QUENCH TRAINING ANALYSIS OF Nb_3Sn ACCELERATOR MAGNETS*

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Abstract

Present Nb_3Sn accelerator magnets show long training compared to traditional NbTi magnets. It affects the required design margin or the nominal operation field resulting in higher magnet production and operational costs. FNAL has initiated a study aiming to find and explain correlations between magnet design, fabrication and performance parameters based on existing Nb_3Sn magnet training data. The paper introduces the core investigation points and shows first results.

INTRODUCTION

Nb_3Sn accelerator magnet technology has made significant progress during the past decades. Thanks to that 11-12 T Nb_3Sn dipoles and quadrupoles are planned to be used in accelerators such as LHC in near future for the luminosity upgrade [1], [2] and in a longer term for the LHC energy upgrade or a Future Circular Collider [3]. However, all the state of the art Nb_3Sn accelerator magnets show quite long training. This specific feature significantly raises the required design margin or limits the nominal operation field of Nb_3Sn accelerator magnets and, thus, increases their cost.

To resolve the problem of Nb_3Sn accelerator magnet training FNAL has launched a study aiming to analyze the relatively large amount of Nb_3Sn magnet test data accumulated at the FNAL magnet test facility. The ultimate goal of this study is to correlate magnet design and manufacturing features and magnet material properties with training performance parameters which would allow in the future optimizing the magnet design and fabrication to minimize or even eliminate magnet training. This paper describes the general strategy of the analysis, discusses the main parameters and parametrization techniques and presents first results based on partial data processing.

DATASET

At current times there are several tens of accelerator magnets based on Nb_3Sn technology produced worldwide. A big fraction of those magnets were fabricated and tested at FNAL albeit in collaboration with others. Part of the initial models suffered from unavoidable first-attempt missteps and data should be carefully vetted before accepting them for analysis. For that reason magnets that were tested latest in time are the ones to start analysing first. Currently MBHS [4] series magnets (dipoles and mirror models) are fully included and HFDA [5] (dipoles and mirror models), TQC [6], HQ [7], [8] and MQXF [2] series (quadrupoles and mirror models) are partially included in the study. Further plans are to include data from outside FNAL, notably from LBNL and CERN tests.

TRAINING PARAMETRIZATION

To be able to correlate magnet parameters with its training, parametrization of the training evolution is needed. Figure 1 shows an example of magnet training curve and its possible parametrization. Training examples given here and later are from MBHSP02 – a dipole model from the 11 T program at FNAL [4], [9]. It is worth noting that training is sometimes conducted at different temperatures. Magnet training could be normalized to magnet short sample limit (SSL). In the analysis, those points were taken into account as well.

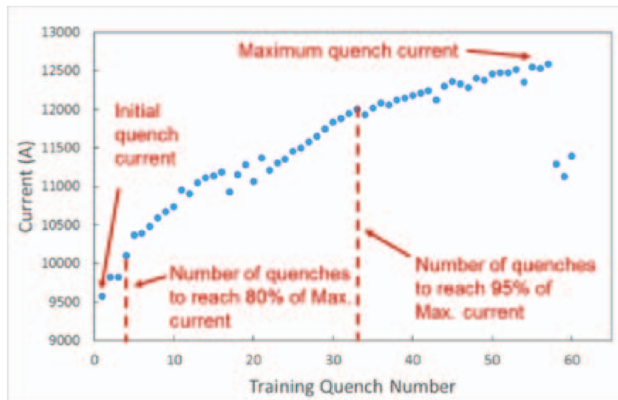

Figure 1: Magnet training and training curve parametrization.

The parametrization of magnet training curves chosen in this study includes the following parameters:

- First quench current and highest quench current

It is assumed that the magnet remembers its maximum current after the training cycle which is sometimes not completely accurate. If the magnet is far from trained or if the training was unsuccessful for other reasons (damaged cable, etc.) a careful consideration about including those data is needed.

- Number of training quenches to chosen current

Currently we work with 80% and 95% from the training plateau. The latter is considered a threshold beyond which a magnet is nearly at the plateau. The former serves as a threshold for assessing initial (typically faster) training. Both are subject to further optimization.

- Current differentials

The difference between currents in consecutive training quenches is called current differential. An example of current differentials vs. quench number is shown in Fig. 2. The points from consecutive quenches with significant magnet temperature differences (typically 1.9 K vs 4.5 K) are removed from consideration and analysed independently. Detraining quenches have negative differential

* Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy
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although to account for possible fluctuations a threshold of 0.5% is imposed. The number of detraining quenches in the defined three regions of training, between 0%, 80%, 95% and 100%, is counted. In addition the numbers of quenches to reach the plateau and the first detraining quench are also used.

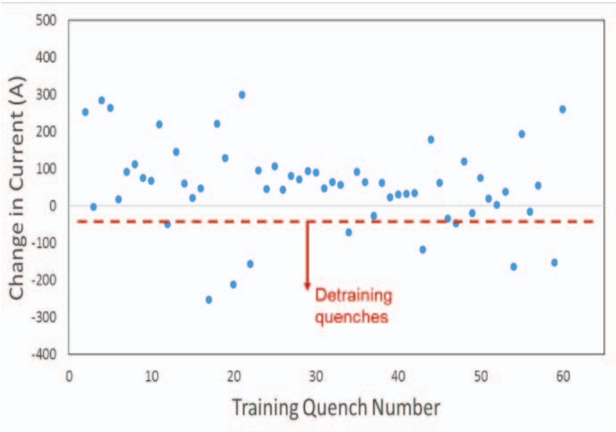

Figure 2: Quench differentials.

Most of the parameters described above are absolute – currents and number of quenches. However normalized parameters are included in the study as well. Currents are normalized to the SSL; number of quenches is normalized to their total number, in a region or during the whole training. The various combinations are all considered in the analysis, thresholds are adjusted.

Table 1 summarizes the 1st quench currents normalized on the magnet SSL and the number of quenches to reach 80% and 90% of the magnet SSL for the analysed dipole and quadrupole series. As seen the first quench current has a large spread for both type of magnets with mirror models typically consistent. Most of the assemblies required many quenches to reach 80% of SSL and some never reached 90% of SSL. Few models had very fast training. It is not straightforward to explain this rich variety but some correlations are already apparent.

Table 1: First Quench Currents and Number of Quenches to Reach 80% and 90% of Magnet SSL

Magnet series	1st quench current/SSL [%]	Nq to 80% of SSL	Nq to 90% of SSL
HFDA	83-88 (60-78)	1 (2-4)	3-6 (9-18)
MBHSP	64-67 (62)	42*-65* (9)	(18)
TQC	59 (59-74)	26 (2-6)	(6-13)
HQ	72-81*(72-74)	1*-2 (5-11)	24* (10-29)
MQXF	66* (70*)	13* (5*)	18* (19*)

* indicates 1.9 K (vs 4.5 K) and numbers in brackets are for mirror assemblies. The range is based on several magnets.

Figures 3 and 4 present correlation plots for magnets and (virgin) coils, respectively. The dataset includes dipoles, quadrupoles and mirror models. The correlation coefficients ***c*** for the coils (Fig. 4) per series are as follows: *c(MBH)* = -0.76, *c(TQ)* = - 0.67, *c(MQX)* = -0.92, *c(HQ)* = -0.90. The two lowest RRR points for HQ are excluded. They come from coils 15 and 16 (the same is true when considering magnets RRR correlations on Fig. 3) and they are significant outliers in the series although fitting well with all the other series as seen on the figures. The correlation coefficient for the whole dataset with no exclusions is -0.46. In any case, the indications are clear that the first quench current is highly correlated to RRR. The underlying cause is being investigated and may as well be related to other factors like heat treatment.

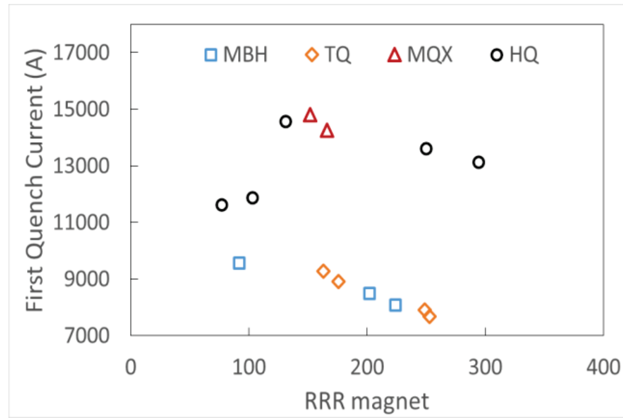

Figure 3: Correlation plot between magnet RRR and first quench current. Only points in individual magnet series can be correlated for the absolute current.

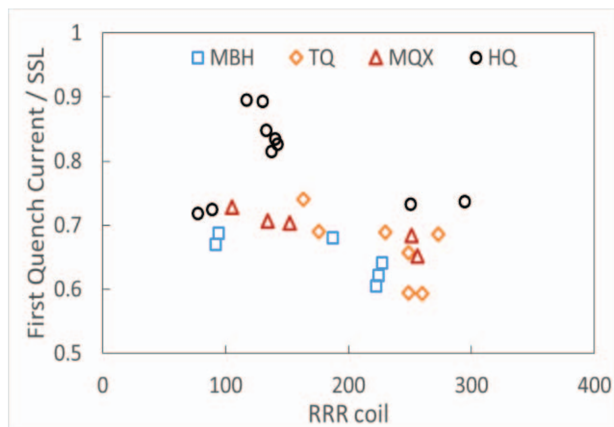

Figure 4: Correlation plot between coil RRR and first quench current normalized to SSL.

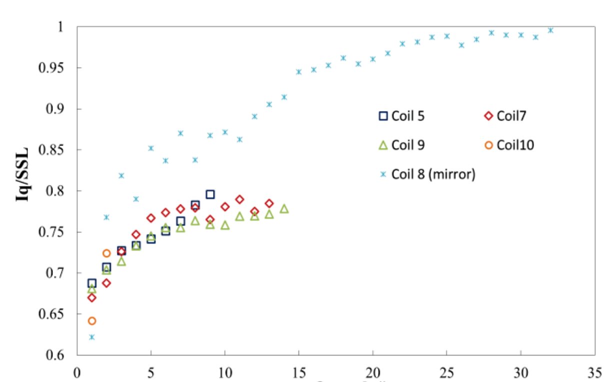

Figure 5: Coil training at 4.5 K extracted from MBHSP02 (coil 5 and 7), MBHSP03 (coil 9 and 10) and MBHSM01 (coil 8) 11 T program magnet assemblies.

Magnet training can also be viewed from point of view of training of individual coils in a magnet. Figure 5 shows the coil training for the 11 T program magnets at FNAL [4]. The training curve for the dipole coils follows a largely similar pattern different from the mirror structure. At the same time the fraction of training quenches a coil in a magnet gets differs – between 13% and 62 % from the figure. Those suggest that both the magnet structure and individual coil defects affect the training.

STRAIN GAUGE DATA

In addition to the current information there are also strain/stress data for each quench. Typically normalized quantities are more relevant and those are extracted. The main input variables of interest, Fig. 6, are the initial strain per ramp (to quench), the change in the strain at the beginning of consecutive ramp-ups to quench, change of strain per ramp. Then the normalization is either to the ramp current (which is the change in current per ramp) or to the initial strain per ramp (alternatively – to the initial strain in the first ramp).

Training-like behaviour is observed and assessed in terms of stress (strain). Figure 7 shows relative changes in axial strain between quenches with respect to the initial strain. Axial measurements are considered more prone to quench locations and thus more "general" though curves for pole/coils/skin gauges are of interest as well. It is a reading from a single strain-gauge, the separation after quench 22 indicates change in temperature (4.5 to 1.9 K), the last three quenches are also at 4.5 K. The quench current training is also shown.

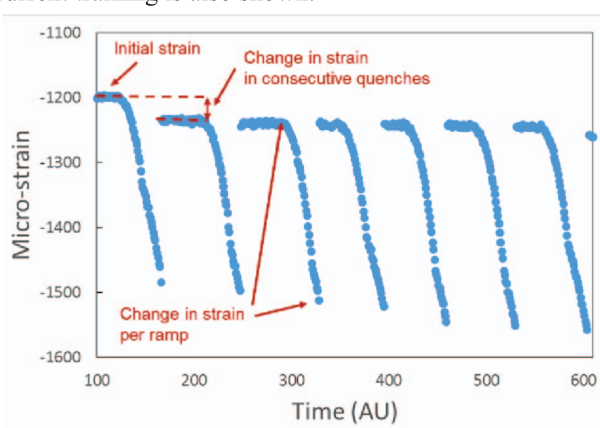

Figure 6: Strain changes in axial direction for several quenches. Time is in arbitrary units, it is cut between quenches.

Relative changes in strain during ramp-ups to quench, in particular normalized to the current squared, is potentially valuable dependence, it is plotted on Fig. 8 vs quench number. The absolute strain per unit of current (squared) grows during training and an evaluation is ongoing to determine how typical this behaviour is.

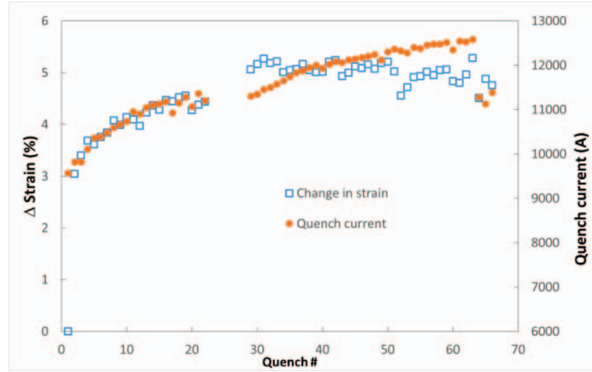

Figure 7: Change in axial strain between quenches.

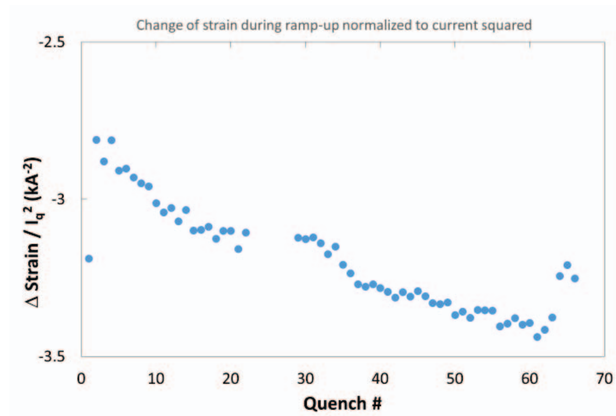

Figure 8: Change in axial strain during ramp-up to quench normalized to current squared.

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