ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS036

# QUENCH DETECTION AND DIAGNOSTIC SYSTEMS FOR THE SUPERCONDUCTING CIRCUITS OF THE HL-LHC*

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*Abstract*

The High Luminosity Upgrade of the LHC [1] will incorporate a new generation of superconducting elements such as high field superconducting magnets based on $Nb_3Sn$ conductors and $MgB_2$ high temperature superconducting links for magnet powering. The proper protection and diagnostics of those elements require the development of a new generation of integrated quench detection and data acquisition systems as well as novel methods for quench detection. The next generation of quench detection systems is to a large extent software defined and serves at the same time as high performance data acquisition system.

## INTRODUCTION

The protection of the superconducting elements of the High Luminosity Upgrade of the LHC (HL-LHC) will rely on highly dependable quench detection systems (QDS) adapted to the specific properties of superconducting materials such as $Nb_3Sn$ and $MgB_2$ . For the HL-LHC QDS a unified approach, the Universal Quench Detection System (UQDS, see Fig. 1) has been proposed [2]. A part from the enhanced capabilities for quench detection, the integrated data acquisition system offers significantly higher sampling rates and resolution than previously installed systems.

## THE UNIVERSAL QUENCH DETECTION SYSTEM UQDS

As a flexible and generic system, the UQDS architecture is not bound to a specific quench detection algorithm and can be easily configured according to the requirements of the protected superconducting element or circuit. One of the key elements of the UQDS architecture are the analogue front-end channels equipped with a high-resolution analogue to digital converter (ADC) of the successive approximation type. In the current implementation up to 16 of such channels connect to a field programmable gate array (FPGA), which processes the acquired data and executes the quench detection algorithms. Optionally, the number of analog input channels can be extended up to 32. Insulated DC-DC converters and digital isolators for the serial data interfaces provide galvanic isolation of the analogue channels. The galvanic isolation of each individual analogue front-end channel allows a flexible usage of the magnet instrumentation, as there is no limitation by any common-mode potential differences in the comparison of the magnet voltages. To enhance reliability, UQDS units are always deployed as a set of two independent units reading signals from two redundant sets of instrumentation voltage taps. Each unit is powered by two independent power supply units, which are supplied by different uninterruptible power supply (UPS) 230 V AC feeds. The UQDS units are equipped with configurable hardware interlocks for the power abort signal and the activation of the protection elements of the magnet circuit such as quench heater discharge power supplies (DQHDS), Coupling Loss Induced Quench units (CLIQ) [3] and energy extraction systems. The built-in field-bus interface, either of the WORLDFIP™or the POWERLINK™standard, provides the data link to the front-end computers of the accelerator control system.

Figure 1: UQDS v2.1 crate serving as the base line prototype for the HL-LHC quench detection system.

## UQDS APPLICATION FOR HL-LHC

Table 1 summarizes the foreseen deployment of UQDS units within the HL-LHC, which will cover 72 superconducting magnet circuits. The present implementation requires only the UQDS systems for the 11 T dipoles to be radiation tolerant with an expected maximum total integrated dose rate of 10 Gy/year [4]. The allocation of UQDS units is not yet final and depends as well on the number of analog input channels per unit.

### *Quench Detection for 11 T Dipole Magnets*

The $Nb_3Sn$ based 11 T dipole magnets type MBH [1] will be installed in series to the LHC main bending dipoles in sectors 6-7 and 7-8. Located close to both sides of IP7, the shorter but stronger 11 T magnet will provide space to insert additional collimators. The quench detection algorithm [5]

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Table 1: UQDS Deployment for HL-LHC

| **Application** | **UQDS units** |
|---|---|
| 11 T dipole magnets + trim circuits | 6 |
| Inner triplets (IT) + D1 | 40 |
| D2 and corrector magnets | 16 |
| $MgB_2$ cable links for IT, D1 | 24 |
| $MgB_2$ cable links and D2 | 16 |
| HTS current leads | 24 |
| Total | 126 |

uses a complex scheme, where an insulated channel measures the voltage over each pole and the adjacent bus-bars. The bus-bars between the two magnet halves are covered by two additional channels. Comparisons between the poles of the physically separated sub-modules MBHA and MBHB serve as an efficient method to detect aperture symmetric quenches.

### *Flux Jumps*

$Nb_3Sn$ based magnets suffer from so-called flux jumps [6], which result in voltage spikes detected by the electronics. The quench detection algorithm needs therefore to be adapted in order to reduce its sensitivity to these signals and the risk of false positives, e.g. with the help of non-linear digital filters. Since flux jumps are more dominant at lower currents, the application of current dependent detection settings is as well a suitable solution. The effect of the flux jump phenomenon on the magnet voltage is clearly visible in Fig. 2 showing data recorded during a training quench of a 11 T hybrid prototype magnet. While the very strong perturbations at the start of the current ramp are caused by the test bench power converter and not representative for LHC operation, one can identify two areas with enhanced flux jump activity. The perturbations observed at low current I < 500A could affect as well the current regulation of the power converter [7]. As the observed current levels are still below injection current of the main dipoles, operation with beam will not be affected.

### *Quench Detection for the Inner Triplets, D1 and D2 in the Interaction Regions around IP1 and IP5*

The quench detection algorithms for the inner triplet circuits follow the same principles as for the protection of the 11 T dipoles. Due to the complexity of the triplet circuit, the number of required channels for quench detection is significantly higher. the current implementation will use 100 UQDS channels per triplet circuit to process the signals from 160 voltage taps. UQDS units will be used as well for the protection of the D1, D2 and the new CCT type D2 corrector magnets. All quench detection systems for the inner triplet, the D1 and D2 magnets and the corrector package will be installed in the shielded underground areas UR1 and UR5 and are therefore not required to be radiation tolerant.

### *Quench Heater Circuit and CLIQ Supervision and Triggering*

The supervision and activation of the quench heater circuits and CLIQ units is managed by a dedicated supervision and trigger controller (DQHSU). The DQHSU records data from quench heater and CLIQ discharges with sampling rates up to 192 kS/s and ensures the correctly timed activation of the DQHDS and CLIQ units. As the activation of quench heaters or CLIQ units creates an impact on the circulating beams [8] [9], it is important to initiate a beam abort sequence beforehand. While a spurious activation of one or more quench heater or CLIQ units is still safe for LHC operation [1] [9], it is in such a case nevertheless wishful to dump the beams and force the trigger of the not yet activated units. Table 2 lists the various steps and the required time. Due the time constraints for the beam abort, the DQHSU may be equipped with a direct link to the beam interlock system (BIS). The estimated total time is < 1 ms, i.e about 11 turns of the beam

Table 2: Beam Abort Sequence Timing in Case of Spurious Quench Heater or CLIQ Activation

| **Step** | **Duration** |
|---|---|
| Detection DQHDS (di/dt ≈ 4 MA/s) | 100 $\mu$s |
| Detection CLIQ (di/dt ≈ 200 kA/s) | < 500 $\mu$s |
| Communication DQHSU → BIS | 200 $\mu$s |
| Beam abort sequence | 270 $\mu$s |
| Total | < 1 ms |

### *Quench Detection for $MgB_2$ Based High Temperature Superconducting Links*

For the protection of the $MgB_2$ multi-cable assemblies [10], which incorporate cables with current ratings from 2 kA to 18 kA, specially configured and adapted UQDS units will be deployed. In case the detection threshold is exceeded, those systems trigger a power abort and activate the protection systems of the respective circuit such as CLIQ units, DQHDS or energy extraction systems. For each pair of cables the UQDS triggers on the differential voltage signal as well on the absolute voltage signal as one cannot exclude symmetric quenches in a pair of cables. Preliminary quench detection settings assume a threshold voltage $U_{TH} \leq |\ 100\ \mathrm{mV}\ |$ and an evaluation and discrimination time $t_{DIS}$ = 100 ms. The final validation of the quench detection settings requires powering tests with inductive loads as foreseen during the HL-LHC IT STRING test [11]. For supplementary protection of the link a $Nb_3Sn$ wire routed through the cable assembly will be connected to an additional UQDS channel.

[1] For CLIQ units this is only valid in case of the revised connection scheme proposed recently.

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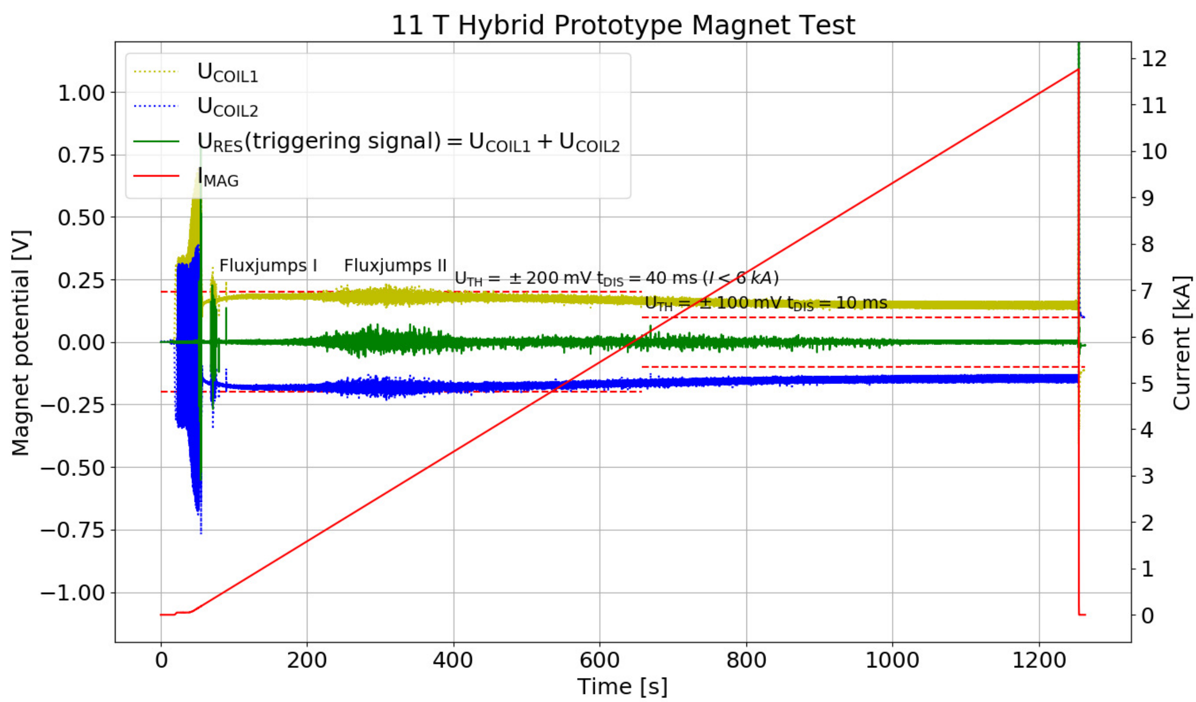


Figure 2: Recorded data of a training quench of a 11 T hybrid prototype magnet at I = 11762 A. The UQDS system has been configured with current depended detection settings to overcome the flux jump region at low currents. The system served as well as data acquisition system with 205.8 kS/s and an effective resolution of 687 $\mu$V at ±22.5 V input range. The quench detection settings are given by the threshold voltage $U_{TH}$ and the evaluation and discrimination time $t_{DIS}$.

## HL-LHC IMPACT ON EXISTING LHC QUENCH DETECTION ELECTRONICS

The enhanced luminosity of the HL-LHC will increase the radiation levels in the dispersion suppressor areas around IP1 and IP5 to levels requiring an upgrade of the quench detection electronics currently installed in those areas. The latest simulations indicate a total integrated dose of up to 100 Gy/year in some locations [4]. For those integrated dose levels, it is still possible to develop the respective QDS electronics using qualified Commercial of the Shelf (COTS) components. Taking into account the strong gradients inside the radiation loss distribution, another option is in some cases the relocation of QDS electronics.

With the high intensity beams of the HL-LHC the risk of beam induced symmetric quenches in the insertion region magnets is significantly increased.The deployment of the novel current derivative sensors [12], which allow detection of symmetric quenches, is considered as an adequate solution to overcome the limitations of the presently installed systems.

## CONCLUSION

Recent tests with prototype magnets and superconducting cable links confirmed the validity of the designs for the next generation of quench detection systems. Those tests confirmed as well the significantly enhanced capabilities of the built-in data acquisition, which will ease circuit diagnostics and fault analysis especially during the LHC hardware commissioning phase. The first use case in LHC will be the protection of the $Nb_3Sn$ 11 T dipoles [13] to be installed in sectors 6-7 and 7-8. The rather complex protection scheme for the inner triplet circuit will be validated prior to LHC installation within the HL-LHC IT STRING test [11].

## ACKNOWLEDGEMENTS

The authors would like to thank M. Bajko, G. Willering and the CERN SM18 magnet test facility staff for the kind support and help during the tests with the 11 T hybrid prototype magnet and the $MgB_2$ cable link prototype.

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