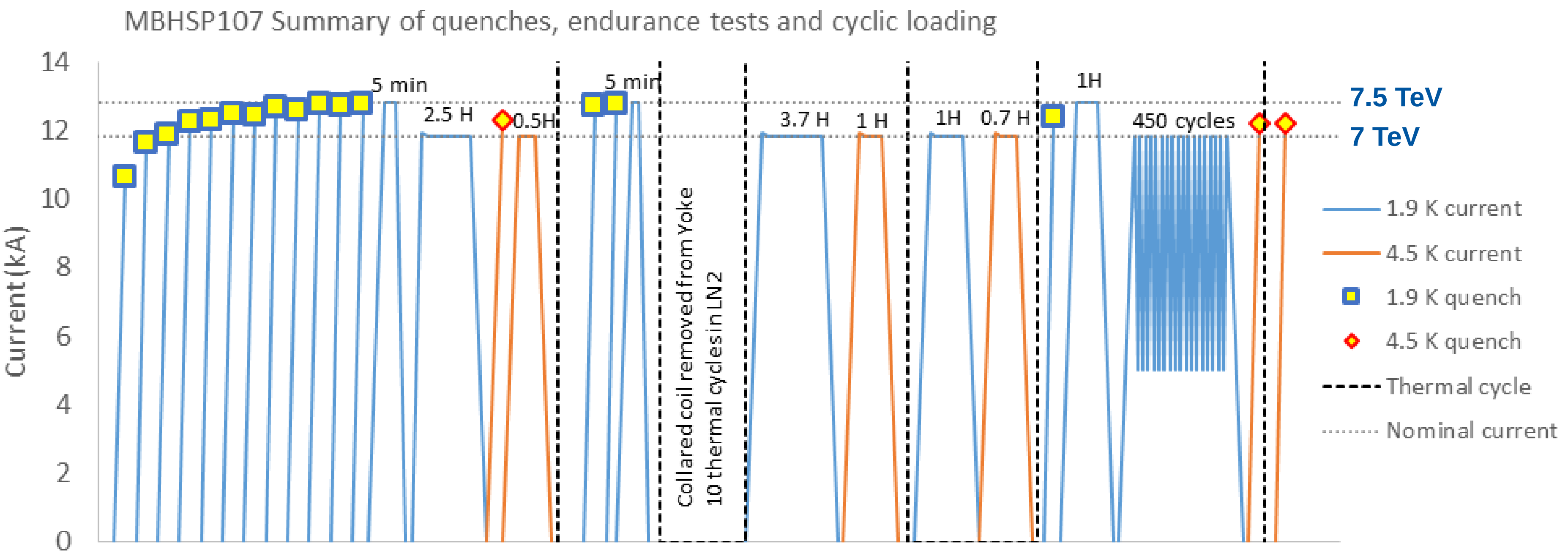


b_2 arises from iron saturation and is as expected (~±14 u);
b_3 is a bit larger than expected (~7 u).

(Courtesy of L. Fiscarelli and S. Izquierdo Bermudez, CERN)

SP107 Test History

- SP107 is the first short model magnet issued from the 11 T Task Force with optimized processes; it underwent endurance testing (5 WUCD to LHe, 10 WUCD to LN2, over 450 EM cycles), it repeatedly achieved nominal current and was pushed 3 times up to ultimate current without degradation.



(Courtesy of G. Willering, CERN)

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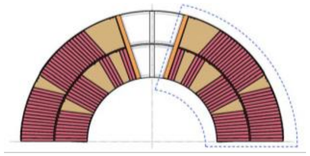
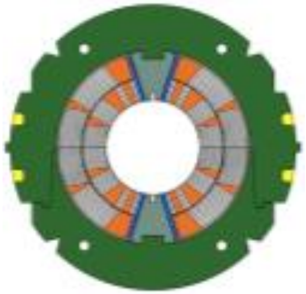
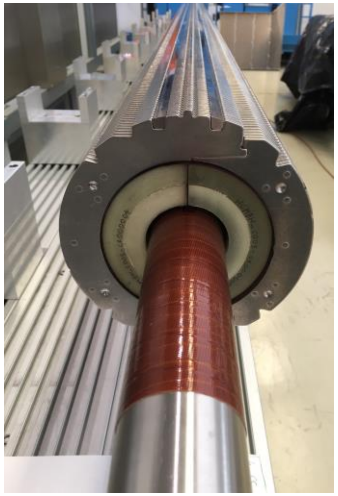
Production Scenario

- Nb_3Sn wires: contract with Bruker-OST for a total of ~3.7 metric tons.
- Rutherford-type cabling: at CERN (30 x 655 m Unit Lengths; 5 additional ULs under consideration).
- Coils and Collared-Coils: service contract with GE, on CERN premises using CERN tooling (30 coils, including visual inspection, electrical tests, and metrology and assembly of 24 coils into 12 collared coils, including visual inspection, electrical tests, metrology and warm magnetic measurements).
- Cold masses: at CERN (4 units + 2 spare).
- Cryostating: at CERN (4 units + 2 spare).



11 T Coil

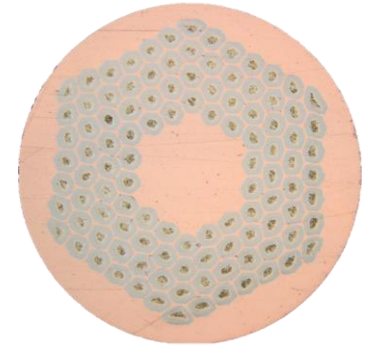




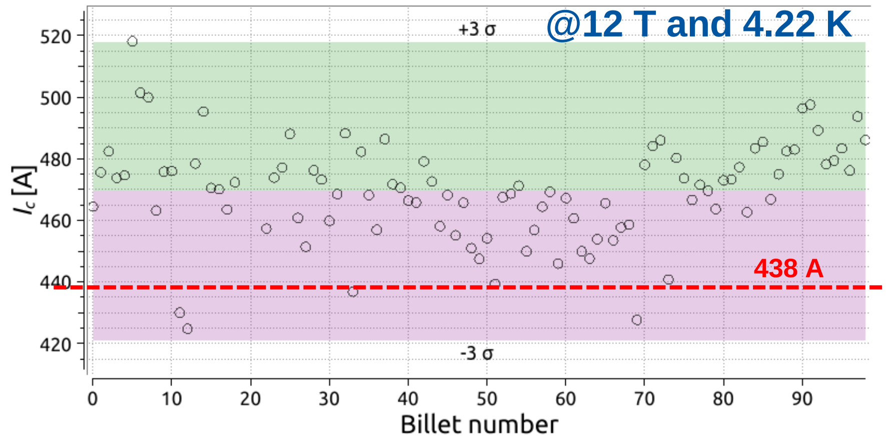
11 T Collared-Coil Assembly

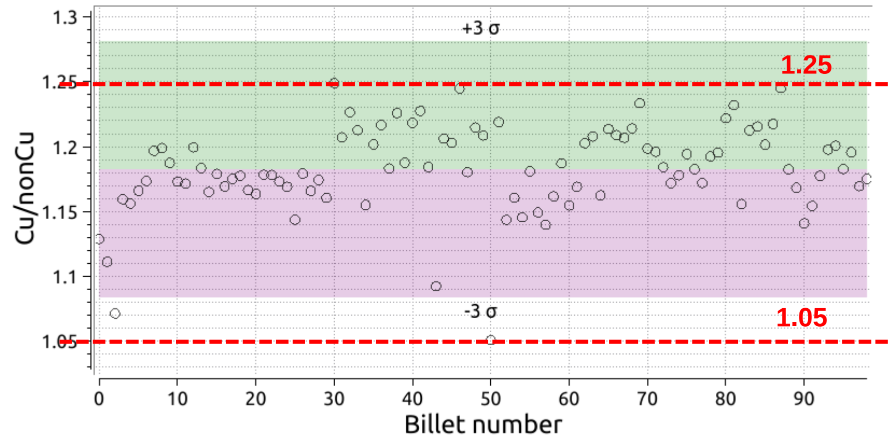
(Courtesy of F. Savary, CERN)

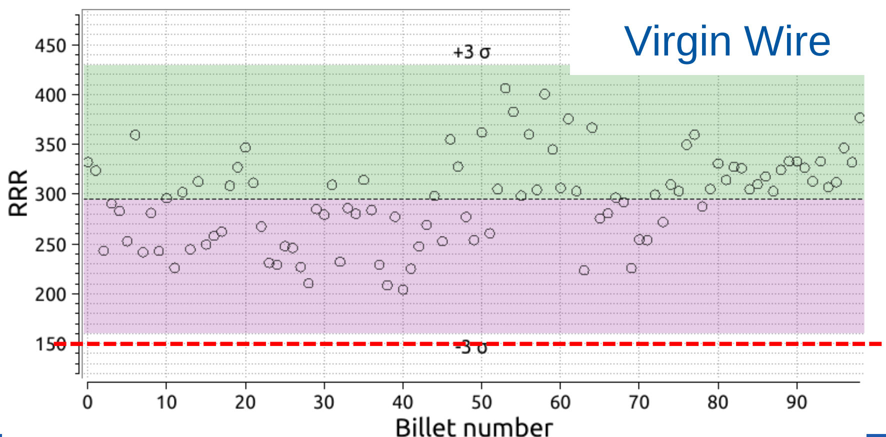
Nb_3Sn Wire Production

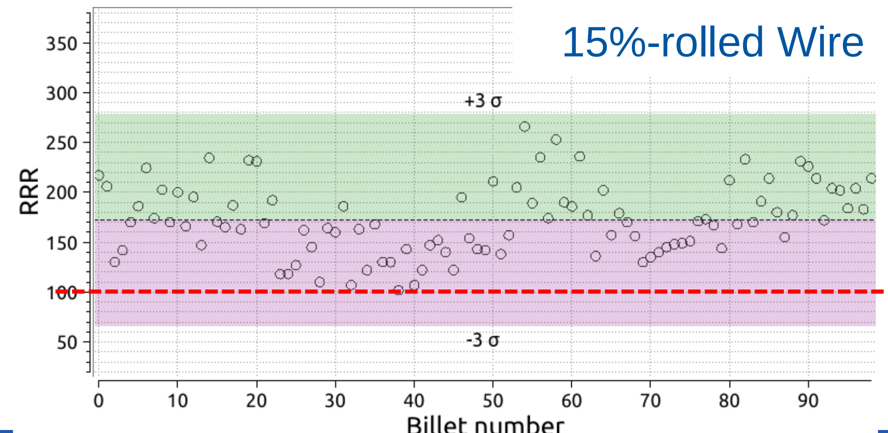


- Production of 3.7 tons of RRP 108/127 (0.7 mm ∅) is completed.





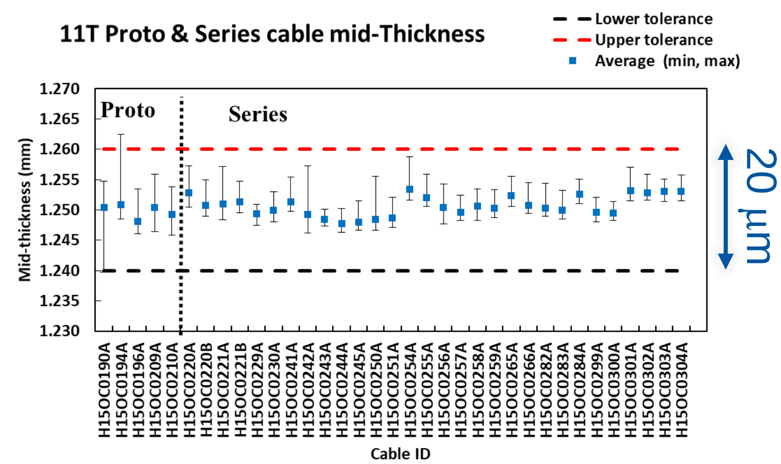


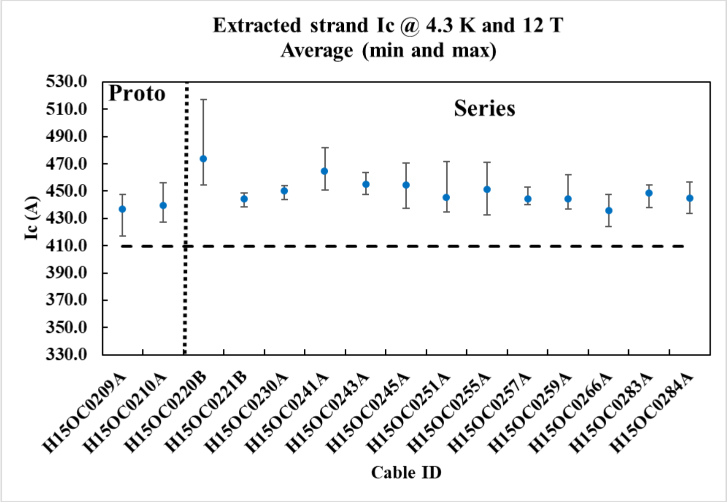


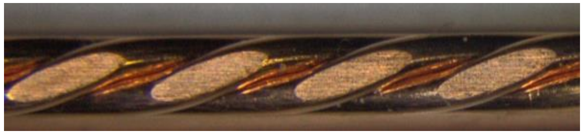
(Courtesy of B. Bordini, CERN)

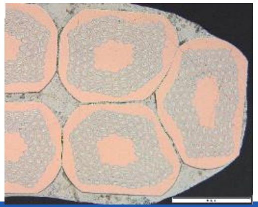
Rutherford-Type Cable Production

- 40-strand Rutherford-type cable with inner core.
- 30 series ULs have been completed, 5 additional ULs to be produced by end of 2019.
- All cable ULs are within specs (4 ULs with electrical QC tests remaining; no NCR), including
  - cable dimensions,
  - no cross-over or breakage.
- Electrical QC tests are based on extracted strand measurements
  - av, I_c degradation: ~2.8% @4.3 K and 12T,
  - av. RRR reduction: 29%.
- Production rate has been increased to 2 ULs per cabling run (4 to 5 billets).
- Accurate control of strand mechanical tension of has proven critical.



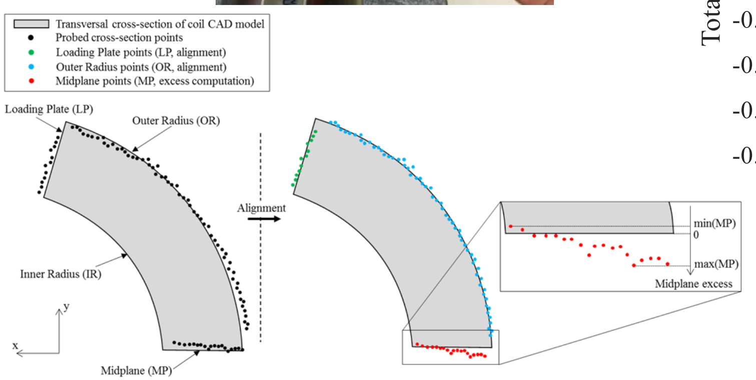


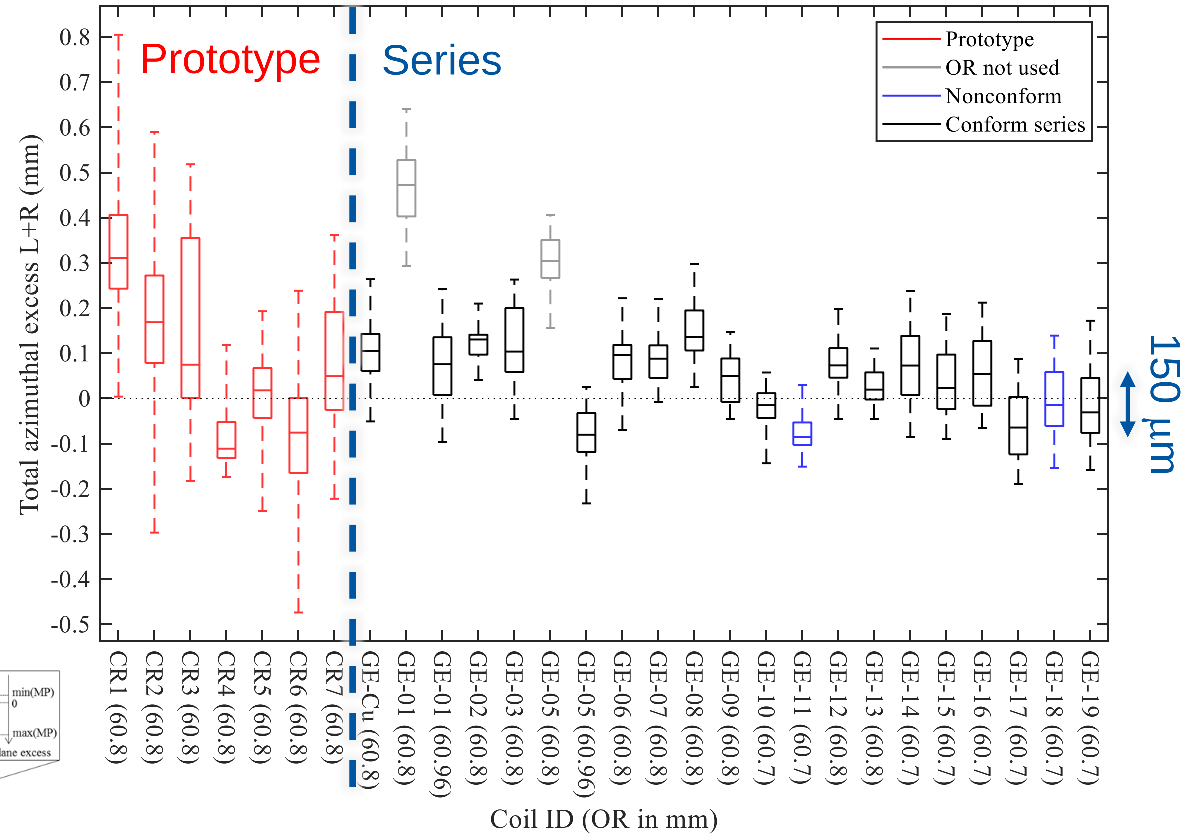




Coil Production

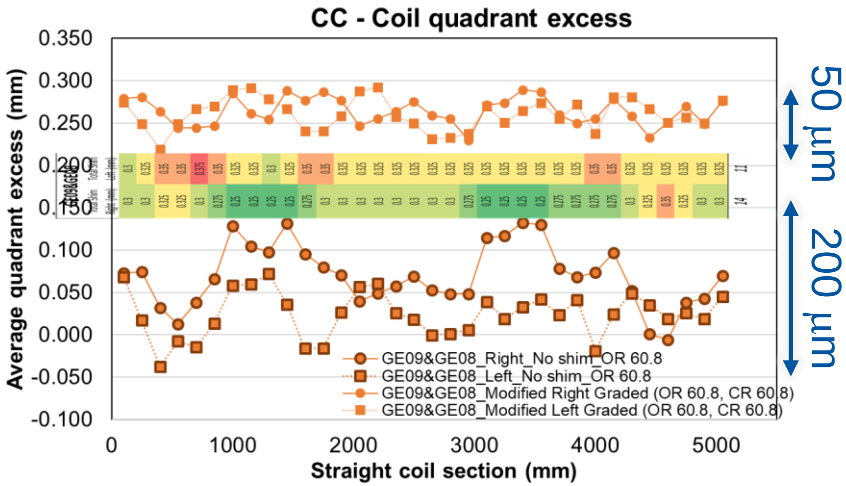
- 19 coils (out of 30) have been produced by GE as part of service contract; azimuthal coil sizes are controlled by Faro arm measurements.



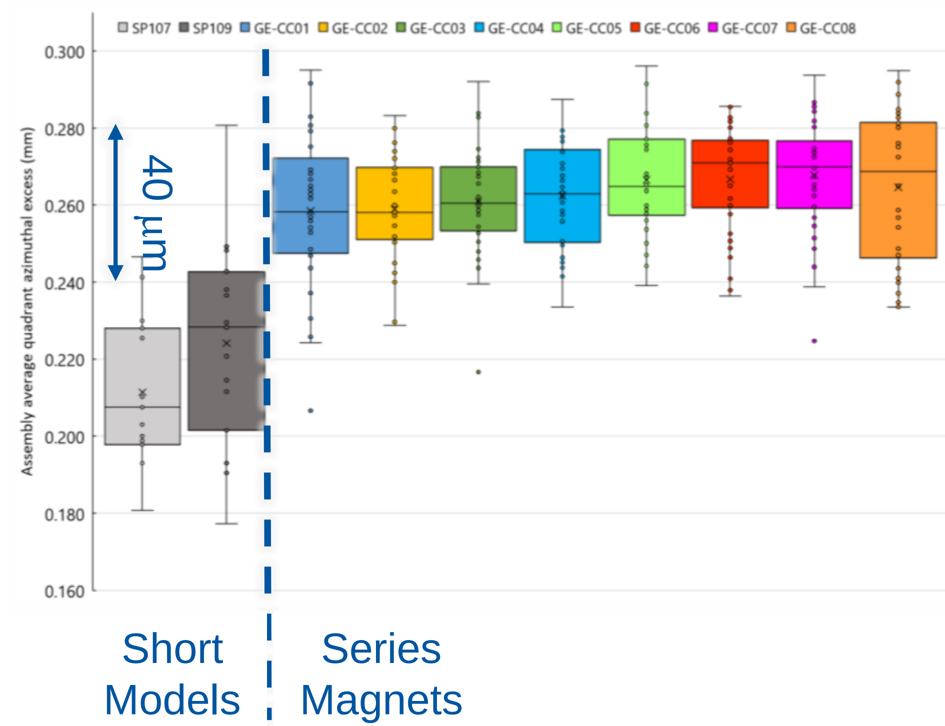


(Courtesy of D. Pulikowski, CERN)

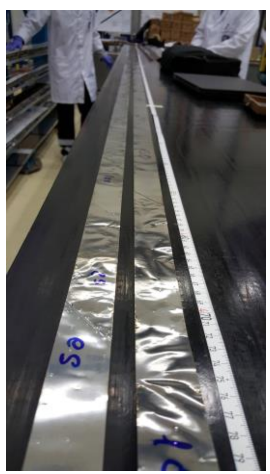
Shimming



- Azimuthal coil size variations along the length are compensated using graded (stainless steel) shims with 25 µm steps.



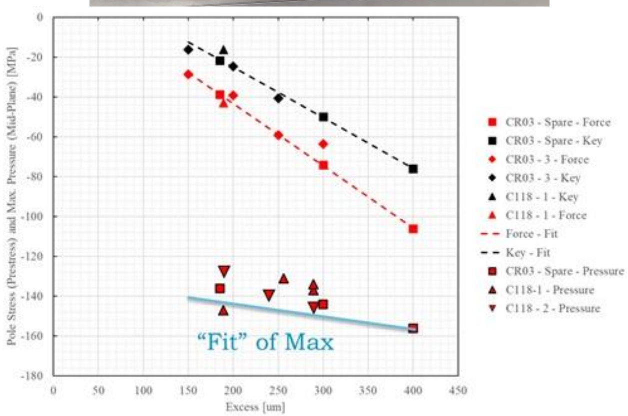
- With a Young's modulus of ~30 GPa, 25 µm corresponds to ~15 MPa on inner coil and ~11 MPA on outer coil.

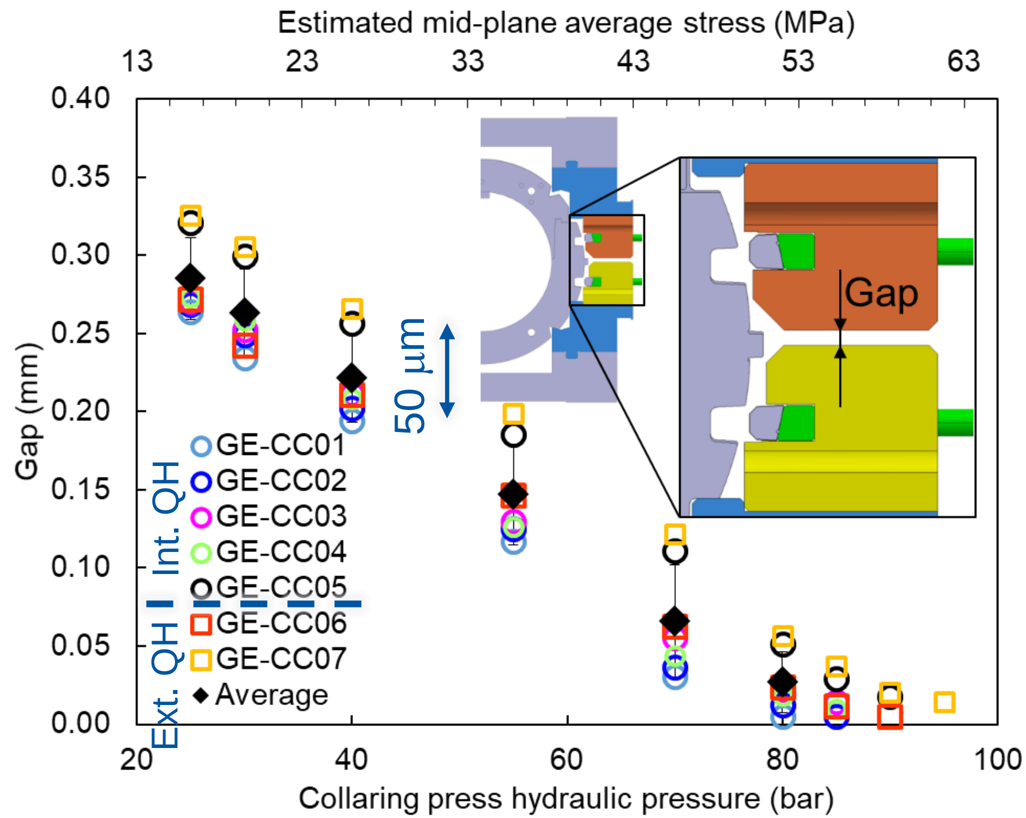


(Courtesy of J.-L. Rudeiros Fernandez, CERN)

Collaring

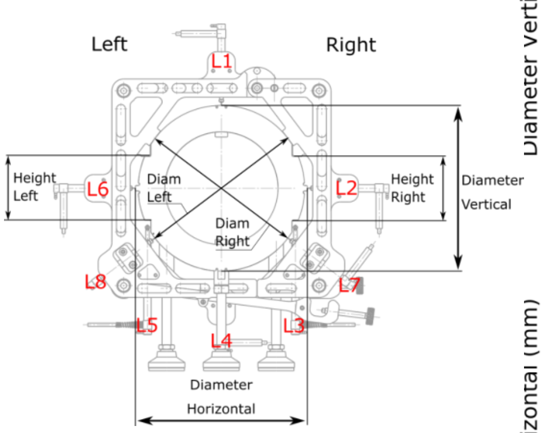
- Parameters optimized to limit transverse stress on midplane turn (< 150 MPa peak).
- Process controlled by measuring gap between top and bottom parts of pressing tool; good reproducibility of gap vs. hydraulic pressure.

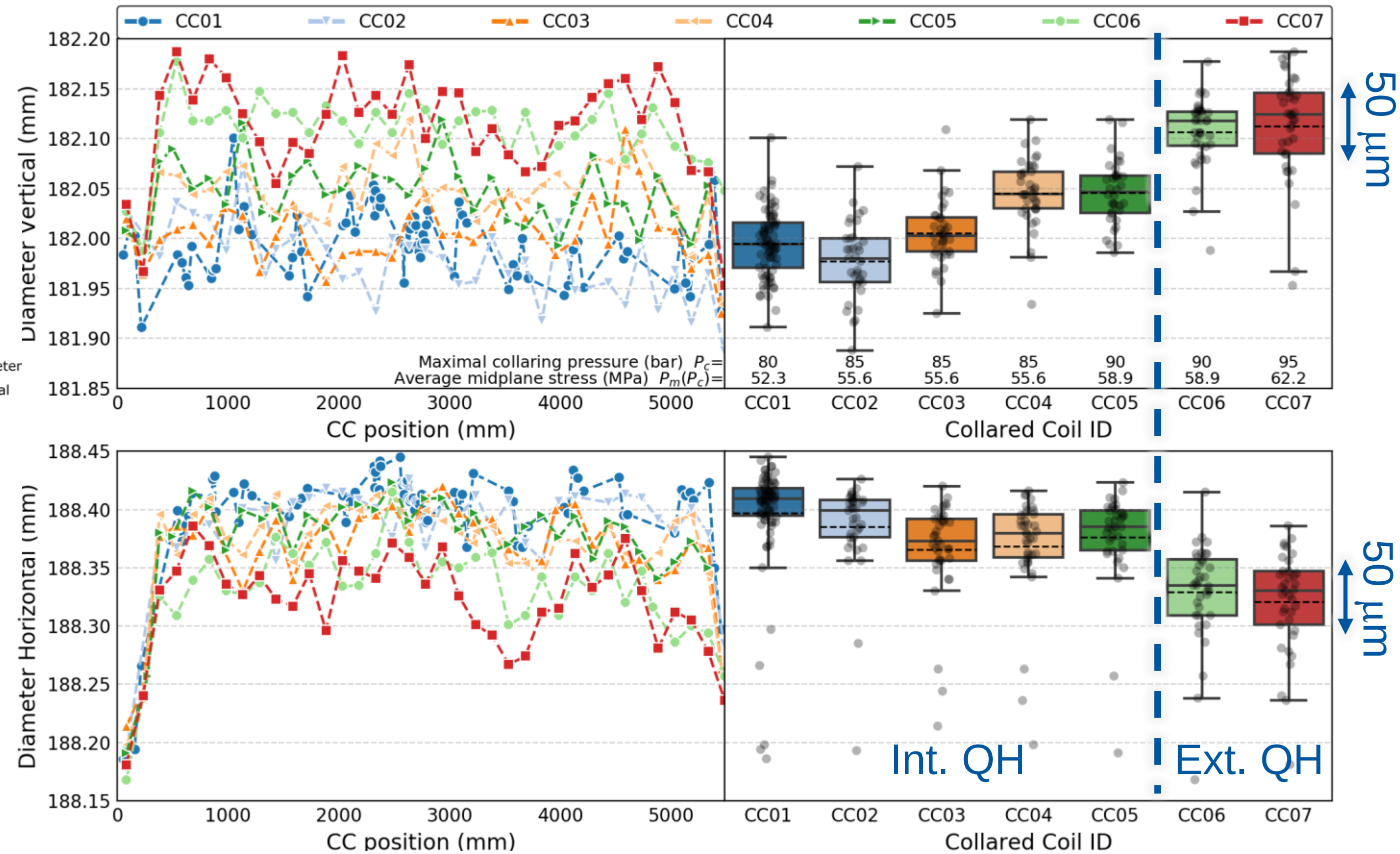




Collared-Coil Production

- 8 (out of 12) collared-coil assemblies have been produced by GE as part of service contract; outer diameters are controlled within 50 μm.





(Courtesy of D. Pulikowski and J.-L. Rudeiros Fernandez, CERN)

Schedule

Magnets equipped with **impregnated** QH

Magnets equipped with **external** QH

S1: LMBH**B**002 2019-08-22			
CC02		CC03	
C01	C05	C06	C07

S2: LMBH**A**001 2019-12-16			
CC04		CC05	
C08	C09	C12	C13

1^{st} Pair
Tunnel installation
in Q1 2020

S3: LMBHA002 2020-02-24			
CC06		CC07	
C10	C14	C15	C16

S4: LMBH**B**003 2020-04-15			
CC08		CC09	
C17	C19	C20	C21

2^{nd} Pair
Tunnel installation
in Q2 2020

S5: LMBH**B**004 2020-07-20			
CC10		CC11	
C22	C23	C24	C25

S6: LMBHA003 2020-09-28			
CC12		CC13	
C26	C27	C28	C29

Spare Pair

(Courtesy of F. Savary, CERN)

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  - Cable Degradation
  - Quench Heaters
  - Flux Jumps

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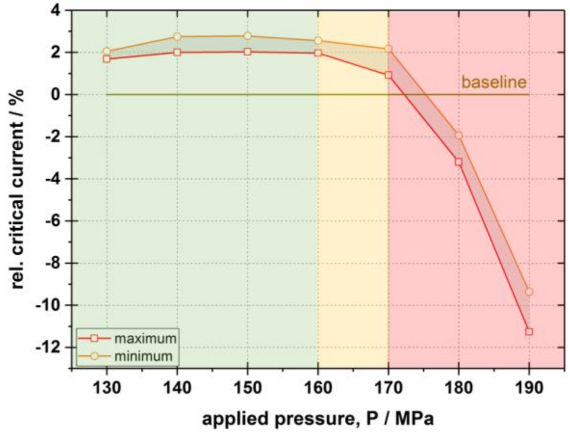
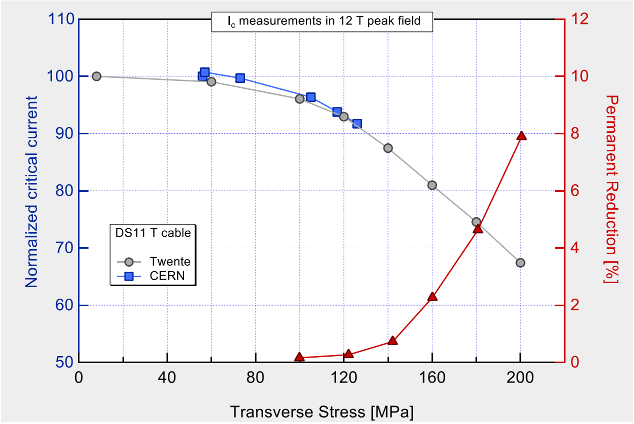
Cable Degradation – 1/2

- Measurements of cable I_C vs. transverse pressure applied at room temperature (mimicking collaring) or at 1.9 K (mimicking Lorentz forces) show a degradation that become irreversible above a certain threshold.



I_c vs. transverse pressure applied at RT coil on 11 T cable (courtesy of C. Barth, CERN)



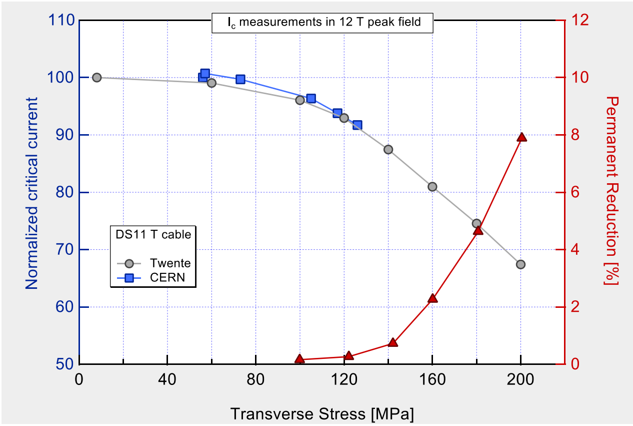
15% @150 MPa

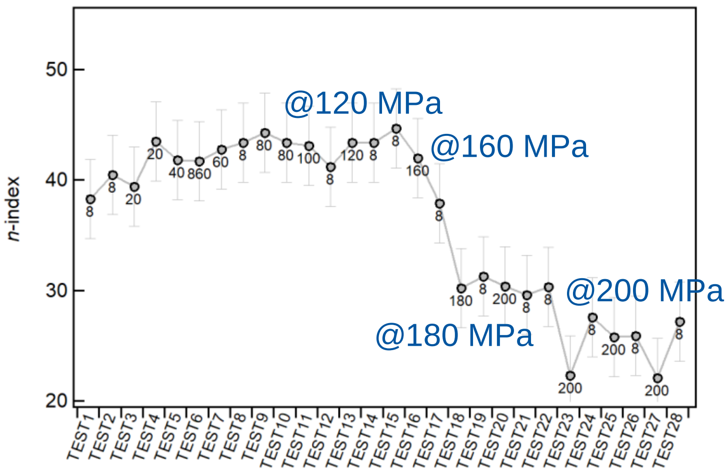
25% @180 MPa

I_c vs. transverse pressure applied at cold on 11 T cable (courtesy of B. Bordini, CERN)

- When pressed at RT, degradation onset is in the 160-180 MPa range; when pressed at cold, reversible degradation starts from 80-90 MPa and irreversible degradation starts from 120-130 MPa.

Cable Degradation – 2/2





- Data from Twente University (for cable pressed at cold) seem to indicate two irreversible degradation regimes

(1) between 120-160 MPa: I_C degrades but *N*-value stays constant;

(2) above 160 MPa: both I_C and *N*-value degrade.

- This may suggest two different mechanisms

(1) Cu plasticization;

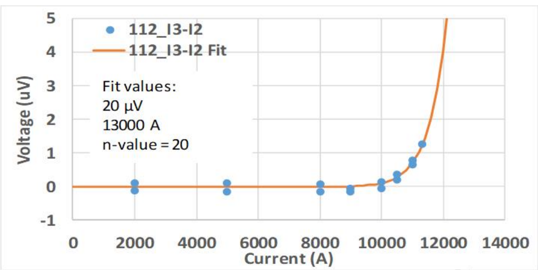
(2) filament cracking.

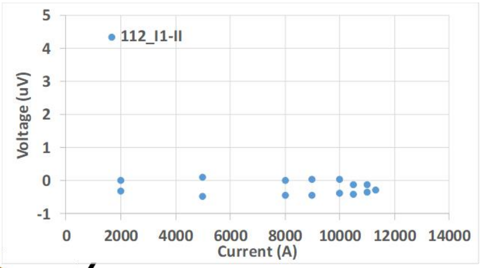
- Filament cracking is of course to be avoided if one wants to achieve stable and reproducible behaviour.

(Courtesy of B. Bordini, CERN and M. Dhalle, Twente University)

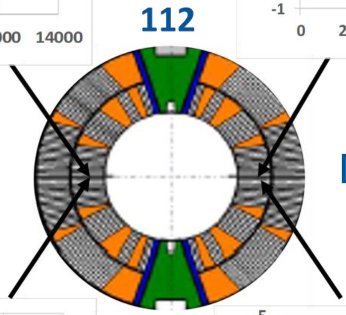
V-*I* Curves on Magnets

- Confirmation of potential in-coil performance degradation of conductor has been provided by direct measurements of *V*-*I* curves on midplane turns of short 11 T model magnets.



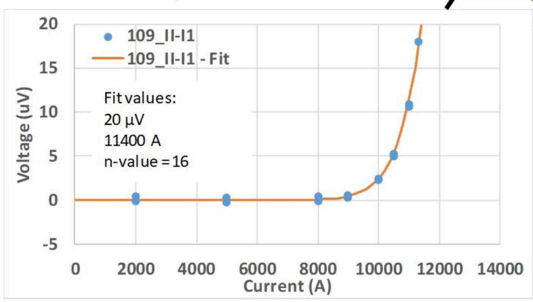


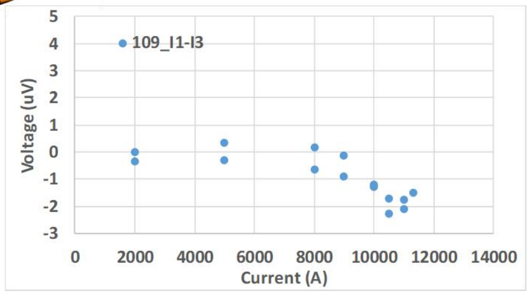
20 µV at 13000 A



DP102

20 µV at 11400 A



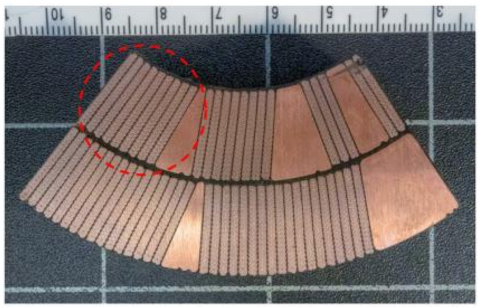


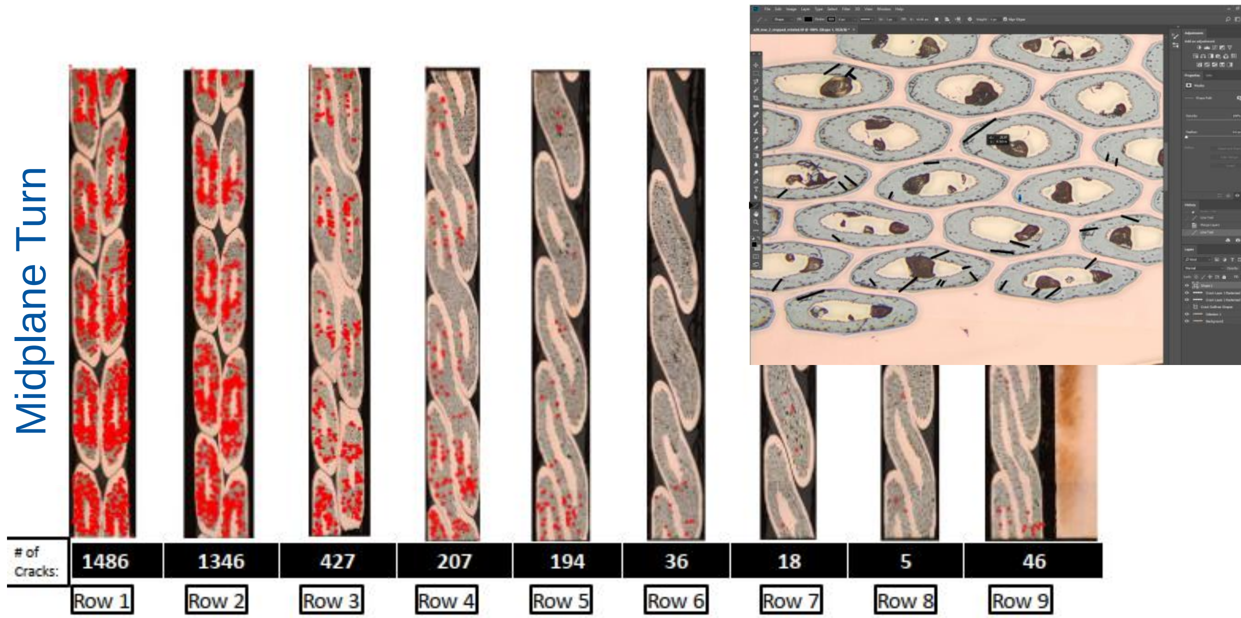
First measurement of *V*-*I* curves on midplane turns of DP102 (October 2017)

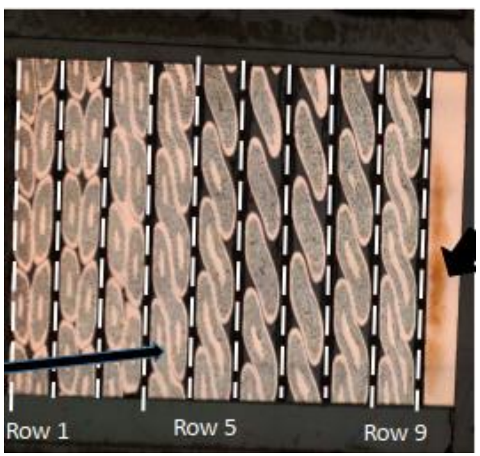
(Courtesy of G. Willering, CERN)

Filament Cracking

• Evidence of filament cracking (one of likely causes of irreversible degradation) has been observed on a section cut from DP102 coil #109 (note that this coil was used/re-used for several assemblies, which were cold tested/energized).





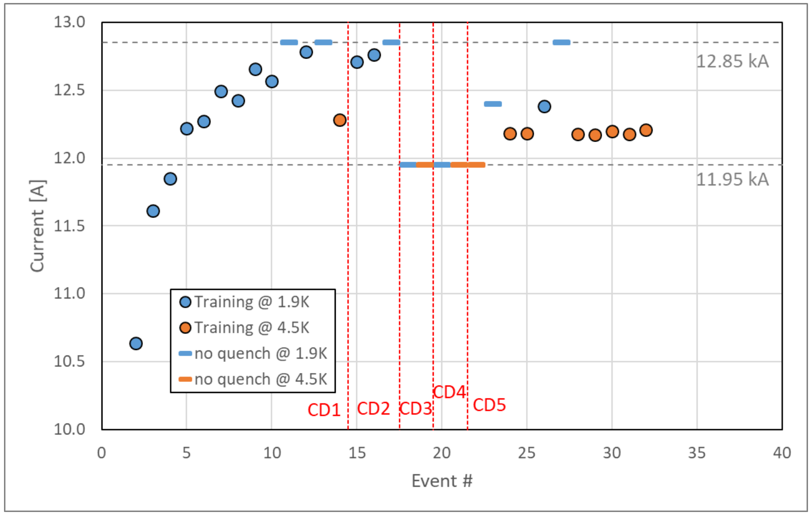


Filament crack counting on midplane block cut in the straight section of a 11 T short model coil (DP102 #109)

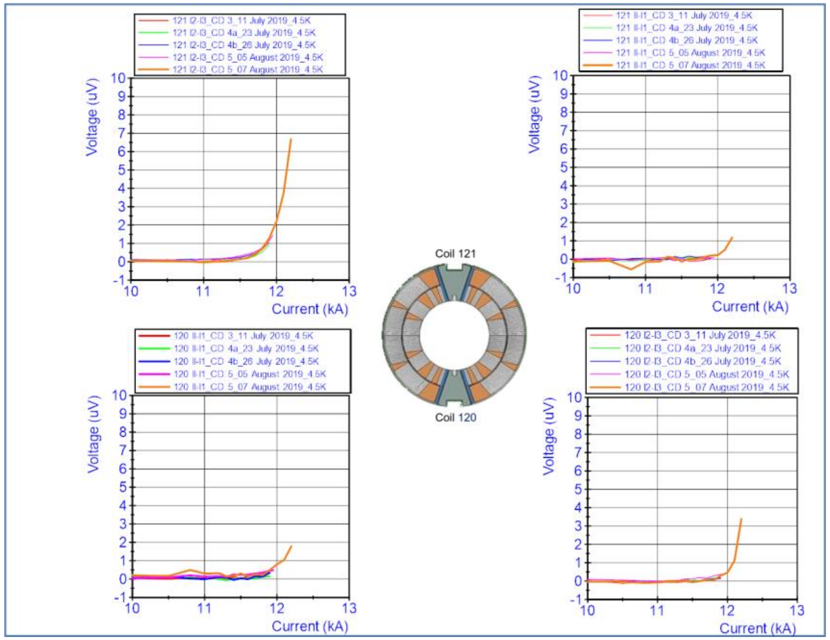
(Courtesy of R. Mullinix, O. Van Oss, J. Cooper, S. Balachandran, B. Starch and P.J. Lee, NHMFL)

The Case of SP107

- As already mentioned, the endurance tests of SP107 show stable behaviour, with the magnet able to repeatedly reach ultimate with little retraining.



- V-I curves are measured on the midplane turns of SP107; but no variation is observed over last 3 test cycles.

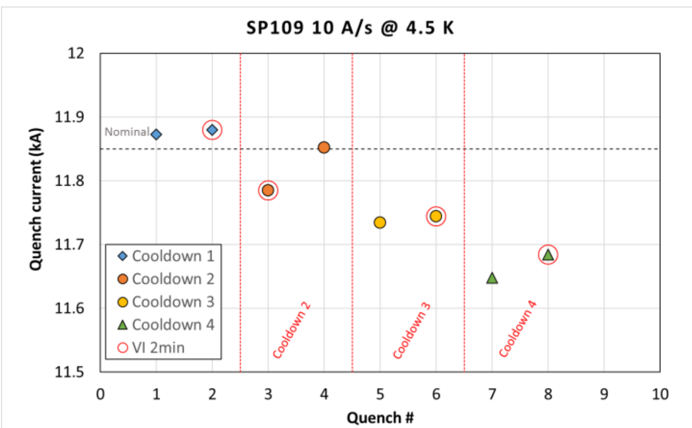


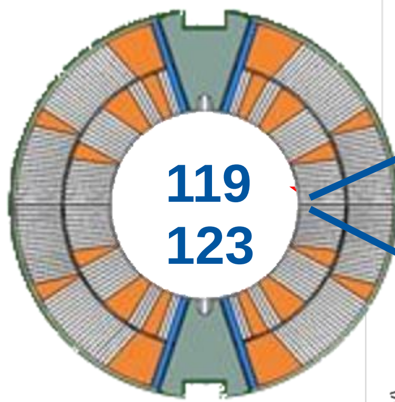
- This consistent and reproducible behavior seems to indicate that, up to ultimate current, we stay in a “controlled” degradation regime (*i.e.*, below irreversible degradation or filament-cracking threshold).

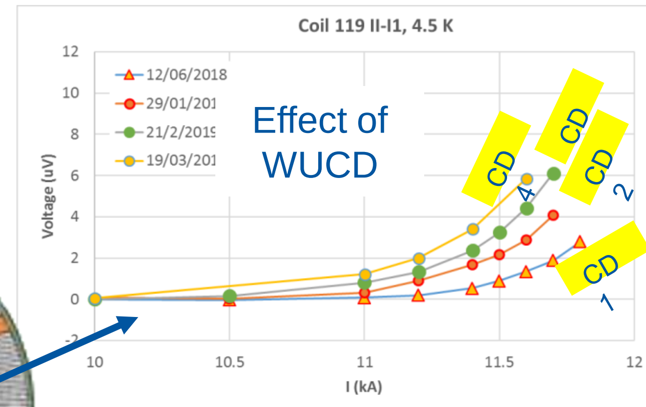
(Courtesy of M. Duda, F. Mangiarotti and G. Willering, CERN)

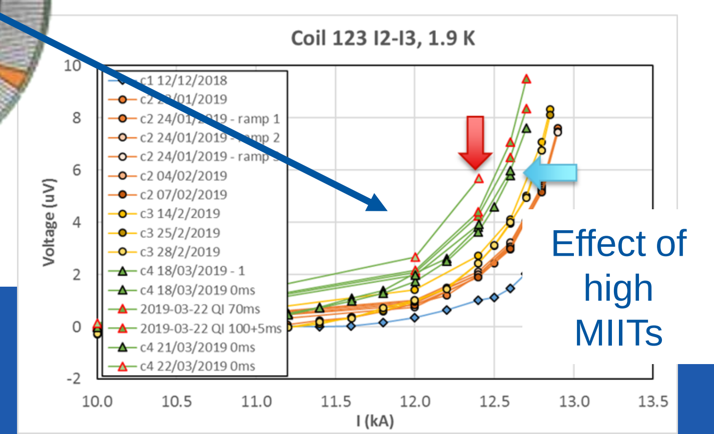
The Case of SP109 – 1/2

- Unlike SP107, the endurance tests of SP109 show that, although the magnet did reach ultimate current, the thermal stresses originating during warm-up/cool-down or during a midplane quench with a hot spot temperature in excess of 300 K result in a slight and progressive performance degradation, observed in both quench currents and *V*-*I* curves.
- Question: is this a specific feature of SP109 or, when nearing ultimate current, are the transverse stresses so high that there is a risk of "uncontrolled" degradation?







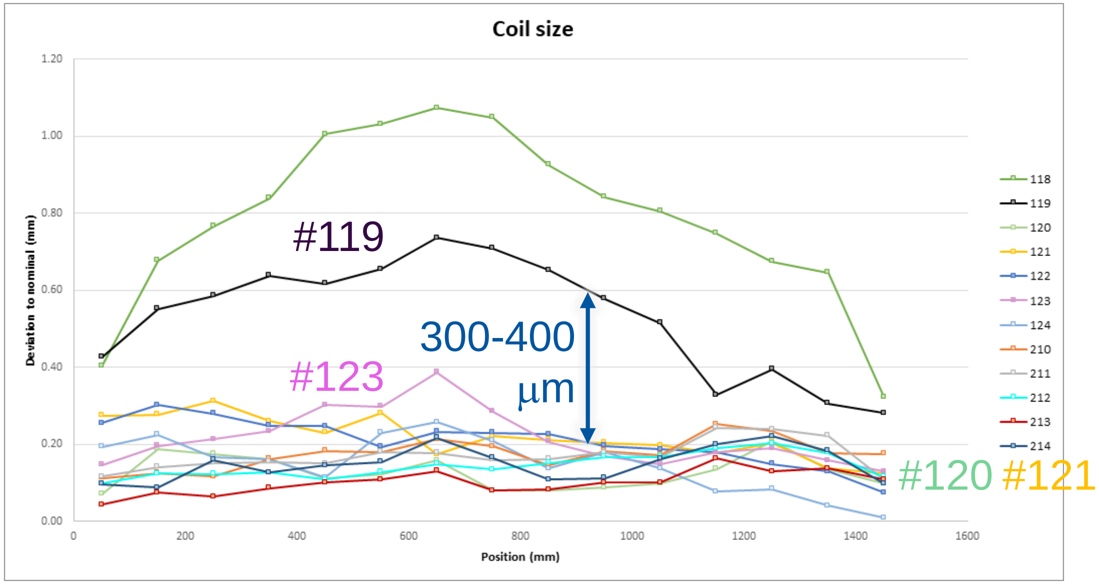


(Courtesy of M. Duda, F. Mangiarotti and G. Willering, CERN)

The Case of SP109 – 2/2

- The initial plan of the 11 T Task Force was to build two identical model magnets: SP107 and SP108; among the set of coils that were produced, 2 of them experienced an issue during VPI and came out oversized (#118 & 119).

- To save time, it was decided to assemble SP107 with 2 nominal-size coils (#120 & 121) and the other model, re-maned SP109, with one nominal (#123) and one oversized coil (#119) compensated by polyimide shimming.



- Unfortunately, it is not possible at this stage to conclude on the different degradation behaviour of SP107 and SP109; the CERN management has decided to cap the testing of 11 T magnets to nominal current + 100 A.

(Courtesy of J.C. Perez, CERN)

Content

- Introduction
- Production Status
- Outstanding Issues
- Outlook

From Development to Models to Prototypes to (Small) Series Production

- The road from R&D to short models, to prototypes and to (small) series production has been strenuous because Nb_3Sn magnet manufacturing processes are more cumbersome and less forgiving than for Nb–Ti.
- Compared to the size of SSC/LHC magnet development programs, HL-LHC magnet development programs have been more limited in duration, resources and partnerships while relying on a new and challenging technology.
- Also, the 20-to-25 years that have elapsed since SSC/LHC magnet development have generated gaps in knowledge transfer.
- Given the risks, both US and CERN have decided to “internalize” their production, and since the required number of magnets is small, each of the production units can be treated with extra care; although challenging, the goals of HL-LHC remain achievable.

CERN Nb_3Sn R&D Strategy

- Present Nb_3Sn technology will enable to achieve HL-LHC goals, but more efforts are required to bring the technology to the maturity and robustness required for industrialization and large-scale production.
- There are also reasonable hopes that Nb_3Sn can be used beyond the performances of HL-LHC magnets and one needs to explore what is the ultimate field range achievable with Nb_3Sn accelerator magnets.
- The above considerations yield to two very different sets of problems that call for different types of R&D with different time scales.
- CERN is presently brainstorming on a redefinition of its Nb_3Sn R&D strategy along the following lines

(1) HL-LHC-*like* dipole to secure the technology;

(2) Ultimate Nb_3Sn dipole for a next step hadron collider.

Preliminary

HL-LHC-*like* Dipole

- Objective: to capitalize on HL-LHC progress by developing a robust and cost-effective 12-T range dipole magnet suitable for industrialization.
- Scope:
  - *secure* with sufficient margin the field range achieved with HL-LHC magnets
  - *develop and qualify* engineering solutions for production on a large scale (10^3 magnets)
  - produce *accelerator-quality prototypes* as a final result.
- Time scale: 2021…2027.

Ultimate Nb_3Sn Dipole

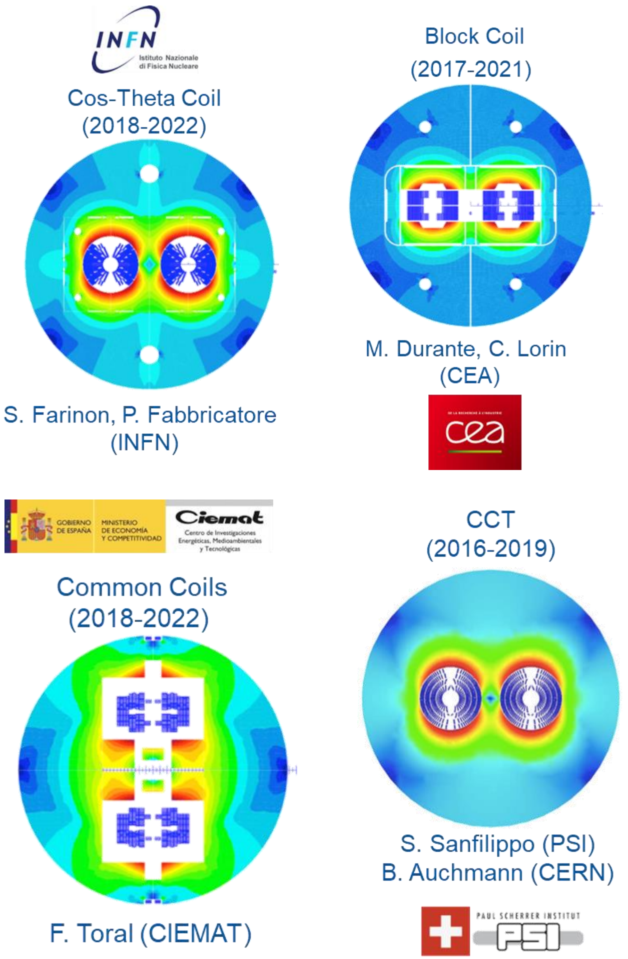
- Objective: to explore conductor and magnet technology at the upper limit of Nb_3Sn (LTS) with a projected upper target of 16 T
- Scope:

– *pursue* the worldwide efforts started with the FCC program with wire manufacturers and collaborations (CEA, CIEMAT, INFN, CHART2 and US MDP);

– *re-adjust milestones* to introduce more explicit basic R&D steps;

– produce accelerator-relevant short models as *technology demonstrators,* in connection with basic R&D.

- Time scale: 2020…2025.



16 T FCC Dipole Magnet Zoo (Courtesy of D. Tommasini, CERN)

CERN R&D Strategy (Cont.)

- CERN is also brainstorming on what to research and develop in other areas and 6 additional themes are being considered

(3) HTS dipole beyond Nb_3Sn ultimate performance for a next step hadron collider;

(4) HTS wiggler/undulator for a next step linear collider;

(5) Very high field test station for cables and inserts;

(6) Centers of Competence as unique concentration of knowledge, tools and infrastructures to become a reference and service center;

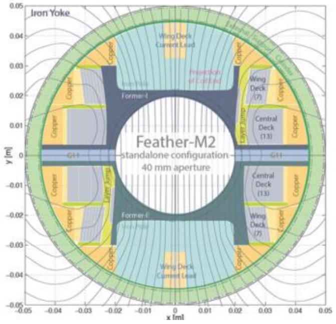
(7) Super-ferric demonstrator for consolidation of CERN Experimental Area;

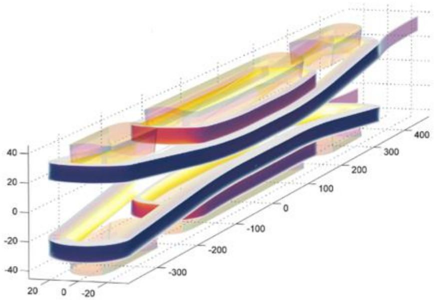
(8) Synchrotron and gantry magnets for hadron therapy.

Preliminary

HTS Dipole

- Objective: explore conductor and magnet technology at field beyond Nb_3Sn, using HTS, with a projected upper target of 20 T.
- Scope: program mainly driven by basic R&D; demonstrators are high-field inserts to be tested in background facilities (no model).
- Time scale: 2020…2024.





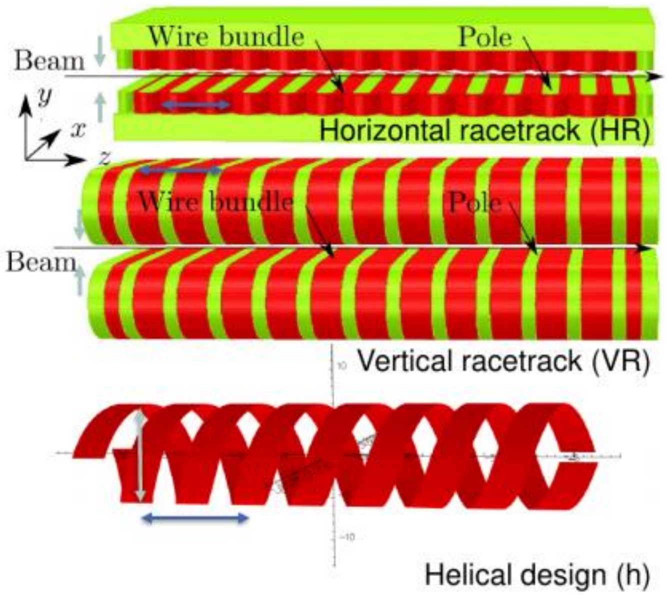
Feather 2.3-4 HTS Insert
(Courtesy of G. Kirby
and J. van Nugteren, CERN)

Preliminary

R&D themes: 4, 7, 8

HTS Wiggler/Undulator

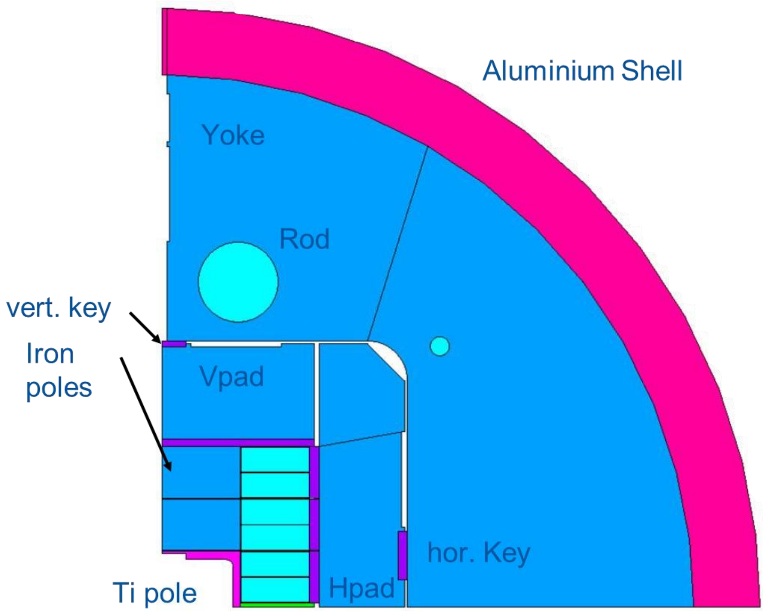
- Objective: design and prototype a HTS wiggler/undulator with a combination of field/period/gap that cannot be achieved by LTS.
- Scope: design a wiggler/undulator demonstrator for a test in a beam line (synchrotron light source or free electron laser); this project could help materializing the R&D on the HTS dipole (to be aligned with existing and planned collaborations and studies –KIT, CHART-II, ARIES-II).
- Time scale: 2019…2024.



Winding geometries
under consideration
for superconducting wigglers
(Courtesy of D. Schoerling. CERN)

Very High Field Test Facility

- Objective: new test bed for LTS and HTS cables and inserts, approaching operating conditions of very high-field accelerator magnets
  - $B_{bkg} \approx 15$ T
  - $I_{op} > 20$ kA
  - $T_{op} \approx 1.9$ K … 100 K
  - Large aperture (≈ 150 mm)
- Scope: conductor procurement and magnet construction; this project could help materializing the R&D on the ultimate Nb_3Sn dipole.
- Time scale: 2019…2025.



Conceptual Design of HEPDipo (Courtesy of L. Bottura, P. Ferracin and D. Martins Araujo, CERN)

Conclusion

- WP11 is now well into the production phase and starts accumulating data, which demonstrate that key processes (*e.g.*, coil manufacture and collaring) are under control.
- The test of the 1st series 11 T dipole magnet meets operational requirements for tunnel installation.
- If 2nd series magnet (to be tested in November 2019) is equally successful, tunnel installation of the pair is foreseen in Q1 of 2020.
- The installation of the first Nb_3Sn accelerator magnets into the LHC tunnel will mark an historical milestone.
- CERN is developing a pragmatic approach to the definition of its Nb_3Sn R&D beyond HL-LHC and is considering a dual strategy of engineering development around 12 T and research towards 16 T.
- CERN is also considering which niche applications of HTS to promote beyond 16 T.

Back-Up Slides

11 T Dipole Magnet Timeline

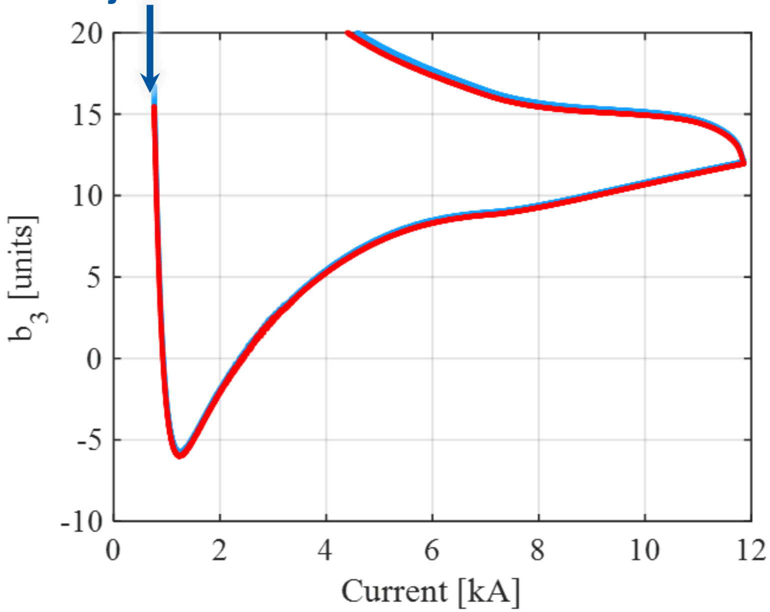
- *2004-2008: NED (CARE)*
- *2009: Start of FRESCA2 (EUCARD)*
- **Chamonix 2010: Request for increased collimation efficiency**
- **June 2010: Launch of HL-LHC project**
- **2 July 2010: Memorandum with 11 T magnet concept**
- 29 July 2010: 1st discussion with Fermilab
- October 2010: inclusion of 11 T as WP11 in FP7-HiLumi LHC Design Study
- **October 2010: Launch of Fermilab program (GARD funding)**
- **Q3 2010 to Q3 2012 Technology transfer from Fermilab to CERN**
- 2012-2013: Design/tooling development at CERN
- **May 2013: Collimation review recommends installation of 4 units (8 x 11 T magnets) in LS2 (IR2 and/or IR7)**
- Q4 of 2014: Test of SP101
- **May/June 2015: Test of SP102, reached 12.1 T (12.75 T peak)**
- October 2015: SMC11-3, reached 13.5 T peak
- **Q1 of 2016: Test of DP101, reached 12.5 T (13.1 T peak)**
- **October 2016: Re-baselining of WP11 (2 units + 1 spare in IR7)**
- October 2017: First observation of V-I curve on DP102
- **November 2017: Start of 11 T Task Force**
- **Early 2018: Start of GE contract**
- *April 2018: FRESCA2, reached 14.6 T (14.95 T peak)*
- June-August 2018: Test of 1st prototype
- **August 2018: test of 1st Task Force model magnet (SP107)**
- February-March 2019: Test of hybrid prototype
- **July/August 2019: Test of 1st series production magnet**

+ 250 A

LMBHB002 Field Quality – 2/2

Persistent Magnetization Currents (2nd cycle, both apertures)

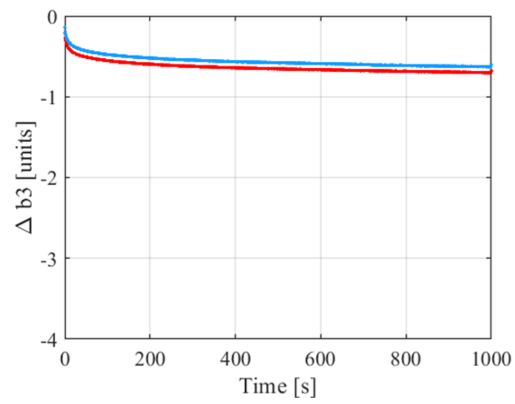
Injection



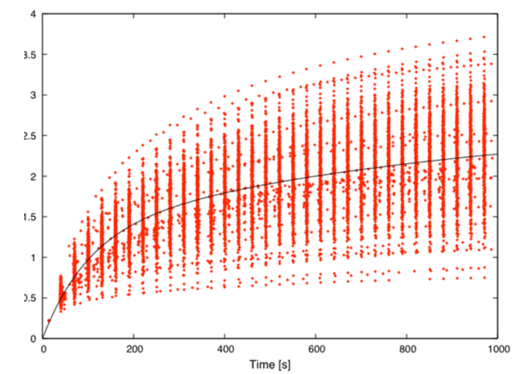
Injection on wrong side of magnetization peak

Time decay at Injection (760 A)

MBH002



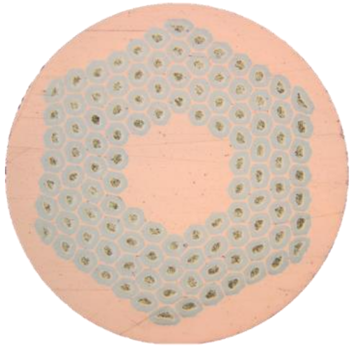
432 Apert. of LHC Dipoles



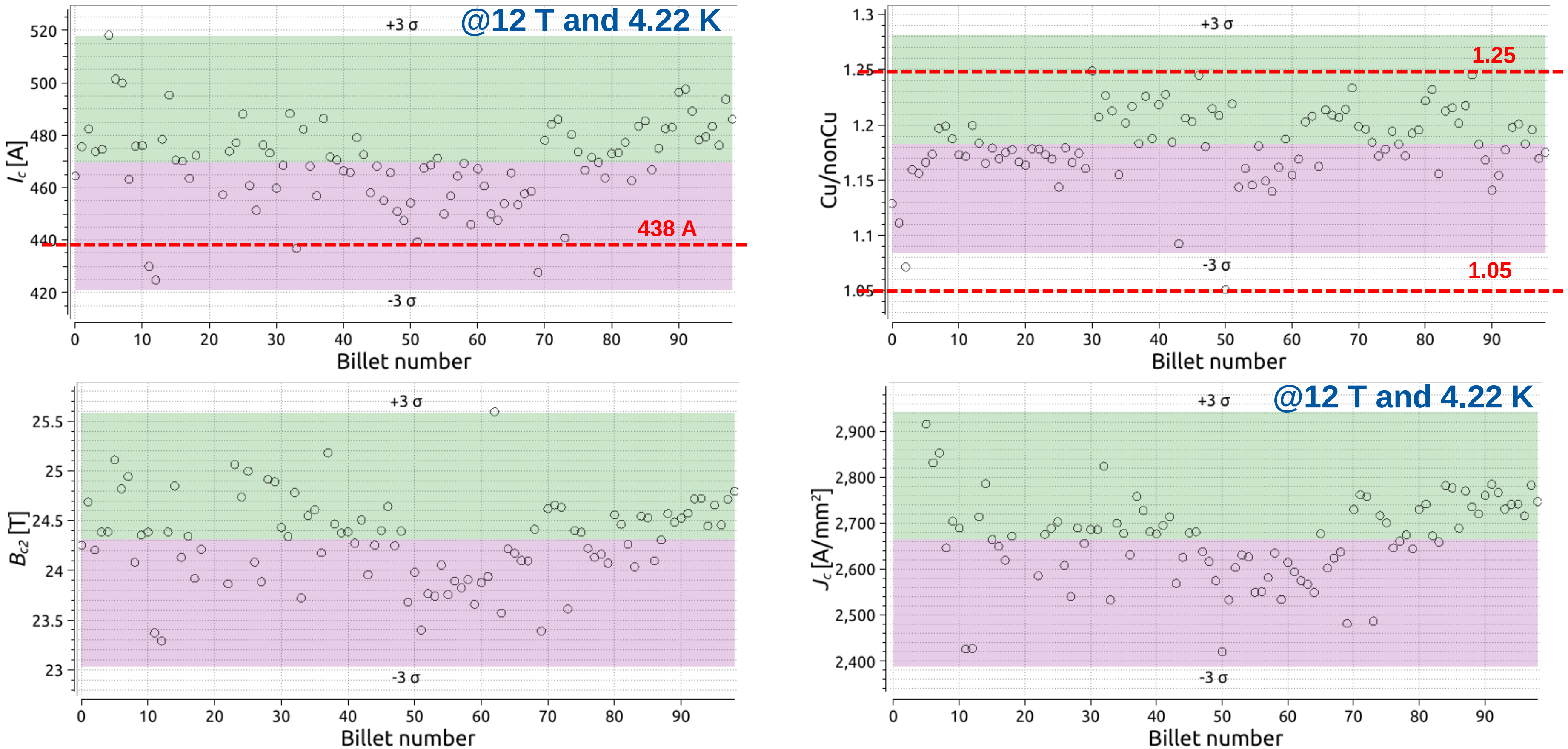
b_3 time decay at injection is smaller than for LHC Nb–Ti dipole magnets

(Courtesy of L. Fiscarelli, CERN)

Nb_3Sn Wire Production – 1/2

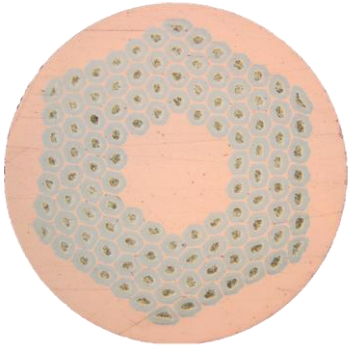


- Production of 3.7 tons of RRP 108/127 (0.7 mm ∅) is completed.

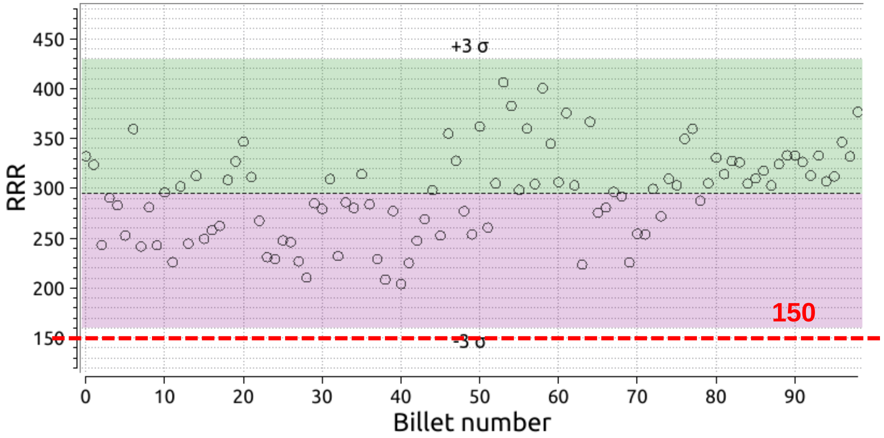


(Courtesy of B. Bordini, CERN)

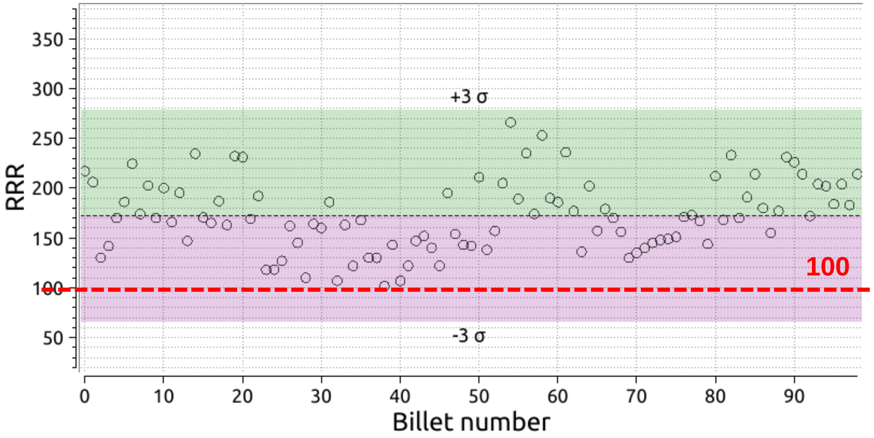
Nb_3Sn Wire Production – 2/2



- 15% rolling results in a RRR reduction of about ~40%.



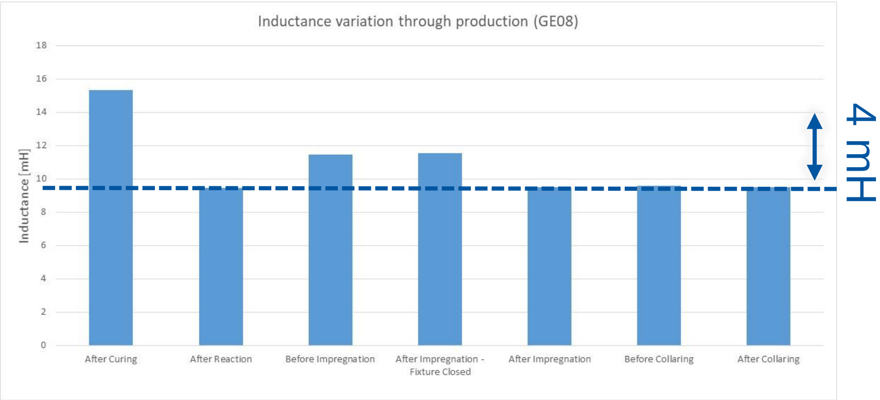
Virgin Wire



15%-rolled Wire

(Courtesy of B. Bordini, CERN)

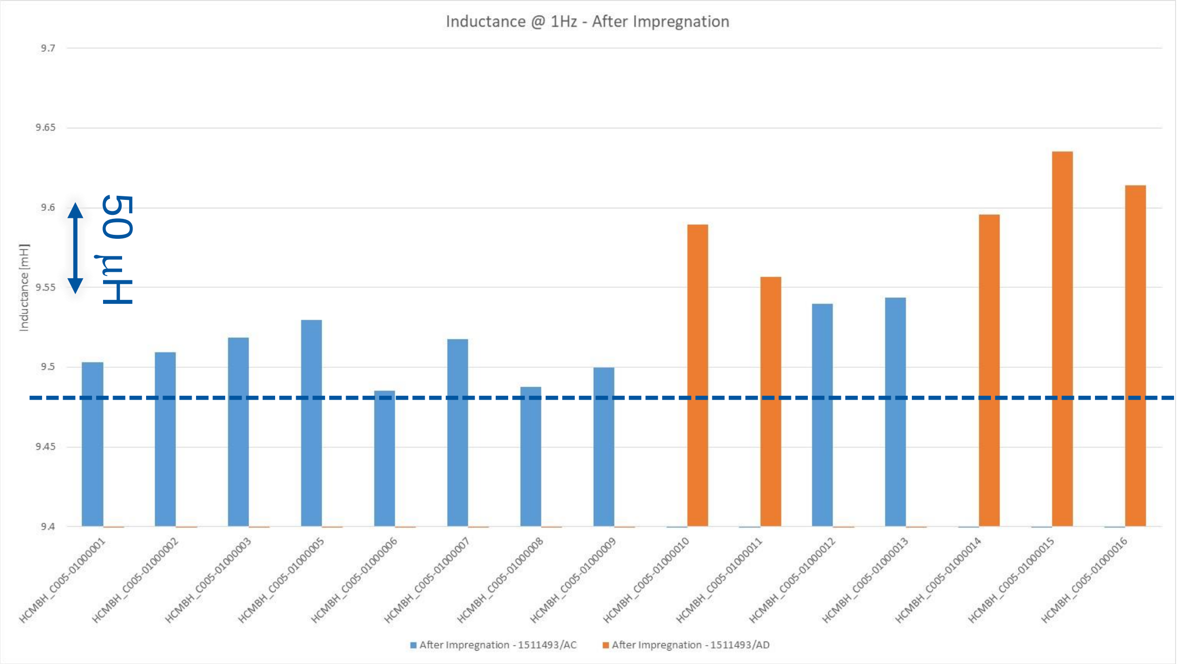
Coil Electrical Tests



Inductance measurement after each coil manufacturing step

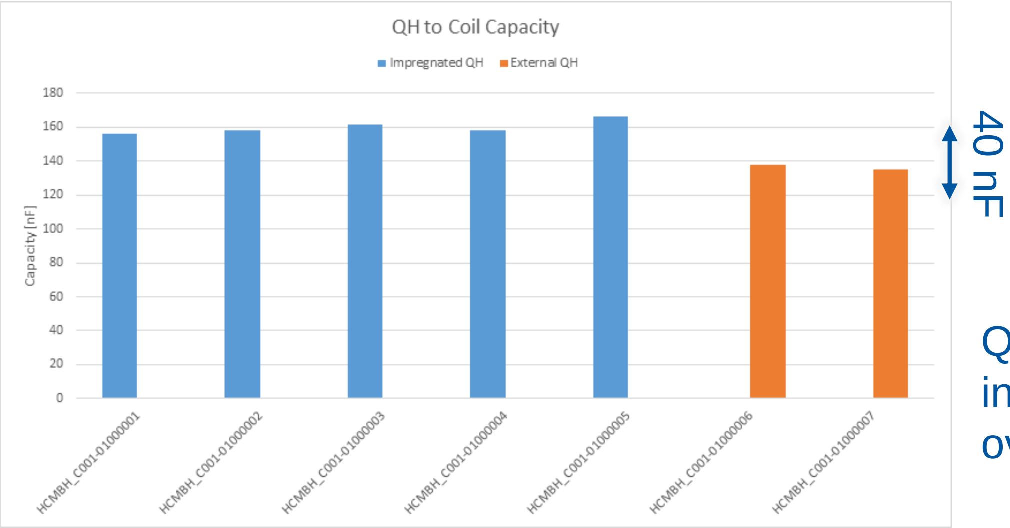
Inductance measurement over coil production (after VPI); coils with external QH have a slightly larger inductance

9.48 mH (Comp.)

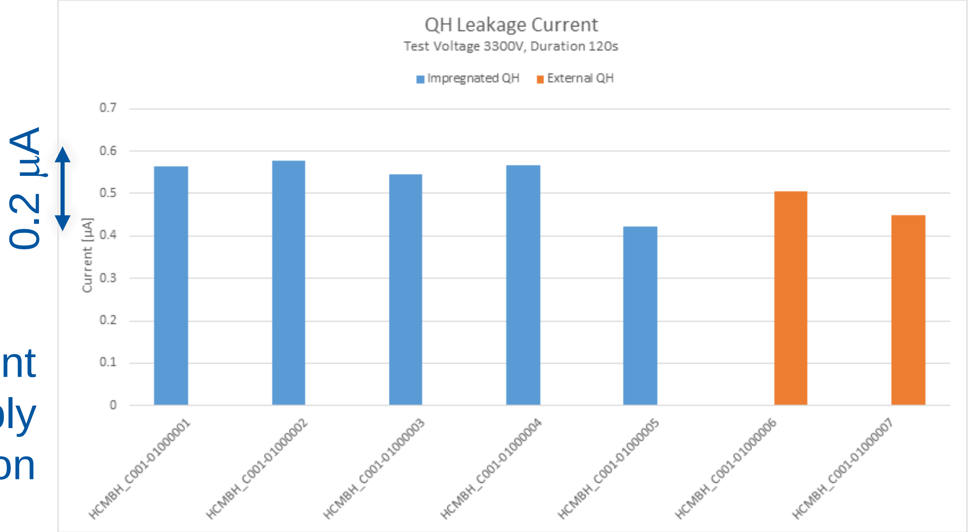


(Courtesy of J. Petrik, CERN)

Collared-Coil Electrical Tests



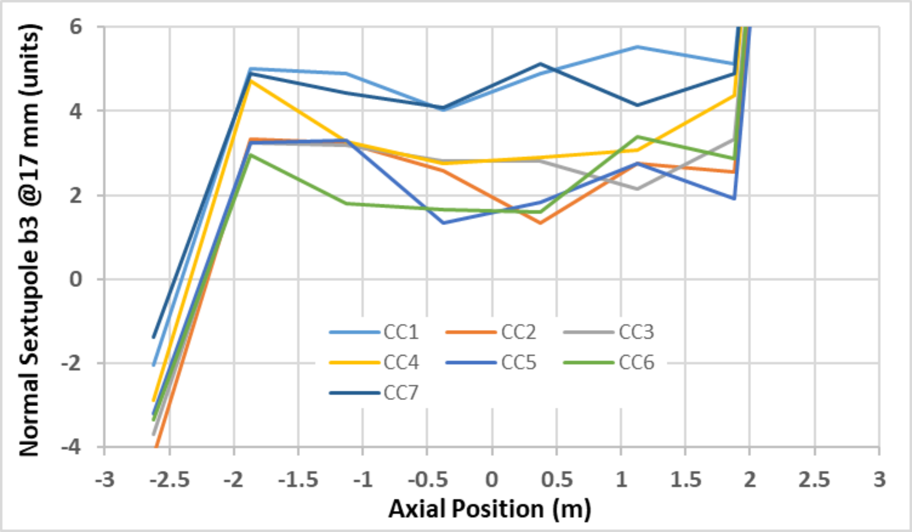
QH to coil capacity
inside collared-coil assembly
over production



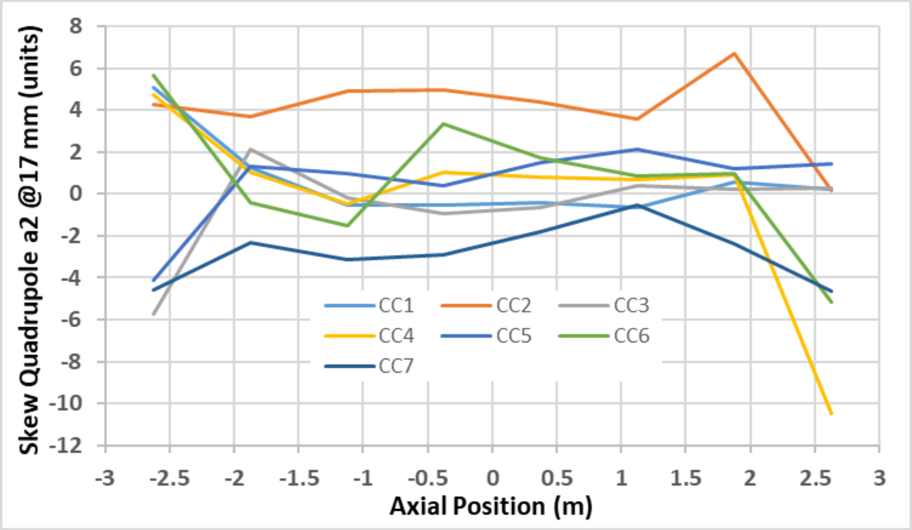
QH Leakage current
Inside collared-coil assembly
over production

(Courtesy of J. Petrik, CERN)

Collared-Coil Magnetic Measurements



b_3 (@17 mm) vs. axial position over collared-coil production



a_2 (@17mm) vs. axial position over collared-coil production

(Courtesy of L. Fiscarelli, CERN)

Coil Mechanical Properties

- Virgin loading

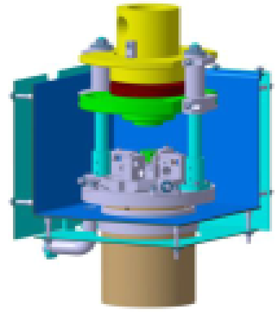
14 ± 2 GPa

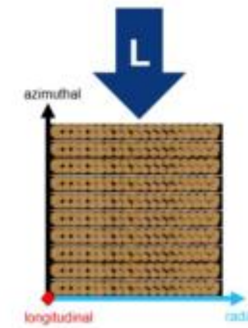
- RT loading/unloading

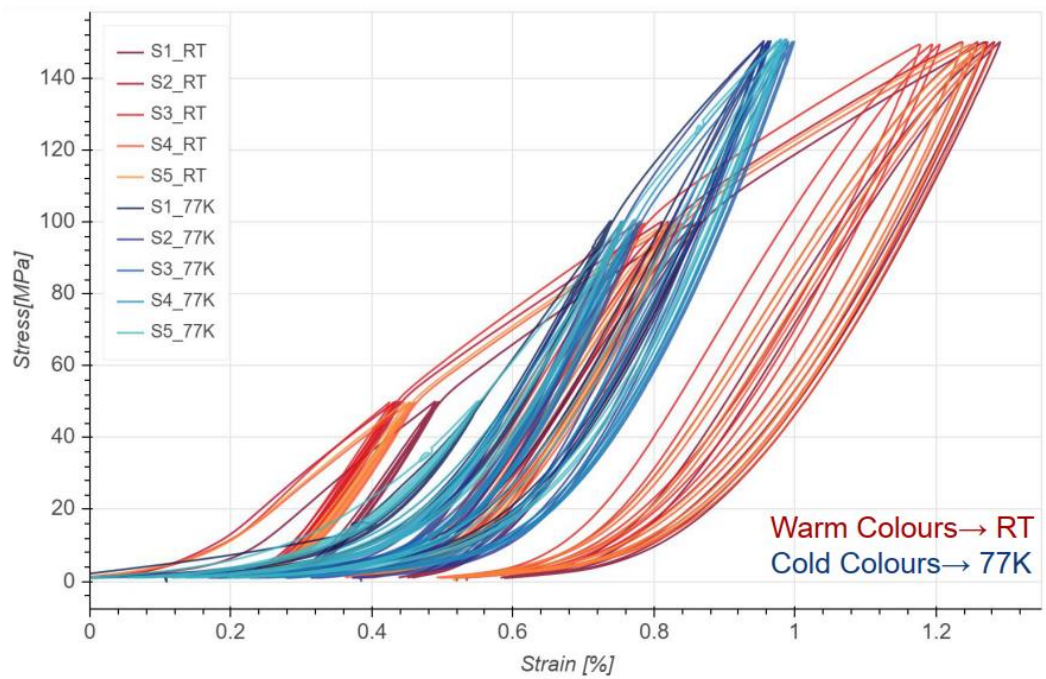
31 ± 3 GPa

- 77 K loading/unloading

39 ± 3 GPa

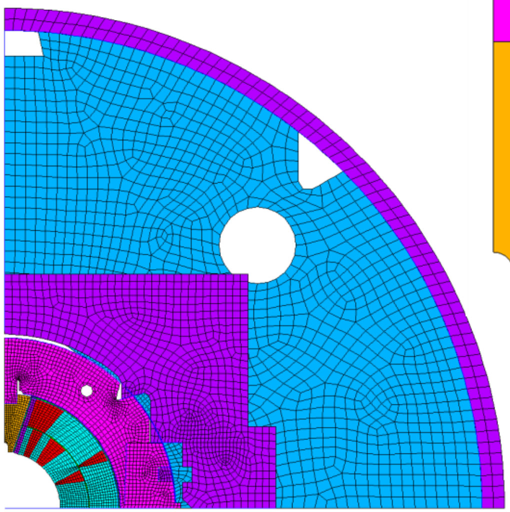


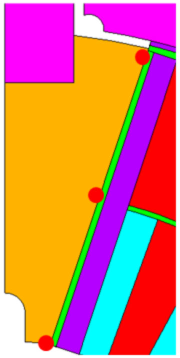




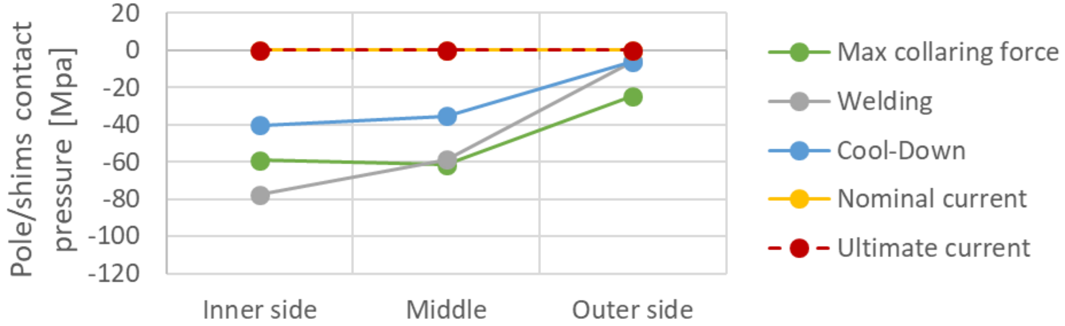
(Courtesy of M. Guinchard and O. Sacristan, CERN EN-MME)

Coil Stress Distribution



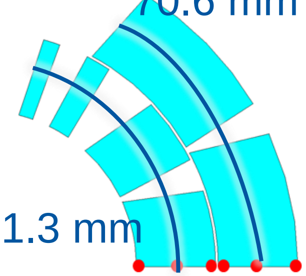


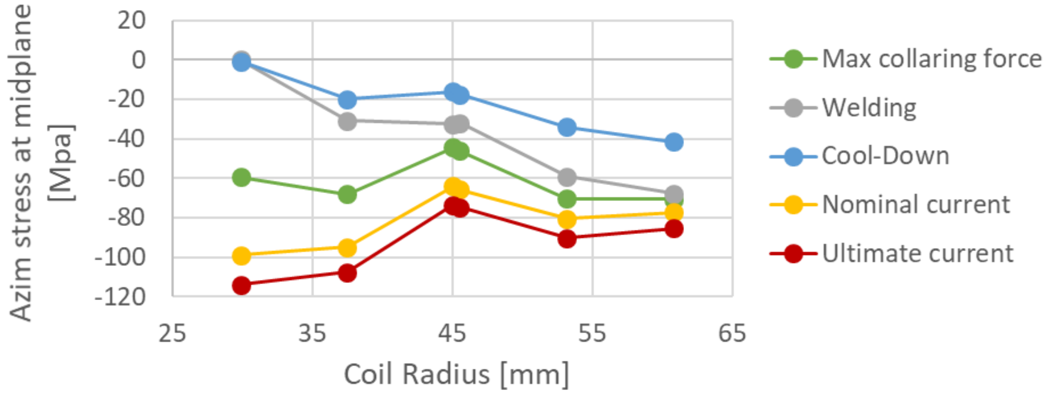
Full unloading @nominal



Preliminary

- Nominal case (300 μm excess)



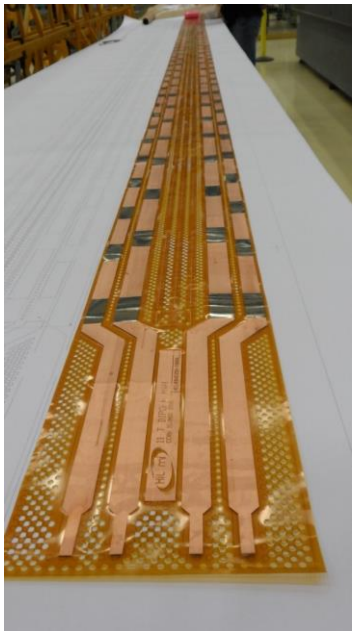


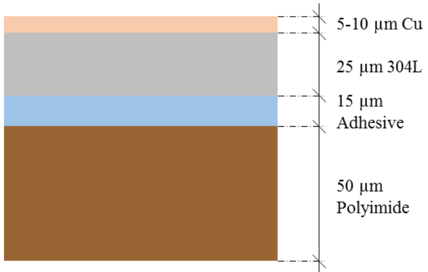
Peak stress < 120 MPa @ultimate
(w/o stress concentration due to mica)

(Courtesy of E. Gautheron, CERN)

Quench Protection Heaters – 1/2

• The magnet quench protection is ensured by heaters, which need to be robust and reliable; a critical issue is to define the QC electrical test requirements.





• The most severe risk of voltage breakdown occurs during a magnet quench in the tunnel unit circuit.

• Simulations have been carried out for two cases

(1) standard case at nominal current[1], which gives
V_{peak} = 682 + 430 V at T = 204 K (with T_{max} = 332 K);

(2) realistic failure scenario in tunnel unit circuit (assuming 1 out of 16 QH failure)[1], which gives
V_{peak} = 920 + 430 V at T = 206 K (with T_{max} = 340 K).

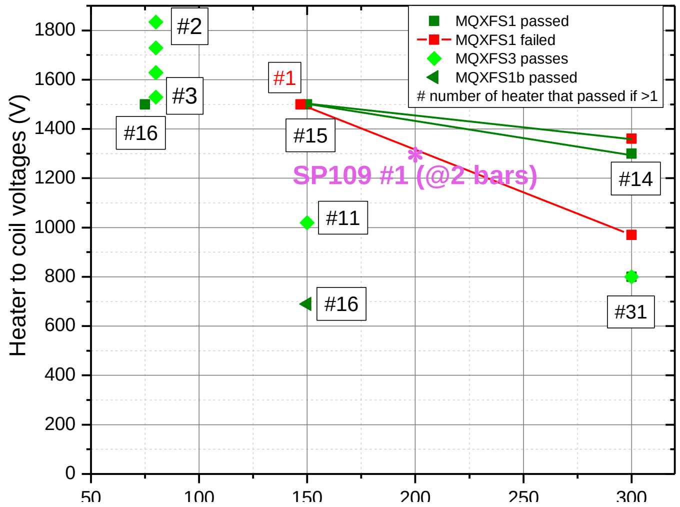
• Based on these simulations, it has been agreed that the most relevant QC test on a magnet is ~1.6 kV in GHe around 200 K and ~10 bars (which can be scaled down to 750 V at 200 K and ~3 bars).

[1] assuming a spread of Cu/non-Cu ratio and RRR of 1.19±0.02 and 175±25.

(Courtesy of F. Rodriguez Mateos and A. Verweij, CERN TE-MPE)

Quench Protection Heaters – 2/2

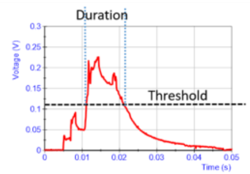
- Initial baseline for 11 T magnets was to impregnate the quench heaters with the coils (as for MQXFA&B).
- There are limited test results on both 11 T and MQXF model magnets at intermediate temperatures (100-200 K) in GHe at 1-2 bars that indicate that, for impregnated heaters, voltage breakdowns can occur around ~1.3-1.5 kV.
- To mitigate this risk, the decision was taken in January 2019 to take the quench heaters out of the impregnated coils.

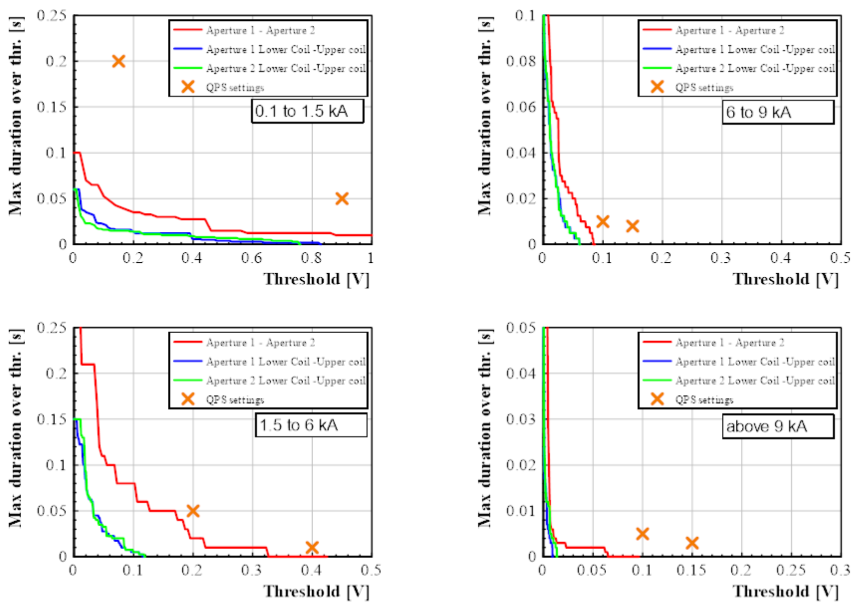


HV tests in GHe @1 bar on 47 MQXF QH after coldtest (Courtesy G. Ambrosio, FNAL)

- The ext. quench heater solution will be validated on 1 additional, twin-aperture, short model magnet (DP201) to be tested before December 2019; in the meantime, production is proceeding with external quench heaters.

Flux Jumps

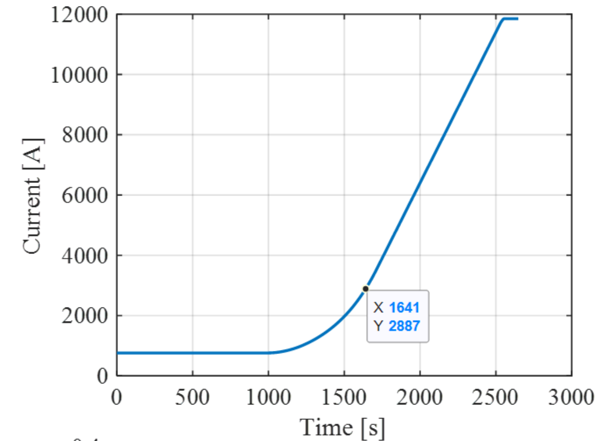


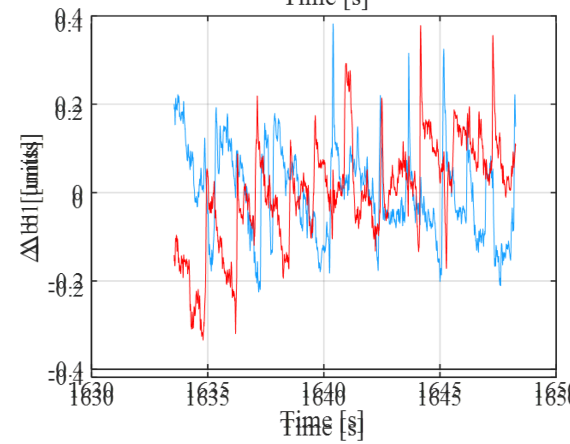


(Courtesy of G. Willering, CERN)

Large flux jumps during current ramping call for variable detection thresholds and validation times on the QPS.

	Threshold, validation time	
Current range	**Lowest treshold**	**Shortest validation time**
I < 1.5 kA	150 mV, 200 ms	900 mV, 50 ms
1.5 kA < I < 6 kA	200 mV, 50 ms	400 mV, 10 ms
6 kA < I < 9 kA	100 mV, 10 ms	150 mV, 8 ms
9 kA < I	100 mV, 5 ms	150 mV, 3 ms





(Courtesy of L. Fiscarelli, CERN)

Flux jumps result in a “noise” on the flux with a relative amplitude of up to $1*10^{-4}$; not an issue for HL-LHC, but beam impact to be assessed for a future machine.

Content

- Introduction
- Production Status
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- Outlook

Lessons Learned from HL-LHC – 1/2

- Focus of HL-LHC magnet development programs has been to achieve performance; more development is clearly needed before taking the next step towards industrialization and large-volume production of Nb_3Sn accelerator magnets.
- Key technical/technological issues to be addressed

(1) conductor performance and operating margin (incl. degradation under transverse stress);

(2) training origin and cure;

(3) electrical insulation and resin impregnation;

(4) optimization of coil manufacturing processes and associated contact tooling (incl. wind-ability, management of thermal expansions and handling of heat treated coils);

(5) magnet mechanics and coil peak stresses (incl. optimization of coil support structure and of assembly processes/parameters);

Lessons Learned from HL-LHC – 2/2

(6) scalability of manufacturing processes to long lengths;

(7) quench detection and magnet protection (circuit + machine);

(8) magnet thermal management (in particular for beam losses);

(9) instrumentation;

(10) Quality Assurance (incl. mature and comprehensive execution and control procedures associated to competency matrices and stable and well-trained production teams for each work station)

(11) Quality Control (incl. geometrical measurements and electrical tests);

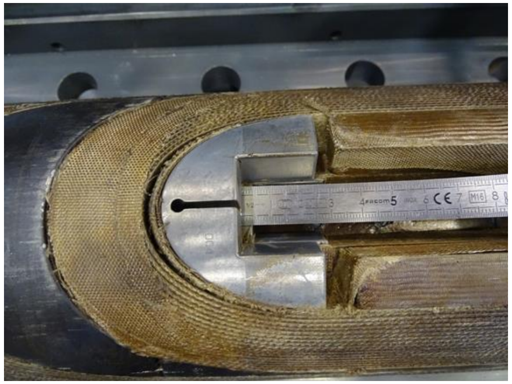
(12) cryogenic test and operating conditions (in particular during warm-up and cool-down);

(13) value engineering to limit risks and contain cost (incl. spare policy).

(4) Thermal Expansion during HT – 1/2

- During heat treatment, the Nb_3Sn conductor undergoes a volume expansion, which, if not well managed (in particular on long coils), can result in deleterious degradations.
- As an example, on coil CR07, which was used for the assembly of the 11 T prototype magnet, large gaps were observed after heat treatment at the non-connection side.
- The gaps were filled up by hand with fiberglass before VPI.

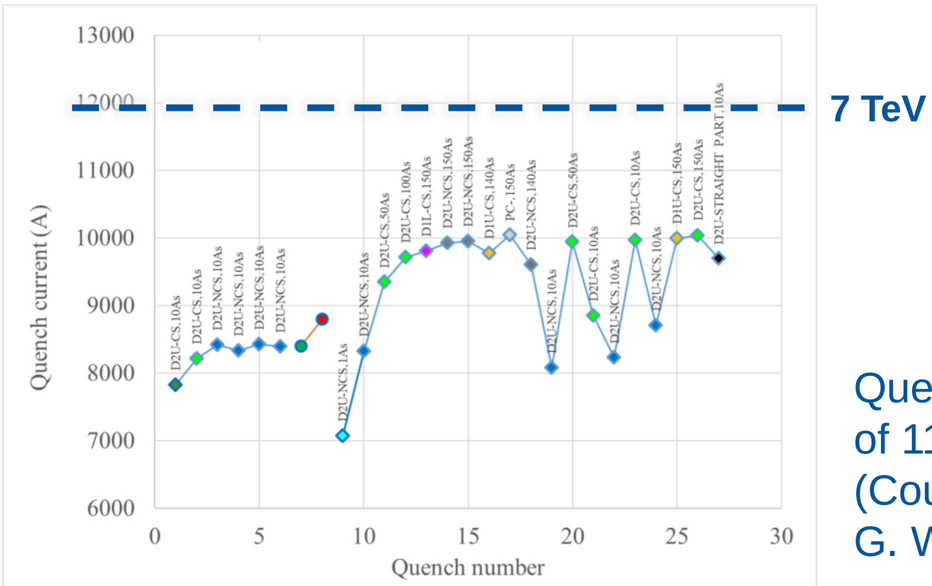
Views of outer surface of non-connection side of coil CR07: after heat treatment, showing a gap of ~3 mm (left), while fixing it (middle), after impregnation (right)



(Courtesy of F. Savary, CERN)

(4) Thermal Expansion during HT – 2/2

- The 11 T prototype magnet performance was limited well below nominal current, with most quenches originating in the “problematic” coil.

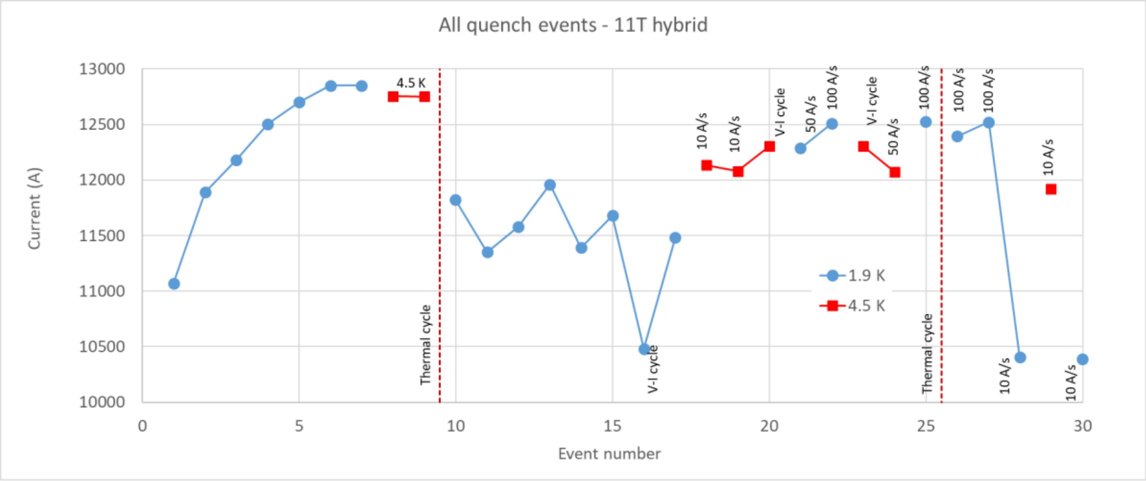


Quench Performance of 11 T Prototype (Courtesy of G. Willering, CERN)

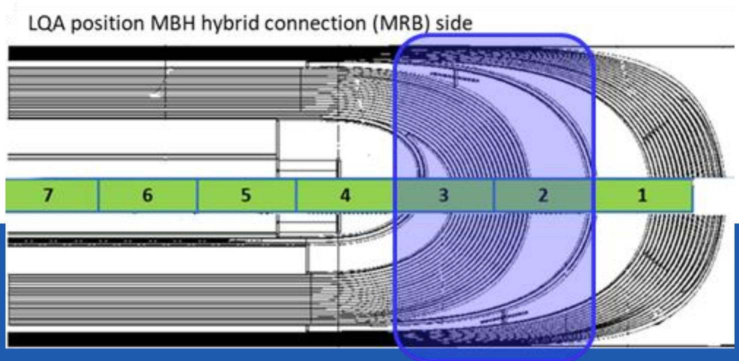
- The root cause for the gaps was attributed to a conductor insulation over-thickness, which resulted in a coil oversize of ~0.6-0.9 mm @30 MPa and hindered the coil ability to expand uniformly within heat treatment retort; this was subsequently fixed by adjusting the braiding pattern of the fiberglass.

(12) ΔT During Warm-Up/Cooldown – 1/2

- Resin-impregnated systems are prone to cracking when subjected to stress gradients that may develop during uncontrolled warm-ups/cooldowns.
- We were reminded of it the hard way during the test of the first, “series” collared-coil assembly produced by GE at CERN, mounted in the 2-in-1 prototype structure and tested horizontally as a single aperture.



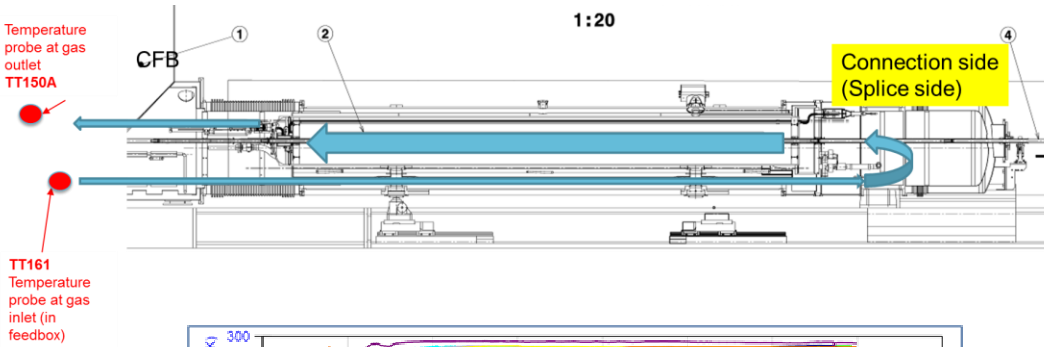
(Courtesy of G. Willering, CERN)

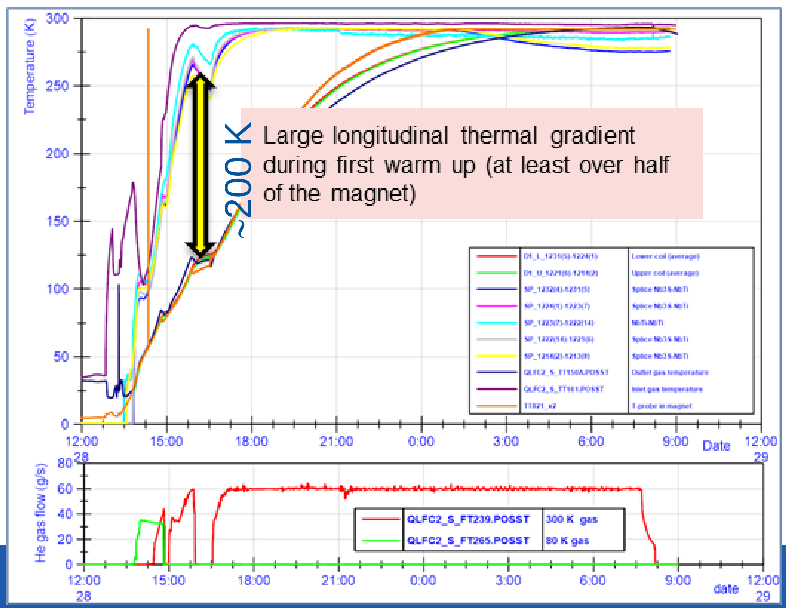


- The magnet initially achieved nominal current in 2 quenches and ultimate in 5 quenches.
- After first WUCD, the magnet exhibited detraining, with all quenches (but one) located in the same area of the same coil head (at connection side).

(12) ΔT During Warm-Up/Cooldown – 2/2

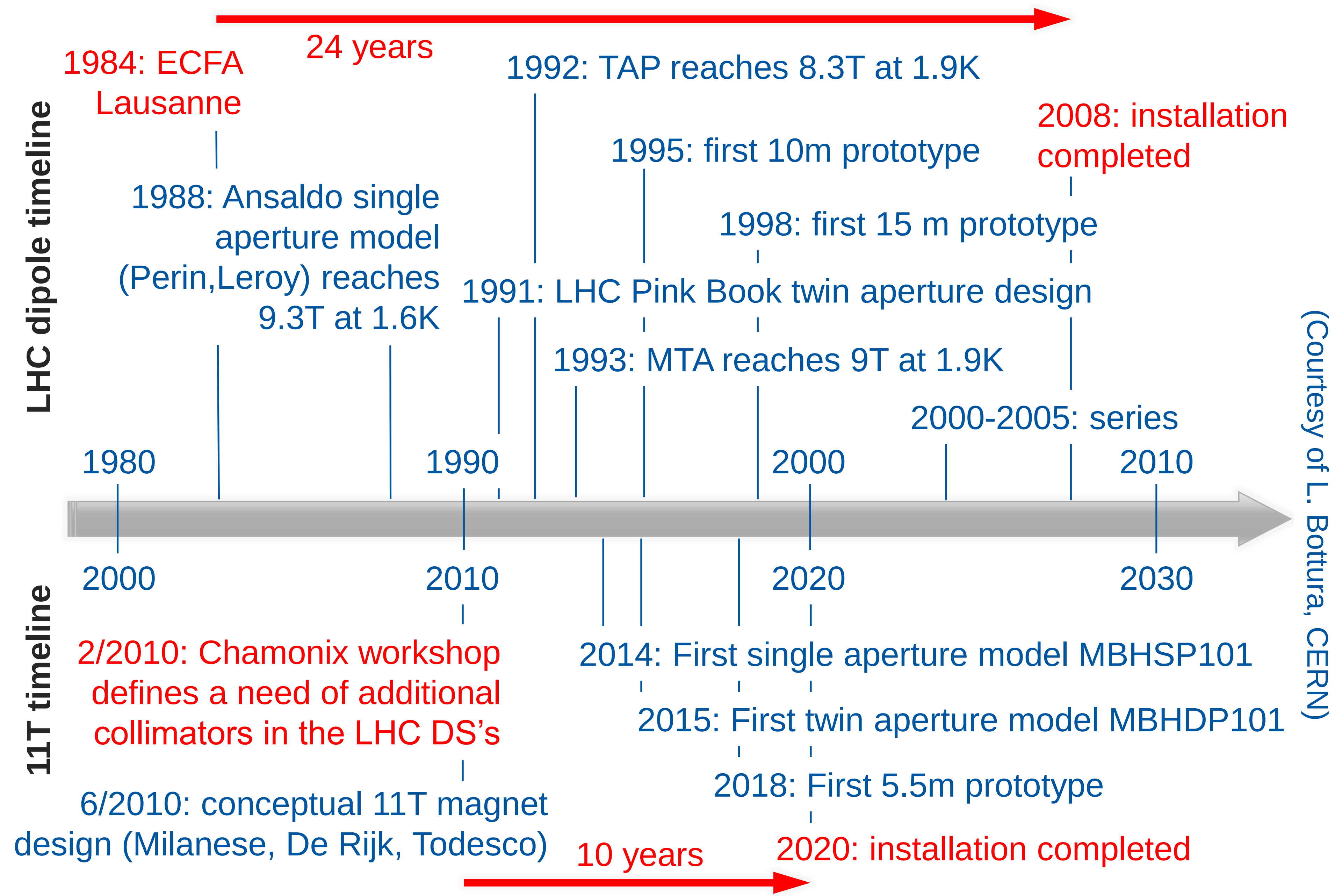
- Analysis of WUCD procedure showed that the magnet had been subjected to uncontrolled temperature gradients (in excess of 200 K), with the thermal front first hitting the magnet end where the detraining quenches originated.





(Courtesy of G. Willering, CERN)

- In LHC, WUCD of magnet strings are tightly controlled, with temperature gradients limited to 50 K between magnets and cooldown rates limited to 10 K/Hr.
- A ΔT of 50 K is now imposed to the testing of all Nb_3Sn magnets at SM18.
- This was successfully applied to the 1st series 11 T magnet, which did not exhibit any detraining after WUCD.



CERN

Let us put the Nb_3Sn development for HL-LHC in perspective

R&D Themes Overview – 1

1. Nb_3Sn Conductors

- bring multiple suppliers to HL-LHC performances (2022);
- support development towards 1500 A/mm^2 at 4.2 K and 16 T (2025);
- develop and possibly implement SC Open Laboratory initiative;
- initiate and support parallel R&D efforts on cabling and cabling degradation.

2. Nb_3Sn Magnet Technology

- consolidate technology development program and carry out value engineering effort to bring Nb_3Sn accelerator magnet technology to full maturity and enable industrialization (2025).

3. Nb_3Sn Accelerator Magnet

- cost-effective, 12 T range accelerator magnets;
- sequence of demo dipoles with same design and re-usable structure but aiming at increasing performances (12 to 16 T; 2025-2030).

R&D Themes Overview – 2

4. Non-LTS Conductors and HTS Coil/Magnet Technology

- develop engineering specifications for HTS tape development (2020) and support development of Non-LTS conductors;
- define and initiate HTS technology development program (2020);
- explore potential of HTS through small coils and inserts aiming at increasing field boosts (3 to 7 T; 2025).

5. Special HEP Magnets and MSC Know-How Valorisation

- special magnets for future HEP projects: *e.g.*, FCC e-e, CLIC, wigglers, spectrometers;
- valorise Nb_3Sn know-how by supporting other high-field applications: *e.g.*, 14 T MRI;
- valorise development of Non-LTS superconductors (MgB_2 or HTS) by exploring new potential applications: *e.g.*, power transmission lines and large superferric magnets (2020-2030);
- valorise MSC know-how by supporting new medical applications and HTS undulators;
- networking with magnet community & industry and consulting.

R&D Themes Overview – 3

6. Infrastructures

- maintenance/upgrade of large manufacturing and test infrastructures.

7. Instruments, design & analysis software tools and databases

- develop/upgrade specific instruments for qualification, quality control and testing;
- maintain/consolidate/develop suites of software tools and databases used for design, analysis, data acquisition, data storage and production follow up.

8. Polymers & radiation hard materials and cryostat components

- develop and qualify polymers and radiation hard materials for magnets and other applications at CERN;
- develop and qualify designs and materials for seals, feedthroughs and multilayer insulation.