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A Rotating Coil Apparatus with Sub-micrometer Magnetic Center Measurement Stability*

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Abstract

A rotating double coil apparatus has been designed and built so that the relative magnetic center change of a quadrupole is measured to an uncertainty smaller than 0.02 micrometers (=micron, μm) for a single measurement. Furthermore, repeated measurements over about an hour vary by less than 0.1 μm and by less than 1 μm for periods of 24 hrs or longer. Correlation analyses of long data runs show that the magnet center measurement is sensitive to mechanical effects, such as vibration and rotating part wear, as well as to environmental effects, such as temperature and relative humidity. Evolving apparatus design has minimized mechanical noise and environmental isolation has reduced the effects of the surrounding environment so that sub-micron level measurement uncertainties and micron level stability have been achieved for multi-day measurement periods. Apparatus design evolution will be described in detail and correlation data taken on water-cooled electromagnet and adjustable permanent quadrupoles, which are about 350 mm in overall length, will be shown. These quads were prototypes for the linac quads of the Next Linear Collider (NLC) that had to meet the requirement that their magnetic centers change less than 1 micron during a 20% change in field strength. Thus it was necessary to develop an apparatus that could track the magnetic center with a fraction of a micron uncertainty.

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Abstract—**A rotating double coil apparatus has been designed and built so that the relative magnetic center change of a quadrupole is measured to an uncertainty smaller than 0.02 micrometers (=micron, µm) for a single measurement. Furthermore, repeated measurements over about an hour vary by less than 0.1 µm and by less than 1 µm for periods of 24 hrs or longer. Correlation analyses of long data runs show that the magnet center measurement is sensitive to mechanical effects, such as vibration and rotating part wear, as well as to environmental effects, such as temperature and relative humidity. Evolving apparatus design has minimized mechanical noise and environmental isolation has reduced the effects of the surrounding environment so that sub-micron level measurement uncertainties and micron level stability have been achieved for multi-day measurement periods. Apparatus design evolution will be described in detail and correlation data taken on water-cooled electromagnet and adjustable permanent quadrupoles, which are about 350 mm in overall length, will be shown. These quads were prototypes for the linac quads of the Next Linear Collider (NLC) that had to meet the requirement that their magnetic centers change less than 1 micron during a 20% change in field strength. Thus it was necessary to develop an apparatus that could track the magnetic center with a fraction of a micron uncertainty**.

***Index Terms*— Accelerator magnets, magnetic center, magnetic variables measurement.**

I. Introduction

THE International Linear Collider (ILC) is a proposed future international particle accelerator. It would create high-energy, 500 GeV- 1 TeV, particle collisions between electrons and positrons. Since 1994 two different accelerating technologies were being considered as the basis for an e^+e^- linear collider. The Next Linear Collider (NLC) was a proposed future electron/positron collider based on room temperature copper accelerator structures powered with 11.4GHz X-band RF. The other technology proposed to use 1.3GHz RF in niobium accelerating structures at 2K [1]. With either technology the facing linacs are tens of kilometers long, contain hundreds of quadrupoles and the beams at the interaction point must have each been compressed to a 3 nanometer thickness in order for large numbers of the electrons and positrons to interact and produce events for the particle physicists to analyze. In 2004 the international high energy physics community decided to stop design work on the room temperature linac and to adopt the superconducting accelerating technology. The superconducting linear collider is called the International Linear Collider (ILC).

The small beam emittances created in the damping rings upstream of the linacs must be preserved as the beams pass through the linacs. This is achieved by having the beams centered in the zero field region at the magnetic centers of the linac quadrupoles to within 2 micrometers (µm) for the NLC or within 10-20 µm for the ILC [2].

Conventional alignment techniques do not achieve a 1 - 10µm accuracy so linac quadrupoles in linear colliders will be aligned using a technique called "Beam Based Alignment" (BBA) [3]. Performing BBA on these quadrupoles leads to a stringent requirement on the stability of the quads' magnetic center. A BBA calibration process requires that the quadrupole strength be lowered by 20%, during which the magnetic center must not shift by more than 1 µm (NLC requirement).

The linac quadrupoles must be designed to meet this magnetic center stability requirement and to prove they have achieved it a measurement set-up must be established that can precisely measure their magnetic centers to much better then 1 µm relative precision. This precision had not previously been reached in any measurement apparatus. This paper describes the evolution, over 4 years, of a rotating measuring coil set-up developed by the Magnetic Measurements Group at SLAC which does. It was tested on various NLC prototype quadrupoles, including a water-cooled electromagnet and an adjustable permanent magnet quadrupole. They had 12.7mm diameter bores and 215.9mm core lengths [4]-[5].

II. Detailed Description of Measurement Set-up

A. Overview

A system with a rotating measurement coil, supports for the ends of that coil, support for the magnet, a granite table to support all the above and electronics to read out and integrate the induced voltages has been under development since June

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2000. Continual improvements in the system have been made since then which will be described below, so that other labs faced with measuring magnetic centers to 0.05 μm precision will be warned about potential problems. The major challenge is to keep the axis of rotation of the measuring coil fixed relative to the magnet's geometric center. Fig. 1 is a photo of an already improved set-up, as it was in late 2002, measuring an NLC prototype water-cooled electromagnetic quad [4].

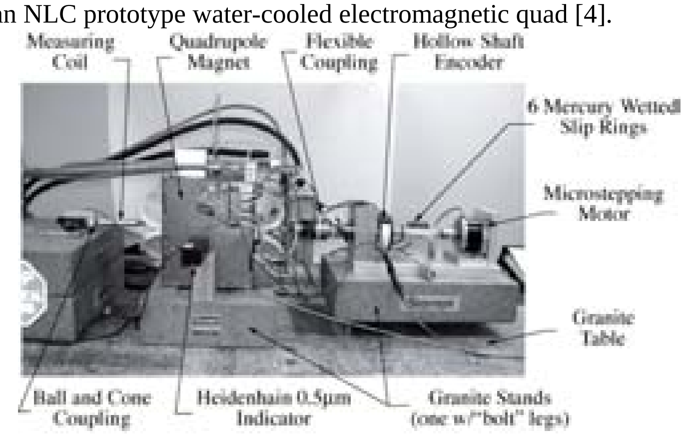

Fig.1. Rotating coil set-up in late 2002 measuring an NLC linac electro-quad.

B. Double Rotating Coil Construction

The two measuring coils are wound from *Multifilar*® 38 gauge magnet wire formed into a 10 wires-wide ribbon. Five turns of the ribbon are wound around a 355.6mm long G-10 form; slots in its ends keep the wires in place. Two identical forms are inserted into a 431.8mm long 9.525mm diameter G-10 rod such that the windings are in a plane with one side each at the center of the rod, the other sides each at a 3.8mm radius. The individual wires are soldered together to make 50 turns in each coil and the 4 leads come out near one end of the G-10 rod. The two coils can be connected in 3 different ways as described below. The rotating coil itself has not been changed since 2000. The challenge is to find the best way to connect shafts to the G-10 rod ends and cause the rod to rotate without bowing, wobbling or vibrating relative to the geometric centerline of a quadrupole. The quad itself must also be prevented from changing shape or vibrating, so that mechanical reasons for movements of the magnetic center can be distinguished from truly magnetic reasons.

C. Double Coil Connections and Signal Processing

For integrated field strength measurements the two coils are wired in series summation, so that the two coils act as one large coil. This arrangement reduces the effect of coil bowing and of coil offset on the integrated strength measurement. A stretched wire system is used to calibrate the accuracy of the strength measurement. The center and multipole harmonics measurements are done with the two coils wired in series opposition (bucked), so that the main quadrupole field is somewhat cancelled; the surviving odd terms have a greater signal to full scale ratio. The main quadrupole harmonic and all even harmonics are measured using a single winding. The ratio of the dipole strength to the quadrupole strength is proportional to the offset of the coil from the magnetic center of the magnet.

The measurement coil rotates, at 1Hz, 13 times in one direction, then 13 in the opposite direction, with only the voltages from the middle 8 rotations being used; this is repeated 4 times for one magnetic center measurement. The voltages induced in the coils as they rotate through the quad's magnetic field are sent through 6 mercury wetted slip rings to a multiplexer. This allows real-time switching between the individual coil signals or the sum of the two coils.

The selected signal goes to a *Metrolab* digital integrator, which is the heart of the coil measurement system; it integrates the coil signal with respect to pulses received from an encoder attached to the coil drive system. To have the largest signal to noise ratio the gain of the integrator preamplifier is set by turning the coil, measuring the maximum signal and then picking a gain that does not exceed 3/5 of the maximum integrator range. By averaging over 4 measurements the electronic noise and integrator drift are minimized. The coil is driven by a stepper motor and its associated driver. A GPIB Ethernet transfer box allows a computer running C language programs in *Lab Windows/CVI* to control and monitor all of the instruments of the double coil system. See the electronics diagram in Fig. 2.

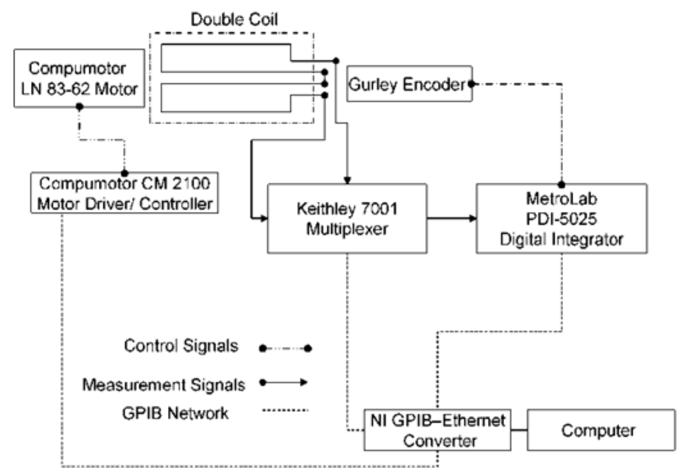

Fig. 2. Rotating coil drive mechanism and signal processing electronics.

III. Finding the Best Supports

Most of the mechanisms which lead to movements of the magnetic center are caused by variations in the temperatures of various parts of the set-up. We have 6 thermocouples measuring different parts of the set-up, their readings are stored by the computer. There are 3 separate supports in the set-up and their structure can lead to unwanted movement. So as to test the precision of the measurement system we placed the magnet on a twin rail horizontal slide so we could move it deliberately, but discovered that a change of 0.8ºC in the ambient temperature caused a 3μm shift in X. The "X position" in Fig. 3 is the horizontal distance of the measured magnetic center from the center of the rotating coil which is at X=0, Y=0 by definition. We believe the varying expansion of the spring in the slide, varying with the ambient temperature, caused the X variation. The similarity in the shapes of the two parameters' plots shows their connection.

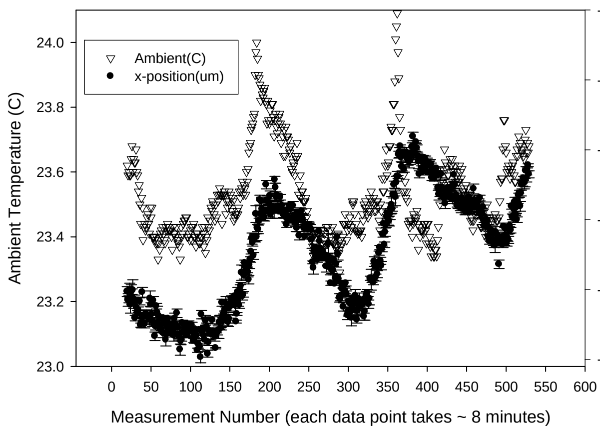

Fig 3. Electromagnetic quad in an early set-up: magnet sits on a translation slide. Slide has a long screw and a spring. Plots show delayed correlation of the X position with ambient temperature. Run lasted 2.5 days.

We took the magnet off the slide and instead used a small granite stand under the magnet, similar to the ones under the apparatus at each end of the rotating coil. It is necessary to make the heights of all parts match up, so we drilled 3 holes in the bottom of each granite stand, screwed threaded bolts in them and adjusted their protruding lengths. Fig. 4 shows that this was not a good solution when the air temperature varies.

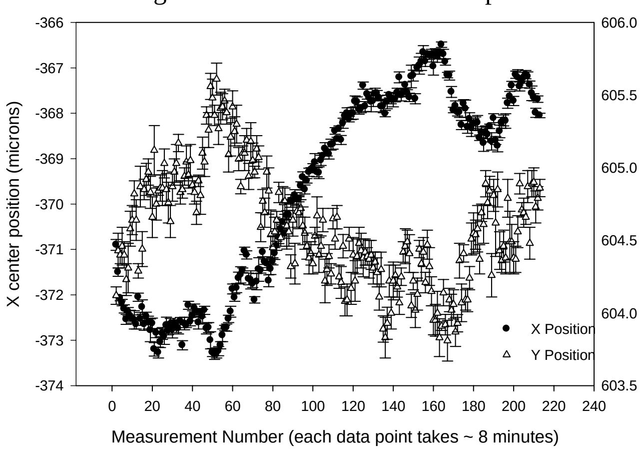

Fig.4. NLC Electromagnetic quad in a set-up with all 3 granite stands on 3 threaded bolt "legs" each. X center varies about 3 times more than Y center. Both correlated with ambient temp. Granite table was not on its rubber feet.

The ambient temperature varied by a mere 0.55ºC over 16 hours, but this was enough to cause a 6µm X variation. So we removed the threaded bolts and made the 3 main stands from a mixture of aluminium and granite blocks of matching heights and the X center stopped varying. A heavy granite table under the whole set-up is supposed to dampen the vibrations coming through the floor from nearby motors. During the run in Fig. 4 the table was standing on steel jacks instead of its extensive rubber pads. Vibrations caused the measurement errors in X and Y to triple in size, from 0.02-0.09 µm to 0.06-0.19 µm. The bolt legs did not contribute to the error size. With careful attention to the air-conditioning system in the dedicated room, the ambient temperature can be controlled to +/- 0.1 ºC.

IV. Cooling Water & Other Temperature Effects

Any temperature variation in the magnet's core will affect the Y co-ordinate of the magnetic center through the steel changing height. Temperature changes in the incoming Low Conductivity Water (LCW) are reflected in the steel and magnet's coils' temperatures. See Fig. 5, which shows a 1.5 µm/ºC effect. So we installed a 5kW water heater and *Honeywell* temperature controller which maintain the LCW temperature, as it enters the magnet's coils, to ±0.075 ºC.

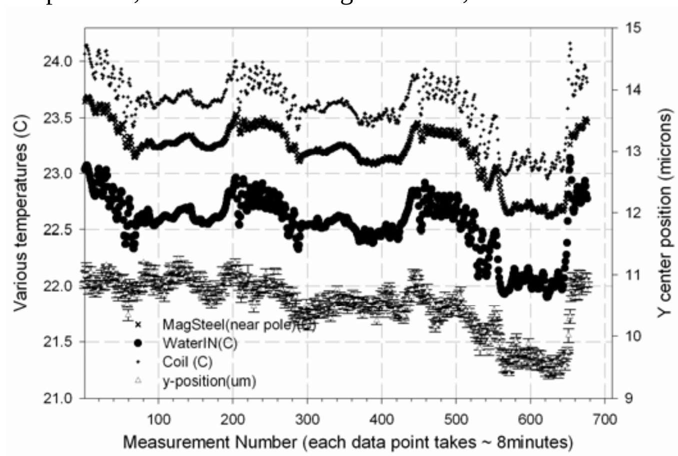

Fig. 5. NLC quad in set-up *before* incoming cooling water temperature was controlled. Plot shows effects of LCW temperature on temperatures of coil, core and measured Y center position. Run lasted 2.75 days.

We monitor the relative humidity (RH) in the room, but have no control over it. Typically it correlates with the ambient temperature, but on occasion it will change quickly while the temperature does not. In those cases we observe that both X and Y vary and correlate with the RH, for e.g. the RH changes from 44% to 29% in 3 hours and X changes by 2.4 µm. We have not ascertained the mechanism for this correlation, we suspected the G10 rod. We sprayed it with varnish to reduce its water absorption, but that had no effect.

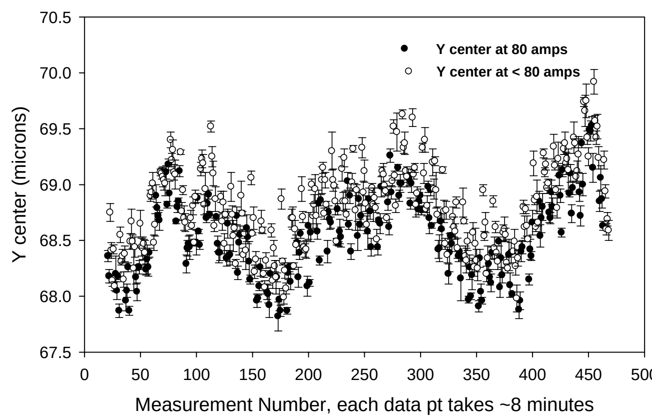

Fig. 6. NLC Electro-Quad in stable set-up. During 2.5 day long run Y center position measured during repeated BBA current variations. Plot shows set-up is capable of validating magnet's center behavior when current is varied.

With sufficiently stable temperature and RH conditions the set-up using ball & cone bearings at both ends of the G10 rod was able to track X and Y with acceptable precision as the quad's current was varied to mimic 75 BBA runs (see Fig. 6).

V. FINDING THE BEST BEARINGS

Finding a way to support the ends of the G10 rod, keeping it aligned and rotating smoothly while temperatures vary is the trickiest part of the apparatus. For 3 years we used SS balls pulled onto *Rulon* PTFE cups by the action of a bellows. The non-drive end had a small translation stage with a spring to allow thermal expansion while providing pressure on the ball. But the axial pressure on the rod causes its gradual distortion, affecting the center measurement; too much pressure caused the center to wander by several microns in 24 hours.

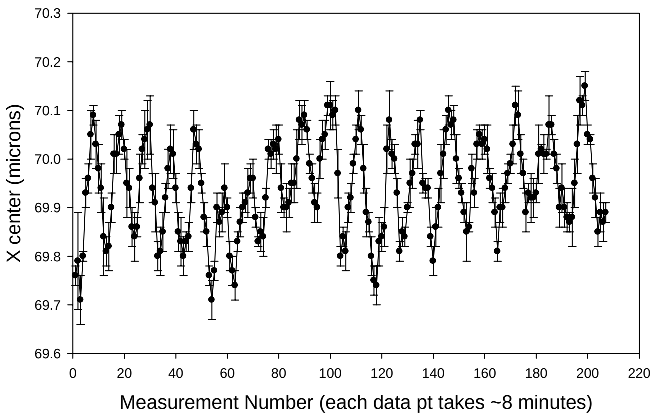

Fig. 7. Unacceptable X measurements because of imperfect ball bearing at the non-drive end of the rotating measuring coil. NLC Electro-quad in set-up.

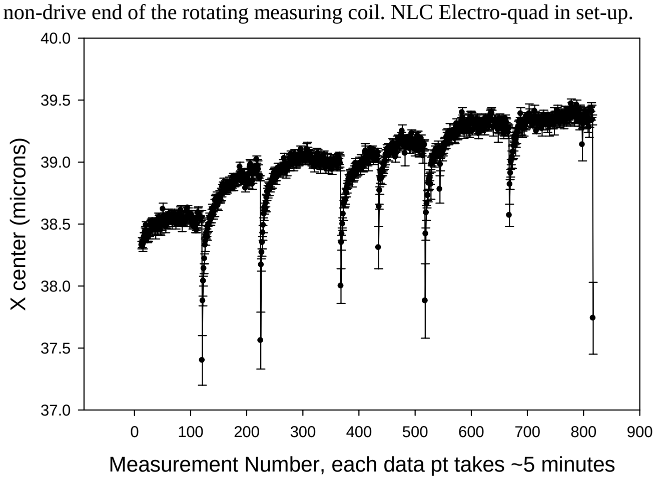

Fig. 8. Adjustable permanent magnet quad in set-up with a needle and sapphire vee bearing. Plot shows how needle jumps to a new position away from crux and works way back. Unacceptable X data because needle bearing not fixed.

So we tried some artificial sapphire miniature jewel bearings (from *Bird Precision*) which have high hardness, low friction coefficients and are not costly. There were some problems with a vee shaped jewel, into which a needle shaft attached to the G10 rod pointed. Pressure from the slide spring was needed to keep it in place, too much pressure led to the effects shown in Fig 8. So we switched to an "Olive Hole Ring" jewel with a curved inner contour, through which a cylindrical shaft sits. The shaft cannot move in X or Y and it rotates with no wobble. No pressure is used, so there is no apparent center wandering, nor jumping.

VI. BEST MEASUREMENT SET-UP

Our current set-up shown in Fig. 9 produces the excellently stable center measurements shown in Fig.10.

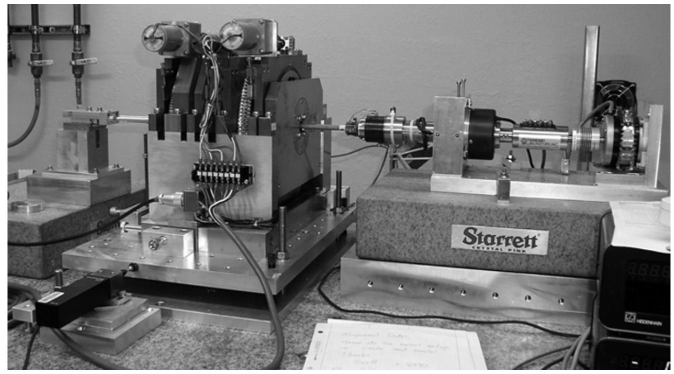

Fig 9. Adjustable Permanent Magnet Quad [5] in best set-up to date, with sapphire ring bearing on non-drive end of coil; solid supports.

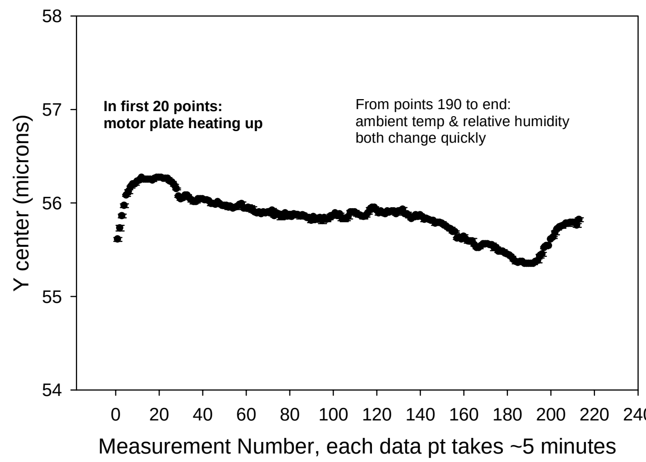

Fig. 10. Adjustable PM quad in best measurement set-up to date. Most mechanical problems been eliminated. Y measurements still influenced by apparatus temperatures and relative humidity, but they have much less effect.

VII. CONCLUSION

We have developed a magnetic center measurement apparatus working in a controlled environment that allows real magnetic effects to be distinguished from mechanical effects at a tenth of a micron level over a 1-2 hour time period, and at a 0.5µm level over approximately 12 hours.

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