Quench Limits

M. Sapinski, CERN, Geneva, Switzerland

Abstract

With thirteen beam induced quenches and numerous Machine Development tests, the current knowledge of LHC magnets quench limits still contains a lot of unknowns. Various approaches to determine the quench limits are reviewed and results of the tests are presented. Attempt to reconstruct a coherent picture emerging from these results is taken. The available methods of computation of the quench levels are presented together with dedicated particle shower simulations which are necessary to understand the tests. The future experiments, needed to reach better understanding of quench limits as well as limits for the machine operation are investigated. The possible strategies to set BLM thresholds are discussed.

INTRODUCTION

Knowledge of the quench limits allows a more efficient operation of the machine and gives an important input in the design of new superconducting magnets. Such information is used to set up beam abort thresholds in the Beam Loss Monitors (BLM) and allows the determination of safe accelerator parameters at the beginning of the run. The quench test with the beam reproduce beam losses which are or can be realistic scenarios, therefore they are ultimate check of quench limits.

Until now the LHC almost did not suffer from beam-induced quenches [1]. This is mainly due to operation at half of the nominal beam energy, leaving a large quench margin and due to a very good control of the beam. However after the first Long Shutdown (LS1) this situation will change and detailed knowledge of quench limits will become crucial.

The paper in the first four sections shows the main difficulties in defining and determination of quench limits. In the second part the previous quench tests and those proposed for the 2012 run are discussed.

DEFINITIONS

The definition of the quench limit, used in this paper, is the maximum amount of energy which can be deposited locally in a superconducting coil without quenching the magnet i.e. without provoking transition of the whole superconducting coil to a normal conducting state. The local energy deposition is used because even a small resistive zone may lead to the quench of the whole magnet. Expressing this in terms of energy density (usually in $\mathrm{mJ/cm^3}$) allows the definition of the quench limit without referring to a specific volume of the quenched superconductor.

In the case of steady-state beam losses, the quench limit is expressed in terms of dissipated power density, i.e. $\mathrm{mW/cm^3}$. The energy or power deposited in the coil is referred to in this paper as a beam loss, because only beam-loss induced quenches are considered in quench tests.

The LHC superconducting magnets are equipped with Quench Protection System (QPS) which allows to safely dump the current when a quench starts to develop. The stages of quench development are illustrated in Figure 1:

1. Onset of resistive zone (when the superconductor temperature becomes larger than critical temperature, at about 5 ms in Figure 1).
2. The development of the resistive zone, during the period when $\mathrm{T} > \mathrm{T_{cs}}$; the QPS system triggers the quench heaters if the resistive zone does not disappear fast enough (the actual threshold depends on the system configuration for particular superconducting element [2]).
3. After a decision time (which is the moment where the red curve - thermal runaway, separates from blue curve - recovery) the superconductor may heal and come back to superconducting state or the quench will start to expand on the whole coil.

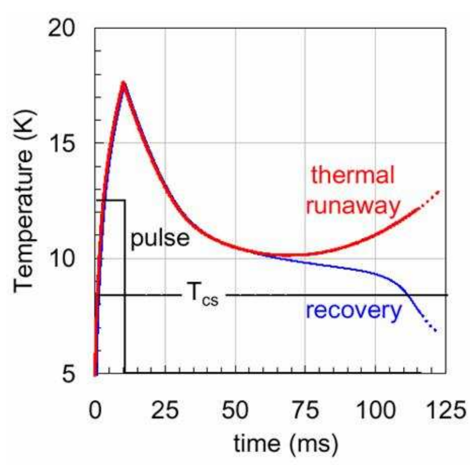

Figure 1: Development of a coil temperature in case of quench being close to quench limit. $\mathrm{T_{cs}}$ is the critical temperature. Courtesy of L. Bottura.

The QPS system does not allow the 3rd stage of the quench process to be reached, unless of course a very strong loss brings the coil directly to thermal runaway state. The magnet is quenched before by the quench heaters. Although in the literature the 3rd stage is the actual definition of the quench limit. The 2nd stage is the "*operational* *quench*", i.e. the stage which is important from LHC operation point-of-view (BLM thresholds should protect from "operational quench"). The "*operational quench*" which would recover if the QPS system did not interact is referred as *quenchino* in CCC slang. The 1st point, i.e. the onset of the resistive zone, is usually what is determined during the quench tests, because this is a reference point which can be easily defined (green line in Figure 10).

From an operational point of view, it is important to know that the energy difference between the self-healing *quenchino* and real quench (i.e. beam loss which would bring coil to the quench even without intervention of QPS) is relatively small, especially for high magnet currents.

DEPENDENCIES

Quench limits depend on many parameters, including the magnet current, Cu/NbTi ratio, type of isolation, helium bath temperature, etc. They also depend on the characteristics of the beam loss which are discussed in this section:

- Duration of the loss.
- Loss pattern.

The dependence on the magnet current, i.e. beam energy, is not discussed here, although one of the quench tests proposed later addresses this aspect as well. This section is used as a disclaimer showing that the accuracy of quench limit determination is strongly affected by various beam loss parameters.

Loss duration

In Figure 2 the quench limit as a function of duration of the beam loss is presented. The curves are based on the approximate knowledge of heat transport mechanisms and heat capacity of the materials as presented in [3].

For very short losses the temperature increase of the superconductor is not affected by heat transport mechanisms. The amount of energy required to reach the critical temperature is equal to the difference of enthalpy between quenched and initial states (enthalpy margin).

For losses longer than 1 ms the heat transfer to helium bath starts to play a role, and the quench limit raises by more than an order of magnitude because of the large specific heat of the superfluid helium. The heat capacity of the bath reaches saturation for losses of about 0.1 s and the steady-state transfer to cryogenic system becomes effective for losses longer than a few second.

It must be stressed that modelling the quench limit for intermediate duration losses is difficult because various mechanisms of heat transfer contribute, and the timescales at which they become effective are not well known. Programs used for calculation of the quench limits (for instance QP3) typically give smoother curves than those in Figure 2.

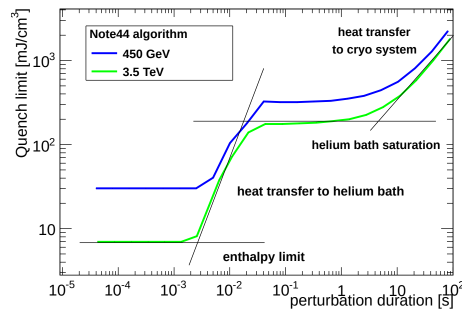

Figure 2: Quench limit as a function of energy perturbation duration, according to the algorithm from [3].

Loss pattern

The particles can deposit energy in various parts of the coil. In cases of all investigated losses, the energy density decreases strongly with the distance from the cold bore. Therefore the conditions in the most inner cable of the coil determine the quench limit.

The magnetic field in the superconducting coils is typically larger for cables far from the midplane. Therefore the enthalpy margin is also lower for this cables. An example for the dipole magnet enthalpy limit is shown in Figure 3. The typical loss expected in the dipole is horizontal, therefore it is impacting less sensitive cables.

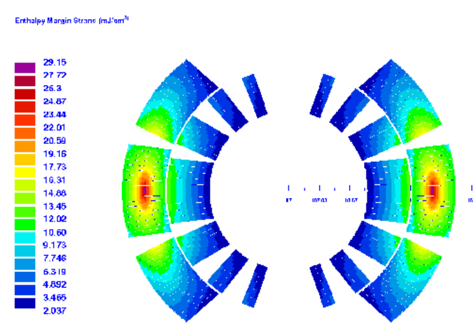

Figure 3: Quench limit in function of energy perturbation duration.

Longitudinally the properties of the coil also vary. In the coil endings, which are typically most exposed to particle showers, the cables are bent and the amount of helium is reduced due to the presence of additional resin used to form the coil shape. Quench limits measured in this part of the coil might be significantly different from the limits in the middle of the magnet.

QUENCH LIMIT SEEN IN BLMS

The quench limits can be expressed in terms of the signal observed in the BLMs at the moment of the magnet quench. This is motivated by the fact that BLMs should protect from magnet quenching, because for high beam energies the recovery from the quench lasts much longer than refilling of the machine. It is tempting to believe that the quench limit as seen by BLMs ($\mathrm{S_{BLM}}$) is simply proportional to the quench limit in the coil (QL):

$$\mathrm{S_{BLM}} = \mathrm{R} \cdot \mathrm{QL} \tag{1}$$

where the proportionality factor is a ratio of the energy deposited in the BLM to the maximum energy deposited in the coil:

$$\mathrm{R} = \mathrm{E_{BLM}} / \mathrm{E_{coil}^{max}} \tag{2}$$

Unfortunately the proportionality factor R depends on the details of the geometry and the loss. For instance one lost proton typically gives more signal in the BLM placed after an interconnection than along the magnet cold mass, which acts as a shielding.

The losses are spread or localized. The upper plot of Figure 4 shows the longitudinal shower shape in the coil (blue) and in the BLM location (red) for a pointlike loss. The lower plot shows the BLM quench limit ($\mathrm{S_{BLM}}$) as a function of the width of the gaussian used to smear both distributions. For more localized losses the quench-protecting BLM thresholds are smaller than for spread losses. The current BLM thresholds are conservatively set according to fairly localized orbital bump scenario.

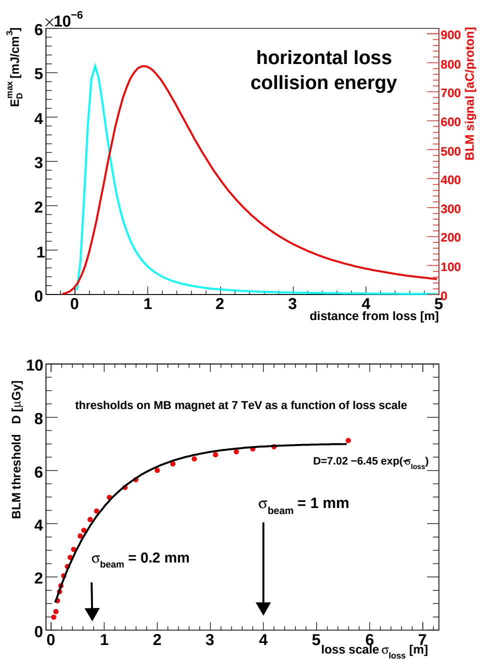

Figure 4: BLM signal at quench as a function of loss scale for MB magnet simulation [4]. The threshold in the lower plot is calculated as a function of the size of the beam hitting the beam screen with impact angle of $240\ \mu\mathrm{rad}$.

HOW DO WE LEARN ABOUT QUENCH LIMITS?

There are four approaches to study quench limits. The first three are briefly described in this section, while the rest of the paper is devoted to quench tests.

Algorithms and Numerical codes

A lot of work related to the computation of the quench limits in superconducting coils has been done. For instance the enthalpy limits, relevant for very short losses, are calculated in ROXIE [5], which is mainly used to evaluate the magnetic field maps. Another example is QP3 code [6], which is often used for comparison with quench tests results. The current BLM thresholds are calculated based on modified algorithm described in [3].

Laboratory measurements

Various measurements can be performed in the laboratory. A good example is the measurement of the heat transfer rate from the superconducting cables to the helium bath through the cable electrical insulation [7]. These measurements allow to calculate the steady-state quench limit of the magnet [8]. It is illustrated in Figure 5 where a steady state quench limit is presented as a function of current in the magnet. The magnetic field value considered corresponds to the midplane of the inner layer of the dipole (MB). The curves represent the power that can be extracted from the cable as long as the cable center(red curve)/edge(black curve) is superconducting. The most conservative assumption is to consider the lower (red) of the two curves, although the cable edge curve is probably closer to reality because the beam losses are mainly concentrated in the cable edge. However even the cable edge curve might be conservative, because the heat deposit in the considered tests is uniform over the cable cross-section.

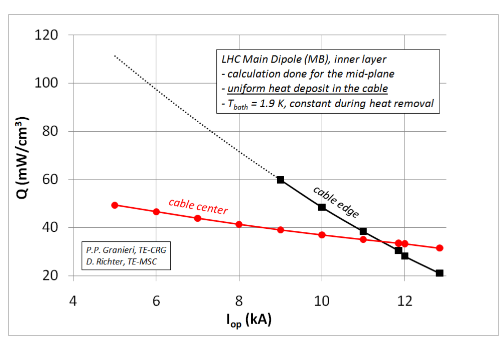

Figure 5: Steady state quench limit as a function of magnet current (see text). Uniform cable heating and a constant bath temperature of 1.9 K are considered.

The main limitation of any laboratory measurement is the lack of the beam with its specific radial heating pattern. In the laboratory tests performed so far the cables were uniformly heated, and the geometry of the samples were different from the real coil. In the tests foreseen for the next months the experimental setup will be modified to reproduce more precisely the magnet behavior, thus allowing to obtain a more reliable quench limit estimates.

Operational Quenches

During the 2010 and 2011 runs only three events took place which can be qualified as operational quenches. All of them happened during the injection process and were due to the malfunction of the injection kickers.

Careful analysis of these events [9] (together with quench tests at injection [10]) allows the estimation of the amount of protons necessary to quench the magnet. The results of the analysis for all three events are summarized in Figure 6. Red bars represent the estimated amount of lost protons which lead to a quench and blue bars show the highest losses measured without a quench. The presented results are shown for the injection regions in L2 and R8 (cells 6-17).

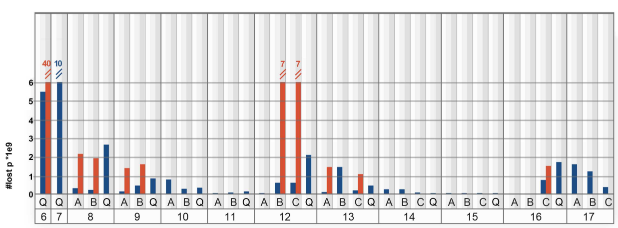

Figure 6: Quench levels at injection. ABC stands for MB A, B or C magnets and Q for quadrupole magnets. For instance Q6 does not quench with $5.5 \cdot 10^9$ protons and quenches with $4 \cdot 10^{10}$ protons.

As this experience shows the operational quenches provide a very limited precision on quench levels and are difficult to analyze.

WHAT HAVE WE LEARNED?

The quench tests with LHC magnets and with the beam provide the best conditions to study the quench limits. Investigating a magnet on a beam test could have a similar potential, but it was never done.

In Figure 7 the current knowledge coming from these tests, injection events and UFOs is summarized. Red points mark the successful beam-induced quenches and black arrows mark the lower limits of quench levels, from tests in which the quench did not happened.

Quench levels are expressed here in terms of BLM signals because most of them were performed to determine the BLM beam-abort thresholds. This is also a generic plot, not for a specific loss pattern nor a specific magnet coil.

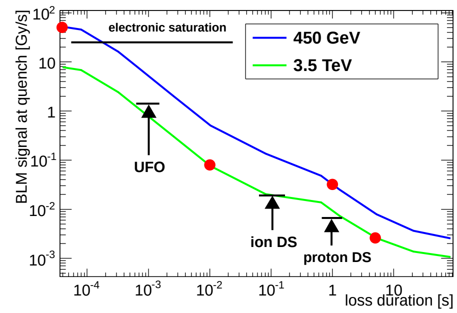

Figure 7: Summary of performed quench tests. From left: injection events and quench tests at injection, lack of UFO-generated quenches, wire scanner test, ion dispersion suppressor test, orbital bump at injection, proton dispersion suppressor test and orbital bump at 3.5 TeV.

QUENCH TESTS

In this section the quench tests and conclusions obtained are described. The tests proposed for 2012 run are also discussed here as they are the logical continuation of tests performed in previous years.

Orbital bump test

In autumn 2010 four quenches with orbital bump were performed in cell 14R2: three at injection energy and one with 3.5 TeV beam. The results of these quenches lead to the decrease of the BLM thresholds for long integration times [11].

A preliminary analysis of these tests, supported by Geant4 simulations, has been presented [12]. In Figure 8 the ratio of the BLM signals simulated with Geant4 and measured is shown for 6 monitors and 3 assumed beam impact distributions. Relatively good agreement is visible for impact concentrated in the second half of MQ. The corresponding results inside the coil compared with QP3 results are shown in Table 1 (MQ, 5 s loss).

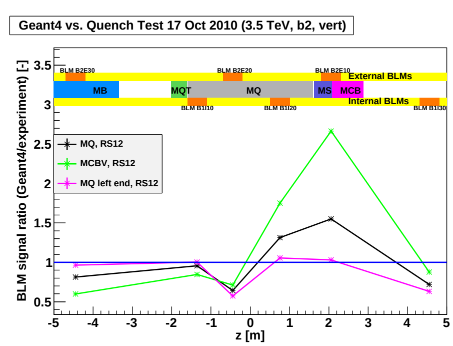

Figure 8: Comparison of Geant4 simulations with BLM signals registered during quench test.

During this test losses were generated which did not lead to magnet quench. However the energy deposition in the magnet was large enough for the cryogenic system to measure the energy deposited in the magnet. This gave result corresponding to about 80-95% of the total energy of the lost beam. In Figure 9 the energy increase is shown in two steps corresponding to two losses. This measurement can be used as an additional input for quench test analysis.

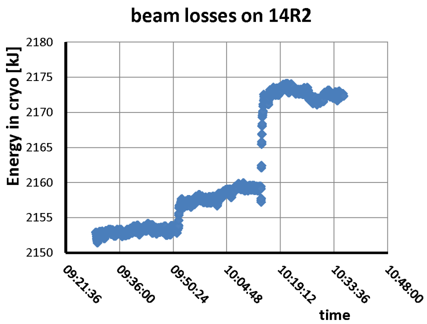

Figure 9: Measurements of energy deposition in the magnet using cryogenic sensors. Courtesy of K. Brodzinski.

Due to the clean experimental conditions allowing a precise determination of the loss pattern and low beam intensity involved[1] it is suggested to repeat the quench test with an orbital bump. In order to control the loss duration and amplitude it is proposed to use transverse damper (ADT) or BLM orbit feedback technique [13]. Installation of additional BLMs in the new test location is foreseen.

In addition to the cryogenic observations, especially important for long losses, it is proposed to use oscilloscope to read QPS signals in parallel to QPS electronics. The advantages are: much faster signal probing (20 kS/s instead of 500 S/s) and better resolution (0.3 mV instead of 5 mV). This readout was tested in 2011, although the results were not conclusive because it remains unclear if the observed signal originated from quench or was picked up by the cables.

UFO test

The UFO losses are in millisecond timescale. This corresponds to the time of the scan of the LHC beam with the wire scanner. The quench limits in this timescale can be already affected by the large heat capacity of the helium inside the cables. A test in which the quench of the MBRB magnet was induced by losses from the wire scanner has been performed [14]. The various signals registered during this quench are shown in Figure 10.

The FLUKA reproduction of BLM signals agrees very well with measurements as presented in Figure 11. The comparison of the energy depositions in the coil is presented in Table 1 (MBRB, 10 ms). A good agreement between FLUKA prediction and QP3 estimation is found.

[1]Orbital bump remains a valid failure scenario against which BLM should protect.

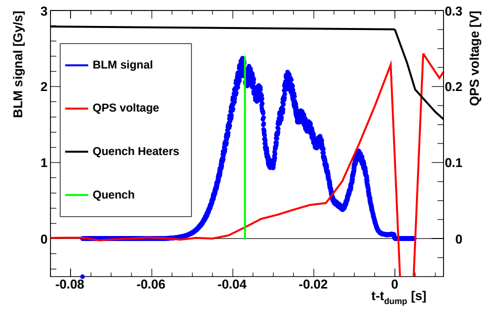

Figure 10: Overlap of BLM signals (blue), QPS signals (red), Quench heaters discharge signal (black).

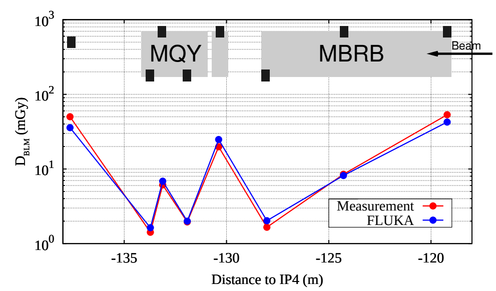

Figure 11: BLM dose measurement during the wire scanner quench test (red) and simulated by FLUKA (blue).

To further investigate the quench limits in the UFO timescale, there are three possible options:

- Increase of BLM thresholds in some LHC sectors and wait for UFO events to appear (*UFO fishing*, discussed in [15]).
- Repeat the wire scanner quench test with more beam intensity in order to approach 1 ms loss timescale.
- Perform orbital bump test, as described in the previous section, with very fast beam excitation by ADT.

Dispersion suppressor test

The dispersion suppressor quench test relies on reaching the quench limit at the dispersion suppressor magnets (between Q8 and Q11), which see the highest leakage from

Table 1: Quench limits from tests at 3.5 TeV.

test	Energy density $[\mathrm{mJ/cm^3}]$	
	Geant4/FLUKA and experiment	QP3 with simulated radial shape
MBRB 10 ms	12	16
MQ 5 s	1370	550

the cleaning insertion of IR7 into cold magnets. Therefore high losses were created on the primary collimators in IR7.

In 2011 this was done by crossing the third integer tune resonance. The particles, which were then lost in the dispersion suppressor downstream of the cleaning insertion were mainly protons which have experience single diffractive scattering in the primary collimators, as predicted from simulations. Theses studies are important as the leakage into the dispersion suppressor could limit the maximum possible beam intensity in the LHC due to collimation. The test and its results are described in detail in [16]. During the test no quench was observed for nominal collimation conditions (500 kW loss on primary collimators), but this result is consistent with BLM signals which reached 64% of the expected quench level.

In 2012 it is proposed to repeat the test with a comparable loss rate over several seconds (compared to one second in 2011) to measure if longer losses could cause a quench in the dispersion suppressor and therefore limit the achievable maximum beam intensity. Therefore it is proposed to use the ADT to excite the beam in a more controlled way, as successfully tested in 2011 [17].

Dispersion suppressor test with ions

The test with ions is similar to the one with protons, i.e. the beam is blown when crossing a third integer tune resonance.

However, the interactions of ions with collimators lead to production of various isotope nuclei, which are lost downstream at well defined locations because the dispersion suppressor is acting as a spectrometer. An example of such a loss map is shown in Figure 12, where individual peaks corresponding to the different isotope species can be seen [18].

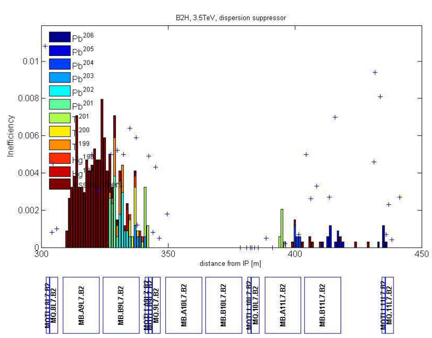

Figure 12: Loss map with individual isotopes contributions from Pb ion beam interaction with collimators (histogram of simulation results and measurement crosses).

Analysis of the quench test revealed that usually the resonance crossing with ions lead to much faster loss than in case of protons (0.1 s instead of 1 s), therefore a different quench limit region is probed. It must be noted that this timescale is also interesting because many beam instabilities were observed to develop within about 0.1 s.

Signals registered in BLMs were up to 3 times higher than expected at quench, but this was observed for monitors after interconnection, which are particularly sensitive to the loss pattern. Therefore, the direct conclusions about quench limits cannot be drawn. For one second loss the highest signal observed (in cell 8L7) was about 100 times higher than during ion luminosity runs (cell 10L2), what gives the first estimation of possible luminosity increase.

This test shall be repeated in 2012 with ion beam, using ADT for control beam blowup, because knowledge of steady state quench limit in dispersion suppressor is a key parameter to estimate the luminosity reach for ion runs after LS1.

WHAT SHOULD WE LEARN IN 2012?

The understanding of quench limits is critical for running LHC after LS1. From the past quench tests only part of the necessary information can be extracted. In order to understand quench limits a set of quench test should be performed in 2012.

The two most important quench limits to be investigated are those in UFO timescale and those for steady state losses. The understanding the UFO quench limits may lead to fine-tuning of BLM thresholds and even relocation of monitors on the arcs. The understanding the steady-state quench limit will allow to estimate the intensity and luminosity limits of the machine in the current configuration. It is essential for construction of additional protection devices which eventually will allow to increase these limits.

Therefore it is proposed to perform the following tests:

- For UFO losses:
  - UFO fishing (i.e. allow for quench due to UFO loss).
  - Orbital bump with millisecond loss duration.
  - Wire scanner quench test with higher intensity.
- For steady state losses:
  - Proton dispersion suppressor test.
  - Ion dispersion suppressor test.
  - Orbital bump with about 1 minute loss duration.

In addition, the injection test with beam dumped on a collimator is also proposed. This test, which is a follow up of 2011 test, will help to establish beam energy dependence of the quench limits.

As previously stated the BLM thresholds are set according to an approximate algorithm. The data obtained during 2012 tests should allow for the validation of the QP3 code and for the use of this tool for BLM threshold generation. This is an efficient strategy to fine-tune BLM thresholds.

Due to slight increase of the risk when quenching with higher magnet current, it it is recommended to perform the tests at 3.5 TeV (whenever possible) and in locations which are known to have the best quality of splices (for instance use of cell 17R5 for orbital bump test).

As there are at least three different groups interested in quench tests, it is proposed to establish a working group, which will meet several times during the year to decide on the priorities of the tests and to discuss the technical aspects.

ACKNOWLEDGEMENTS

The author wants to thank the following people for their particular help in preparation of the paper: B. Dehning, A. Nordt, R. Assman, R. Steinhagen, A. Priebe, P. P. Granieri, D. Wollman, S. Redaelli, G. Bellodi, A. Verweij, M. Bednarek, K. Brodzinski, W. Hofler, D. Valuch, E. Nebot, J. Jowett, S. Mallows, Ch. Bracco, K. Dahlerup-Petersen and T. Baer.

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