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Notes on Main Injector Quadrupole Reliability

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Abstract

The records of magnet installation and replacement as well as the repair information on Main Injector magnets is fragmented. We will try to gather together a set of records which will permit us to know both the repair history and the available spares for Main Injector quadrupole magnets.

1 Introduction

The Fermilab Main Injector [1] [1] required new dipoles but repurposed the 84″ quadrupoles from the Main Ring for the regular cells. These are labeled IQB quadrupoles. Additional quadrupoles were built for the dispersion suppressor and to match to the regular cells. IQD's are 116″ quadrupoles and IQC's are 100″ quadrupoles. All 84″ quadrupoles were removed from the Main Ring and evaluated for use in the Main Injector. The magnets required for transport in the remnant of the Main Ring (F Sector) were selected from those which were not of ring quality with attention paid to the expected failures. The same plan was applied to select magnets for the 150 GeV transport from the Main Injector to the Tevatron (P150 and A150). The P150 line continues for other functions but the A150 line magnets have been removed and are available for beam line spares. The commissioning of the Main Injector (beginning in September 1998) and early operation employed the selected magnets magnets with replacements made when failures occurred.

In the regions where beam transfer Lambertson magnets impacted the aperture, new large aperture WQB [2], [3] quadrupoles were build, measured, and installed in 2006. This substantially improved the available aperture. Of course, this also increase the supply of spare 84″ Quadrupoles. A review of magnet reliability for the first decade of Main Injector operation is available [4].

2 Initial Installation Record

Phil Martin and C. Shekhar Mishra coordinated the installation of magnets for the Main Injector. Included in this Beams-doc is a version labeled 5-7-98_Magnet_Assignments.xls but I find that does not have a completed list of assigned magnets. It is organized to have arc sections separate from straight sections. A description of the A150 and P150 lines with magnet type are there with only some of the assigned magnets. While creating lists of installed magnets, Bruce Brown acquired and updated this list. A version from 980629 and 031030 are included. Together these may have a reasonable picture of the original magnet installation list and some early replacements. For the inquisitive, the list begins at MI Location 609 because that (along with 309) marks the two-fold symmetry point in the lattice. It is the initial station for some lattice files (others begin at the injection position).

A project to extract magnet field strength and shape data required a list of magnets. We employ magnet locations and spare magnet lists from the reports so prepared.

3 Quadrupoles from Main Ring

The quadrupoles which were created for the Main Ring came in two lengths which were frequently referred to as 4000 series (4 foot - 52″) and 7000 series (7 foot – 84″). To match

[1] See https://www-tdserver1.fnal.gov/AcceleratorSupport/FMI-Magnets/magcount.txt

the naming schemes employed for the VAX magnet measurement system build in the 1980's for measuring the magnet for the P-Bar source, these were re-specified as BQA and BQB where for example 4001 => BQA001 and 7002 => BQB002. When moving to specifying magnets for use in the Main Injector, we redesignated the BQB => IQB when the measured quality was thought to be perhaps sufficient for them to be selected for use in the Main Injector.

3.1 52″ Quads or 4000 Series

The magnets labeled as BQA in the Main Ring era (4000 series) were not employed in the Main Injector Lattice. The designation of IQJ was applied to some reworked 4000 series quadrupoles. In particular, one IQJ is used in the abort line and several 4000 series magnets remain in the Main Ring remanent. We note that a few 52″ quadrupoles have been found with different manifolds (series vs. parallel water paths). We will not address BQA or other 52″ quads in detail [2]. We also have identified IQA017-1 in our records and it may also be a useful spare. It was measured on 1998-11-02 while Main Injector commissioning was underway.

3.2 Old Style Quadrupoles

After many early Main Ring quadrupoles were completed, it was decided that a change in the core shape would be made. We understand that this was to improve the field quality at high field, including the desire to operate at 500 GeV (achieved but not suitable for particle physics). Initially some stacked cores were selected and one of the two half cores was machined to remove 10 mils (0.010″) from the parting plane. These magnets were designated "Old Style" (the irony is not lost of these authors) and they had slightly negative 8Pole (contrasting with a 5 to 7 units of 8Pole in "New Style" 84″ quadrupoles. The larger gap also provided a weaker strength. Initially, they were placed into the Main Ring in a pattern to reduce the impact of the strength change on the width of the half-integer resonance. The Main Injector Project required sufficiently fewer quadrupoles such that no "Old Style" magnets were selected for Main Injector synchrotron use. Eventually an additional stamping die was created and (many, most, nearly all??) 'New Style 'IQB's used these laminations. We note that we are working from memory of what we were told. We believe this is all from changes before 1973.

3.3 Support and Vacuum Considerations for Quadrupole Designation

In addition to IQB designations, the vacuum pipe or support configurations at various locations were indicated by designating other 'IQ84' quadrupoles as IQE, IQF, IQG, and IQH. This required the magnet factory to provide magnets as spares for these configurations. Consult the Technical Design Handbook to interpret these designations. The conversion from IQB to/from these styles change vacuum and/or support but not the magnetic properties. We have been reminded that with the introduction of the WQB for the MI Injection location, the IQG (rolled for use at MI Injection) has no current requirements in the Main Injector. IQH are used in the abort line which does not require ring quality

[2] Additional details on 52″ quads as well as 84″ rework details are found in https://www-tdserver1.fnal.gov/acceleratorsupport/SY120/MRQuads/RefMenu.html

magnets. We also note that 5520-TE-333127 Rev N is a common traveler for rework of Main Ring Quadrupoles.

3.4 Selection for Main Injector Quadrupoles

Using the measurements, the strength at high field was used to place weaker magnets as "D" locations (odd numbered half cells) and stronger magnets at "F" locations (even numbered half cells) to reduce the width of the half-integer resonance at high field. The strength at injection fields is not well correlated with the strength at high fields so the injection strength of these magnets is nearly the same for "F" and "D". Table 1 provides statistics for 127 (of the 128) magnets which were in the ring in 2002.

Table 1: Statistics for installed 84″ quad magnets at 127 locations

STRENGTH DATA FOR IQ84 MAGNETS AT 2800 A			
Property	All	Focusing	Defocusing
Average Strength:	34.1716 T-m	34.1870 T-m	34.1565 T-m
Root Mean Square(RMS):	0.02142 T-m	0.01598 T-m	0.01409 T-m
Relative RMS:	6.268E-4	4.675E-4	4.125E-4
STRENGTH DATA FOR IQ84 MAGNETS AT 200 A			
Property	All	Focusing	Defocusing
Average Strength:	2.4618 T-m	2.4618 T-m	2.4618 T-m
Root Mean Square(RMS):	0.002406 T-m	0.002419 T-m	0.002412 T-m
Relative RMS:	9.774E-4	9.825E-4	9.7988E-4

A few magnets deserve special mention at this time due to various situations which changed our opinions.

IQB098 This magnet was in the A150 line (Q903) but review found its measurement were faulty. It was reported that the injection field strength was unusual. Remeasurement finds it a ring quality magnet. Installed as Q202 on 6/13/2019.

IQB226 This magnet was provided for the Main Ring remnant (F48-1). I was sufficiently radioactive that no rework was done to make it Ring suitable. Upon review we will designate as a spare for Ring use. It has been replaced at F48-1 and is available.

IQB268 This magnet was measured in August 1998 (just before commissioning of the Main Injector began) and it was kept as BQB268 until it was review, reclassified, and mechanically converted to IQB268 in 2019.

IQB334 This magnet was installed as Q504 (7/6/1998) and remained there until it failed (10/26/2016) with bad hi pot after a water leak. It was repaired at the Magnet Factory but when measured at MTF the field quality was unsatisfactory.

We mention also that IQB335 and IQB345 had only stretched wire measurements in the 1990's but recent measurements find IQB345 to be ring quality.

4 New Main Quadrupoles for Main Injector

Using new laminations from 'Main Injector Steel', the Main Injector Project produced IQC (100″) and IQD (116″) quadrupoles. The IQB (84″) quadrupoles provide focusing for the regular cells in the lattice. The IQD quadrupoles provide focusing in the dispersion suppressor cells. Cell boundaries (from this viewpoint) are at the center of IQB or IQD quadrupoles whereas the IQC quadrupoles can be thought of as being half of an IQB mated to half of an IQD. They are used where regular cells are followed (or follow) dispersion suppressor cells. IQD's are installed at 48 locations. The initial complement of IQD for the Main Injector Project was 53 magnets. IQC's are installed at 32 locations and 38 magnets (Serial 001 - 040 with 002 and 003 reused for parts) were created for the Main Injector Project. Although the design profile for the IQC and IQD cores match the design for the "new style" Main Ring quadrupoles, each coil is longer so to allow sufficient water flow a larger diameter cooling hole is provided in the copper from which they are wound. We also note that the IQC and IQD magnets include trim coils. In part, this is because the difference in steel causes the strength ratios to be different as one goes up the ramp in current.

4.1 Improved Quadrupole Fabrication

Commissioning of the Main Injector began in September 1998. By January 2002, 3 IQC and 3 IQD quadrupoles had failed [5] [3]. The 'enhanced' coils design using G10 and kapton in combination with the traditional pot-in-core coil insulation system was not robust. Design and tooling for coils to be potted before assembly was executed. The potting fixture parts are shared among the IQB, IQC, and IQD designs. Four new IQC and four new IQD complete yokes were stacked and completed. Four new IQD coils were wound, insulated (including potting) and complete magnets assembled. In addition to IQD053 which was measured in 2002 (IQD001-0 - IQD052-0 were measured in 1995-6), new magnets IQD254-0, 255-0, 256-0, and 257-0 were created and measured in 2007. Coils were wound and cores stacked and completed for 4 IQC magnets but work stopped for budget considerations and the failures did not continue for about a decade. After a failure in 2013 and two failures in 2019, there are no spare IQC magnets (March 2020).

4.2 Replacements of IQC and IQD Quadrupoles

Table 2 shows the failure history of IQC and IQD quadrupoles.

5 Large Aperture Quadrupoles

The WQB[2] large aperture quadrupoles were required to match the strength of IQB quadrupoles well enough to allow a small correction coil to meet the strength matching requirements. Special steel was selected. It was discovered that the 4 turn-per-pole IQB coil could be matched with a 7 turn-per-pole WQB allowing a $\sqrt{7/4}$ enhancement in the pole tip radius. A larger beam pipe was also constructed and installed. This series design was employed at 7 locations, freeing 7 IQB magnets as spares for other Main Injector locations.

[3] For analysis of magnet failures, it must be noted that one IQD failed when its cooling water path was valved out when operations restarted after a shutdown

Table 2: Failures of 100″ and 116″ Quadrupoles

	Magnet	Magnet		
Location	Removed	Installed	Date	Reason
517	IQD036	IQD050	07/13/1999	GROUND FAULT
516	IQC029	IQC034	10/31/1999	GROUND FAULT
220	IQC023	IQC012	01/04/2000	GROUND FAULT
601	IQC018	IQC020	03/17/2000	WATER LEAK
610	IQD026	IQD045	11/18/2001	NO LCW
641	IQD006	IQD009	01/21/2002	GROUND FAULT
229	IQC001	IQC018	12/04/2013	WATER LEAK
408	IQC026	IQC038	10/22/2019	GROUND FAULT
408	IQC038	IQC039	12/28/2019	WATER LEAK, GROUND FAULT

No failures of WQB magnets have occured from 2006 - 2020. Since these magnet were developed to improve the available aperture in beam transfer regions, it was no surprise that the magnets being replaced were, in some cases, quite radioactive The dominant long half life isotope from iron activation is Mn-54 with a 312 day half life. Of the magnets moved for this, all but one had radiation measured above the 1 mR limit for ordinary handling as Class 1. Four magnets showed between 2 and 6 mR while the remainder were 20, 40, and 40 mR upon removal (including IQE072 which was moved from Q522 to Q521. They were left in remote storage for years before use. After about 2 years (743 days) only two remained above the 1 mR limit. In the same shutdown, Q521 was replaced to use only the star shaped vacuum pipe, thus improving the aperture at that location.

Table 3: Installation of Large Aperture WQB Quadrupoles

	Magnet	Magnet		
Location	Removed	Installed	Date	Reason
222	IQB-045	WQB-007	3/20/2006	Wide Aperture Quad Upgrade
608	IQE-225	WQB-005	3/23/2006	Wide Aperture Quad Upgrade
620	IQE-134	WQB-002	3/28/2006	Wide Aperture Quad Upgrade
101	IQG-333	WQB-001	3/30/2006	Wide Aperture Quad Upgrade
402	IQE-065	WQB-004	4/7/2006	Wide Aperture Quad Upgrade
522	IQE-072	WQB-003	4/17/2006	Wide Aperture Quad Upgrade
321	IQB-071	WQB-006	5/1/2006	Wide Aperture Quad Upgrade
521	IQB-177	IQE-072	4/11/2006	Improve Aperture - Star pipe

6 Rebuilding 84″ Quadrupoles

From the commissioning of the Main Ring through the mid-1980's, a program of rebuilding 4000 and 7000 series quadrupoles continued along with the program to build replacement Main Ring Dipoles. [See discussion in MTF-93-0004 [6] and MTF-93-0009 [7].] The last quadrupole in that series was IQB349, circa 1985. Although there were many failures (about 30 of the 84″ quadrupoles) since 1998, the existing supply from the Main Ring and the 7

quads available after the WQB upgrade were sufficient until after the end of the Tevatron Era.

6.1 Debonding Oven

For Main Ring dipoles and quadrupoles which had coils bonded into the cores with epoxy, a system to recover the coils and cores was developed. A debonding oven was created [4] As we began re-instituting a system to rebuild IQB magnets a few were debonded. However, an effort to rebuild and re-instrument the debonding oven has been needed and that work continues (March 2020). We have concerns that temperature extremes in the debonding oven might have deformed some cores.

6.2 Clamping Bar Effort

In Summer 2014, the effort to restart construction of 84″ quadrupoles began. Initial discussions suggested building two rebuilt IQB's per year to match an expected failure rate of 2 IQB's per year. Since it was known that the success rate in rebuilding quadrupoles was not nearly ideal, efforts to understand the failures began. A design enhancement for tuning was to add clamping bars to each half core so that the stress across the parting plane could be studied. This was proposed in August 2016. [5] Table 4 shows the status of those efforts.

Table 4: Rebuild Efforts for 84″ Quadrupoles

New Quad	Old Core	Start Date	Test Date	Status
IQBB401-0	IQB295	20170303	2017-04-26	Unsatisfactory Harmonics
IQBB402-0	IQB132	20170519	2017-08-27	Good spare
IQBB403-0	IQB169	20180628	In Queue	
IQBB404-0	IQB310	20190107	In Queue	Likely not good

7 Available Spare Quadrupoles for the Main Injector

The status of spare IQ84 quadrupole is shown in spreadsheet MIQuadSpares_2020.xlsx and in Table 5. We might choose to update the document and spreadsheet without updating this table. We note that of the available 84″ quadrupoles, IQB065-1, IQF134-1, and IQE225-1 were made available when WQB quads were installed.

8 Conclusion

Efforts are underway to build additional 84″ quadrupoles and to make measurements of all available magnets. An additional source of quadrupoles which were not in the Main Ring has been discovered and these will also be evaluated.

[4] Dr. Wilson imposed a ban on new 'buildings' at that time so the structure which was built for the oven was declared an awning. (private communication to BCBrown)

[5] Went preparing to rebuild IQB310 we found that the welds had barely been holding the side plates to the cores. In response, we obtained the Assembly Record from storage and imaged it. It revealed that the rebuild occured in 1977.

Table 5: Spare Main Injector Quadrupoles - see spreadsheet MIQuadSpares_2020.xlsx for comments. Strength comparison based on Quads installed in 2002

QUADS	LOC	STATUS	Str 2800	NORMAL8p	Str 200	NORMAL8p
SPARE			Sigma	relative	sigma	relative
			Strength - Rel RMS/Mean			
IQE048-1	MI60	Good Spare	1.681	6.65E-04	1.0200	7.17E-04
IQB065-1	IB1	Good Spare	-0.340	5.94E-04	-0.3078	6.23E-04
IQF134-1	TPL	Good Spare	-0.0320	7.23E-04	-0.679	6.87E-04
IQB173-1	TPL	Good Spare	0.0826	6.28E-04	0.4610	6.12E-04
IQE225-1	TPL	Good Spare	-0.0027	7.02E-04	0.6468	7.44E-04
IQB226-1	IB2	Need Meas	-0.440	5.60E-04	-7.473	5.96E-
IQB236-1	IB2	Need Meas	0.9587	6.03E-04	-0.0260	6.92E-04
IQB268-1	IB2	Need Meas	-0.2122	6.33E-04	-0.2672	5.74E-04
IQB320-1	TPL	Good Spare	1.9273	8.37E-04	2.2315	9.23E-04
IQB345-1	TPL	Good Spare	-0.4410	5.20E-04	1.2046	5.42E-04
IQBB401-0		Decommission				
IQBB402-0		Good Spare	-1.1244	5.09E-04	-1.760	3.99E-04
IQBB403-0		Need Meas				
IQBB404-0		???				
IQA-017	TPL	Needs Eval				
IQJ-083	TPL	Good Spare				
IQC001	TPL	Water Leak				
IQC026	MI-60	Bad HiPot				
IQC038	IB2	Leak, Bad HiPot				
IQC40	TPL	Bad HiPot				
IQD-017	MI60	Good Spare				
IQD-053	TPL	Good Spare				
IQD-254	TPL	Good Spare				
IQD-255	TPL	Good Spare				
IQD-256	TPL	Good Spare				
IQD-257	TPL	Good Spare				

A Tunnel Repairs

Perhaps additional insight into magnet reliability can be obtained by the additional information on magnet repairs in the tunnel. We have not maintained careful records but we have some notes from shutdowns in 2016, 2017 and 2019. A worksheet "Tunnel Repairs" is included in "Spare MI Quads_20200220.xls" and updated versions may be added there.

Table 6: Recent Repairs in Tunnel

Location	Shutdown	Magnet	Date Installed	Comments
Q401	2016	IQB093	4/10/1998	Experts evaluating per 12 Oct 2016
Q338	2016	IQC015	8/18/1997	repaired in place
Q203	2016	IQB262	3/13/1998	repaired
Q503	2016	IQB094	7/6/1998	repaired
Q504	2016	IQB334	7/6/1998	Repair failed, Installed IQB045 10/26/2016
Q503	2017	IQB094	7/6/1998	Repaired 11/1/2017
Q428	2017	IQB234	5/18/2009	Repaired 10/30/2017
Q302	2017	IQB146	4/10/1998	Repaired 10/26/17
LAM402B	2017	ILA007	5/26/1998	Repaired
Q102	2017	IQE068	4/23/1998	Repaired
Q126	2017	IQB203	4/10/1998	Repaired 10/24/2017
LAM402B	2018	ILA007	5/26/1998	Repaired again 7/24/2018
Q102	2018	IQE068	4/23/1998	Repaired 7/16/2018
D615-1	2018	IDC061	8/6/1997	Brazed on 7/20/2018 - leak fixed.
D230-2	2018	IDD002	8/21/1996	Repaired on 7/13/2018
Q202	2019	IQB236	4/10/1998	Replaced and repaired at IB#2
Q507	2019	IQB349	6/17/1998	Fitting replaced (Unold - 10/29/2019)
Q420	2019	IQB241	6/28/2000	Fitting repaired (Unold - 10/29/2019)
Q110		IQB110	3/10/1998	Leaking March 2020

B Notes on BQB Spares

In gathering information about ring quality spares, we have acquired other information which will will add here.

BQB195 This is an 'old style' magnet as confirmed by 1998 measurements. A manifold leak was repaired and it is a good spare. It is in the input queue for MTF measurements (March 2020).

C Notes on IQB Rebuilds

E-mail from Sherry F. Baketz on 2/27/2020

The bolt together design of the quads was already in place when I became involved with the project in 2017. We had just started building IQBB401 at that time. IQBB401 measured to have an unacceptable octupole component after being burned and rebuilt. The prior serial number of this magnet was noted as IQB295. I am not able to find records of the actual burn of IQB295. I have attached a table of the core measurements used in the four IQBB magnets built. These measurements were taken in a free state on a granite table. When the cores are assembled, the legs are drawn together thus somewhat reducing the effect of any warping that may be present. IQBB401 has a warped core. The pole tips are closer to the parting plane and the legs are spread apart. Omar Kazi ran Poisson Superfish simulations with these core measurements and the simulation predicted a significant magnetic effect in the form of an undesirable octupole. In the case of IQBB401, the actual octupole measurements were not as severe as the simulation, although still deemed unacceptable. The coils from IQBB401 were used in IQBB403. IQBB401 cores are currently being stored in TPL.

IQBB402 was made from IQB132. This magnet is a good spare.

IQBB403 is waiting for magnetic measurements. IQBB403 was made from IQB169. IQB169 and IQB310 were burned together. IQB310 was in flames at least once during the burn process. Some of the IQB310 tie plate welds were broken upon inspection after burn. We know that the oven temperature was not uniform during that event and this is not likely an isolated incident. This could be the root cause of some of the cores warping during burning. Upgrades to the furnace are in process. From IQB169 core measurements, we expect this magnet to magnetically be acceptable.

IQBB404 is waiting for magnetic measurements. This magnet was made from IQB310. IQB310 core measurements after burn also indicate similar warping as IQBB401 cores, however not as significant. Omar Kazi simulations also predict IQB310 cores to produce an undesirable octupole. Magnetic measurements will provide us with more data to determine the correlation between simulated octupole in Poisson and actual measured octupole. We expect this magnet will not be magnetically acceptable.

Regarding reliability, the IQB potted magnets have soft soldered manifold joints. The potted magnet design has encased some of these joints in epoxy so leaks are not able to easily be identified or repaired. IQBB magnets have brazed manifold joints and all joints are visible and easily accessible for inspection and repair.

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