# Some FEL UV Quadrupole Measurements

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## 1. Introduction

The main quadrupole specification for the FEL UV machine requires that the quadrupoles have an absolute setability of 1 x $10^{-3}$ and repeatability to 1 x $10^{-3}$ [1]. This specification translates into knowing the absolute integrated gradient of each QX quadrupole to +/- 5 G, (10 G total variation out of 10,000 G full strength) and the QX must repeat to +/- 5 G, (10 G total variation out of 10,000 G full strength) at any point over the entire excitation range.

The investigation of the quadrupoles' ability to meet these specifications was initiated as a result of beam based measurements in the IR FEL machine that indicated some number of unidentified quadrupoles were not restoring on the order of 10% when trying to perform a machine restore. To this end, measurements were constructed to specifically quantify the reproducibility of the QX quadrupole magnets. The scope of the project was later expanded to include the quantification of how various control systems affected the setability of the QX quadrupoles. Additionally, and as a spin off of the setability measurements, the resolution of the rotating coil stand was investigated when using probe P2B with two QX magnets configured for a difference measurement, also referred to as a 'bucked' measurement.

The QX quadrupoles are a 6 inch long, solid core magnet with a 3.125 inch bore, shown in Figure 1. These magnets have an integrated gradient of about 1000 G/amp. Original field maps generated for these quads were taken using the Magnet Measurement Facility (MMF) BOSS power supply on the CAMAC rotating coil stand using the P3A, Halbach style, rotating probe. The P3A probe is 36.3 inches long, 3.0 inches in diameter and made of Ultem. It is made of two half cylinders glued to a flat plate wire guide.

The FEL and CEBAF machine use the same powering and control systems for their quadrupoles. Since this system differs from the MMF powering and control system, the investigation of repeatability started by examining the differences between these and other system configurations. These tests took place from June 29, 2005 until July 15, 2005, when the magnets were crated and sent to STI Optronics in Bellevue, WA for absolute measurement on all of the twenty-six QX quadrupole magnets.

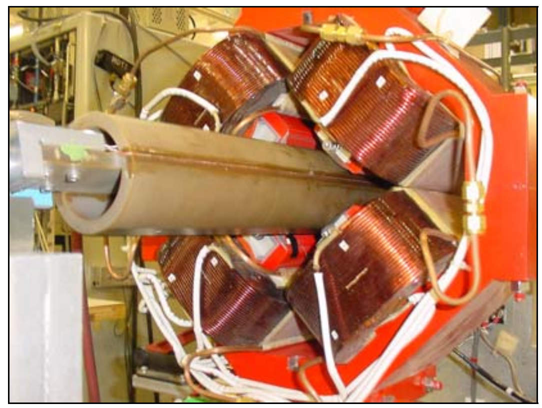

Figure 1. QX Quadrupole with P3A

## 2. Magnet Control System Description

Several different magnet control systems, consisting of a power supply, an interface system and current setting protocol, were used in performing the various measurements on the magnets. The goal here was to quantify the level to which each system demonstrated reproducibility in the magnet.

All systems used hysteresis limits of +/- 9.9 amps, and National Instruments, Lab Windows, software was the platform used to take data and control the systems below (with the exception of the Trim Rack system that was controlled by EPICS). This section describes the various systems used during the measurements.

***BOSS Power Supply and Bang-Bang Protocol***

This system used the BOSS 36V/12A power supply with a GPIB, IEEE 488 interface and its voltage limit set to 32 V. The current in the magnet was cycled and set using a representative Bang-Bang hysteresis protocol and 'sag compensation' algorithm used by the FEL EPICS control system described later. This is essentially the same configuration in which the QX magnets were originally measured. However the BOSS power supply has since been repaired and calibrated in February 2005 and would not repeat its previous performance. This system is referred to as *'BOSS BANG BANG'* and *'BOSS Repeat'* in Table 1 and 2 below.

***Danfysik 896 Power Supply and 3 Piece Linear Ramp Protocol***

This system used the Danfysik 896 70V/20A power supply to set current in the magnet using a three-piece ramp algorithm. The three piece ramp is a linear system that ramps the magnet at a rate of 1.0 amp per second for the first 90% of the set current, then continues at a rate of 0.1 amp per second for the next 9% of the set current and finally approaches the set current at a rate of 0.01 amp per second the last 1% of the set current. This three piece approach to current setting was chosen in an effort reduce set current overshoot and to set the magnet so that the fields and domains look reasonably like the magnet was hysteresis cycled adiabatically. While also limiting cycling duration to a reasonable value by increasing the ramp rate when the current is far from the final set current. An FP-1601 Ethernet controller and FP A10610, 12 bit analog I/O, that was configured for –10.2 V - +10.2 V operation, was used as the voltage input to the Danfysik and was controlled by a dedicated PC. This system is referred to as *'DAN 3 pc Ramp'* in Table 1 and 2 below.

***Trim Jr Prototype Power Supply and 3 Piece Linear Ramp Protocol***

This system consisted of a prototype upgrade to the CEBAF trim card. It is lovingly referred to as Trim Jr., and was available for use as a testing platform. Trim Jr. has an onboard logic chip that could potentially be programmed to exactly match the three-piece linear ramp protocol, described in the preceding paragraph, if measurements provided justification to do so. The Trim Jr., in its prototype form, has an internal power supply. This power supply needed analog regulation and used the same FP-1601 Ethernet controller, FP-A10610 and three-piece linear ramp as the Danfysik 896 described above. This system is referred to as *'Trim Jr'* in Table 1 below.

***Trim Rack and EPICS Control System***

This Trim Rack system was located in the Injector Test Cave adjacent to the MMF and consists of an EMI Bulk Power Supply and +/- 10 amp trim card. It was controlled using the EPICS control system launched from a PC in the MMF. The EPICS control system is the exact control system, containing the hysteresis and current setting protocol that is used in the FEL and CEBAF. EPICS uses a Bang-Bang current setting protocol with 'sag compensation'.

The Bang-Bang protocol sets the current to a given value as fast as the hardware will allow. The purpose of this protocol was isolation from control system latencies: reliance upon ramping by the hardware alone and the four second delay, part of the sag compensation method described below, are to avoid any reasonable possibility of changes in magnetic properties because of additional delays within the control system. The protocol was designed for laminated quadrupoles and was empirically determined to provide adequate reproducibility for the correctors as well [2].

Sag compensation was implemented as a way of flipping weak magnetic domains at the time of current setting to avoid long-term magnetic drift. Unpublished work by M. Tiefenback indicated laminated CEBAF quadrupoles exhibited sag, a weakening over time, of their magnetic field on a time scale of about 30 minutes. He found this sag could be accelerated by reducing the current 0.01 A below the desired current [3]. By incrementally approaching the desired final current ($I_{final}$) from the top of the hysteresis curve, the current was set to ($I_{final}$ + 1 A), ($I_{final}$ + 0.1 A), ($I_{final}$), delay 4 seconds, undershoot the set current ($I_{final}$ - 0.01 A), finally ($I_{final}$). Sag compensation caused the measured field to go to its many-hours-long asymptotic value with no measurable sag remaining.

All current setting done on this system was done 'on loop', meaning two hysteresis cycles were run before the magnet was set to a specific measurement current. This system is referred to as *'Trim Rack'* in Table 1 below.

| 5 AMPS | BOSS BANG BANG | DAN 3 pc Ramp | BOSS Repeat | Trim Jr | Trim Rack | Different Trim Card | Trim Rack | 200' Lead Trim Rack |
|---|---|---|---|---|---|---|---|---|
| Current (Sigma) | 0.014% | 0.002% | 0.032% | 0.004% | 0.000% | 0.001% | 0.002% | 0.000% |
| Current (Max) | 0.043% | 0.008% | 0.101% | 0.014% | 0.000% | 0.001% | 0.007% | 0.001% |
| | | | | | | | | |
| Hall Proben (Sigma) | -0.018% | -0.012% | -0.034% | -0.009% | -0.012% | -0.002% | -0.001% | -0.016% |
| Hall Proben (Max) | -0.064% | -0.029% | -0.107% | -0.029% | -0.029% | -0.007% | -0.004% | -0.054% |
| | | | | | | | | |
| Rotating Coil (sigma) | 0.050% | 0.051% | 0.049% | 0.068% | 0.035% | 0.044% | 0.089% | 0.060% |
| Rotating Coil (Max) | 0.114% | 0.159% | 0.122% | 0.199% | 0.118% | 0.161% | 0.309% | 0.189% |
| | | | | | | | | |
| Corrected Field (G) | -1398.44 | -1395.31 | -1395.5508 | -1405.14 | -1395.32 | -1395.34 | -1398.47 | -1398.45 |
| Corrected Gradient (G) | 4915.66 | 4957.85 | 4942.81 | 4977.95 | 4932.37 | 4937.29 | 4940.55 | 4946.89 |

**Table 1. Short Term Repeatability at 5 Amps (10 Measurements)**

| | BOSS BANG BANG | Danfysik 896 3 pc Ramp | Trim Rack EPICS | 200' Lead Trim Rack |
|---|---|---|---|---|
| Current | 0.091% | 0.033% | 0.007% | 0.003% |
| Hall Probe | 0.085% | 0.034% | 0.019% | 0.026% |
| Rotating Coil | 0.514% | 0.424% | 0.399% | 0.335% |

**Table 2. Maximum Deviations of LongTerm Repeatability at 5 Amps (3 Hour Duration)**

**3. Repeatability Measurements**

*Measurement Description*

The QX017 magnet was setup on the rotating coil stand with the P3A probe. The CAMAC electronics rack had been malfunctioning, so the newly developed Metrolab PDI 5025 stand was used to collect and integrate the rotating coil data. A Hall probe was taped to the magnet pole tip to record the local field at that location. A picture of this setup is shown in Figure 2.

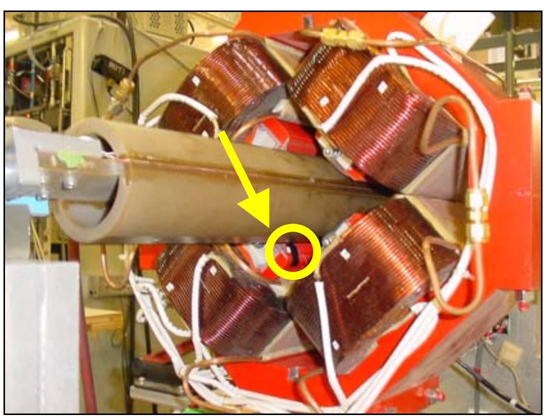

Figure 2. Hall Probe on QX017

*Short Term Repeatability*

The magnet was cycled through two hysteresis loops and set to 5 amps according to the specific control system being tested. The Hall probe and rotating coil data was recorded. This process was repeated 10 times on each of the four systems, to obtain results related to the sort-term repeatability of the specific control system. Table 1. shows the normalized standard deviation (Sigma) as well as the maximum, peak-to-peak deviation (Max) for the current, Hall probe and rotating coil measurements. The current repeatability on all four systems met or exceeded the $1 * 10^{-3}$ repeatability specification. The actual magnet performance however was quite different and only met, or came close to meeting, specification on the trim systems. These measurements show that the maximum worst case short term repeatability on the rotating coil stand was ~0.3% or ~15 G out of 5000 G gradient integral.

*Long Term Repeatability*

To quantify the system performance over a long period, the magnet was cycled through two hysteresis loops and set to 5 amps where it dwelled for three hours. Hall probe and current readings were taken every 5 seconds, while rotating coil measurements were taken every 5 minutes over the three-hour period. The Trim Jr. system was not considered during this set of measurements.

Table 2. shows the maximum deviation of individual systems over the course of the three hour measurement. The Trim system, even with an extra 200' of leads added, outperforms the

Danfysik and BOSS systems in all aspects of the measurement. In this long term measurement, the rotating coil stand did not reproduce as well as it did in the short-term repeatability measurements, with the maximum worst case long term repeatability being ~0.5% or 25 G out of 5000 G gradient integral.

## 4. Setability Measurements

*Measurement Setup*

The setability measurement used each of the four control systems previously described to cycle the magnet through two hysteresis loops prior to setting each individual measurement current. A set current of 8.9 amps was used for the first measurement, then the current was set to 8 amps and continued decrementally in one amp steps to the bottom of the curve, –9.9 amps, recording Hall probe and rotating coil data at each current along the way. After the –9.9 amp measurement, the magnet was again cycled through two hysteresis loops and set to +9.9 amps for the final measurement.

One measurement was taken that did not use the current setting method described above, and is labeled *BOSS (original protocol)* in Figure 3 and 4. This method used the same protocol on which the QX magnets were originally measured. This protocol is identical to the one described above but hysteresis was only cycled prior to the first and last set currents (8.9 and +9.9 amps), hysteresis was not cycled at points in between the first and last set current.

*Measurement Results*

The results obtained from these measurements are shown in terms of difference from linearity, with respect to some particular slope, for Hall probe and rotating coil data, Figures 3 and 4 respectively. Both Hall probe and rotating coil data sets show similar linearity differences among the systems. The finer precision of the Hall probe is evident by the smoothness of the curves with respect to the rotating coil.

These measurements show that the field is not settable across platforms, meaning one cannot measure the magnet on a given system and expect to get the same result using a different system. The data not only shows that a systematic offset occurs between systems, but because the curves are not parallel, there also exists a slope difference to the data typical of hysteretic effects.

Of note, in operation it is practical to run hysteresis prior to setting field in the quadrupoles. Hysteresis was not cycled prior to each set current during the original QX production measurements due to time constraints.

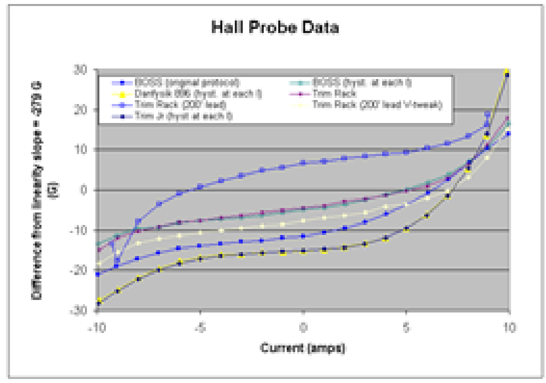


Figure 3. Linearized Hall Probe Data

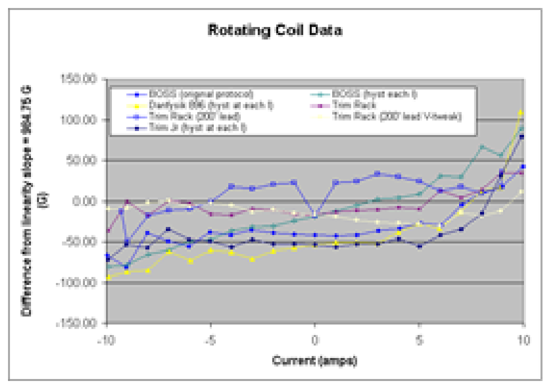


Figure 4. Linearized Gradient Integral Data

## 5. Difference Measurements

*The Difference Method*

The measurement scope continued to expand into using the 2" diameter, single wire, long probe, to perform difference (bucked) measurements on the QX magnets. By spinning a probe in two magnets simultaneously, wired with opposite polarity, one is able to characterize the relative strength difference between the two magnets. This method improves signal to noise for each measurement and reduces the variability in conditions [4]. By knowing the absolute strength of one of the magnets, in principle, one can determine the absolute strength of the magnet that is bucked against it.

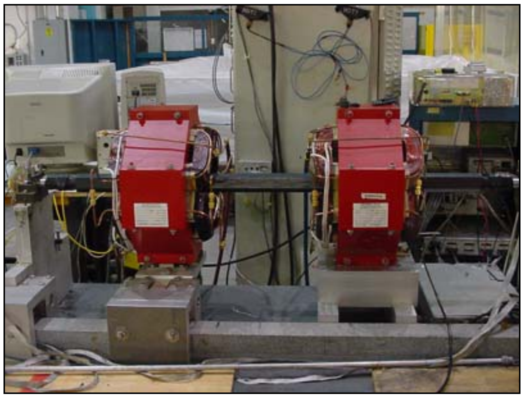

Figure 5. Bucked Measurement Setup, P2B (QX075 – QX026)

*Measurement Setup*

These measurements were made using three QX quadrupoles: QX026 as the standard magnet (stationary), QX043 as the reference magnet (moveable) and QX075 as the subject magnet (also moveable). For this difference measurement, the stationary magnet, QX026, was blocked up, for lack of a second alignment fixture, at the motor end of the rotating coil stand and aligned to the measurement probe. A moveable magnet, either the reference magnet or the subject magnet was then set on the alignment fixture and aligned to the probe opposite the stationary magnet. The moveable magnet was wired according to standard convention with the supply lead (positive lead) connected to terminal number one on the magnet's terminal strip. The stationary magnet was then connected in series with the return lead of the movable magnet that was attached to terminal two of the stationary magnet's terminal strip. The result of measuring magnets in this configuration was a difference in gradient integral ($\Delta B'L$) between the two magnets being measured, essentially resulting in a net strength or weakness, one magnet to the other. This setup is shown in Figure 5.

*Measurement Results*

A series of measurements were performed using these three magnets over several days primarily in the following configurations (QX043 – QX026) and (QX075 – QX026).

The bucked measurements showed that the difference between QX026 and QX043, could be resolved to a $\Delta B'L$ of 1.85 G over the course of thirteen total measurements conducted on three individual days over a ten day time span [5].

Results with inconsistent set currents invalidated several sets of data over the course of the measurements. Further, the magnet pair of (QX075 – QX026) was inadvertently overpowered nearly 10% or 1 amp during measurements on 7-11-05. Both magnets were degaussed, but the ability to compare post-degauss data to earlier pre-degaussed data was compromised.

*Method Validation*

For validation purposes, the difference in gradient integral in this three-magnet system should work out to EQ 1. All three combinations shown in EQ 1. could be readily measured to confirm system integrity.

EQ 1. $$(B'L_{43} - B'L_{26}) - (B'L_{75} - B'L_{26}) = (B'L_{43} - B'L_{75})$$

Since however, the PDI 5025 only produces absolute (positive) integrated voltage signals, the difference measurements between any two magnets are in terms of absolute differences only. Depending on the sign of individual difference measurements in EQ 1., ($B'L_{43} - B'L_{26}$) and ($B'L_{75} - B'L_{26}$), the relative strength solution for ($B'L_{43} - B'L_{75}$) should work out to one of two solutions shown in EQ 2.,

EQ 2. $$|B'L_{43} - B'L_{26}| - |B'L_{75} - B'L_{26}| = (B'L_{43} - B'L_{75}) \quad \text{or} \quad (B'L_{43} + B'L_{75})$$

The exact sign convention, to satisfy EQ 1., could have been determined by the V vs t profile of the stationary quadrupole when compared to the V vs t profile of a difference measurement, or by comparing the phase relationships, but time was not spent to make that determination.

*Validation Measurements*

After degaussing QX026 and QX075, all three magnets were remeasured on July $13^{th}$ in an effort to confirm system integrity as stated above. At 5 amps, the measurements revealed that:

$(B'L_{43} - B'L_{26}) = 66.4$ G

and

$(B'L_{75} - B'L_{26}) = 60.5$ G.

Therefore, if both differences have the same sign,
$(B'L_{43} - B'L_{26}) - (B'L_{75} - B'L_{26}) = (60.5 - 66.4) = 5.9$ G

or if the differences have opposite signs,
$(60.5 + 66.4) = 126.9$ G

But when $(B'L_{43} - B'L_{75})$ was measured directly,
$(B'L_{43} - B'L_{75}) = 66.4$ G

This result does not directly validate these difference measurements. One, of several, possible explanations for the discrepancy is a systematic offset in the integration. If the digital integrator consistently produced a 60.5 G B'L offset, then one could subtract this number from all results and the measurement would close out exactly. If this were the case, the difference across all three magnets would be on the order of 6 G or 0.06%.

More investigation will be performed regarding the difference measurement method to find why the results were not directly consistent.

## 6. Some Performance Variables

Much discussion was generated concerning the root cause(s) of the observed irreproducibility that begun the investigation leading to these measurements. Several possibilities were identified specific to the JLab infrastructure, and mentioned here, intermixed with operational concerns inhibiting the absolute setability of any given magnet. These points are listed only as good general information and to convey practical operational problems that can degrade or inhibit magnet performance.

1. Inadequate voltage available for powering quadrupoles based on distance from a power supply, particularly when the coils reach operating temperature (resistance concerns).
2. Varying lead lengths across magnets (one magnet could have 25 feet of leads while another could have 250 feet)
3. Impulse sag, from cycling quadrupoles in a trim rack after setting adjacent quadrupoles in the same rack
4. Operational concerns (were magnets restored exactly how they arrived at their set point)
5. Differences in current output across various trim cards
6. Current setting protocol (ramp rate, dwell time and overshoot)

## 7. Conclusions

1. The P3A probe was repeatable over a three hour period to 25 G total variation out of a 5000 G B'L, and in short term measurements to 15 G total variation out of 5000 G B'L.
2. The difference measurements were repeatable over a ten day period to 2 G or 0.02% of full strength field.
3. More investigation is required in performing difference measurements since they did not close out according to the validation principals.
4. The trim control systems exhibited the best performance and were repeatable on the $1*10^{-4}$ level while the BOSS and Danfysik repeated on the $1*10^{-3}$.
5. Adding ~200 ft of cabling changes the offset of the absolute integrated gradient profile of the quadrupole ~15 G.

## 8. Comments

1. Probe P3A was repeatable over the span of several days to +/- 50 G, or +/-0.5%. P3A had not gone through a calibration process prior to theses measurements to provide a tolerance on absolute gradient integrals. Such calibration could have been accomplished by several methods. One method, measuring against a known permanent magnet quadrupole, has been budgeted for several fiscal cycles, but not funded.
2. A system for specifying magnetic measurements requirements should be adopted and should communicate the requirements in a manner that is clear, consistent, documented and readily available for those concerned to access.
3. With less than $40k in hardware and a one year commitment to build a measurement stand capable of $1*10^{-3}$ absolute measurements, the $80k investment in measurements performed at STI Optronics could have been negated and the JLab MMF would have been left with greatly improved infrastructure.

## 9. References

[1] D. Douglas, "Error Estimates for the IR FEL Transport System", CEBAF-TN-96-035, July 15, 1996, Table 5. page 39.
[2] M. Tiefenback, Private Communication

[3] Ibid.
[4] L. Harwood, “Beam Transport Magnet Measurement”, CEBAF Tech Note 187, November 27, 1989
[5] Tommy’s files M:\MagTest\DataBase\Qx\Analysis\2005\QX043_Bucked_QX026\QX075_Bucked_QX026.xls.