Training at 7 TeV in the LHC

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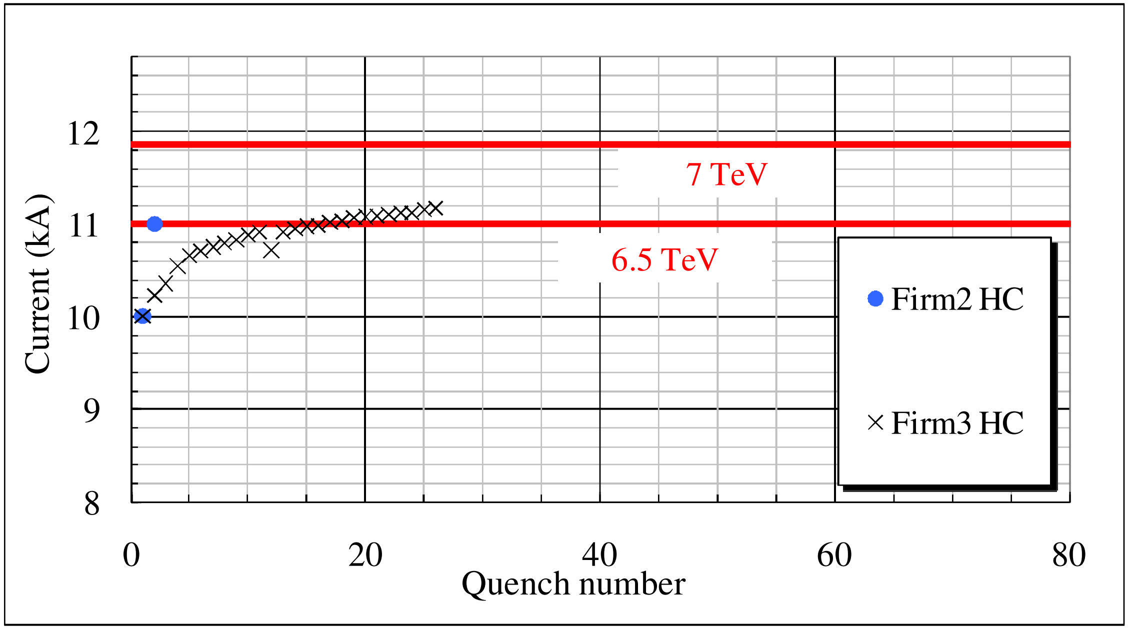
Acknowledgements: all the colleagues involved
in magnet manufacturing, testing and commissioning

CONTENTS

- Reminder of the problem and available data
- Forecast to 7 TeV
- The Firm3 anomaly
- Loss of training vs manufacturing parameters

Reminder of the problem and available data

- Sector 5-6 has been trained up to 6.6 TeV
  - First quench at 10 kA, 700 A gained rapidly (5 quenches)
  - Then a slow training, all in Firm3 magnets
  - Only one magnet quenched twice (perhaps), only one detraining
    - Remember that in this sector 55% are from Firm3, but …



Training in 5-6 during hardware commissioning

Reminder of the problem and available data

- Critical missing information
  - What would have been the training of the other sectors?

- What we managed to do:
  - All sectors reached 5 TeV without quench
  - 6 sectors reached 5.5 TeV with 2 quenches
  - 2 sectors reached 6 TeV with 3 quenches

- Main open questions about loss of training
  - It is a problem of Firm3 or is it due to other factors ?
  - Is it a problem of the whole production of Firm3 or is it just a bad batch ?
  - What will happen after successive thermal cycles ?
  - Are the quench in the straight part or in the heads ?

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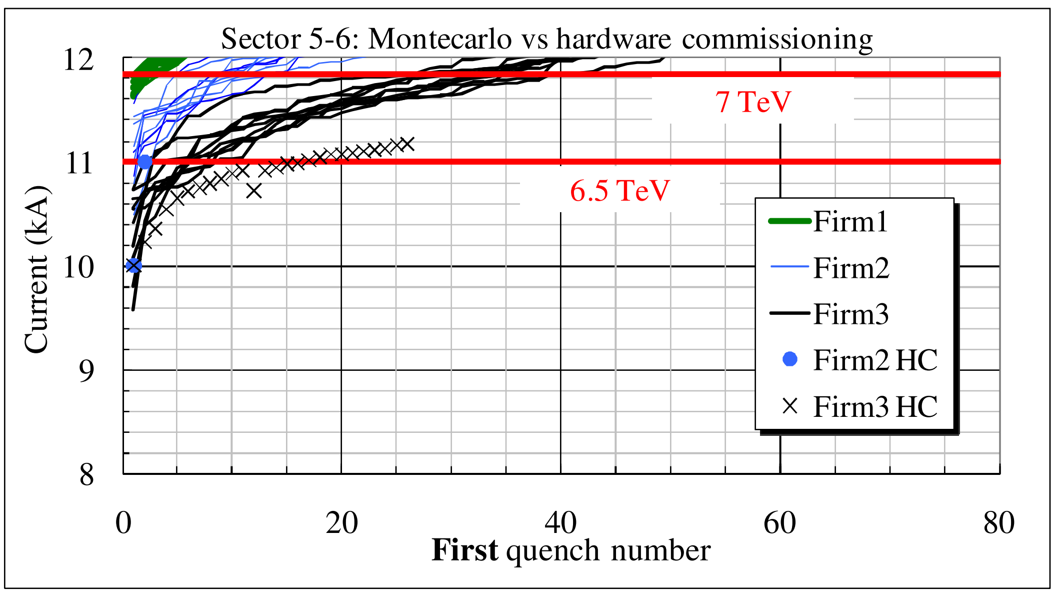
- Available data
- Forecast to 7 TeV
- The Firm3 anomaly
- Loss of training vs manufacturing parameters

Forecast based on surface test data: MonteCarlo on 5-6

- MonteCarlo method based on surface test data (SM18):
  - ☺ Gives the first quench level (10 kA)
  - ☺ Accounts of the fact that training is dominated by Firm3 in the range 10-11 kA, with a bit of Firm2 and nothing from Firm1
  - ☹ Overestimates level reached after 26 quench by 500 A
  - ☹ Slope is different!!

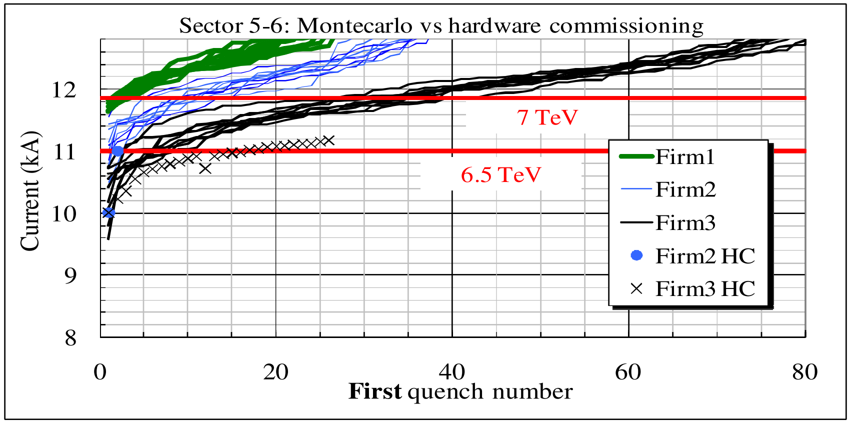


MonteCarlo forecast for 5-6 and hardware commissioning data
[B. Bellesia, N. Catalan Lesheras, E. Todesco, Chamonix 2009]

Forecast based on surface test data: MonteCarlo extended to the LHC

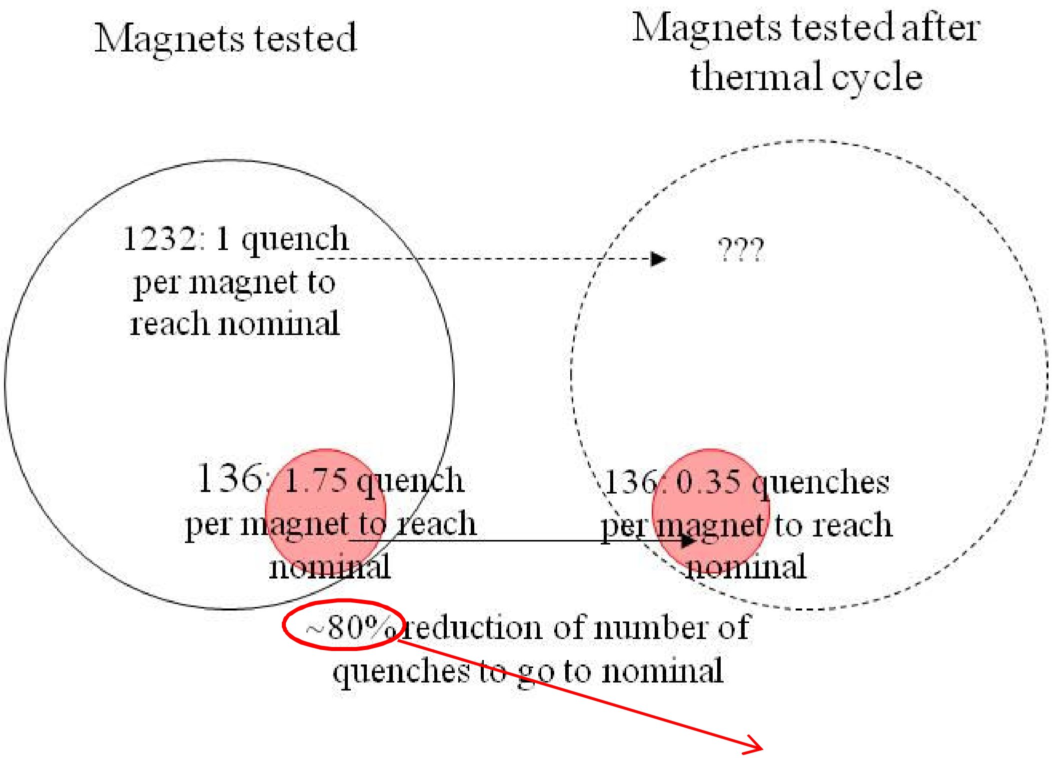
- MonteCarlo method:
  - For 5-6 to reach nominal: 5 quenches from Firm1, 15 from Firm2, 35 from Firm3
  - Correcting for the composition of 5-6, we get 400 quenches to reach nominal for the LHC, or 50 quenches per octant

	Sector 5-6		A generic octant		All the LHC	
	% of magnets	n. of quenches	% of magnets	n. of quenches	% of magnets	n. of quenches
Firm1	19%	5	33%	9	33%	72
Firm2	26%	15	33%	19	33%	155
Firm3	56%	35	33%	21	33%	168
Total	100%	55	100%	49	100%	394



FORECAST BASED ON SURFACE TEST DATA: COMPARISON WITH PREVIOUS ESITMATES

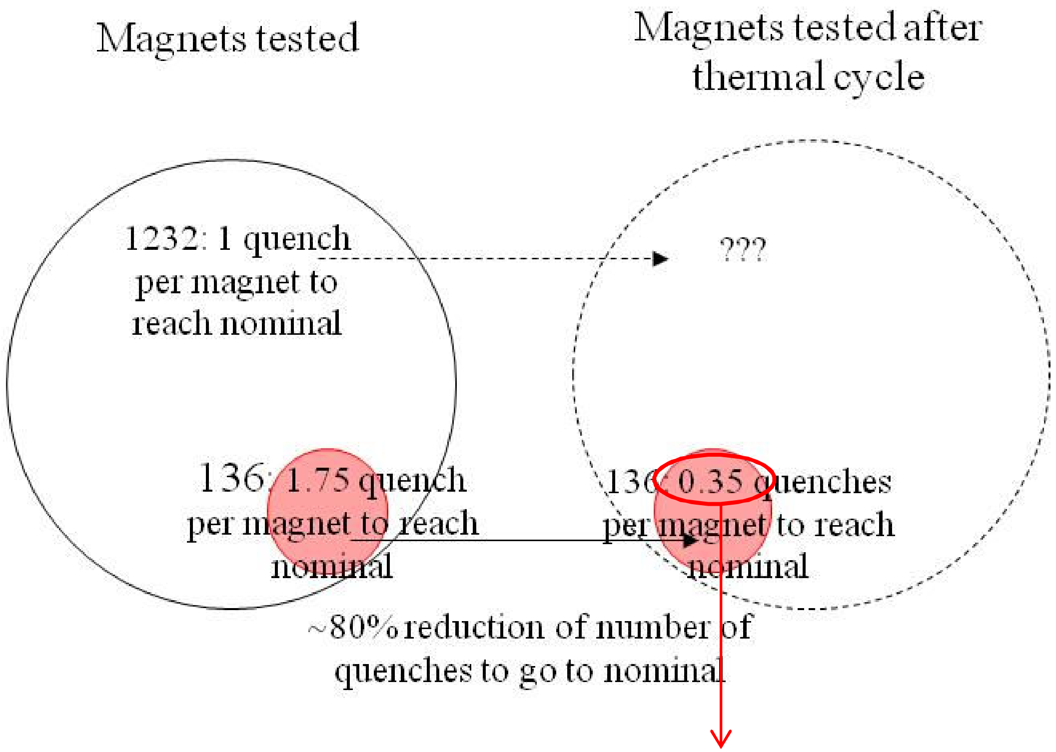
- Previous estimates to reach nominal in the tunnel



- SCALING-1 HYPOTHESIS: Applying the 80% reduction to the whole sample → 0.2 quenches needed to go to nominal → 30 quenches per octant [P. Pugnat, A. Siemko, *IEEE Trans. Appl. Supercond.* **17** (2007) 1091]

FORECAST BASED ON SURFACE TEST DATA: COMPARISON WITH PREVIOUS ESITMATES

- On the other hand …

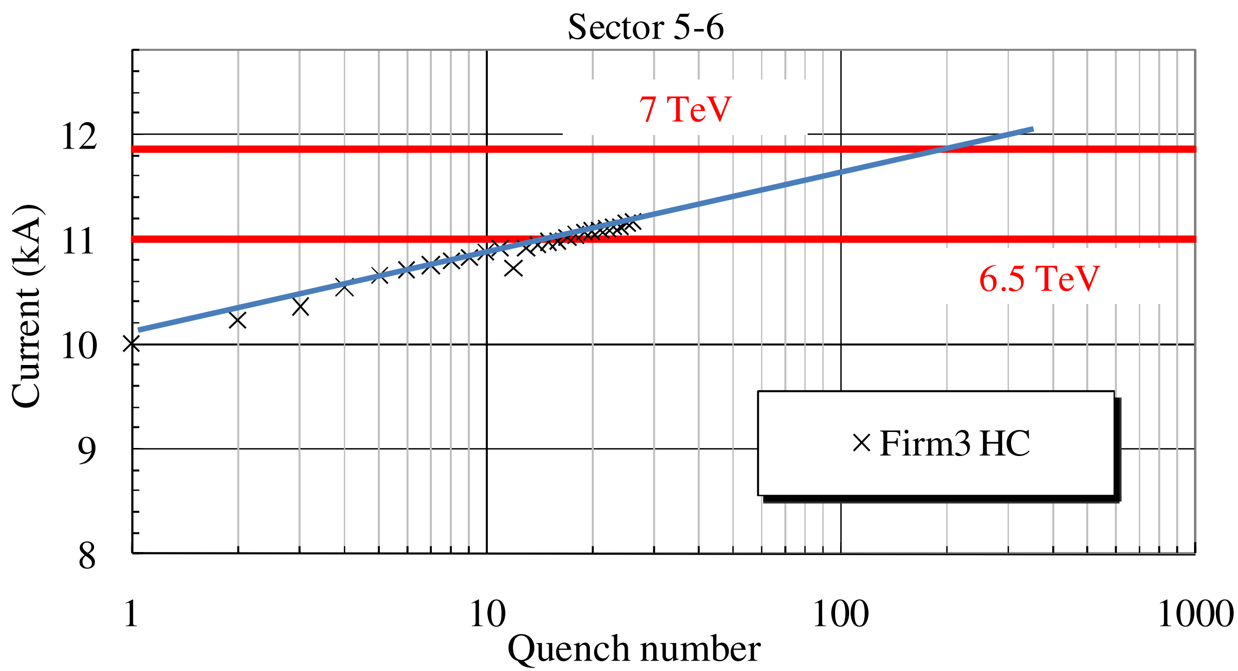


- SCALING-2 HYPOTHESIS: assuming that all magnets after thermal cycle behave as the sampled ones → 0.35 quenches per octant to reach nominal applies to the LHC → 50 quenches to reach nominal

  [C. Lorin, A. Siemko, E. Todesco, A. Verweij, MT-21 *IEEE Trans. Appl. Supercond.* **20** (2010) in press]

Forecast based on harware commissioning data: extrapolation

- Empirical extrapolation of hardware commissioning data based on exponential fit



The exponential fit of current vs quench number for 5-6 hardware commissioning

- ~200 quenches per sector 5-6
- For generic sector having 33% of Firm3: 110±35 quenches per octant to reach nominal [A. Verweij, Chamonix 2009]

Forecast: Summary

- For 6.5 TeV, a short training is expected (10-15 quenches per octant)
  - Needed time: a few days of training per sector

Method	Quenches per octant to 6.5 TeV	Comments
Scaling	12	Based on HC data

- For 7 TeV we have no experience – lower bound: MonteCarlo method, at least 50 quenches needed per octant
  - Needed time: one month per sector ?

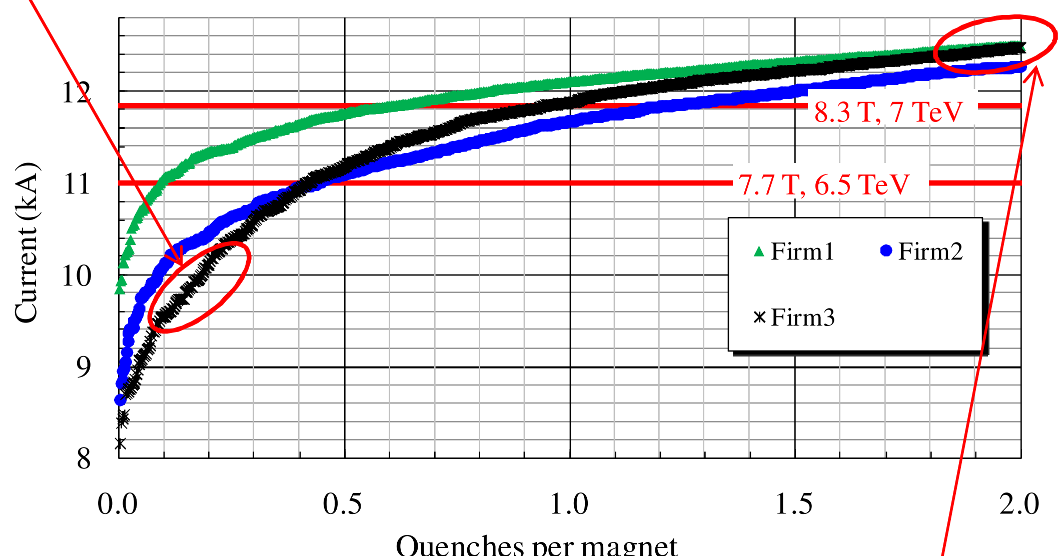
Method	Quenches per octant to nominal	Comments
Scaling-1	30	Based on test data
Scaling-2	50	Based on test data
MonteCarlo	50	Based on test data
Extrapolation	110±25	Based on HC data

CONTENTS

- Available data
- Forecast to 7 TeV
- The Firm3 anomaly
- Loss of training vs manufacturing parameters

The Firm3 anomaly

- Firm3 anomalies in quench perfomance were visible in two different aspects in surface test data
  - (1) Virgin training: Firm3 is dominating the training at low fields
    - Around 10 kA, Firm3 quenches are twice more numerous than Firm2 and Firm1

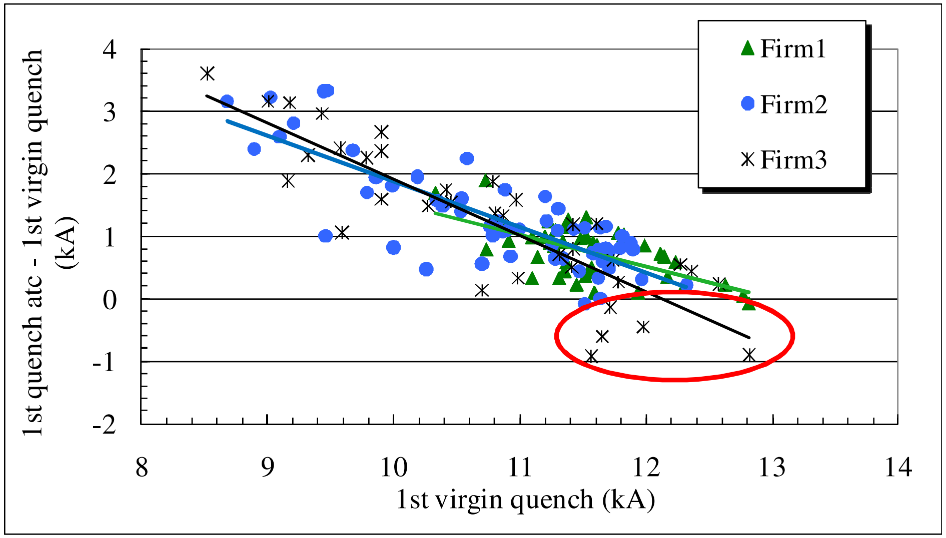


Cumulated performance of the dipoles during virgin training
[B. Bellesia, N. Catalan Lesheras and E. Todesco, Chamonix 2009]

    - But the Firm3 magnets were the first to reach ultimate! This is why they had a lot of bonus

THE FIRM3 ANOMALY

- Firm3 anomalies in quench performance were visible in two different aspects in surface test data
  - (2) Loss of training retention after thermal cycle
    - On the 138 magnets tested after thermal cycle, Firm3 is the only one showing more loss, and net loss after thermal cycle in a few cases



Correlation between level of the first virgin quench and gain after thermal cycle

A FIRM3 ANOMALY ?

- An additional « strangeness » of Firm3 (w.r.t. Firm1 and Firm2): location of the second quench
  - 95%-100% of the 1st quench is in the heads, in all firms
  - 10% of the 2nd quench is in the straight part for Firm1 and Firm2, 2% only for Firm3
  - Does it mean that Firm3 has worse heads or that it has a better straight part ?

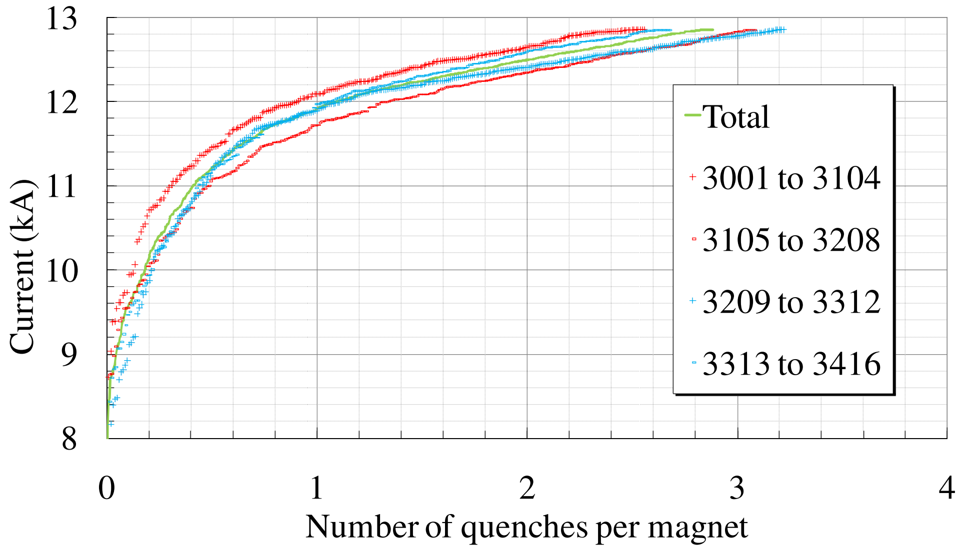
	1st quench			2nd quench		
	Average	Stdev	Fraction in heads	Average	Stdev	Fraction in heads
Firm1	8.32	0.40	97%	8.70	0.27	89%
Firm2	7.87	0.53	100%	8.53	0.38	88%
Firm3	7.95	0.79	96%	8.57	0.46	98%

Average and stdev of first and second virgin quenches, and fraction of them in the heads (measured on a sample)

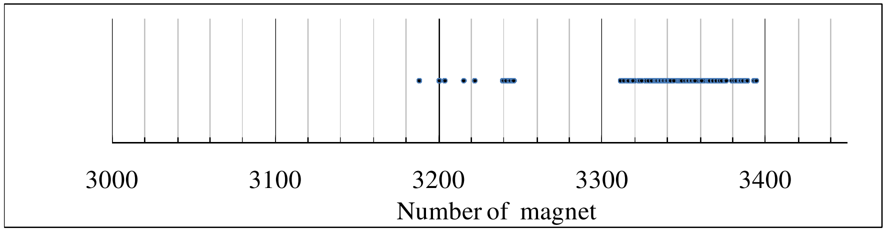
CONTENTS

ANALYSIS: HOMOEGENITY

- 1st question: are Firm3 magnets in 5-6 anomalous w.r.t. the whole Firm3 production?
  - The Firm3 production had a performance degradation: first 100 very good, than worse
  - 5-6 contains magnets from 3300 to 3400, with worse behavior at 10-11 kA – the 3000 to 3100 are better, the 3100 -3300 are the same



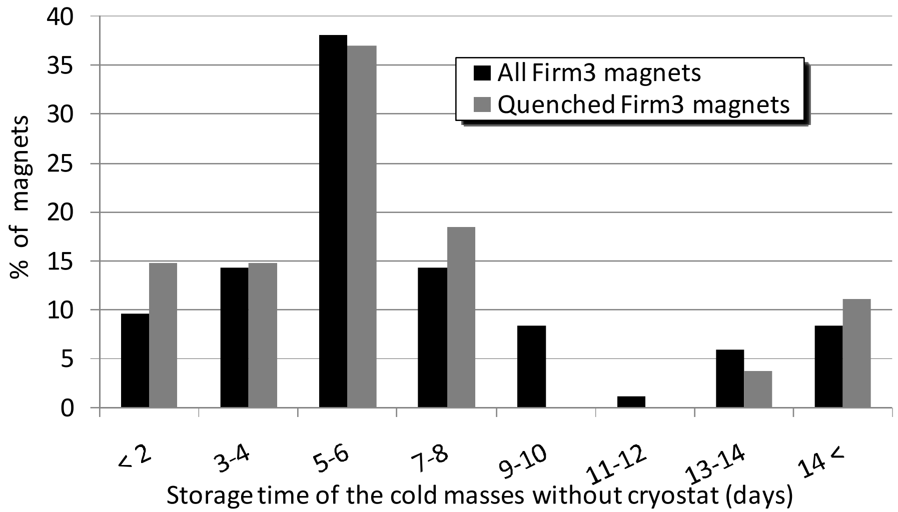
Cumulated virgin training of Firm3 magnets, split in four batches



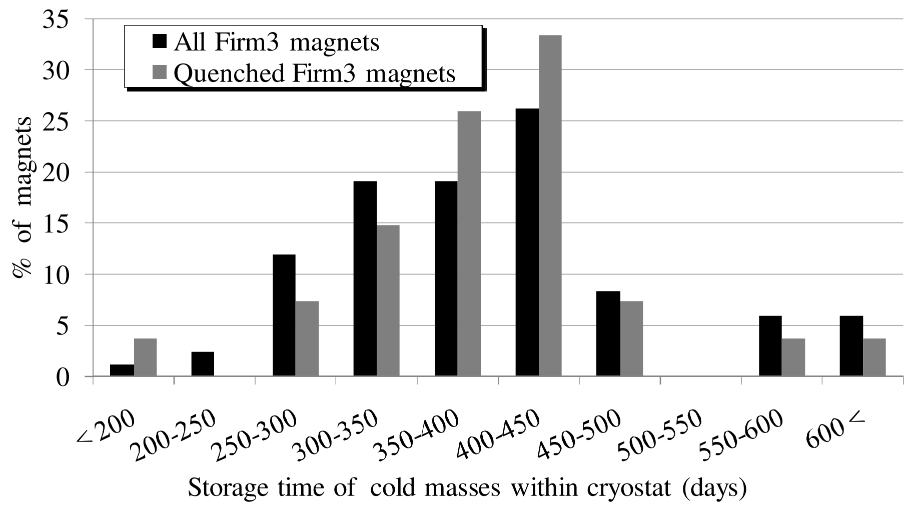
Firm3 magnets installed in 5-6

Analysis: storage time

- 2^{nd} question: is this detraining due to storage time ?
  - There is no indication of a correlation with storage time, neither at the stage of cold masses, nor after test (as cold masses within a cryostat

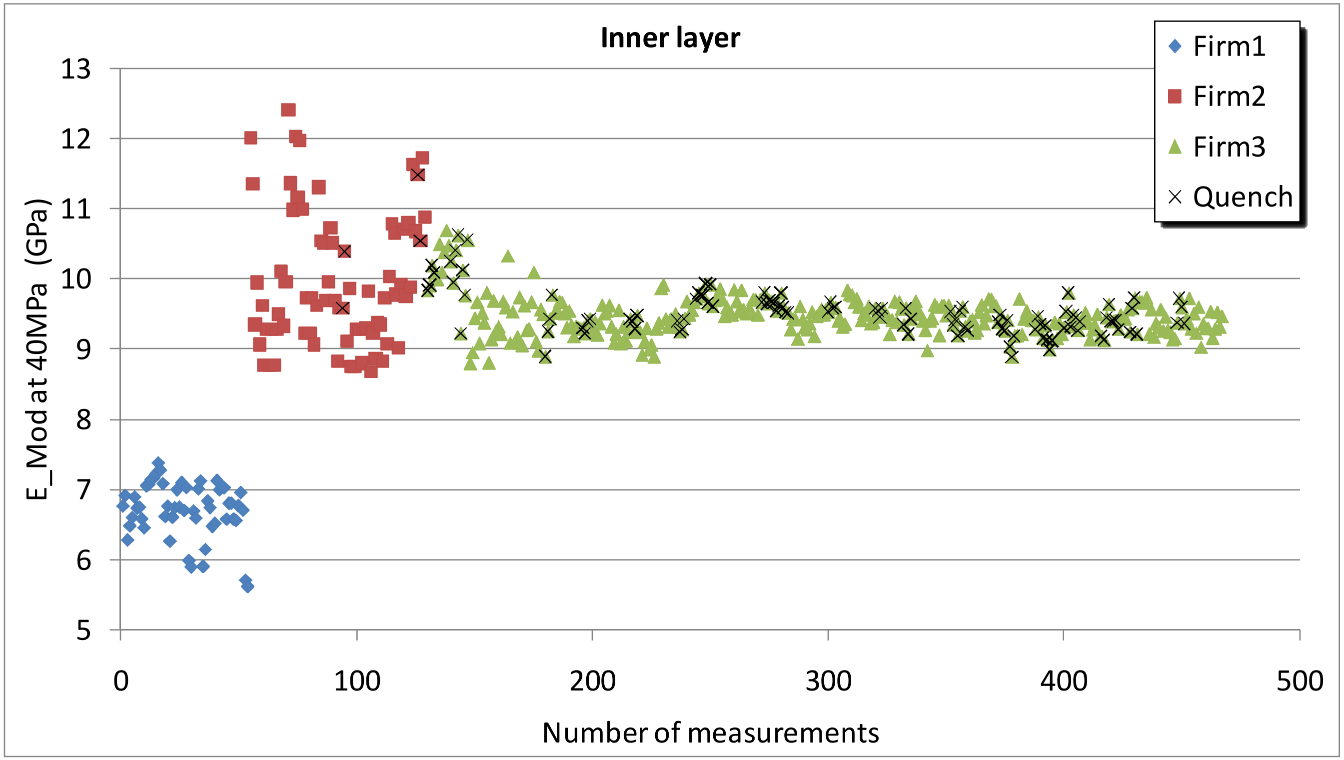


Storage time as a cold mass for Firm3 magnets in 5-6 versus quenched magnets



Storage time as a cryostated dipole for Firm3 magnets in 5-6 versus quenched magnets [courtesy of A. Musso]

- 3rd question: is this due to softer coils ?
  - There is no indication of a correlation with measured elastic modulus



Elastic modulus of coils for magnets in 5-6, inner layer
[courtesy of A. Musso]

ANALYSIS: COIL PROPERTIES

- 3^{nd} question: is this due to softer coils ?
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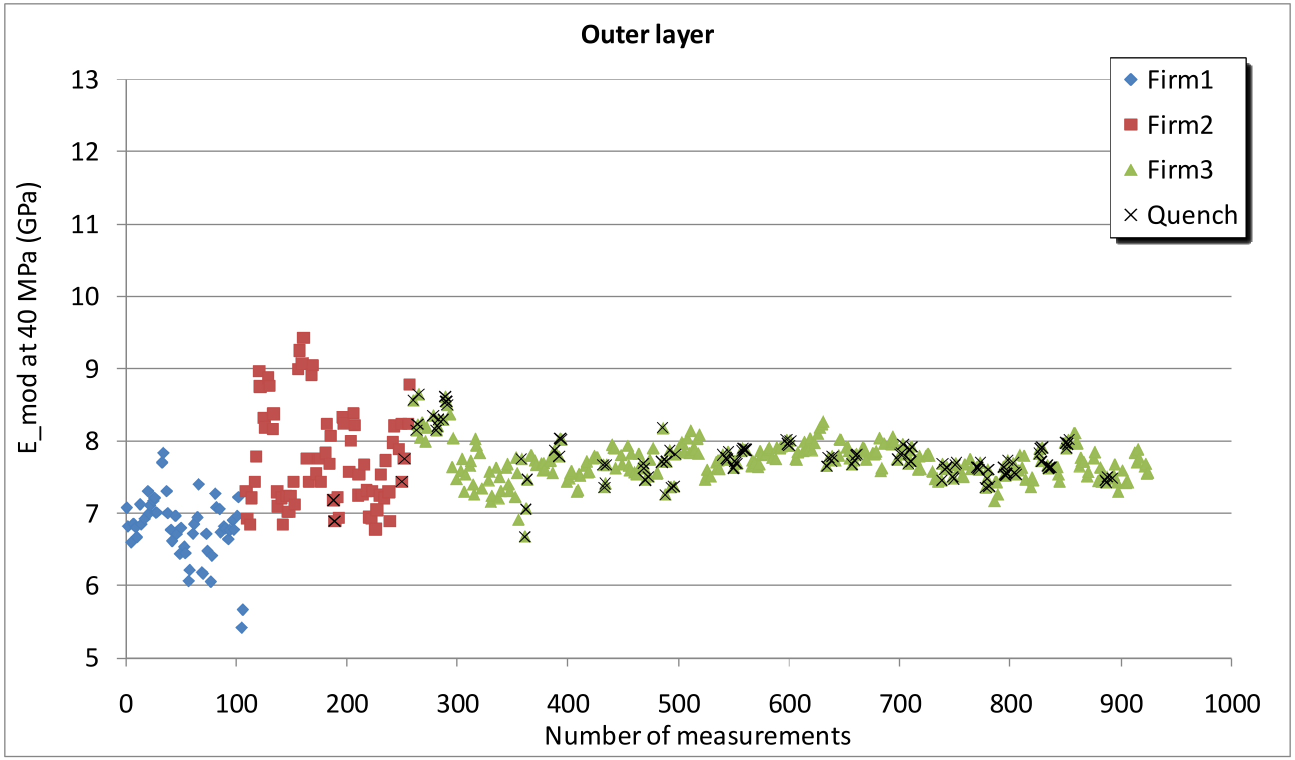


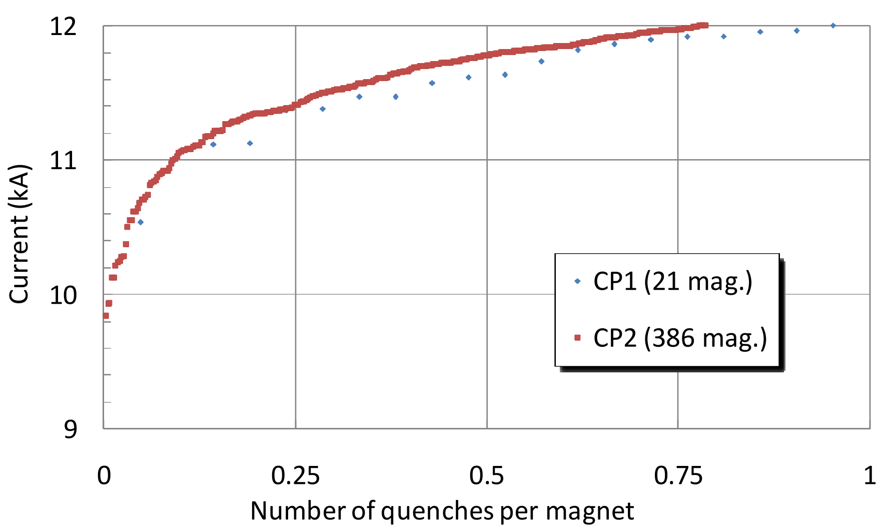
Elastic modulus of coils for magnets in 5-6, outer layer
[courtesy of A. Musso]

Analysis: collars

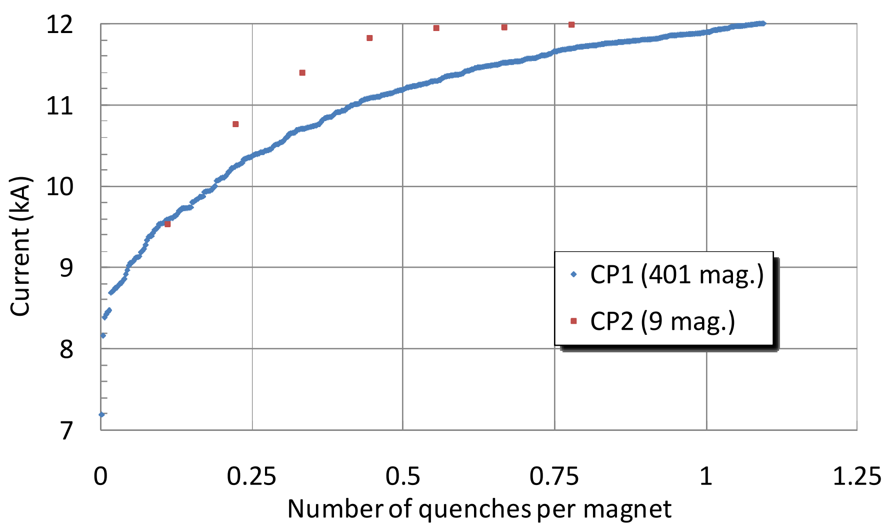
- Two collar producers: one mainly used by Firm1 and 2, the third one by Firm3
  - CP1 (or Firm3?) performance is worse

Nb. of magnets	Firm1	Firm2	Firm3
CP1	21	1	401
CP2	386	443	9
Total	415	445	416

  - Unfortunately, the statistics is not enough to prove if the collars are the problem



Quench performance in Firm1
split according to collar manufacturer



Quench performance in Firm3
split according to collar manufacturer

Tests carried out in 2009

- 16 spare Firm2 magnets have been tested (virgin)
  - 21 quenches to get to nominal – 1.25 quenches per magnet – in perfect agreement with Firm2 data

- 16 magnets from 3-4 have been tested (and reinstalled)
  - Once more, statistics on Firm3 is very low ☹ ☹ ☹
  - Data are not far from the MonteCarlo results
    - 3-4 magnets performance looks reasonable within the thin statistics

	3-4 magnets			MonteCarlo
	Number	Quenches to 7 TeV	Quenches/magnet to 7 TeV	Quenches/magnet to 7 TeV
Firm1	4	1	0.25	0.20
Firm2	10	6	0.60	0.39
Firm3	2	1	0.50	0.39

Re-training of 3-4 magnets tested in 2009 after the incident [M. Bajko, G. Deferne]

Conclusions and Actions

- LHC Energy:
  - 6.5 TeV is at hand with a very limited training, a few days per sector
  - 7 TeV will need much more training - we have no data!
    - HC commissioning data of other sectors will not come soon
- Causes of Firm3 anomaly are under analysis
  - Evidence of anomalies in surface test data:
    - Slow training at low fields and detraining after thermal cycle
    - Different behavior of the heads at the second quench
    - Collar manufacturer used in Firm3 has not been used in Firm2 and Firm1
  - But this is not the whole story!

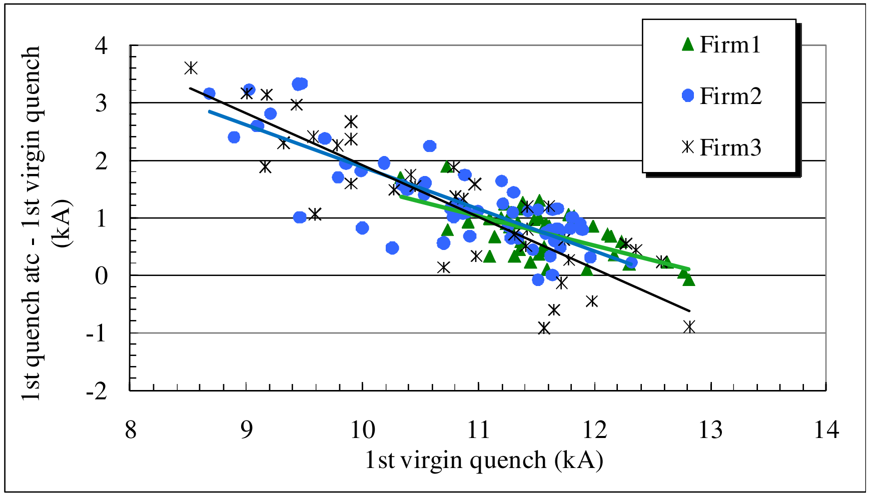
ADDITIONAL TEST

- Main open questions about loss of training
  1. It is a problem of Firm3 or is it due to other factors ?
  2. Is it a problem of the whole production of Firm3 or is it just a bad batch ?
  3. Are the quench in the straight part or in the heads ?
  4. What will happen after successive thermal cycles ?
- Points 1-2 are solved only through training to 7 TeV of the whole machine
- Points 3-4 will not, but could be solved by additional test
  - One could test 2 (or more) magnets per Firm [G. De Rijk proposal]
    - ☺ Several thermal cycles (4-5), with quench location and magnetic measurements
    - ☹ The statistics of 6 magnets could be not significant
    - ☹ The magnets from Firm3 come out of the incident → one would keep the doubt of a bias

SPARES

Forecast based on surface test data: MonteCarlo on 5-6

- MonteCarlo method based on surface test data (SM18):
  - For each 5-6 magnet:
    - Take the first virgin quench measured in surface (available for all)
    - Add the correlation with the quench after a thermal cycle, as measured on the 138 dipoles tested in surface, split per Firm
    - This correlation has a linear part, plus a random one, this is why you need a MonteCarlo

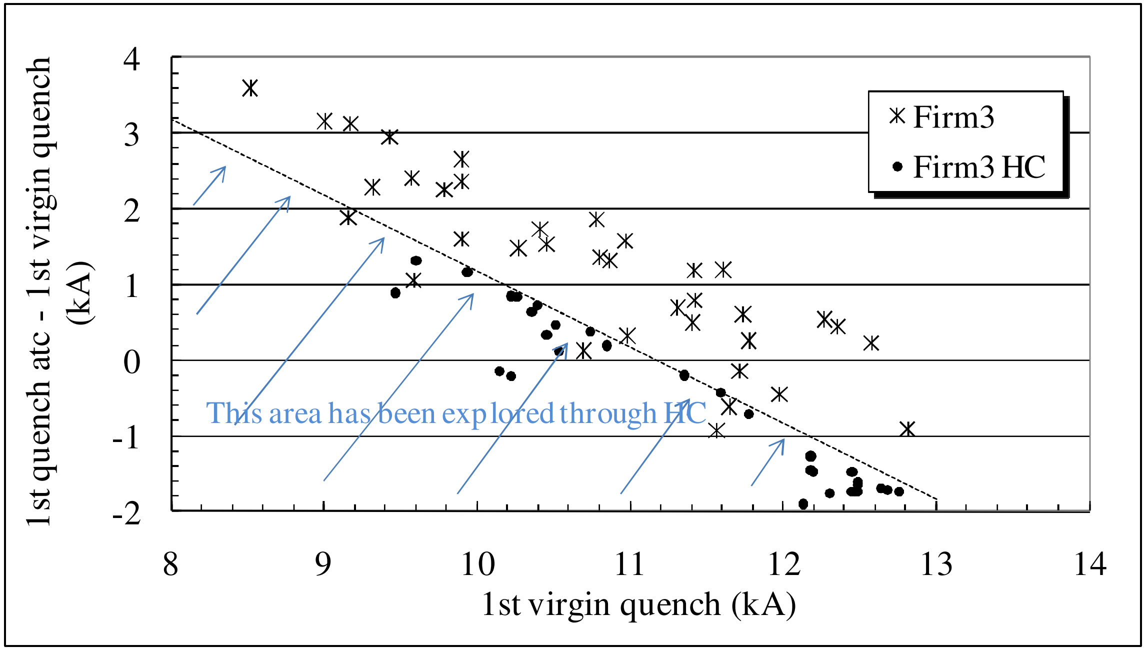


Tested after thermal cycle		
Firm1	44	32%
Firm2	58	42%
Firm3	36	26%
Total	138	100%

Correlation between 1st virgin quench and 1st quench after thermal cycle measured in 138 dipoles
[B. Bellesia, N. Catalan Lesheras, E. Todesco, Chamonix 2009]

The Firm3 anomaly

- Nevertheless, during hardware commissioning the Firm3 detraining was much worse



Correlation between level of the 1st quench and gain after thermal cycle, Firm3 magnets, and hardware commissioning data

- Please note: plot is not fair, we compare a distribution of 84 magnets (balls) in 5-6, unveiled up to the dotted line, with a distribution of 36 magnets tested after thermal cycle (crosses)