Magnet training and margins, and the LHC dipole experience

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With contributions from L. Bottura, D. Tommasini, G. De Rijk

CONTENTS

- Few remarks on margins in Nb_3Sn and Nb-Ti
- Some lessons from the LHC

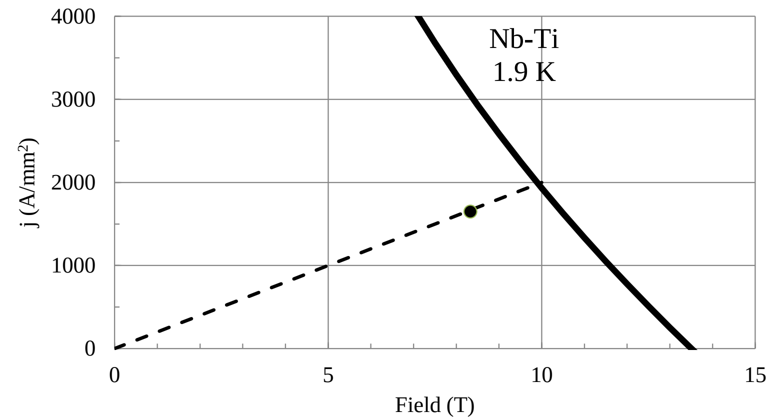
LOADLINE MARGIN

- A widely used concept is the loadline margin
  - 20% margin means that if the critical surface is reached for 10 T, we work at 8 T (equivalently at 80% of maximum performance)
  - Main superconducting magnets working with 10-30% margin
    - Correctors work with more margin
  - The concept is always criticized (no physics) but never replaced:

    the success (efficiency?) of a magnet judged on its ability of reaching the max performance

Margin of the main dipoles in four accelerators

	Nominal			Actual		
	Temp. (K)	Field (T)	Margin	Temp. (K)	Field (T)	Margin
Tevatron	4.6	4.3	4%	4.6	4.2	6%
Hera	4.6	4.7	23%	3.9	5.3	23%
RHIC	4.5	3.5	30%	4.5	3.5	30%
LHC	1.9	8.3	14%	1.9	*7.8**	*19%*



20% margin for the LHC dipoles

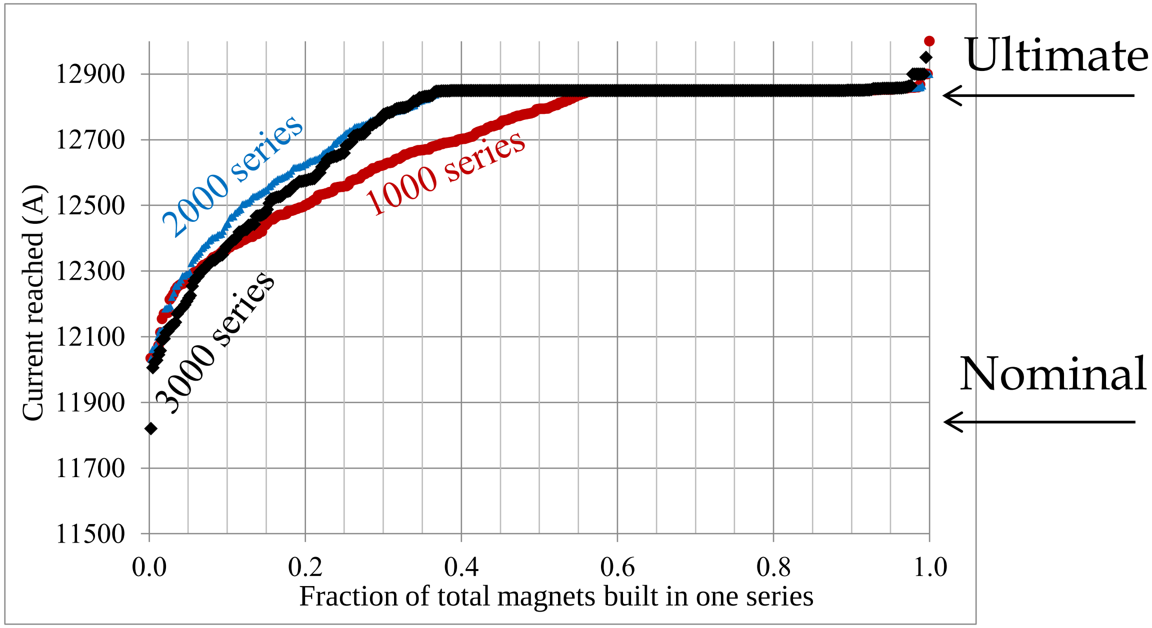
LOADLINE MARGIN IN HL-LHC AND FCC

- In HL-LHC we started with a 20% margin for both 11 T and QXF (around 2012)
  - For QXF we had the possibility of increasing the margin with a small performance loss – we took this opportunity and went to 25% after the 2015 review (A. Yamamoto et al.)
  - Efforts to make 11 T longer, but limited by hardware
  - Today we are at 23% margin for QXF, and 19% for 11 T at nominal
  - Today we are at 17% margin for QXF, and 13% for 11 T at ultimate
  - Reaching ultimate is a requirement of the project

- In FCC we started with a 18% margin
  - We decided to reduce to 14% after the 2016 review (S. Gourlay)

SOME LHC FACTS

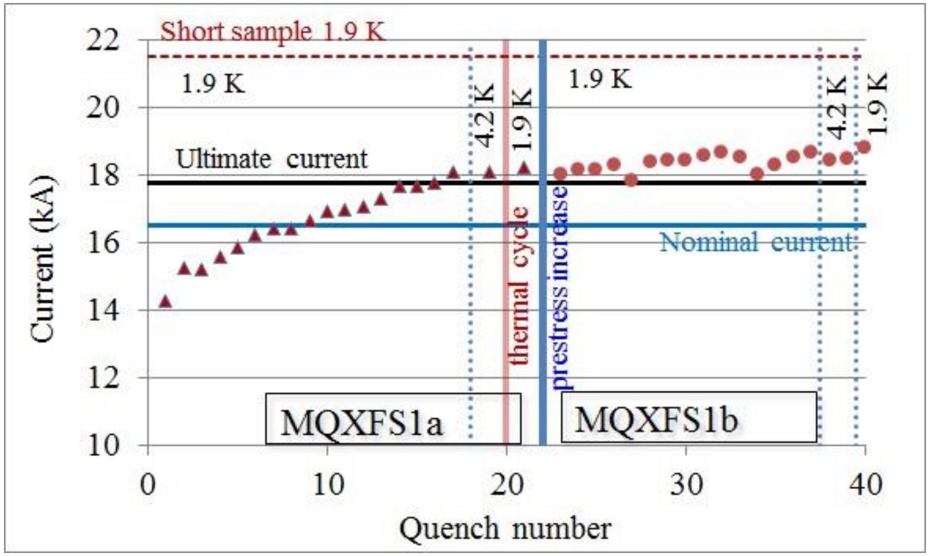
- In LHC we brought during individual test all ≈1200 magnets above nominal (14% margin), and 50% of them at ultimate (7% margin)
  - 50% were not pushed to ultimate only for time reasons
  - About 2% of the magnets did not reach required performance and were reworked

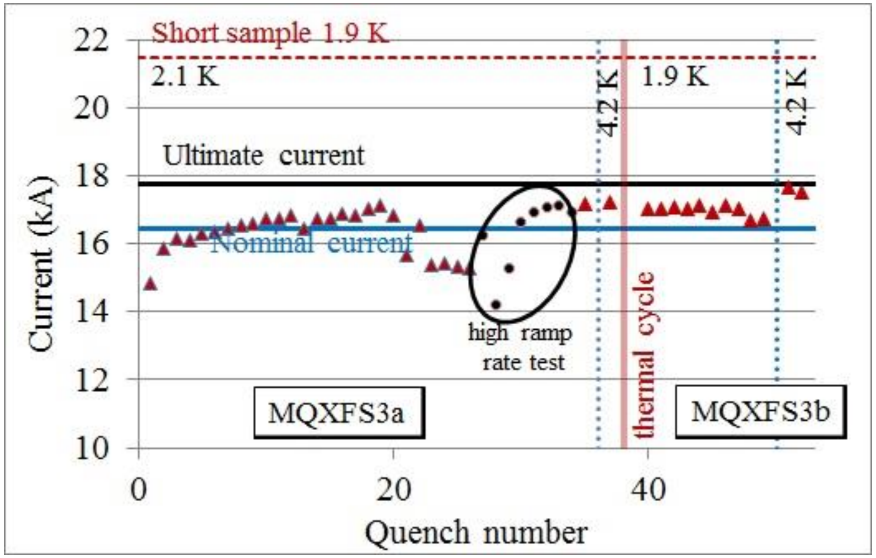


Maximum current reached in individual test

SOME HL-LHC FACTS

- In the LARP experience, and in first models of HL-LHC we see
  - A considerable training in virgin condition (more than in Nb-Ti)
  - A good memory after thermal cycle
  - 70% of short sample reached by all models, 80% for a large fraction of models, but 90% looks far away

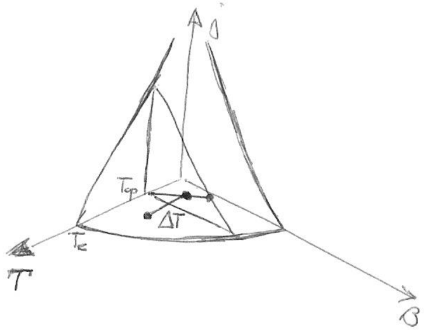




20% margin for the LHC dipoles

TEMPERATURE MARGIN

- A more physical quantity w.r.t. loadline margin is the temperature margin
  - How much we can heat locally to operational current to reach the critical surface (at the operational current density and field)?



  - Temperature margin is a valid concept for magnets limited by heat load
- For FCC
  - Dipoles will be under a strong synchrotron radiation, but it is mostly intercepted by the beam screen (talks by F. Infantino, L. Tavian)
  - Triplet will have a heavy W shielding limiting the peak heat load in the coil to 2 mW/cm^3 with 15 mm of W – so also in this case not limited by heat load on the coil (as in HL-LHC) (F. Cerutti et al.)

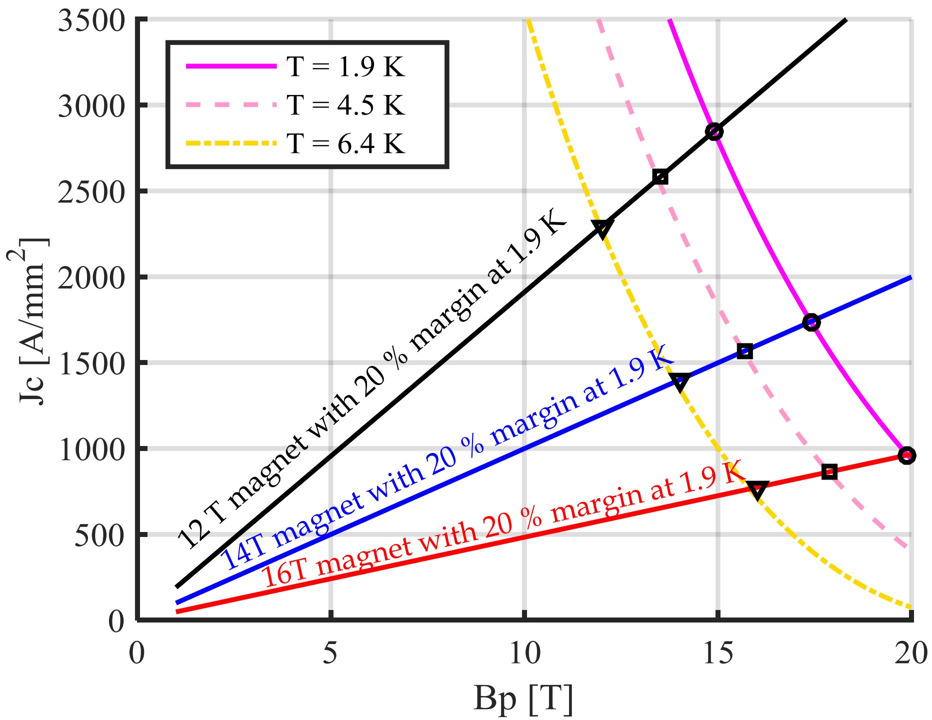
ENTHALPY MARGIN

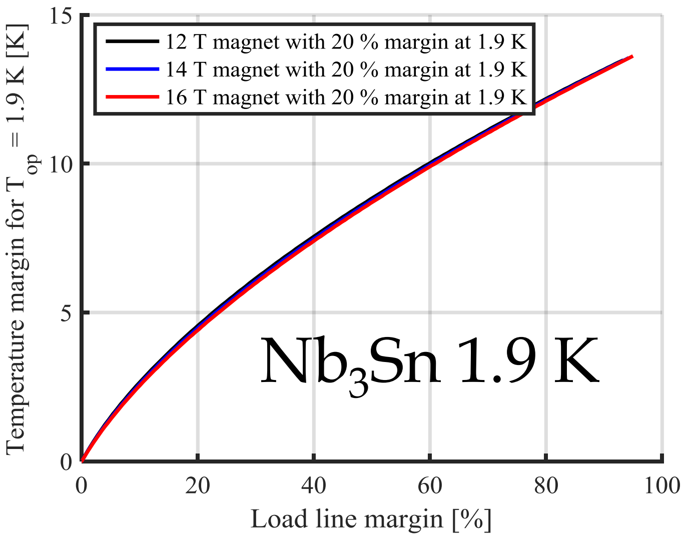
- Magnet training mechanisms are related to energy deposition over short times, and therefore what is relevant is the enthalpy margin and not the temperature margin
  - Enthalpy margin is the integral of the specific heat from T_{op} to $T_{op} + T_{marg}$
  - First message: relevant quantity for training on individual test bench is enthalpy margin

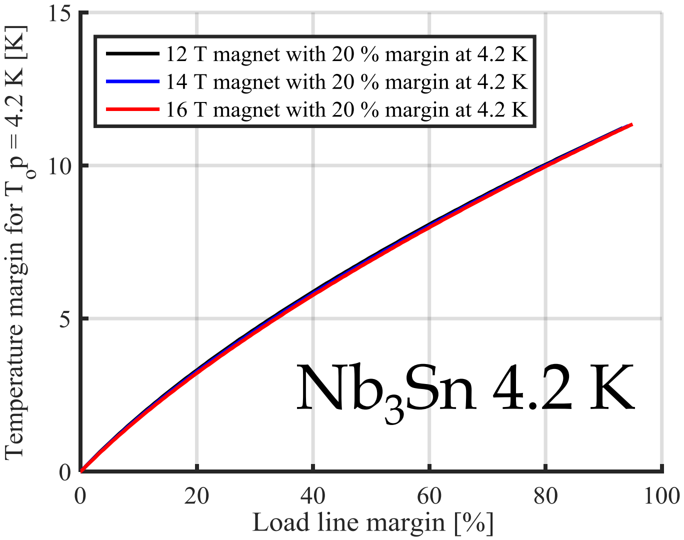
- The second half of the story is the energy spectrum of the perturbations
  - Magnets with same enthalpy, but less perturbations will train less
  - How this spectrum scale with *B*, and with *j* ? is there a simple scaling

TEMPERATURE MARGIN

- For Nb_3Sn and Nb-Ti the temperature margin depends only on the loadline margin and very weakly on the field
  - Second message: given a material and an operational temperature, load line margin and temperature margin are equivalent







TEMPERATURE MARGIN

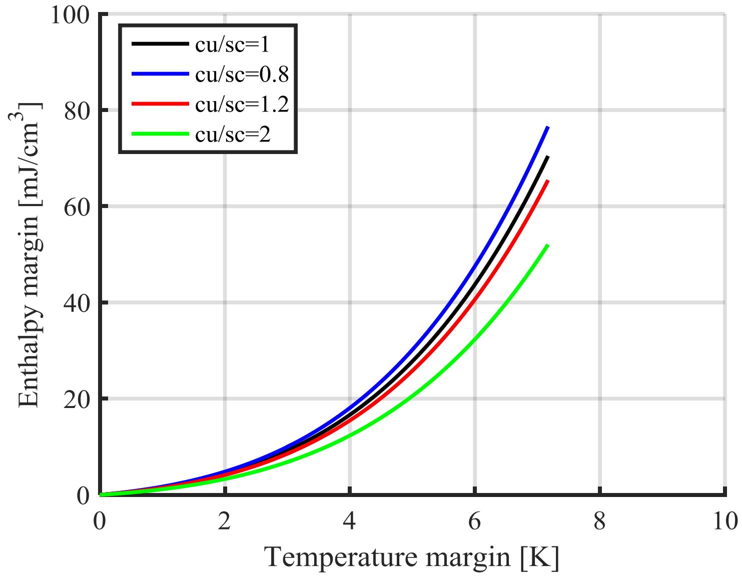
- The temperature margin of Nb_3Sn about 2.5 times larger than Nb-Ti for the same loadline margin
  - Due to scaling from 13 to 25 T, plus the convexity of Nb_3Sn critical surface w.r.t. Nb-Ti
  - Example for 20% margin on the loadline

Temperature margins at 20% on loadline		
Operational temperature	1.9 K	4.2 K
Nb-Ti	2.1 K	1.2 K
Nb_3Sn	4.5 K	3.0 K

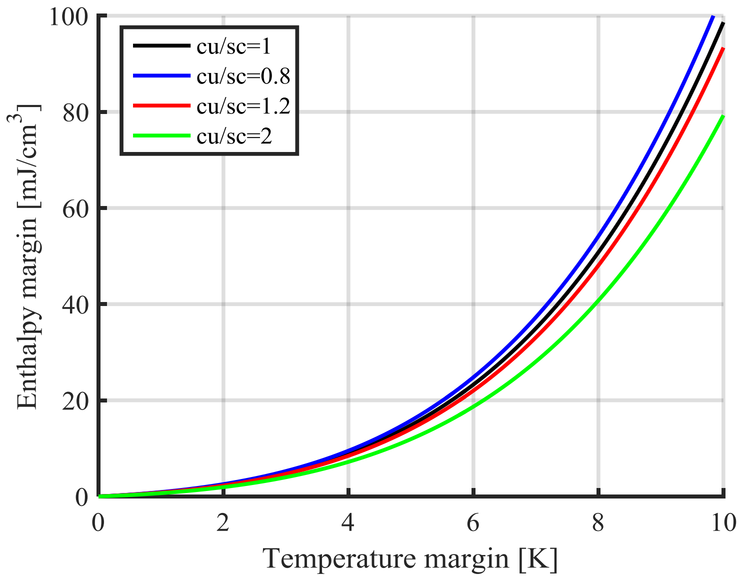
ENTHALPY MARGIN

- Enthalpy margins have a very weak dependence on the field
- Enthalpy margins weakly depend on cable composition
  - More copper means less enthalpy, going from 50% copper to 30% copper in the strand you decrease enthalpy margin by 25%
  - Third message: more stabilizer reduces the enthalpy margin, but not dramatically

Nb-Ti at 1.9 K



Nb_3Sn at 1.9 K

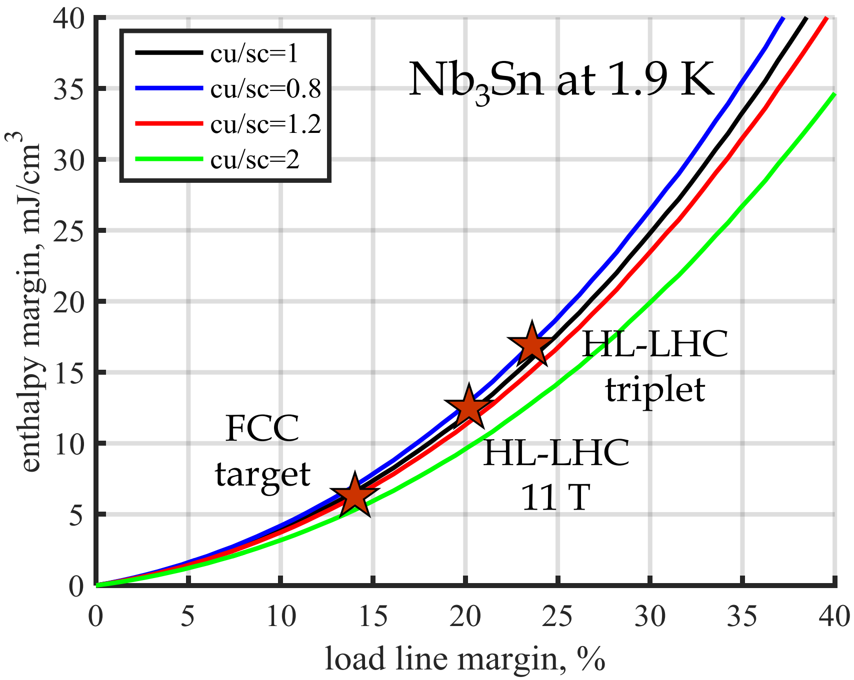


ENTHALPY MARGIN

- Let us fix again the 20% loadline margin
  - Enthalpy margins of Nb_3Sn are 2.5 times larger than Nb-Ti

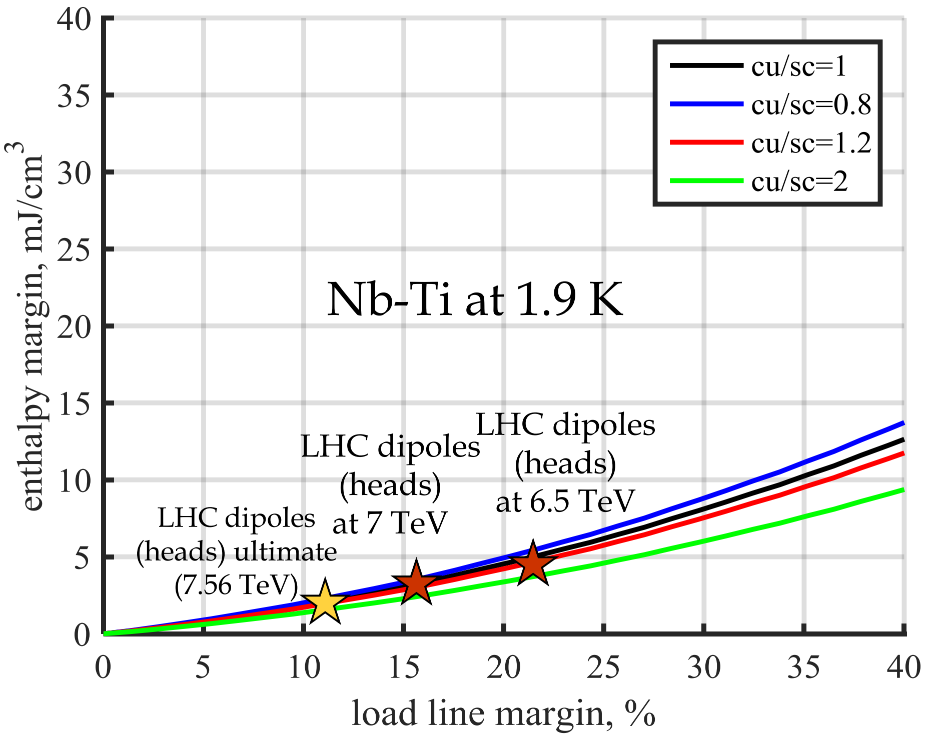
Enthalpy margins at 20%on loadline		
Operational temperature	1.9 K	4.2 K
Nb-Ti	4.5 mJ/cm^3	6.5 mJ/cm^3
Nb_3Sn	12 mJ/cm^3	16 mJ/cm^3

SUMMARY PLOTS



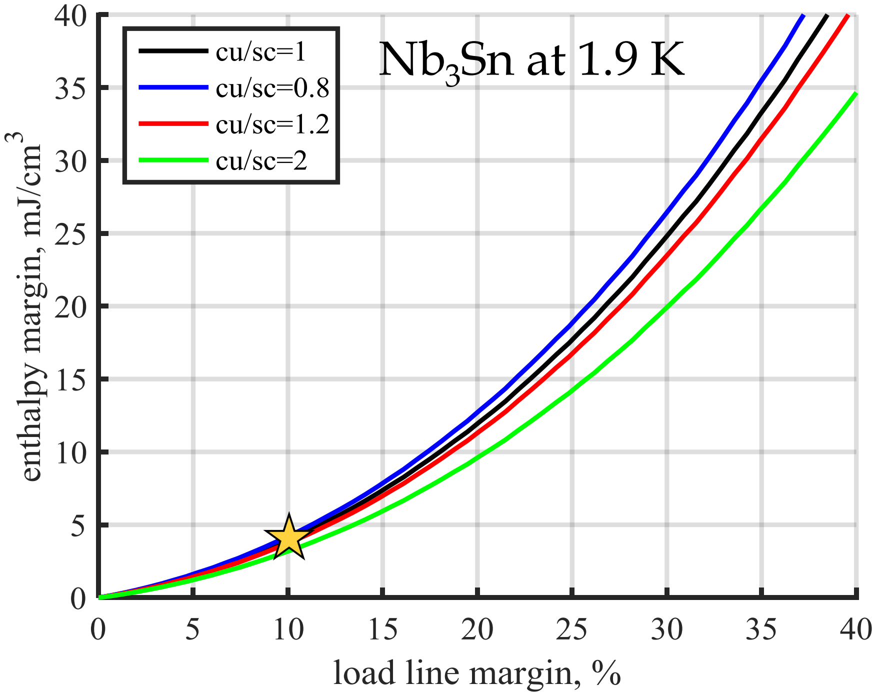
Note:
- LHC dipoles have impregnated heads and non-impregnated straight part
- Loadline margin in the heads is about 3% larger than in the straight part
- HeII gives a relevant contribution for non impregnated coils operating at 1.9 K

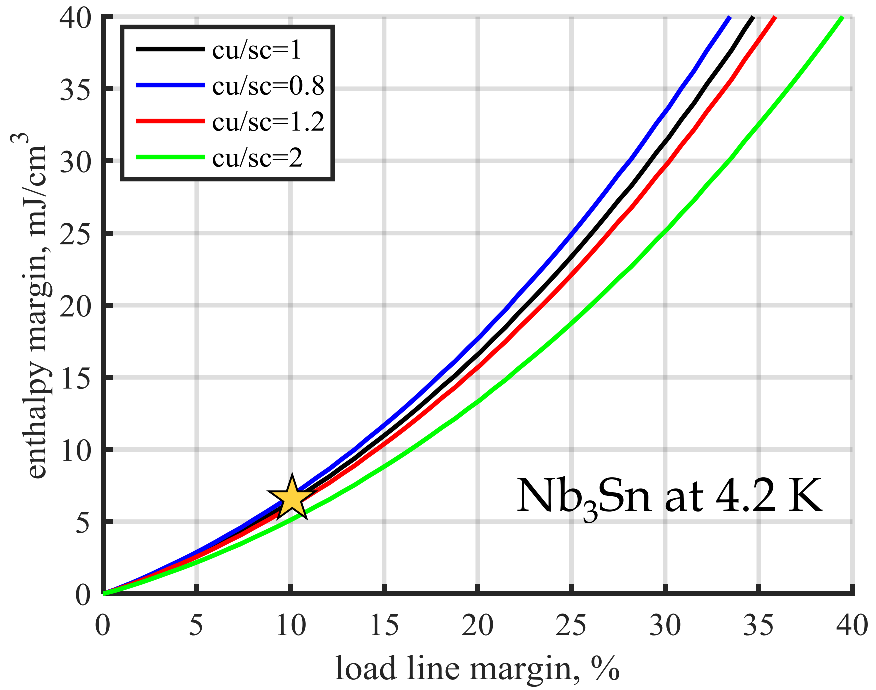
Note:
- HTS has a much larger temperature margin, and enthalpy margin, well above the scale of these plots



ENTHALPY MARGIN 4.2 K OPERATION

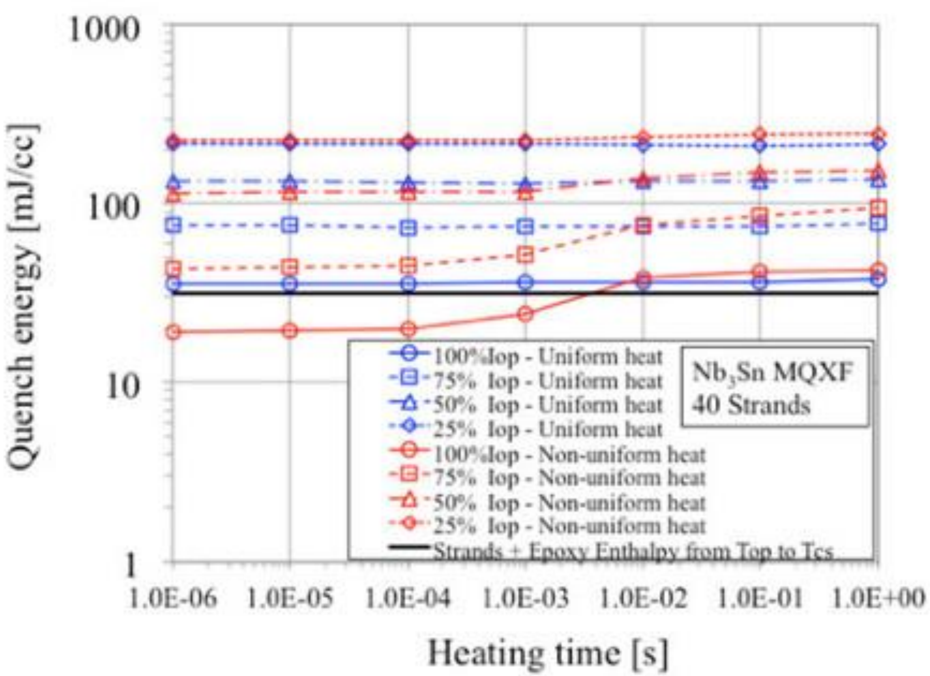
- There is some evidence that HL-LHC Nb_3Sn magnets reach 90-95% of loadline more easily at 4.2 K than at 1.9 K
  - Also seen in Nb-Ti dipoles of LHC
  - Is this related to margin ? Or is it instabilities? Or degradation due to stress?
  - With 10% margin (90% on loadline) the enthalpy margin at 4.2 K is about 60% larger





QUENCH MODELS

- To have a quench limit one has to go from enthalpy margin to a full model of superconductor, current distribution, and heat propagation
  - So the quench limit can be estimated as a function of the impulse duration
  - Many models developed in the past (Bottura, Verweij, Breschi, Bielert, …)



Felcini, Breschi, Bottura IEEE TAS, 27, 2017

QUENCH MODELS AND EXPERIMENTS

- There is a scale of increasing complexity and unknowns in modeling
  - Temperature margin: weak dependence on parameterization used
  - Enthalpy margin: more unknowns on
    - Specific heats
    - What to include? Insulation ?
  - Quench limits with multiphysics codes
    - Physics, integration, properties of specific heats, thermal conductivities, …
- Experimental data
  - Relevant experience from machine development sessions (quench test in the LHC, with different beam losses configurations to model instantaneous or continuous losses) (M. Sapinski, et al.)
  - Special settings for tests on cables/strands

    (Takala *IEEE Trans. Appl. Supercond.* 22 (2012) 6000704)

CONTENTS

- Remarks on margins in Nb_3Sn and Nb-Ti
- Lessons from the LHC

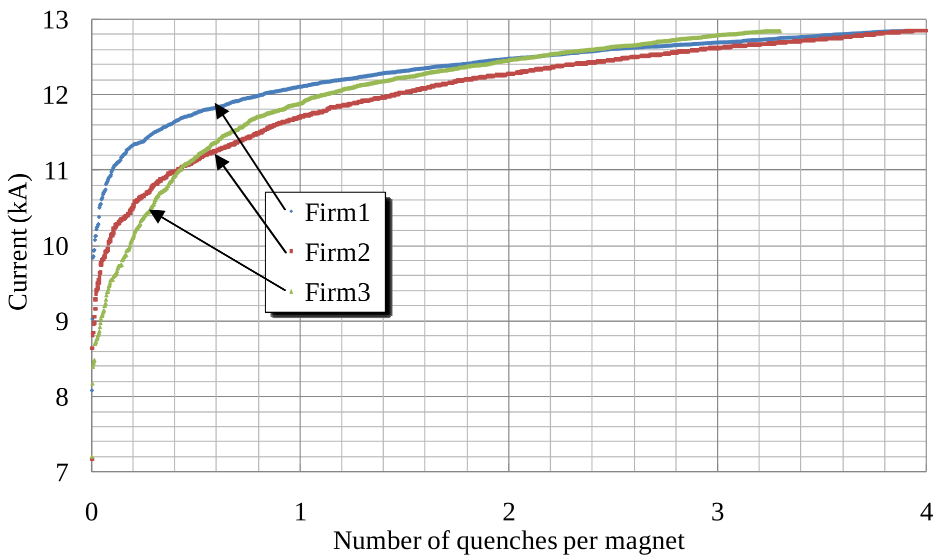
COMMON SENSE

- The machine is limited by the worse magnets
  - Any variant in the design is an additional risk and a performance loss
  - Lesson 1: Do not have variants but select a design and stick to it

- During individual tests, in the LHC we had the target of reach ultimate current
  - Attention was mainly focussed on how long to reach ultimate, but
  - Lesson 2: at the moment of commissioning we will see only the worse magnets

SURPRISES

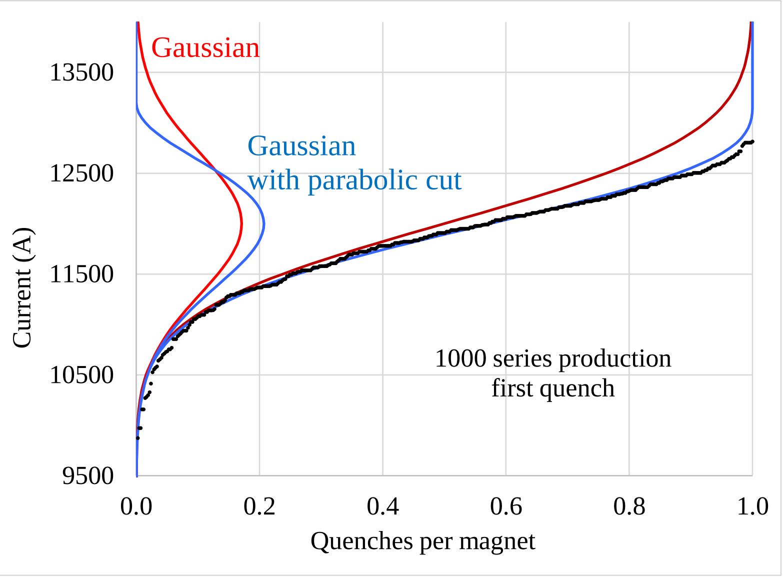
- LHC dipoles were manufactured by three firms (series 1000, 2000 and 3000)
- The LHC surprise in 2008
  - The magnet of series 2000 was considered to be the slowest trainers, but 90% of the quenches were in series 3000
  - Indeed, this was already visible in the virgin training
  - Lesson 3: there are several ways to look at data, be careful !



Quenches per magnet vs current in virgin condition (first test after magnet assembly)

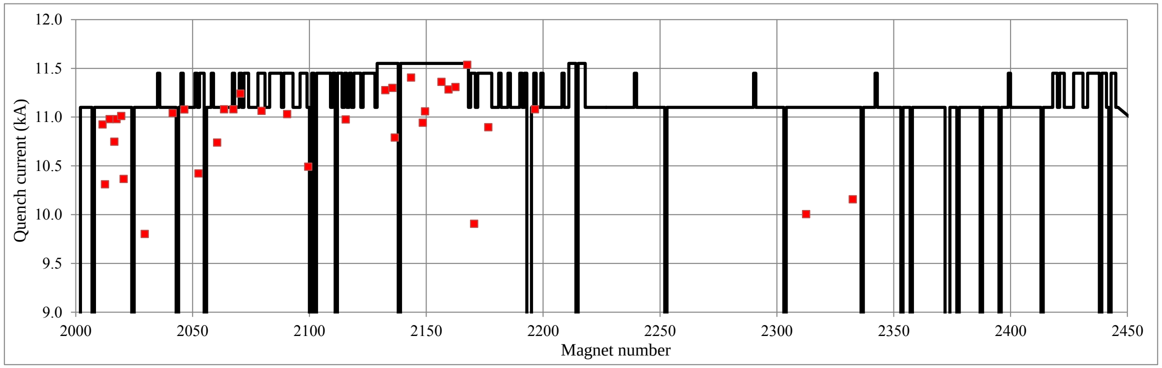
SPREAD

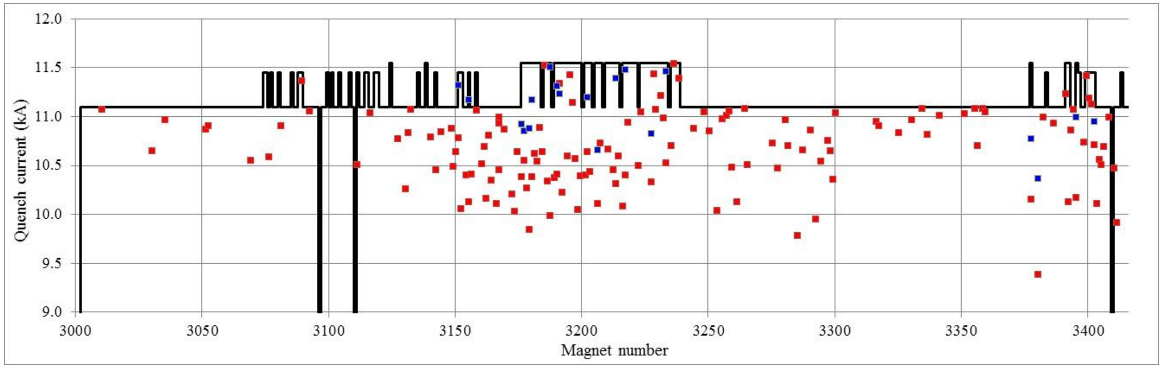
- There is very large spread of quench performance in a series of magnets – compatible with Gaussian tails
  - Case of 1000 series: sigma of first quench is 500 A, corresponding to 3.5% of loadline margin (2 sigma is ±7%)
  - Very difficult to draw conclusions on one magnet
  - Lesson 4a: Build several magnets with the same design, not just one
  - Lesson 4b: it can be very difficult to judge a design improvement on two different magnets only



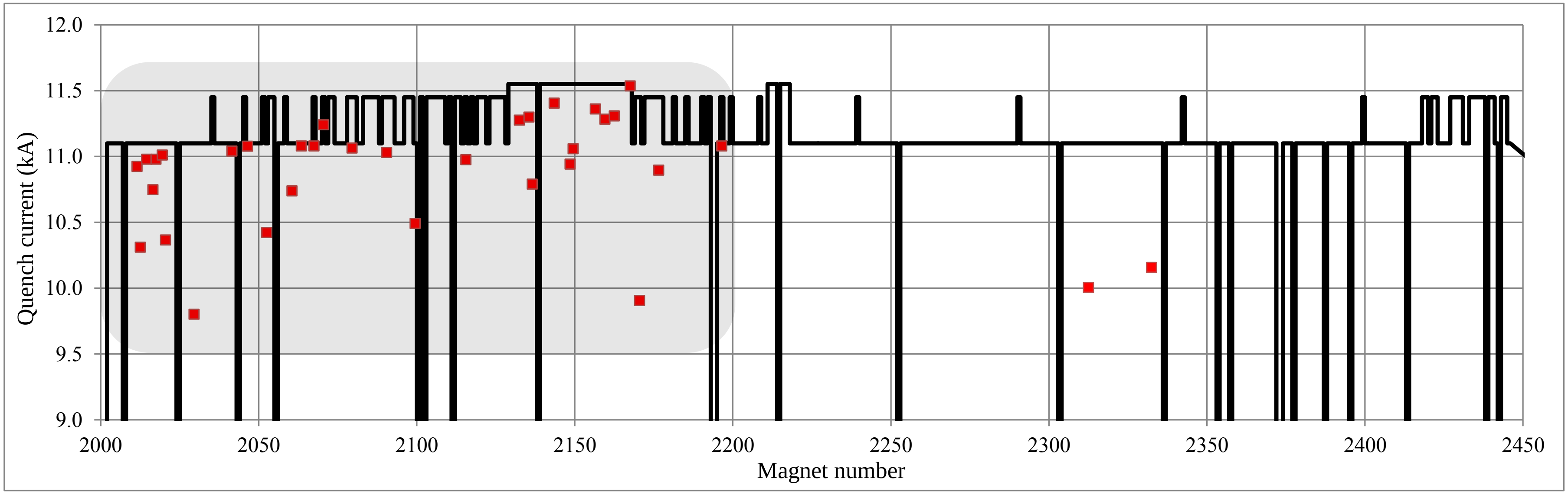
BATCHES AND BIAS

- We have batches of slow and fast trainers
  - With absolutely no explanation
  - With no correlation to virgin performance
  - Lesson 5: make a uniform sampling after thermal cycle during test campaign – otherwise your statistics will be plagued with bias





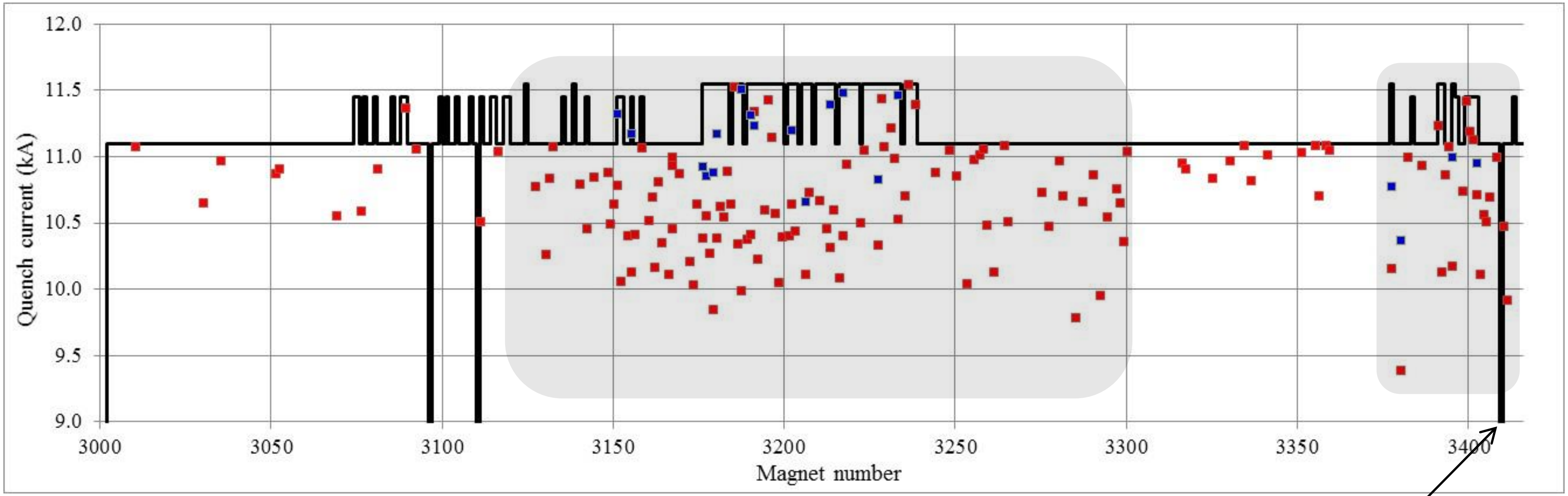
BATCHES IN 2000 SERIES



Quenches during 2015-2016 commissioning in 2000 series magnets (MP3 and HC team)

- Overview of quenches along the production: 2000 series
  - Red: first quench
  - We had no second quenches
  - Line: max current reached in the LHC
- Clear pattern with more numerous quenches in the 2000-2200 series

BATCHES IN 3000 SERIES



Quenches during 2015-2016 commissioning in 3000 series magnets (MP3 and HC team)

- Overview of quenches along the production: 3000 series
    - Red: first quench in the LHC
    - Blue: second quench in the LHC
    - Line: max current reached in the LHC
    - Performance with strong differences along the production
    - Worse batches are 3120-3300 and 3370-3417
    - Only three magnets not installed, we took 3409 and tested two more times

OPERATION

- Lesson 6: in LHC RunII (6.5 TeV), 1200 magnets operating at 80% short sample (20% loadline margin) without any showstopper
  - Only a few spontaneous quenches, not affecting operation

- CERN management decided operation at 7 TeV for RunIII, this means 86% of short sample (14% loadline margin)
  - See talk by F. Bordry
  - We will see if we will start seeing limitations due to this reduced margin

- CERN management asked to evaluate the possibility of operating at ultimate 7.56 TeV, this means 93% of short sample (7% loadline margin)
  - This option was considered since the very beginning of LHC conception

CONCLUSIONS

- Margin is a critical issue for FCC magnets
  - With 16 T target, each % of margin is expensive
  - After the review the loadline margin for the FCC magnet was lowered from 18% to 14%
- Loadline margin continues to be used as a sign of successful magnets in our community
  - Nb_3Sn enthalpy is about 2.5 larger than impregnated Nb-Ti with 20% loadline margin – but training looks longer
- We have several lessons learnt from LHC magnet
  - Spreads in performance are relevant – build not one but few identical magnets, as the US-LARP did
  - 1200 LHC dipoles worked with 20% margin in the past 3 years producing many Higgs, and we are targeting going down to 14% (7 TeV)