# TRAINING OF THE LHC DIPOLES ABOVE 6.5 TEV OPERATIONAL CURRENT

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Based on the hardware commissioning data of 2017, 2016, 2015 and 2008
and on production data 2001-2006
Thanks to MP3 team, SM18 team (present and past),
and project engineers at the time of production

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- Distributions of quench currents
- The powering above 6.5 TeV
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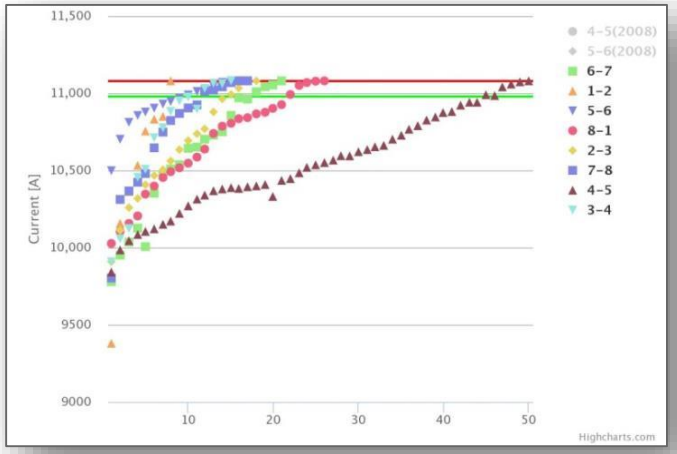
# A BIT OF HISTORY

- LHC dipoles assembled by three manufacturers (series 1000, 2000 and 3000)
  - Built to print, same procedures with few exceptions
- LHC energy/dipole field/current/loadline margin:
  - Nominal LHC energy of 7 TeV: dipole at 8.3 T, corresponding to 11.85 kA, dipoles at 86% of loadline margin
  - Ultimate LHC energy of 7.5 TeV: dipoles at 8.9 T, corresponding to 12.75 kA, dipoles at 92% of loadline margin
- Individual tests: all magnets tested at 1.9 K
  - All powered above 12.0 kA (i.e. for 7 TeV operation)
  - About 50% powered to 12.85 kA (i.e. for 7.5 TeV operation)
  - Less than 10% went through thermal cycle (biased sample)
- LHC operated at 3.5 TeV, then at 4 TeV in RunI
  - Consolidation of dipole splices in 2013-14 allowed to go to high energies

# SUMMARY OF 6.5 TEV COMMISSIONING

Quench Behaviour Team

- In 2015 we aimed at operation at 6.5 TeV (10980 A)
  - We took 100 A operational margin, so we trained LHC up to 11080 A
  - 172 quenches
    - Large difference between series confirmed
      - 5 quenches from 1000 series (1%)
      - 27 quenches from 2000 series (12%)
      - 140 quenches from 3000 series (87%)
    - Negligible number of second quenches (6%), all in 3000 series
      - Second quench definition: magnet quenching twice




| sector | installed per sector 1000 | 2000 | 3000 | total |
|---|---|---|---|---|
| 12 | 50 | 95 | 9 | 154 |
| 23 | 56 | 58 | 40 | 154 |
| 34 | 44 | 81 | 29 | 154 |
| 45 | 48 | 44 | 62 | 154 |
| 56 | 28 | 42 | 84 | 154 |
| 67 | 57 | 36 | 61 | 154 |
| 78 | 53 | 40 | 61 | 154 |
| 81 | 64 | 24 | 66 | 154 |
| LHC | 400 | 420 | 412 | 1232 |

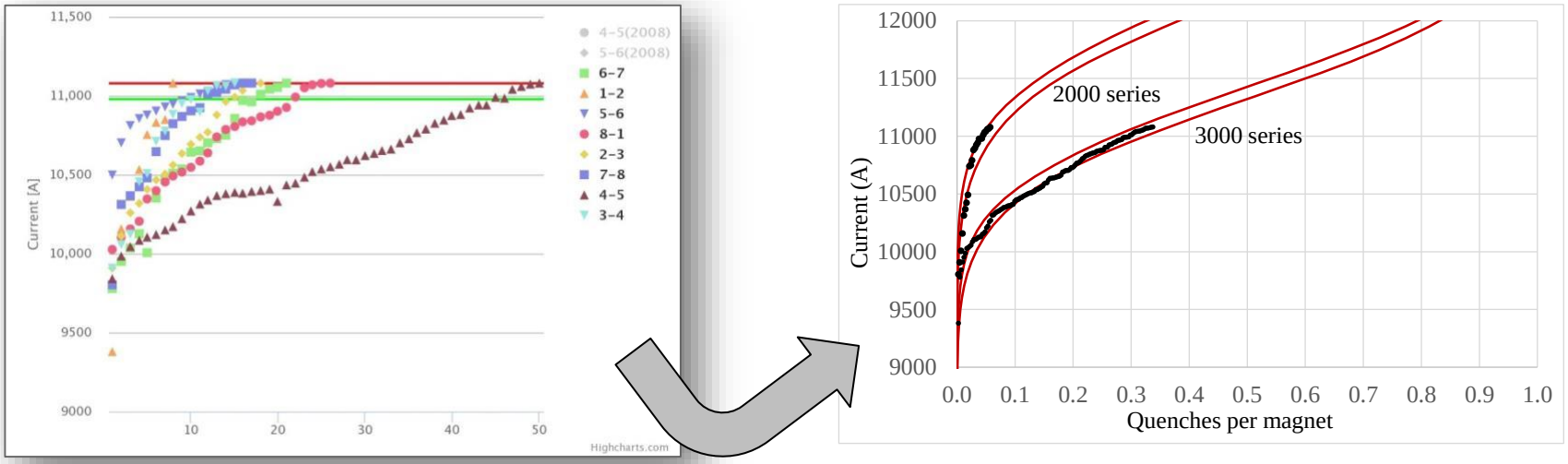
Quenches to 11080 A in 2015

| sector | 1000 | 2000 | 3000 | total |
|---|---|---|---|---|
| 12 | 2 | 1 | 4 (1) | 7 (1) |
| 23 | 0 | 2 | 15 | 17 |
| 34 | 1 | 7 | 8 (1) | 16 (1) |
| 45 | 0 | 3 | 46 (7) | 49 (7) |
| 56 | 0 | 0 | 17 | 17 |
| 67 | 0 | 1 | 19 | 20 |
| 78 | 2 | 10 | 6 | 18 |
| 81 | 0 | 3 | 25 (2) | 28 (2) |
| LHC | 5 | 27 | 140 (11) | 172 (11) |

A. Verweij and MP3 team, 2015

# SUMMARY OF 6.5 TEV COMMISSIONING

- In early 2016 the management decided to aim at 7 TeV as LHC operational energy after 2019-2020 shutdown
  - Based on the very smooth operation at 6.5 TeV (see J. P. Tock talk)
  - Based on a on Gaussian fit of the quench distributions, giving about 500-600 quenches to reach 7 TeV
    - Training curve as integral of a Gaussian distribution (E. Todesco, et al. ASC 2016)

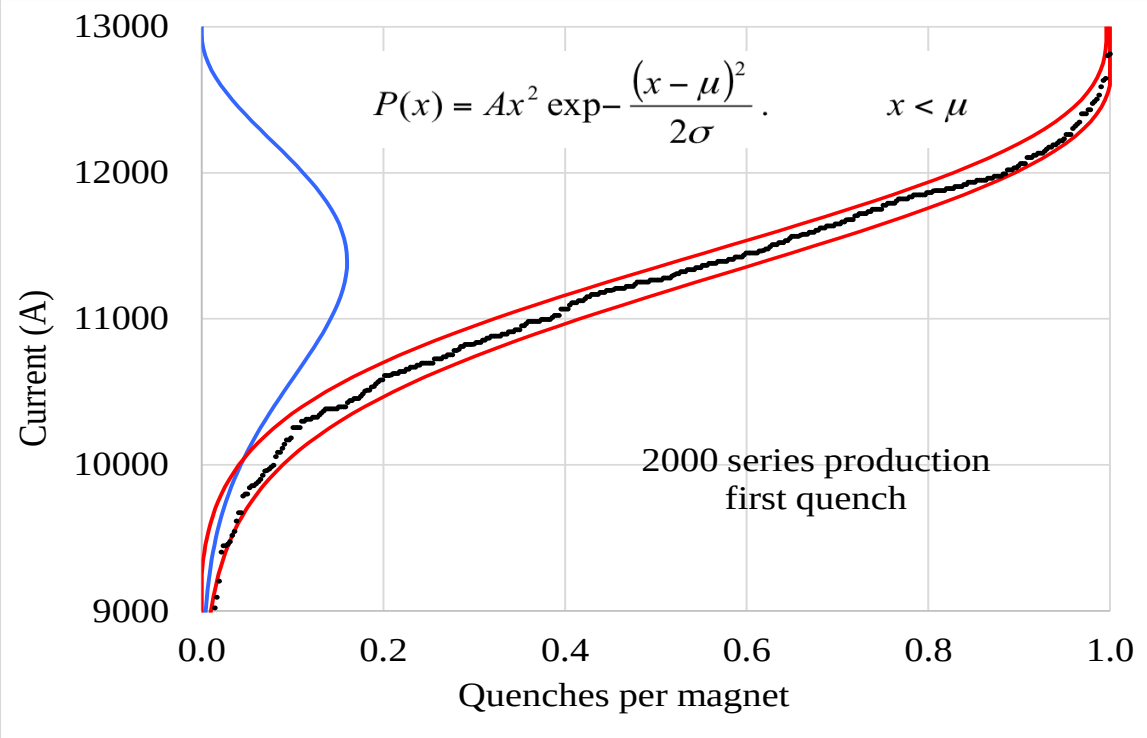



Training of the 8 sectors of LHC (left), and the same data separated by series with Gaussian fit (right)

- In winter 2016-2017, 308 dipoles powered above 6.5 TeV

# DISTRIBUTIONS

- First observations of a Gaussian tail in quench distribution suggested using an asymmetric Gaussian for the fit
  - Further analysis showed that a Gaussian multipled by a parabola fit well the data




Modified Gaussian fit for the first quench in individual test (D. Mapelli thesis)

# POWERING ABOVE 6.5 TEV

Quench Behaviour Team

- We had 32 quenches above 11.08 kA
  - The campaign has been stopped around 11.5 kA by
    - Short circuit in sector 34
    - Available time in sector 45

2016: quenches from 11080 A to 11415/11536 A

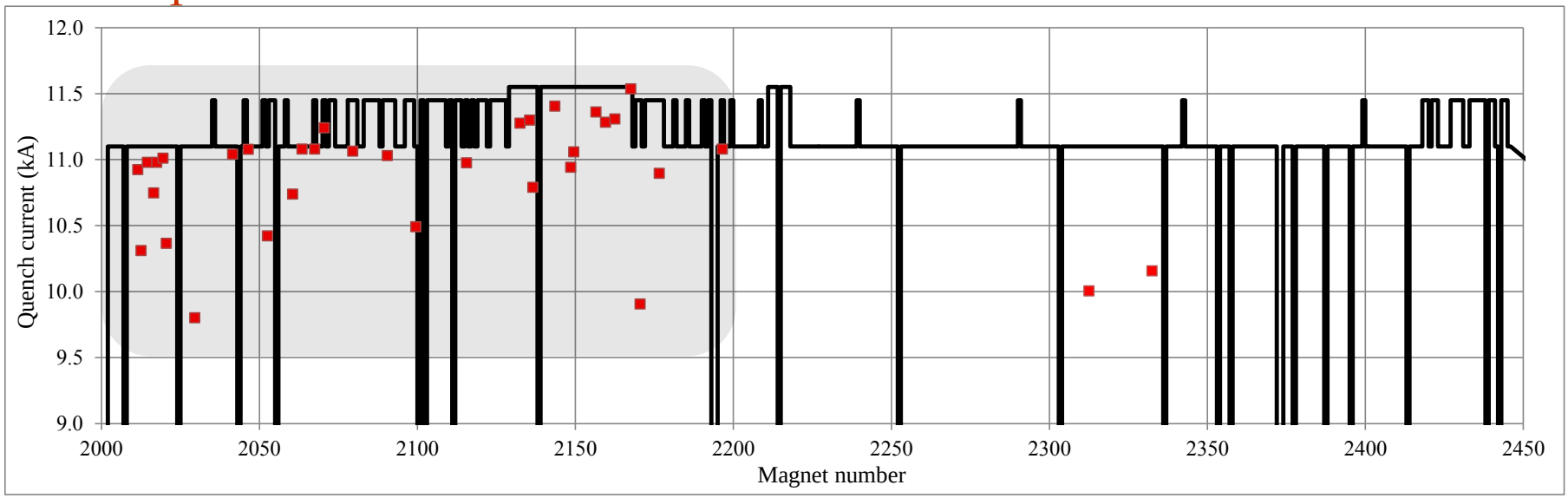
| sector | 1000 | 2000 | 3000 | total | current (A) |
|---|---|---|---|---|---|
| 34 | 1 | 1 | 6 (2) | 8 (2) | 11415 |
| 45 | 0 | 7 | 17 (8) | 24 (8) | 11536 |
| total | 1 | 8 | 23 (10) | 32 (10) | |

A. Verweij and MP3 team, 2016-2017

    - Decision to consolidate diodes in 2019-20 to avoid shorts (J. P. Tock talk)
- The campaign confirmed the main features
  - Large difference between series, large difference within series
  - No second quenches in 1000 and 2000 series
  - No visible showstopper
- Capability of the MP3 team to safely deal with large number of quenches, and all the complexity of the protection system

# DIFFERENCES ALONG THE PRODUCTION

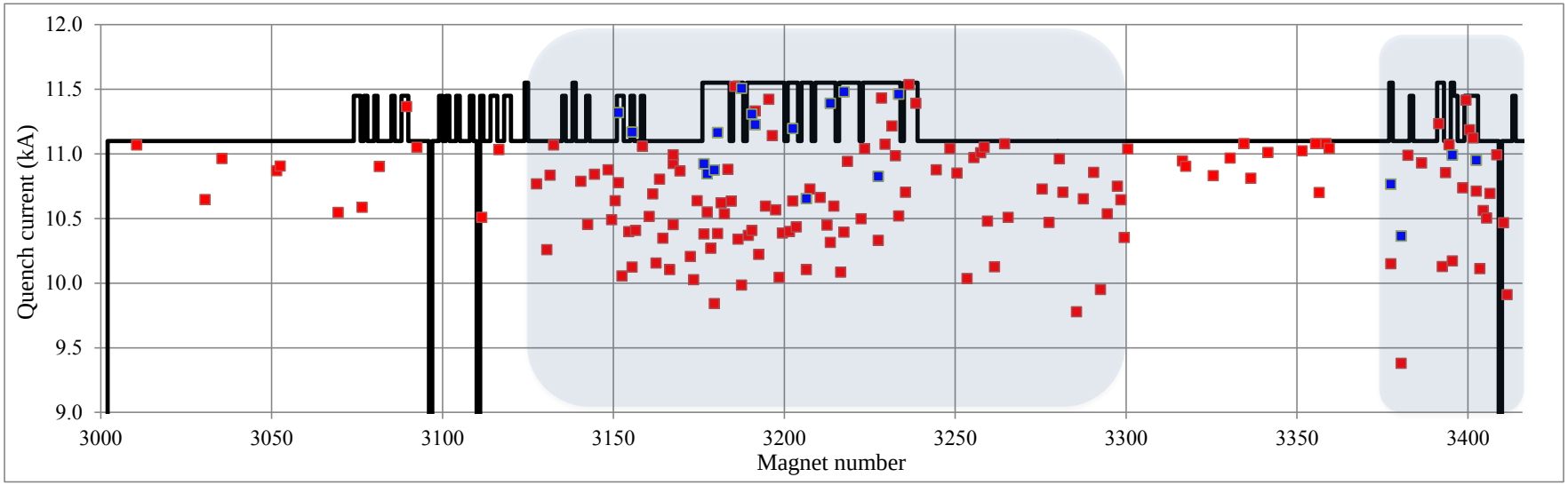
- The campaign confirmed very large differences along the 2000 and 3000 series production
  - 2000 series has the second half of the magnets with negligible quench




  - Red dots: first quenches after installation
    - No second quenches observed
  - Black line: maximum current reached in the LHC

# DIFFERENCES ALONG THE PRODUCTION

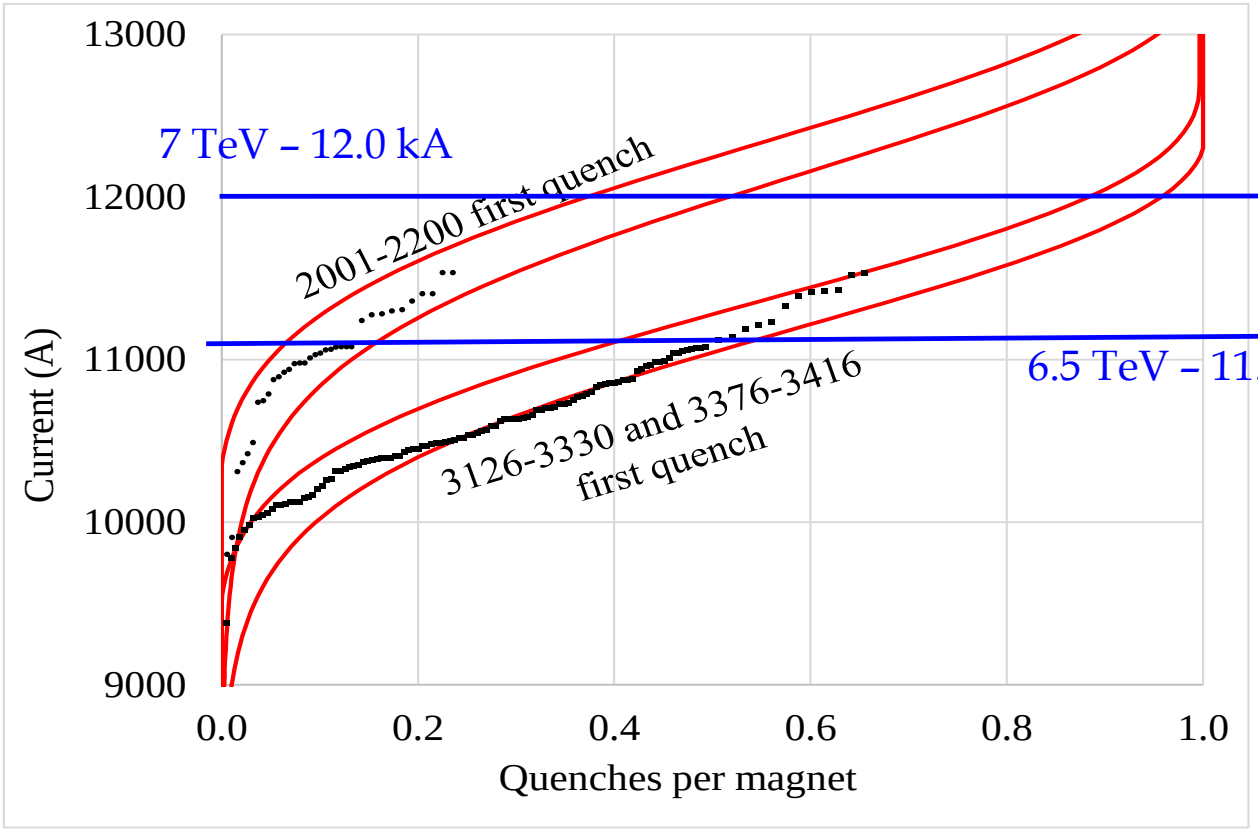
- The campaign confirmed that second quenches are seen only in part of the 3000 production
  - In both cases the reasons for these variation are still unknown




- Red dots: first quenches after installation
- Blue dots: second quenches after installation
- Black line: maximum current reached

# MODIFIED GAUSSIAN FIT

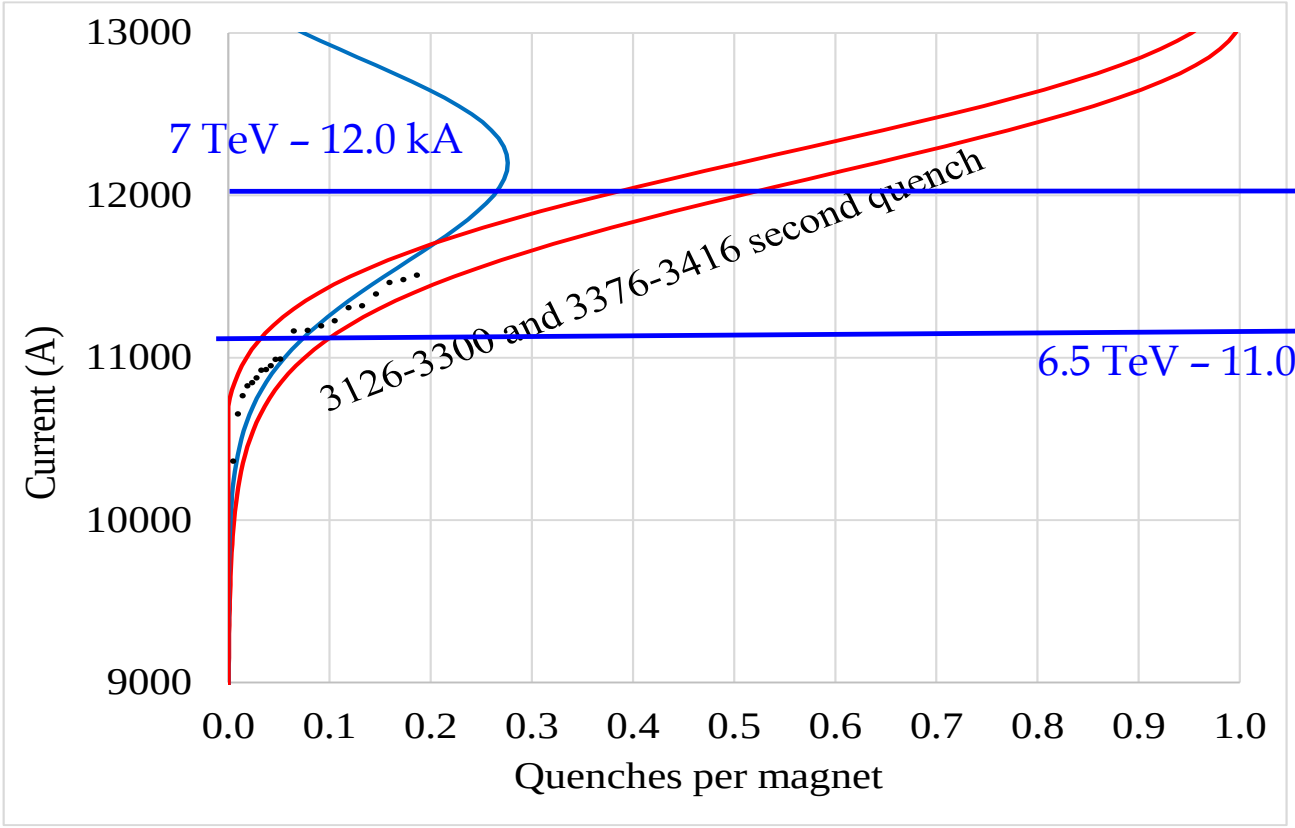
- Data above 11.08 kA follow the modified Gaussian fit
  - Statistics is low, so there is a large statistical error – but no wall is visible




Modified Gaussian fit for first quench of two batches of 2000 and 3000 series, and training after installation

# MODIFIED GAUSSIAN FIT

- Same for the case of the second quench
  - Statistics is low, so there is a large statistical error – but no wall is visible

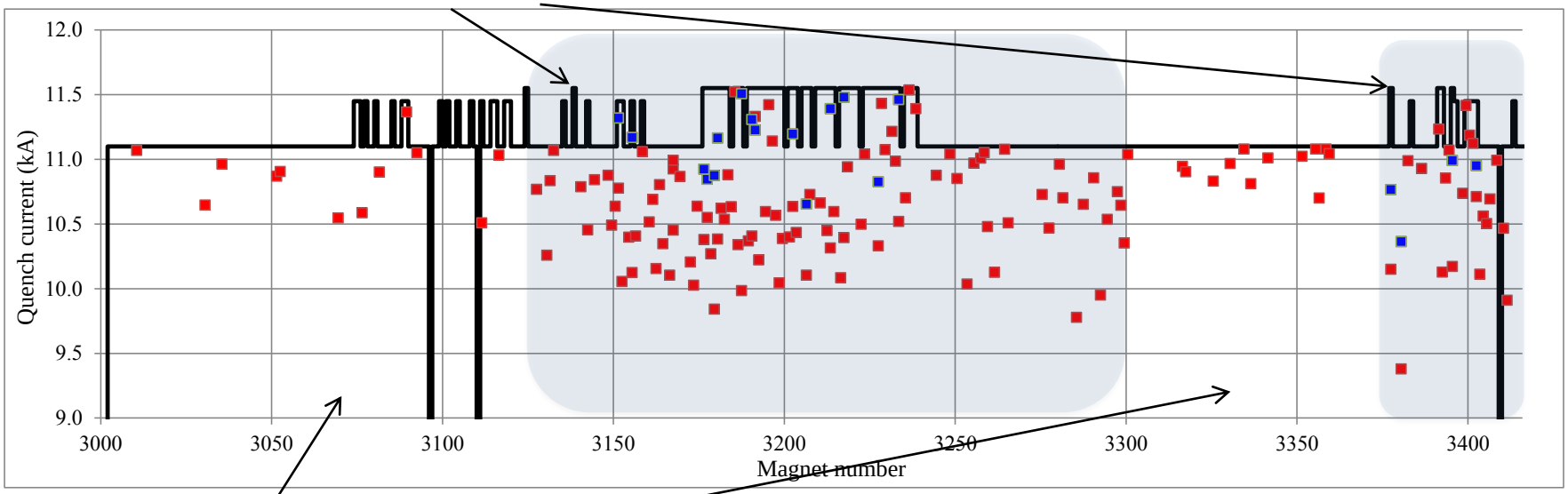



Modified Gaussian fit for second quenches, and training after installation

# CORRELATION TO INDIVIDUAL TESTS

- We find a strong correlation of the training after installation to individual tests after thermal cycle

35% of these magnets tested ATC had a quench below 11.08 kA




0% of these magnets tested ATC had a quench below 11.08 kA

- On the other hand, no correlation to quench at first powering (35% in both batches)

# SUMMARY

- LHC will aim at 7 TeV operation after 2019-2020 shutdown
  - This corresponds operating 1232 dipoles at 86% of the short sample current
  - A new powering campaign above 6.5 TeV has been done in winter 2016-2017 on one quarter of the LHC (308 dipoles)

- Data confirm the absence of showstoppers towards higher fields (and energies)
  - Half of the LHC magnets have negligible quench
  - The other half follow modified Gaussian distributions, and after initial saturation (integration of the tails) we are now in a quasi-linear regime (integration of the peaks)
  - A 500-600 quench estimate to reach 7 TeV operation is confirmed

- Strong differences between the three series, and within the 2000 and 3000 series, are visible, seen in individual tests after thermal cycle, and not understood