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**US HL‑LHC Accelerator Upgrade Project**

**Guidelines for MQXFA Vertical Test Data Organization**

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# Scope

This document describes the organization of the test data of the MQXFA magnets, to be installed in HL‑LHC as the Q1 and Q3 inner triplet optical elements in front of the interaction points 1 (ATLAS) and 5 (CMS). A pair of ~4.5 meter long MQXFA magnets is assembled in a stainless‑steel helium vessel, including the end domes, to make the Q1 Cold Mass or the Q3 Cold Mass. The US HL‑LHC Accelerator Upgrade Project is responsible for the design, manufacturing and test of the Q1/Q3 Cold‑Masses and the complete MQXFA magnets [1]. CERN provides the cryostat components and is responsible for integration and installation in HL‑LHC [2].

This document provides an overview of the test objectives and the data organization plans, followed by details of the data types and formats, the structure of the file systems and the storage and distribution platform. It should be noted that in the context of the AUP project, responsibility for data acquisition, storage and distribution at each production step is with the respective WBS component. This document covers the data plan for WBS 302.4-01, magnet vertical test.

# Related US‑HiLumi Project Documents

1. US‑HiLumi.Doc.36 MQXFA Functional Requirements Specification
2. US‑HiLumi.Doc.948 MQXFA Final Design Report
3. US.HiLumi.Doc.1103 Acceptance Criteria Part A: MQXFA Magnet
4. US-HiLumi.Doc.826 MQXFA Electrical Design Criteria
5. US-HiLumi.Doc.1109 Test stand functional requirements (MQXFA magnets)

# Vertical magnet test objectives and implementation

The primary objective of MQXFA cold testing in the vertical dewar is ensuring that the magnet meets key performance requirements prior to installation in the LQXFA cold mass; or if the magnet does not fully meet requirements, to characterize its technical limitations in order to help identify their causes and possible repair options. The main elements of the test are:

* At room temperature before cool down
	+ Electrical checkouts and tests ensuring the integrity of the insulation
	+ Magnetic measurements: transfer function, field integral and field harmonics
* After cool down to 1.9 K
	+ Electrical checkouts and tests ensuring the integrity of the insulation after cool down
	+ Quench protection system validation prior to training
	+ Quench training to ultimate current
	+ Magnetic measurements: integral field strength and field harmonics
	+ Holding the ultimate current for an extended period of time
	+ Splice measurements
* During warm up
	+ RRR measurement
* At room temperature after warm up
	+ Electrical checkouts to ensure the integrity of the insulation after the test

# Overview of MQXFA Test Data Requirements

A complex data acquisition and storage system is required during a superconducting accelerator magnet test to ensure safe operation and capture all relevant information about the magnet and system performance. From a project perspective the following objectives need to be addressed:

* Availability of key information on test progress/data in real time
* Exchange and integration of data among different WBS elements
* Distribution of validated/reduced data in a readily accessible format
* Test Logs and reports including history information and pointers to data files

The test systems and instrumentation include:

* Cryogenics (temperature and pressure sensors)
* Mechanical measurements (strain gauge powering and readout)
* Magnet powering system controls and monitoring
* Quench detection (from voltage taps placed at critical locations)
* Quench protection (heaters/CLIQ powering and monitoring)
* Quench localization (voltage taps, quench antenna and acoustic sensors)
* Magnetic measurements (rotating probe drive system and readout)

The following table indicates typical DAQ requirements for the various categories of signals.

Table 1: magnet instrumentation and DAQ characteristics



In developing the data collection and organization strategy, the following factors need to be taken into account:

* Providing the information needed for magnet acceptance
* Providing reference information for future reference in case problems develop
* Facilitating data sharing and analysis across the collaborating institutions

# Data types and formats

# Electrical QA Data

The voltage withstand requirements are shown in Table 2. Records of achieved maximum voltages and the corresponding leakage currents will be filled in with the results of each test. In addition, the waveforms recorded during the impulse tests at different voltages will be recorded in digital format.

Table 2: voltage withstand requirements [HiLumi.Doc.826]

|  |  |  |
| --- | --- | --- |
| Maximum expected coil voltage at quench (V) [2] | To ground | 670 |
| To quench heater | 900 |
| Minimum design withstand coil voltage at nominal operating conditions\*\* (V) | To ground | 1840 |
| To quench heater | 2300 |
| Minimum design withstand coil voltage at warm\* (V) | To ground | 3680 |
| To quench heater | 3680\*\*\* |
| Test voltage to ground for installed systems at nominal operating conditions (V) | 804 |
| Test voltage to ground for installed systems at warm (V) | 368 |
| Test voltage to heater for installed systems at nominal operating conditions (V) | 1080 |
| Test voltage to heater for installed systems at warm (V) | 460 |
| Maximum leakage current (µA) – not including leakage of the test station | 10 |
| Test voltage duration (s) | 30 |

# Cryogenic monitoring during cool-down, warm-up and between ramps

The cryogenic instrumentation includes temperature and pressure sensors in the cryostat as shown in Table 3. Readings will be obtained with 1 minute time interval during cooldown, warm-up and in between ramps, and recorded in a text file.

# Strain gauge data

The mechanical instrumentation is based on strain gauges placed on the aluminum shell, axial rods and (for the prototypes only) coil poles. Readings will be obtained with 1 minute time interval during cooldown, warm-up and in between ramps, and recorded in a text file. Two types of gauges (referred to as LARP and CERN gauges) are used in the prototypes. Therefore two sets of data files are provided. Details of the signals for each type of gauge are provided in Table 4 and 5.

Table 4: LARP gauge field description



Table 5: CERN gauge field description



# Current ramp monitor

During a current ramp, the mechanical and cryogenic monitoring is performed at the higher rate (1 Hz). In addition, the magnet current, voltages from the quench detection systems, and ground fault signal need to be monitored and recorded. The quench detection signals include: voltage and voltage derivatives of the entire coil and half coil; voltage across the copper leads, the superconducting leads and external/internal splices; and the ground fault monitor.

*Table 1: Ramp monitor header and field description*





A voltage spike detection system is also used to monitor voltage disturbances due to flux jumps or sudden displacements of the conductor under magnetic forces. The system shall be capable of measuring voltage signals from two half-coil segments with continuously sampled at a rate of at least 100 kHz, and if a spike in the bucked signal of these channels exceeds a user-defined threshold in the range of 5 mV to 1000 mV, the data around the spike shall be saved with a minimum time window of 0.5 seconds.

# Quench monitor

During the ramp, all key instrumentation for current monitoring, quench detection, characterization and protection is monitored at high frequency. These data includes:

* Power supply
* Protection system (heaters and CLIQ)
* Voltage taps
* Quench antenna

Following a quench, the data is recorded over a time window extending before and after the quench trigger with the following characteristics:

* Minimum Sampling Rate: 10 kHz
* Minimum pre-trigger number of samples: 20,000
* Minimum post-trigger number of samples: 20,000
* Minimum time window for logging data: 4 seconds; between before trigger and after a trigger

*Table 2: Quench monitor header and fields description*





# Magnetic measurements

Magnetic measurements are performed using a rotating probe. A vacuum jacketed tube placed in the magnet bore houses the probe maintaining and allows it to operate close to room temperature. The probe is short compared to the magnet: a longitudinal drive system is used to position the probe at a sequence of longitudinal steps to perform a complete scan over the length of the magnet.

The following data is required for recording the magnetic measurement results:

* Header section (common to an entire set of data points corresponding to a complete measurement, as indicated in the test plan (z-scan, accelerator cycle etc.)
	+ Measurement description
	+ Magnet name/rework #
	+ Measurement name/reference
	+ Test date
	+ Test cycle number
	+ Magnet temperature
	+ Pointer to probe(s) configuration (coils being read, which winding used for which harmonic, digital bucking, amplifiers/gains, etc)
	+ Pointer to probe(s) coil parameters (length, radii, angles, etc. of probe(s))
	+ Pointer to measurement and preparation cycle definition
	+ Pointer to powering configuration (power supply type and/or shunt/transductor setup/calibration)
	+ Pointer to coordinate system reference frame and conventions
	+ Reference radius
	+ Centering method (feed-down/zeroed harmonic, hysteresis, etc.)
	+ N orders reported
	+ Fundamental field
	+ Comments

Measurement record for each data point, usually an average over several probe rotations performed in uniform conditions:

* + Record number
	+ Number\_of\_averaged\_measurements (e.g. probe rotations)
	+ Measured current, Current s.d.
	+ Z position
	+ Time stamp/ elapsed time
	+ dx\_probe-position, s.d. dx
	+ dy\_probe-position, s.d. dy
	+ Fundamental field-angle, field angle s.d.
	+ Transfer function (Fundamental field / recorded current / referenceRadius^(fundField-1))
	+ Fields in T at the reference radius (N orders: 𝐵\_1, 𝐵\_2, … 𝐵\_𝑁, 𝐴\_1, 𝐴\_2, … 𝐴\_𝑁)
	+ S.d. of Fields in T at the reference radius (N orders: 𝐵\_1, 𝐵\_2, … 𝐵\_𝑁, 𝐴\_1, 𝐴\_2, … 𝐴\_𝑁)

# Test summary files

Various forms of communication are used to report the test status in relation to test plan, and then needs for re-evaluation depending on magnet performance and system/resource availability. These include email reports at the end of each test day, web pages reporting key status information, and logbooks/e-logs. A detailed e-log is also essential for later analysis and pointers to data. In addition, a summary file reporting the sequence of current ramps with key information about each run/quench has proven useful as a quick reference and pointer to the detailed information for each step of the test. A template is shown below.





# Structure of the file system

Data for the production testing of MQXFA will be organized in the following folder structure:



Each folder will include the following data files

* Electrical QA: tables of achieved voltage and leakage currents for hi-pot measurement prescribed by the QA plan, and recorded waveforms from the impulse test at each prescribed voltage
* Cryo data:
* Strain gauge data: slow monitoring during cool-down and in-between ramps, and increased rate during the magnet ramps
* Ramp data
* Quench data: one file for each fast discharge, including measurements from each relevant detection and protection element
* Magnetic measurements: one sub-folder for each measurement detailed in the test plan, including both raw and reduced data (field harmonics)
* Test summary folder: e-log, quench summary spreadsheet, test report

# Data storage and distribution platform

For a project which is mostly contained in a single laboratory, internal servers provide a straightforward approach to data storage and distribution. In particular this solution ensures that servers are managed in accordance with local IT policies and access by team members falls within pre-established procedures.

For project distributed among several Laboratories, such as HL-LHC AUP, the requirements are more complex and include:

* Conformance to policies of collaborating Labs & sponsoring agencies
* Streamlined procedures relative to those required to access Lab servers
* Sufficient storage capability (both total and single file)
* Safe/transparent backup and recovery capabilities, high availability
* High speed of data upload, download, and handling for all sites
* Refined access control tools to meet individual program needs
* Accessibility from different platforms (browsers, OS, devices incl. mobile)
* Availability of mirroring/syncing apps for a variety of platforms
* Built-in tools for file access

These functionalities are best met through a cloud-based storage platform. Among the possible options, we have selected the google drive system which is provided as a Lab-wide service at one of the collaborating institutions, with unlimited storage at not direct cost to the project. The data is created on the local test facility systems and mirrored on g-drive. Read only access is controlled by means of individual accounts to the project team members who perform the test data analysis and integration with magnet design, conductor and fabrication information, and feedback to the production process.

Access to the data repository is obtained through google drive. No public access is foreseen at this time.

# References

1. US HL‑LHC Accelerator Upgrade Project, Q1/Q3 Cryo‑Assemblies Final Design Report, US‑HiLumi‑doc‑948, June 2018
2. G. Apollinari et al., “High‑Luminosity Large Hadron Collider (HL‑LHC) Technical Design Report” CERN Yellow Reports: Monographs, Vol. 4/2017, CERN‑2017‑007‑M (CERN, Geneva, 2017) https://doi.org/10.23731/CYRM‑2017‑004