SLAC-PUB-8990
January 2002

High Reliability Prototype Quadrupole for the Next Linear Collider[*]

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To be published in IEEE Transactions on Applied Superconductivity

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[*] Work supported by Department of Energy contract DE–AC03–76SF00515.

High Reliability Prototype Quadrupole for the Next Linear Collider

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[1]***Abstract*****-- The Next Linear Collider (NLC) will require over 5600 magnets, each of which must be highly reliable and/or quickly repairable in order that the NLC reach its 85% overall availability goal. A multidiscipline engineering team was assembled at SLAC to develop a more reliable electromagnet design than historically had been achieved at SLAC. This team carried out a Failure Mode and Effects Analysis (FMEA) on a standard SLAC quadrupole magnet system. They overcame a number of longstanding design prejudices, producing 10 major design changes. This paper describes how a prototype magnet was constructed and the extensive testing carried out on it to prove full functionality with an improvement in reliability. The magnet's fabrication cost will be compared to the cost of a magnet with the same requirements made in the historic SLAC way. The NLC will use over 1600 of these 12.7 mm bore quadrupoles with a range of integrated strengths from 0.6 to 132 Tesla, a maximum gradient of 135 Tesla per meter, an adjustment range of 0 to –20% and core lengths from 324 mm to 972 mm. The magnetic center must remain stable to within 1 micron during the 20% adjustment. A magnetic measurement set-up has been developed that can measure sub-micron shifts of a magnetic center. The prototype satisfied the center shift requirement over the full range of integrated strengths.**

Index Terms**—FMEA, magnet, magnetic center, reliability.**

I. INTRODUCTION

The Next Linear Collider [1] (NLC) is a proposed future electron/positron collider that is based on copper accelerator structures powered with 11.4GHz X-band RF. It is designed to begin operations with a center-of-mass (cms) energy of 500GeV or less, depending on the physics interest, and to be adiabatically upgraded to 1 TeV cms with a luminosity of 2~3 x 10^{34} $cm^{-2}s^{-1}$. The facility will be roughly 30 km in length and will support two independent interaction regions. For the two main linacs there will ultimately be over 1600 quadrupoles.

The proposed NLC has an 85% availability goal, so its more than 5600 magnets must be highly reliable or quickly repairable. Reliability engineering must be started as early as the conceptual design stage of a project and involve all engineering disciplines and accelerator physicists.

The Failure Mode and Effects Analysis (FMEA) process [2] considers each mode of failure of every component of the system, identifies their causes and ascertains the effects of each failure mode on system operation. Such a process was applied to a standard SLAC water-cooled electromagnet, designed and fabricated in the way that we have followed at SLAC for the past 20 or so years.

The causes of the most severe and likely to occur failures of a such a standard SLAC water- cooled electromagnet were identified as (a) water leaks and corrosion (b) various assembly errors. A prototype quadrupole for the linac of the NLC was built. It incorporated ten major design changes in the conductor, terminals, core and coil fabrication in order to improve its reliability over a standard SLAC magnet [3].

II. MAGNET REQUIREMENTS

The prototype magnet must meet the requirements listed in Table I.

TABLE I

MAGNET REQUIREMENTS FOR A 1TEV NLC

Item	Value	
Full Aperture	12.7 mm	
Quantity Length	288	324 mm
	424	432 mm
	932	965 mm
Pole tip field	0.62 Tesla for 324 mm	
	0.86 Tesla for other	
Adjustment	+0 to –20%	
Temperature stability	0.5% at 25 ± 1 °C	
Sextupole	$b_3/b_2 < 0.02$ at r=5mm	
Field accuracy	±0.5% at any field	
Center location	To Fiducial ± 0.1mm	
Magnetic Center stability	± 0.001 mm over range of adjustment	

NLC beams must be centered in the zero field at the magnetic center of each linac quadrupole to within 0.002mm (2 micrometers (µm)) so as to avoid emittance growth. A beam that is 3µm off from the quadrupole's magnetic centers is unacceptable!

Conventional alignment techniques do not have a 1-2µm accuracy so the NLC will align its linac quadrupoles using a

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Manuscript received September 24, 2001. This work was supported by the U.S. Department of Energy under contract No. DE-AC03-76SF00515.

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technique called “Beam Based Alignment” (BBA) [4]. Using this process on these quadrupoles drives the magnetic center stability requirement of ±0.001 mm. When a beam position monitor detects movement of the beam the position of the related quadrupole will be adjusted to bring the beam back on the correct trajectory. The BPM to quadrupole center calibration process requires that the quadrupole strength be lowered by 20% in five steps of 4% each, each step taking about 5 seconds, during which change the magnetic center must not shift by more than 1 µm. This calibration will be done approximately monthly.

III. MAGNET FABRICATION FEATURES

This section describes the design and fabrication features of the NLC prototype linac quadrupole that were chosen because they would improve its reliability and/or reduce its cost. It has a solid C1006 steel core, 4 quadrants were ground on the outside then bolted together and 4 poletips and coil pockets were Electrical Discharge Machined (EDM) in the same operation. This gave a 0.005 mm reproducibility on the poletips and better coil pocket stability and dimensional tolerances. But the machining cost was less than milling out the poletips.

Hollow seamless ROUND copper tubing (per ASTM B75 standard) was used for conductor. This has several advantages compared to square conductor: easier to wind; not prone to twisting; does not keystone; much smoother internal surface with fewer crevices and defects where corrosion can start (the surface finish for round copper tubing is about 10 times better than for square tubing with a round hole); allows direct attachment to compression fittings. Furthermore it took just 3 hours to wind the coil with round conductor, compared to 8 hours for square, thus the coil winding costs considerably less.

New style power terminals were used: commercial motor disconnects were modified to be brazed onto the conductor coil leads. They are cheaper and more reliable than custom made multifunction terminals and ones that depend on torques to be joined to the power cables.

The coils were potted instead of made by wet lay-up, this gives better dimensional stability and enhanced water resistance. The anticipated reduction in the number of coils shorting out from water spraying from nearby water leaks is worth the higher cost.

A detailed comparison of the fabrication costs of this prototype with the same quadrupole fabricated in the standard SLAC way predicts that, in full production it will cost about 20% less.

Fig. 1 is a photo of the prototype quadrupole on its magnetic measurement test set-up, which is described in section V.

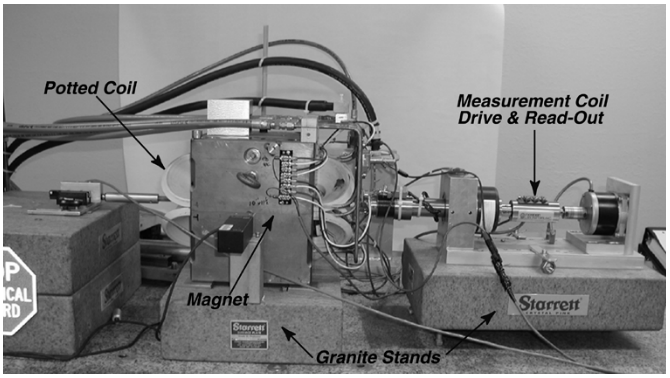

Fig. 1 Side view of the prototype quad being measured on a special magnetic measurement set-up.

IV. QUAD MEETS REQUIREMENTS

The NLC Linac will have over 1600 quads in 3 different core lengths: 324, 432, 965mm. All the quadrupoles’ core cross-sections will be the same as the prototype. Poletip fields vary depending on the magnet’s position along the Linac, the lowest is 0.12T, and the maximum required poletip field is 0.857T. This design functions and meets requirements at all currents between 20 and 133 amps.

It reaches maximum field with 133 amps and, with 4 water circuits, the cooling water temperature rise is less than 1.2°C. It was kept deliberately low to minimize thermal effects on the magnetic center. The steel is not saturated, the integral strength versus current remains linear to 133A.

The most important multipole requirement is that the sextupole/quadrupole at radius of 5mm be less than 0.02. It has been measured to be 0.01 at 30, 80 and 150A. The ratio 12-pole/quadrupole measured 0.0004 at 5mm.

The magnet was measured, then disassembled into 2 halves, then re-assembled without any special effort, and re-measured. Its integrated gradient per amp changed by less than 0.1%; its 12 pole/quad did not change.

The voltage across the 2 parts of the motor disconnect power terminal has been monitored as the magnet has been cycled up and down in current many times, it has behaved without any problem.

V. SPECIAL MAGNETIC MEASUREMENT SET-UP

In order to ascertain if the requirements of the beam-based alignment process are being met, the magnetic center of the quadrupole must be measured relative to its nominal geometric center to much less than 1 µm.

A rotating measuring coil is used. Its axis of rotation must remain fixed relative to the magnet’s geometric center for meaningful data to be acquired. The magnetic measurements are done on a granite table in a temperature controlled room. A rotating coil is used to measure the magnet strength, the field harmonics, and the magnetic center. It is supported on granite stands, as is the magnet. A stretched wire system was used to calibrate the coil. The measurement coil has two windings of 50 turns each, which lie in a plane and go from the coil axis to the outer radius of 3.8 mm. The two windings are wired so their signals add when measuring the magnet strength. This provides some immunity from coil bowing effecting the coil strength calibration. The two windings are wired so their signals cancel when measuring the magnetic center. This allows a more accurate determination of the dipole signal when the large quadrupole signal is removed. The ratio of the dipole strength to the quadrupole strength is used to compute the position of the magnetic center. The harmonics measurements are done with two coil winding configurations. A single winding is used to give the quadrupole, octupole, etc. (even) harmonics. The two windings in the bucking configuration are used to determine the dipole, sextupole, etc. (odd) harmonics.

The measurement coil rotates 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 from the measurement coil are sent through mercury wetted slip rings to a multiplexer and then to a *Metrolab* digital integrator. We are measuring X and Y magnetic centers with "statistical" errors of 0.01 to 0.2 microns, these are the rms deviations of the signals from the multiple rotations, the errors are well below 0.10 microns most of the time. It takes 6 minutes to make one center measurement. In reality the BBA process will take only about 25 seconds, but we cannot get precise enough center data in that short time frame.

VI. MAGNETIC CENTER DATA

This section contains several plots that show how the quadrupole's magnetic center behaves in various circumstances. It was absolutely necessary to have the measurement set-up in a temperature controlled room, with less than a 0.6°C excursion in air temperature. Otherwise the assembly carrying the rotating coil moved too much relative to the magnet and the measured y co-ordinate of the magnetic center appeared to move when it had not. Five computer-read thermocouples were placed on different parts of the set-up and monitored during every run.

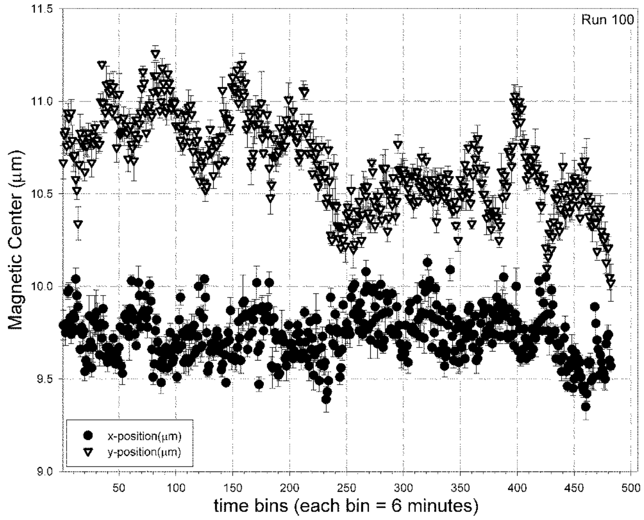

Fig. 2 Magnet run at 133amps for 48 hours in thermally stable air conditions.

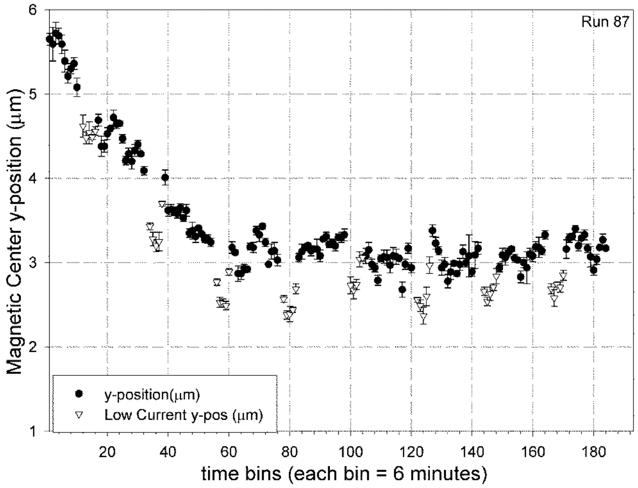

Fig. 3 Simulated BBA procedure repeated 8 times during 18 hours continuous run. BBA currents are 133- 80- 106.6- 112- 117.22- 122.48- 127.8- 133amps.

Fig. 2 shows the x and y coordinates of the magnetic center measured over a 48 hour continuous run at 133 amps. The range of variations in x is less than 0.75µm and in y it is about 1.25µm. The y variations are caused mostly by variations in the temperatures of the steel core and the rotating coil assembly as explained below.

Fig. 3 shows how the y position of the magnetic center behaves as the current is changed to make the –20% strength change from nominal current. In order to meet the less than 1 µm shift we established that it was necessary to take the magnet DOWN to a current LESS than the 80% of nominal current and then come UP to the 80% current. When the magnet was taken down to at least 50% of its nominal current before coming back up, then the center shift criteria was met for the complete operating range of the magnet, i.e. it was tested at 40, 60, 100 and 133 amps nominal.

The drop in y-position from ~ 6 µm to ~ 3 µm in the first 60 time bins in Fig. 3 was caused by a decrease in the incoming cooling water temperature, which changed the steel core temperature, which caused a small (but critical at the micrometer level) change in the vertical height of the magnet and hence a decrease in its magnetic center's y position. We tried to control and stabilize the temperature of the incoming Low Conductivity Water and had moderate success. But it was coming almost directly from the cooling towers and still had, as seen in Fig. 4, periodic variations lasting about 50 minutes, together with a diurnal variation.

The x position was not affected by the cooling water variations, nor any ambient temperature variations and it satisfied the BBA requirements too.

Fig. 5 shows how the magnet steel temperature correlated with the incoming cooling water temperature (with only about a 1 minute time lag). Fig. 6 shows how the y position moves when the steel core temperature changes (from any cause).

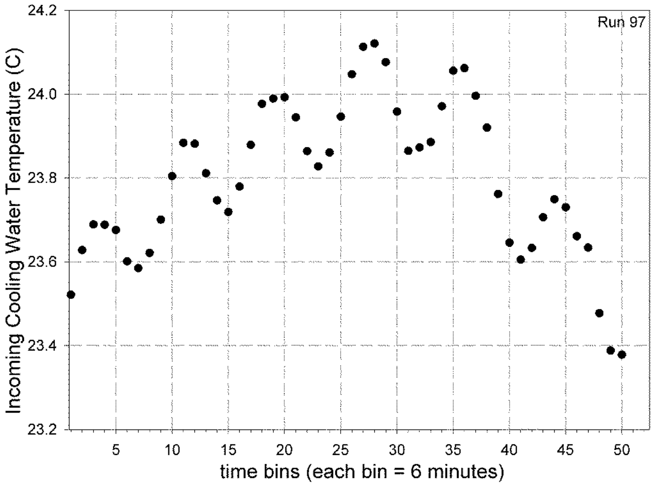

Fig. 4. Variation of incoming LCW temperature with time.

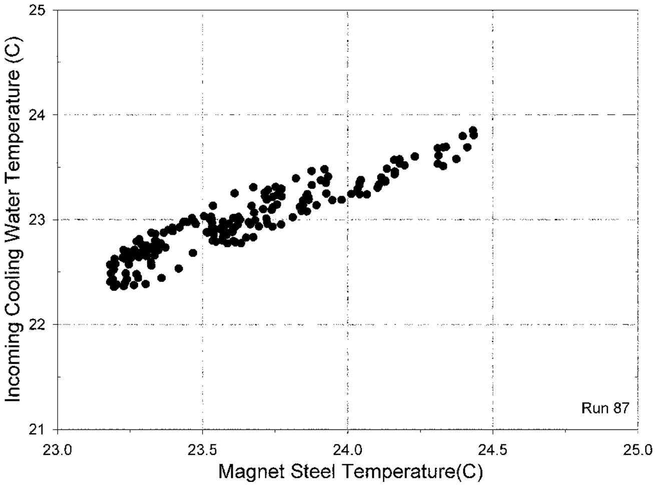

Fig. 5. Close correlation between incoming cooling water temperature and magnet core temperature (through the magnet coils' temperature).

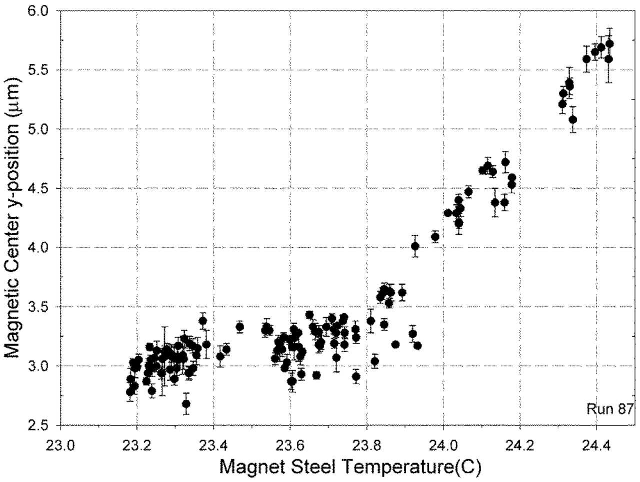

Fig. 6 Magnetic center's y position goes up as the steel temperature goes up and the magnet increases in height.

These plots show clearly how careful one has to be to control the thermal circumstances of both the magnetic center measuring apparatus and magnet, else one will be misled when measuring magnetic centers at the sub-micron level.

VII. COMPARISON WITH PERMANENT MAGNET PROTOTYPES

Four different designs of hybrid permanent magnet protoyypes made to meet the same requirements have undergone similar testing. The preliminary versions satisfy all requirements *except* the center stability, which ranges from 20 µm to less than 4 µm [5],[6]. Work is continuing on some of these adjustable permanent magnets to ascertain if the center stability requirement can be reached.

VIII. CONCLUSIONS

The prototype NLC electromagnetic quadrupole meets all its design requirements, including the exceedingly tight magnetic center stability during the beam based alignment procedure.

The temperature of the incoming LCW will need to be controlled to better than 0.2 °C to avoid center movement. The ambient beamline tunnel temperature will greatly influence the magnetic center position. Automated magnet movers will be essential to deal with slow changes in tunnel temperature.

The magnet has run reliably through hundreds of current sequences. The temperature of the LCW incoming to the prototype magnet will be better controlled and testing will continue!

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