ENERGY OF THE LHC
AFTER LONG SHUTDOWN 1 (2013-2014)

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With relevant inputs from colleagues
L. Bottura, F. Bordry, G. d’Angelo, G. De Rijk, P. Fessia, K. Foraz,
E. Nowak, A. Siemko, J. P. Tock, D. Tommasini, A. Verweij
Measurements at SM18 of 3-4 magnets
G. Dib, G. Deferne
Production data of training at SM18
V. Chohan, the SM18 team and the Indian collaboration
Estimates to reach 6-6.5 TeV
- Magnets measured during production
- Magnets (mainly of 5-6) training during hardware commissioning
- Magnets tested in 2009-2011 (from 3-4 incident)

Models for 7 TeV

Risks related to quench heater weakness

Strategy
First approach: take the measurements after thermal cycle, compute the quench probability and apply to the LHC


About 10% sampling (119 magnets tested out of 1232)

«After a TC performed on ~11.5% of MB […] ~25% of MB required at least one training quench to reach the nominal field equal to 8.33 T […] the number of quenches that may occur during the first powering cycles up to nominal field is around 330»

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Probably biased?

- According to the specification, magnets which had «bad performance» in virgin state went under a test after thermal cycle
- Estimate lowered to 200 total quenches to account for this effect, thus giving 25 quenches/sector

Second analysis performed at the end of the production

Large spread induced by the inclusion/exclusion of bad cases

Need of training to get to 6.5 TeV

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ESTIMATES TO REACH 6-6.5 TEV:
2 - MONTECARLO OF PRODUCTION DATA

- Take the data before thermal cycle, use the correlations in performance before and after thermal cycle with a MonteCarlo [B. Bellesia, N. Catalan Lasheras, E. Todesco, Chamonix 2009]
  - Contrary to previous scaling, we also use data in virgin conditions
  - Similar result, but first evidence of a weakness of Firm3 present in the production data

![Sector 5-6: Montecarlo vs hardware commissioning graph](image)

Current (kA) - First quench number

Firm1, Firm2, Firm3, Firm2 HC, Firm3 HC

7 TeV, 6.5 TeV
ESTIMATES TO REACH 6-6.5 TeV:
3 - TRAINING IN THE TUNNEL IN 2008

• Hardware commissioning data in 2008 (training in the LHC)
  • All sectors reached 5 TeV, seven reached 5.5 TeV
  • Two sectors trained up to 6 TeV with few quenches
  • Sector 5-6 pushed up to 6.6 TeV with ~30 quenches
  • Surprise: nearly all quenches from Firm3 magnets

• Scaling of these data
  • More pessimistic w.r.t production data – sign of degradation

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32 magnets measured, coming from 3-4 incident
- Low sampling (15 from Firm1 – 11 from Firm2 – 6 from Firm3)
- Could be biased if the magnets suffered from incident
- «For these magnets, coils have not been touched, at most the electrical connections were cured» [P. Fessia]
- Unfortunately, only 6 from Firm3

Scaling of these data
- Consistent with production data 😊😊😊

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- Magnets measured during production
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Models for 7 TeV

Risks related to quench heater weakness

Strategy
A log fit was proposed for fitting training data in the tunnel

\[ I(n) \approx A + B \log n \]

Is the same type of log \( t \) dependence is used for creep
(Also used for flux creep in Tevatron data of chromaticity decay)

Not physical in the limit \( t \to \infty \)

900 to 1300 quenches to reach 7 TeV
Slip-stick model gives a functional equation for training


\[
E_f \propto F_r \Delta x \propto I^4
\]

\[
E_{f1}(I) = \alpha \left( I^4 - I_1^4 \right)
\]

\[
E_m(I) = f_m(I; I_{ss}) \approx \beta (I_{ss} - I)
\]
The slip-stick model gives a functional equation for training:

\[ I(n) \rightarrow I_{ss}\left[1 - \exp(-n/n_q)\right] \]

One parameter is freed to have a better fit of initial part of virgin data:

- And extrapolation is taken on 5-6 data (2008 training in the tunnel)
- This gives an estimate of \(~110\) quenches per octant for 7 TeV (as lower limit of from log fit)

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Both a log fit and an exp fit work … isn’t it strange?

It may happen over certain range

- I show it for chroma decay which has similar exp fit
  - The double exp fit is used today in FiDeL for keeping chroma constant at LHC injection

Double exp used to fit chroma decay at injection

The same data in log scale!
SUMMARY OF ESTIMATES

- Final comparison of different estimates

![Graph showing number of quenches in the LHC vs. energy (TeV)]

- Scaling of production after thermal cycle
- Scaling/extr. on hardware commissioning
- Scaling on magnets from 3-4
Large error associated to the estimates

- For scaling up to 6.5 TeV, low sampling
- For 7 TeV the model and the extrapolation, adding to the sampling

We have to guess an average probability of quenching

- It could look like a binomial
  \[ F(k; n, p) = \binom{n}{k} p^k (1 - p)^{n-k} \]
  \[ \frac{1}{n} \mu[F(k; n, p)] = p \]
  \[ \frac{1}{n} \sigma[F(k; n, p)] = \sqrt{\frac{p(1-p)}{n}} \]
  … but it is not

I am still convinced the error is proportional to the \(1/\sqrt{n}\)

- Discretization errors are already large
  - 0 quenches could mean 0.5 quenches per magnet … this would give 50 quenches to get to 6.5 TeV in 3-4 magnets

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<td>11</td>
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<td>Expected quenches in LHC</td>
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SUMMARY OF ESTIMATES

- Final comparison (zoom of previous data)
  - Different models give an idea of the associated errors

![Graph showing number of quenches in the LHC versus energy (TeV). The graph includes data points for scaling of production after thermal cycle, scaling on hardware commissioning, and scaling on magnets from 3-4.]
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Risks related to quench heater weakness

Strategy
RISKS

- 7 dipoles from Firm2 have non conformity in the quench heaters [from J. P. Tock]
  - 3 at the level of the IFS, no need of disassembly – just a warm up
  - 4 inside the magnet, they will be replaced in 2013 shutdown

- In 2010, about 100 magnet quenches at current 2 kA and 6 kA [from A. Siemko, this Chamonix]
  - Plus, since 2008, quench heaters have been fired ~6000 times in the tunnel at 0 A [from E. Nowak]
    - Firing per magnet ranging from 3 to 17, average 5
      - Now voltage reduced from 900 V to 200 V during hardware commissioning

- During a magnet training quench, on average 4 magnets quench [from A. Verwej]
  - So, if we make 100 training quenches we have 400 quench heater firing, still well in the shadow
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Strategy
**STRATEGY**

- Push the four initial sectors to 6.5 TeV (Nov 2013- Mar 2014)
  - See if our estimates are valid: ~50 quenches expected in four sectors

Best guess of 2013-2014 shutdown schedule [K. Foraz]

😊 Fix 6.5 TeV as LHC energy and push the other four sectors there
😊 If more quenches are needed, fix 6.25 TeV as LHC energy and push there the other four sectors (~10 quenches expected in four sectors)
CONCLUSIONS

- Magnets coming from 3-4 do not show degradation of performance

- Our best estimates to train the LHC (with large errors)
  - ~ 30 quenches to reach 6.25 TeV
  - ~ 100 quenches to reach 6.5 TeV

- Two quenches/day → 2 to 5 days of training per sector
  - With 100 quenches one expects 400 quench heater firings

- The plan
  - Try to reach 6.5 TeV in four sectors in March 2014
  - Based on that experience, we decide if to go at 6.5 TeV or step back to 6.25 TeV in March 2014

- This still leaves three months for MonteCarlo
Quadrupoles performance:

- **SM18:**
  MQ as good as Firm1 MB

- **2008 hardware commissioning:**
  «During HWC they show no need of retraining, reaching nominal with a few quenches »