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ENHANCING MEASUREMENT QUALITY IN HL-LHC MAGNET TESTING USING SOFTWARE TECHNIQUES ON DIGITAL MULTIMETER CARDS-BASED SYSTEM

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Abstract

The HL-LHC magnets play a critical role in the ongoing High-Luminosity Large Hadron Collider project, which aims to increase the luminosity of the LHC and enable more precise studies of fundamental physics. Ensuring the performance and reliability of these magnets requires high-precision measurements of their electrical properties during testing. To meet the R&D program needs of the new superconducting magnet technology, an accurate and generic voltage measurement system was developed after the testing and validation campaign of the LHC magnets. The system was based on a set of digital multimeter (DMM) cards installed in a PXI modular chassis and controlled using CERN's in-house software development. It allowed for the measurement of the electrical properties of the magnet prototypes during their study phase. However, during the renovation of the magnet test benches and in preparation for the HL-LHC magnet series measurement, some limitations and instabilities were discovered during long recording measurements. As a result, it was decided to redesign the measurement system. The emergence and promises of the new PXIe platform, along with the requirement to build eight new systems to be operated similarly to the existing four, led to a complete redesign of the software. This article describes the various software techniques employed to address platform compatibility issues and significantly improve measurement accuracy, thus ensuring the reliability and quality of the data obtained from the HL-LHC magnet tests.

INTRODUCTION

During the LHC magnet series tests in early 2000's, several mobile measurement systems were built to allow accurate analysis of their properties, with the same temperature and pressure conditions expected in the LHC emulated in the SM18 magnet test hall. A generic voltage measurement device [1], based on six KEITHLEY® 2001 digital multimeters (DMM) was used to record data for the specific acceptance tests: Residual Resistivity Ratio (RRR), energy losses in superconducting cable strands (Loss) and coil splice resistance measurement (Splice). The multimeters were remotely controlled via a GPIB bus from a SUN microsystem workstation, running a dedicated LabVIEW® software. Three mobile racks were used for RRR measurements and two for the Loss/Splice tests. They were extensively used for the 1232 dipoles and 480 quadrupoles magnet tests, prior to their installation in the LHC tunnel.

USING THE PXI PLATFORM AS A NEW STANDARD

After the intensive qualification campaign of the LHC magnets, a thorough review of the existing measurement and control systems took place, with the aim of preparing for the future HL-LHC [2] project. The availability of the PXI platform [3], which has become a new industry standard for Commercial Off-The-Shelf (COTS) modular systems, coupled with the approaching end-of-life for VME components, influenced the choice for the next generation of equipment.

Numerous measurement systems have been redesigned using PXI components. This same approach was applied to the legacy RRR and Loss/Splice mobile racks. After conducting a market survey, the PXI-4071 card from National Instruments (NI) was selected. This 7½-Digit Digital Multimeter (DMM) was deemed a strong candidate to handle all three test types within the same system.

THE NEW DMM MOBILE RACKS

The redesign plan aimed not only to introduce a new, more accurate, and versatile voltage measurement system but also to incorporate new features specifically designed to streamline the operation and testing of magnets.

The Hardware Considerations

The DMM system consists of an 18-slot PXI-1045 chassis that contains the following components: a PXI-8108 CPU running Windows 7 and the LabVIEW® application, up to 16 DMM cards, and a PXI-6221 DAQ card. This entire setup is installed in a 29 U mobile rack, complete with a screen, keyboard, and mouse for user interaction.

The DAQ card was used to read digital signals from a dedicated connector attached to the local magnet test bench. This simple connection reduced many sources of error, and allowed error tracking in the result files by automatically embedding the bench name as a 3-bit code.

The GUI incorporated a control panel for power converters. It featured a current profile editor and allowed for the selection and control of the converter, enabling comprehensive management of magnet current during DMM measurements.

The choice of the chassis and CPU was made in conjunction with hardware selections made two years prior for the renovation of the HF/LF DAQ systems. Ten of these systems were deployed across SM18 test benches, and the decision to use the same chassis and CPU was driven by maintenance considerations.

This standardization reduced component diversity, enhancing the ability to share spare parts and facilitate module swaps between systems in case of failure.

Regarding the DMM software, CERN's internal LabVIEW® software development spanned several months and resulted in the first operational system in 2011. The software featured three main panels:

- DMM Settings Panel: This panel allowed users to configure settings for the PXI DMM cards, including Signal Name, Voltage Range, Aperture Time, Resolution, and Auto Zero. It accommodated the selection of up to 16 cards.
- Powering Control Panel: this panel enabled control of the power converters, and the bench connector reading ensured the proper association of power converters with their respective benches, preventing control of a converter from another test bench.
- Metadata and Measurement Parameters Panel: This panel presented metadata fields associated with the magnet (to be stored within the result file), measurement parameters (test type such as RRR / Splice / Loss, measurement time duration, and sampling time), and two graphs displaying the current (from the selected power converter) and the DMM readout voltages.

Smooth Operation

After a few months of operation, an additional PCMCIA-based WIFI card was integrated, along with the development of an FTP file manager. This innovation allowed for automated discovery and transfer of local DMM result files to a DFS repository, facilitating future offline analysis using the DIAdem® tool.

By 2016, four DMM systems were in active operation, serving both HL-LHC and other R&D magnet prototypes [4]. Over the period spanning 2012 to 2016, a total of more than 13,400 data files were generated. The PXI-4071 cards demonstrated excellent performance, offering exceptional accuracy, even though only 10% of their capabilities were utilized. Furthermore, the PXI platform itself demonstrated its reliability and robustness, enduring the challenges of a demanding operational environment characterized by significant temperature and humidity fluctuations, dust resulting from civil engineering activities, and numerous sources of electrical disturbances.

UPGRADING TOWARD THE NEW PXIe STANDARD EVOLUTION

In preparation for the development of two new DMM racks for the CERN-GSI FAIR project [5], a new market survey for industrial modular instrumentation was conducted in 2016.

A Powerful New Standard

The marked trend was favouring PXIe [6] as the dominant platform. Leading providers were either revamping their PXI modules into PXIe format or exclusively introducing new components in PXIe. This upgraded iteration of the PXI standard brought about significant improvements in system bandwidth (from 132 MB/s to 24 GB/s), clock synchronization (from 10 to 100 MHz), and the possibility to employ PXI cards in a PXIe chassis, provided they were equipped with Hybrid slot technology.

This survey also shed light on the forthcoming availability of the PXIe-4081 DMM card, positioned as the successor for new developments, while signaling the end of the PXI-4071, with a last-time-to-buy deadline set for December 2018.

New Software Version of DMM for PXIe

With the inception of the FAIR project, and a collaboration with CERN to test FAIR magnets, came the prospect of acquiring new hardware. We opted for a PXIe-1075 chassis, which would accommodate a PXIe-8821 CPU, a set of PXIe-4081 DMMs, and a PXIe-6341 DAQ card (refer to Fig. 1). Simultaneously, during the procurement phase for two new mobile DMM systems, we undertook the development of a dedicated PXIe version of the DMM software. This adaptation was the result of six years of experience with the DMM racks, affording us the opportunity to assess the support cases we had managed and gather user feedback regarding missing or underutilized features.

It's worth noting that we removed the embedded control of the power converters due to the specific requirement to oversee up to nine converters in parallel.

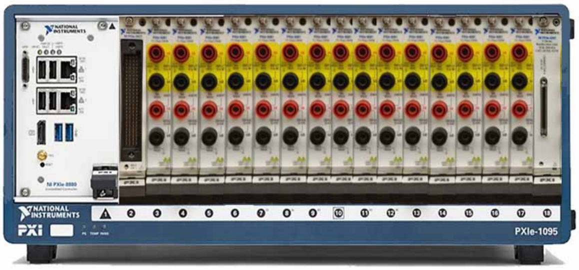


Figure 1: New system based on PXIe chassis and PXIe-4081 DMM cards.

The ADC Calibration field (internal feature of the card) was added in the setup panel, giving the option to compensate the ADC gain drift by using the very accurate internal reference voltage of the PXIe-4081 card. The LabVIEW® low level driver for the PXIe-4081, was also adapted due to the unexpected absence of some parameters.

On the measurement panel, the removal of the current graph gave more space for the DMM readout voltages.

At the bus triggering level, new lines were selected to ensure a better synchronization of the DMM readings, with new capabilities offered by the selected DAQ card.

Mid 2018 this new software was validated and ready to control the FAIR DMM racks (Fig. 2). Operational tests of the first GSI-FAIR magnet (GSI Super-FRS FPF2YMQ12 Multiplet) delivered by ASG Superconductors were launched in March 2019 [7].

UNIFICATION OF THE PXI AND PXIe PLATFORMS

The adaptability and flexibility of the measurement systems in the CERN magnet test facility is key. Given the intricacies of the infrastructure, the ever-changing priorities of magnet tests, and the occasional need for in-depth analysis when issues arise with a magnet, we must be able to swiftly adjust our plans. In this context, the ability to interchange cards and other components between measurement systems becomes a necessity. We aim to provide operators with the capability to reassign hardware to a test bench with a higher-priority magnet within just a few hours.

This critical consideration guided our hardware selection process for the deployment of six new DMM systems, essential for evaluating the performance of the HL-LHC magnet series [8]. Pragmatically, we decided to reuse the PXIe card references previously employed for the FAIR project. We opted for a new PXIe-1084 chassis, primarily because of its seventeen hybrid slots, as opposed to only eight in the PXIe-1075. This choice allowed operators to use both PXI and PXIe-based DMM cards within the same chassis. The consensus among stakeholders was that developing another software version to enable the use of older-generation DMM cards inside the new chassis would significantly reduce initial costs for the organization while facilitating a gradual transition to PXIe-4081 DMMs over the coming years.

However, the increasing number of hardware combinations and the existence of two prior software versions raised concerns about the long-term maintainability of the new system. To avoid the complications of excessive diversification, we made the decision to consolidate the software versions into a single unified application compatible with all hardware generations. In this endeavour, we refrained from reusing any code from the existing software. Instead, we completely redeveloped the entire architecture and application concept. One of the challenges we faced was structuring the source code in a scalable and abstracted manner, enabling future expansion of the application and the seamless implementation of new hardware with minimal changes to the core code in the years ahead.

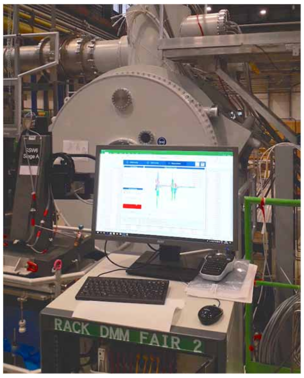


Figure 2: DMM Hybrid application used for magnet tests in FAIR facility.

Utilizing OOP and Actor Framework to Create a Scalable Measurement System Architecture

To begin, one of our primary design considerations was abstracting the interaction with hardware, a move that greatly simplified the integration of multiple hardware generations along with their respective drivers. Our goal was to establish a Hardware Abstraction Layer (HAL) capable of accommodating DMMs from various manufacturers.

Another integral facet of our object-oriented approach was the implementation of polymorphism in measurement handlers. This approach allowed us to describe the acquisition process as a series of generic steps that could be applied to multiple measurement types. While each measurement type necessitates specific configuration data and implementation details from a high-level perspective, the processes share the same underlying logic. By encapsulating these intricacies, we achieved significant improvements in modularity, scalability, and code readability.

Another main design decision involved selecting the appropriate design pattern for application development. Given that operating multiple DMMs concurrently requires interfacing with multiple instances of hardware drivers (without the possibility of handle aggregation), the Actor Framework emerged as a reliable solution. Consequently, all hardware devices managed through the software have their dedicated, abstract, actor-based handler modules, which can be initiated as concurrent clones. Additionally, we designed all general application modules as actors too, encompassing functions such as file interfacing, a graphical interface, top-level acquisition process management, and application business logic. This compartmentalization of code not only streamlines development and validation processes but also facilitates the incorporation of new functionalities into the project.

Handling Differences between PXI and PXIe Based DMM Cards

While both generations of NI DMMs share significant similarities in construction and specification and utilize the same low-level drivers, the development of previous software versions brought to light critical differences between them [9]. Addressing these disparities was a primary concern during the development of the unified application.

Some issues, such as contrasting default trigger polarities (Falling Edge for PXI-4071, Rising Edge for PXIe-4081) and inconsistent error scenarios, were relatively straightforward to resolve, however, other dissimilarities demanded a more thoughtful approach. One such difference was related to the trigger latching behavior, which had a notable impact on how the application would handle missed triggers. PXI-4071 devices can latch the trigger and initiate a new acquisition right after the previous one has finished. In contrast, the newer PXIe-4081 does not implement this mechanism, meaning that every unattended trigger between “retriggering” is lost.

Another discrepancy pertained to the "Trigger" and "Sample Trigger" source origin. Triggering options were less refined on older PXI cards, as both trigger signals were required to have the same source (unless used in Immediate mode). However, the primary incompatibility arose from the dropped support for the "Get Measurement Period" function in PXIe-4081 cards. This function was previously used to calculate the measurement time of a specified DMM configuration. The absence of measurement time information made it challenging to determine the minimum safe sampling speed that would ensure no missed triggers. Consequently, a new auto-triggering mode was implemented, allowing DMMs to retrigger themselves and operate at the highest possible frequency. An additional manual sampling rate field incorporates limits estimated through our in-house algorithm to protect users from selecting excessively low time values.

Analysis of Triggering Techniques Employed Into Application Logic

The DMM devices employed in the project offered significantly higher measurement quality compared to standard NI DAQ devices. However, NI DAQs excelled in terms of simultaneously measured channels. To tackle this challenge, a multiplexer card was introduced into each chassis running the application. This addition expanded the potential number of monitored signals per system at the expense of sampling speed. It also introduced an additional complexity in the triggering logic.

The measurements conducted by the application can be categorized into four main groups: automatic DMM sampling, manual DMM sampling, automatic DMM and MUX (multiplexer) sampling, and manual DMM and MUX sampling (see Fig. 3). Each category utilized multiple trigger signals to ensure stable and reliable operation.

In the case of automatic DMM sampling, the fastest possible speed was achieved by coordinating the master DMM's measurement completion signal with a retriggerable DAQ task that sent the trigger signal again to all DMM cards via a pre-configured Trigger/Sample Trigger line. In this scenario, it was crucial that both the master DMM and the DAQ card were positioned at opposite ends of the chassis to compensate for trigger propagation delays, which could otherwise result in missing samples on DMMs with unfinished acquisitions. Another DAQ task was employed to implement a counter that monitored the intervals between the first few samples and calculated the measurement period. In manual mode, this process was simplified, as the measurement was directly sampled by a DAQ task with an interval value specified by the operator.

When automatic DMM and MUX mode was selected, the triggering configuration resembled the handshaking scenario from automatic DMM mode. However, in this case, the multiplexer served as the handshake device [10]. As soon as the measurement was completed on the master DMM, the multiplexer switched, sending a Scan Advanced trigger to all DMMs the moment the switching was finished.

Complexity increased significantly when manual DMM and MUX mode was utilized. Three sub-scenarios were implemented. If only PXIe-4081 devices were used in the measurement, the application could take advantage of the ability to select different Trigger and Sample Trigger sources. The Trigger signal was operated by a DAQ task with sampling specified by the user (in this context, each sample consisted of a sequence of acquisitions comprising all selected multiplexer channels). Meanwhile, Sample Trigger was synchronized with the MUX, advancing through its channels. However, this synchronization was not possible when some of the slave DMMs were of the older PXI type. In such a scenario, DMMs not assigned to the MUX would not follow the master DMM's handshake timing but instead measure the requested number of samples one after another.

Finally, if the master DMM was a PXI-4071, the DAQ task would no longer be used to initiate measurement sequences. To work around the hardware limitations of these devices, each sampling sequence would be started with a software-timed Software Trigger function.

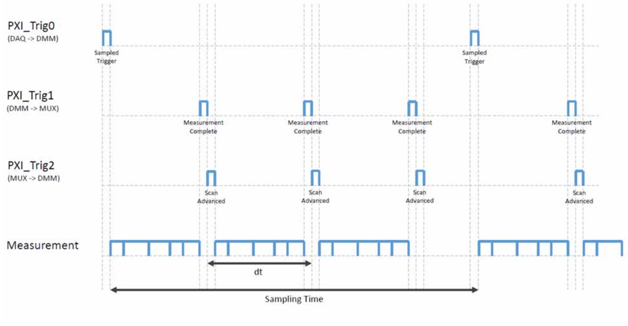


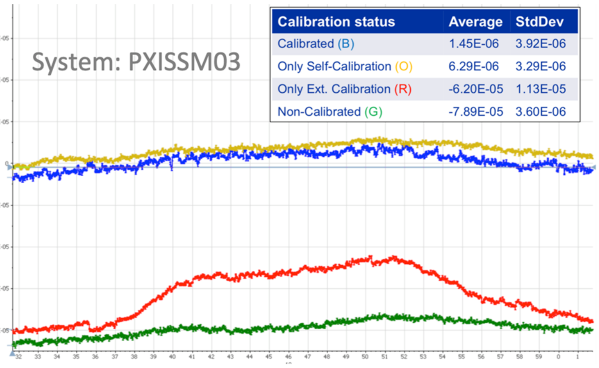
Figure 3: Triggering logic for DMM and MUX manually sampled mode.

Validating Measurement Capabilities of the Application

After the development phase, the new application went through a series of tests (Fig. 4), aimed at validating the measurement capabilities, as well as finding optimal accuracy versus sample acquisition length configurations for the magnet test facility needs. It was confirmed that the software is capable of operating in a wide range of configurations (with acquisition times from 1 millisecond to 2 seconds) and on both short and long-time scale (minutes to days of continuous acquisition).

Figure 4: Four DMM Hybrid racks used at the same time during tests of a Superconducting-Link.

The influence of hardware calibration was also tested. NI DMM modules give access to two types of calibration: software calibration (self-calibration) and factory calibration. We have experimentally proven that to preserve the accuracy it is necessary to follow the manufacturer's recommendation concerning the regularity of both calibration types. Furthermore, equipment should be stored in stable environmental conditions as even small temperature changes can greatly affect measurements. After 90 days, 10°C temperature difference from T_{cal} can double the inaccuracy from 2.05uV to 5.5uV for PXIe-4081 [11]. Interestingly, we have learned that self-calibration has a greater impact on measurement offset, while external calibration reduces fluctuations on signal readings (Fig. 5).



Calibration status	Average	StdDev
Calibrated (B)	1.45E-06	3.92E-06
Only Self-Calibration (O)	6.29E-06	3.29E-06
Only Ext. Calibration (R)	-6.20E-05	1.13E-05
Non-Calibrated (G)	-7.89E-05	3.60E-06

Figure 5: Comparison of calibration status of PXI-4071 cards on mobile rack DMM3.

The self-calibration procedure was therefore introduced in the DMM application, monitoring the card calibration date and T_{cal} temperature. This feature allows a warning to be displayed to the user prior a new measurement, showing which cards should be calibrated, and offering an easy way to launch the self-calibration procedure. For the external calibration the CERN PXI Calibration Service, introduced in 2012 as an in-house development, provides a fast and cheap solution.

Next step in our validation process was analysing the impact of various measurement parameters available for NI DMMs on the quality of the data. We have compared the measurements performed with and without the following parameters: AutoZero, ADC Calibration, DC Noise Rejection and Averaging. The results of our analysis showed that the AutoZero feature is critical for measurements longer than tens of seconds in order to avoid an oscillating reading offset. ADC Calibration can help to reduce long term measurement drift by adjusting reference voltage to current conditions. DC Noise Rejection was identified as useful in case of measurements carried out in a high noise environment, as it removes high frequency outliers from the measured signal. Finally, Averaging combines multiple samples into one, smoothing out the signal and increasing the accuracy at the cost of time resolution.

CONCLUSION

After two years of operation, we can confidently affirm that the system has successfully achieved its objectives and demonstrates a clear superiority in terms of reliability and performance compared to previous generations. End users have appreciated the flexibility and enhancements that the new software has brought to their daily routines, and it now serves as a unified application across all measurement stations. Numerous improvements in the graphical user interface have simplified measurement configuration and control, with new features and monitoring options also introduced.

Of course, it's essential to acknowledge that some issues were encountered and additional refinements were required during this period. For example, initially the deployment of the application was a manual process, which posed challenges given that the program runs on eleven mobile systems. This year, we streamlined the deployment by automating it through the use of the CERN cloud synchronization client (CERNBox).

One notable challenge was related to high CPU consumption in specific measurement scenarios. Operators observed that in demanding scenarios, involving the simultaneous operation of multiple DMM devices, the application could utilize a significant portion of the system's processing power, leading to data loss. Extensive testing revealed that this issue was unrelated to the software architecture and originated from the internal drivers of the NI DMMs. Eventually, it was determined that elevating the priority for the Windows application process completely resolved the problem.

At present, the application has been running in production for over a year without any issues, and there is no need for further development in the foreseeable future.

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