RETRAINING AND DETRAINING IN THE LHC

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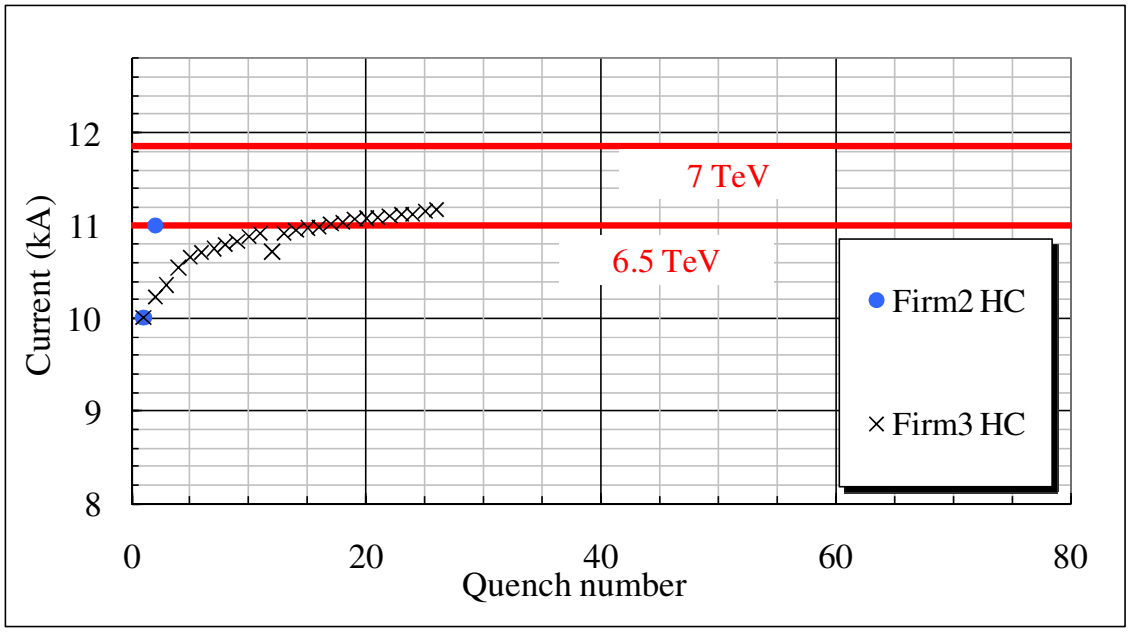
Acknowledgements: C. Lorin, A. Musso, A. Siemko, L. Rossi, A. Verweij, and all the colleagues involved in manufacturing, testing and commissioning

CONTENTS

- Available data
- Forecast to 7 TeV
  - MonteCarlo
  - Previous estimates
  - Extrapolation
- The Firm3 anomaly
  - Virgin cycle
  - Detraining after thermal cycle
- Analysis
  - Homogeneity of the production
  - Correlations vs storage time
  - Correlations vs elastic modulus

THE AVAILABLE DATA FROM HARDWARE COMMISSIONING

- 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

THE AVAILABLE DATA FROM HARDWARE COMMISSIONING

- Other sectors:
  - 5 TeV (8.46 kA) – all sectors went to this energy wihtout quenches
  - 5.5 TeV (9.31 kA) – 6 sectors went to this energy with 1 quench
  - 6 TeV (10.16 kA) – 2 sectors (4-5 and 5-6) went to this energy with 3 quenches
  - 6.5 TeV (11.0 kA) – 1 sector (5-6) went to this energy with 17 quenches

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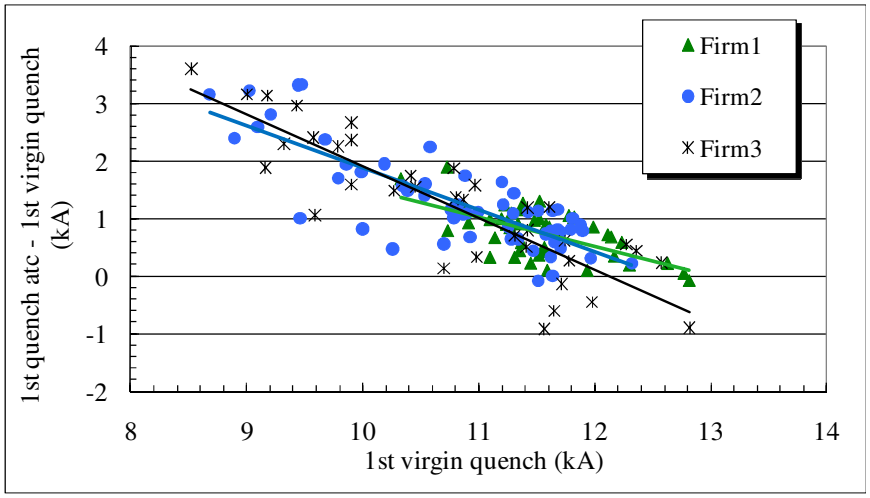
FORECAST BASED ON SURFACE TEST DATA: MONTECARLO ON 5-6

- 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

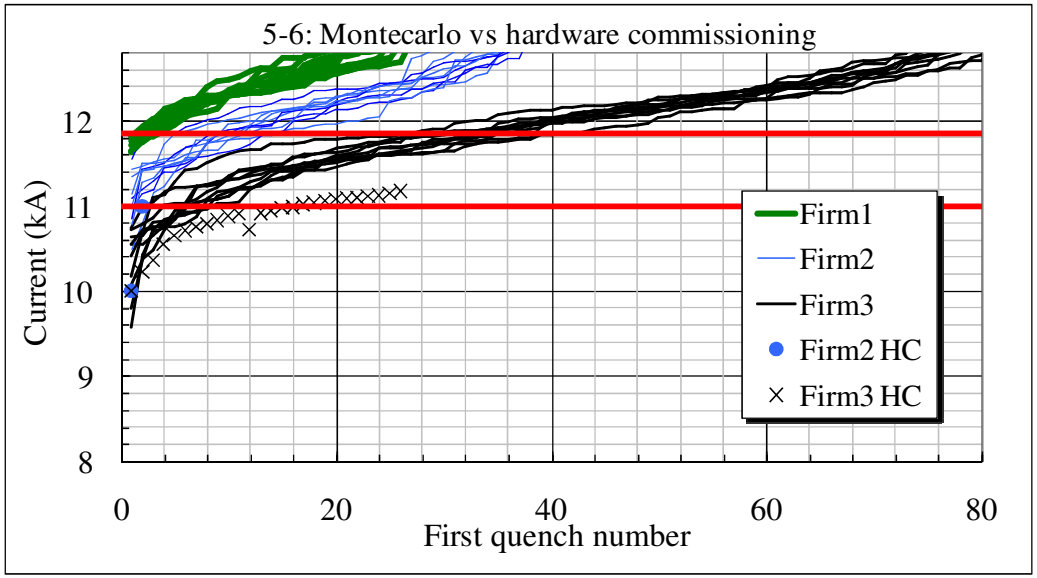


Tested after thermal cycle		
Firm1	44	32%
Firm2	58	42%
Firm3	36	26%
Total	138	100%

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

FORECAST BASED ON SURFACE TEST DATA: MONTECARLO ON 5-6

- MonteCarlo method based on surface test data:
  - ☺ 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!!

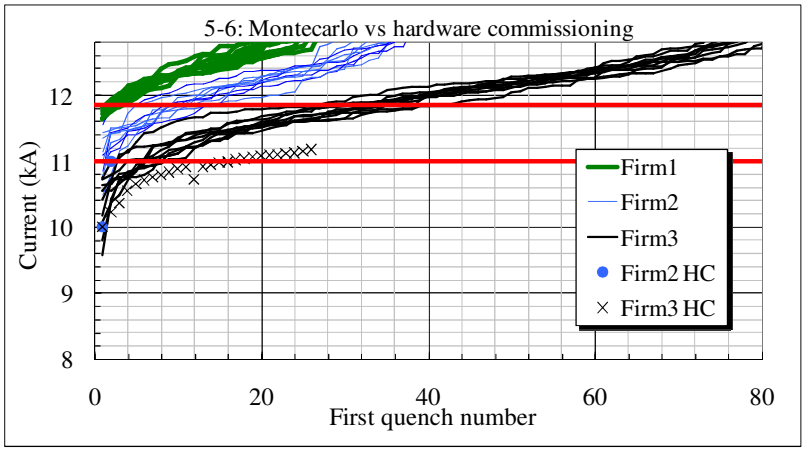


MonteCarlo forecast for 5-6 and hardware commissioning data
[B. Bellesia, N. Catalan Lesheras, E. Todesco, Chamonix 2009]

FORECAST BASED ON SURFACE TEST DATA: MONTECARLO EXTENDED TO THE LHC

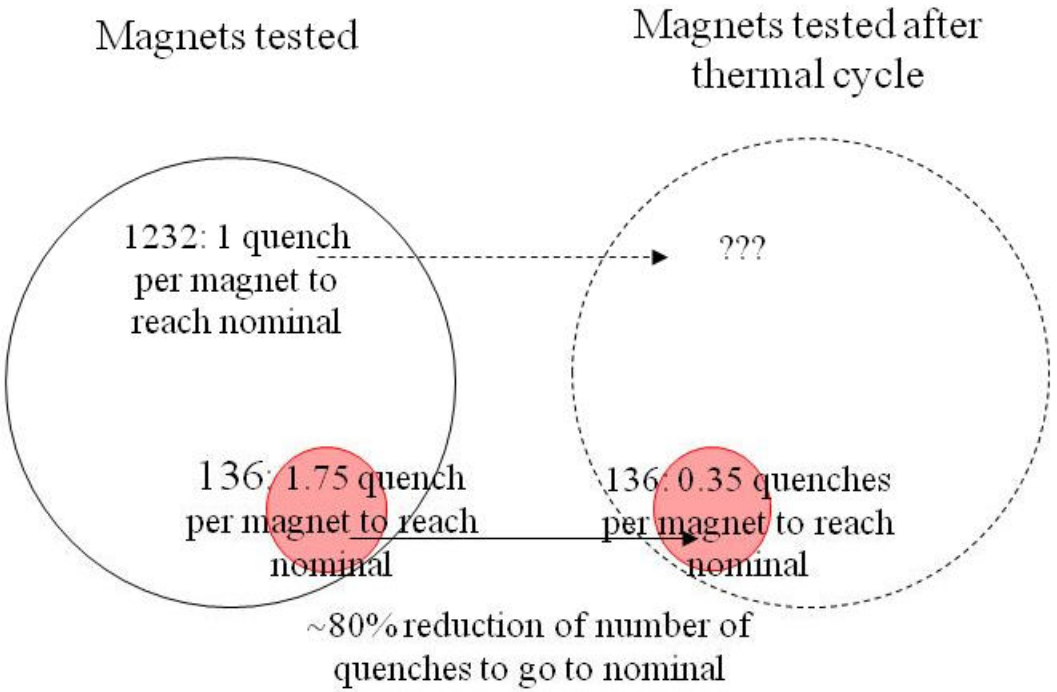
- MonteCarlo method:
  - For 5-6 to reach nominal: 5 quenches from Firm1, 15 from Firm2, 35 from Firm3
  - Correcting for the composition of 5-6, we get 400 quenches to reach nominal for the LHC, or 50 quenches per octant

	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

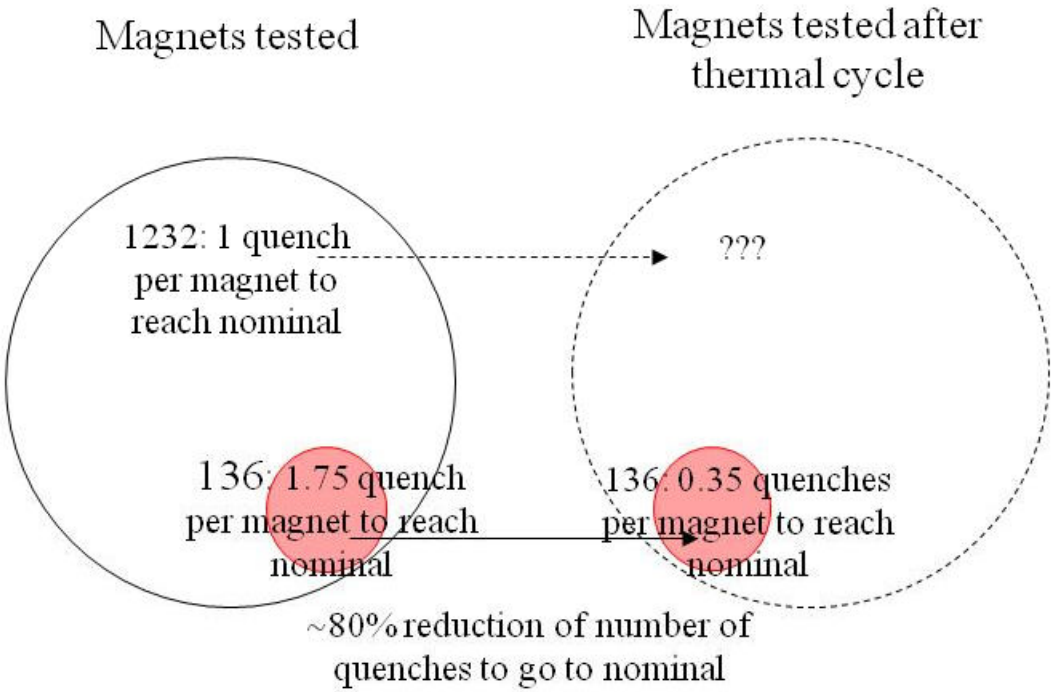


- SCALING-1 HYPOTHESIS: Applying the 80% reduction to the whole sample → 0.2 quenches needed to go to nominal → 30 quenches per octant

[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 …

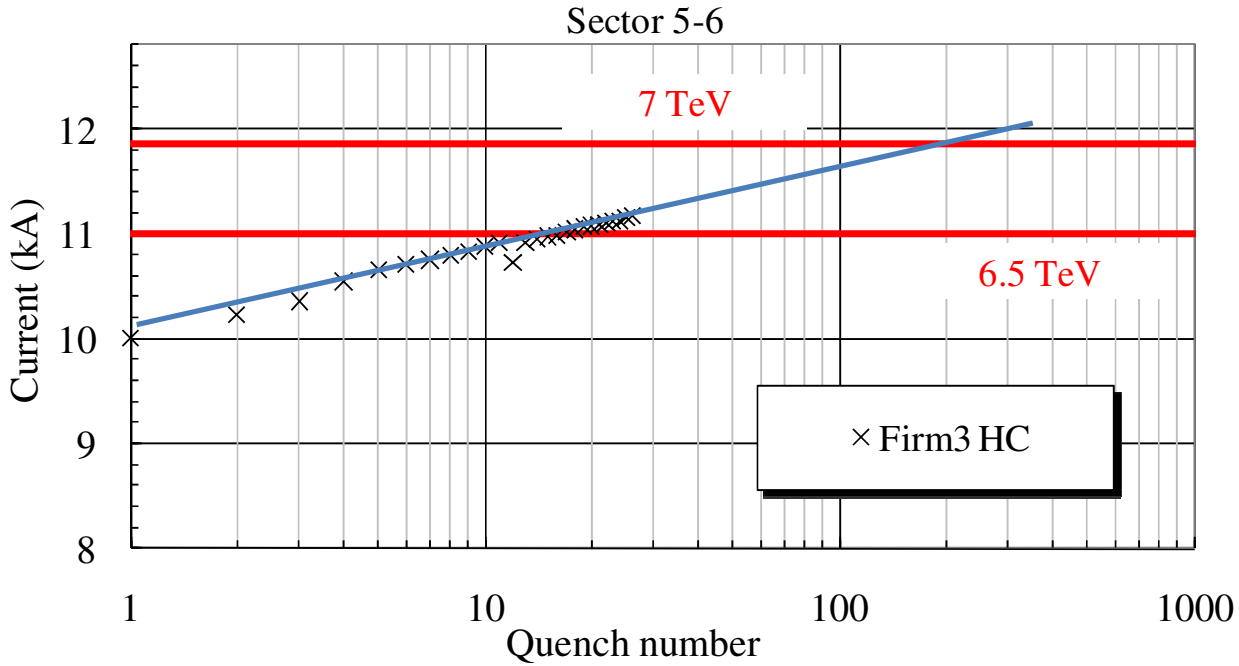


- SCALING-2 HYPOTHESIS: assuming that all magnets after thermal cycle behave as the sampled ones → 0.35 quenches per octant to reach nominal applies to the LHC → 50 quenches to reach nominal

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

FORECAST BASED ON HARWARE COMMISSIONING DATA: EXTRAPOLATION

- Empirical extrapolation of hardware commissioning data based on exponential fit (very pessimistic)



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

- Last method: MonteCarlo for Firm1 and Firm2, plus total loss of memory of Firm3
  - Remember Firm3 took 1 quench per magnet to go to 7 TeV in virgin conditions
  - Estimate= 72 (Firm1)+155 (Firm2)+416 (Firm3)=640 quenches = 80 quenches per octant
- Summary training to 7 TeV

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
MonteCarlo Firm1/2 + total detraining Firm3	80	Based on test and HC data
Extrapolation	110±25	Based on HC data

- 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

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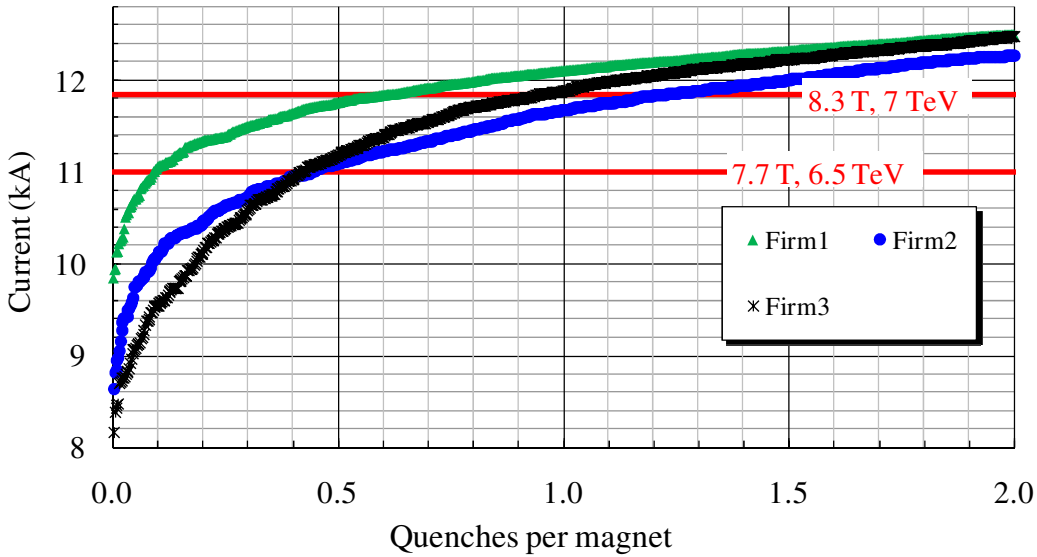
THE FIRM3 ANOMALY

- 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 more numerous than Firm2 and Firm1

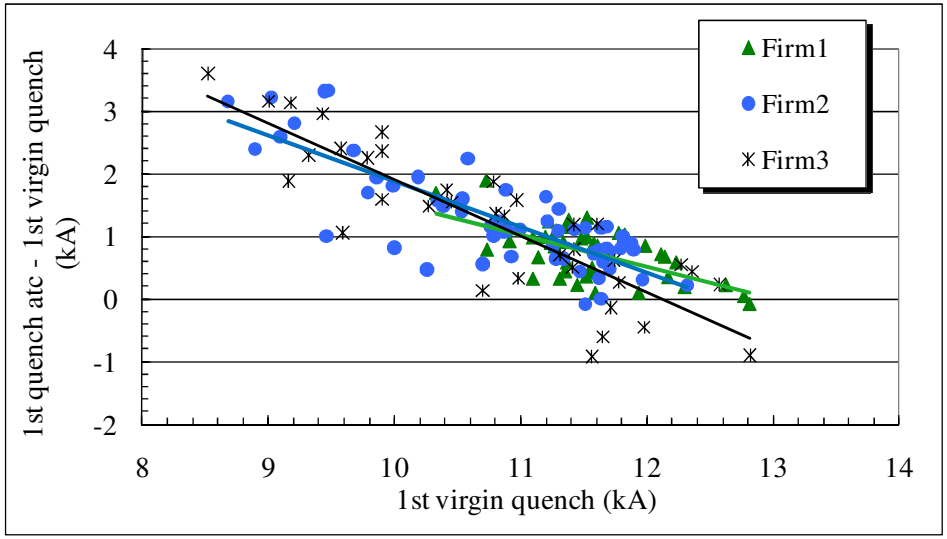


Cumulated performance of the dipoles during virgin training
[B. Bellesia, N. Catalan Lesheras and E. Todesco, Chamonix 2009]

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

THE FIRM3 ANOMALY

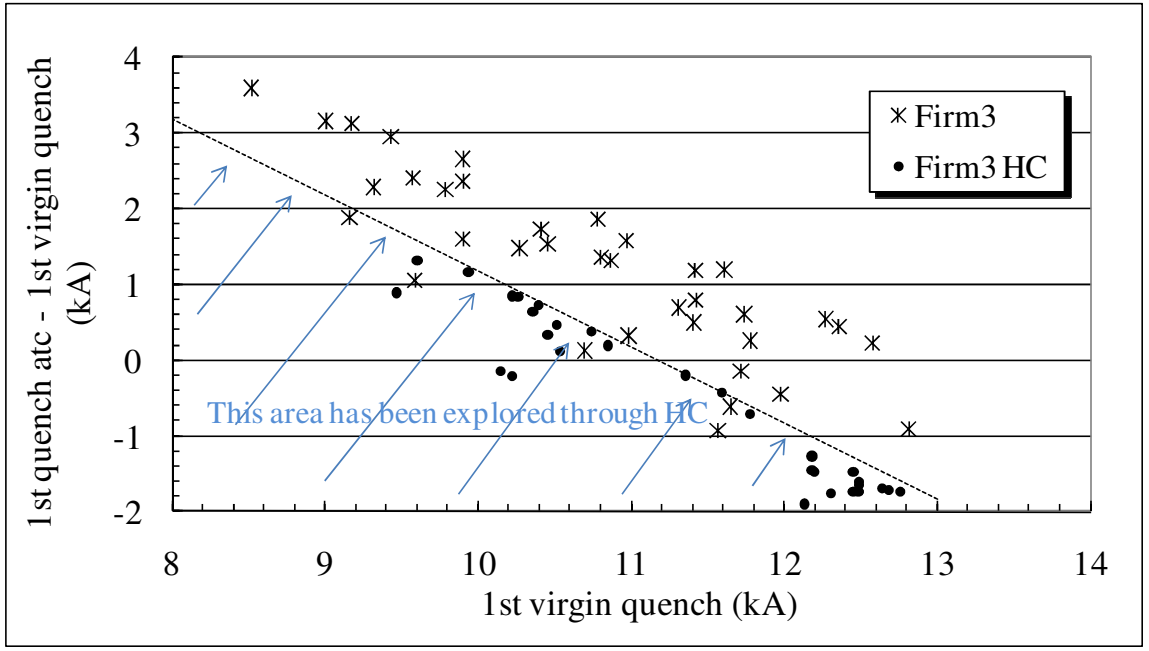
- Firm3 anomalies in quench perfomance were visible in two different aspects in surface test data
  - (2) De-training after thermal cycle
    - On the 138 magnets tested after thermal cycle, Firm3 is the only one showing more detraining, and net loss after thermal cycle in a few cases



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

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)

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
  - Is this relevant ?
  - 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)
[courtesy of C. Lorin]

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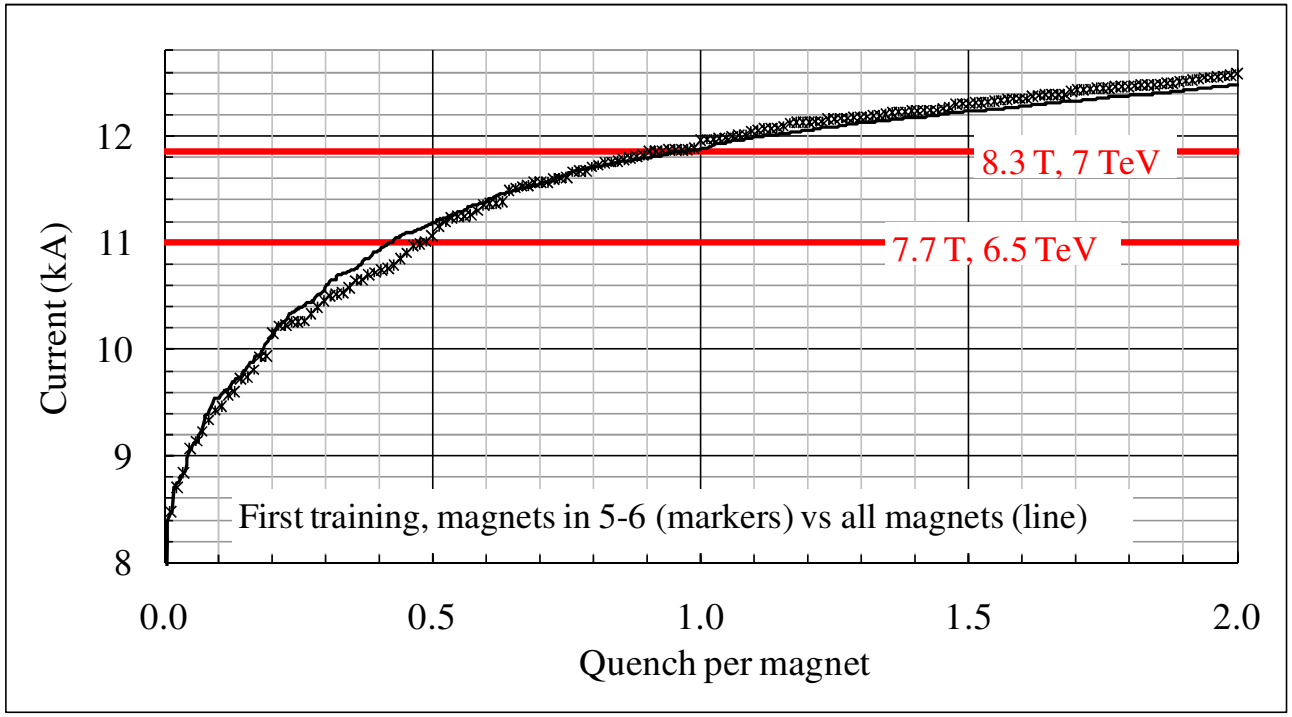
ANALYSIS: HOMOEGENITY

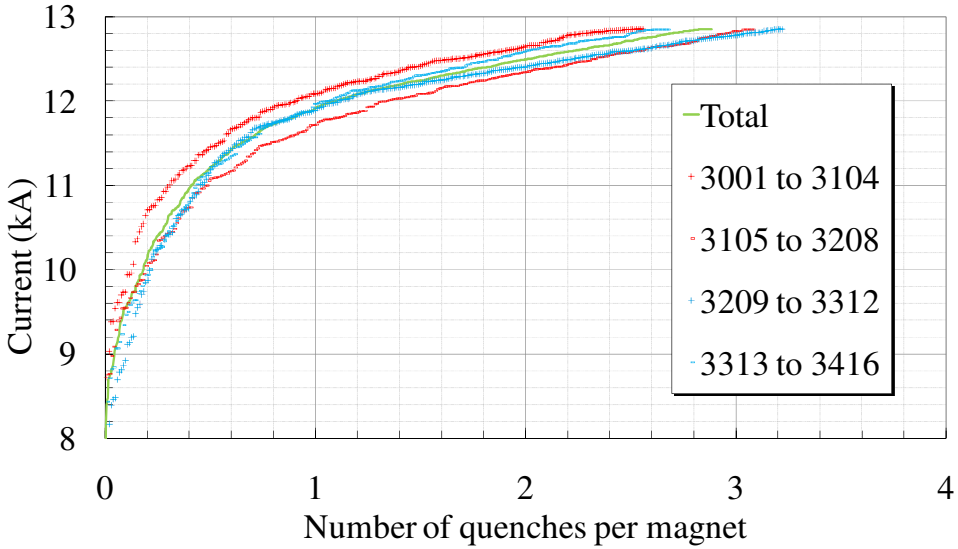
- 1st question: are Firm3 magnets in 5-6 anomalous w.r.t. the whole Firm3 production?
  - No, the cumulated training of Firm3 magnets in 5-6 is very similar to the whole batch



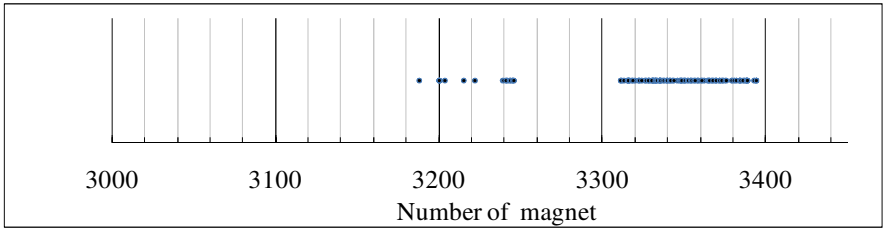
Cumulated performance of virgin training of all Firm3 magnets, and of Firm3 magnets in 5-6

ANALYSIS: HOMOEGENITY

- 1st question: are Firm3 magnets in 5-6 anomalous w.r.t. the whole Firm3 production?
  - But it is true that there has been a degradation along the production: first 100 very good, than worse
  - 5-6 contains a specific batch, mainly magnets from 3300 to 3400



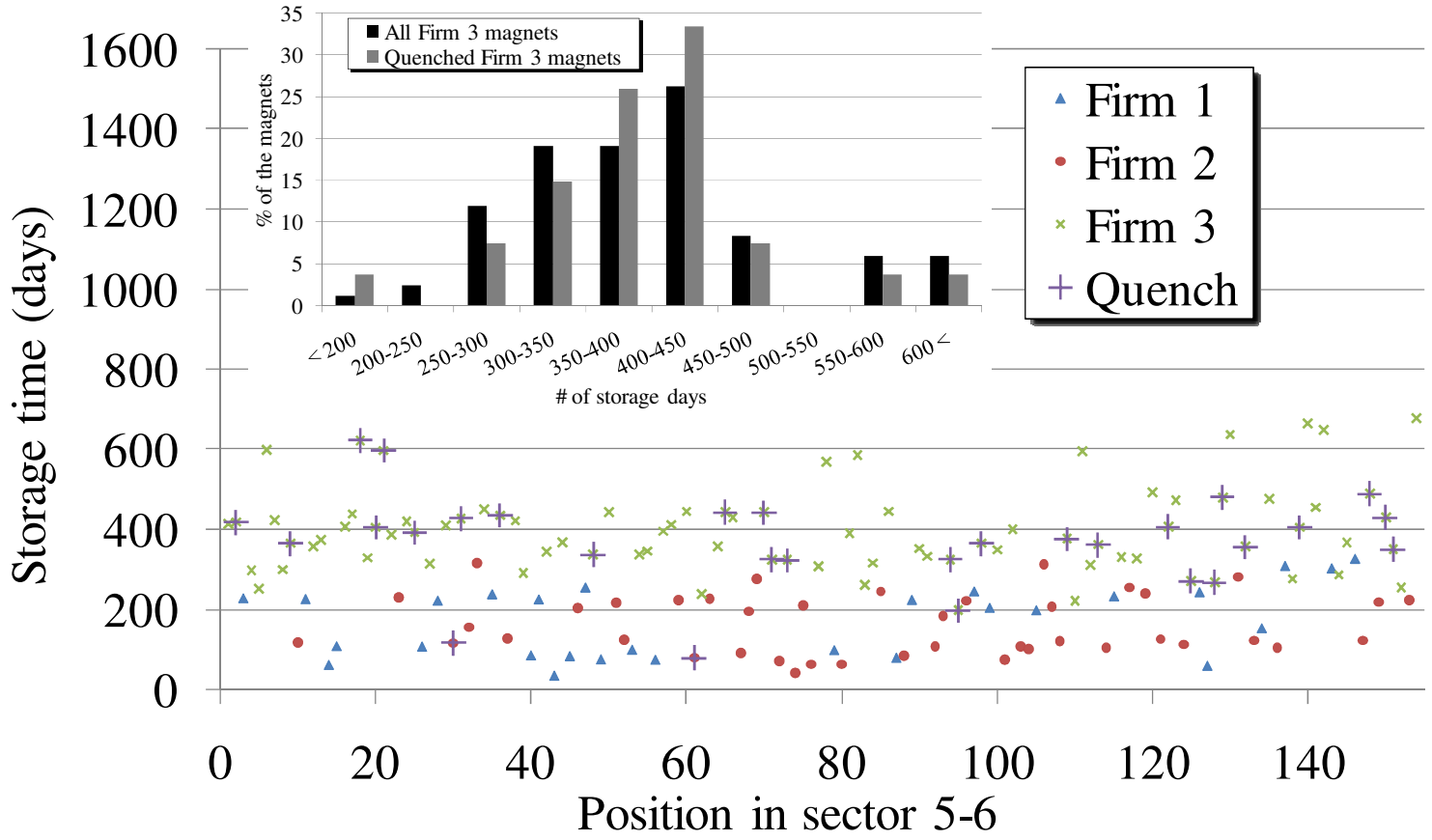
Cumulated virgin training of Firm3 magnets, split in four batches
[courtesy of C. Lorin]



Firm3 magnets installed in 5-6

ANALYSIS: HOMOEGENITY

- 2nd question: is this detraining due to storage time ?
  - There is no indication of a correlation with storage time

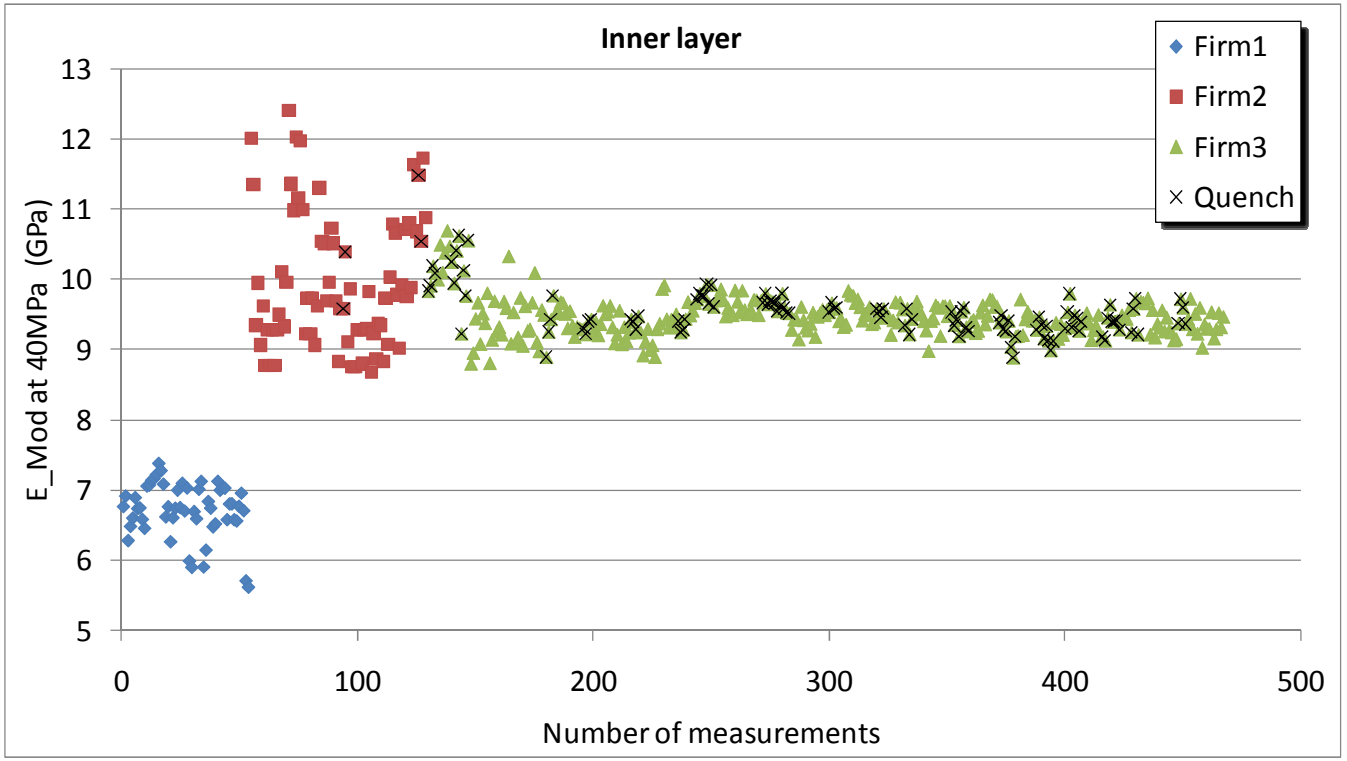


Storage time for magnets in 5-6 versus quenched magnets

[courtesy of A. Musso and C. Lorin]

ANALYSIS: HOMOEGENITY

- 3nd 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 and C. Lorin]

ANALYSIS: HOMOEGENITY

- 3nd 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, outer layer

[courtesy of A. Musso and C. Lorin]

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 more training - we have no data!
    - HC commissioning data of other sectors will not come before 1 year

- Causes of Firm3 anomaly are under analysis
  - Evidence of anomalies in surface test data:
    - Slow training at low fields and detraining after thermal cycle ,
  - But this is not the whole story!

CONCLUSIONS AND ACTIONS

- Actions
  - Continue the analysis of correlations with production parameters
  - One could make an extensive campaign of quenches over several thermal cycles on 2 magnets per Firm, with quench location [proposal from G .De Rijk]
    - After the incident this is possible, before all Firm3 magnets were in the tunnel ☺
  - But …
    - One could risk to damage the spares
    - The statistics could be not significant
    - The magnets from Firm3 come out of the incident → one would keep the doubt of a bias