**MQXFS1b Protection Studies Plan**

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# Protection studies goals and constraints

MQXFS1b will complement and extend the protection studies performed in MQXFS1a with a focus in the following areas

* Prove the quench protection of the magnet in machine relevant conditions
* Current range for protection studies expanded to include I.ult (17.8 kA)
* Test configurations will include the CLIQ system (for the first time on the MQXF)
* Heater circuit and HFU settings will be updated based on the latest analysis to better reproduce the conditions of the long magnet in the accelerator
* Heater studies will include both CERN and LARP heaters with new settings, and reproducibility studies will be performed

The test plan needs to take into account specific MQXFS1b constraints which limit the study of the protection system in machine relevant conditions:

* 3 out of 8 IL strips failed insulation test during the MQXFS1a checkout, hence they cannot be powered;
* The available IL heaters may not fully representative of the final configuration based on previous test results (Bubbles/delamination and delays)
* HFU currently installed may be insufficient to power simultaneously OL and IL heater strips with LHC machine relevant parameters

Protection studies are organized considering both their relevance to the program and potential risk. The risk assessment is based on the maximum temperature and voltage that might be achieved. For MQXFS1b protection studies the allowable Thot is increased from 200 K (MQXFS1a) to 350 K (Fig. 1). High MIIt studies (Thot>350K) are not foreseen until the next test (MQXFS1c). For training, the limit is increased from 150K to 250K.



Fig. 1: Defined temperatures ranges and corresponding estimated MIIt ranges

# Protection studies overview

This section provides an overview of the planned protection studies for each of the scenario and phases considered in the test plan:

1. System and magnet checks below 6 kA
* Confirm heater functionality/performance and firing parameters
* CLIQ system checkout at 0 current
* Preliminary assessment of CLIQ performance at low current
1. During training
* Protection delays are normally set to zero and may be increased up to 10 ms for selected quenches in order to study propagation velocities, provided that sufficient margin can be verified to avoid exceeding the 250 K limit.
1. Protection studies
	* Quench integral (Section 6.1)
	* Reference EE discharges (Section 6.1.1)
	* Minimum heater power density to quench (Section 6.2.1)
	* Protection heater delays (Section 6.2.2)
	* CLIQ performance studies (Section 6.3)
	* Failure scenario studies (Section 6.4)

# Reference parameters and conditions

* Currents and corresponding gradients for injection, nominal and ultimate level are specified in Table 1. Short sample estimates (based on weighted average) and RRR from witness samples are provided in Table 2 and 3. RRR from the coil measurements is provided in Table 3b.

Table 1: reference current levels for MQXFS test.

| Current [kA] | Symbol | Gradient [T/m] | Remarks |
| --- | --- | --- | --- |
| 0.96 | I.inj | 8.5 | Injection level |
| 16.48 | I.nom | 132.6 | Nominal level |
| 17.76 | I.ult | 143.2 | Ultimate level |
| 6.0 | I.lim | 48.8 | Current limit (pre-training)  |

Table 2: short sample estimates for MQXFS test.

| Coil | 103 | 104 | L03 | L05 |
| --- | --- | --- | --- | --- |
| Iss [kA] @ 1.9K | 21.5 | 21.8 | 22.28 | 21.84 |
| Iss [kA] @ 4.3K | 19.55 | 19.8 |  |  |
| Iss [kA] @ 4.5K |  |  | 20.12 | 19.72 |

Table 3: Coil RRR from witness samples.

| Coil | 103 | 104 | L03 | L05 |
| --- | --- | --- | --- | --- |
| # samples (XS) | 3 | 3 | 6 | 6 |
| RRR - minimum | 164 | 146 | 232 | 347 |
| RRR - maximum | 186 | 172 | 432 | 604 |

[\*] Definition of weighted average

Table 3b: Coil RRR from coil measurements during MQXFS1a.

| Coil | 103 | 104 | L03 | L05 |
| --- | --- | --- | --- | --- |
| RRR - simple average | 135 | 105 | 250 | 255 |

# Protection system check-out (T= 4.5 K or 1.9K)

## Protection heater

* Goal: confirm proper operation of protection systems
* 120 mΩ dump resistor, no delay
* Quench Heater setup: All outer layer high field heaters and inner layer heaters connected. Outer layer low field heaters not connected in order to deliver sufficient power density.
* Schedule: one provoked quenches at 5 kA (30% nominal current). Measure delay to quench. Check signals for any signs of insulation failures.

## CLIQ system checkout at 0 current

* Procedure: Acquisition card is manually triggered, which triggers a discharge of the CLIQ unit. QH are not charged. The opening of the 30 mΩ EE switch is delayed by 1000 ms.
* Configuration 1-CLIQ, optimized, C=40 mF. Charging voltage: 50 V, 250 V, 500 V
* Configuration 1-CLIQ, optimized, C=80 mF. Charging voltage: 50 V, 250 V, 500 V
* For each test, compare frequency, peak current and damping with simulations. Check proper functioning of the diode string across the magnet. Check delay between acquisition trigger signal and triggering of the unit.

## Preliminary assessment of CLIQ performance at low current

* Procedure: Magnet current ramped to the selected level. Acquisition card is manually triggered, which triggers a discharge of the CLIQ unit. QH units are not charged. The opening of the 30 mΩ EE switch is delayed by 1000 ms.
* Tests at 10% and 20% nominal current (1.65 and 3.30 kA)
* For each test, compare frequency, peak current, damping and quench performance with simulations. Check proper functioning of the diode string across the magnet.
* The delayed EE opening assures redundancy in the magnet protection in the (very improbable) case of natural quench and misfiring of CLIQ unit

# During training

* Standard setting: dump configuration: 30 mHFU settings as determined during provoked quenches, no delays to heaters and dump upon detection of quench
* Use 10 ms delay to study propagation during initial training quenches. If quench integral exceeds 28 MIIt (Thot<250 K) revert to zero delay.
* During MQXFS1a, three IL heater strips (103A02, 05A01, 104A02) failed the hi-pot test to ground at around 700 V. They are thus removed from the protection during the quench training. In order to help maintaining the voltage distribution more homogeneous and reducing the voltages to ground, a fourth IL heater strip belonging to another pole (03A01) is also removed from protection.

# Protection studies

The reference current levels for the protection studies are given in Table 4. The 20%, 50%, 80% and 100% points correspond to the ones used for the MQXFS1 mirror test. Points at 10% and 30% (1.65 kA and 4.94 kA) are added for a more complete assessment of the protection performance at low current, which is becoming more critical with the more recently proposed protection schemes in the accelerator. In the high current range, I.ult is now included having confirmed that this level can be reached, and having extended the allowable Thot relative to the previous test.

Table 4: reference current levels for protection studies

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Current [kA] | 1.65 | 3.30 | 4.94 | 8.24 | 13.18 | 16.48 | 17.76 |
| I/Inom | 0.1 | 0.2 | 0.3 | 0.5 | 0.8 | 1.0 | 1.08 |

## Quench Integral with limited/no energy extraction

* Goal: Perform protection tests in conditions that reflect the baseline machine configuration without energy extraction.

### Reference tests with delayed EE (no QH, no CLIQ) at 10-50% nominal

* Goal: Perform delayed EE discharges (no QH, no CLIQ) to use as a reference for the subsequent “Quench integral” tests including the active protection elements. In this way we will be able to determine if the active protection elements are capable to effectively start a quench in the coil, since the measured current before the EE opening will be lower than the current measured during these reference tests.
* Procedure: Magnet current ramped to the selected level. Acquisition card is manually triggered, which triggers a delayed opening of the 30 mΩ EE system. QH units are not charged. CLIQ unit is not charged.

The opening of the switch is delayed by a different time according to the current level. Tests at 10% and 20% nominal current with 1000 ms EE delay; tests at 30% nominal current with 500 ms delay; tests at 50% nominal current with 100 ms EE delay.

### CLIQ + OL-QH quench integral tests (with max EE delay) at 10-108% nominal current

* Procedure: Magnet current ramped to the selected level. Acquisition card is manually triggered, which triggers a discharge of the CLIQ unit and of the OL-QH units. The opening of the 30 mΩ EE switch is delayed by 1000 ms, which at high current corresponds to a case without EE since the discharge will be faster than 1000 ms.
* Redundancy during these tests is assured by the two independent protection elements (OL-QH and CLIQ).
* Gradually increase the magnet current. Stop testing if the QI is approaching the 34 MIIt (350 K) limit.
* For each test, compare frequency, peak current, damping and quench performance with simulations. Check proper functioning of the diode string across the magnet.
* CLIQ configuration: 1-CLIQ, optimized, C=80 mF.
* QH configuration: due to test facility constraints, not possible to test simultaneously 8 heater circuits with machine relevant parameters.
	+ 4 heater circuits (out HF) with machine relevant parameters: preferred solution
	+ 8 heater circuits (out HF+LF) with parameters leading to lower performance than in the machine: if the previous solution does not achieve satisfactory performance
* To consider: Selected tests with different CLIQ capacitance and charging voltages.

### OL-QH quench integral tests (with max EE delay) at 10-108% nominal current

* Procedure: Magnet current ramped to the selected level. Acquisition card is manually triggered, which triggers all heater circuits included in the test. The opening of the 30 mΩ EE switch is delayed by 1000 ms, which at high current corresponds to a case without EE since the discharge will be faster than 1000 ms.
* For each test, measure delay to quench, measure quench integral (QI), measure quench propagation (from the OL to the IL), assess effects of quench-back and reduction of differential inductance
* Start with a manual trip at low currents (I/Inom=0.1)
* Gradually increase the magnet current. Stop testing if the QI is approaching the 34 MIIt (350 K) limit.
* QH configuration: due to test facility constraints, not possible to test simultaneously 8 heater circuits with machine relevant parameters.
	+ 4 heater circuits (out HF) with machine relevant parameters: preferred solution
	+ 8 heater circuits (out HF+LF) with parameters leading to lower performance than in the machine: if the previous solution does not achieve satisfactory performance

### OL+IL QH quench integral tests (with max EE delay) at 10-108% nominal current

* Procedure: Same as section 6.1.3, including IL heaters in the powering scheme
* Gradually increase the magnet current. Stop testing if the QI is approaching the 34 MIIt (350 K) limit.
* During MQXFS1a, three IL heater strips (103A02, 05A01, 104A02) failed hipoting test to ground at around 700 V. They are thus removed from the protection during the quench training. In order to help maintaining the voltage distribution more homogeneous and reducing the voltages to ground, a fourth IL heater strip belonging to another pole (03A01) is also removed from protection.

## Heater performance studies

* During the MQXFS1a test campaign, a first series of high-priority CERN-style heater studies were performed. During MQXFS1b, the studies are extended to LARP-style heaters.
* A more efficient strategy for testing the heater delays is adopted. Power density and energy density representative to LHC machine conditions are achieved by adapting the HFU charging voltage and adding a room-temperature resistance to the heater discharge circuit. The selection of the parameters is explained in the excel file [2].
* After MQXFS1a, bubbles and detachment of the impregnation were observed in the inner layer of the coils, in particular in the CERN-manufactured coils. The risks related to the use of the inner layer QH during the MQXF1b should be carefully considered.

### Minimum power density to quench, LARP-design heaters

* Goal: Find minimum heater power density needed to start a quench for different current levels (Table 4)
* Procedure: a single heater is fired at gradually increasing power, while the other heaters and dump are in protection mode
* HFU capacitance: C=19.2 mF
* All three heater designs are included (OL high field, OL low field, IL)
* Note: Minimum power density to quench for CERN-design heaters (MQXF baseline) were already tested during MQXFS1a.

### Protection heater delays, LARP-design heaters

* Goal: measure the delay from heater firing to start of quench at different current levels for power density and energy density representative to LHC machine conditions. This is achieved by adapting the HFU charging voltage and adding a room-temperature resistance to the heater discharge circuit. The selection of the parameters is explained in the excel file [2].
* Procedure: manually fire a test heater circuit while other heaters are protecting the magnet, measure delay to quench, then trigger 30 mΩ energy extraction (not delayed) to minimize cryogenic recovery time
* Current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit from Table 6a/b

Table 6a: Proposed current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit for LARP-design outer HF and LF heater strip tests

|  |  |
| --- | --- |
| **LARP Outer QH** | **Current [kA] and I/Inom** |
| **HFU** | **1.65** | **3.30** | **4.94** | **8.24** | **13.18** | **16.48** |
| **0.1** | **0.2** | **0.3** | **0.5** | **0.8** | **1.0** |
| C=19.2 mF, U=330 V, R=7.57 Ω (of which 2.86 Ω from the 2 QH strips) |  |  |  |  |  |  |

Table 6b: Proposed current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit for LARP-design inner heater strip tests

|  |  |
| --- | --- |
| **LARP Inner QH** | **Current [kA] and I/Inom** |
| **HFU** | **1.65** | **3.30** | **4.94** | **8.24** | **13.18** | **16.48** |
| **0.1** | **0.2** | **0.3** | **0.5** | **0.8** | **1.0** |
| C=19.2 mF, U=330 V, R=4.73 Ω (of which 0.81 Ω from the QH strip) |  |  |  |  |  |  |

### Protection heater delays, CERN-design heaters

* Similar tests were performed during MQXFS1a, mostly on coil 103. Tests on coil 104 should be performed following the new strategy of adding the resistance to the QH discharge circuit.
* Current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit from Table 6c/d/e. The selection of the parameters is explained in the excel file [2].
* Procedure: Same as explained in section 6.2.2
* It can be considered to repeat CERN-design QH delay tests on coil 103 following the strategy of adding the resistance to the QH discharge circuit.

Table 6c: Proposed current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit for CERN-design high-field outer heater strip tests

|  |  |
| --- | --- |
| **CERN Outer QH** | **Current [kA] and I/Inom** |
| **HFU** | **1.65** | **3.30** | **4.94** | **8.24** | **13.18** | **16.48** |
| **0.1** | **0.2** | **0.3** | **0.5** | **0.8** | **1.0** |
| C=19.2 mF, U=330 V, R=1.68 Ω (of which 0.70 Ω from the 2 QH strips) |  |  |  |  |  |  |

Table 6d: Proposed current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit for CERN-design low-field outer heater strip tests

|  |  |
| --- | --- |
| **CERN Inner QH** | **Current [kA] and I/Inom** |
| **HFU** | **1.65** | **3.30** | **4.94** | **8.24** | **13.18** | **16.48** |
| **0.1** | **0.2** | **0.3** | **0.5** | **0.8** | **1.0** |
| C=19.2 mF, U=330 V, R=1.68 Ω (of which 0.79 Ω from the QH strip) |  |  |  |  |  |  |

Table 6e: Proposed current levels, HFU capacitance and charging voltage, and total resistance of the QH discharge circuit for CERN-design inner heater strip tests

|  |  |
| --- | --- |
| **CERN Inner QH** | **Current [kA] and I/Inom** |
| **HFU** | **1.65** | **3.30** | **4.94** | **8.24** | **13.18** | **16.48** |
| **0.1** | **0.2** | **0.3** | **0.5** | **0.8** | **1.0** |
| C=19.2 mF, U=330 V, R=2.47 Ω (of which 0.53 Ω from the QH strip) |  |  |  |  |  |  |

### Protection heater delays, Reproducibility

* Goal: assess the reproducibility of the heater delays by repeating a selection of the tests described in sections 6.2.2 and 6.2.3 in the same conditions.
* Procedure: Same as explained in section 6.2.2

##  CLIQ performance studies

* The plan includes protection studies at low current (10-50% nominal current)
* CLIQ performance studies at high current (50-100% nominal current) are foreseen during the MQXFS1c test campaign
* Most of the tests are of the “Quench Integral” type

### CLIQ only tests (with delayed EE) at 10-50% nominal current

* Goal: Assess performance of the protection system including only CLIQ, to help validating the model in different operating conditions without the effect of QH
* Procedure: Magnet current ramped to the selected level. Acquisition card is manually triggered, which triggers a discharge of the CLIQ unit. QH units not charged. Delayed opening of the 30 mΩ EE switch.
* The opening of the switch is delayed by a different time according to the current level, which assures a safe magnet discharge even in the case of misfiring of the CLIQ unit. Tests at 10% and 20% nominal current with 1000 ms EE delay; tests at 30% nominal current with 500 ms delay; tests at 50% nominal current with 100 ms EE delay.
* Configuration 1-CLIQ, optimized. Two series of tests for C=40 mF and C=80 mF. Possibility to perform series of tests at different charging voltages
* For each test, compare frequency, peak current, damping and quench performance with simulations. Check proper functioning of the diode string across the magnet.
* CLIQ only tests (with delayed EE) above 50% nominal current foreseen during the MQXFS1c test campaign

### CLIQ only tests (with delayed EE) at 10-50% nominal current, with non-baseline configuration

* Goal: Assess performance of different CLIQ connection schemes, to help validating the model in different CLIQ configurations
	+ 1-CLIQ, not optimized
	+ 2-CLIQ, optimized
* Procedure: Same as explained in section 6.3.1

## Quench propagation studies

### Natural quench propagation during training

* Protection delay to be increased during training quenches, compatible with a limit of 28 MIIt, to study quench propagation. If slow training progress is observed in these conditions, revert to zero delay. (see section 5)

### Propagation of heater generated quenches during Quench Integral studies

* For each test, measure delay to quench, measure quench integral (QI), measure quench propagation (from the OL to the IL), assess effects of quench-back and reduction of differential inductance (see section 6.1.3)

### Additional propagation of heater generated quenches

* Procedure: manually trigger the quench detection, which triggers all heaters but some selected circuits; 30 mΩ energy extraction delayed by 1000 ms; no delay for PH
* Using a sub-set of current levels from Table 4: 10%, 20%, 30%, 50%, 100% of nominal current
* Heater configuration: same as in section 6.1.3, without firing 1 OL-HF and 1 OL-LF (attached to the same pole)
* For each test, measure voltages across the layers and to ground and compare to the model
* Compare to the QI studies performed previously (see section 6.1)
* Gradually increase the magnet current. Stop testing if the QI is approaching the 34 MIIt (350 K) limit.

# Measurements during warmup and at room temperature

* RRR for coil segments (take few measurements from 20 K to 300 K)

# References

[1] MQXFS1 test plan overview

[2] Excel file “QH\_Strips\_MQXFS1\_v5.xlsx”, downloadable at www