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# FNAL Superconducting Quadrupole Test

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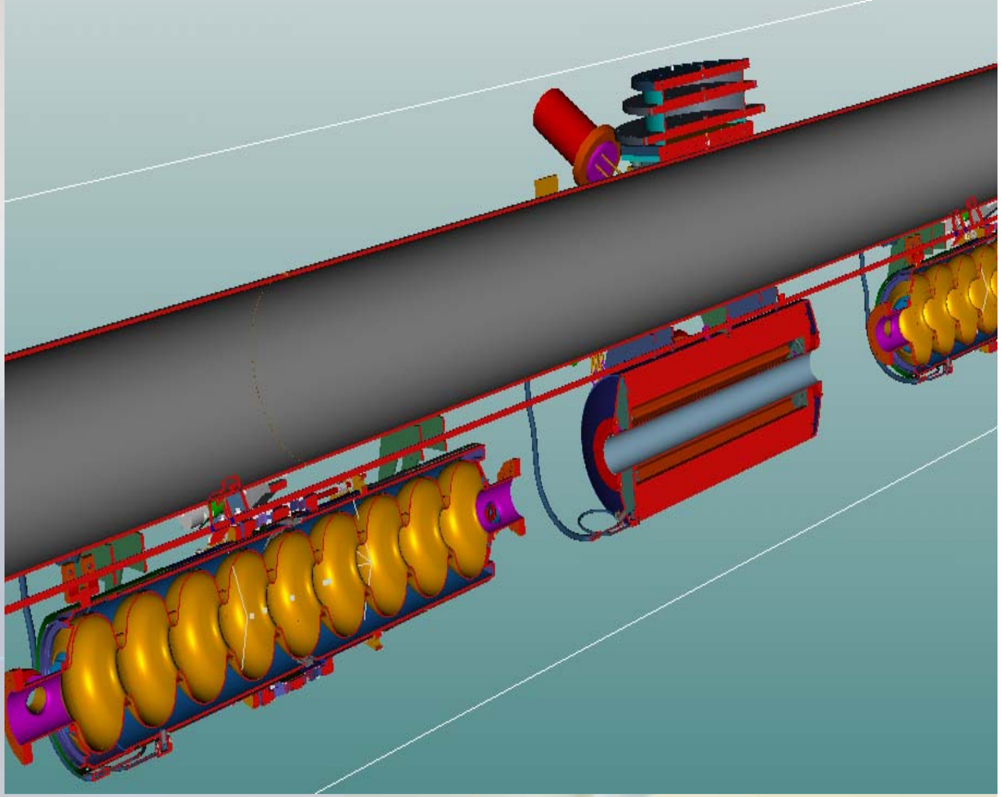
# Outline

- LC Superconducting Quadrupole
- Quadrupole Model Design
- Model Fabrication
- Rotational Coil Tests
- Fixed Probe Tests
- Test Results and Plans

# LC Superconducting Quadrupole

**The first model of superconducting quadrupole for Linear Accelerator was designed, built and tested at Fermilab. The quadrupole has a 78 mm aperture, and a cold mass length of 680 mm. A superferric magnet configuration with iron poles and four racetrack coils was chosen based on magnet performance, cost, and reliability considerations. Each coil is wound using enamel insulated, 0.5 mm diameter, NbTi superconductor. The quadrupole package also includes racetrack type dipole steering coils. The quadrupole model was built and tested. During tests the special attention were paid on the magnetic center stability and coupling effects between dipole and quadrupole coils.**

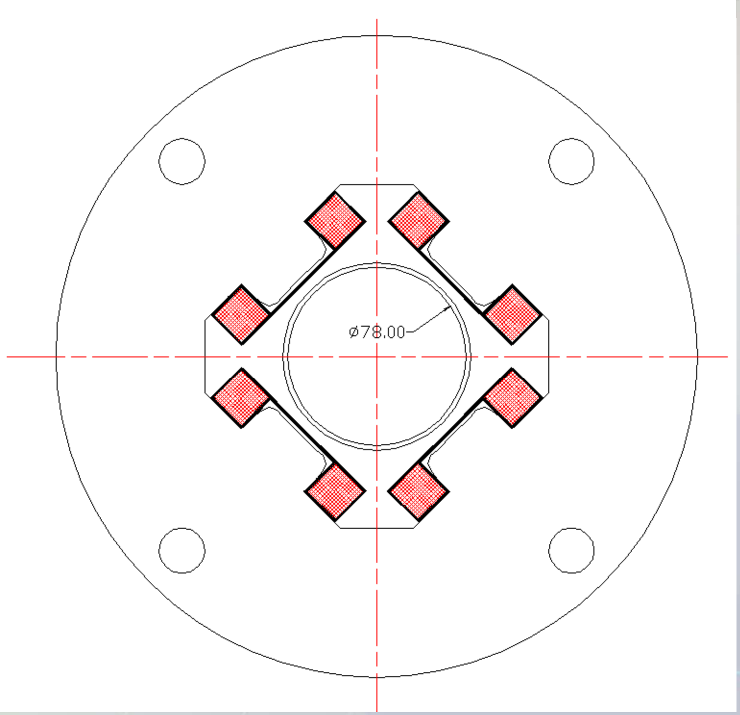


# LC Quadrupole Specification

| Parameter | Unit | Value |
|---|---|---|
| Integrated gradient | T | 36 |
| Aperture | mm | 78 |
| Effective length | mm | 660 |
| Peak gradient | T/m | 54 |
| Field non-linearity at 5 mm radius | % | 0.05 |
| Dipole trim coils integrated strength | T-m | 0.075 |
| Quadrupole strength adjustment for BBA | % | -20 |
| Magnetic center stability at BBA | micron | 5 |
| Magnetic center offset in cryomodule | mm | 0.5 |
| Quadrupole azimuthal offset in cryomodule | mrad | 0.3 |
| Liquid helium temperature | K | 2 |

**The variation of quadrupole strength will be used during BBA procedure. The 20 % decrease of quadrupole strength will cause the test beam displacement if magnet magnetic center has an offset relatively the beam center. This offset and corresponding beam deflection will be monitored by Beam Position Monitor (BPM) with submicron accuracy and this value will drive the currents in dipole vertical and horizontal correctors using closed loop feedback system. So, the quadrupole magnetic center during the accelerator operation must be at any time in the offset range of less than 5 microns.**

# Quadrupole Model Design

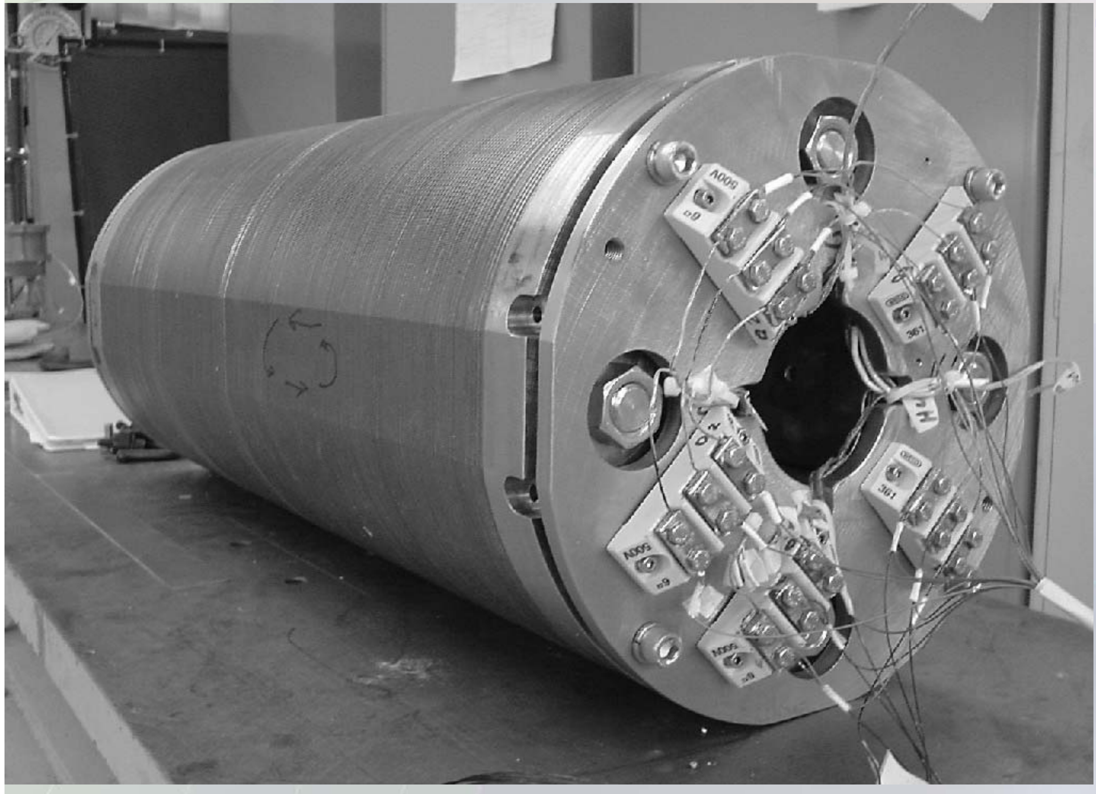


**It was chosen a "superferric" design where saturated iron poles form a substancial part of the magnetic field in the quadrupole aperture.**

## QUADRUPOLE MODEL PARAMETERS

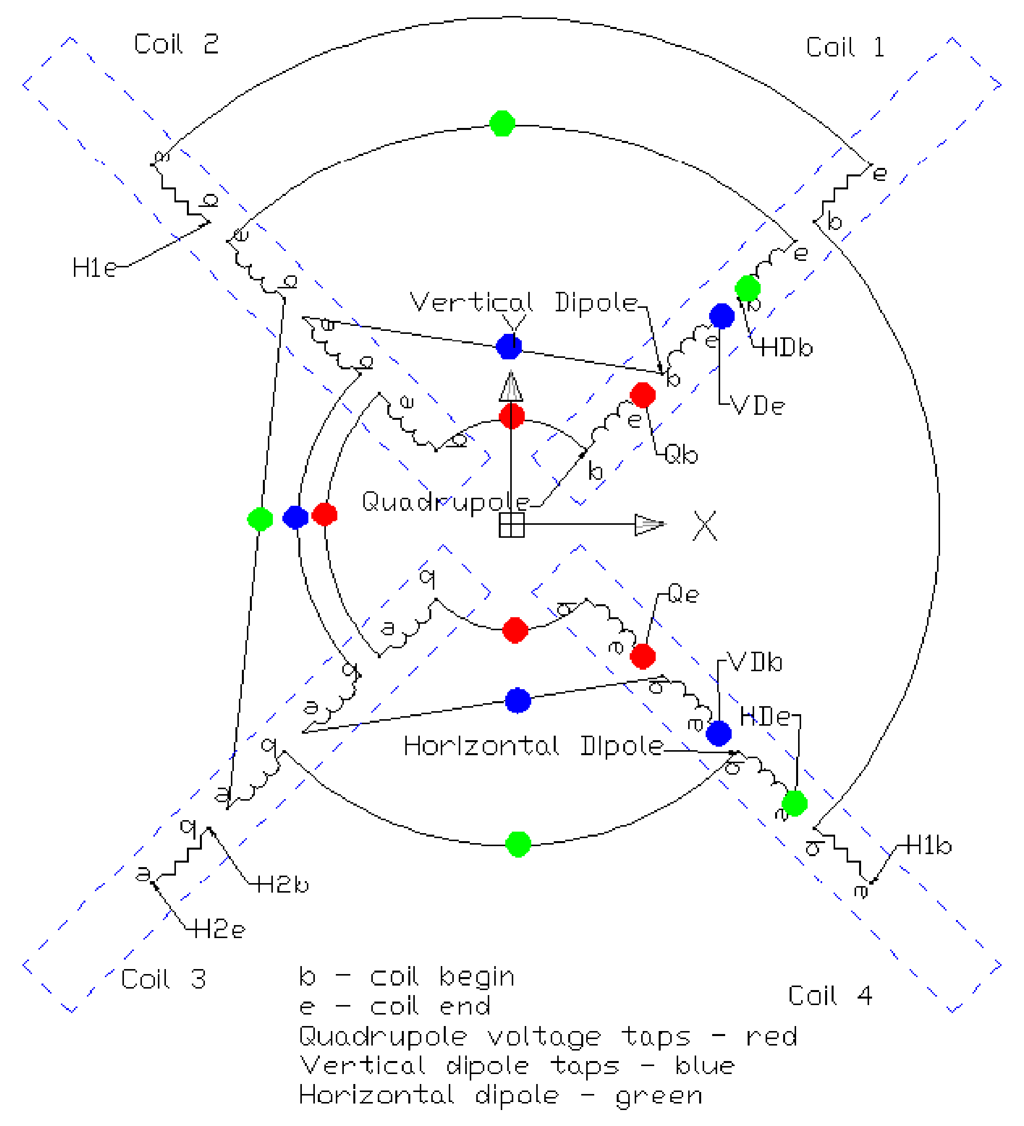
| Parameter | Unit | Value |
|---|---|---|
| Peak current at 36 T gradient | A | 100 |
| Magnet length | mm | 680 |
| NbTi superconductor diameter | mm | 0.5 |
| Superconductor filament size | µm | 3.7 |
| Superconductor critical current at 5 T and 4.2 K | A | 200 |
| Coil maximum field | T | 3.3 |
| Quadrupole coil number of turns/pole | | 700 |
| Yoke outer diameter | mm | 280 |

# Quadrupole Fabrication



**Several technical decisions were chosen to simplify magnet manufacturing: superferric magnet configuration, racetrack coils, single wire winding technique, coils wound into stainless steel channels which are used as winding mandrels and as closed molds for epoxy vacuum impregnation, laminated iron yoke with a single lamination used for cross-section (i.e., not 4 pieces), coils are assembled with yoke through the magnet aperture and welded to the yoke only at the ends for an easy model disassembly.**

# Quadrupole Wiring Scheme



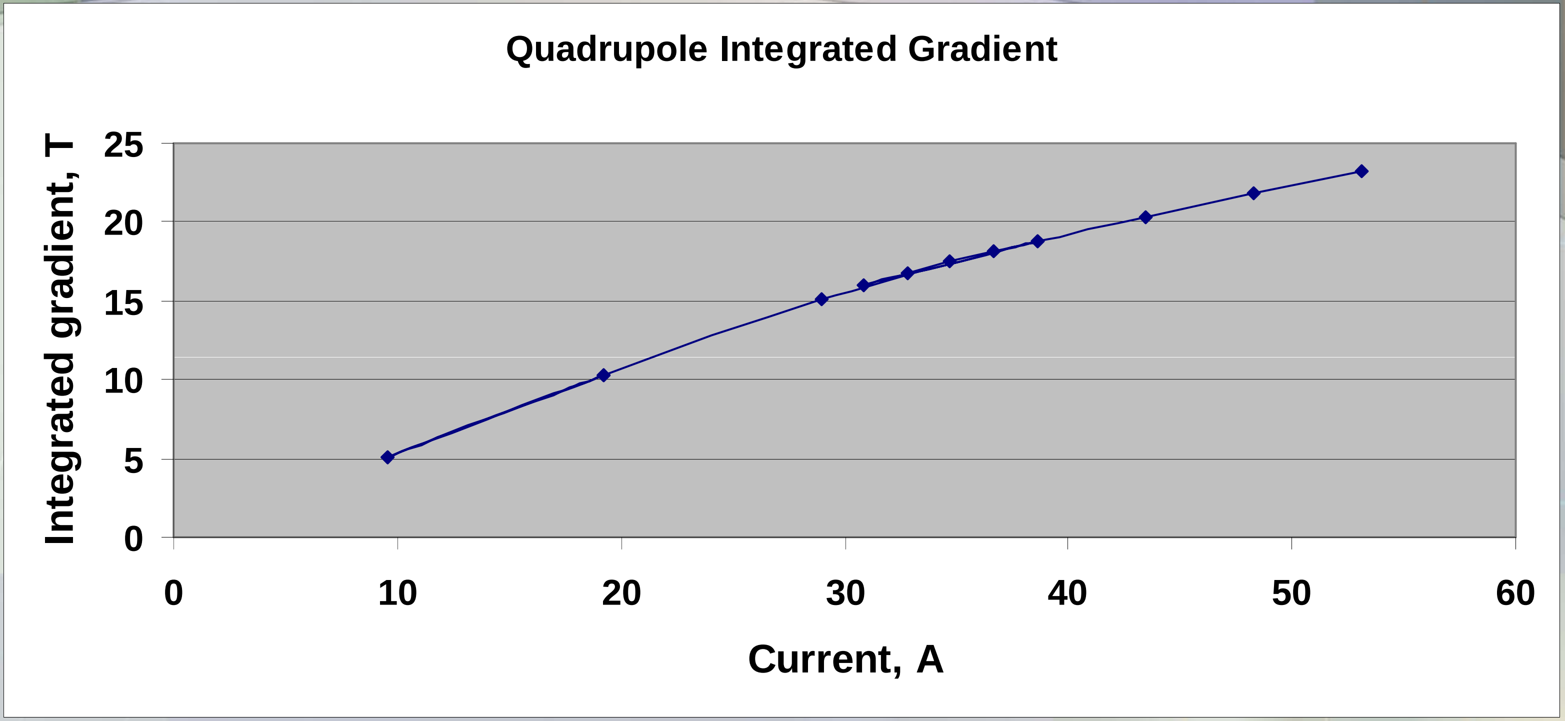
Quadrupole consists of 4 coils.

Each coil has 3 sections of NbTi superconductor: one is for quadrupole and two for vertical and horizontal dipoles.

There is also heaters in each coil wound from a stainless steel wire.

Quadrupole and dipole sections connected in quadrupole and dipole configuration as shown in figure.

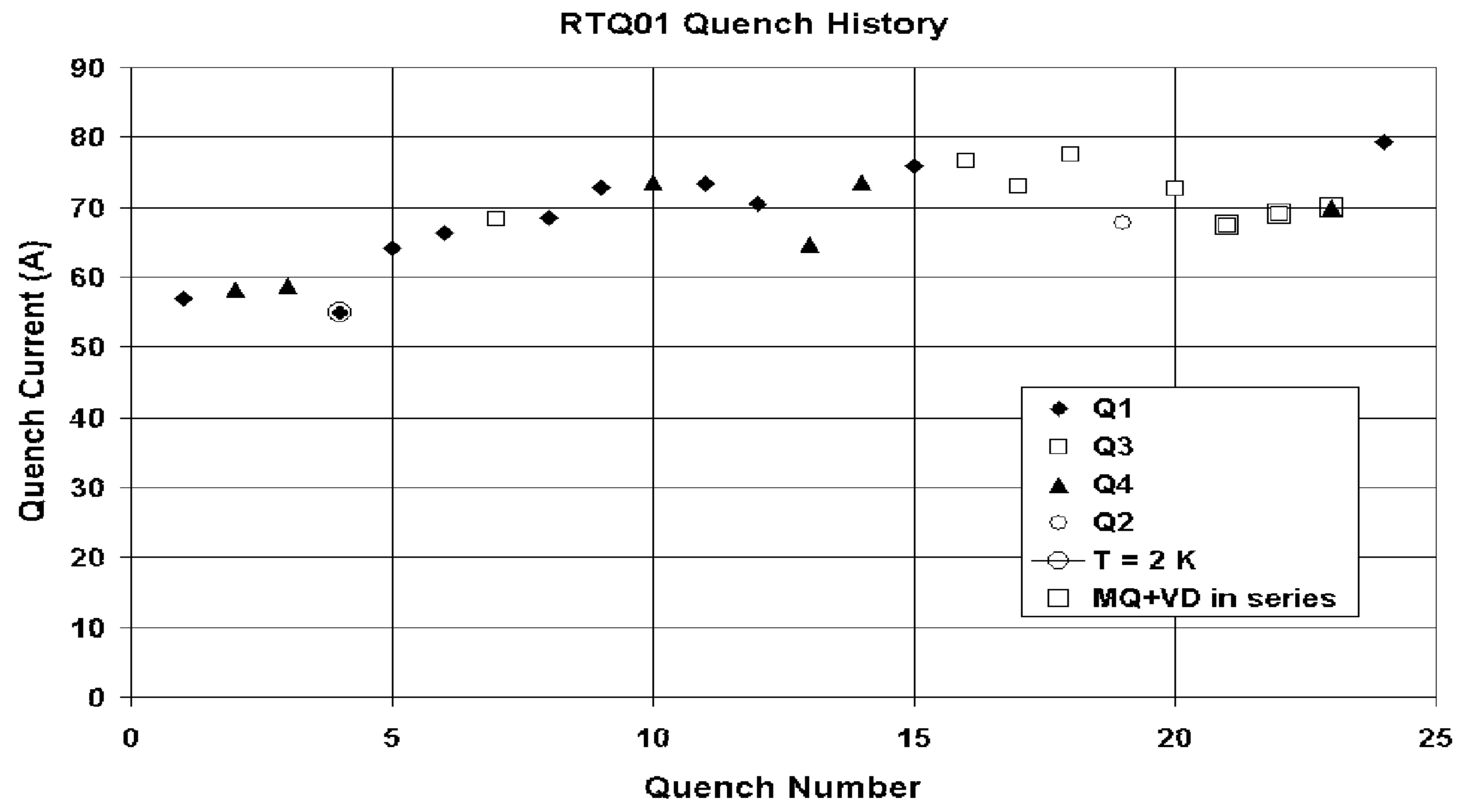
# Quadrupole Integarted Gradient



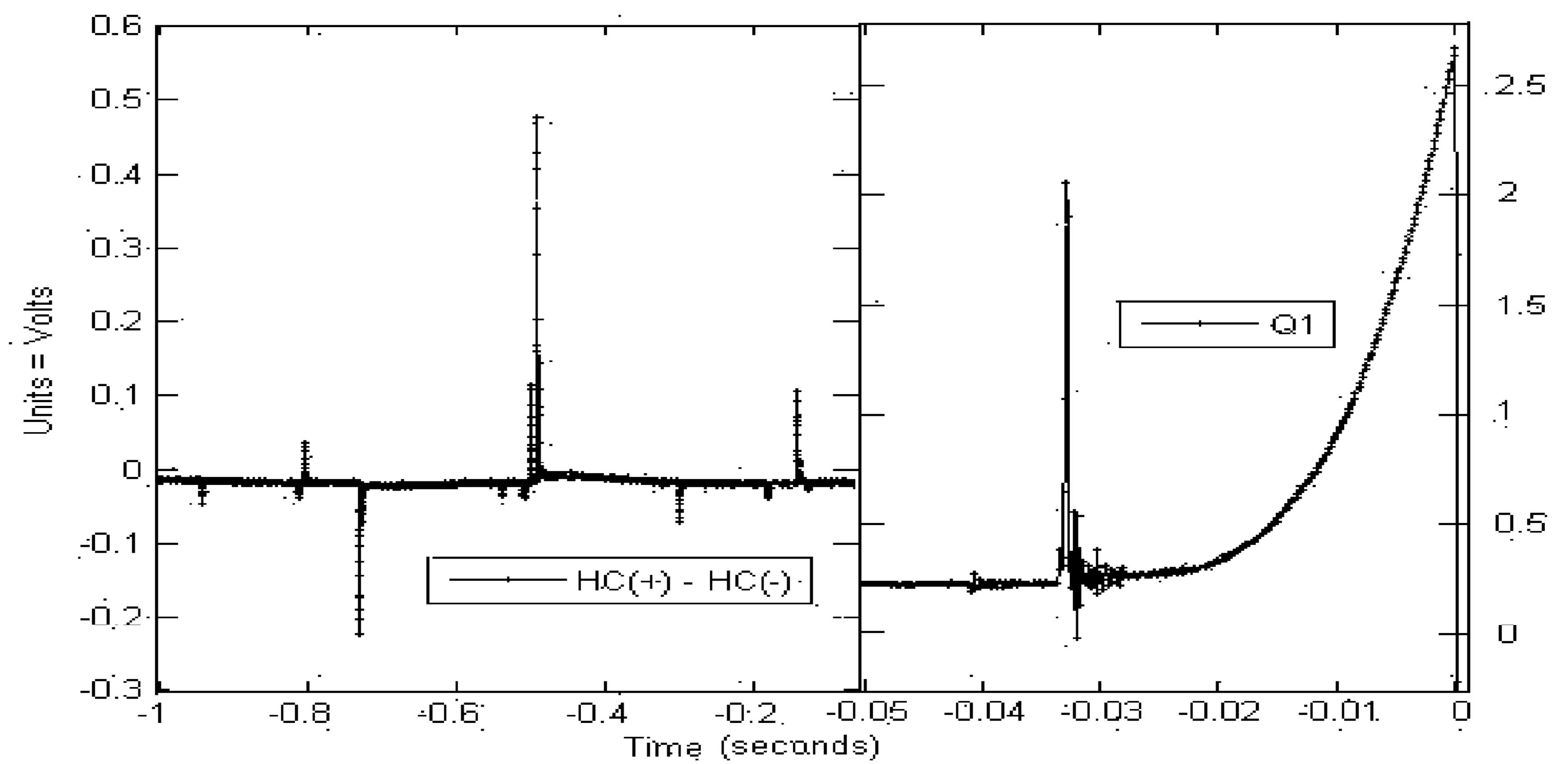
The magnet integrated gradient was measured at 700 turns/pole.

200 turns were used for dipoles. The final points at 60-80 A  are not shown.

# Quadrupole Model Quench History



# Quench Event and Location



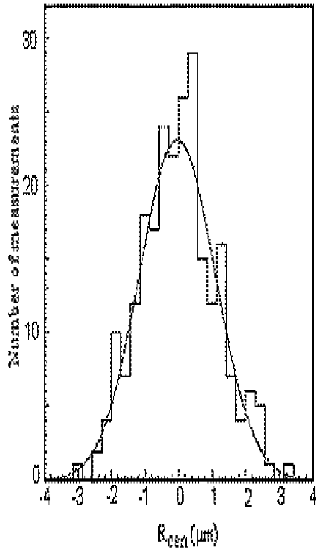
**Typical quench event (quench N24, at 79.3 A current)**

# Field Measurements by Rotational Coils

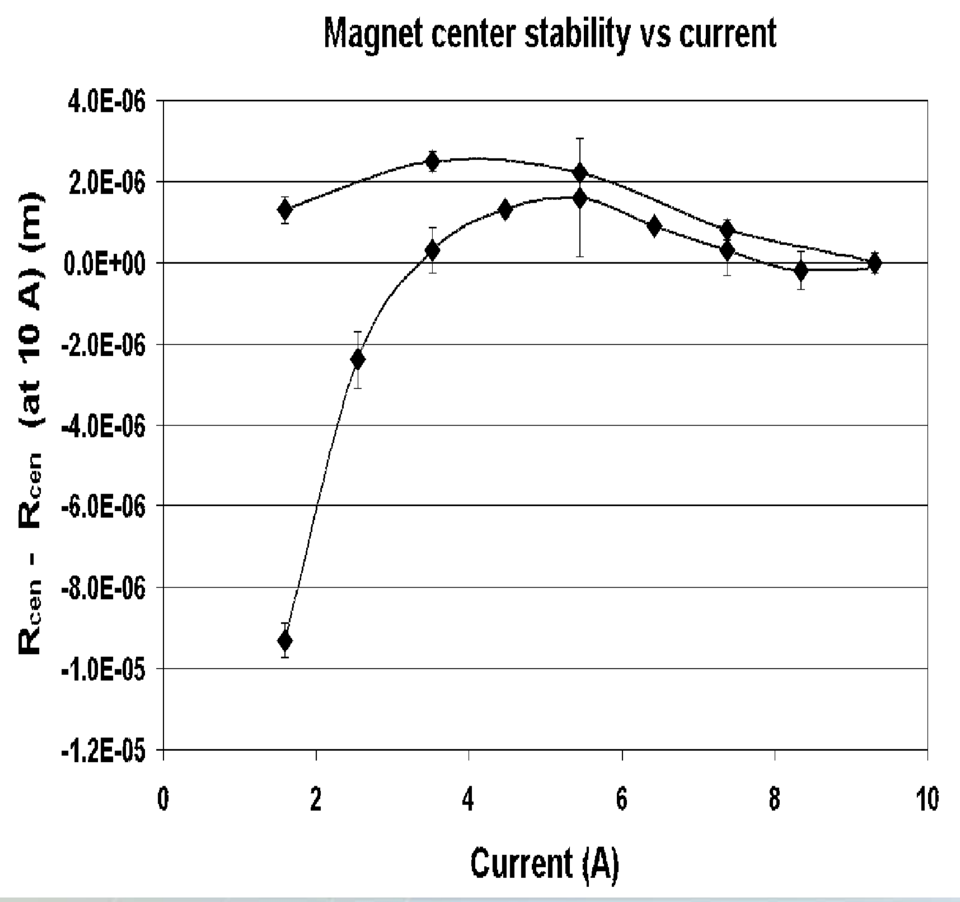
**The well known field measurement method by rotational coils was implemented for the quadrupole model measurements. The basic idea of the proposed approach is to collect data from many measurements of the magnet center position with maximum achievable accuracy (in our case in order of 12 um per measurement) for a period of time (~ 200 s). In a case when the center positions follow the Gaussian law, one can show that the mean value of the N measurements could be determined as accurately as s/√N, where s is the sigma of the Gaussian distribution.**

**The measured field is expressed in terms of harmonic coefficients defined in a series expansion given by**

$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$



# Magnetic Center Stability (1)

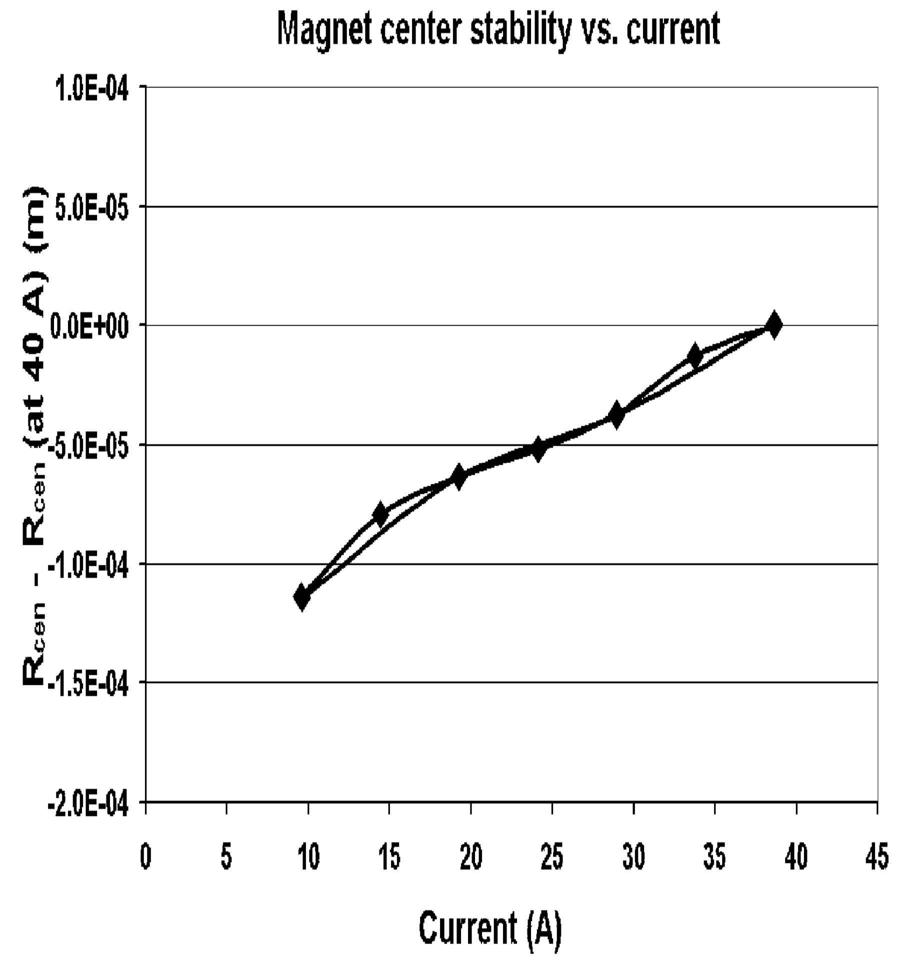


The determination of the quadrupole magnet center relative to the probe position was done using the standard technique of zeroing the dipole component assuming that it is purely generated from a probe offset.As a result, the quadrupole center coordinates, xcen and ycen were obtained. Distribution of the distance Rcen between the probe axis and the quadrupole center of the magnet for approximately 200 measurements.

The first sets of measurements were performed when the magnet was powered up to 10 A. Left figure shows the result of the quadrupole center displacement (DRcen(I) = Rcen (I) - Rcen(10A)) versus the current ramp where Rcen of the 10 A measurement was subtracted from the other currents.

*One might conclude that the magnet center moves in the limits of ±2.5 mm when the current is between 3 A and 10 A.*

# Magnetic Center Stability (2)

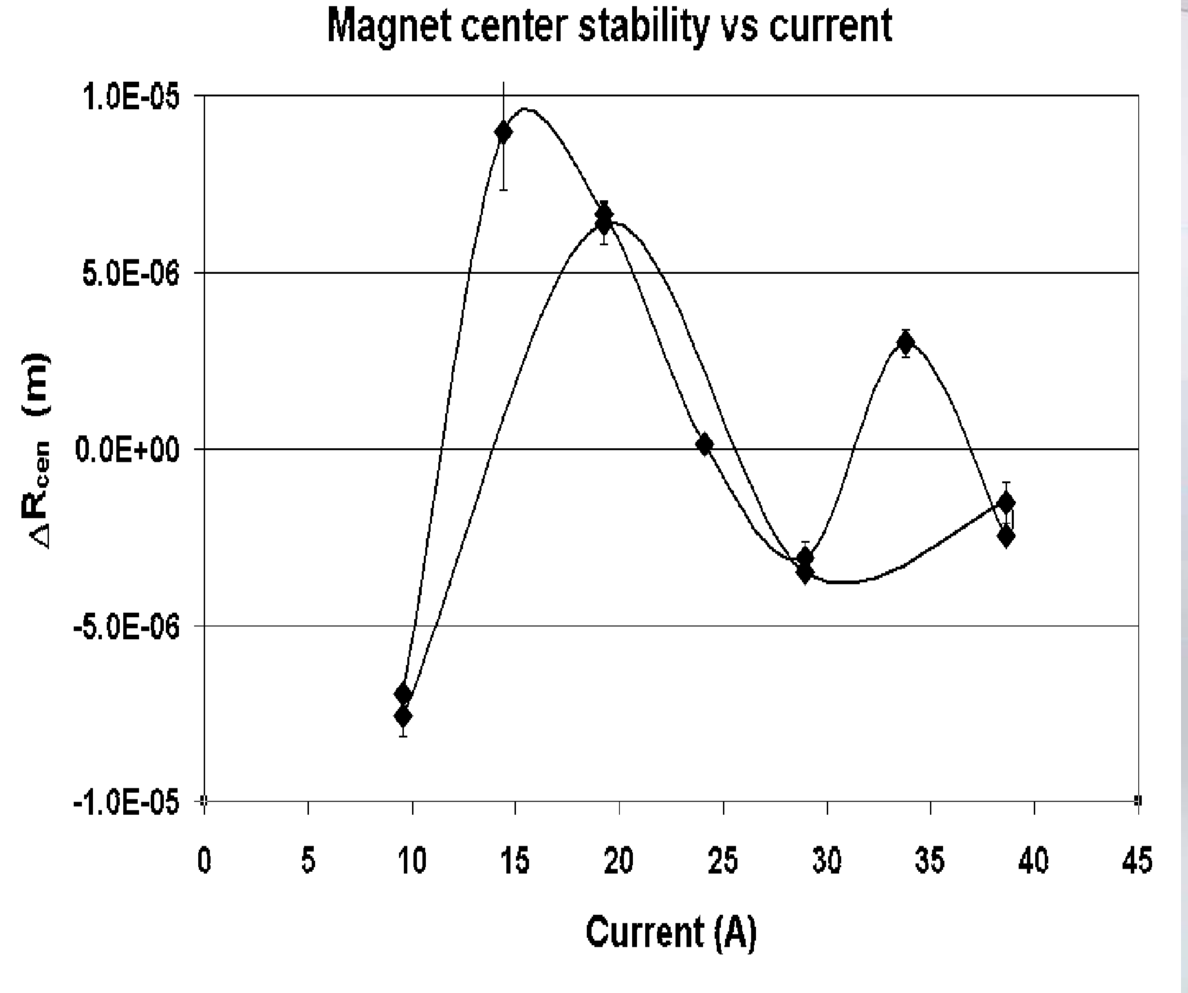


**In the next set of measurements, we increased the operational current, covering to the region of 10-40 A. The result is shown in left figure.**

***Unexpectedly, the quadrupole center moved linearly with a derivative 4 µm/A of quadrupole current. It corresponds to 8 µm at 10 A and 32 µm at 40 A during 20% current change at BBA.***

**This effect will be investigated during next tests and may be caused by the probe or quadrupole coils offsets, or unequal number of turns in the coils.**

# Magnet Center Stability (3)

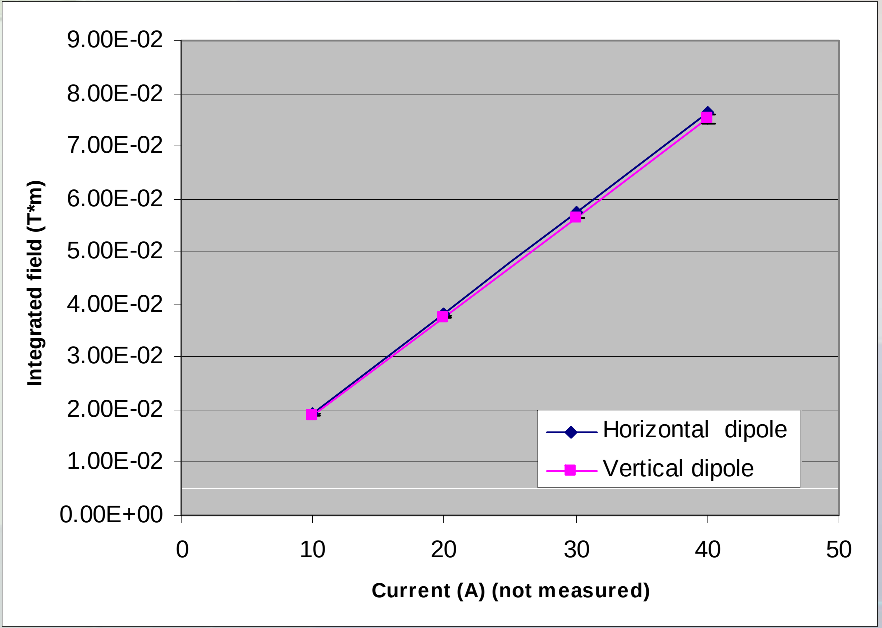


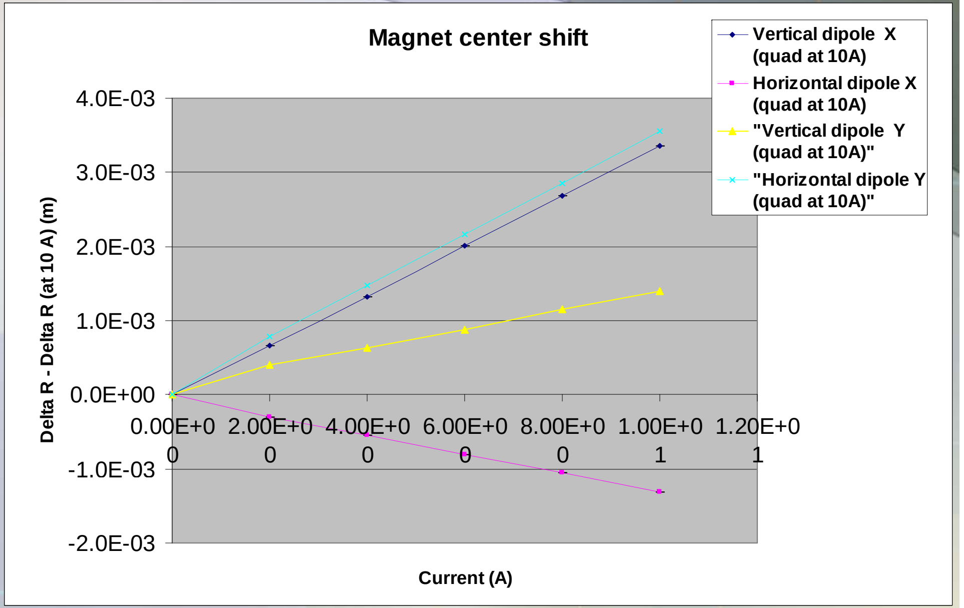
**The quadrupole package is assembled with two built-in dipole correctors: horizontal and vertical.**

**Utilizing these two correctors, one could compensate for the linear dependence shown in the above figure.**

**After subtracting this correction, the variation of quadrupole center is in the limits of ~ 8 um**

# Dipole Correctors

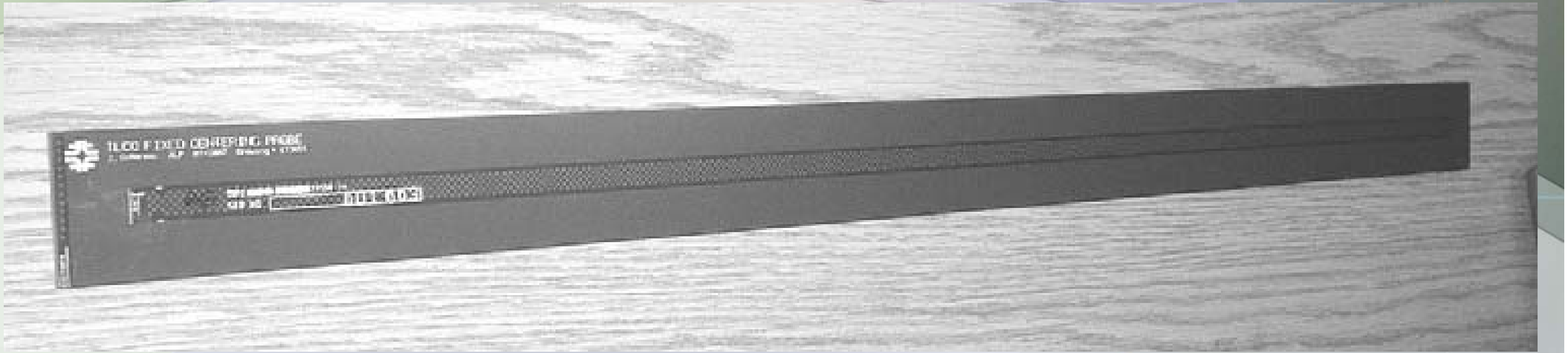




The dipole correctors generate specified integrated field 0.075 T-m at current 40 A

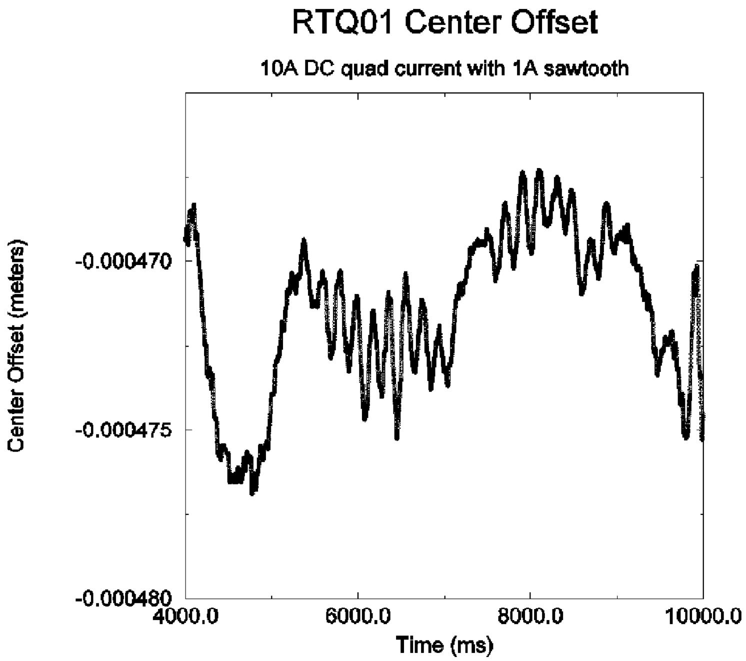
Dipoles provide linear magnetic center shift.

# Measurements by a Fixed Probe



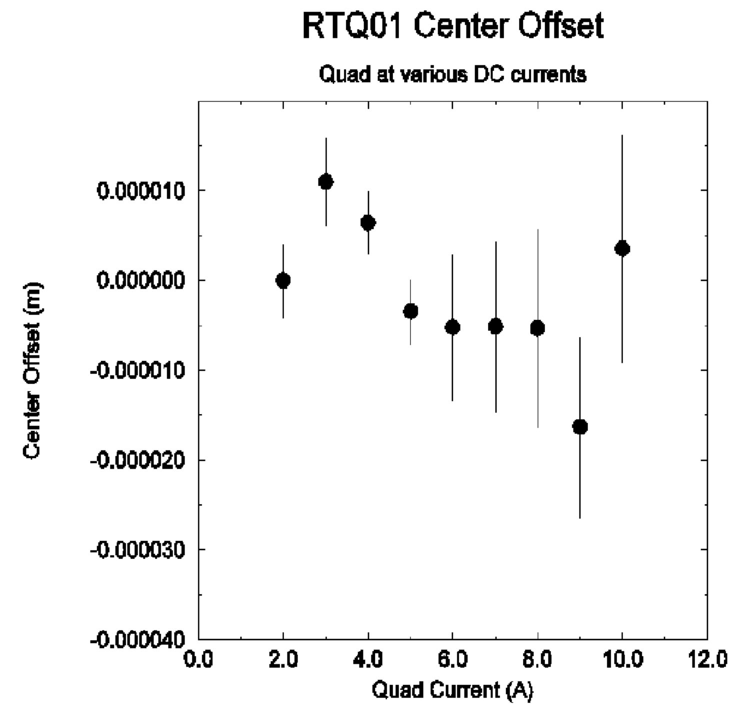
**An attempt was made to measure the stability of the quadrupole center by developing a fixed centering probe to measure flux changes during ramping of the magnet current. The probe is 0.7 m long and was fabricated on a printed circuit board with 1200 turns over 28 layers. Most layers have a spiraling pattern of traces forming simple rectangular loops. These loops are sensitive to the dipole fields present when their axis is not coincident to the quadrupole axis. This total 1152 turns on 24 layers (48 turns per layer). Nested between these layers are 4 layers having two rectangular, adjacent loops of opposite polarity. To the extent that the loops are identical, they will buck dipole fields, but be fully sensitive to the quadrupole field. The two loops each have 12 turns for a total of 48 turns over the nested layers. A photo of the probe is shown below. The total trace length on the board is over 1700 m.**

# Fixed Probe Accuracy



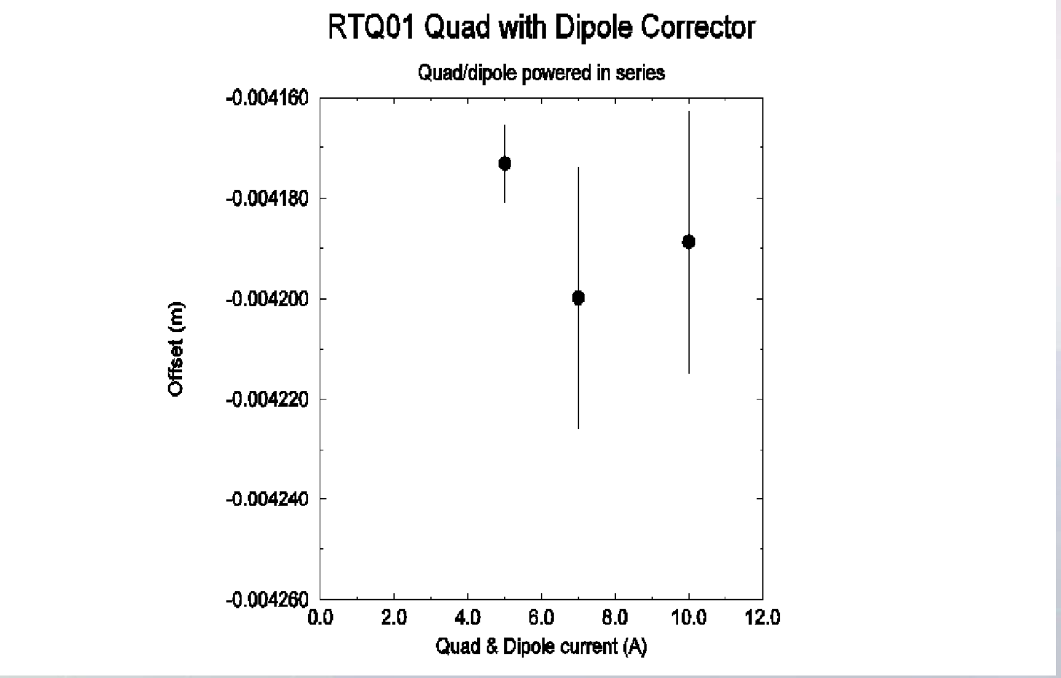
**Close examination of the offset calculated from the flux ratio (left figure) shows that it additionally contains a periodic signal of amplitude ~5 microns and frequency 4-5Hz. This is thought to be caused by ground vibrations from the nearby central helium liquefier plant; these periodic vibrations have been observed previously in the building.**

# Center Stability. Fixed Probe (1)



**The center stability for quadrupole only data is shown in left. The data seems to show some shifts at the level of 10 microns, but the error bars are also at about this level for the higher currents.**

# Center Stability. Fixed Probe (2)



**With the vertical dipole corrector powered in series with the quadrupole, the center stability is shown in left. Note that the dipole can add a very large offset to the quad but because of the series powering, changes proportionally.**

***With the FCP, center offset resolution appears to be on the order of 5-20 microns***

# Test Results and Plans

**The first Fermilab Superconducting Quadrupole for Linear Accelerators was built and tested. The test results show:**

***-Low superconductor magnetization effects because of small superconductor filament size. Measured magnetic center shift ±2.5 mm at currents 3 A - 10 A;***

***-Large influence on the results probes offsets;***

***-Promising accuracy of two magnetic center shift measurement methods: rotational coils and the fixed flat probe;***

***-Useful approach to power in series dipole and quadrupole coils for investigation coupling effects and eliminating currents misbalance;***

***-Because of very large number of turns and various combinations of Lorenz forces between quadrupole and dipole coils the magnet needs substantial training;***

***-In any scenario of BBA procedure must be used programmed dipole correctors to compensate magnet offsets, magnet manufacturing imperfections, and various coupling effects.***

**The second test is planned at 2009 to continue quadrupole training, measurements at larger currents with upgraded measurement and test stand equipment to improve the setup and measurement accuracy.**