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Alignment and Strength Measurements of the LHC Interaction Region Quadrupole Magnets

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Abstract—**Production and testing of the high-gradient superconducting quadrupole magnets developed by the US-LHC Accelerator Project is being completed. The production process included relative alignment of the two MQXB cold masses of the LQXB in a single cryostat, alignment of corrector magnet assemblies supplied by CERN on each of the triplet elements, and final magnet alignment for transfer to cryostat fiducials. Additionally, all LQXB magnets and one each of the LQXA and LQXC have had alignment measurements at Fermilab's Magnet Test Facility (MTF) during cryogenic testing. This paper gives an overview and summary of the available alignment and strength data taken with the Single Stretched Wire (SSW) system for the LQX magnets. Warm-to-cold changes in alignment parameters are also presented.**

***Index Terms*—Alignment, integral strength, LHC, low-β quadrupole, stretched wire.**

I. Introduction

Fermilab has been building and testing high gradient superconducting magnets for the interaction regions of the LHC. The final focus consists of a triplet of quadrupole elements, LQXA-B-C, which also contain associated corrector magnets. The LQXB consist of two 5.5 m MQXB quadrupoles, designated Q2a and Q2b, developed and built at Fermilab [1]. The LQXA,C contain a 6.37 m MQXA quadrupole cold-mass produced by KEK [2]. The LQX are cryostatted at Fermilab, assembled together with corrector packages supplied by European industry. As the alignment tolerances for these low-β quadrupoles are stringent, alignment has been an integral part of the fabrication process, both in relative alignment of various components, and the fiducialization of the magnetic axis of the final elements to external survey targets. All alignment has used the Single Stretched Wire (SSW) system which also measures the integrated magnet strength.

II. Measurement System

The SSW system has been developed at Fermilab [3] as a general method for alignment and strength measurements. A 100 μm CuBe wire is stretched through the length of the magnet, connected to precision (1 μm accuracy) motion stages at both ends. The return wire of the flux loop lies stationary on the bottom of the beam pipe. Using co- and counter-directional stage motions (i.e. stages moving in the same or opposite directions), the *x, y, z* coordinates of the magnet center and the *roll, pitch, yaw* of the magnet axes can be determined; the stages are then moved so that the wire end-points are coincident with the magnetic axis. Wire lengths for the LQXB on the cryogenic test stand are approximately 18 m, and removal of sag effects are achieved at better than a 1% level by measuring the vibration frequency at various tensions and extrapolating to infinite frequency (infinite tension). Powering is done AC for the warm measurements, and, except for the first magnet, also for alignment tests cold (in order to minimize the time needed for changeover of the high-current power leads). Roll measurements performed cold are done with DC current and, for the LQXB, with Q2a and Q2b powered in series. A laser tracker is used to transfer fiducial positions of the SSW stages to the external fiducials of the magnet. Precise calibration of the distances from the stage fiducials to the actual support point of the wire are obtained using an optical gauging microscope. The system and basic measurements are described in detail elsewhere [3-4]. For alignment of the higher-order corrector elements, the SSW is rotated around the perimeter of the aperture at up to 64 different angles to sample the field as if it were as a rotating coil. Transverse center-offsets are then determined by traditional feed-down techniques, and the angle from phase analysis of the flux vs. angle data.

The coordinate system is defined relative to the main quadrupole, with *x, y* being the horizontal and vertical axes respectively, and *z* along the magnetic axis; roll angle is relative to the main quadrupole being $\theta=0$.

III. Production Alignment

A summary of the alignment measurements needed for each type of LQX is shown in Table I. Alignment measurements in production originally planned to use mechanical techniques with some SSW measurements involved only for initial verification. However, for various reasons, including subtle motions in tooling, changes during welding, and inaccuracies in alignment scribe marks on corrector packages, actual measurements were deemed necessary at the stages listed.

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TABLE I
ALIGNMENT MEASUREMENTS MADE ON LQX MAGNETS

		LQXA	LQXB	LQXC
Production	Initial roll	✓	✓	✓
	Pre/post weld align		✓	
	Multi-corrector pre-align			✓
	Corrector mounting	✓	✓	✓
	Beam tube flange	✓	✓	✓
	Lug adjustment		✓	
Test	Warm before cold test		✓	
	Cold fiducials and strength		✓	
	Warm after cold test		✓	
	Lug adjustment		✓	
	Final warm	✓	✓	✓

Multi-corrector pre-align refers to 3 corrector assemblies of the LQXC being measured on a bench-top prior to first mechanical assembly on the LQXC cold-mass. This was helpful since the scribe marks on the correctors were not a good indicator of alignment position. Note that one LQXC and LQXA also had warm-cold-warm testing measurements.

In the table, LQXB pre- and post-weld alignments refers to setting the relative roll and X, Y alignment of Q2a and Q2b elements before welding of the interconnect tube which joins them. This positioning could not be tuned later with the external cryostat support lugs. As with all of the production alignments, the process was iterative. After welding of the tube, the X, Y offsets were re-checked to see if stresses during welding compromised the original alignment. In cases where it had, measurements were repeated after each subsequent attempt to weld-straighten the connection at center. About 80 percent of the first half of the LQXB production magnets required weld-straightening after the initial weld, but only 30 percent of the final half (and of lesser magnitude), as technique improved.

The corrector packages mounted within each of the LQX elements is summarized in Table II.

TABLE II
LQX CORRECTOR S

Magnet	Corrector Package	Element Name	Function
LQXA	MCBX	MCBXV	vertical dipole
		MCBXH	horiz. dipole
LQXB	MCBX	MCBXV	vertical dipole
		MCBXH	horiz. dipole
LQXC	MCSTX	MCBXV	vertical dipole
		MCBXH	horiz. dipole
		MCSX	normal sextupole
		MCTX	normal dodecapole
	MCSOX	MCSSX	skew sextupole
		MCOX	normal octupole
		MCOSX	skew octupole
	MQSX	MQSX	skew quadrupole

In order to optimize the positions for use in the accelerator, the lowest order of the corrector package was used for centering. Centering tolerance of 1 mm and roll tolerance of 1 mrad were specified as targets for all but the MCBX, which had roll tolerance of 5 mrad. Corrector transverse alignments relative to the main LQXC quadrupole axis are shown in Fig. 1 for all corrector package types; most parameters fall within the 1 mm target alignment. The angular alignment of the MCBX on the LQXB and LQXA magnets is shown in Fig. 2. Note that since the alignment tolerance was relatively large (5 mrad), the first production magnets used the scribe line on the package to set the alignment.

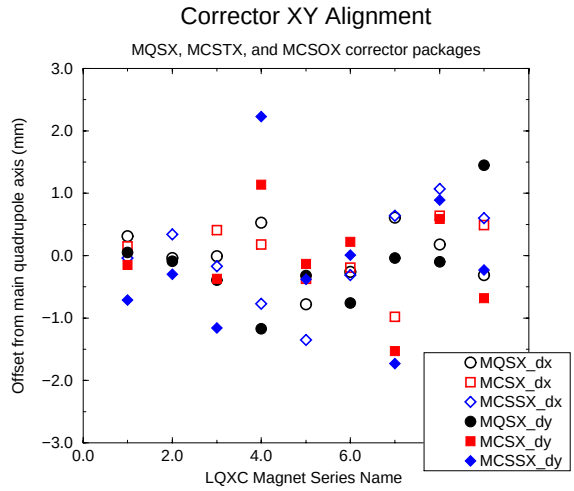

Fig. 1. Corrector package transverse alignment. The lowest order corrector in each package with a zero-field region at center is used (quad and above).

After gross deviations were observed, the roll was instead set based on a measured field angle and is better–controlled.

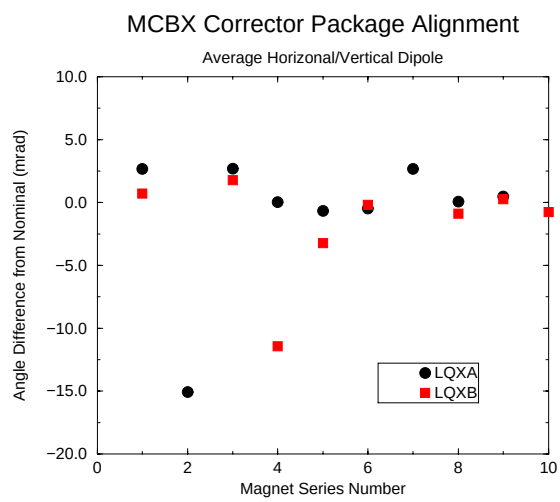

Fig. 2. MCBX corrector roll alignment.

The angular alignment of the MQSX and MCSOX packages on LQXC's are shown in Fig. 3. These are mostly within tolerance.

The angular alignment of the MCSTX package which contains four correctors is shown in Fig. 4. Originally, the roll was being set with the lowest order (dipole) element (MCBXV/H). However, since there was found to be a large misalignment between these and the MCSX element, the alignment switched to using the MCSX. This was realized only late in production (LQXC7-9).

After corrector mounting, the flanges at each end of the beam tube are aligned to the magnet axis. These are anchored via welding to the magnet end dome and need to be well aligned so as not to compromise physical aperture during operation. To accomplish this, the SSW was placed on the

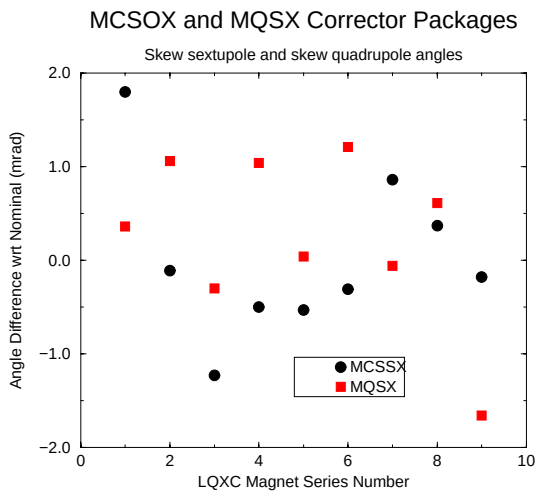

Fig. 3. MQSX and MCSOX corrector roll alignment.

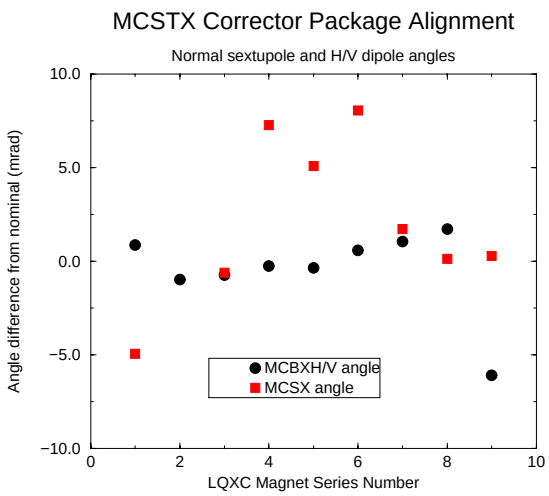

Fig. 4. MCSTX corrector alignment. Note that the basis for angular alignment changes from MCBXV/H to the MCSX corrector later in production.

magnet axis and the flanges mechanically centered to it using a scale. Survey targets are not available since the magnet is still a bare cold mass. A summary plot of the surveyed positions of the flanges during final alignment is shown in Fig. 5. Reliably achieving the 0.5 mm tolerance for flange alignment was difficult given the scale measurements. Additionally, there were motions resulting from welding of the flanges and some inconsistency in wire sag compensation. Note that for the LQXB, the magnetic axis used to establish deviation in Fig. 5 is based on the average through the two cold-masses, not the individual cold mass; the flanges can additionally appear off-center because of relative pitch/yaw between the two.

For the LQXB, an additional alignment step of cryostat lug adjustment was made in the production process (though usually performed before warm test at the test facility). This was used as a fine tuning of the position of the Q2a/Q2b relative alignment after this welded assembly had been installed in its cryostat.

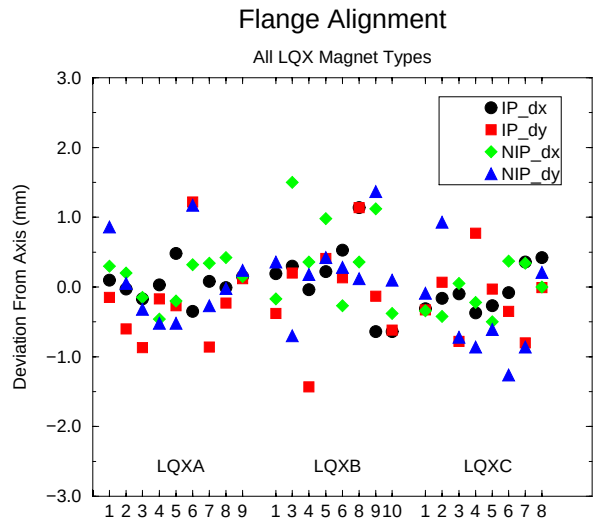

Fig. 5. Flange alignment for all magnet types. IP indicates the end of the magnet closer to the interaction point when installed.

Lug adjustment typically changed the relative angles between the Q2a and Q2b by about 0.2-0.5 mrad.

The SSW was also used to try to confirm the longitudinal position of the magnets within the cryostat. These measurements use counter-directional stage motions and the wire length and body field strength to calculate the location of the magnetic center [4]. Measurements are shown in Fig. 6 compared to nominal mechanical positioning.

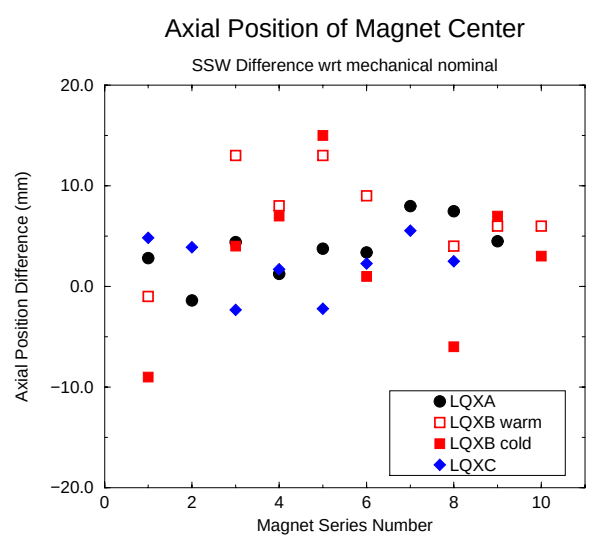

Fig. 6. Difference between measured and nominal longitudinal magnet position within the cryostat as measured by SSW.

There appears to be a systematic difference between SSW and expected mechanical results of a few mm. The RMS is on the order of ~5 mm for the LQXB, but less for the LQXA and LQXC probably because wire motions can be larger (signal sizes greater), since there is no additional constraint from the warm bore tube of the test stand.

IV. Testing

Alignment is complete when the average centers are related to the external fiducials and the relative rotation angles found. Some understanding of anticipated warm-cold change also needs to be arrived at for those magnets which were not cold tested.

A. Average Centers

Determination of the magnetic axis and transfer to external cryostat fiducials with a laser tracker is performed on all LQX magnets warm, and also on the LQXB magnets at cryogenic temperatures. The reproducibility in the average *x. y* center of the magnetic axis for warm and cold LQX magnets was found to be less than 10 μm. The centers are well determined, even with the 18 m wire lengths of the cold test stand and inclusion of possible systematic error in sag calibration. Survey transfer to fiducials is the dominant error, with repeated survey measurements locating a given fiducial with typical RMS error 50-75 μm.

B. Average relative angles

Table III gives the cold average relative rotation angles for the Q2a/Q2b components of the LQXB. The average of the as- measured relative angles for the LQXB are 0.22 mrad for yaw and pitch and 0.4 mrad for roll. These are consistent with accelerator requirements [5]. With lug adjustments made subsequent to final warm-up, the yaw/pitch averages are expected to improve to 0.13/0.14 mrad when installed.

TABLE III
AVERAGE RELATIVE ROTATIONS (MRAD)

Magnet	yaw	pitch	roll	yaw_exp	pitch_exp
LQXB01	0.17	0.23	0.99		
LQXB03	0.57	0.03	0.37	0.19	0.25
LQXB04	0.03	0.01	0.50		
LQXB05	0.07	0.01	0.37		
LQXB06	0.36	0.16	0.59	0.23	0.1
LQXB07	0.04	0.02	0.19		
LQXB08	0.25	0.73	0.34	0.03	0.39
LQXB09	0.26	0.37	0.02	0.24	0.07
LQXB10	0.24	0.39	0.21	0.14	0.15

Yaw_exp and pitch_exp give the expected relative yaw and pitch rotations of the magnet as installed in the tunnel, in cases where lug adjustment was made after cold test.

C. Warm-Cold changes

For magnets measured cold, the average vertical position was observed to change during thermal cycle (TC). Table IV shows the average warm-warm change for various numbers of TCs. Also presented is the warm-cold change for TCs which are not the first cooldown; this may estimate the reversible, warm-cold changes due to thermal contraction, etc., which will persist after the magnet finally 'settles'. Table IV suggests that for an LQX magnet which has not been previously cold tested, an average settling of ~0.3-0.4 mm would need to be anticipated when installing the magnet. This is in addition to the reversible change expected warm to cold. Furthermore, some settling may also occur during shipping [6].

TABLE IV
AVERAGE VERTICAL CHANGES WITH THERMAL CYCLE (MM)

Condition	n_mag	Average	s.d.
1 TC Warm-Warm Shift	22	-0.32	0.16
2 TC Warm-Warm Shift	6	-0.35	0.09
3 TC Warm-Warm Shift	2	-0.43	0.04
Non-first TC Warm-Cold	6	-0.14	0.13

The individual Q2a and Q2b are counted separately. Also included are the single LQXA and LQXC magnets tested cold.

D. Integral Strength

The integral strength of all LQXB magnets was measured cold at various currents. Table V gives the average integral strength transfer function (TF) for the ensemble of 8 magnets measured to date. At each current, strength was measured at various wire tensions. An extrapolation was done to infinite tension (or frequency) to compensate for any wire susceptibility effects.

TABLE V
AVERAGE MAGNET TRANSFER FUNCTION

Current (A)	∫gdl TF (T/kA)	s.d.
669	202.29	0.12
5460 (up)	200.87	0.12
5460 (dn)	200.84	0.13
11345	198.19	0.12
11923	197.85	0.13

Average of integral strength transfer function as measured by SSW with horizontal wire motions. At 5460A, the two values indicate measurements made on the up-ramp and down-ramp to/from 11923A respectively.

V. Conclusions

A summary of the alignment measurements for LQX magnet production has been presented. The production seems to have reasonably met specifications. The final alignment and strength have been measured. Changes in the vertical position, particularly for magnets which have not been cooled-down, are roughly understood; these may affect final positioning at the tenths of a mm level.

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