e-Print: 2112.00823 [physics.ins-det]
DOI: 10.1109/TASC.2022.3155492
FERMILAB-PUB-21-637-SQMS-TD
(accepted)



# A Quench Detection and Monitoring System for Superconducting Magnets at Fermilab

A. Galt, O. Al Atassi, G. Chlachidze, T. Cummings, S. Feher, A. Hocker, S. Kotelnikov, M. Lamm, A. Makulski, J. Nogiec, D. Orris, R. Pilipenko, M. Tartaglia

***Abstract*— A quench detection system was developed for protecting and monitoring the superconducting (SC) solenoids for the Muon-to-Electron Conversion Experiment (Mu2e) at Fermilab. The quench system was designed for a high level of dependability and long-term continuous operation. It is based on three tiers: Tier-1, FPGA-based Digital Quench Detection (DQD); Tier-2, Analog Quench Detection (AQD); and Tier-3, the quench controls and data management system. The Tier-1 and Tier-2 systems are completely independent and fully redundant. The Tier-3 system is based on National Instruments (NI) cRIO and provides the user interface for quench controls and data management. It is independent from Tiers 1 & 2. The DQD provides both quench detection and quench characterization (monitoring) capability. Both DQD and AQD have built-in high voltage isolation and user programmable gains and attenuations. The DQD and AQD also includes user configured current dependent thresholding and validation times.**

**A 1st article of the three-tier system was fully implemented on the new Fermilab magnet test stand for the HL-LHC Accelerator Upgrade Project (AUP). It successfully provided quench protection and monitoring (QPM) for a cold superconducting bus test in November 2020. The Mu2e quench detection design has since been implemented for production testing of the AUP magnets. A detailed description of the system along with results from the AUP superconducting bus test will be presented.**

***Index Terms* — Analog Quench Detector, Digital Quench Detector, Hi-Lumi, Mu2e, Quench Protection, Superconductor.**

## I. INTRODUCTION

The Muon-to-Electron Conversion Experiment (Mu2e) is a particle physics experiment at Fermilab designed to search for the rare process of direct muon to electron conversion in the field of a nucleus. Three large superconducting warm-bore solenoids comprise the magnet system required for this experiment: The Production Solenoid (PS); the Transport Solenoid (TS); and the Detector Solenoid (DS) [1]. The total stored energy at operating current is ~107 MJ.

A highly reliable quench protection system is required to protect the Mu2e superconducting magnets, leads, and bus. The primary requirement for the design of this system is to ensure that a true quench of any superconducting component will always be detected. It must also be designed to minimize false quench triggers and unscheduled downtime that causes unnecessary interruptions to the operation of the experiment. The quench detection system monitors the superconducting magnet coils and bus, the superconducting bus in the transfer lines, the high temperature superconducting (HTS) power and trim leads, and the vapor-cooled copper power main and trim leads. Figure 1 shows a model of the Mu2e solenoid system. The four Mu2e magnets are shown along with their respective transfer lines and feedboxes. The power leads are located on top of the feedboxes, which are located outside the radiation area in the power supply room. The quench detection system is in the same area; therefore, a radiation tolerant quench detection and monitoring (QDM) system is not required. All voltage taps are brought out through the instrumentation trees located near the feedboxes.

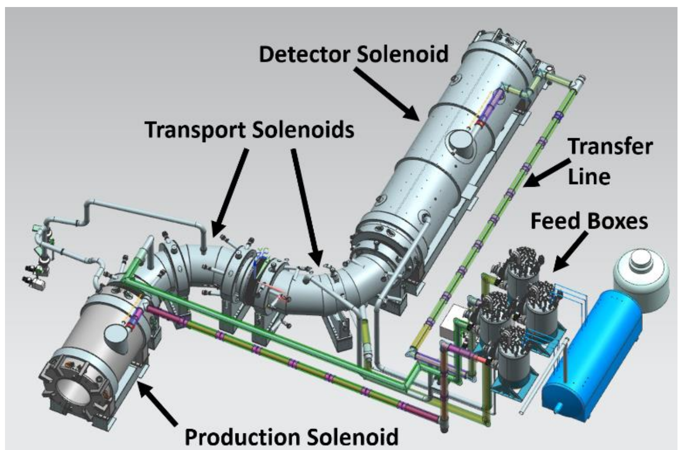


*Figure 1: Mu2e Solenoids System*

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

A. Galt is with Test & Instrumentation, Fermilab, Batavia, IL. United States, 60510 (email: agalt@fnal.gov), O. Al Atassi is with Cryo Operations, Fermilab, Batavia, IL. United States 60510 (e-mail: oalatass@fnal.gov), G. Chlachidze is with Magnet Systems, Fermilab, Batavia, IL. United States, 60510 (email: guram@fnal.gov), T. Cummings is with Test & Instrumentation, Fermilab, Batavia, IL. United States, 60510 (email: tcumming@fnal.gov), S. Feher is with Magnet Systems, Fermilab, Batavia, IL. United States, 60510 (email: fehers@fnal.gov), A. Hocker is with Magnet Systems, Fermilab, Batavia, IL. United States, 60510 (email: fehers@fnal.gov), S. Kotelnikov is with Instrumentation and Controls Development, Fermilab, Batavia, IL. United States, 60510 (email: kotelnik@fnal.gov), M. Lamm is with Magnet Systems, Fermilab, Batavia, IL. United States, 60510 (email: lamm@fnal.gov), A Makulski is with Test & Instrumentation, Fermilab, Batavia, IL. United States, 60510 (email: makulski@fnal.gov), J. Nogiec Hocker is with Magnet Systems, Fermilab, Batavia, IL. United States, 60510 (email: nogiec@fnal.gov), D. Orris is with Test & Instrumentation, Fermilab, Batavia, IL. United States, 60510 (email: orris@fnal.gov), R. Pilipenko is with Instrumentation and Controls Development, Fermilab, Batavia, IL. United States, 60510 (email: pilipen@fnal.gov), M. Tartaglia is with Test & Instrumentation, Fermilab, Batavia, IL. United States, 60510 (email: tartaglia@fnal.gov).

The presented QDM is a significant improvement over the previous designs [3][4]. It offers a proven heterogenous architecture in which Tier-1 is based on digital technology and Tier-2 is based on analog technology. The heterogeneous solution reduces common failure modes, such as, firmware design issues, common component defects and failures, etc. However, the choice of implementation technologies and additional QoS (quality of service) features are different than its predecessors.

Quench detection is performed by the common method of measuring voltages, which are sometimes bucked against other appropriate signals, which are then compared against associated threshold values.

Although the methods for detecting quenches remain the same at its core, the design choices and technologies selected for the implementation create a unique and powerful solution for environments focusing on observability and increased flexibility. The solution supports tailoring and adjusting the parameters of the systems to achieve the balance between sensitivity of detection and availability of the magnet system. These features are important for test facilities and systems with unique configurations of heterogeneous superconducting magnets such as the Mu2e experiment.

The new Mu2e quench detection system design consolidates many different functional blocks and new features into a single 4-channel hardware module, reducing the number of multiple components, external cables, and interfaces. The result is improved long term reliability, faster troubleshooting, and less down time for repairs.

The following is a list of primary features that have been consolidated into the single 4-channel modules:

- Built-in high voltage isolation;
- Programable:
  - Gains;
  - Trigger validation and delay times;
  - Multiple current dependent thresholds;
  - Channels for bucking;
- Fast quench loggers (DQD only) with programmable:
  - Sample rates;
  - Pre and post trigger data windows;
- Open voltage-tap circuit detection;
- Flexible applications: The same module is used for Cu lead, SC bus, and SC magnet threshold detection.

In addition, this system has been designed with an emphasis on observability, which allows the user to monitor real-time quench signal data that can then be used for optimizing system parameters. All digital quench detectors include both fast and slow quench loggers with programmable sample rates and pre and post trigger data windows. The system is configured by simple text configuration files, which can easily be edited and uploaded to the digital quench detection modules via the Tier-3 GUI. The configurable parameters can also be edited in real-time (with safeguards). The digital quench detectors also monitor superconducting device current and calculates dI/dt, which can be used for bucking. These devices have been designed for easy expansion up to 32 channels for digital, and 28 channels for analog quench.

## II. Quench Protection System Design

### A. System Block Diagram

The block diagram of the quench protection system is shown in Figure 2. Independent voltage tap (VT) cables are wired to the instrumentation tree. One set of primary DQD VT, is connected to the Digital Quench Detection while another set of redundant AQD VT, is connected to the Analog Quench Detection for complete redundancy.

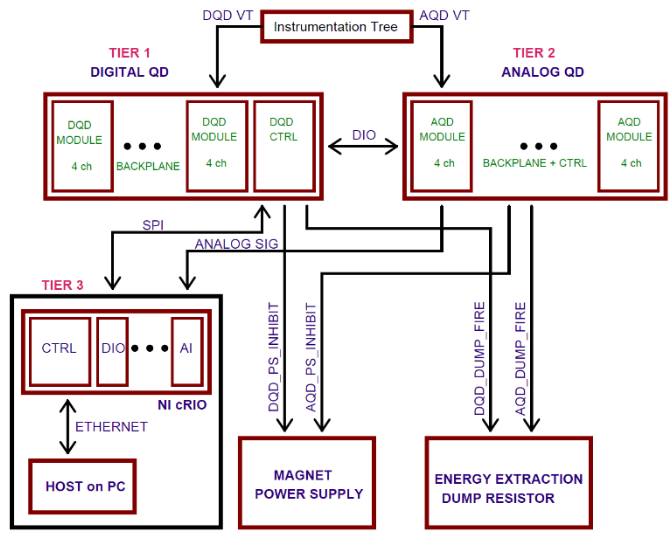


*Figure 2: Quench Protection System Block Diagram*

Both systems have high voltage isolation at their inputs since some VT pairs can generate up to 600 V during energy extraction.

The quench detection design provides a very flexible platform: It can be used for detecting quenches in superconducting magnets (individual and bucked signals), superconducting buses, HTS leads, and resistive voltage threshold crossing of the vapor cooled copper power leads.

### B. Digital Quench Detection Design (Tier-1)

The Digital Quench Detection system has a modular architecture. A DQD chassis, shown in Figure 3, consists of up to 8 DQD Modules, 1 DQD Controller, and a DQD Backplane. The system can be extended up to 32 individual quench channels. Quench signals originating from the voltage taps are connected to the front panel of each DQD Module. Each module can receive up to 4 individual quench signal pairs. The backplane provides communication between all modules and the chassis controller. The controller aggregates the quench signals coming from all modules configured as quench detectors. When a quench is detected, the corresponding quench signal gets transferred from the module to the controller via the backplane. A “DQD_DUMP_FIRE” signal activates the energy extraction system and a “DQD_PS_INHIBIT” switches the superconducting magnet power supply into bypass mode.

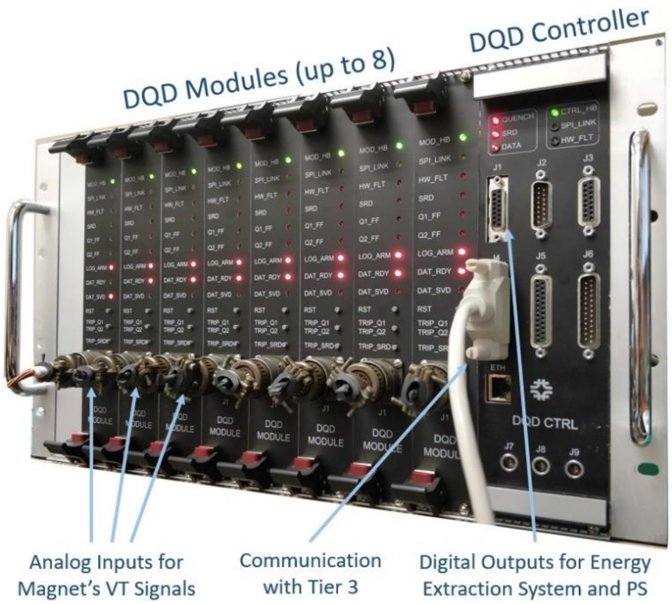


*Figure 3: DQD Chassis*

The block-scheme (Figure 4) illustrates the principle of the DQD Module operation. Each module has 4 individual analog channels and 4 digitally bucked channels that can buck individual channels against each other or against the current derivative (Idot). The field programmable gate array (FPGA) has configurable registers that can be uploaded from the configuration file via the Tier-3 GUI. Each channel can be configured as a "QUENCH1", "QUENCH2", "SRD" (slow ramp down), or "NO_ACTION" type. If "NO_ACTION" is chosen, then this channel is considered as a quench characterization (logging) channel. QUENCH1 is generated when the system detects a quench that requires immediate action (e. g., energy extraction when SC bus quenches). QUENCH2 is generated when the system detects a quench in which the action can be delayed (e. g., user specified delayed energy extraction after a coil quench).

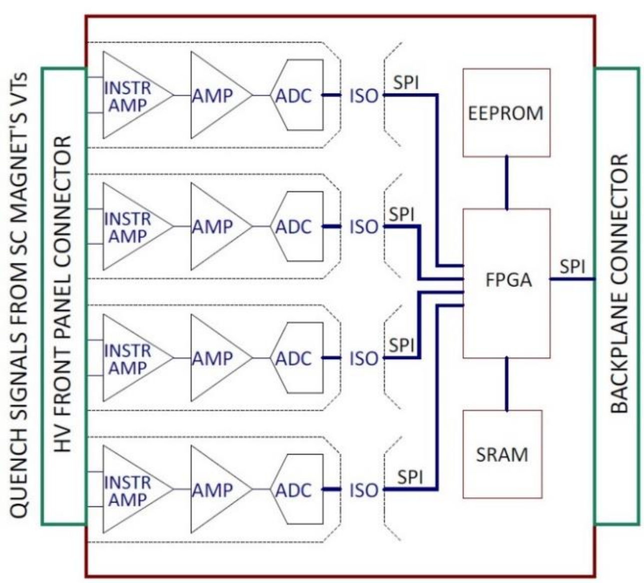


*Figure 4: DQD Module Block-Scheme*

All individual and bucked channels are digitized with a 10 kHz sample rate and saved in the circular buffer, which is implemented using the external SRAM memory. The circular buffer size is 60 kS/channel (480 kS/module).

The DQD module inputs have 2kV channel-to-channel and 2 kV channel-to-ground galvanic isolation for safety and noise rejection. A programmable voltage divider (not shown) is used to attenuate input signals. The signals are then applied to an antialiasing RC filter front end of the instrumentation amplifier. A digitally configurable amplifier is used for conditioning low voltage signals, such as the signals from the low temperature superconducting (LTS) bus or the high temperature superconducting (HTS) power leads. Typical thresholds for detecting quenches in a superconducting bus is 10 mV, and 1 mV for the HTS leads. After additional conditioning, the signal is then digitized by the 16-bit ADC.

The digitized signal is sent to FPGA via the digitally isolated serial peripheral interface (SPI) interface where it is compared with the current dependable quench threshold specified in the "CUR_DEP_THRESH" register. If the signal exceeds the threshold longer than specified in the "VALID_TIME" register, then a quench signal is generated with the delay specified in the "DELAY_TIME" register.

### C. *Analog Quench Detection Design (Tier-2)*

The Analog Quench Detector (AQD) is built with a proven analog component architecture. The system works in parallel with the DQD to provide quench protection redundancy. The AQD module (Figure 5) has both channel-to-channel and channel-to-ground galvanic isolation of 2 kV for safety and noise rejection. To accommodate a wide range of input voltages, each channel has jumper programmable gains ranging from 0.25 to 256. Each channel also has a jumper programmable validation time to reject false quench signals, such as noise spikes. Neighboring channels can be configured to buck coil signals and can be trimmed to compensate for inductance variation between coil segments. The AQD features hardware fault detection that

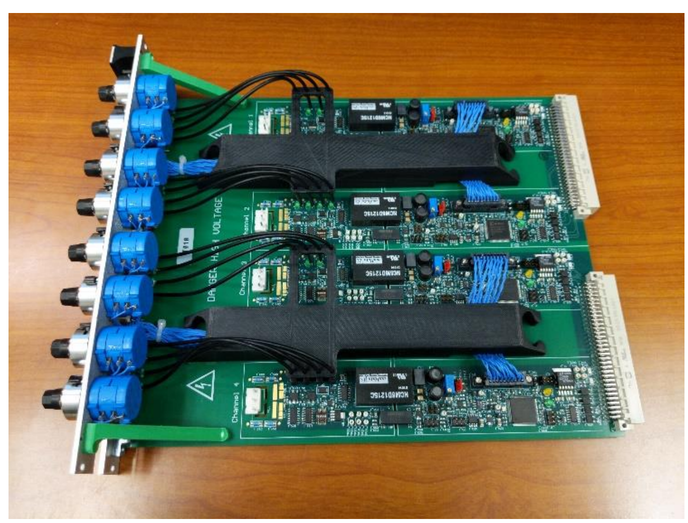

*Figure 5: AQD 4-Channel Module*

monitors power supply voltages, temperature, and input overvoltage.

Trip threshold and balance are set via potentiometers on the front panel for each channel. The front panel also displays the trip and hardware fault status of each channel, as well as the configured gains setting. Each AQD chassis can accommodate seven, four-channel modules. The trip and fault status signals of each module is relayed via 10 kHz modulated signal to the backplane complex programmable logic device (CPLD). The backplane CPLD consolidates these signals and drives modulated output signals as configured in the firmware.

### D. Automated QC Testbench

An automated testbench was developed to thoroughly check the functionality of both the AQD and DQD modules as received from vendors, post assembly. The NI cRIO based system can exhaustively test configuration parameters for both types of modules. The system tests gains, trip latency, validation time, hardware faults, input offset, input noise, and bucking functionality.

The testbench for the DQD uses an SPI interface to configure FPGA registers, while the AQD uses isolated solid-state relays to toggle jumper settings. The testbench UI generates a simple pass/fail report for the operator and a detailed log file for the engineers to review.

### E. Tier-3 Design

The Tier-3 system is based on NI cRIO and uses NI-9401 digital modules for communicating with the DQD Chassis. The purpose of the Tier-3 is to provide a GUI interface for interacting with the DQD system and automatic quench data saving. During start-up the user is prompted to select a DQD configuration file for the DQD. After the file has been successfully uploaded, the quench signal display, shown in Figure 6, pops up with 3 analog signal charts, quench protection system digital statuses, and quench signals. When a quench event occurs, the Tier-3 waits until the DQD circular buffers stop collecting data and then writes the quench data to a file that can be used later for quench data analysis.

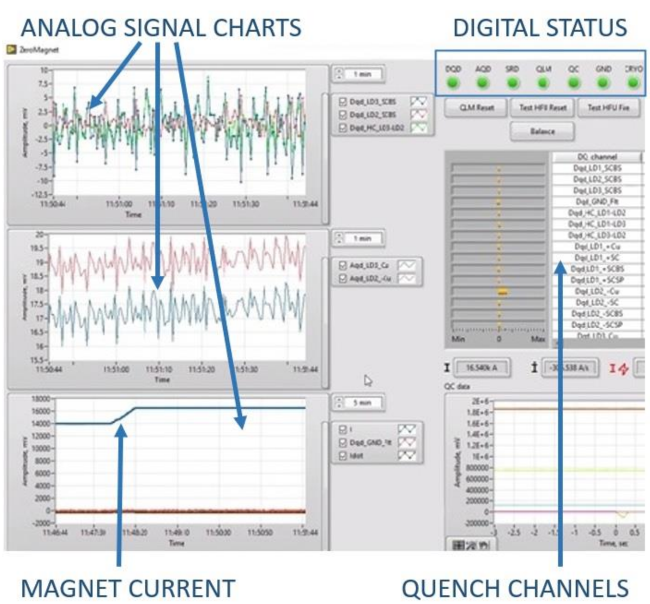


*Figure 6: Tier-3 GUI*

## III. Integration and Testing

### A. 1st Article QDM Test Stand Implementation and Testing

A Mu2e 1st Article quench detection system was implemented in a new superconducting magnet test stand under construction at Fermilab. The stand is in support of the US contribution to the High-Luminosity LHC Accelerator Upgrade Project (AUP) at CERN [2].

The test stand and quench detection system were ready for operation by November 2020. The QPM system was reviewed, and an Operational Readiness Clearance (ORC) was granted for carrying out cold powered tests.

### B. High Current Superconducting Hi-Lumi Bus Test

The test plan required power testing each of the 3 power lead configurations: Lead 1-2, Lead 3-2, and Lead 1-3. The following tests were to be performed for each power lead configuration: 1) Ramp the current in incremental steps up to the target current of 18.5kA; and 2) Ramp to 17.5kA and hold for 0.5 hours – Endurance test.

During the Lead 1-2 ramp to 18.5 kA, a quench occurred at 14,742 A. Further analysis of the quench data found that the quench was located at the SC bus to vapor-cooled lead junction. It was determined that the cause was additional heating at both the SC bus to Cu lead junction, as well as the external flex bus to Cu Flag junction in the lead 2. The problem was mitigated by improving the surface contact to the external junction and by increasing the liquid helium level to remove excess heat at the internal junction. A ramp to > 17 kA as well as a successful endurance run at 16.5 kA followed. A ramp to 18.5 kA and an endurance test at 17.5 kA was successful in the leads 1-3. The operation and functionality of this system proved to be a successful test of the 1st Article QDM.

## IV. Conclusion

A quench protection and monitoring system was developed at Fermilab with special attention to fulfilling the reliability requirements for Mu2e. The QPM has complete redundancy from the quench sensor through to the power supply and energy extraction systems. The quench detection system is a 3-Tier, heterogeneous system that has incorporated several design features to enhance long term dependable operation. The design consolidates many different functional blocks and new features into single 4-channel hardware module. The result is improved long term reliability, faster troubleshooting, and less down time for repairs. The presented QDM system provides all the above functionalities and capabilities typically required for quench protection solutions used in accelerators, experiments, and superconducting magnet research & development test stands.

## REFERENCES


[1] Mu2e Collaboration, "Mu2e Technical Design Report", arXiv: 1501.05241, http://arxiv.org/abs/1501.05241

[2] G. Apollinari *et al.,* "US contribution to the High Luminosity LHC Upgrade: focusing quadrupoles and crab cavities," Journal of Physics: Conference Series 1350 (2019) 012005

[3] M.J. Lamm et al., "A New Facility to Test Superconducting Accelerator Magnets", 17th IEEE Particle Accelerator Conference (PAC 97): Accelerator Science, Technology and Applications, Conf.Proc.C 970512 (1997) 3395.

[4] R. Pilipenko et al., "An FPGA-Based Quench Detection and Continuous Logging System for Testing Superconducting Magnets", *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. no. 9500503.

[5] D. Orris *et al.,* "A New Facility for Testing Superconducting Solenoid Magnets with Large Fringe Fields at Fermilab," FERMILAB-CONF-13-169-TD, PAC 2013 Conference: C12-09029, p.1265-1267

[6] D. Orris *et al.,* "Improvements and Performance of the Fermilab Solenoid Test Facility", *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Jun. 2017, Art. no. 4500205.

[7] G.V. Velev et al., "Design and Construction of a High Field Cable Test Facility at Fermilab", *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, May 2021.