ACCEPTANCE CRITERIA

PART A: MQXFA MAGNET

Abstract

This document specifies the functional requirements for the MQXFA magnet readapted for the American contribution. If all the requirements specified in this document are met, then the U.S. HL-LHC AUP MQXFA deliverables will be accepted by CERN for the HL-LHC project.

Another separate document will be issued by the American contribution for the MQXFA cold mass functional requirements.

Please note that the definition of threshold as it is being used by the American contribution is not the same as objective, according to the HL-LHC quality policy.

TRACEABILITY V1.4

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CERN Verified by: A. Devred, S. Izquierdo	***Date:*** 2020-05-17
AUP Approved by: Giorgio Apollinari, US HL-LHC AUP Project Manager, FNAL	***Date:*** 2020-05-08
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Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
1.4	2020-06-16	See Revision history in Page 3 and comments in EDMS approval process

US HL-LHC Accelerator Upgrade Project

ACCEPTANCE CRITERIA PART A: MQXFA MAGNET

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Revision History

Revision	Date	Section No.	Revision Description
v0	2018-10-19	All	Initial Release
V0.9	2018-11-13		Feedback from Claudet, Baglin, Wollmann, Arduini, Giovannozzi et al. included.
V1.0	2018-11-21		Correction of free aperture from 146.1 to 146.7 mm (misprint) And inclusion of comments of Arduini to version 0.9. Removal of T-26 that was erroneously left in the document
V1.1	2020-02-05	MQXFA-R-T-16	In Requirement MQXFA-R-T-16, added two rows in Table 3 for the additional hi-pot test at 100K specified in the revised Electrical Design Criteria (EDMS 1963398) and removed “before cold test” from the text.
V1.4	2020-06-16	MQXFA-R-O-02	In MQXFA-R-O-02, updated the table of the multipoles (removed the line of order 2 in normal and skew) and corrected sign in tolerance band equation. In MQXFA-R-T-10, changed from 100K to 50K. In R-T-03 changed from “a central gradient of 143.2 T/m” to “an integrated gradient of 596.7 T”. Procedure summary changed from “Rotating coil measurements in magnet straight section” to “Stretched-wire magnetic measurements”; References changed from “Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330]” to “Cryo-assembly test plan [LHC-LQXFA-ES-0002], and magnetic measurement plan [LHC-MQXFA-ES-0007].” R-T-07 changed from “The MQXFA magnet must provide an integrated gradient between 554T and 560T when powered with current of 16.470kA. The difference between the integrated gradient of any pair of series magnets with the same cross-section shall be smaller than 3 T. The MQXFA magnetic length requirement is 4.2 m with a tolerance of ± 5 mm at 1.9 K.” to “The difference between the integrated gradient of any pair of series magnets powered with the nominal current shall be smaller than 6 T for all magnets, and smaller than 3 T for magnets with the same cross-section. At the same reference current, the MQXFA magnetic length difference between any pair of magnets should not exceed 10 mm.” Added R-O-04: Objective requirement of one quench after training (all other features equal to those in R-T-17). R-T-16: correction of expected Coil to Ground voltage from 670 V to 353 V in Table 3. Changed from “prototype” to “pre-series” in R-O-3, R-T-05, R-T-10, R-T-17, R-O-4, and R-T-22. Added reference to Coil Interface Traveler [FNAL#464441] in R-T-08/14/15.

This document is based on the acceptance criteria of the MQXFA magnet as extracted from the functional requirement specification EDMS 1535430. For the definition of threshold and objective requirements, we refer to Section 3 of the same document.

In case of not fulfilment of objective requirements (R-O-01, R-O-07, R-O-02 and R-O-03), a nonconformity shall be opened and treated according to HL-LHC QA plan.

Requirement MQXFA-R-T-01: The MQXFA coil aperture at room temperature without preload is 149.5 mm. Coil bumpers (pions) of 1.2 mm thickness shall be installed on the four coil poles. The minimum free coil aperture at room temperature after coil bumpers installation, magnet assembly and preload shall be 146.7 mm. This guarantees an annulus free for HeII of minimum thickness 1.2 mm, average thickness larger or equal to 1.5 mm.

Verification Method: Design, coil CMM measurements, and mechanical measurements after assembly and preload of each magnet.

Procedure summary: For each coil, the coil lead engineer verifies that the coil meets dimensional requirements based on CMM measurements; for each magnet, the magnet lead engineer verifies that a gauge - or bore tube equivalent - with outer diameter of 146.7 mm, passes through the bore after magnet assembly.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948], Magnet Assembly Traveler [SU-1010-2018].

Requirement MQXFA-R-T-02: The MQXFA nominal outer diameter without preload is 614 mm. The MQXFA outer diameter best-fit after assembly and preload shall not exceed 615 mm.

Verification Method: Mechanical measurements after fabrication of each magnet.

Procedure summary: Laser tracker survey.

Reference: Magnet Assembly Traveler [SU-1008-8070].

Requirement MQXFA-R-O-01: The positions of the local magnetic center and magnetic field angle are measured along the magnet axis with values obtained by averaging sections ≤ 500 mm. In each section, the local magnetic center is to be within ±0.5 mm from the magnet magnetic axis both in horizontal and in vertical direction. The local magnetic field angle in each section is to be ±2 mrad from the average magnetic field angle of the whole magnet, with the exception of the first measurement in the connection side where field angle is affected by magnet leads

Verification Method: Magnetic measurements of magnetic center and magnetic field angle to external fiducials at room temperature.

Procedure summary: Analysis of magnetic measurements, using the laser tracker to measure the probe position and orientation.

Reference: Magnet Assembly Traveler [SU-1010-2018], Reference system [EDMS 367802].

Requirement MQXFA-R-T-03: The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 596.7 T in superfluid helium at 1.9 K.

Verification Method: Magnetic measurements during power test at 1.9 K.

Procedure summary: Stretched-wire magnetic measurements.

Reference: Cryo-assembly test plan [LHC-LQXFA-ES-0002], and magnetic measurement plan [LHC-MQXFA-ES-0007].

Requirement MQXFA-R-O-07: The difference between the integrated gradient of any pair of series magnets powered with the nominal current shall be smaller than 6 T for all magnets, and smaller than 3 T for magnets with the same cross-section. At the same reference current, the MQXFA magnetic length difference between any pair of magnets should not exceed 10 mm. The precision of the measurement of the integrated gradient shall be within ±0.02%.

Verification Method: Magnetic measurements during power test.

Procedure summary: The integrated gradient at nominal current is measured using a stretched wire.

Reference: Cryo-assembly test plan [LHC-LQXFA-ES-0002], and magnetic measurement plan [LHC-MQXFA-ES-0007], Reference system [EDMS 367802].

Requirement MQXFA-R-O-02: The MQXFA field harmonics shall be optimized at nominal current. Table 1 from the MQXFA Functional Requirements Specification [US-HiLumi-doc-36] provides expected values for integral field harmonics at a reference radius of 50 mm.

Verification Method: Magnetic measurements during test at 1.9 K of the cold mass assembly with both magnets powered simultaneously at nominal current. Integral harmonics are compared with the "three sigma range" given in Table II, defined as [$-b_n^{un}$-3 b_n^r , b_n^{un}+3 b_n^r] where b_n^{un} is the uncertainty, and b_n^r is the random component, cfr. MQXFA Functional Requirements Specification [US-HiLumi-doc-36].

Procedure summary: During horizontal test at 1.9 K, measure harmonics (up to b_{10}, a_{10}) at nominal field and compare results to the "three sigma range" plus measurement error (+/-0.05 units up to b_{10}, a_{10}) for each harmonic. If all harmonics up to order 10 are within the "three sigma range" plus measurement error, the field quality is automatically accepted. If one or more harmonics are outside the "three sigma range" plus measurement error, CERN will decide if the non-conformity can be accepted as it is, or if it requires a special position in the lattice, or if this effect can be globally minimized over the triplet.

Reference: **[1]** R. Wolf, "FIELD ERROR NAMING CONVENTIONS FOR LHC MAGNETS", [EDMS 90250], [2] MQXFA Functional Requirements Specification [US-HiLumi-doc-36], [3] Cryo-assembly Test Plan [LHC-LQXFA-ES-0002], [4] Test stand requirements [LHC-LQXFA-ES-0004], [5] Reference system [EDMS 367802].

Table 1 Expected field harmonics in 10-4 units of main component, at 50 mm.

	Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm												
	Straight part											Ends	
	Systematic						Uncertainty		Random				
N(													de
3	0.000	0.000	0.000	0.000	0.000	0.000	0.820	0.820	0.820	0.820			
4	0.000	0.000	0.000	0.000	0.000	0.000	0.570	0.570	0.570	0.570			
5	0.000	0.000	0.000	0.000	0.000	0.000	0.420	0.420	0.420	0.420			
6	-2.200	0.900	0.660	-20.000	-21.300	-0.640	1.100	1.100	1.100	1.100	8.943	-0.025	
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			
8	0.000	0.000	0.000	0.000	0.000	0.000	0.130	0.130	0.130	0.130			
9	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.070	0.070	0.070			
10	-0.110	0.000	0.000	4.000	3.890	-0.110	0.200	0.200	0.200	0.200	-0.189	-0.821	
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			
12	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018			
13	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009			
14	-0.790	0.000	-0.080	1.000	0.210	-0.870	0.023	0.023	0.023	0.023	-0.545	-1.083	
S													
3	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			
4	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			
5	0.000	0.000	0.000	0.000	0.000	0.000	0.430	0.430	0.430	0.430			
6	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.310	0.310	0.310	2.209		
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			
8	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110			
9	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080	0.080	0.080			
10	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040	0.065		
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			
12	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.014	0.014			
13	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010			
14	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	-0.222		
	Magnetic length straight part				Q1/Q3	3.459	Q2a/b	6.409	Mag. Len. Ends		0.400	0.341	

Table 2: Three sigma range for integrated field harmonics at high field

	Normal		Skew	
Order	Min	Max	Min	Max
3	-3.28	3.28	-2.60	2.60
4	-2.28	2.28	-2.60	2.60
5	-1.68	1.68	-1.72	1.72
6	-4.40	4.40	-1.24	1.24
7	-0.76	0.76	-0.76	0.76
8	-0.52	0.52	-0.44	0.44
9	-0.28	0.28	-0.32	0.32
10	-0.80	0.80	-0.16	0.16

Requirement MQXFA-R-O-03: The fringe field target, for the magnet installed in the cryostat, is lower than 50 mT at 10 mm from the outer surface of the cryostat.

Verification Method: Magnetic measurements on the horizontal test stand of the first pre-series cryo-assembly at nominal current.

Procedure summary: Fringe magnetic field measurements with a Hall Probe.

Reference: Cryo-assembly test plan [LHC-LQXFA-ES-0002].

Requirement MQXFA-R-T-05: MQXFA magnets shall be capable of steady-state operation at ultimate current in pressurized static superfluid helium (HeII) bath at 1.3 bar and at a temperature of 1.9 K.

Verification Method: Power tests of pre-series and all series magnets.

Procedure summary: Operation of pre-series magnets at ultimate current at 1.9 K for 300 minutes, and of production magnets for 60 minutes.

Reference: Cryo-assembly Test Plan [LHC-LQXFA-ES-0002].

Requirement MQXFA-R-T-06: The MQXFA cooling channels shall be capable of accommodating two (2) heat exchanger tubes running along the length of the magnet in the yoke cooling channels. The minimum diameter of the MQXFA yoke cooling channels that will provide an adequate gap around the heat exchanger tubes is 77 mm.

Verification Method: Mechanical measurements after assembly and preload of each magnet.

Procedure summary: For each magnet, the magnet lead engineer verifies that a sample of heat exchanger passes through the yoke cooling channels after magnet assembly.

Reference: Magnet Assembly Traveler [SU-1010-2018].

Requirement MQXFA-R-T-07: At least 40% of the coil inner surface shall be free of polyimide.

Verification Method: Considered verified since quench heaters/traces are not going to be used on coil inner surface.

Procedure summary: n/a

Reference: MQXFA Final Design Report [US-HiLumi-doc-948].

Requirement MQXFA-R-T-08: The MQXFA shall have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-11 alignment key equivalent of 8 mm diameter holes repeated every 50 mm; (2) free helium paths interconnecting the four yoke cooling channels holes; and (3) a free cross sectional area of at least 150 cm^2.

Verification Method: Engineering check and visual inspection of each coil/magnet.

Procedure summary Lead magnet engineer verifies parts design and approves drawing, QC checks are performed after delivery of each part to verify compliance, and lead technician verifies by visual inspection that parts are correctly installed after each coil/magnet fabrication.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948]**,** Approved parts drawings: F10005738, F10005750, F10039540, F10039541, F10039545, F10039546 [LHC-MQXFAS-DF-0001]**,** QC Reports: RF#102572, RF#102573, RF#102116, RF#103076, RF#102917, Coil Fabrication Traveler [FNAL#464308], Coil Interface Traveler [FNAL#464441].

Requirement MQXFA-R-T-10: The MQXFA magnet shall be able to survive a maximum temperature gradient of 50 K during a controlled warm-up or cool-down, and to experience the thermal dynamics following a quench without degradation in its performance.

Verification Method: Power test of pre-series magnets.

Procedure summary: 1) Exercise a controlled cool down of the magnet by applying temperature gradient along the magnet. Temperature gradient will be measure using two temperature sensors attached to the structure of the magnet at the lead end (T-lead) and return end (T-return) of the magnet. These sensors are in thermal equilibrium with the structure. Accuracy of the reading is +/- 1 K. During cool down make sure to reach significant $\Delta T =$ T-lead – T-return ≈ 50 K $\pm$ 20 K and verify that the magnet can reach ultimate current after cool down. 2) Verify that after a quench at ultimate current the magnet reaches again steady operation at ultimate current.

Reference: Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330].

Requirement MQXFA-R-T-11: The MQXFA magnets shall be capable of operating at any ramp rate within ±30 A/s.

Verification Method: Power test of each production magnet.

Procedure summary: Verify that the magnet does not quench while ramping to/from ultimate current at ±30 A/s.

Reference: Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330].

Requirement MQXFA-R-T-13: MQXFA magnets must be delivered with a (+) Nb-Ti superconducting lead and a (-) Nb-Ti superconducting lead, both rated for 18 kA and stabilized for connection to the LMQXFA cold mass electrical bus.

Verification Method: Engineering check for each magnet and power test.

Procedure summary: For each magnet, lead engineer verifies that approved lead materials and procedures have been used.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948], Magnet Assembly Traveler [SU-1008-8070].

Requirement MQXFA-R-T-14: Splices are to be soldered with CERN approved materials.

Verification Method: Lead technician verification.

Procedure summary: Lead technician verifies that the approved flux and solder were used for the tinning and soldering operations as specified in the traveler.

Reference: Coil Fabrication Traveler [FNAL#464313], Coil Interface Traveler [FNAL#464441], Magnet Assembly Traveler [SU-1008-8070].

Requirement MQXFA-R-T-29: Splice resistance must be less than 1.0 nΩ at 1.9 K**.**

Verification Method: Measurements during power test of each magnet.

Procedure summary: Measure splice resistance at 1.9 K and verify that it is below 1.0 nΩ.

Reference: Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330].

Requirement MQXFA-R-T-15: Voltage Taps: the MQXFA magnet shall be delivered with three redundant (3x2) quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; and two (2) voltage taps for each internal MQXFA Nb_3Sn-NbTi splice. Each voltage tap used for critical quench detection shall have a redundant voltage tap.

Verification Method: Engineering check and inspection during assembly of each coil and magnet.

Procedure summary: Lead engineers responsible for coil fabrication and magnet assembly approve electrical drawings and check that each coil/magnet meets this requirement.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948], Coil Fabrication Traveler [FNAL#464313], Coil Interface Traveler [FNAL#464441], and Magnet Assembly Traveler [SU-1008-8070], Voltage tap scheme [LHCLMQXF_E0001].

Requirement MQXFA-R-T-16: The MQXFA magnet coils and quench protection heaters shall pass the hi-pot test specified in Table 3 [2].

Table 3 [2]: Required hi-pot test voltages and leakage current
Based on Electrical Design Criteria for HL-LHC Inner Triplet Magnets [EDMS 1963398]

Circuit Element	**Expected Vmax [V]**	**V hi-pot**	**I hi-pot [μA]*****	**Minimum time duration [s]**
Coil to Ground at RT before helium exposure *	n.a.	3.68 kV	10	30
Coil to Quench Heater at RT before helium exposure *	n.a.	3.68 kV	10	30
Coil to Ground at cold **	353	1.84 kV	10	30
Coil to Quench Heater at cold **	900	2.3 kV	10	30
Coil to Ground at RT after helium exposure *	n.a.	368 V	10	30
Coil to Quench Heater at RT after helium exposure *	n.a.	460 V	10	30
Coil to Ground at 100±20K and 1.2±0.2 bar	n.a.	425 V	10	30
Coil to Quench Heater at 100±20K and 1.2±0.2 bar	n.a.	425 V	10	30

* Room Temperature conditions refer to air at 20±3 °C and relative humidity lower than 60%

** Cold conditions refer to nominal cryogenic conditions (superfluid helium)

*** Maximum leakage current does not include leakage of the test station.

Verification Method: Hi-pot measurements for each magnet.

Procedure summary: Conduct hi-pot measurements for the conditions specified in Table 3 and verify that leakage current is below the specified limit. Room temperature measurements are in air or bagged in dry N_2.

Reference: [2] MQXFA Functional Requirements Specification [US-HiLumi-doc-36], Electrical Design Criteria for HL-LHC Inner Triplet Magnets [EDMS 1963398], Magnet Assembly Traveler [SU-1008-8070], Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330].

Requirement MQXFA-R-T-17: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than 3 quenches.

Verification Method: Power test after a thermal cycle for pre-series and series magnets.

Procedure summary: After training is completed, perform a thermal cycle and verify that the magnet reaches nominal operating current with no more than 3 quenches.

Reference: Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330].

Requirement MQXFA-R-O-09: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than one quench.

Verification Method: Power test after a thermal cycle for pre-series and series magnets.

Procedure summary: After training is completed, perform a thermal cycle and verify that the magnet reaches nominal operating current with no more than one quench.

Reference: Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330].

Requirement MQXFA-R-T-18: MQXFA magnets shall not quench while ramping down at 150 A/s from the nominal operating current.

Verification Method: Power test for each magnet.

Procedure summary: Verify that the magnet does not quench while ramping down at 150 A/s from the nominal operating current.

Reference: Cryo-assembly test Plan [LHC-LQXFA-ES-0002].

Requirement MQXFA-R-T-20: All MQXFA components must withstand a radiation dose of 35 MGy, or shall be approved by CERN for use in a specific location as shown in MQXFA Materials List [EDMS 1786261].

Verification Method: Guaranteed by design (see material properties and CERN approval of MQXFA materials list).

Procedure summary: n/a.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948], Approved MQXFA List of Materials [EDMS 1786261].

Requirement MQXFA-R-T-30: MQXFA magnets will operate in the HL-LHC era for an order of magnitude of 10000 cycles. The long-term reliability of the design will be proven having a short model magnet submitted to 1000 powering cycles during individual test.

Verification Method: 1000 power cycles during test of a short model magnet by CERN.

Procedure summary: Perform 1000 powering cycles to nominal current during test of one short model, and verify the ability to operate at ultimate current after the 1000 cycles.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948], CERN MQXFS4 Test Report [EDMS 2266306].

Requirement MQXFA-R-T-31: MQXFA magnets must survive at least 50 quenches.

Verification Method: Power test of a prototype magnet.

Procedure summary: The prototype magnet shall be able to reach ultimate current after 50 quenches (including all quenches for training).

Reference: Magnet test Plan [US-HiLumi-doc-728], Magnet test traveler [BNL-MDC No. LARP-330], MQXFS1 Test Report [US-HiLumi-doc-936]

Requirement MQXFA-R-T-22: The MQXFA magnets shall meet the interface specifications with the following systems: (1) other LMQXFA Cold Mass components; (2) the CERN supplied power system; (3) the CERN supplied quench protection system, and (4) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Document [US-HiLumi-doc-375].

Verification Method: Engineering check, test of magnet/cold mass assembly interface, verification of integrity for each quench heater circuit during cryo-assembly powering test.

Procedure summary: L2s check compliance of fabrication drawings with approved interface specifications and approve drawings for fabrication. Cold mass test allows to validate the magnet/cold mass assembly interface. The integrity of each quench heater circuit is validated during cold powering test of the cryo-assembly at 6 kA by comparing each HFU voltage discharge with benchmark discharge, and by comparing

MIITs with benchmark MIITs. Benchmark HFU discharge and MIITs will be established during powering tests of pre-series cryo-assembly.

Reference: MQXFA Final Design Report [US-HiLumi-doc-948], Interface Control Document 302.2.10-CERN [US-HiLumi-doc-375], MQXFA Magnet Interface Specification [US-HiLumi-doc-1674].

Requirement MQXFA-R-T-23: The MQXFA magnets must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3) [EDMS 1550065].

Verification Method: CERN approval of safety documentation.

Procedure summary: Safety documentation is submitted to CERN for approval, and CERN verifies compliance with the LSA and any other safety agreements.

Reference: Launch Safety Agreement [EDMS 1550065].

Requirement MQXFA-R-T-24: All travelers must be completed and delivered to CERN, and all NCR must be closed.

Verification Method: AUP QA Manager verifies that all travelers are completed and delivered to CERN MTF, and that all NCR are closed.