Performance update of 11 T Nb_3Sn 2-meter long dipole model magnets and the first 5.5-meter series magnet for HL-LHC

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Introduction 11T magnets

The 11T model magnet test program has given important feedback on the training performance and performance limits of the magnets. In general a good training performance and memory has been shown. In the last models an even higher attention was given to the control and homogeneity of coil geometry and stress on the conductor in the mid plane of the magnet.

The performance of the latest 2-meter single aperture models, named SP107 and SP109 are summarized. Model SP107 has all final design parameters and features included, which were also implemented in the first 11T 5.5 meter long double aperture series magnet for the LHC. The results of the validation tests for the series magnet are shown as well.

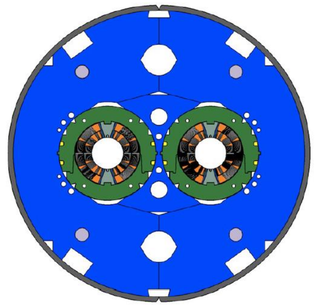
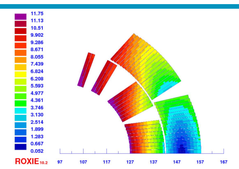


Table: overview of 2 meter model magnets made at CERN. SP stands for single aperture, DP for double aperture. Coils have been reused in some cases. The maximum current reached is listed for each model.

Model	Coils	I_{max} (kA)	I_{ss} (kA) @1.9 K/4.3 K
SP101	106, 107	11.9	14.5/13.1
SP102	106, 108	12.8*	14.5/13.1
SP103	109, 111	12.8*	14.2/12.8
DP101	106, 108 109, 111	13.3	14.2/12.8
SP104	112, 113	12.3	14.4/13.0
SP105	114, 115	12.4	14.6/13.3
DP102	109, 112 114, 115	11.4	14.4/13.0
SP106	116, 117	13.47	14.8/13.6
SP107	120, 121	12.85*	14.4/13.1
SP109	119, 123	12.95*	14.5/13.1
MBH-hybrid		11.95*	14.9/13.6
MBH-series		11.95*	15.0/13.6

*Test target: no attempts to train higher.



Magnetic flux density in the coil at nominal operating current of 11.85 kA, with 11.2 T bore field.

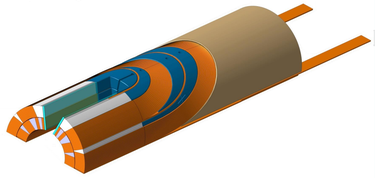
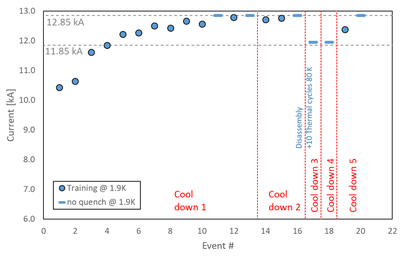
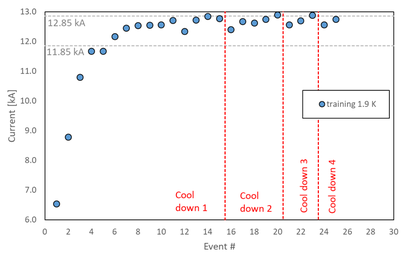


Image of the head of a coil, showing the impregnated coil part. The sliding pole is placed between the light-blue stainless steel pole shims.

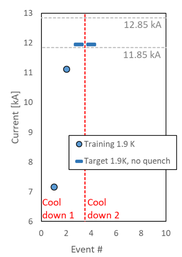
Training of Models SP107 and SP109



Model SP107
Fast training to nominal current of 11.85 kA
Very good memory to second thermal cycle.
After cool down 2, the collared coil was removed from the yoke and cycled 10 times from 300 K to 80 K. Afterwards the memory showed excelent without a quench to nominal current and only one quench to ultimate current.



Model SP109
Fast training to nominal current of 11.85 kA
Very good memory to second thermal cycle.
Each consecutive cool down less quenches needed.



First MBH 11T series magnet
Two quenches to target of 11.95 kA (11.85 kA + 100 A)
No quenches at all in second cool down.

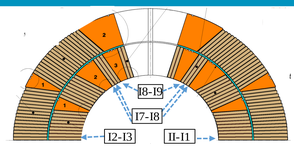
Observations
- Except for two slow training magnets with local damage in a layer jump, training has been fast and, moreover, memory is very good.
- Training seems to be mainly originating in the coil pack, and much less impacted by the overall structural mechanics. In SP107 the memory after removing the collared coil from the yoke, followed by 10 thermal cycles from 300 K to 80 K and re-yoking resulted in 1 detraining quench only compared to 10 virgin quenches.
- A low first quench current (down to 6.5 kA) do not indicate a "bad magnet".

Training and training memory are not considered the biggest challenge for this magnet.

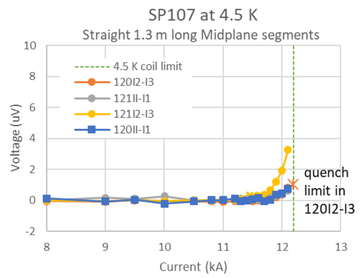
Short sample limit location at 4.5 K

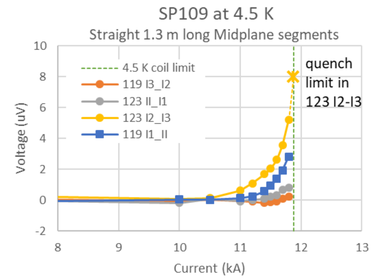
Most short models showed that the short sample limit was in the inner layer midplane, where high field and high stress combine. Consistency between 4.5 K and 1.9 K V-I measurements, but also quench currents show that in the midplane we can find the lowest $I_c(B,T,\varepsilon)$ is in this location.

This is easiest demonstrated at 4.5 K, see figures below. The measured voltages at 2 minute flattops did not show any sign of decay.



Voltage taps I2-I3 and II-I1 both cover a 1.3 meter long inner layer midplane segment.
More voltage taps have been placed for precise quench localisation.

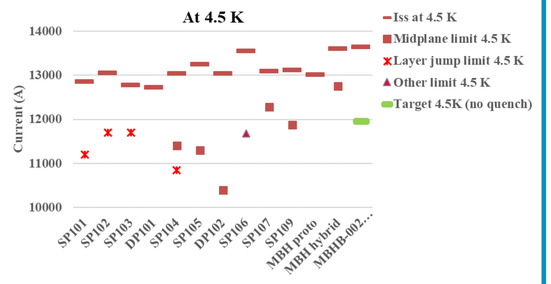




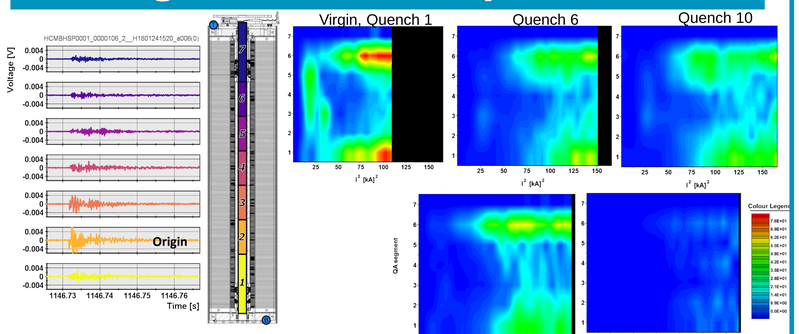
Voltage measured at 2 minute flattops for different current levels give the points in the V-I curves. The left figure shows all 4 straight mid plane segments in model SP107, the right figure the curve for SP109.

Model magnets SP107 and SP109 both reach beyond nominal current at 4.5 K, showing temperature margin of the coils and reaching up to 91 and 94 % of the short sample current, respectively.

The series magnet reached the target of 11.95 kA (100 A above nominal current) without quench, showing temperature margin above the operational temperature of 1.9 K.



Training – Vibration analysis in SP107

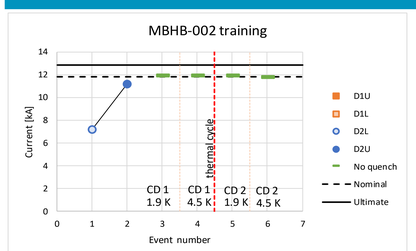


After thermal cycle Quench 1

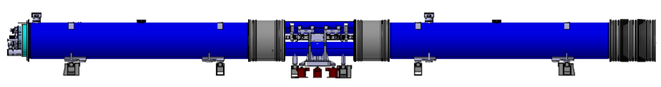
After thermal cycle Quench 2

- Localized and calculate amplitude of each vibration using earth quake analogy.
- Resulting color plots showing activity amplitude and location shows good memory after powering and thermal cycle.

First 5.5 m series magnet qualified for LHC



Main results from tests in Summer 2019
- $I_{nominal}$ + 100 A margin OK with 2 training quenches
- No detraining quenches
- Full memory
- No quenches at 4.5 K
- No quenches at continuous cycling at 100 A/s (with 10 A/s as nominal ramp rate)
- 12 hours stable current
- All splices < 0.2 nΩ
- Quench heaters fired > 50 times
- HV insulation tests OK up to 3.3 kV



Discussion and Conclusions

Model program successfully showed where improvements were needed.
- Short sample limit (lowest $I_c(B,T,\varepsilon)$) is found in the inner layer midplane turns for all models.
- Latests models SP107 and SP109 were fast trainers
- Technology transfer to long series magnets successful with first 5.5m 11T series magnet qualified for installation in the LHC.

The test results reflect the work done by many persons involved in the project, in design and production until the tests. The authors are gratefull to all contributors.

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