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Some Results on TeV I Quadrupole Magnet Strengths

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Contents

Abstract

Brief design and measurement results are presented on TeV I project quadrupoles. Some fabrication and measurement history will be presented in order to clarify the results. Results will be provided on most available magnets including some new results from measurements for the MI 8 GeV line project. Ultimate accuracy of strength results should approach 0.2% but this effort will not attack all of the hysteresis, saturation and cross-calibration issues and will achieve a consistent description at better than the 1% level.

1 Introduction

Some confusion exists concerning measurements of PBar Source Magnets. Previously prepared reports have been on a per-magnet basis and some global issues remain to be expressed which will provide guidance in selecting correct new results and in presenting summaries of results. This document will only begin to address these issues. We hope to guide current machine simulation and future measurement summaries with this work.

2 Design Properties

The magnets for the Anti-proton Source were build under the Tevatron I Project. The design properties are documented in Chapter 12 of the design report[1]. Using the design geometry, we will calculate properties of the magnets which we will then compare with measurement. After sufficient prototype measurement and modeling, magnets were built with body fields which met the requirements for field uniformity and end design which contributed a fixed strength increment and no field errors.

Thus one expects that the integrated strength consists of a term which is proportional to the body strength times the steel length plus a term (possibly negative for some designs) for the endfield strength. The design gradient, B_2 is

$$B_2 = \frac{\mu_0 N_g I}{A^2} \tag{1}$$

where N_g is the number of turns driving a gap (twice the number of turns per pole), I is the current in a coil and A is the poletip radius with contributions from iron neglected. Two such designs were required for the anti-proton source: Small Quadrupoles (SQ) and Large Quadrupoles (LQ).

Magnet Type	Pole Tip Radius	Turns/Gap	Body Gradient
SQ	1.75″(44.45 mm)	66	41.98E-3 T/m/A
LQ	3.3125″(84.1375 mm)	42	7.456E-3 T/m/A

The LQ design specified a nominal current of about 1207 A (Standard measurements were at 1305 A as required when more saturation was encountered that was projected.) whereas the SQ design called for a nominal 234.5 A (standard measurements were at 230 A) so the two designs give similar body gradients. The design report lists the following magnets with the above described coils:

Series	Design Eff. Len. m	Nominal Eff. Len. Inches	Design Strength T/A
SQA	0.4572	18.00	0.01919
SQB	0.64008	25.20	0.02687
SQC	0.70104	27.60	0.02943
SQD	0.82804	32.60	0.03476
SQE	1.31166	51.64	0.05506
LQB	0.64262	25.3	0.00479
LQC	0.77216	30.4	0.00576
LQD	0.83007	32.68	0.00619
LQE	0.87376	34.4	0.00651

3 Measurements

The production measurement system for PBar Source quadrupoles[2] produced strength measurements and shape measurements which were summarized in ASCII reports that were delivered to the TeV I Project by MTF. The strength reported was based on the FLATCOIL technique with emphasis on differential strength measurements. This provided the required information to sort the magnets by strength for placement, but interpretation is complicated by the failure to record remanent field with this technique. However, the HARMONICS measurement reported rotating coil shape measurements for all of the magnets. These were normalized by measuring the strength at the measurement current. This data was not examined in the 1980's since it was believed that the measurements had shown the magnets to have the desired properties.

The production measurement system used a DEC VAX 11/730 Computer running VMS connected to a series of CAMAC crates. Data were stored in VAX Binary files with one raw and one reduced file per data run. These files were 'swept' into VAX indexed files and were accessible via FORTRAN calls or with VAX DATATRIEVE. This measurement system was preceded by a prototype system consisting of a Multibus I based computer running an early Unix variant. The magnet measurements for the Debuncher, Accumulator and TeV I beamlines were completed between March and August of 1984. Some additional calibration, remeasurement and cross-check measurements continued into the fall of 1984. The production FLATCOIL system was used for this entire time. The production HARMONICS measurement system was not available until late spring so the bulk of the SQC's were measured on the Prototype system. Typically the rotating coil measurements of Small Quads were done at the nominal 230 A current with two measurements of strength and 6 runs devoted to harmonics.

The VAX system for magnet measurements has been superseded at MTF by one based on Sun computers running Unix with data acquisition driven thru VME and VXI crates[3][4]. Data is stored in a SYBASE database[5] from which reports provide raw, reduced, or analyzed data. This measurement system was created for measurements of the magnets for the Main Injector project. Requests by the PBar Source group have included an interest in measurements of one magnet of each of the Small Quadrupole series with the new system. In addition, some Small Quadrupoles have been rebuilt due to water leaks, and others have been required for the 8 GeV transfer line to the Main Injector. Up to this point such measurements have been carried out between the late fall of 1995 and the spring of 1997. New measurements have all been carried out using rotating coils. The probes built for the TeV I project have been used. However, the availability of the new checklist driven measurements has permitted a considerably more extensive set of measurements to be completed. Measurements at 25 A intervals on the upramp to 400 A, continuing on the downramp to 0 A were typical.

4 Recent Analysis Efforts

Various PBar Source and Main Injector project personnel have discussed with the author their concerns about the measurement results which they were using. This prompted an effort to document the properties in a way which would permit an easy comparison of results and an evaluation of all available results. In addition, the deceleration required for the charmonium experiment in the Accumulator causes one to attempt to document the strength at currents other than those demanded for 8 GeV storage. Although all data has been carefully preserved, not all is equally accessible. In an attempt to provide a reliable answer with minimal demands on the MTF support staff and also with an achievable effort from the author, the choice was made to attempt to use the rotating coil data. Results will be presented based on the 1984 measurements and comparisons made with the newer data. Finally, a brief discussion of hysteresis from the new data will be presented. A 'notebook' which describes some of the analysis effort has been appended to the source file for this document. This file is pbar_quad_str.tex and will be available in the MTF document area.

4.1 Production Series Information

The use of three letter designations for magnet design series was initiated by Fred Mills for the TeV I project. It was decided that subgroups of these designs would be created using serial number groupings which kept distinct the various minor fabrication variations. The following designations separate interesting subgroups of these magnet series:

Series	Serial Range	Distinctive Feature	Designated Use
SQA	001-040		Accumulator
SQA	500-521		Booster to MR 8 GeV Line
SQC	001-022	Beveled Endpack	TeV I Beamlines
SQC	101-204	Stepped Endpack	Debuncher
SQC	301-319	Debuncher SQC Steel Longer Coil	Accumulator
SQC	401-402	Prototype SQC Steel	Beamlines
LQA	001-007	Original 24 Turn Coil	1984 Installation
LQA	101-107	Same Steel 22 Turn Coil	1986 Installation

The SQC production was started while the final steel shape was being determined. A beveled end correction was more than sufficient for the beamlines so endpacks for that design were created and magnet production began. The steel length and end pack design for the Debuncher SQC magnets was finalized but before they could be fully evaluated, the coil winding for the Accumulator SQC magnets needed to start. It was decided to add length to those coils, deferring the decision on steel length. In fact, the same steel length was used for SQC300 series as SQC100 series and the measured strength difference is too small to be yet known. The developments were done with prototypes, first of 48 inch length (The design report calls them SQP's but they were later designated SQF's.) later with the approximately 27 inch length of the SQC's. Removable end packs were used to provide easily machined pieces which were modified during the R&D phase. When all development was completed, these magnets had the 'removable' endpacks welded into place and are numbered as SQC400 series. They have a clearly different length than other SQC's.

The other SQ series were built without special distinctions. Later, the SQA design was selected for the 1986 rebuild of the Booster to Main Ring 8 GeV Line. Those magnets were designated as the SQA500 series.

The only item of distinction for the LQ magnets was the rebuild of the LQA series. The requirement for these magnets was exceptionally weak. The initial choice of strength was not adequately weak. It required a current so much lower that it exceeded the range of the 'shunt' power supplies if it was on a Quadrupole bus. Initial running of the Accumulator was accomplished by powering the LQA's from the Dipole bus. In 1986, new coils were wound and installed and the magnets were re-tested. For this measurement, the series was designated as the LQA100 series.

4.2 SQ Series Strength from VAX Harmonics

In the Winter and Spring of 1997, questions for both Accumulator operation and Booster to MI 8 GeV Line operation raised issues of magnet strength for the SQ series quadrupoles. Unpublished analysis of the original measurements had suggested that most measurements had a precision of about 10 to 20 units (0.1% - 0.2%). An analysis of some 1995 - 97 data suggested that problems existed which were worse than 2%. It was not obvious what was wrong. In an attempt to get a clear picture, it was decided to pursue older measurements. It was found that most SQ series measurements made with the VAX-based HARMONICS system were available on disk and could be examined. Since there was no previous wisdom from these measurements, it was felt that they would provide a good starting place to discover the series properties.

The VAX HARMONICS Reduced data was available in the file A3TEVHARMRED.DAT;1 which is stored in the directory ALMOND::USER3:[MDTFCZAR.TEVIDATA] which was created on 11-MAR-1986 00:15:12.00 by sweeping data from Station A3's directory. It was accessed using Datatrieve Domain A3HARMRED. Measured strength (T/A for this early VAX data) and current were extracted to files which were then transfered to a Sun (dietsmith in the Beams Division Cartoon cluster) for processing with the xmgr plotting program. Data selection was arbitrary but two runs per magnet were kept for plotting and averaging. Nearly complete data were available for all except the SQC series. A few SQC100 and SQC 300 series magnets brought back for various reasons were measured in the Summer of 1984.

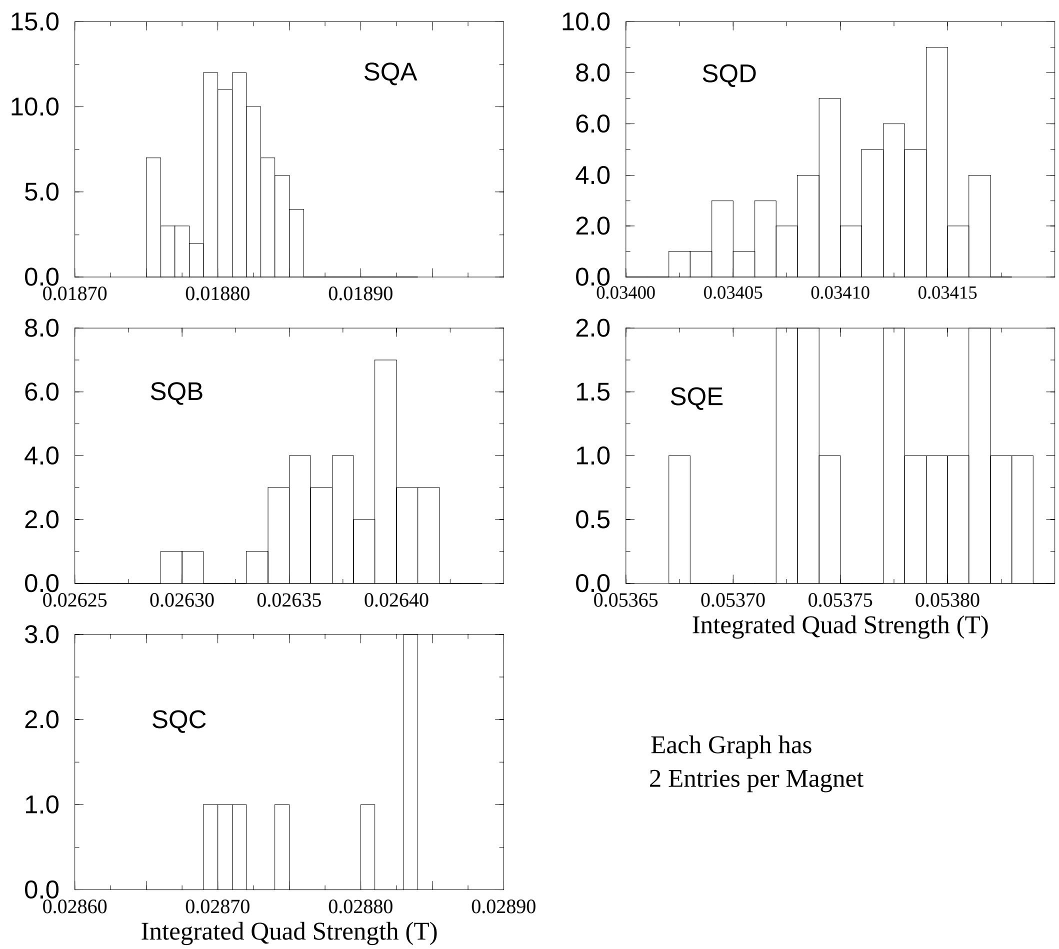

Figure 1: Distribution of Strength for SQ Magnets. Note that only a few of the SQC's were measured in this era.

In Figure 1 we plot the measured strengths of the SQ quadrupoles. In Table 1, the columns two and three provide the mean and σ/mean from these

Magnet	Measured Mean T/A	Measured σ/mean	Design Eff. Len. m	Apparent Gradient T/m/A
SQA	0.018805	0.00163	0.4572	0.04113
SQB	0.026374	0.00111	0.64008	0.0412
SQC	0.02877	0.00201	0.70104	0.04104
SQD	0.03412	0.00129	0.82804	0.04121
SQE	0.053787	0.00097	1.31166	0.04101
Average		0.0014		0.04112

Table 1: Strength Results from 1984 VAX Harmonics Measurements of SQ Series Magnets

measurements. The design effective length is taken as above from Chapter 12 of the design report. We divide the strength by the design length to find an apparent gradient. The average apparent gradient is 0.04112 T/m/A with relative variation 0.22 %. The apparent gradient is a useful parameter to characterize the SQ magnets since it averages over magnets in a given series and characterizes the extent to which the design effective length ratios were achieved.

We infer that this effective gradient must be different from the actual body gradient (which is determined by pole geometry and coil turns). Using the design pole geometry, we calculated above a peak gradient per current of .04198 T/m/A. The ratio 0.04112 / .04198 = 0.97952. To have the gradient wrong by 2% would require a 1% radius error or 0.0175″, whereas we would believe that the actual effective lengths are probably 2% different than the design. To complete this picture, we will wish to examine the data on steel lengths and attempt to demonstrate that the as-built magnet matches the design goal: integrated gradient = body gradient $\times$ (steel length + end extension).

4.3 CHISOX HARMONICS Measurements of SQ Magnets

Confirmation of the above measurements has been obtained from recent measurements with the check-list driven CHISOX measurement system. The measurements were not repeated in detail since we wanted to characterize the magnets at higher fields and during both upramp and downramp operation. The data acquired deserves careful analysis but in this document we will only obtain a few results. Dana Walbridge provided measurement-time analysis to see that the data was well measured. In doing so, he produced the now-usual plots of non-linear response[6][7][8] for which he required a fit to the linear excitation. At my request he provided me with a list of these results which are shown as columns 1 and 2 in Table 2. To compare these results with the 1984 ones, we divide by the design effective length to convert the integrated gradient per Ampere to a peak gradient per ampere. We divide this by the observed 0.04112 T/m/A from the 1984 measurements and place the results in column 4.

Magnet	B_2L/I T/A	B_2/I T/m/A	Ratio to 1984	Corrected Ratio	Measurement Date
SQA001-0	0.01786	0.03907	0.95025	1.00887	Dec 10 1996
SQA509-1	0.01889	0.04132	1.00479		Dec 14 1995
SQA510-1	0.01889	0.04131	1.0046		Dec 14 1995
SQC001-0	0.02746	0.03917	0.95246	1.01122	Dec 9 1996
SQC022-1	0.02905	0.04144	1.00785		Dec 11 1995
SQC107-0	0.02733	0.03899	0.94808	1.00658	Dec 5 1996
SQC124-1	0.02888	0.0412	1.00199		May 6 1997
SQC140-1	0.02739	0.03907	0.95008	1.00869	Feb 20 1997
SQC205-0	0.02741	0.0391	0.95097	1.00964	Dec 12 1996
SQC206-0	0.02733	0.03899	0.94821	1.00671	Feb 24 1997
SQC313-1	0.02898	0.04135	1.00549		Jul 1 1997
SQC320-0	0.02894	0.04128	1.00383		Apr 22 1997
SQC321-0	0.02895	0.04129	1.00417		Jun 13 1997
SQC401-0	0.02844	0.04057	0.98672		Apr 10 1996
SQC402-0	0.0268	0.03823	0.92976	.98712	Dec 6 1996

Table 2: Strength Results from CHISOX HARMONICS Measurements of SQ Series Magnets

When shown the pattern of disagreement in Column 4, Dana then produced the list of dates in Column 6 and discovered that the data with the 6% mismatch was all taken with a measurement run plan which had the following flaw: the requested probe was ambiguous. MH830930 (Electronic

Readable ID 24) was used but the checklist and installed instruments expected MH830314 (Electronic Readable ID 25) which was the one used for all the production measurements and is about 3% larger in radius. The correction to apply is the square of the ratio of radii in the database which is 1.06169. For those magnets whose data was mis-analyzed, the correction is made in column 5. Unfortunately, the wrong results were used for much 8 GeV Line tuning over the last several months.

Several observations are appropriate at this point. First we note that the SQA measurements are 0.61% high compared to the expectation based on 1984 measurements. The SQC100 and SQC300 Series (together) are 0.59% high. Since our measurement specifications and the analysis techniques employed in this note are not designed to measure precisely the same quantity and since we have not attempted any careful comparison of current readout systems, we consider this a resounding triumph for both systems. Furthermore, upon examining the 1995 probe cross-calibrations we find that a correction of 0.45% would be applied to correct for the difference between the radii in the database and the observed probe response. The two measured beamline SQC's (001,022) are 0.95% high which gives weak evidence that the beveled endpacks give magnets which are $0.35 \pm 0.2\%$ stronger than the Debuncher and Accumulator SQC's. This is only to contrast with rumors which have circulated and to contrast with the SQC400 series magnets which are only 98.7% of the expectation. These prototypes were certainly not like the production magnets and not guaranteed to be much like each other. However, they may be described by saying they appear to be alike at the 0.1% level and are 98.1% as strong as the SQC100 and SQC300 series.

4.4 SQC Hysteresis

Detailed studies of hysteresis are planned for SQ magnets but the scale of the effects can be seen from the measurements which have been done on many of the magnets measured with the CHISOX system. For examination we choose SQC124-1 which was measured on May 6, 1997. Reduced data was extracted by Dana Walbridge. In a 2020 spreadsheet a fit was made to downramp data from 150 A down. This is fit by a slope of .02905 T/A with an intercept (integrated remanent strength) of .05515 T. Subtracting Slope $\times$ I from the measured excitation curve yields the non-linear response shown in Figure 2. The hysteretic response is described by the non-linear upramp (lower curve), the non-linear downramp (upper curve) and transitions between them. In Figure 3 we subtract the upramp strength from the downramp strength

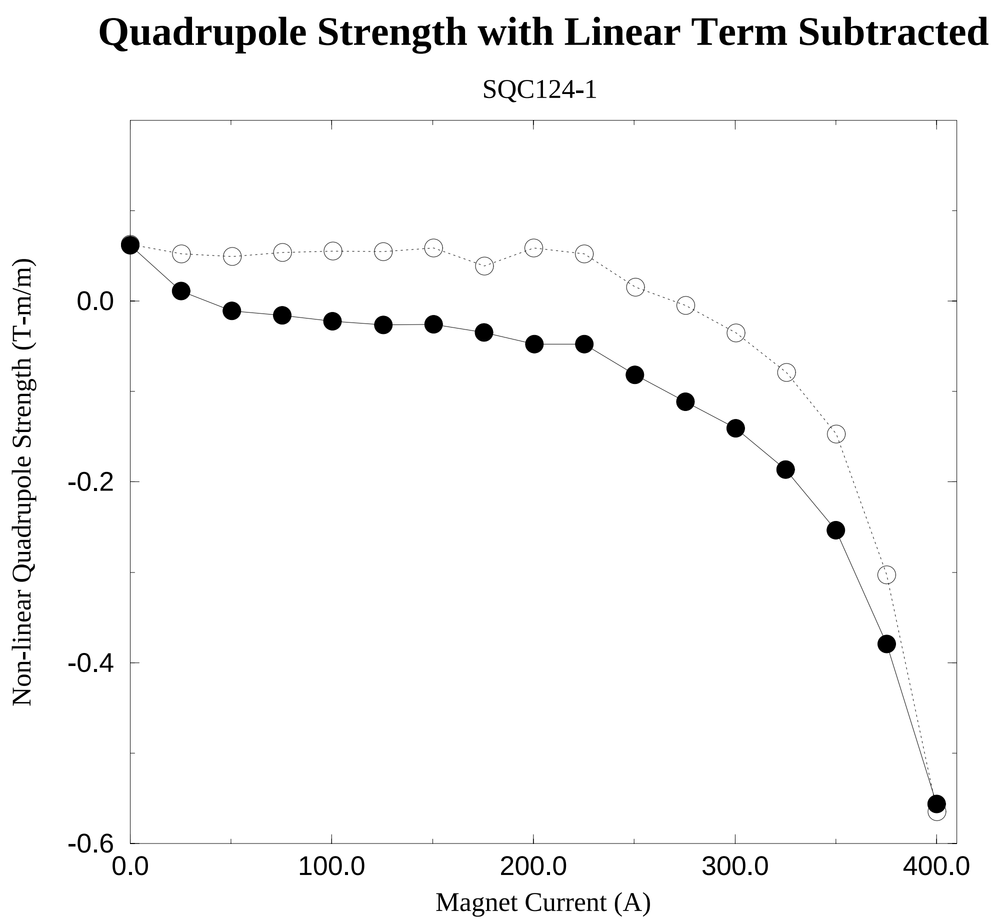

Figure 2: Non-linear Excitation Response of SQC124-1

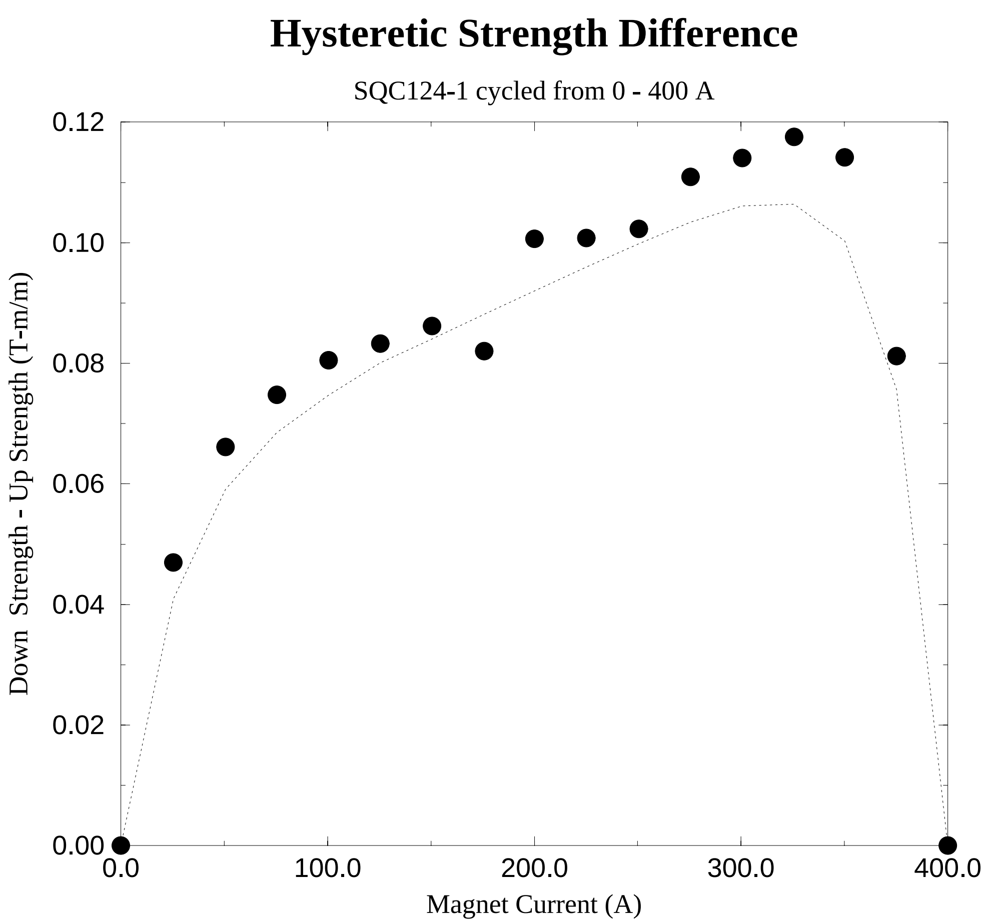

Figure 3: Downramp minus Upramp response for SQC124 when cycling between 0 and 400 A. Data shown as Dots with crude parameterization indicated by line.

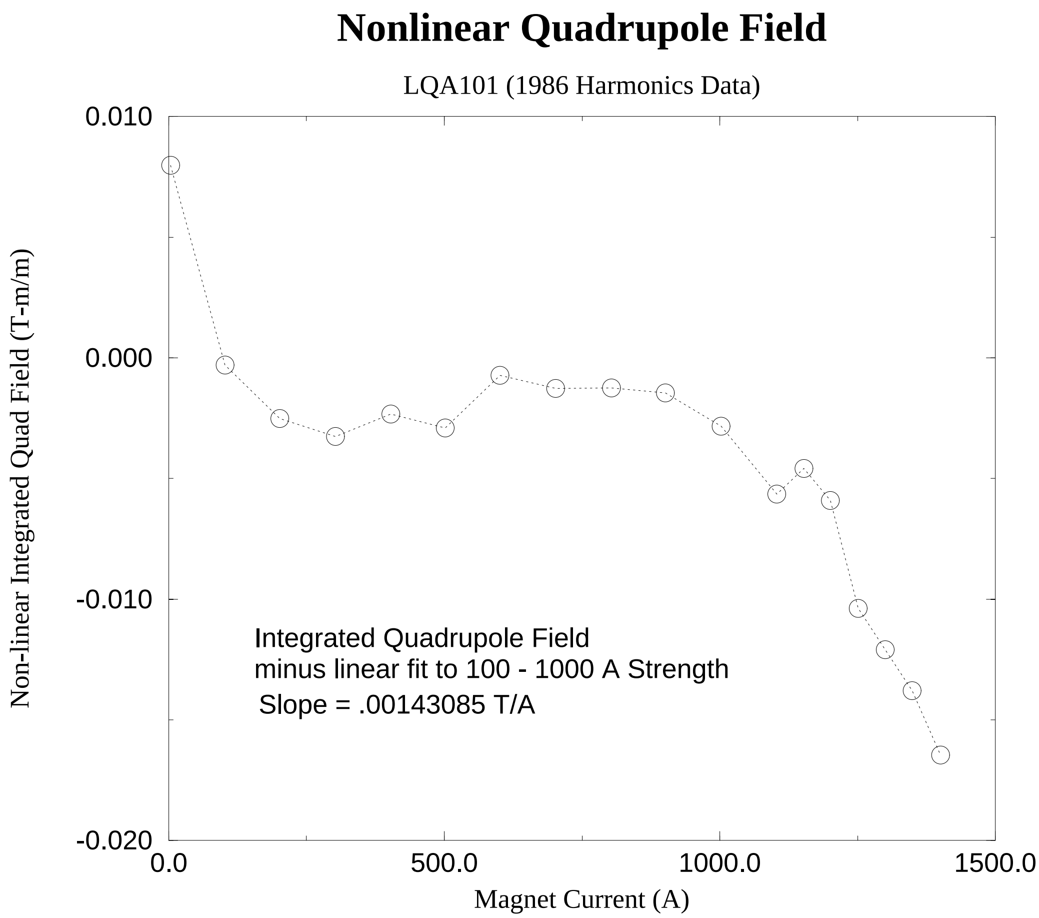

Figure 4: LQA101 Excitation on Up Ramp

to measure the magnitude of the hysteretic effects. We observe that for this magnet the down-up difference grows linearly with current. The crude description shown by the dotted line in Figure 3 includes the linear increase plus an exponential transition with an amplitude given by the full difference at the current reversal and an exponential characteristic current of 25 A.

4.5 LQA Strength Measurements

Since the LQA magnets are so short (11.980″ steel length), we will consider them as a separate issue. For this quick review, we will employ two sources of information. Following the 1986 measurements, the data were swept into indexed files and a report prepared from the harmonics measurements. It is currently available in ALMOND::USER3:[MDTFCZAR.TEVIDATA.NEWLQADATA] as file LQA-HARMREPT.TXT;5. From it I have extracted the strength report, processed it in a 2020 Spreadsheet program to produce results which I have then placed in tables or plots.

Of the 7 LQA magnets, 5 had multiple strength measurements at currents near the new nominal of 1305 A. For each set, we calculate a mean and a standard deviation (σ) about that mean. The average σ/mean is 0.17% which is consistent with other efforts to measure weak quadrupoles. If we simply characterize the 1305 A data by a transfer constant (the ratio of strength to current (T/A)), we find that the average transfer constant is 14.2317E-4 T/A with a σ/mean of 0.29%. The variation is 0.035″ or about 0.5 of a lamination thickness (1.5 mm or 0.060″). A quadrupole with 11 turns per pole and a pole tip radius of 84.1375 mm should have a body gradient of 35.05E-4 T/m/A. Using this and the measured transfer function we find an effective length of 0.3644 m or 14.347″. Comparing this to the iron length gives an end field contribution of 1.184″ per end.[1]

An upramp excitation curve for LQA101 is available in this data set. The upramp strength between 100 and 1000 A was fitted to a straight line, giving a slope of 14.309E-4 T/A with an intercept of -18.78E-4 T. We subtract the slope $\times$ current from the measured strength and designate that as the non-linear quadrupole field. It is plotted in Figure 4. We add the remanent field of 127.72E-4 T to the intercept to derive a low field hysteresis width estimate of 146.5E-4 T. The nonlinear saturation (strength - slope $\times$ current) is 120.9E-4 T at 1300 A which is about 0.655% of the linear field. These magnets are much less saturated than other LQ's but the remanent field is less negligible on the scale of the design excitation strength.

The seven LQA's were measured to have a mean remanent field of 132.4E-4 T with a σ/mean of 6.4%. Using the 12″ steel length rather than effective length determined above for the powered magnet we conclude that the pole-tip remanent field is 36.5E-4 T.

[1] The design report[1] specifies an iron length of 14.604″. However, the Fabrication Traveler specifies a design length of 11.980″ and measured lengths are shown which are consistent with this. The spare was examined in September 1997 and is consistent with Traveler information.

MAGNET	Current	Strength	TC	σ TC/TC
	A	T	T/A	
LQA101	1305	1.856118572	0.001422313	0.002185435
LQA102	1305	1.856729408	0.001422781	0.001940451
LQA103	1305	1.854401708	0.001420997	0.00226345
LQA104	1305	1.867825588	0.001431284	
LQA105	1305	1.860702097	0.001425825	
LQA106	1305	1.852509957	0.001419548	0.000829479
LQA107	1305	1.85238881	0.001419455	0.001421344
Average	1305	1.857239449	0.001423172	0.001728032
Sigma			4.19154e-06	
Sigma/Avg			0.002945206	

Table 3: Strength Results from 1986 VAX Harmonics Measurements of LQA Series Magnets

X

5 Conclusions

We find rumors of confusing measurements of PBar Source quadrupoles to be well founded. Measurements which were reduced with the wrong probe radius are identified which produce 6% errors in the reported quadrupole strength. Another source of confusion in using TeV I measurements comes from the remanent field ($\sim$ 0.8% of nominal 230 A strength for SQC124-1, $\sim$ 0.7% of nominal 1305 A strength for LQA101). Its contribution to the measured field is directly accounted for in HARMONICS measurements but FLATCOIL excitation measurements only measure the change from remanent to the chosen excitation level. Care is required to provide a consistent set of results. Measurements of SQC400 series magnets cannot be considered to represent the SQC quadrupoles in the Debuncher or the Accumulator since these were prototypes with a different fabrication method.

We find that the effective lengths in the TeV I Design Report[1] correctly describe the ratio of strengths measured by the HARMONICS measurements of 1984. The integrated strength is about 2% less than would be predicted by multiplying the design effective length by a gradient determined by the lamination geometry and the turns in the coil. After correcting for a probe identification error, we find that the 1995-7 measurements agree with the averages from the 1984 measurements to about 0.6% and the most of that disagreement will be removed by correctly applying probe inter-calibration data. A consistent description of the average SQ magnets emerges which is quite adequate for describing the magnets in the lattice at the 0.2% level for 8 GeV operation of the Accumulator.

Data on LQA measurements have been located and summarized to provide a result for describing this magnet in lattice models. This data from 1986 HARMONICS measurements was compared with FLATCOIL measurements which were summarized in February 1985. When corrected for the coil change and the remanent field, better than 1% agreement is found. A more careful analysis may be desired at some point, but the HARMONICS measurements appear to provide a very adequate description.

A complete description of the hysteresis for these magnets will require additional measurements. However, the pattern which is observed for other magnets appears to be sustained in the available measurements of SQC124 and LQA101. Upramp excitation produces a small deviation from the linear response provided by an ideal electromagnet. Downramp excitation produces a response which is shifted more positive by an amount which is similar in magnitude to the remanent field but slightly increasing at higher excitation levels. Transitions from the upramp to the downramp response are described by a transition curve which is nearly exponential with a characteristic current of about 25 A for SQC magnets. A complete description for transitions from arbitrary peak or reset values will require further measurements but is likely to be quite simple in character.

The existing measurements should support a much more detailed examination and may provide 0.1% or better knowledge of the magnet strengths. That will await further careful work on the existing measurements but for now, since neither saturation nor remanent fields are more than about 1% at excitation levels required in the Debuncher and Accumulator, and since we appear to have a consistent picture of existing measurements at better than the 0.5% level, one should be able to use these results to eliminate incorrect values from existing lattice or beam line descriptions of the SQ and LQA magnets.

6 Acknowledgments

This work is based on efforts with two major magnet measurement systems which each required many man years of effort. In addition to my co-authors on the published descriptions of these systems I would acknowledge a special debt to Peter Mazur and Dave Harding for their contributions to the long term operation and understanding of both systems, to Jim Pachnik, Julian Plymale, Rick Shenk, and Jim Sim for the leadership and support in software and data management. Dana Walbridge provided ongoing contributions but especially deserves thanks for compiling the SQ results which enabled us to complete this analysis in a timely fashion. The MTF measurement crew has demonstrated remarkable skill and patience in providing the many measurements on which this paper is based. Thanks to all.

A LQA Coil History

The following is taken from an E-Mail message from Bruce Brown Date: Tue, 22 Apr 1997 15:44:28 -0500 (CDT)

Those who worked on the TeV I magnets remember that the LQA's were built too strong the first time and rebuilt. But where is that documented? I was recently asked how many turns are in them and I was not sure. Last Monday (April 14), with help from Nelson Chester, and consultation with Dave Harding, I believe I have obtained the answers. I will confirm that by comparing data from the initial and rebuilt magnets and send you confirmation, but for now I don't want this information to get lost.

Design Report (I have the September 1983 version, but later versions don't seem to have change this) says that most LQ's use 84 turns but the LQA's use 40 turns. This is to be interpreted as 21 turns per pole and 10 turns per pole.

The original magnets were built and measured with labels LQA001 - 007. We located notebooks which were believed to be the complete drawing sets and appear to have the drawings which correspond to these magnets. We also located inspection travelers for these magnets with 1984 dates, indicating that a single layer 7 turn coil and a two layer 2 turn/3 turn coil were used. Thus the 1984 magnets had 12 turns/pole. This documentation appears to call for a steel length of 11.980", which is not in agreement with the other information I have. We need to check this.

It was known when we measured the LQA's that the required strength was obtained at currents near 1150 A rather than the nearly 1300 A that the rest of the Large Quads required, causing them to be powered from the dipole bus in the first Accumulator running. They were then rebuilt. We found the inspection travelers, which were labeled LQA001-R, etc. The measurements were performed with the labels LQA101 - 107 in 1986. The inspection travelers describe two coils: the 7 turn (single layer) and a 4 turn (also single layer, I presume). We didn't find drawings for the 4 turn coil in the usual place. Probably could get them if we tried.... I conclude that the current LQA have 11 turns/pole.

I expect to dig out measurements of both designs in the near future. For now, I believe that the correct coil description is 11 turns/pole.

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