Comparison of Cold Powering Performance of 2-m long Nb_3Sn 11 T Model Magnets

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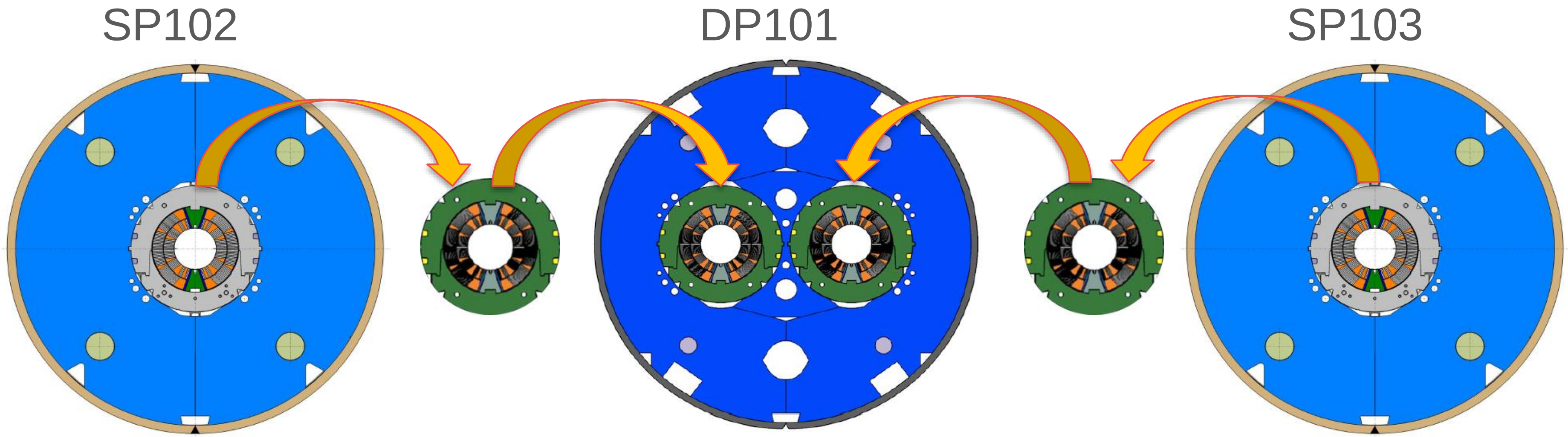
Mon-Af-Or7-02

Introduction

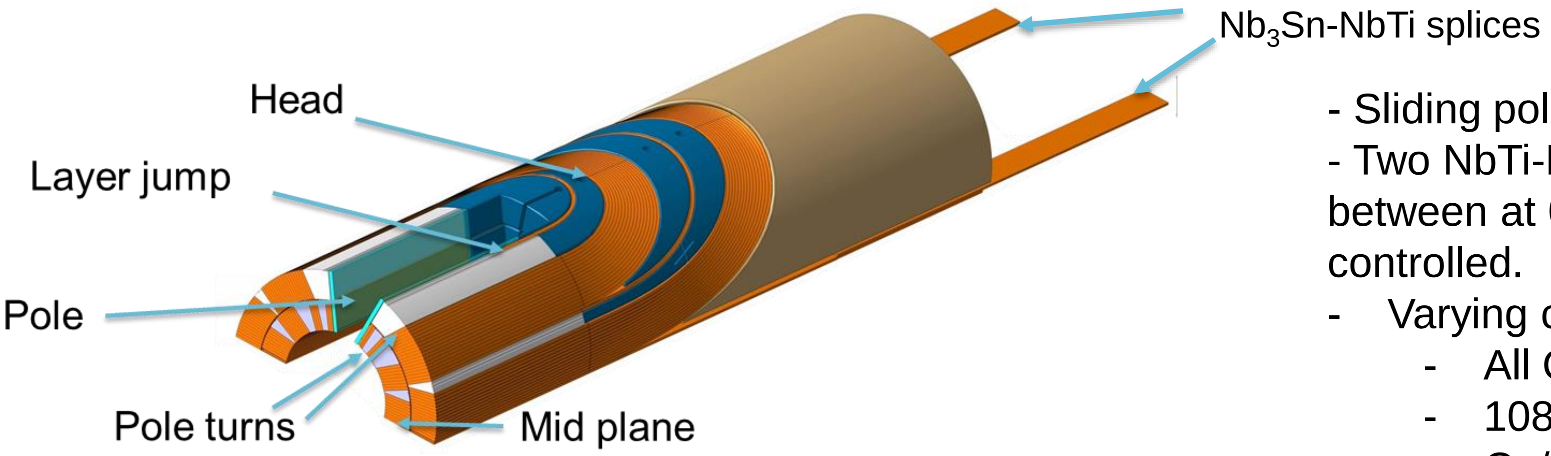
At FNAL the collaboration started with multiple single and one double aperture models
At CERN so far 5 single aperture models were produced and one double aperture model.

A double aperture is made by combining two single aperture collared coils
SP102 + SP103 form DP101 – test results previously published
SP104a + SP105b form DP102 – to be tested in October

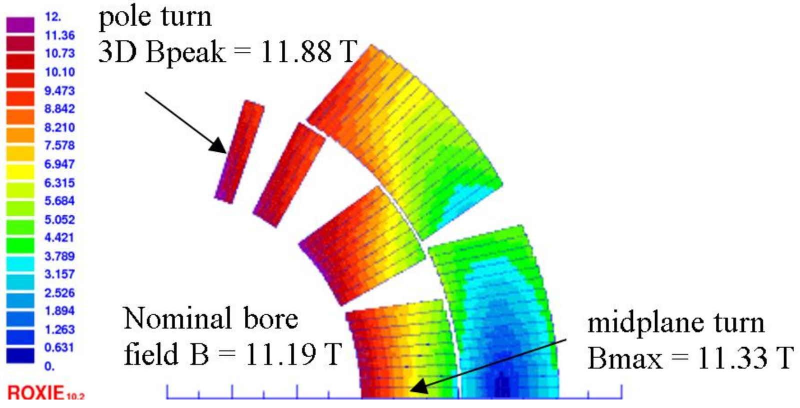


G. P. Willering et al., "Cold powering performance of the first 2 meter Nb3Sn DS11T twin aperture model magnet at CERN", *IEEE Trans. Appl. Supercond.*,

Introduction



- Sliding pole concept
- Two NbTi-Nb$_3$Sn splices per coil, all between at 0.3 ± 0.2 nΩ. Technology well controlled.
- Varying conductor types used:
  - All OST RRP
  - 108/127, 132/169, 150/169
  - Cu/non-Cu 0.97 to 1.27
  - RRR between 65 and 165



S. Izquierdo Bermudez

TABLE I
COIL PROPERTIES FOR THE TESTED SHORT MODELS

Model	Coil	Cu/non Cu	SC type	R_{293K} mΩ	$RRR_{293/4K}$	$R_{splice\text{-}in}$ nΩ	$R_{splice\text{-}out}$ nΩ
SP101	106	1.22	108/127	423	65	0.1	0.32
	107	1.22	108/127	426	95	0.42	0.48
SP102	106	1.22	108/127	423	65	-	-
	108	1.22	132/169	407	165	-	-
SP103	109	1.27	132/169	400	125	0.27	0.27
	111	1.27	132/169	401	119	0.21	0.17
SP104	112	1.27	132/169	403	125	0.49	-
	113	1.27	132/169	403	115	0.15	0.15
SP105	114	0.98	150/169	432	115	0.39	0.31
	115	0.97	150/169	436	110	0.24	0.13

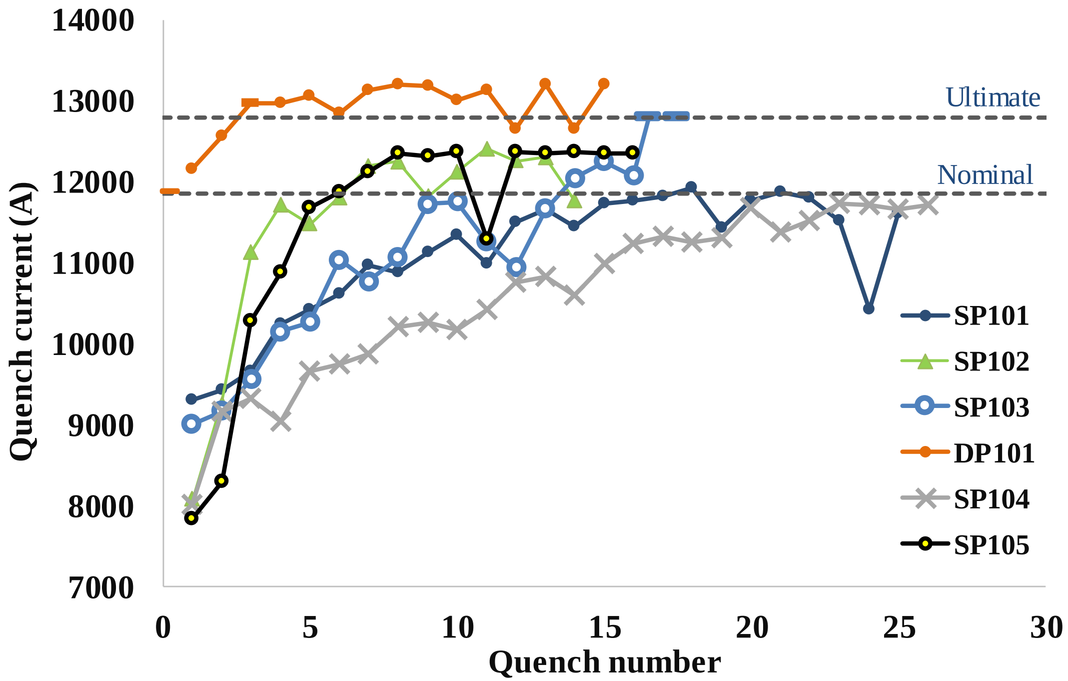
Outline

- Quench performance 11T model magnets
- Performance characteristics SP104
- Performance characteristics SP105
- Mid plane limitation
- Conclusion

Other 11T publications this conference

Mon-Af-Po1.01-06	*L. Fiscarelli, Magnetic Measurements on Short Models and Long Coil Assemblies of the 11-T dipoles for HL-LHC*
Mon-Af-Po1.01-10	*S. Izquierdo Bermudez, Quench Protection of the 11 T Nb3Sn Dipole for the High Luminosity LHC*
Mon-Af-Or7-01	*F. Savary, Design and construction of the first full-length prototype of the 11T dipole magnet for the High Luminosity LHC Project at CERN*
Mon-Mo-Or3-03	*M. Daly, Multi-scale approach to the mechanical behaviour of epoxy impregnated Nb3Sn Dipole Coils for the 11T Dipole*
Wed-Af-Po3.10-03	*C. Scheuerlein, Thermomechanical behavior of the HL-LHC 11 tesla Nb3Sn magnet coil constituents during reaction heat treatment*
Wed-Af-Po3.10-17	*T. Gradt, Friction-coefficient between the Ti6Al4V loading pole and the 316LN steel shims of the HL-LHC 11 T magnets*

Overview Powering Performance 2-m 11T models



Slowest training to nominal current for SP104
Fastest training to nominal current for SP105

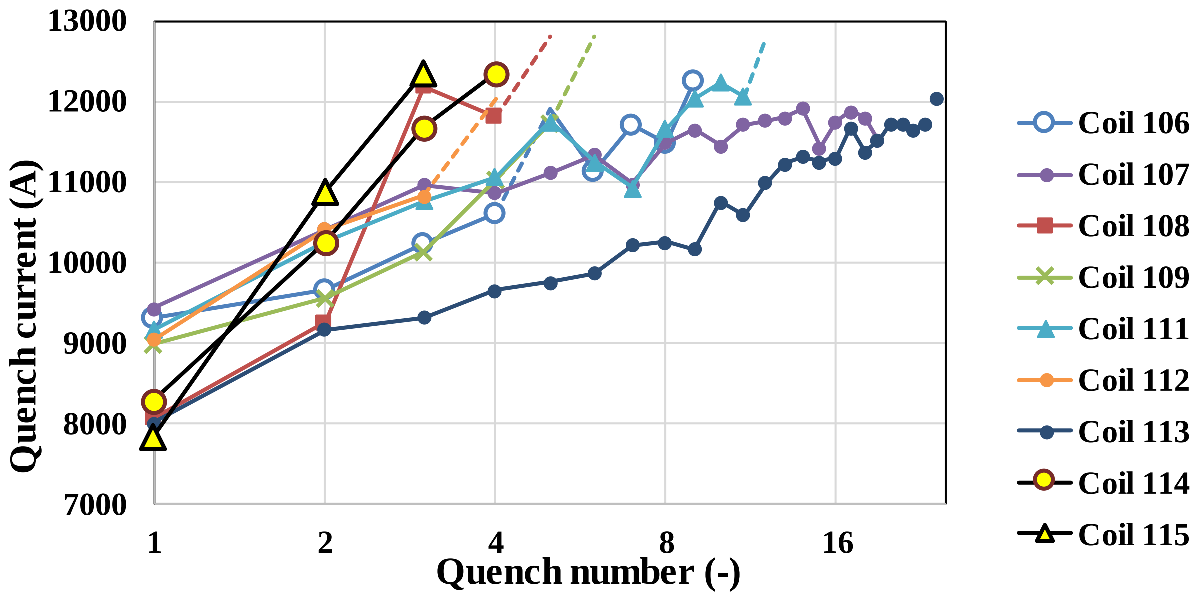
The double aperture magnet, DP101, only needed 2 training quenches to ultimate current, showing excellent memory after thermal cycle and reassembly of collared coils.

I_{nom} = 11.85 kA
I_{ult} = 12.8 kA

	I_{max} (kA)
SP101	11.9
SP102	12.8 (target)
SP103	12.8 (target)
DP101	13.3
SP104	12.2
SP105	12.4

Focus of this presentation

Quench performance 11T models



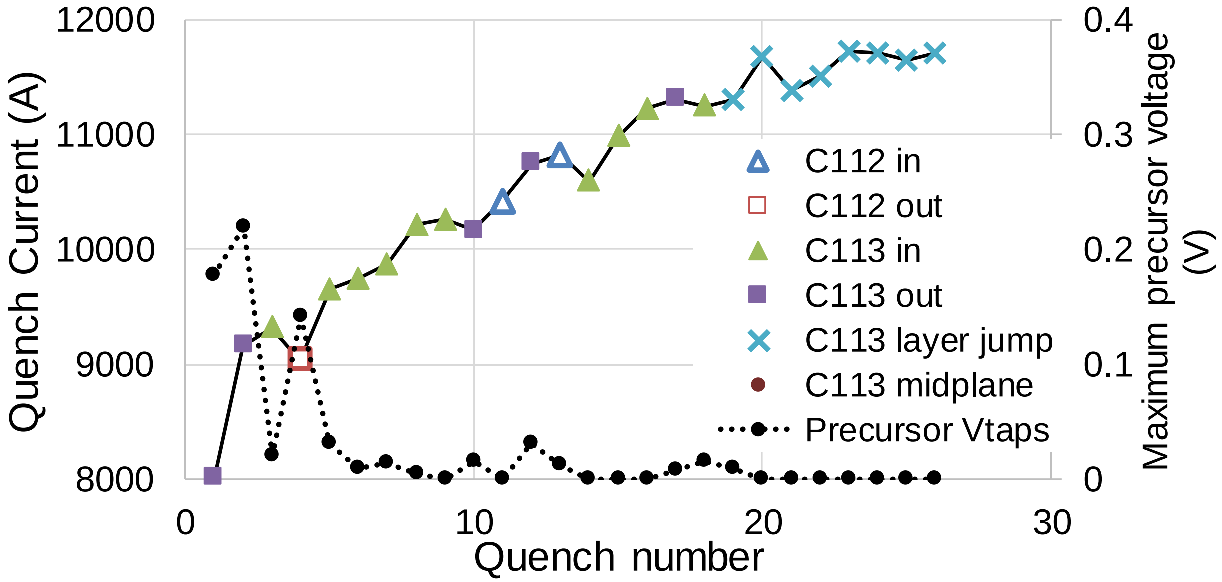
Model	Virgin coil	# Quench to I_{nom}
SP101	C106 C107	4 12
SP102	C108	2
SP103	C109 C111	5 8
SP104	C112 C113	3 23
SP105	C114 C115	3 2

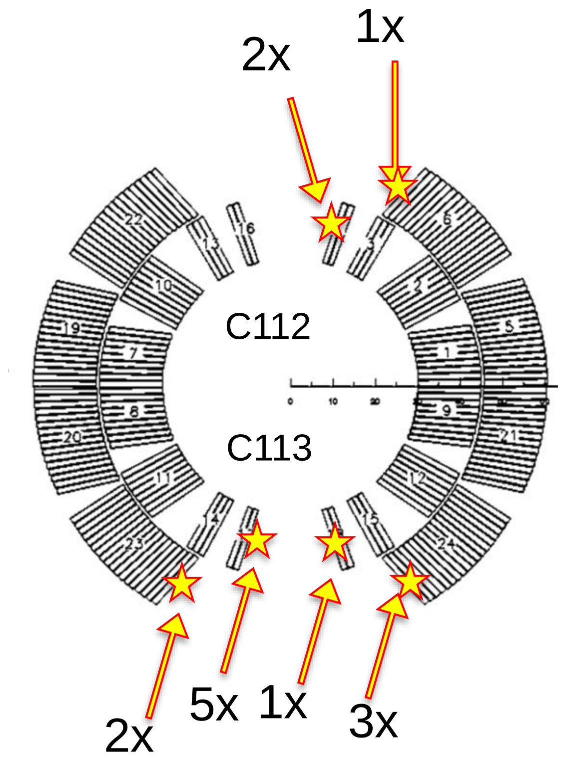
Quench curve per coil in "virgin" condition

Of the last 4 coils, 3 had a very fast training to nominal current with only 2 or 3 quenches.

Coil 113 showed a very slow training with 23 quench to nominal current.

Performance characteristics SP104





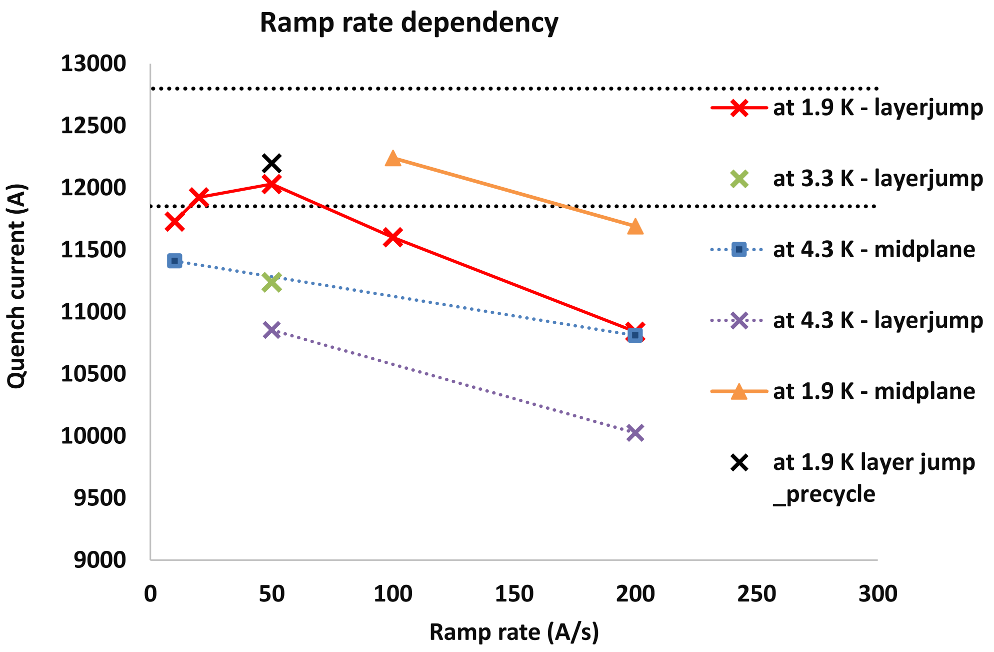
Precursors indicate strongest movement early in training, but little movement in Coil 113 pole turn quenches.

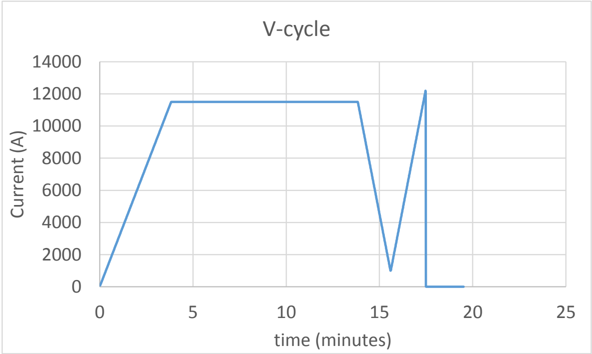
Initial training at fixed 10 A/s ramp rate was limited to the layer jump in coil 113 at 11.7 kA.

Inner layer pole turn quench propagation velocity was very high > 150 m/s (>5 times too fast)

Training to 11.3 kA dominated by C113 pole turn quenches, but spread around the inner and outer layer pole

Performance characteristics SP104





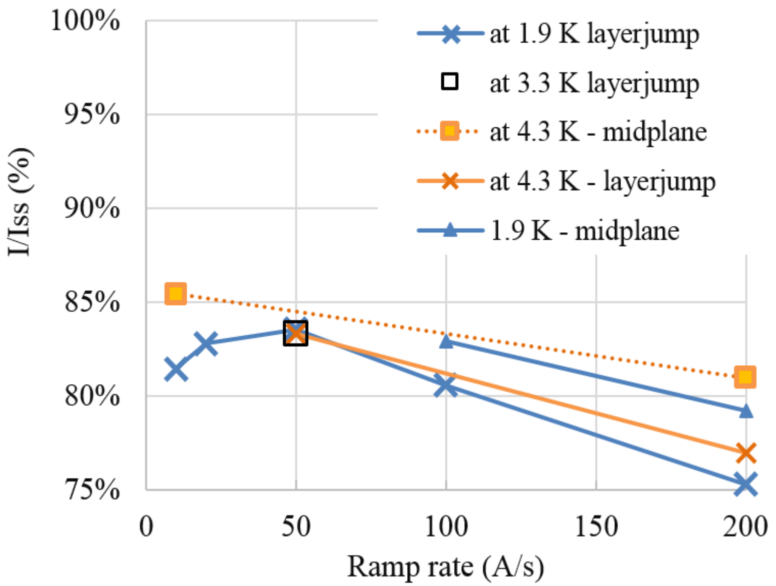
V-cycle, designed to induce coupling currents with opposite signs during ramp down so they have reduced impact

Normal ramp rate studies:
Initial training at 10 A/s limited at 11.7 kA.
Optimum at 50 A/s at 12 kA

V-cycle:
Could overcome the limitation in the layer jump at ramp rates of 100 and 200 A/s, reached limitation in the mid-plane.

Among all cycles the V-cycle at 100 A/s gave the highest quench current of 12.24 kA.

Performance characteristics SP104



Normalizing the data to I/I_{ss} the midplane limitation was a the same level at 1.9 K, 3.3 K and 4.3 K, with a maximum of 83 % at 50 A/s.

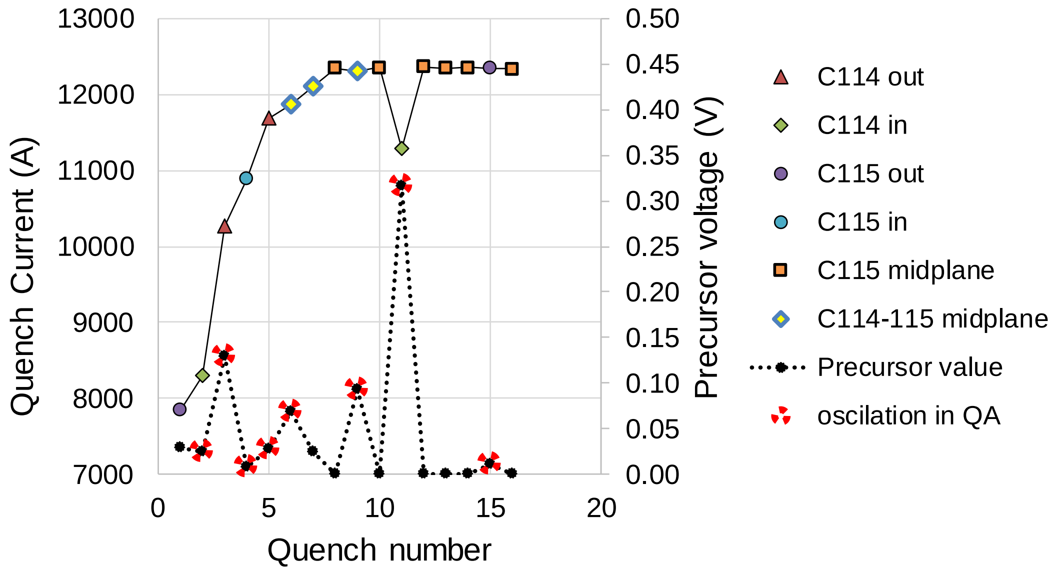
Conclusion

Layer jump limitation:
Local non-homogeneities in Coil 113 around layer jump. Coil removed for further investigation.

Slow training:
Could the large amount of training quenches in coil 113 could be explained by in-homogeneous current distribution, i.e. quenches in strands with much higher current than average and lower temperature margin?

Mid plane limitation:
See slide 11.

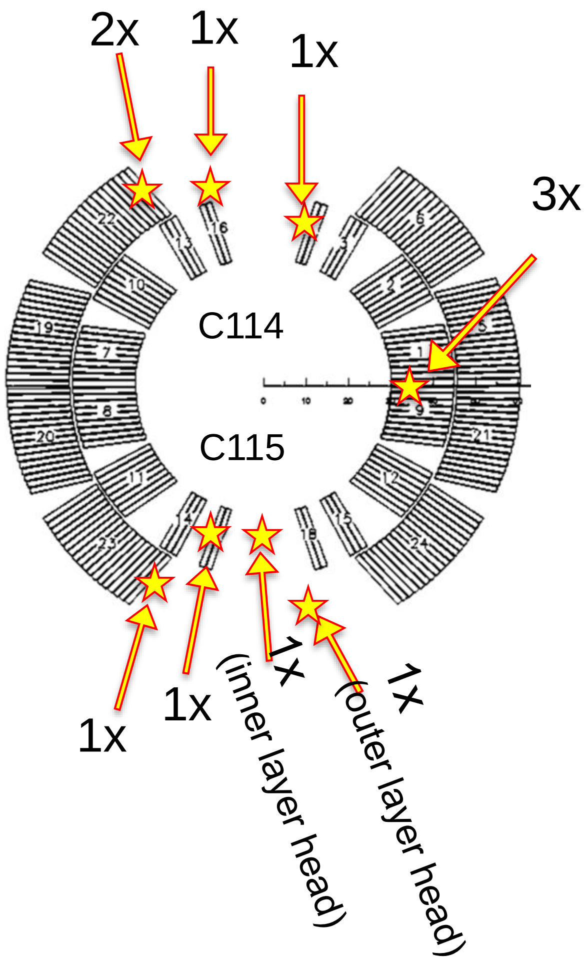
Performance characteristics SP105



Even with the lowest first quench current, fastest training to nominal current. Very well performing aperture, but limited in the mid-plane.

With precursors and quench antenna signals we see no mechanical movement for the limiting mid plane quenches.

Large detraining preceded by a very large precursor.

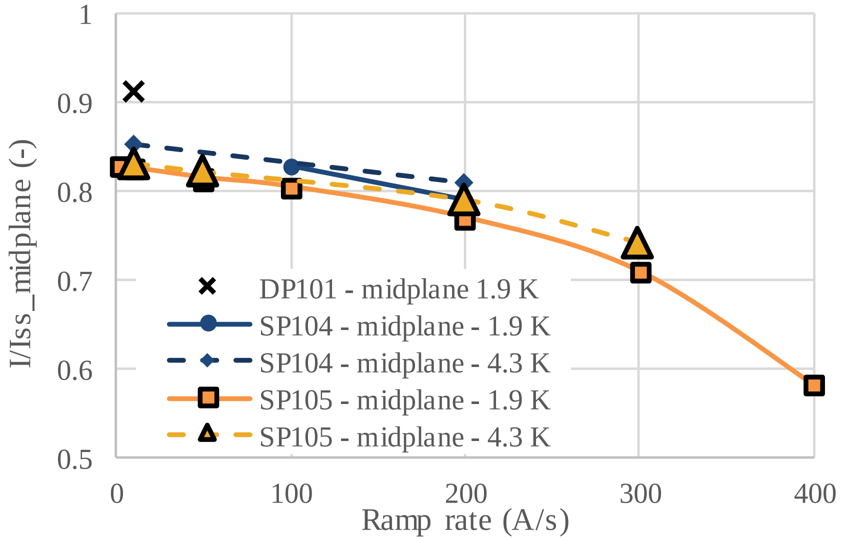


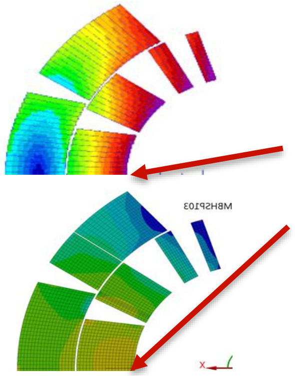
Spread in quench locations, no specific location.

Mid plane limitation

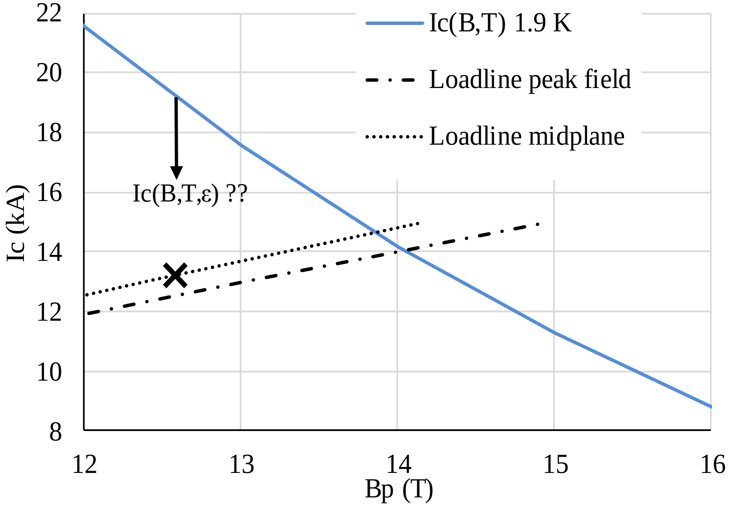
So far, all 3 models that were tested to their limit, were limited in their mid plane, DP101, SP104 and SP105.

Clear image when showing their I/I_{ss} limit at 1.9 K and 4.3 K. Higher limit for DP101 than for SP104 and SP105.





High Field
High Stress



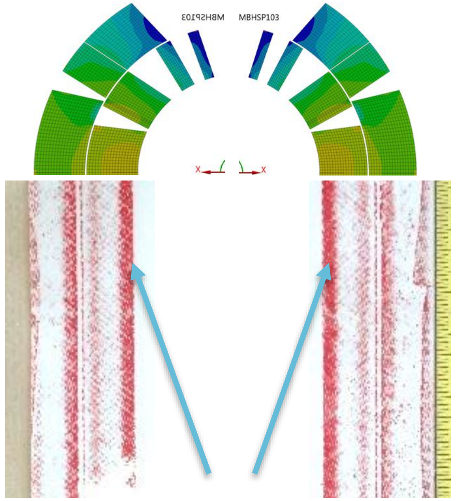
Identified need to redraw the $I_c(B,T)$ line for the mid plane including ε.
Needing knowledge of local strain and effect on strain on Nb_3Sn RRP.

Mid plane limitation

SP104 and SP105 are limited in the mid plane (high stress).
Re-collared in SP104b and SP105b with 15 MPa lower pre-stress.
Collaring with Fuji paper performed for a further understanding of the stress distribution.

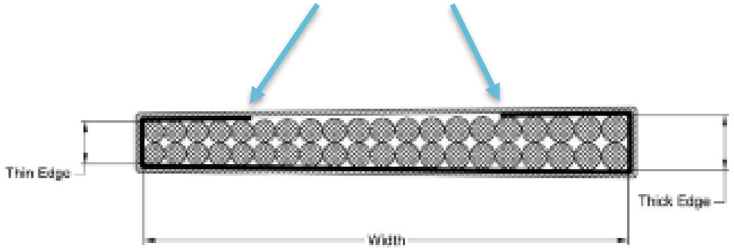
Unexpected stress concentration along the edges of the mid-plane cables.
Possible causes:

- Different rigidity inner/outer cable edge, also w.r.t. the middle
- Coil bending during collaring.
- Influence of Mica insulation: One short model aperture will be produced with a different
  Mica layout.



Large stress concentration on mid plane

Half-overlapping Mica sheets



Lessons are learnt and will be taken into account for future high field magnet design considerations.

Mid plane limitations – further investigations

Multiple investigation paths ongoing:

- Reversible I_c strain dependence measurements on Nb_3Sn RRP cable samples.
  - J-E. Duvauchelle et al., ”Critical Current Measurements of Nb3Sn Rutherford Cables under Transverse Pressure”, EUCAS 2017
- Higher precision calculations of the mechanics during operation
  - C. Löffler, “Finite Element Analysis of the mechanical conditions in the Nb3Sn cable of the DS11T dipole magnet during operation”, EUCAS 2017
- Modeling of the very high propagation velocities in the mid plane and how they can be explained
  - F. Mangiarotti et al., "Quench propagation in Nb3Sn cos-theta 11 T dipole model magnets in high stress areas", EUCAS 2017
- Irreversible degradation of Nb_3Sn cable due to transversal compression stress
  - P. Ebermann et al., “Characterization of irreversible degradation of Nb3Sn Rutherford cables due to transversal compression stress at room temperature” EUCAS 2017
- Residual strain investigations in Nb_3Sn 11 T dipole magnet coils
  - C. Scheuerlein et al, “Residual strain in the Nb_3Sn 11 T dipole magnet coils for HL-LHC”, Supercond. Sci. Technol., submitted for publication

Conclusions

- Stable operation of 11T model magnets shown for 1 to 10 hours at 12.3 to 12.8 kA.
- As concluded earlier: Remarkable performance with magnets in double aperture structure after reassembly: 0 quenches to nominal current, 2 quenches to ultimate.
- Non-homogeneity around layer jump in coil 113, probably local issue.
- All models experience their short sample limit at the mid plane.
  - Furhter investigation ongoing, mainly focusing at half-overlapping Mica sheets
  - Reduced mid-plane stress for next double aperture model by 15 MPa with re-collared coils. Test foreseen in October.

- Model program gave vital feedback on mid plane limitations, which may teach us important lessons for future magnet design.

Thank you