11T program at FNAL – quench performance

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for the FNAL team

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CERN-FNAL Collaboration Meeting
on DS 11T Dipole grounds

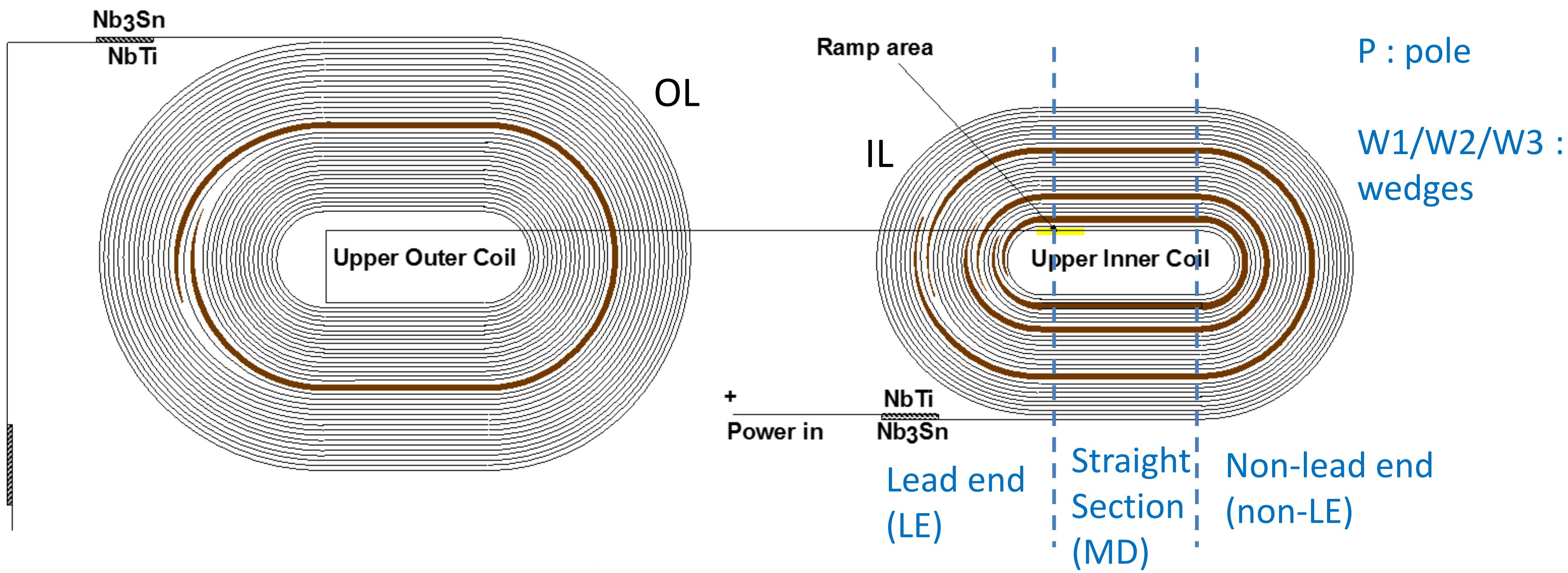
Introduction

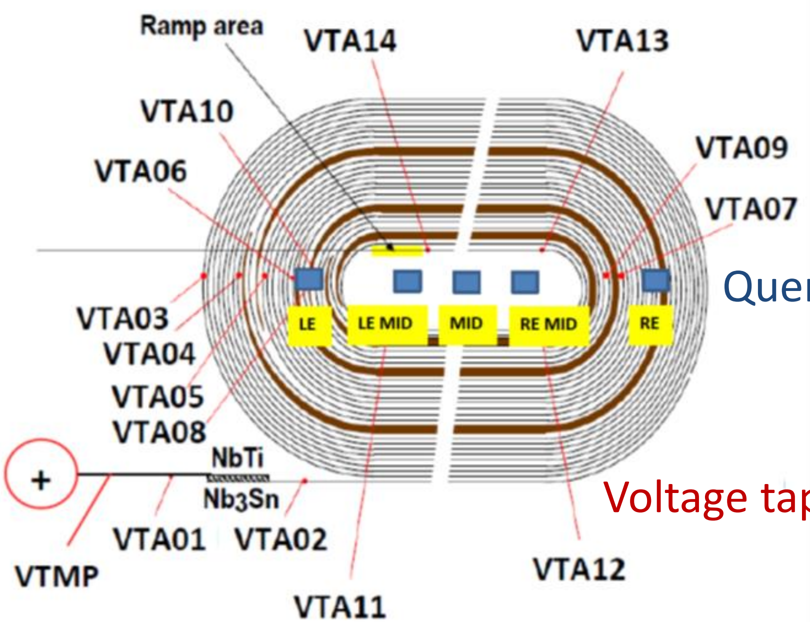
- ❑ The 11 T magnet tests considered here had ~ three years span – June/July 2012 to March 2015

- ❑ Overall – five magnets (eight coils) were tested
  - ✓ Three single aperture dipoles
    (one demonstrator with two long coils)
  - ✓ One dual aperture dipole
  - ✓ One mirror (collarless) magnet

- ❑ All of them trained to 70-80 % of SSL (the mirror magnet reached higher - 97% though with larger uncertainty on SSL)

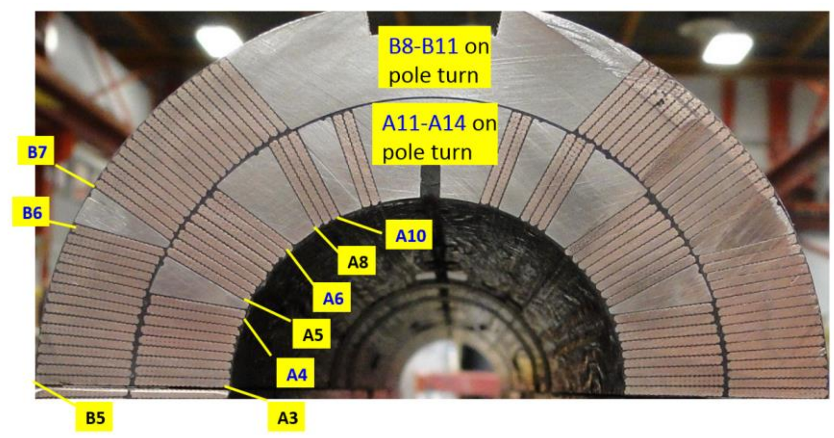
Typical coil schematics/instrumentation





Quench antenna

Voltage taps



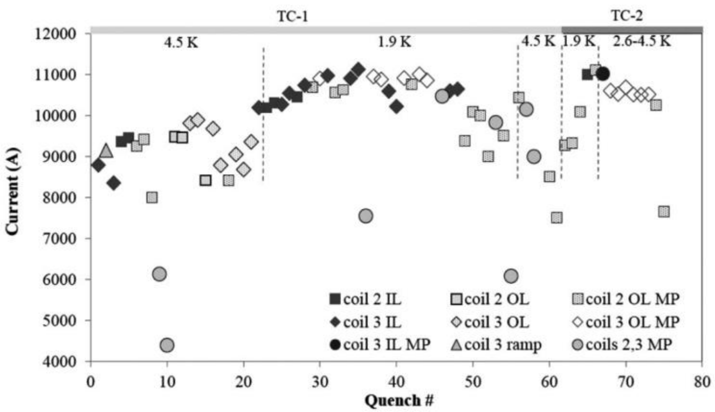
There were test-to-test variations in instrumentation

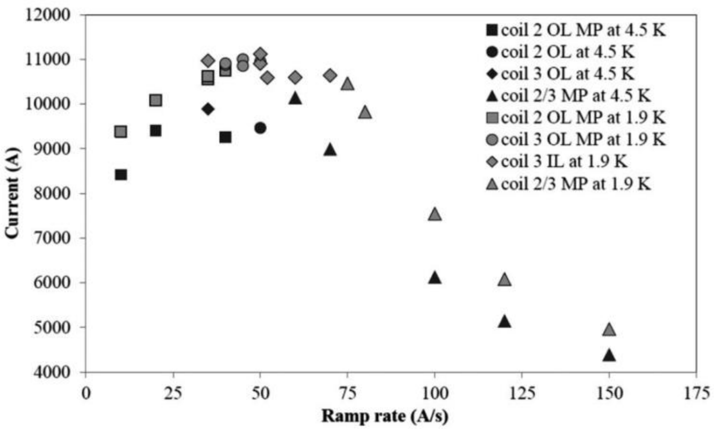
Magnet tests history

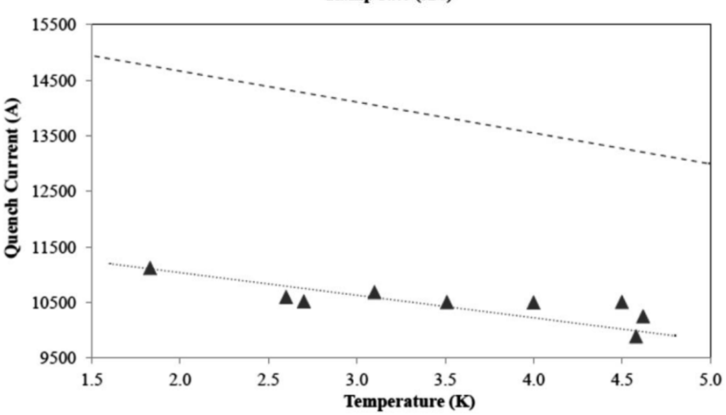
	MBHSP01	MBHSP02	MBHSM01	MBHSP03	MBHDP01
type	dipole	dipole	mirror	dipole	dual aperture dipole
Coils used	MBH02 & 03 (2m long)	MBH05 & 07 (1m long)	MBH08 (1m long)	MBH09 & 10 (1m long)	MBHSP02 & MBHSP03 (1m long)
Cable	RRP 108/127 (no SS core)	RRP 150/169, with SS core	RRP 108/127, with SS core	RRP 108/127, with SS core	RRP 108/127, with SS core, RRP 150/169, with SS core
SSL @ 1.9 K	15.1 kA	16.0 kA	14.5 – 15.8 kA	15.1 kA	15.1 kA
Current reached	10.4 A @ 1.9 K (74% of SSL)	12.6 A @ 1.9 K (79% of SSL)	14.1 A @ 1.9 K (97% of SSL)	12.1 A @ 1.9 K (80% of SSL)	12.1 A @ 1.9 K (80% of SSL)
Bore field reached (designed filed: 12 T)	10.4 T (86.7% of designed field)	11.6 T (96.7% of designed field)	~12.5 T in coil	11.6 T (96.7% of designed field)	11.5 T (95.8% of designed field)
Quench antenna	3, axial	3, axial	5, axial	5, axial	5, axial
Comments from training	Mid-plane points of limitation	smooth	detraining	Detraining/ fluctuations	smooth
Dates tested	June-July 2012	Feb.-March 2013	Dec. 2013- Jan. 2014	May-June 2014	Feb.-March 2015

time →

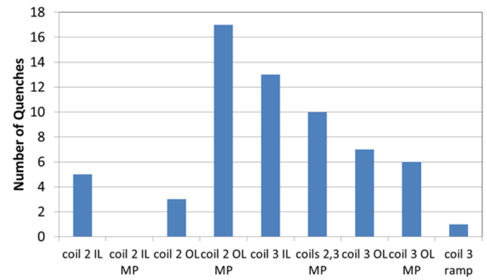
MBHSP01 (demonstrator)

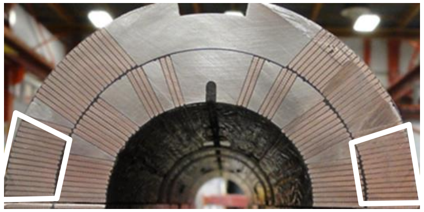






- ❑ Most quenches at low ramp rates, all holding quenches and quenches at intermediate temperatures initiated in the mid-plane block of the outer coil layer

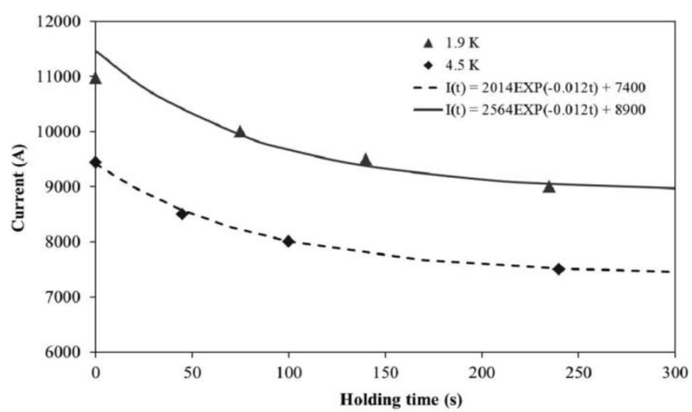




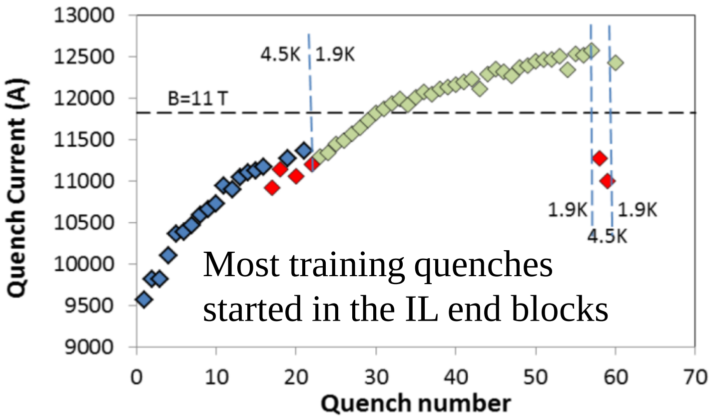
- ❑ Conductor damage in the mid-plane area during coil fabrication or magnet assembly could cause the observed degradation

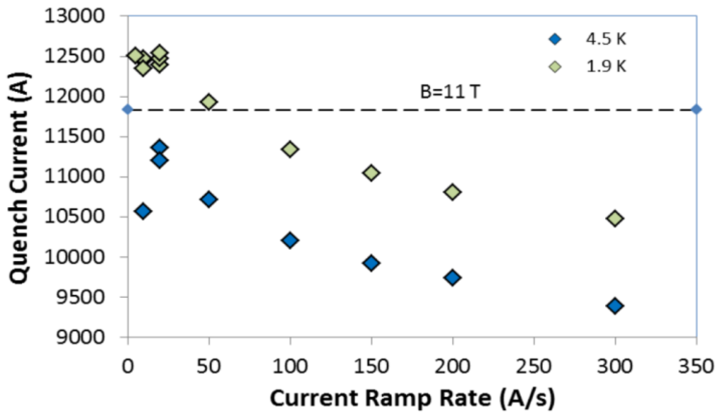
- ❑ "reversed" ramp rate dependence at current ramp rates below ~60 A/s was observed

(training was performed in 40-70 A/s range)



MBHSP02





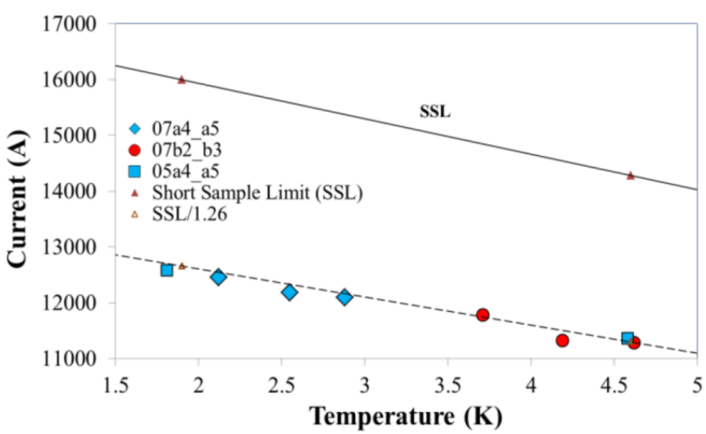
To reduce the stress and asymmetries in the OL mid-plane region the following steps were taken

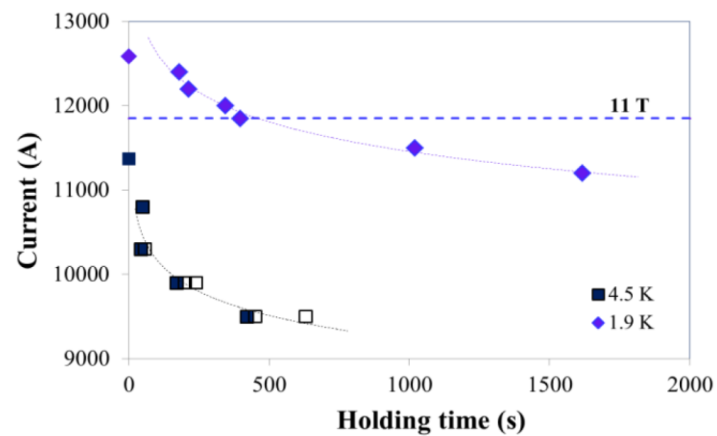
- modified coil end parts and collar packs ID at the mid-plane region
- thicker radial shim and smaller bending shim

❑ The maximum field in the aperture was **11.7 T** or 97.5% of the magnet design field

❑ The stainless steel core used in this model suppressed cable eddy currents and significantly reduced the magnet ramp rate sensitivity at the high current ramp rates

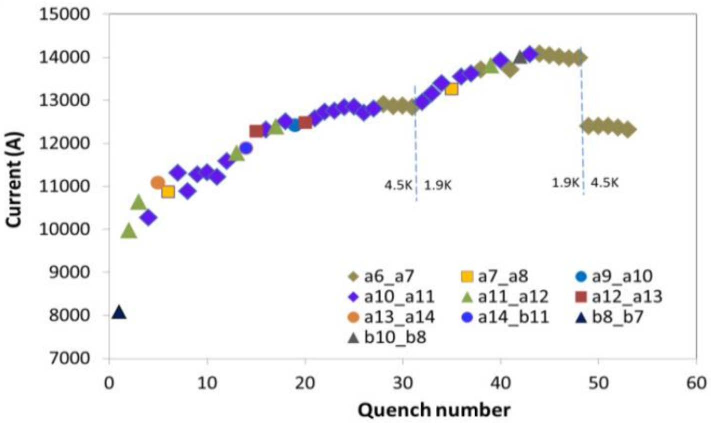
❑ The temperature dependence on the quench current suggests that there is a large critical current degradation in magnet coils

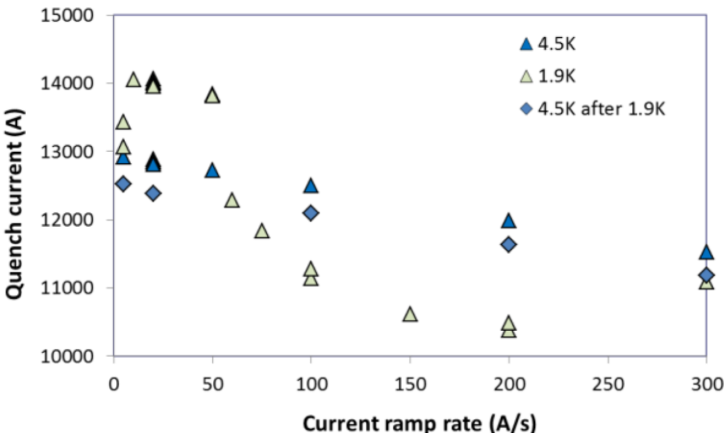


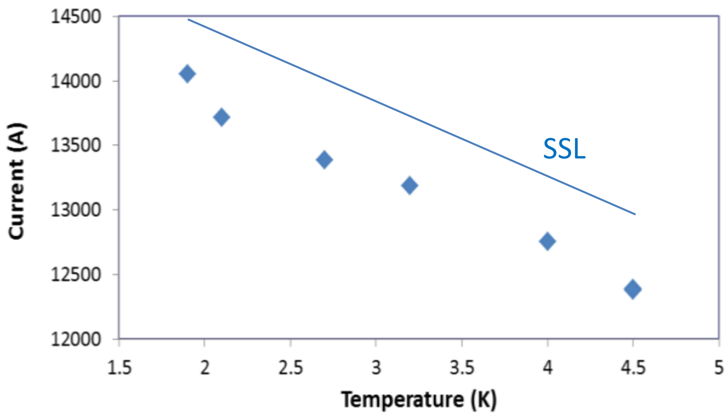


all the holding quenches started in the outer-layer mid-plane block of coil 7

MBHSM01 (mirror)

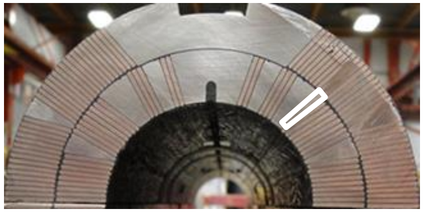






The goal of this test was to understand the role of coil design and (reduced) pre-stress on its quench performance

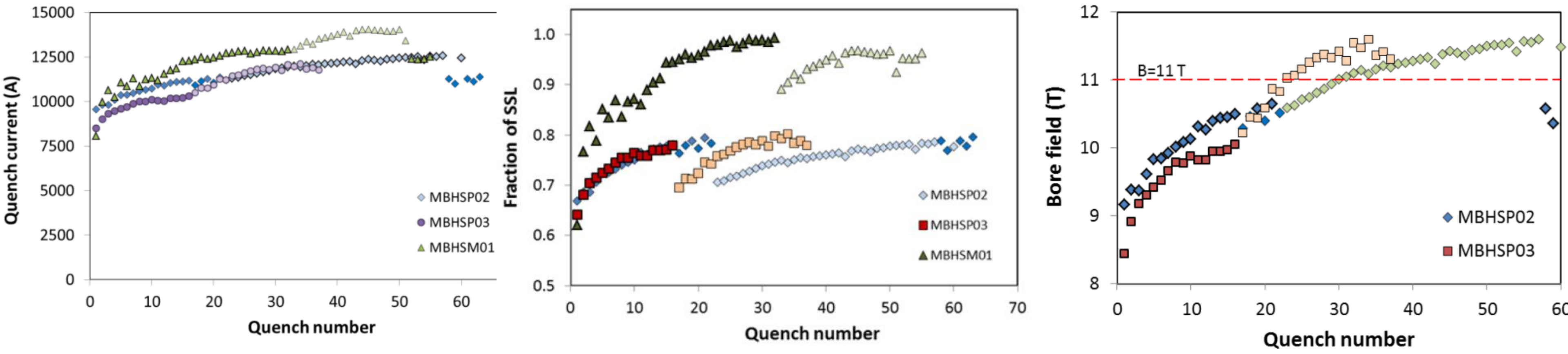
- ❑ Quench current reached almost 100% of SSL at 4.5K and 97% of SSL at 1.9 K (~**12.6 T**)
- ❑ Most quenches (including plateau training quenches) developed next to the 2nd wedge on the non-transition and non-lead end side



- ❑ At 1.9 K the ramp rate sensitivity becomes stronger at current ramp rates above 50 A/s (unlike 4.5 K dependence)
- ❑ The sharp reduction of magnet quench current above the lambda-point points to the strong effect of coil cooling conditions on magnet quench performance

No quenches at holding current for 25 min (12 kA @ 4.5 K; 13 kA @ 1.9 K)

MBHSP03



The improved quench performance of coil #8 (wrt #5 and #7 in MBHSP02 with similar design and fabrication process) in the dipole mirror structure suggested that the large mid-plane shim was likely a major cause of the conductor degradation in the dipole model MBHSP02

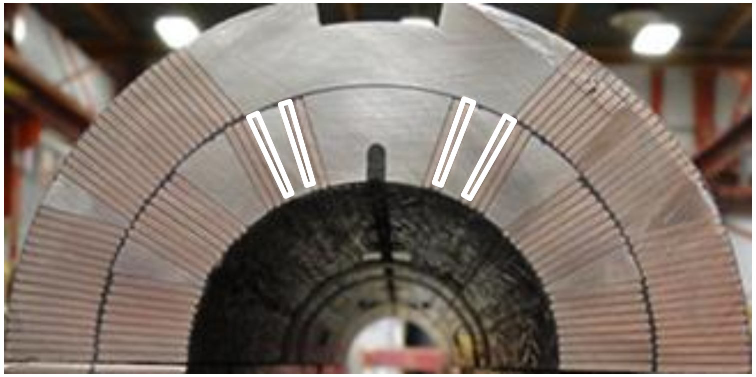
- This shim in MBHSP03 was reduced to the level necessary to compensate for the difference in collar and yoke thermal contraction. As a result we saw
  - ✓ more rapid training
  - ✓ no quenches were detected in MBHSP03 after ~30 min at steady currents up to the nominal LHC operation current.

- Despite the different strand design and critical current density, and the coil pre-stress level the relative values of the first 18 quenches at 4.5 K for both dipole models were very close.

MBHSP03 (2)

- Fluctuations of quench currents, seen in MBHSP03, are likely due to epoxy cracking between the pole blocks and coil turns caused by the low pole pre-stress in this model
  - ✓ **To avoid possible conductor degradation magnet training was stopped**

The most common quench location was around the first wedge (LE)



MBHDP01 (dual aperture)

- In a single-aperture configuration both collared coils were trained to the same magnetic field in the aperture of ~11.6 T at 1.9 K.
  - ✓ in MBHSP02 this field level was reached at 12.58 kA
  - ✓ in MBHSP03 at 12.12 kA

- Due to large degradation, MBHSP02 reached its conductor limit whereas MBHSP03 did not

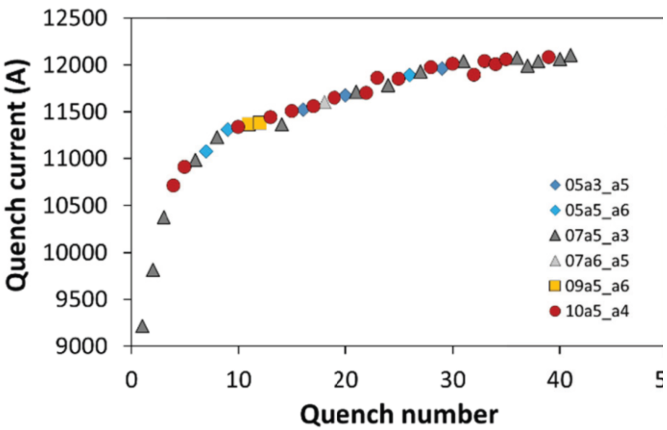
- Since the two collared coils are connected in series in a twin aperture configuration, it was expected that MBHDP01 would be limited by MBHSP02 collared coil with coils 05 and 07.

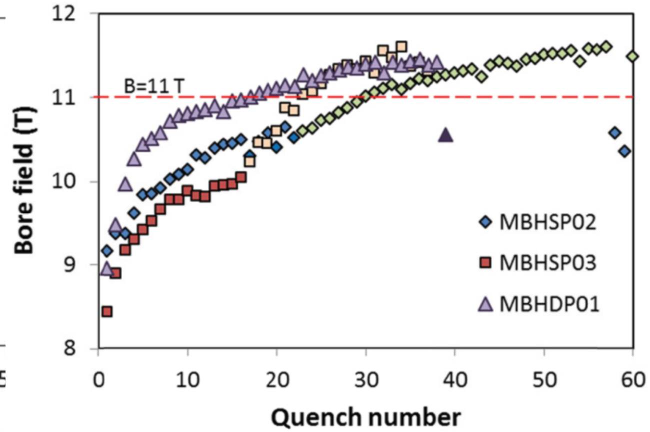
Main objectives of this test were

a) observation and comparison of collared coil performance in single- and twin-aperture configurations

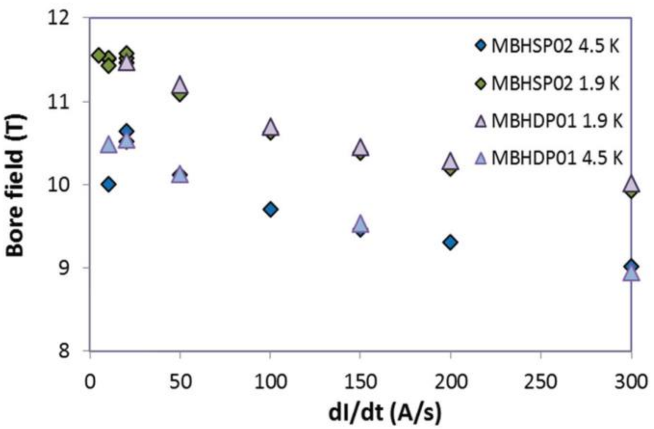
b) observation of the effect of coils 09 and 10 disassembly and re-collaring with higher pre-stress and the effect of smaller bending of coils 05 and 07 on magnet training and conductor degradation.

MBHDP01 (dual aperture) /2/

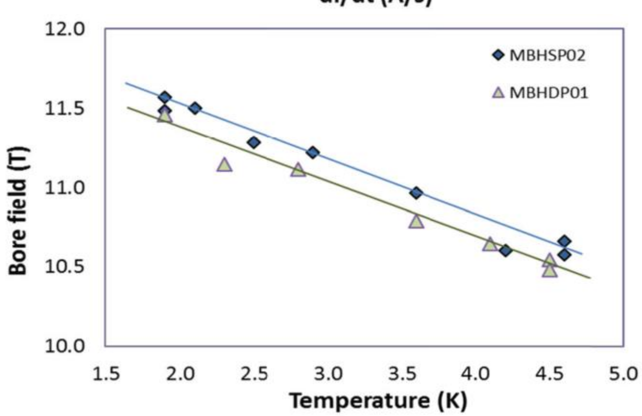


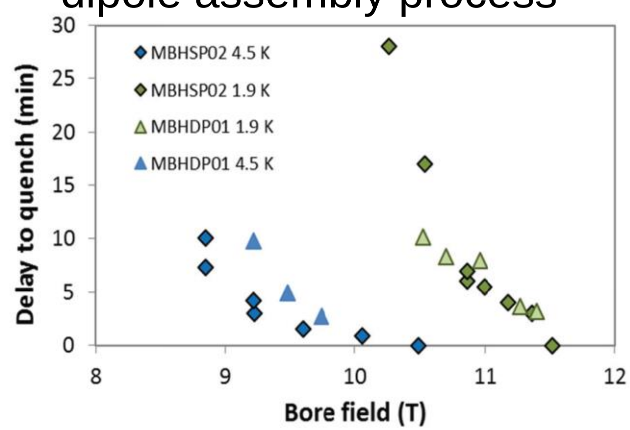


MBHDP01 reached the maximum bore field of **11.5 T** at the current of 12.1 kA which is only 0.1 T lower than in the single aperture models.



- As expected, the magnet demonstrated similar (to single aperture models) quench performance which was limited by large conductor degradation in the collared coil used in MBHSP02
- No additional coil degradation was introduced during re-assembly of one of the collared coils and twin-aperture dipole assembly process

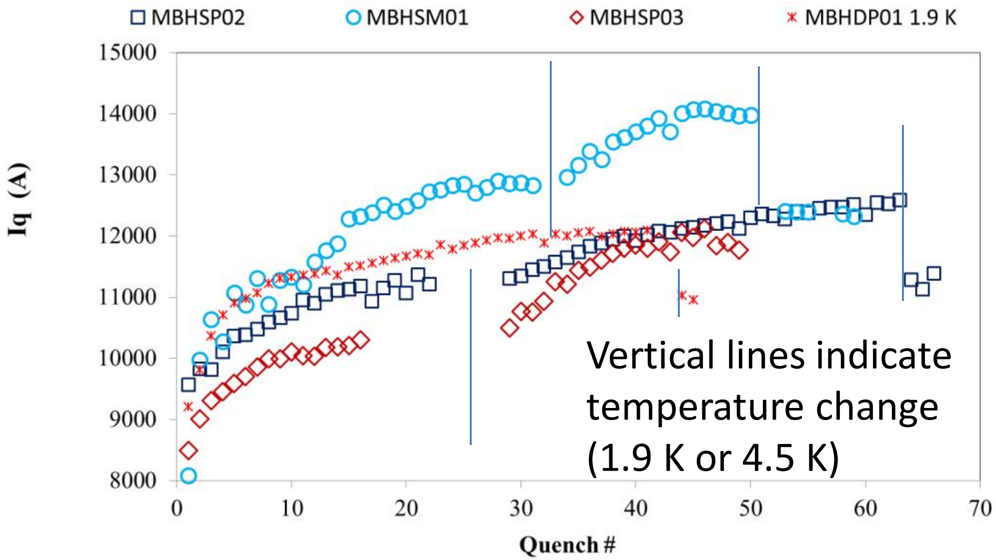




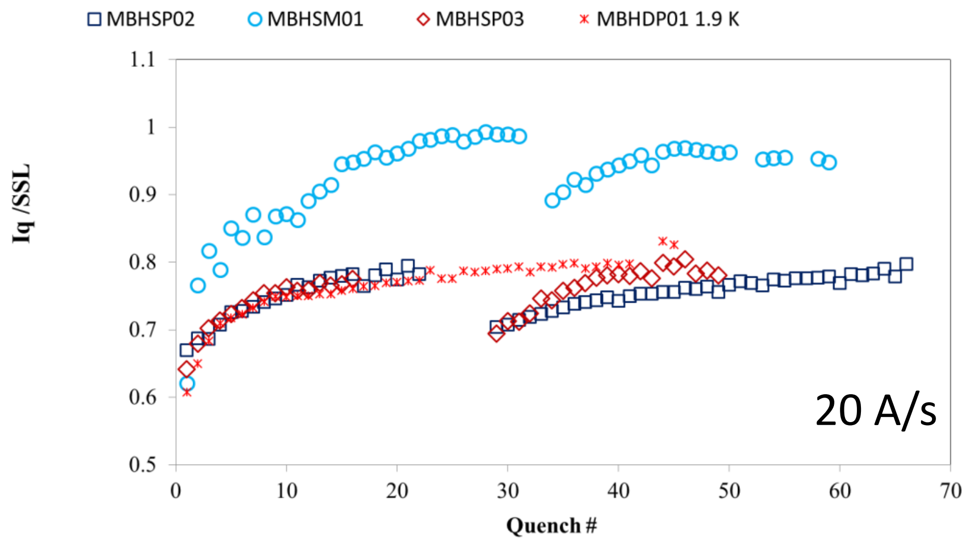
Most non-holding current quenches originated in the IL pole blocks.

Holding current quenches were in the OL MP block of coil 07.

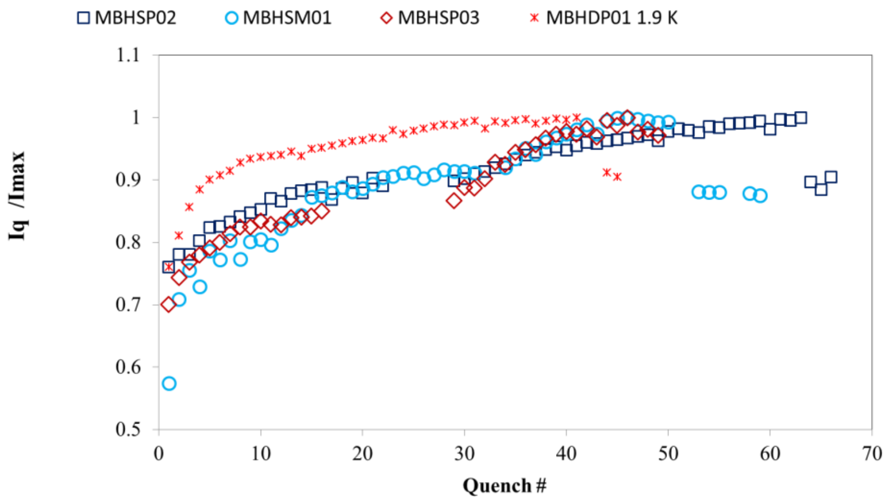
Magnets training



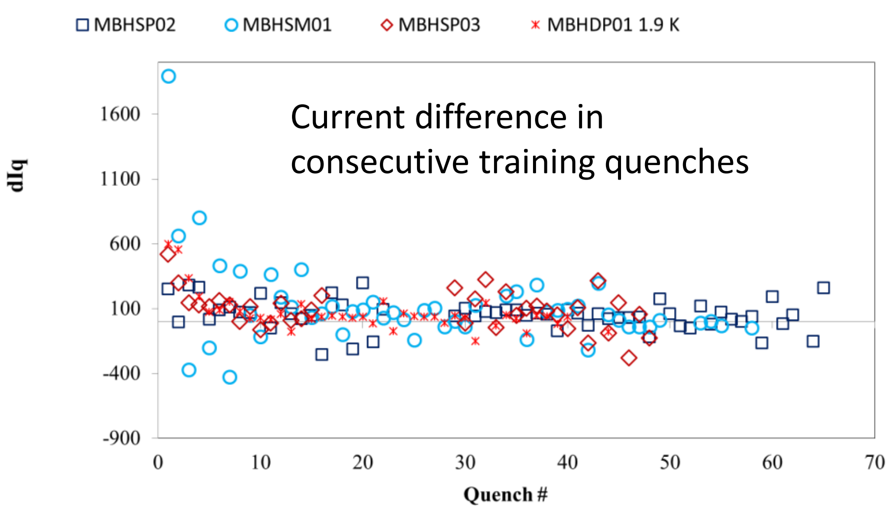
- During training the absolute quench current does not depend on the temperature (1.9-4.5 K)
- After training the relative to SSL current does not depend on the temperature
- MBHDP01 was not fully trained

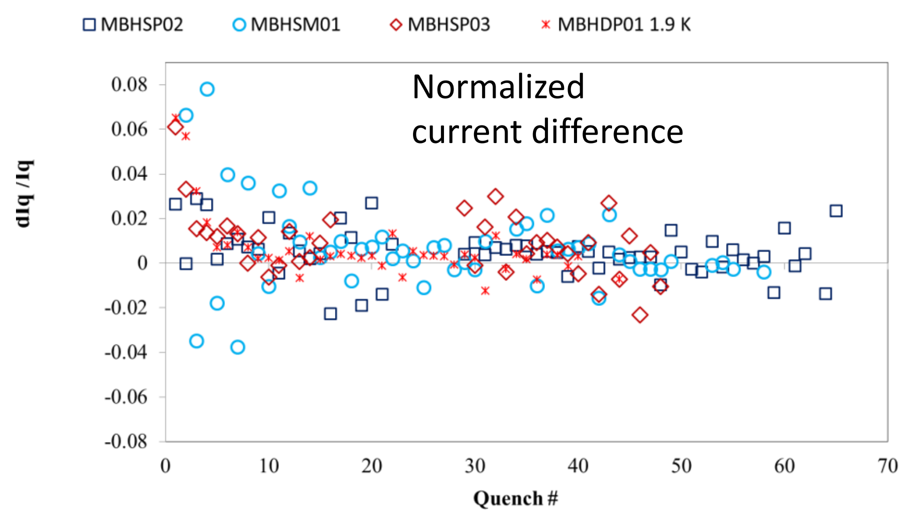


Training shape and differential

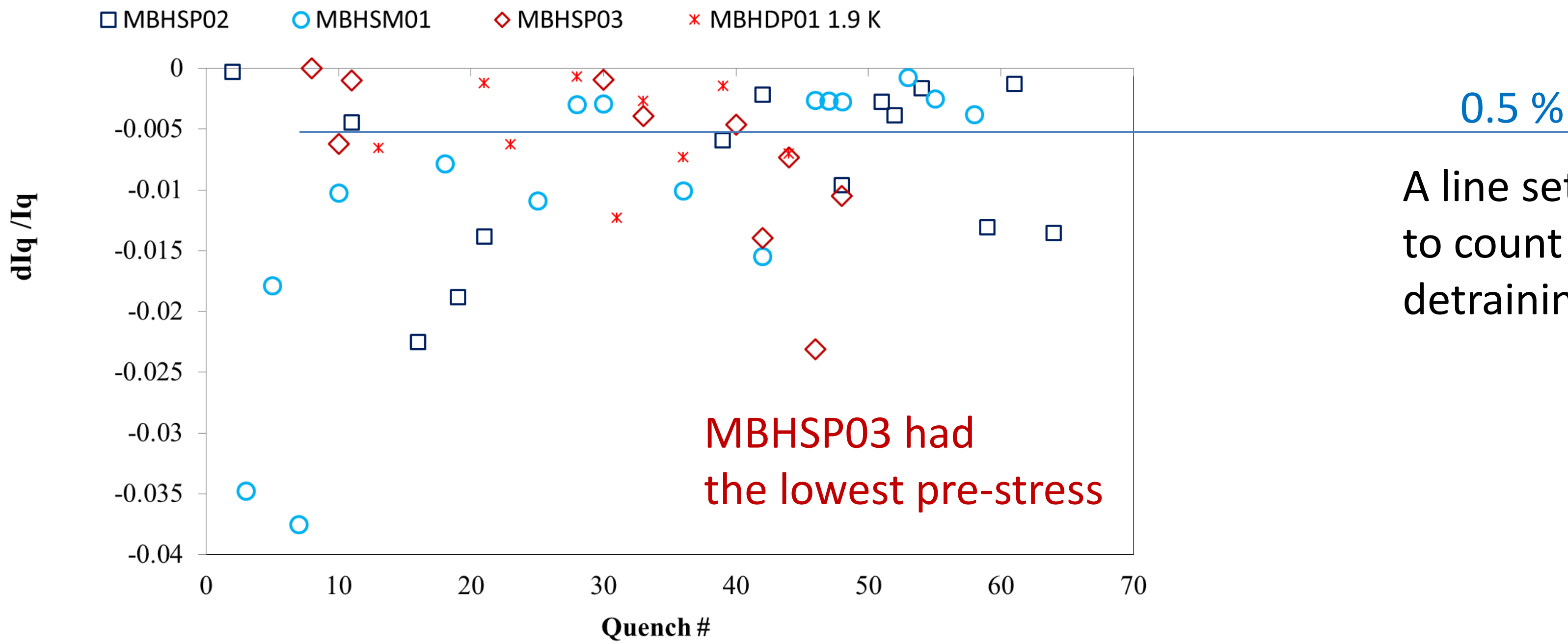


- The training starts fast for ~10 quenches
- Faster training for mirror and previously trained coils
- Detraining/degradation observed in some coils
  - ✓ MBHSP01 (coil 2/3)
  - ✓ MBHSM01 (coil 8)
  - ✓ MBSP03 (coil 9/10)





Detraining quenches



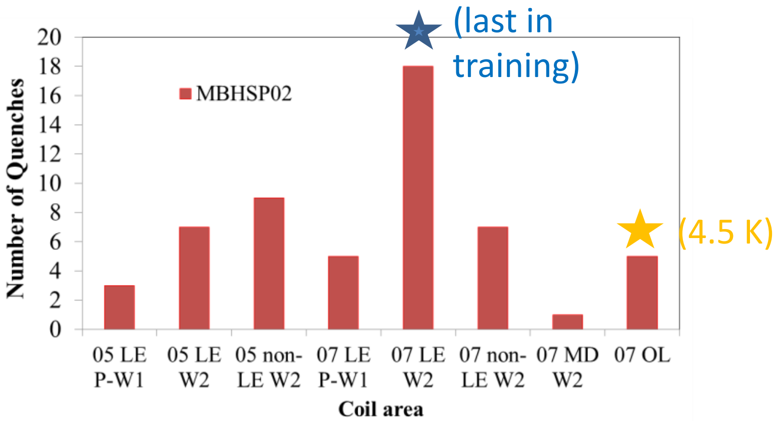
A line set to count fraction of detraining quenches

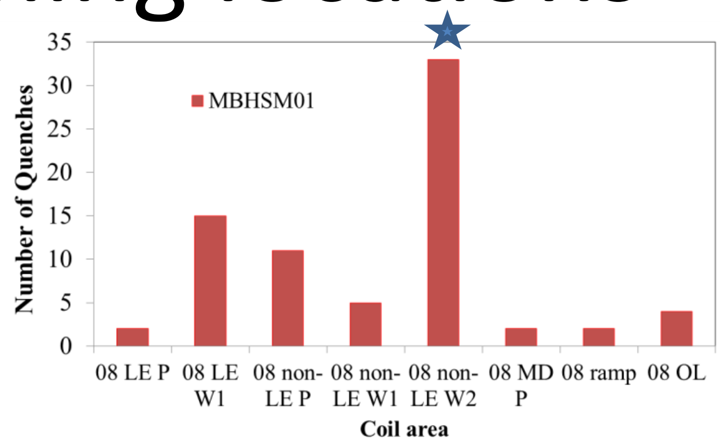
	MBHSP02	MBHSM01	MBHSP03	MBHDP01
Detraining quenches	(11±2)%	(15±3)%	(13±3)%	(13±3)%

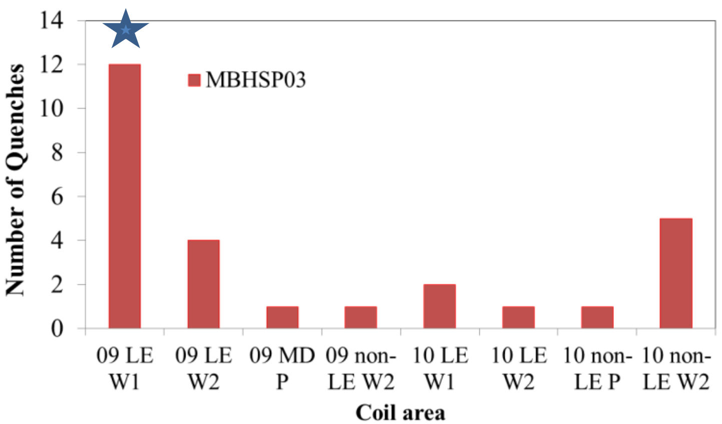
(binomial error)

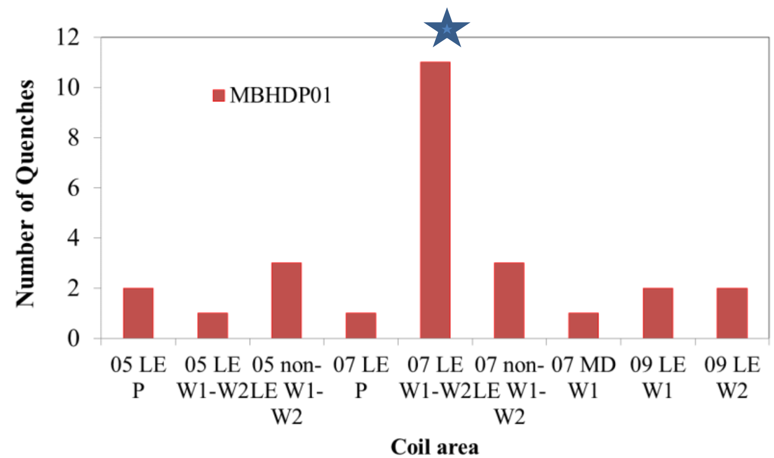
The total fraction of detraining quenches is not too useful –
the trend and magnitude toward the end of the curve are more relevant

Quench training locations



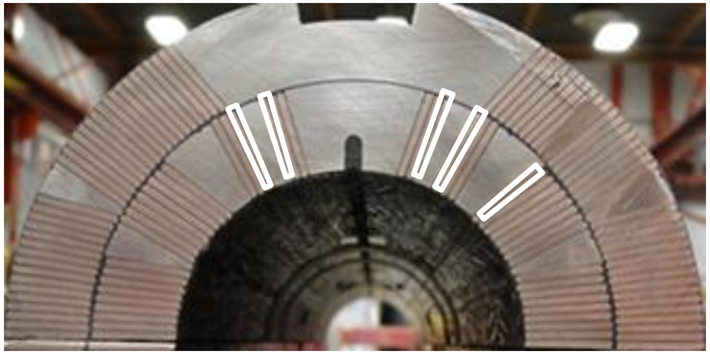




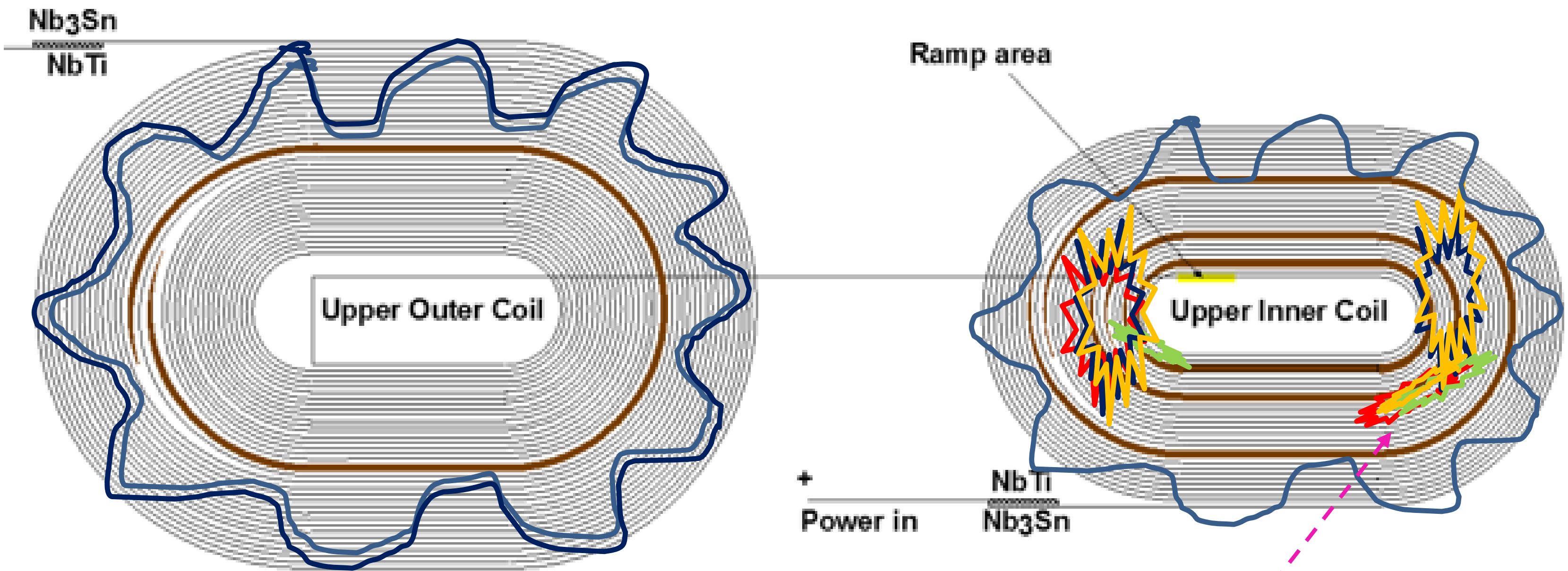


Most quenches develop in the non-straight sections around the first wedge (and the pole) or often asymmetrically around the second wedge (non-LE).

For MBHSP01 quenches are mostly in the mid-plane sections (OL but also IL).

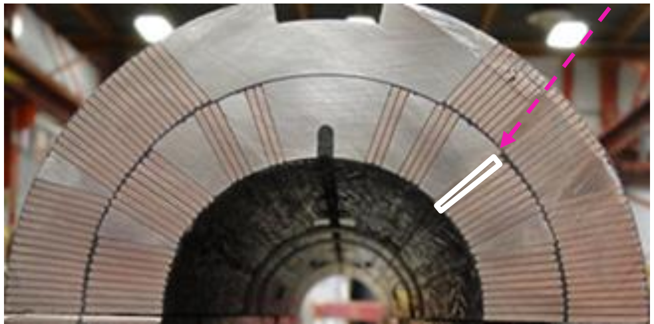


Quench training locations (2)

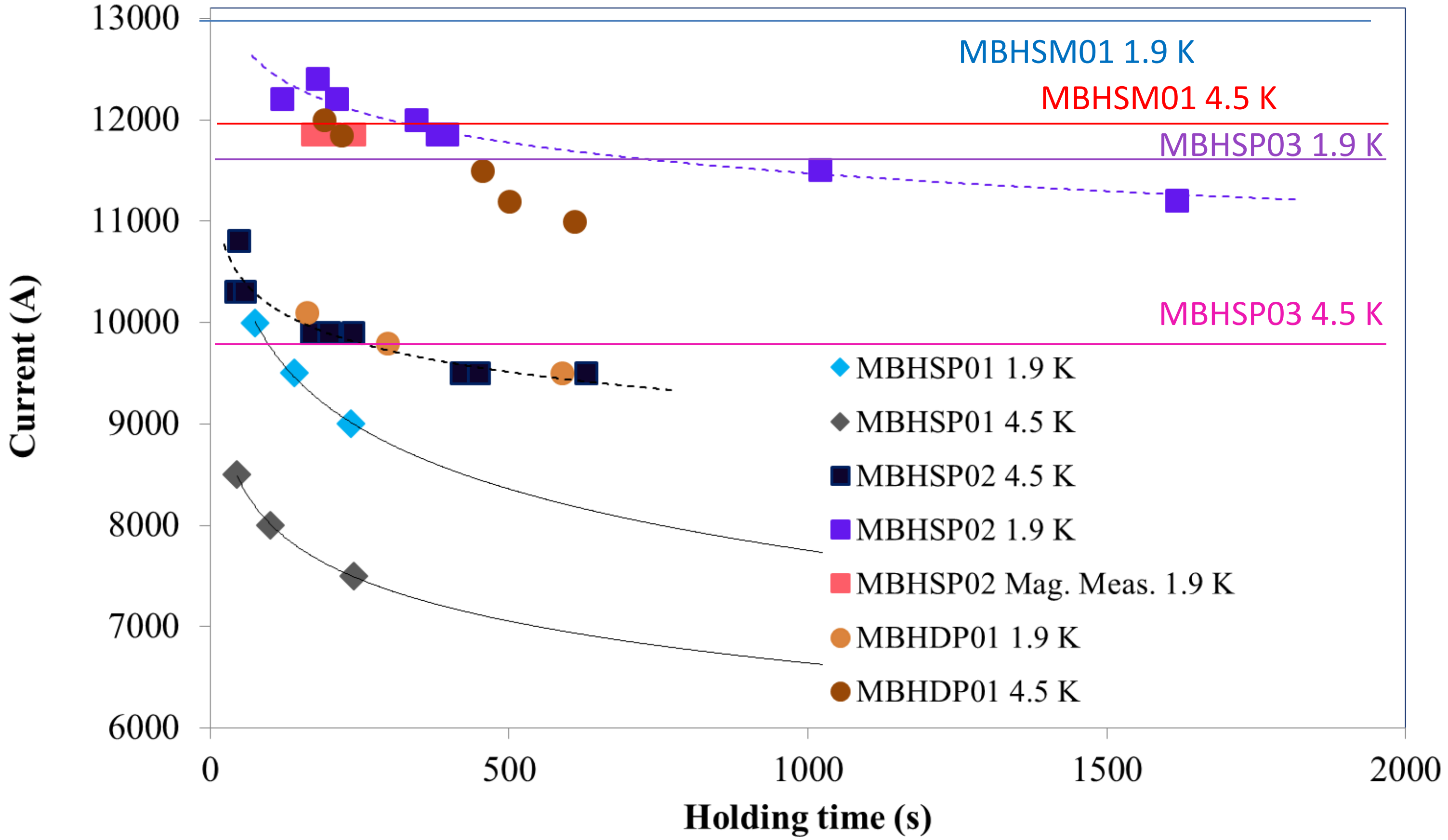


MBHSP01
MBHSP02
MBHSP03
MBHSM01
MBHDP01

We clearly see asymmetric behavior – quenches develop on the non-transition side of the
IL and this was also predicted by ANSYS simulations
(see Igor's talk as well).



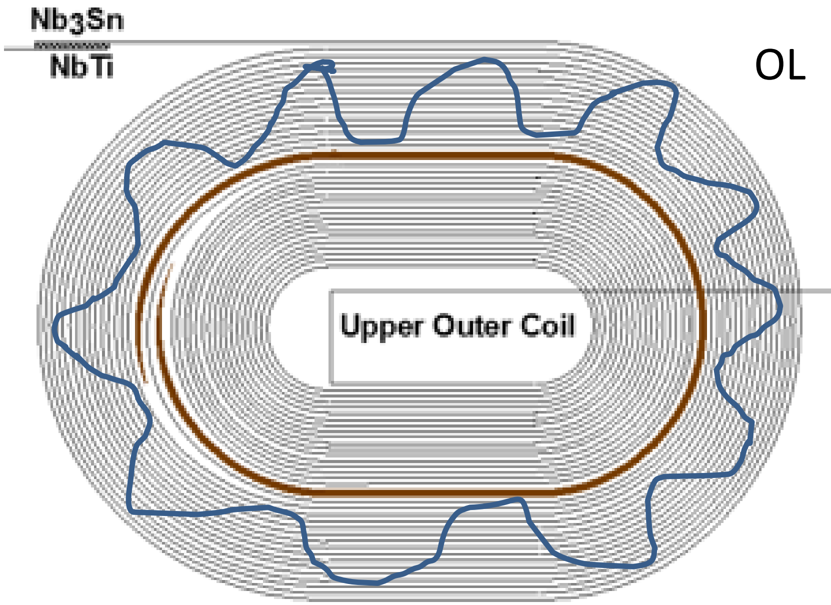
Holding current tests



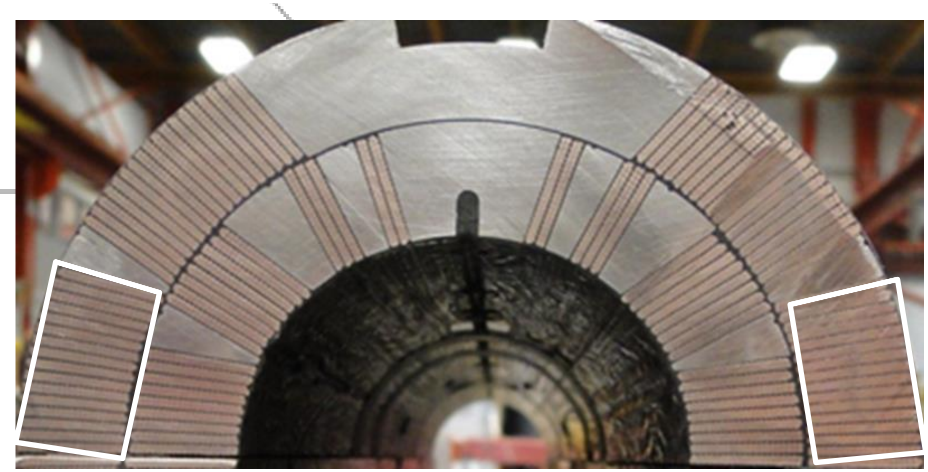
MBHSP01 shows steeper dependence on time but the type of dependence is similar (trendlines are logarithmic functions)

MBHDP01 is consistent with rest in terms of field (instead of current).

Quench location in holding tests



OL



MBHSP01 – coils 2/3, MBHSP02/MBHDP01 – coil 7

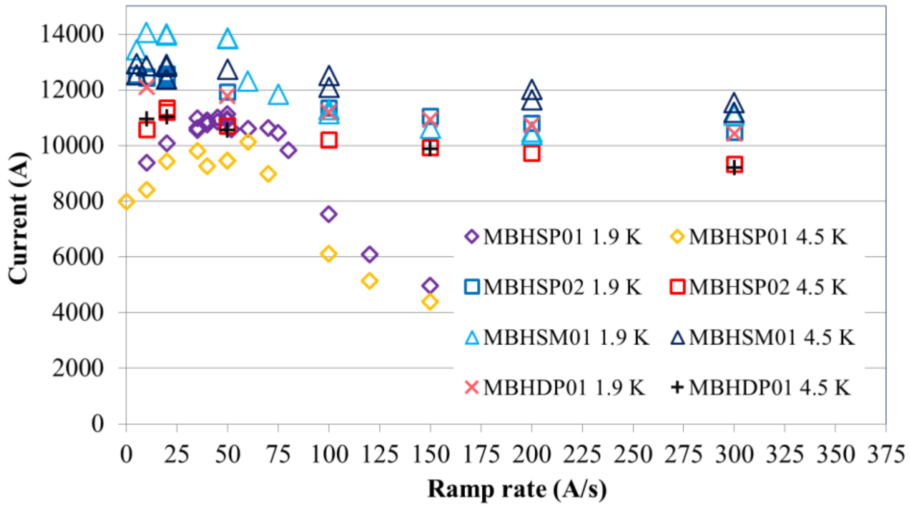
In all magnets where the holding current tests failed, quenches happen in the same OL coil segment.

Ramp rate dependence

- MBHSP01 show anomaly at low ramp rate and strong dependence of the quench current at high ramp rates
  (no stainless steel core – worse control on Eddy currents)

- MBHSM01 also shows irregular behavior vs ramp rate at 1.9 K but not at 4.5 K

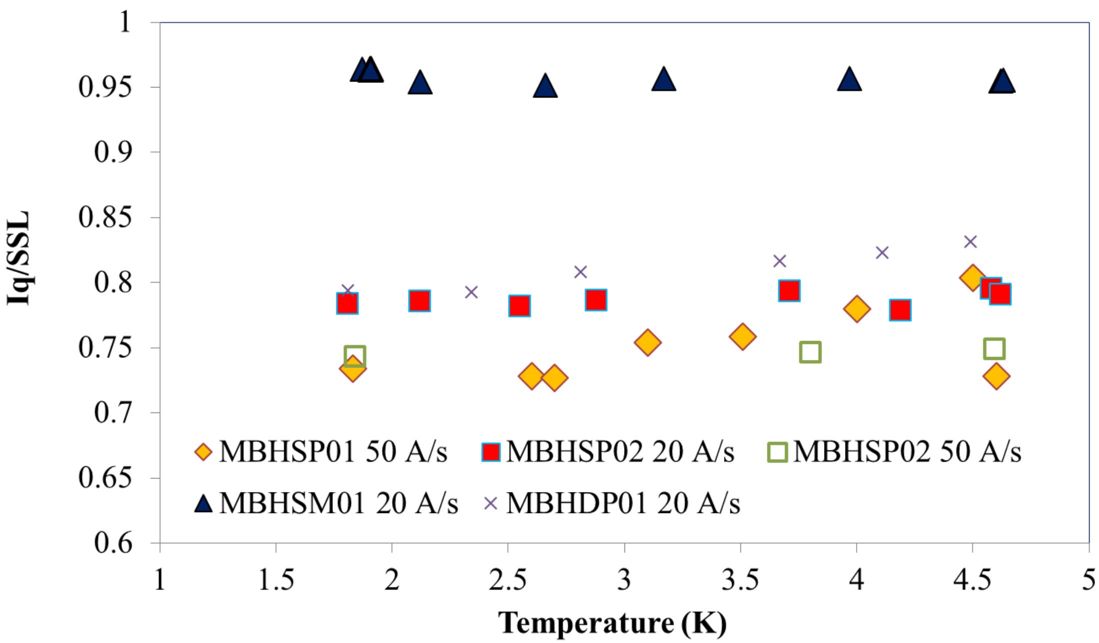
- With these exceptions all magnets have similar mild dependence on the ramp rate
  (all of them are with SS core)



- At different temperature the curve simply shifts

Quenches happen in "usual" locations (similar to training) with an exception at lowest ramp rate: for magnets which failed holding current tests, when a reverse dependence is observed quenches develop in the mid-plane segment in the OL

Temperature dependence



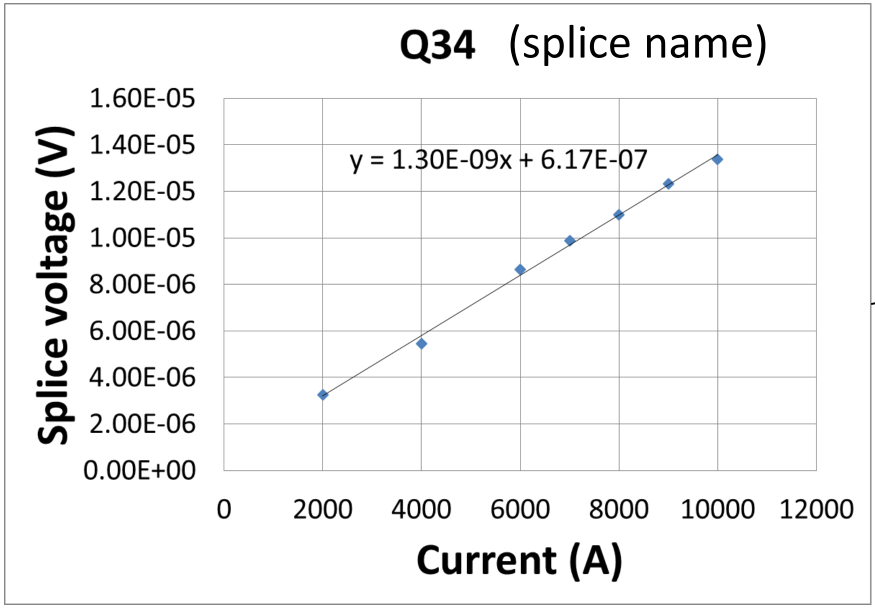
Quench locations follow the pattern in training quenches. Worth mentioning :
At the end of the training of MBHSP02, quenches at 4.5 K developed in the OL of coil 07 - the same location for quenches above 3 K.

- The curves suggest that there is a large critical current degradation in coils (for trained magnets the curve is flat)

- MBHDP01 was not fully trained

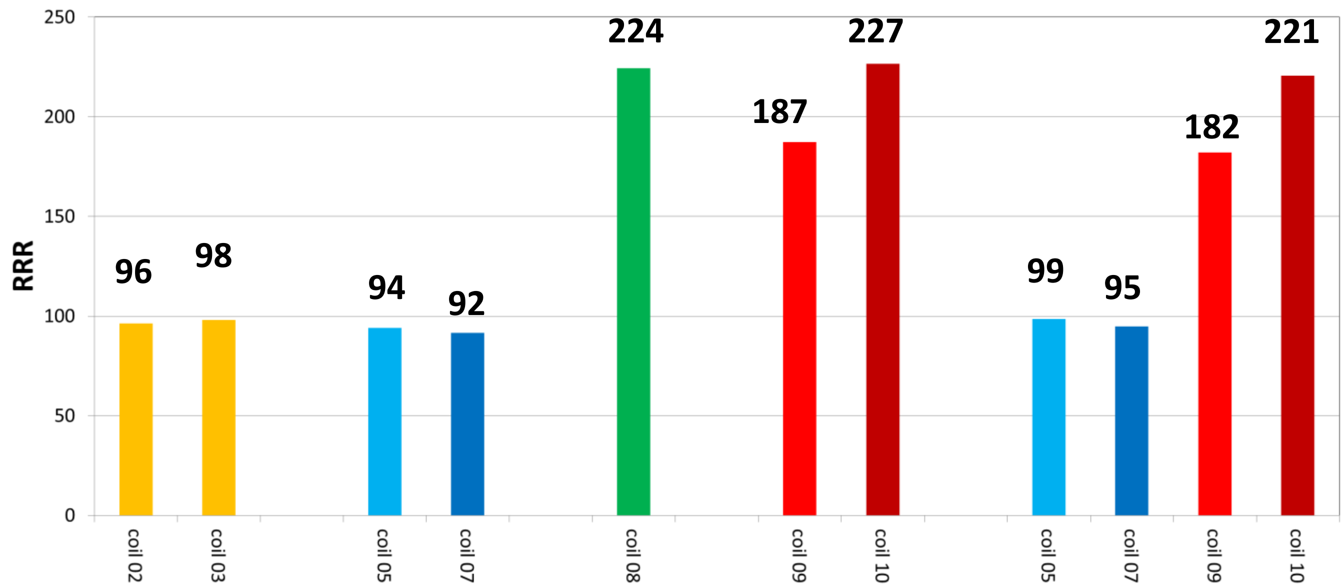
Splice resistance

- In early tests we were able to obtain upper limits for splice resistances : 2 nOhm
- In later measurements we still had problems with some of the channels but we substantially improved the measurement precision
- Nevertheless reliable measurements of the splice resistances show they are within 0.5-1.5 nOhm.



The example is from MBHDP01 – NbTi-NbTi splice between coil 09 and coil 10 with measured resistance of 1.3 nOhm

RRR



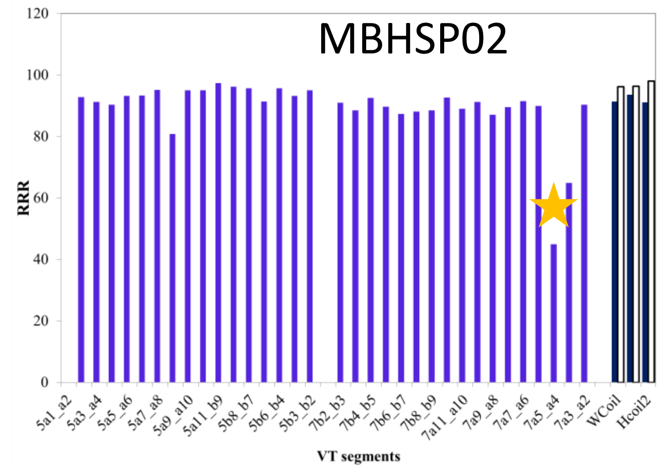
	MBHSP01	MBHSP02	MBHSM01	MBHSP03	MBHDP01
Quench order	02/03	07/05	08	10/09	07/10/05/09
Limiting coil	02/03	07/05	08	09/10	07/10

RRR for coils is unaffected by the magnets fabrication process.

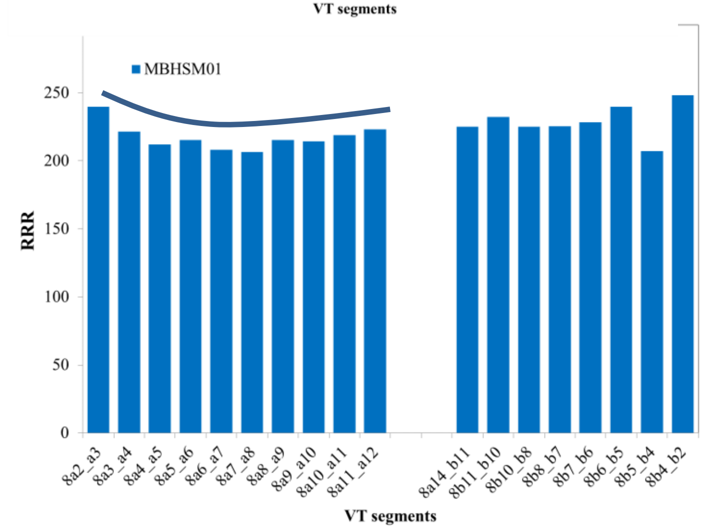
RRR (2)

- Although RRR for coils were stable and RRR of segments within the coil show little variations there were exceptions

- In one case (only) we notice possible correlation between low RRR and a quench location – MBHSP02, coil 7, IL, ★ around second wedge



- In coils 8 and 9 there was a pattern – slightly higher RRR in pole and mid-plane regions of IL



Summary on tested models

MBHSP02

Modified coil end parts and collar packs ID at MP region, thicker radial shim and smaller bending shim : reduce the stress and asymmetries in the mid-plane

Better stability, no mid-plane limitation at training

Still mid-plane limitation at holding current (and low ramp-rate tests)

MBHSM01

Mirror structure, no collars, reduced coil pre-stress and bending

No mid-plane limitation points, fast training (low pre-stress)

Very good training levels but detraining observed

MBHSP03

Modified ends, new stamped collar with larger ID, thicker protection shell, less bending

Conservative coil prestress for coils bigger at MP

Faster than MBHSP02 training; quench current erratic behavior observed, likely due to epoxy cracking between inner layer pole blocks and coil pole turns – training interrupted

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MBHDP01

First Nb3Sn dual aperture dipole magnet

No coil degradation with the new assembly/structure

Performance limited by large conductor degradation in a coil used in MBHSP02

Summary

- Five magnet models, including the demonstrator, tested
- We reached 97% of the designed bore magnetic field
- We tried to improve each new model based on results of previous tests with variable success
- Significant coil degradation was observed in all tests except MBHSM01
- Training is reproducible including MBHSM01

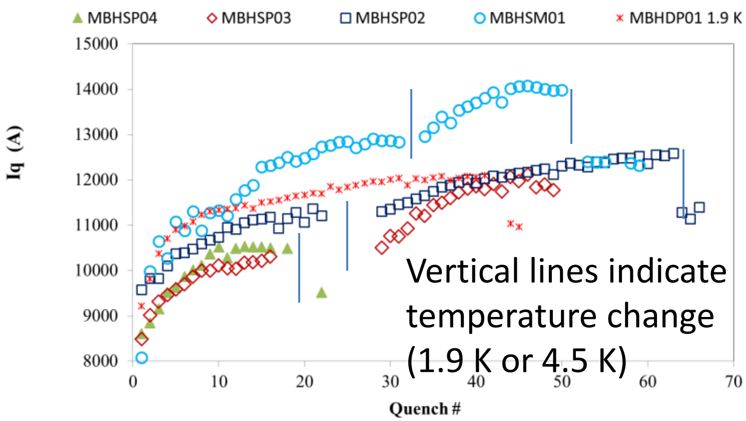
- Further improvements in end parts and instrumentation at particular locations would have been beneficial
- Forthcoming tests with MBHDP01 are being planned

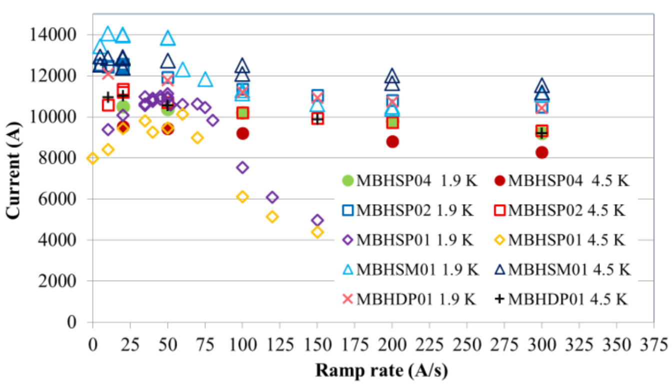
Back up slides

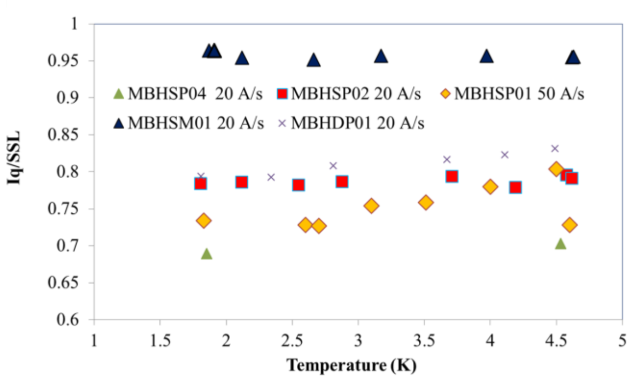
Back up summary

- Magnet training at ~80% of SSL (mirror : 97%)
- When untrained, a magnet quench current dose not depend on the temperature (for Nb_3Sn)
- Quench locations typically in non-straight section of the coils (around the first wedge/pole or second wedge of the IL)
- All holding current quenches develop in the mid-plane section of the OL (same for very low ramp rates when magnet fails holding current tests)
- The holding current and the time of holding are related logarithmically
- SS core cables significantly reduce the quench current dependence on the ramp rate
- RRR for coils is stable in different magnet assemblies

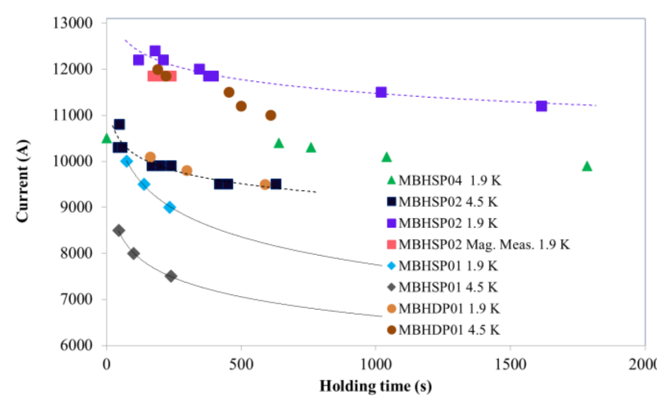
MBHSP04



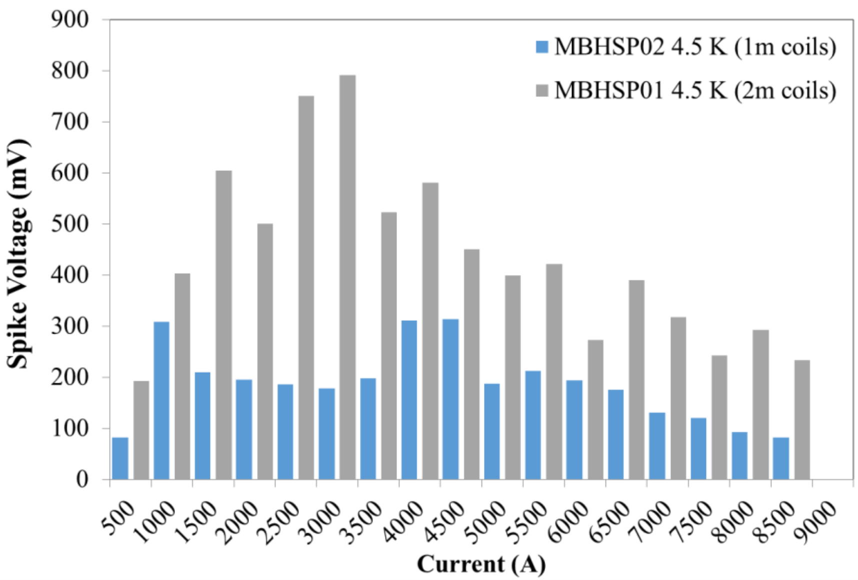


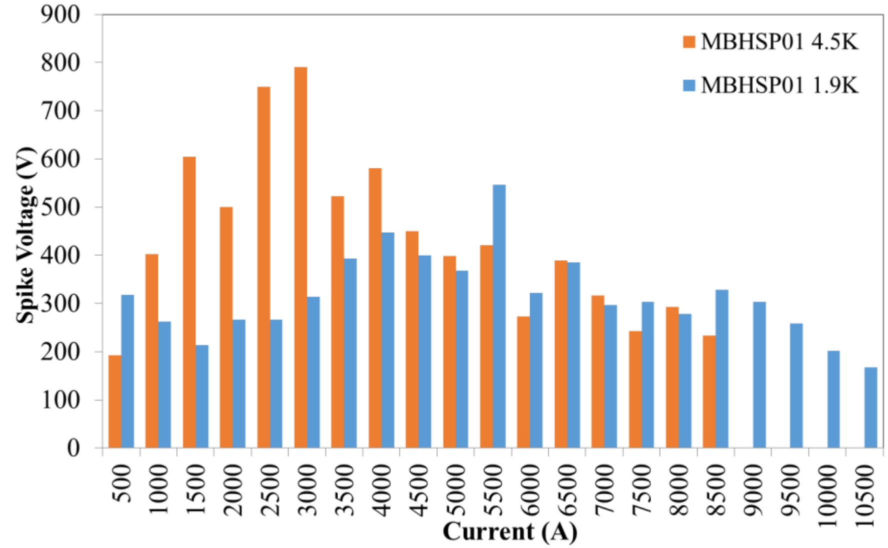


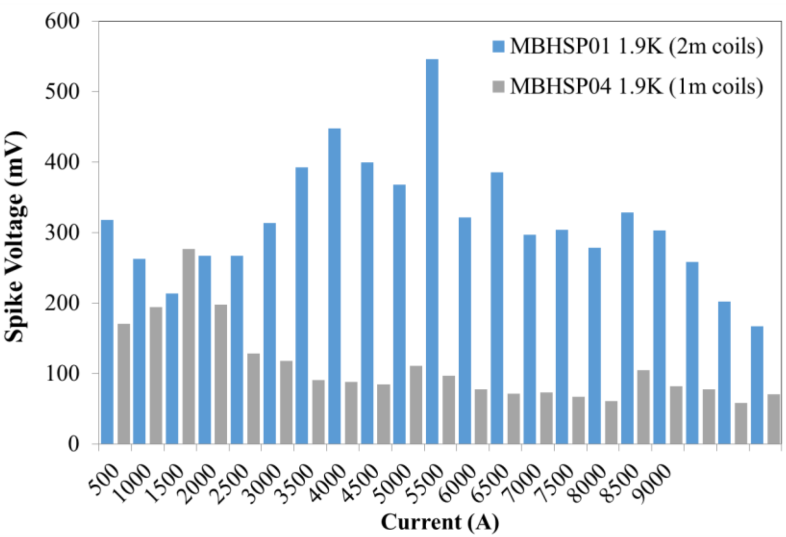
- ❑ Collarless dipole magnet with high pre-stress
- ❑ Very significant detraining observed in coil 08 (one quench location for all quenches, same as the last seen in MBHSM01)
- ❑ No training quenches seen up to 69% SSL in coil 11



Flux jumps analysis



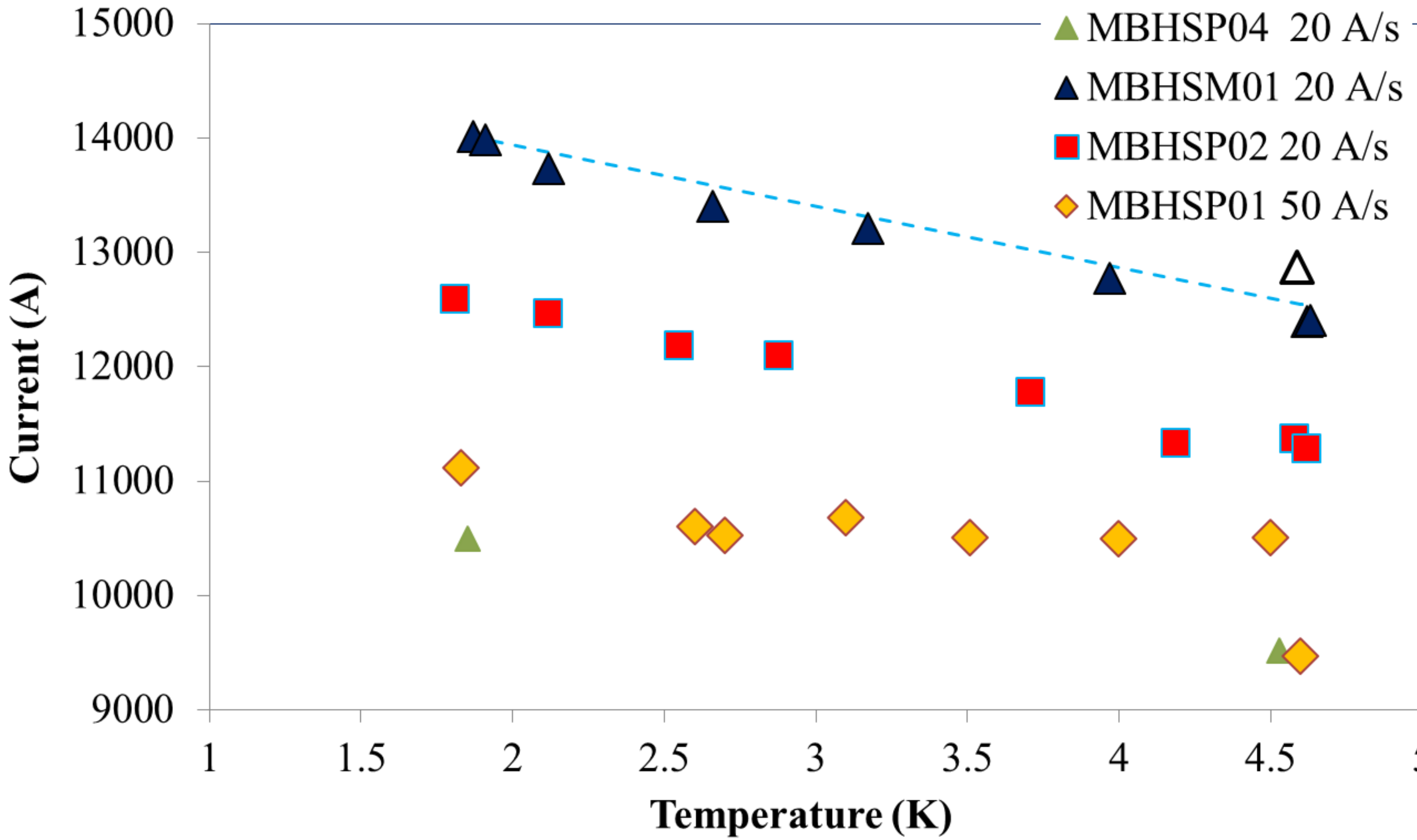




	MBHSP01	**MBHSP02**	**MBHSP04**
Coils used	MBH02 & 03 (2m long)	MBH05 & 07 (1m long)	MBH08(mirror) & 11 (1m long)
Cable	RRP 108/127 (no SS core)	RRP 150/169, with SS core	RRP 108/127, with SS core

Correlations with quenches were not observed.

Back up



MBHSP04 20 A/s
MBHSM01 20 A/s
MBHSP02 20 A/s
MBHSP01 50 A/s
Current (A)
15000
14000
13000
12000
11000
10000
9000
1
1.5
2
2.5
3
3.5
4
4.5
5
Temperature (K)

Back up

magnet	coil	Max Iq (A)	Iq/SSL (%)	Quench order (training)
MBHSP01	02	10683	71	1
	03	11120	74	2
MBHSP02	05	12586	79	2
	07	12548	78	1
MBHSM01	08	14082	97	1
MBHSP03	09	11911	79	2
	10	12122	80	1
MBHDP01	05	11962	79 (75)	3
	07	12078	80 (76)	1
	09	11380	75	4
	10	12093	80	2

Different SSL for 05/07 and 09/10 coils