# Combined Function Magnet for the FEL Injector

T. Hiatt, K. Baggett, M. Beck, G. Biallas and K. Sullivan
Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

## 1. Introduction

The FEL injector was in need of a vertical corrector dipole magnet in the space limited injector beam line. It was proposed that this vertical corrector be built into the QJ Panofsky style quadrupole already resident in the FEL injector. This new corrector magnet was given the designation VT. This type of combined function magnet has been used before on several of the QT Panofsky style quadrupoles to make a GC dipole corrector. These combined function magnets are located adjacent to the GY dipole magnets in the 1$^{st}$ and 2$^{nd}$ arc.

The idea behind these combined function magnets is to power the two main horizontally oriented quadrupole coils in such a way as to produce a horizontal dipole field for vertical beam correction. In principle, this horizontal dipole field would superimpose directly on top of the existing quadrupole field that the Panofsky magnet was designed to produce.

## 2. Initial Testing

Preliminary measurements, without the presence of the quadrupole field, showed that the field integrals across the +/- 2.3 cm good field region were not sufficient to meet the dipole specification by a factor of 10. In order to flatten out the integrals across the good field region, trim coils were added to enhance the horizontal dipole field at the extremes of the good field region. The addition of four experimental, 42 turn, trim coils, powered independently of the two main quadrupole coils, did achieve consistent field integrals across the good field region to acceptable levels.

The two main horizontal quadrupole coils drive flux in opposite direction, when powered by a single power supply and functioning solely as a quadrupole. It is therefore necessary to have floating, ungrounded current source, power supplies for each horizontal quadrupole coil when superimposing the dipole field on top of the existing quadrupole field. In one horizontal coil, the current source subtracts current from the coil, and in the other horizontal coil, the current source adds current to the coil. Operationally this means that the combined function magnet will need a minimum of three power supplies to operate as a quadrupole and dipole simultaneously. One power supply would power the quadrupole proper, and the two other supplies would either add or subtract current to each of the two main horizontal coils accordingly.

The trim coils do not need to be powered on their own independent power supply, as done during initial testing, but can be run in series with the addition or subtraction currents described above. This requires modifying the turn count of the trim coils, so that the amp turn count, when powered in series with the addition or subtraction of currents in the main coils, provides the same amp turn count that was found for flat field integrals across the good field region when the trim coils were powered independently.

The trim coils, used for the VT corrector dipole, ended up with 31 turns of #18 wire held together with epoxy and wire ties. The coils were wired so that the top set of trim coils was powered in series with the addition or subtraction of the current in the top quadrupole coil, and similarly for the bottom.

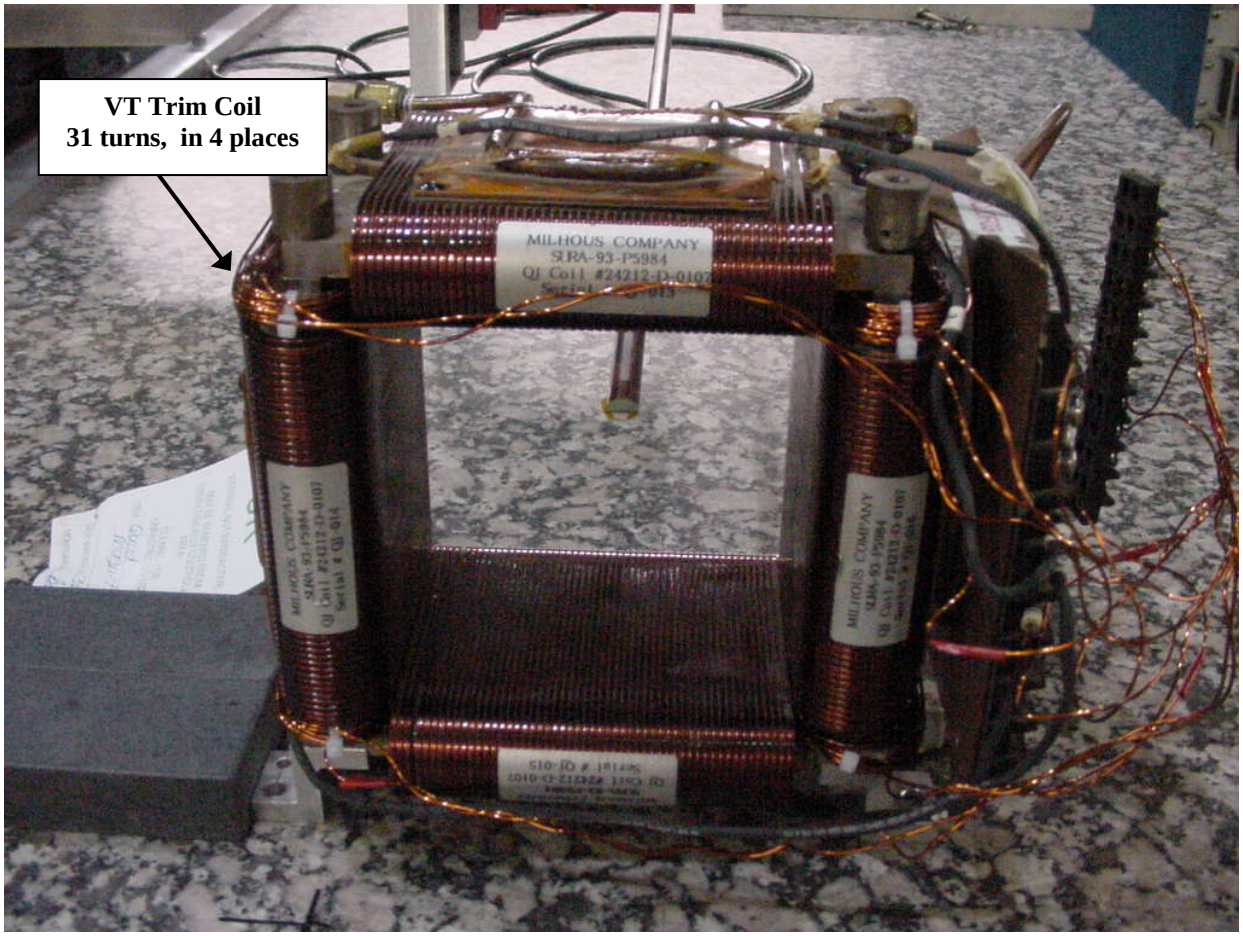


Figure 1. Combined Function Magnet with Trim Coils

## 3. Measurements

*Powering*

Measurements were made by powering the QJ quadrupole using a standard trim card power supply from the trim rack adjacent to the Injector Test Cave. Two ungrounded EMI, 36/12 BOS/S power supplies, set to current regulation mode, were used to control the two VT dipole circuits.

Setting the current in the QJ was accomplished using the standard EPICS current setting and hysteresis protocol. Setting the current in the VT was accomplished by directly setting the desired current on each BOS/S supply after the QJ had reached its desired set current. Each time the current was changed, the BOS/S supplies were set to 0 amps, and the QJ was set to the desired current, according to standard EPICS protocol. Then the

BOS/S supplies were set directly to the desired current at a ramp rate of about 1 amp/sec. The two BOS/S supplies were located across the room from each other so there was approximately a 10 second delay between setting the currents in the two supplies.

The electrical circuits were validated by using two hand held current meters (Fluke DVMs) to observe the two dipole current paths. The current meters verified that all three circuits were isolated from one another and there appeared to be no current leakage or backflow amongst the circuits. The circuit diagram is shown if Figure 3.

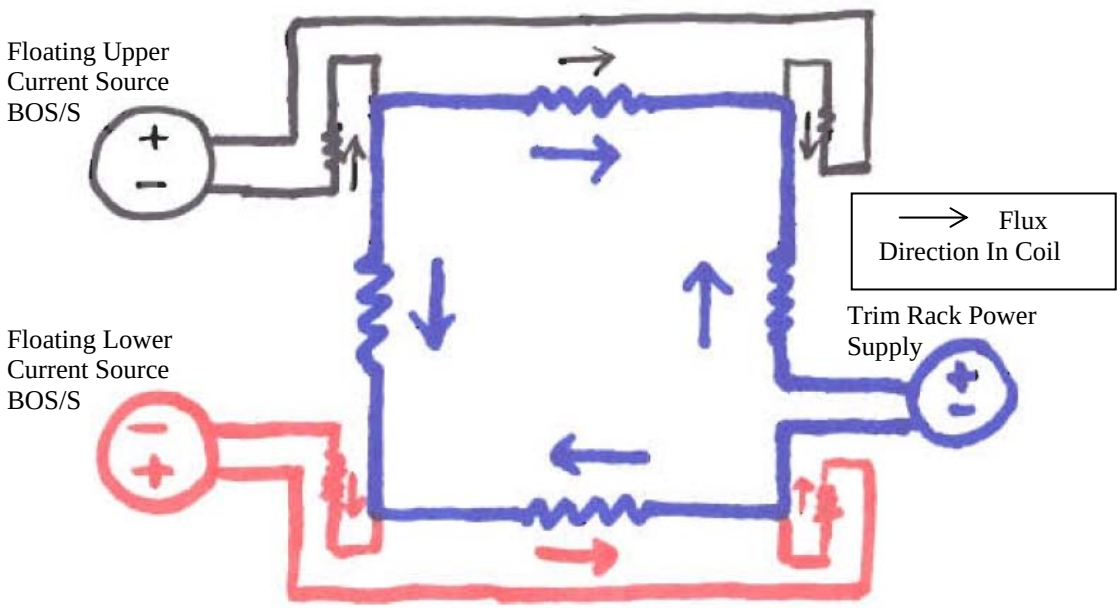


Figure 3. QJ-VT Wiring Schematic - Arrows Indicate Flux Direction Inside the Coils

*Data Taking*

Longitudinal integral measurements were made using the Stepper Stand at eleven transverse locations across a +/- 2.3 cm good field region in 0.46 cm steps, for a variety of quadrupole and dipole current settings. For each current combination the longitudinal integrals were plotted with respect to transverse position as shown in Figure 4.

*Data Analysis*

A linear fit was performed on the integrals with respect to transverse position, and a difference calculation was made to determine how well each individual integral compared to an ideal linear fit line for that data set. This difference from the linear fit is shown by the red data set in Figure 4. and is typical of all of the various current combinations. A third order, polynomial fit was made to the integral vs. position data set and the equation for that data set is shown in Figure 4. as well. The integrated gradient (quadrupole term) of the combined function magnet is shown as the linear term of the polynomial fit, and the field integral (dipole term) of the magnet is shown as the offset of the fit. Sextupole and octupole terms are also shown.

*Measurement Results*

To conserve data taking time and match the requirements of the magnets fixed position in the FEL Injector, the quadrupole was measured at both polarities up to only 40% of its nominal maximum current of 5 amps. For each quadrupole setting, the dipole corrector was measured at three discrete current settings that produce negative vertical steering (electrons steer downward). The quadrupole integrated gradients and the dipole field integrals are shown in Table 1. and Table 2. respectively for the various combinations of current settings.

Table 3. shows the quadrupole term is linear with respect to quadrupole current on the order of +/-0.1%. Further the quadrupole term, is constant with respect to the various dipole current settings, while the dipole term, is neither constant with the quadrupole current settings, nor linear with the dipole current settings

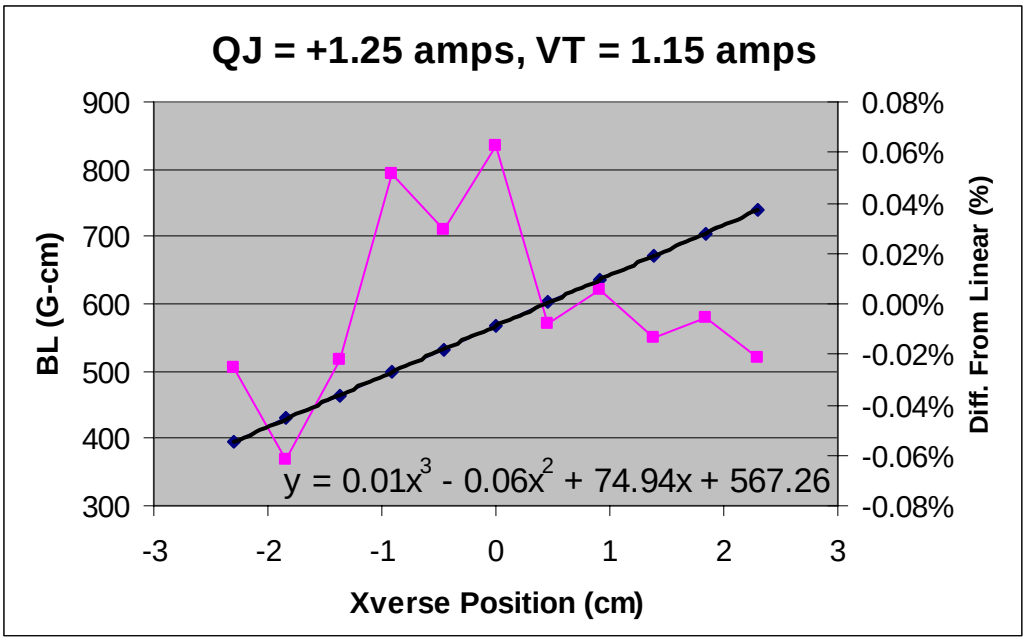


Figure 4. Difference from Linearity for transverse integrals for a given current combination.

| QJ Integrated Gradient (G) | | | |
|---|---|---|---|
| | **0.76** | **0.97** | **1.15** |
| **2** | 120.05 | 119.57 | 119.58 |
| **1.25** | 74.45 | 74.28 | 74.94 |
| **0.5** | 30.16 | 29.95 | 29.79 |
| **-0.5** | -29.9 | -29.97 | -30.06 |
| **-1.25** | -74.85 | -74.96 | -75.09 |
| **-2** | -119.88 | -119.69 | -119.98 |
| **Quad Setting (amps) - Vertical Column** | | | |
| **Corrector Setting (amps) - Horizontal Row** | | | |

Table 1. Quadrupole Integrated Gradients

| VT Field Integral (G-cm) | | | |
|---|---|---|---|
| | **0.76** | **0.97** | **1.15** |
| **2** | 359.8 | 469.25 | 563.29 |
| **1.25** | 356.84 | 464.43 | 567.26 |
| **0.5** | 359.67 | 469.41 | 571.08 |
| **-0.5** | 363.34 | 481.69 | 573.11 |
| **-1.25** | 376.16 | 485.1 | 576.93 |
| **-2** | 378.52 | 488.59 | 581.03 |
| **Quad Setting (amps) - Vertical Column** | | | |
| **Corrector Setting (amps) - Horizontal Row** | | | |

Table 2. Dipole Field Integrals

| QJ Difference From Linearity (%) | | | |
|---|---|---|---|
| | **0.76** | **0.97** | **1.15** |
| **2** | -0.179% | -0.110% | 0.105% |
| **1.25** | 0.374% | 0.265% | -0.146% |
| **0.5** | -0.164% | -0.161% | 0.028% |
| **-0.5** | -0.044% | -0.050% | -0.031% |
| **-1.25** | -0.033% | 0.074% | 0.043% |
| **-2** | 0.045% | -0.018% | 0.001% |
| **Quad Setting (amps) - Vertical Column** | | | |
| **Corrector Setting (amps) - Horizontal Row** | | | |

Table 3. Quadrupole Difference From Linearity

## 4. Conclusions

The combined function QJ – VT magnet seems to be a workable solution for adding vertical steering to a congested injector beam line. In operation this combined function magnet will use three independent, ungrounded current source power supplies. The measurements described above showed the power supplies to be electrically isolated and capable of powering the magnet in the desired manner. With the addition of the trim coils, the QJ quadrupole field was constant across the various dipole settings and was linear to about +/- 0.1% across its quadrupole current settings. The VT corrector did not perform as well and the dipole field was not constant with respect to quadrupole settings to +/- 2.5% and was not linear with respect to its dipole current setting to a maximum of 3%. Since the VT will be set periscopically, there will be no further investigation into the inconstant behavior of the VT dipole.