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

Contents

- 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

Estimates to reach 6-6.5 TeV:
1 - Scaling of production data

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

  [P. Pugnat, A. Siemko, *IEEE Trans. Appl. Supercond.* 17 (2007) 1091.]

- 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»

Method	Year	6 TeV	6.25 TeV	6.5 TeV	7 TeV
Scaling of production data after thermal cycle	2006				200-330

- 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

Estimates to reach 6-6.5 TeV: 1 - Scaling of production data

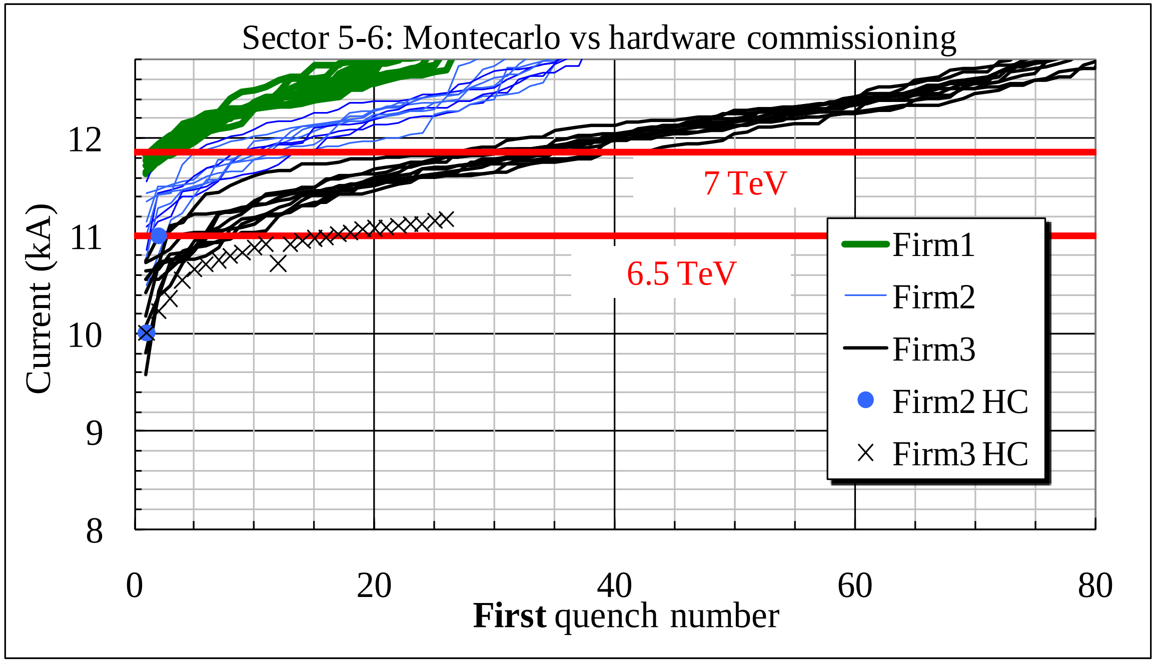
- Simplest approach: take the measurements after thermal cycle, compute the quench probability and apply to the LHC [P. Pugnat, A. Siemko, *IEEE Trans. Appl. Supercond.* 17 (2007) 1091.]
- Second analysis performed at the end of the production

  [E. Todesco et al., Chamonix 2009, C. Lorin, E. Todesco, CERN ATS Report 2010-164]
  - Large spread induced by the inclusion/exclusion of bad cases
  - Need of training to get to 6.5 TeV

Method	Year	6 TeV	6.25 TeV	6.5 TeV	7 TeV
Scaling of production data after thermal cycle	2006				200-330
Scaling of production data after thermal cycle	**2008**	**0**	**0**	**50-80**	**230-550**

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



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

Method	Year	6 TeV	6.25 TeV	6.5 TeV	7 TeV
Scaling of production data after thermal cycle	2006				200-330
Scaling of production data after thermal cycle	2008	0	0	50-80	230-550
Scaling of hardware commissioning	**2008**	**10**	**30**	**100**	**?**

Estimates to reach 6-6.5 TeV:
4 - Incident magnets tested in 2009-2011

- 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 ☺ ☺ ☺

Method	Year	6 TeV	6.25 TeV	6.5 TeV	7 TeV
Scaling of production data after thermal cycle	2006				200-330
Scaling of production data after thermal cycle	2008	0	0	50-80	230-550
Scaling of hardware commissioning	2008	10	30	100	?
Test of 3-4 magnets recovered after incident	**2011**	**0**	**0**	**0**	**330**

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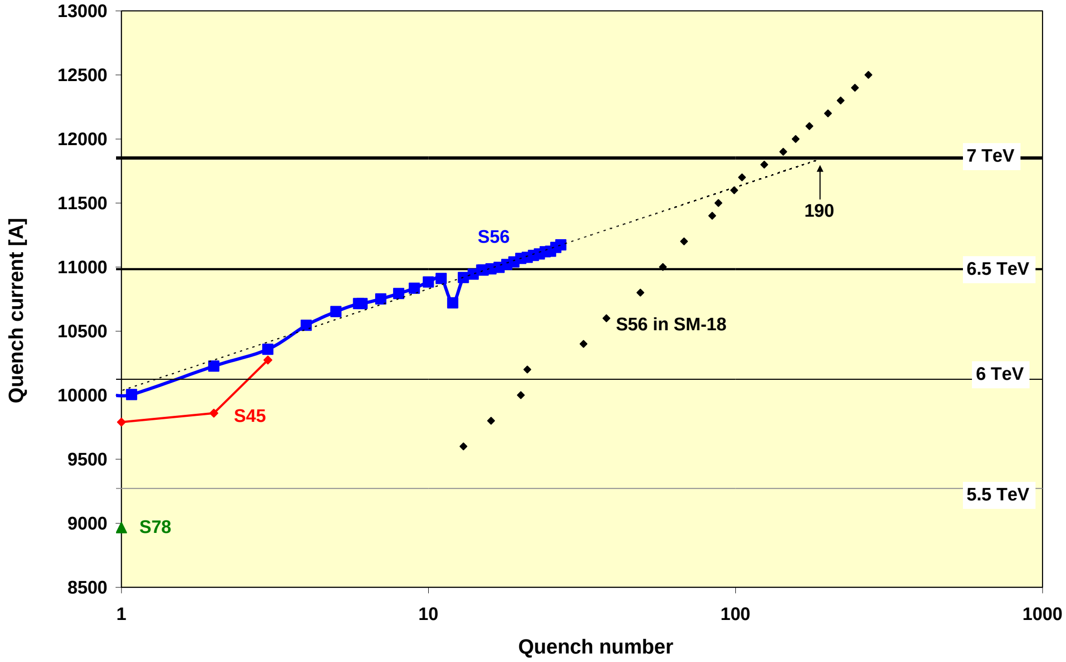
Models for 7 TeV: Quench «Creep»

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



$$I(n) \approx A + B \log n$$

A. Verweij,
Chamonix 2009
CERN ATS **2009-001** (2009) 25

  - Is the same type of log *t* dependence is used for creep

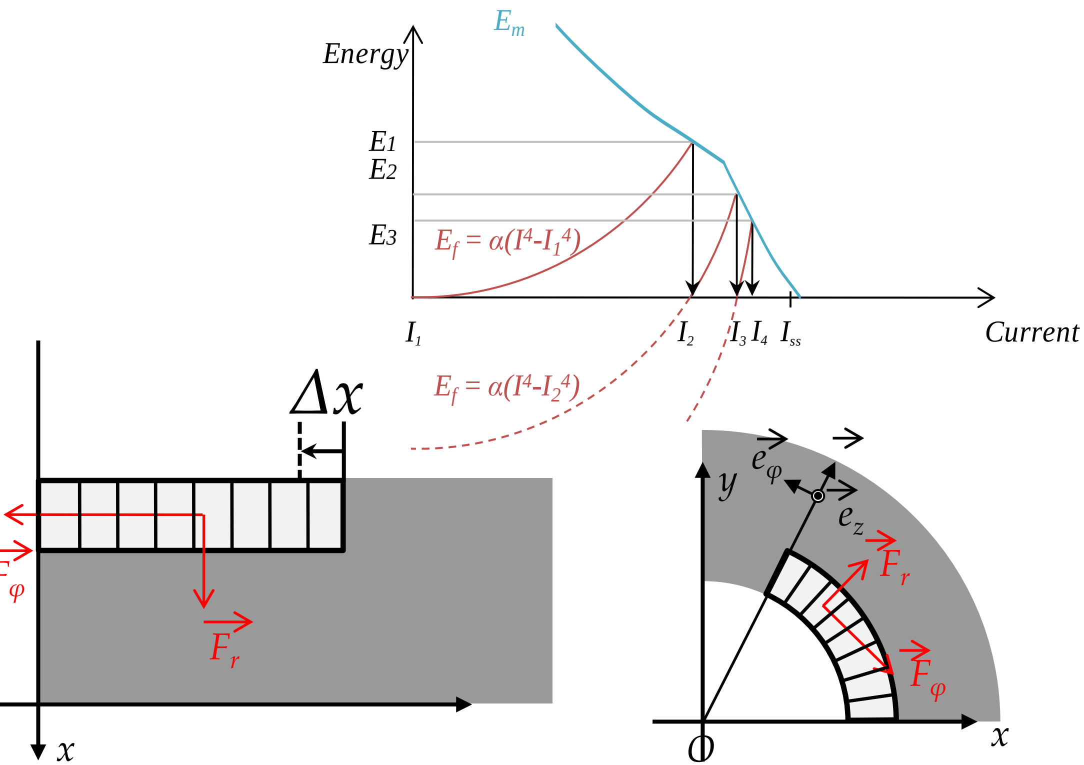
    (Also used for flux creep in Tevatron data of chromaticity decay)

    - Not physical in the limit $t \to \infty$

- 900 to 1300 quenches to reach 7 TeV

MODELS FOR 7 TEV: SLIP-STICK MODEL

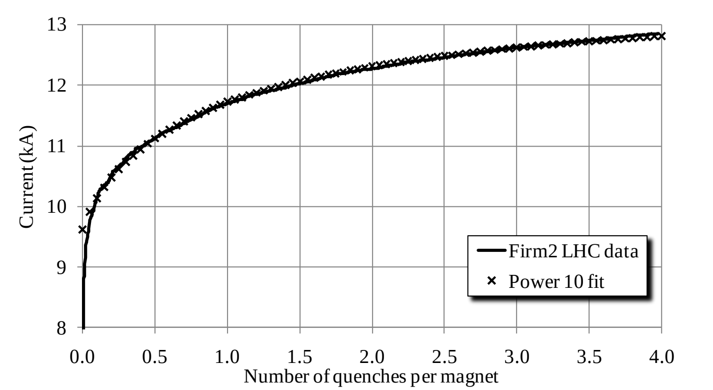
- Slip-stick model gives a functional equation for training
  - Equilibrium between superconductor margin and energy dissipated by friction [P. P. Granieri, C. Lorin, E. Todesco, *IEEE Trans. Appl. Supercond.* **21** (2011) 3555]



$$E_f \propto F_r \Delta x \propto I^4$$

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

$$E_m(I) = f_m(I; I_{ss}) \approx \beta(I_{ss} - I)$$



Models for 7 TeV: Slip-Stick Model

- The slip-stick model gives a functional equation for training
  - This model shown that asymptotic behaviour reached exponentially

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

- 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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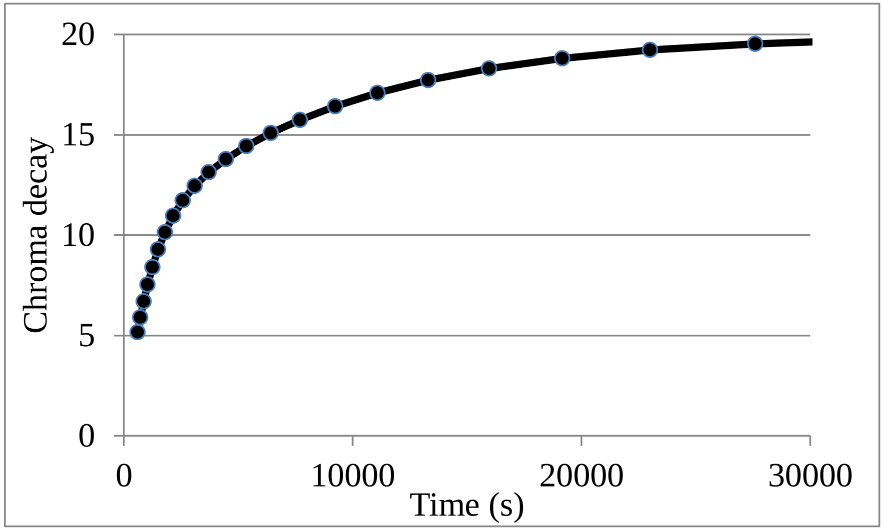
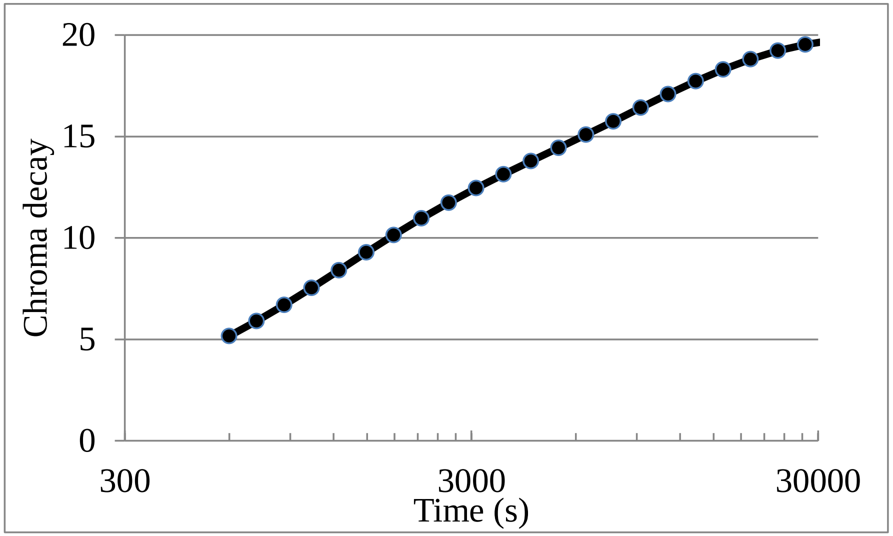
Scaling of production data after thermal cycle	2008	0	0	50-80	230-550
Scaling/**extrapolation** of hardware commissioning	2008	10	30	100	**900-1300**
Test of 3-4 magnets recovered after incident	2011	0	0	0	330

LOG VERSUS EXP

- 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



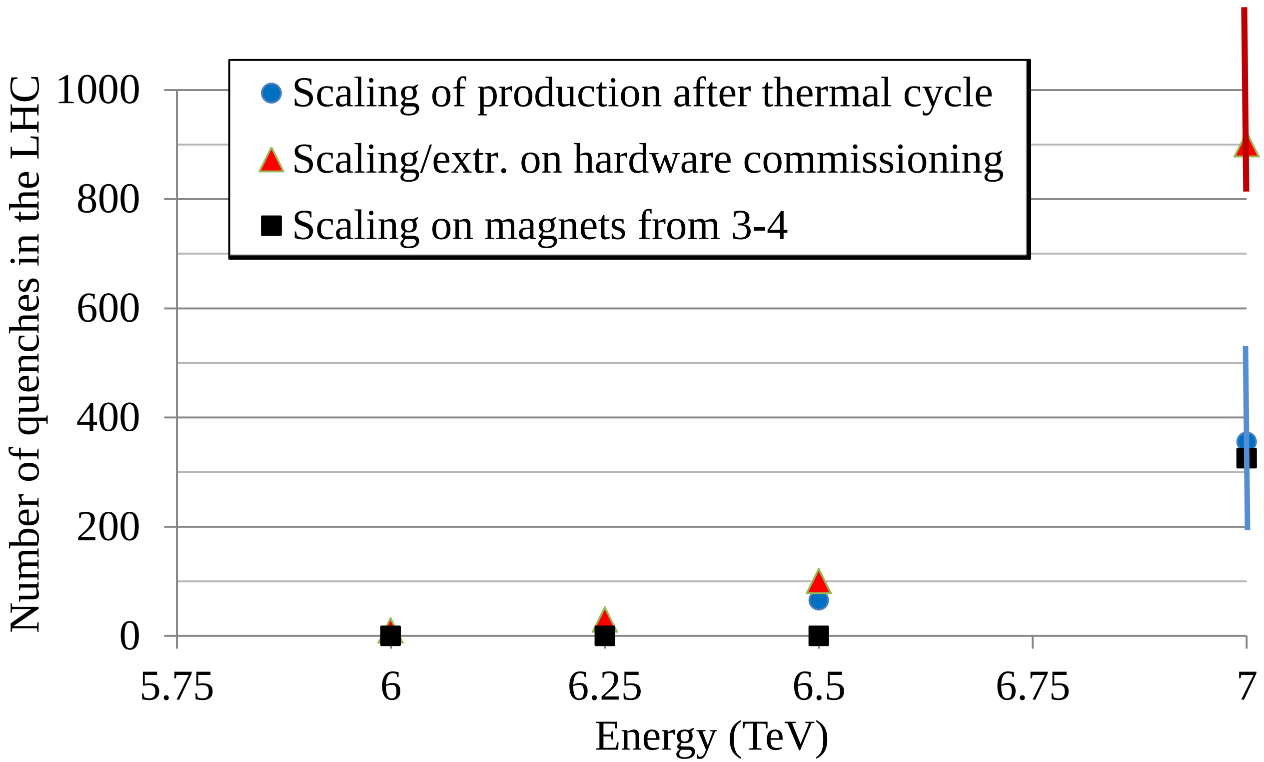
Double exp used to fit chroma decay at injection



The same data in log scale !

SUMMARY OF ESTIMATES

- Final comparison of different estimates



SUMMARY OF ESTIMATES

- 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

$$F(k;n,p)=\binom{n}{k}p^{k}(1-p)^{k}$$

… but it is not

$$\frac{1}{n}\mu\left[F(k;n,p)\right]=p \qquad \frac{1}{n}\sigma\left[F(k;n,p)\right]=\sqrt{\frac{p(1-p)}{n}}$$

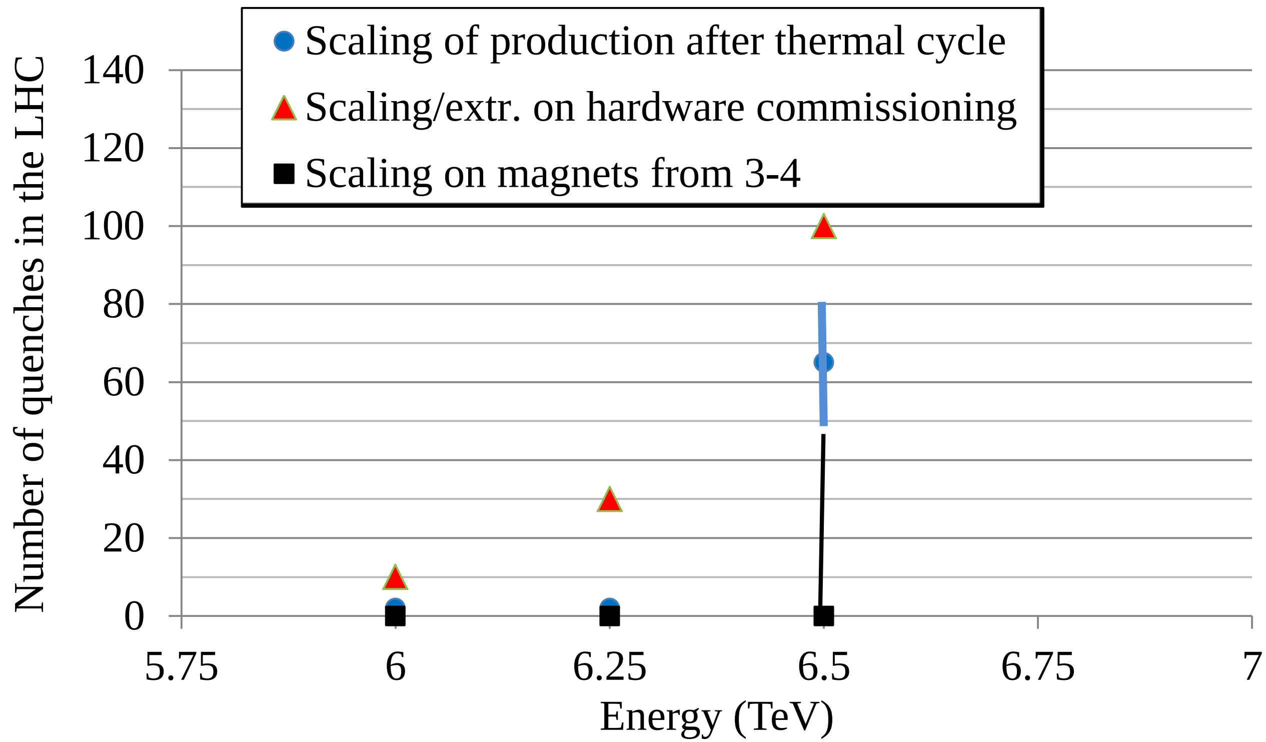
I am still convinced the error is proportional to the $1/\sqrt{n}$

- 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

	6 TeV		6.25 TeV		6.5 TeV		7 TeV	
	Tested	Quench	Tested	Quench	Tested	Quench	Tested	Quench
Firm1	15	0%	15	0%	15	0%	15	20%
Firm2	11	0%	11	0%	11	0%	11	27%
Firm3	6	0%	6	0%	6	0%	6	33%
Expected quenches in LHC	0		0		0		331	

Summary of Estimates

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



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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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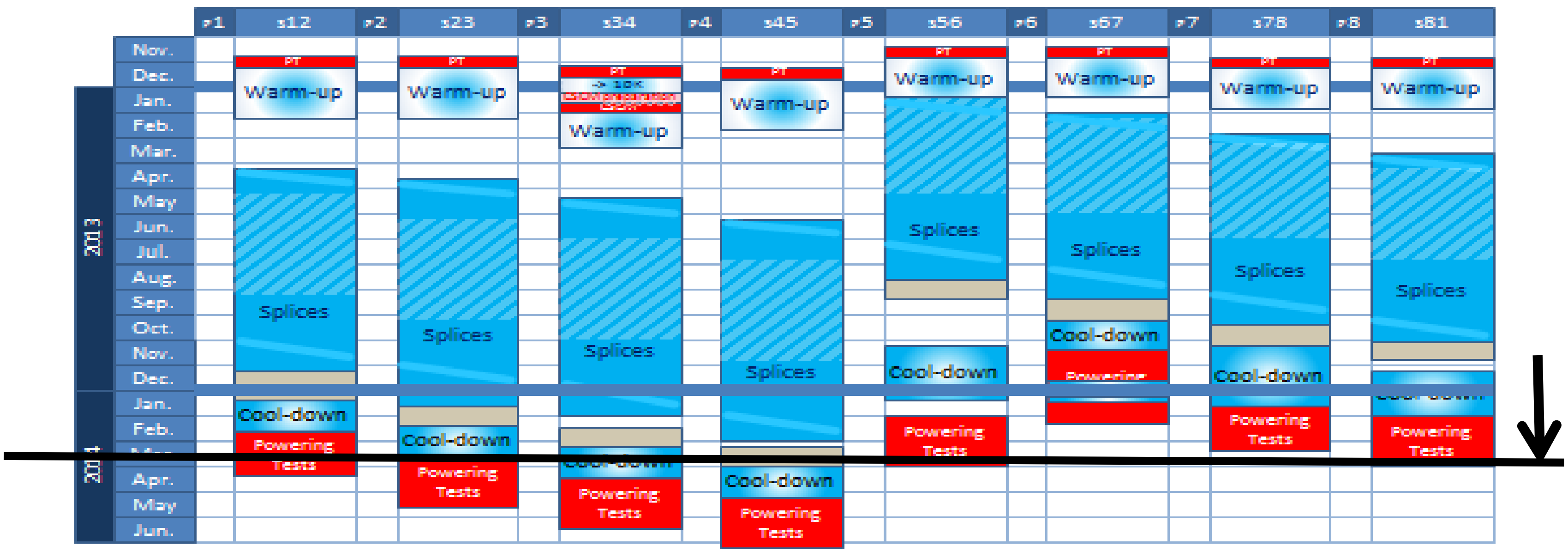
STRATEGY

- 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)

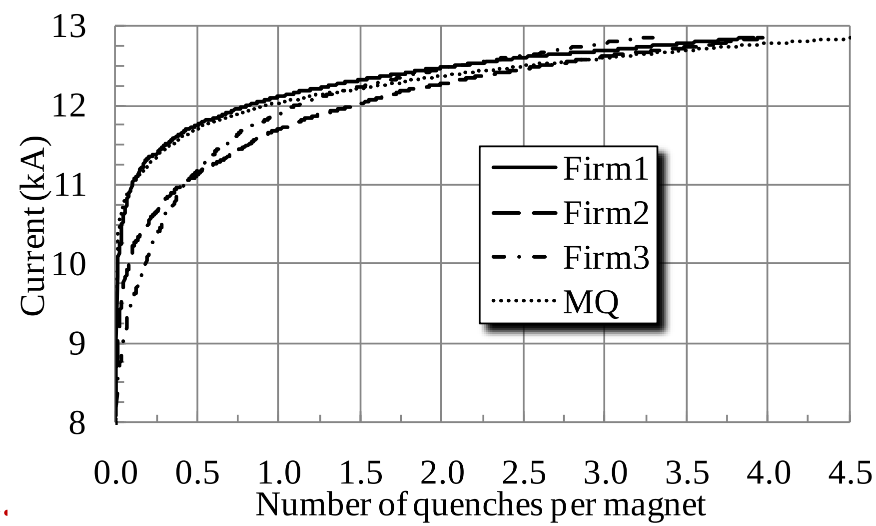
CONCLUSIONS

- 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

BACK-UP

- 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 »

    ]