Measuring the Magnetic Center Behavior and Field Quality of an ILC Superconducting Combined Quadrupole-Dipole Prototype

Cherrill M. Spencer, Chris Adolphsen , Martin Berndt, David R. Jensen, Ron Rogers, John C. Sheppard, Steve St Lorant, Thomas B. Weber, John Weisend II, Heinrich Brueck, Fernando Toral

***Abstract*— The main linacs of the proposed International Linear Collider (ILC) consist of superconducting cavities operated at 2K. The accelerating cavities are contained in a contiguous series of cryogenic modules that also house the main linac quadrupoles, thus the quadrupoles also need to be superconducting. In an early ILC design, these magnets are about 0.6 m long, have cos (2θ) coils, and operate at constant field gradients up to 60 T/m. In order to preserve the small beam emittances in the ILC linacs, the e+ and e- beams need to traverse the quadrupoles near their magnetic centers. A quadrupole shunting technique is used to measure the quadrupole alignment with the beams; this process requires the magnetic centers move by no more than about 5 micrometers when their strength is changed. To determine if such tight stability is achievable in a superconducting quadrupole, we at SLAC measured the magnetic center motions in a prototype ILC quadrupole built at CIEMAT in Spain. A rotating coil technique was used with a better than 0.1 micrometer precision in the relative field center position, and less than a 2 micrometer systematic error over 30 minutes. This paper describes the warm-bore cryomodule that houses the quadrupole in its Helium vessel, the magnetic center measurement system, the measured center data and strength and harmonics magnetic data.**

***Index Terms*—magnetic measurements, superconducting quadrupole magnet,**

I. INTRODUCTION

The main linacs of the proposed International Linear Collider (ILC) consist of superconducting cavities operated at 2 K. The accelerating cavities are contained in a contiguous series of cryogenic modules that also house the main linac quadrupoles, thus the quadrupoles also need to be superconducting. In an early ILC design, these magnets are about 0.6 m long, have cos (2θ) coils, and operate at field gradients up to 60 T/m. In order to preserve the small beam emittances in the ILC linacs, the e+ and e- beams need to traverse the quadrupoles near their magnetic centers. A quadrupole shunting technique is used to measure the quadrupole alignment with the beams; this process requires the magnetic centers move by no more than about 5 micrometers when their strength is changed. To determine if such tight center stability is achievable in a superconducting quadrupole, we at the SLAC National Accelerator Laboratory measured the magnetic center motions in a quadrupole designed and built at CIEMAT in Madrid, Spain [1] for the TESLA collider test facility at DESY. DESY lent SLAC the prototype magnet.

To our knowledge no-one has ever measured the magnetic center behavior of any superconducting quadrupole to the sub-micrometer level before and it requires a specially designed measurement system working in a carefully controlled environment to do so. The Magnetic Measurements Group (MMG) at SLAC spent 5 years developing such a system for measuring room temperature magnets [2] and we applied the same techniques to this superconducting magnet.

II. COMBINED FUNCTION QUADRUPOLE-TWO DIPOLES

The magnet is small and low field, its specifications are given in Table I.The same design would be used for all ILC linac quads.The field quality and magnetic center stability specifications are imposed by ILC requirements.

TABLE I. MAGNET SPECIFICATIONS FROM DESIGNER

Parameters	Nominal	Units	Comments
Maximum Gradient	60	Tesla/meter	At 100 A. Magnet runs at constant current
Bore diameter	90/79	mm	At Coils/ At tube i.d.
Effective Length	0.5787	m	From 3D *ROXIE* model
Field non-linearity at 5 mm radius	0.05	% of quad	Over 5 A -100 A
Magnetic center stability for 20% Beam Based Alignment	+/-5	μm	Over 5 A -100 A
Outer Dipole coil integrated strength	0.0513	Tesla·m	At 40 A
Outer Dipole/Inner Dipole Strength	1.026	-	From 3D *ROXIE* model
Liquid He Temp	2	K	

The quadrupole's cos(2θ) shaped epoxy impregnated superconducting coils were accurately positioned on the same

Manuscript received 20 October 2009. This work supported by the U.S. Department of Energy under contract DE–AC02–76SF00515.

Cherrill M. Spencer, Chris Adolphsen , Martin Berndt, David R. Jensen, Ron Rogers, John C. Sheppard, Steve St Lorant, Thomas B. Weber, John Weisend II are with the SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA (Cherrill Spencer phone: 650-926-3474, fax: 650-926-2407, e-mail: cherrill@slac.stanford.edu).

Heinrich Brueck is with DESY, 22603 Hamburg, Germany. (e-mail: brueck@desy.de).

Fernando Toral is with the Laboratorio Conjunto de Superconductividad Aplicada CIEMAT-CEDEX, 28040 Madrid, Spain (e-mail: fernando.toral@ciemat.es).

assembly mandrel as the two sets of cosθ dipole windings and they were all cured at the same time. The coils are surrounded by a segmented steel cylindrical yoke; each of its 16 quadrant shells is 150 mm long. The entire assembly is restrained radially by a massive tubular aluminium collar with a ~260 mm outer diameter.

The dipole coils are for horizontal and vertical steering. One can also think of their effect as moving the magnetic center of the quadrupole. The electron beam must pass through the magnetic center of each linac quad to preserve its very small emittance. These dipole coils must be strong enough to move the quad center by several mm, to offset the overall motion of the large accelerator cavities in which they will sit.

III. DESIGN, BUILD AND OPERATE WARM-BORE CRYOSTAT

The magnetic center measuring system uses a *horizontal* rotating coil so a warm bore horizontal cryostat had to be designed and built to house the magnet and accommodate the measuring coil [3]. The various requirements led to the magnet being mounted in a small helium vessel surrounded in turn by a liquid nitrogen-cooled 80 K shield and a room temperature vacuum vessel. The magnet was bath-cooled in 4.5 K liquid He. Fixing the magnet within the He vessel so that it had very low vibration, so the magnetic center measurements would see only magnet effects was a challenge successfully met with dual concentric support G-10 rings.

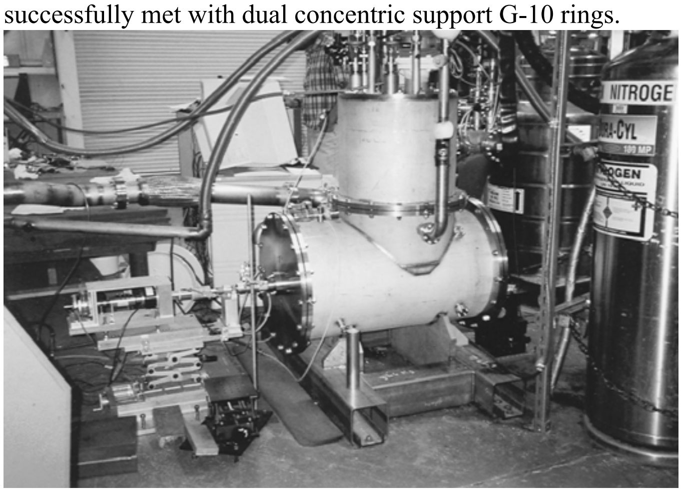

Fig.1 Warm-bore cryostat containing the quadrupole with the rotating coil apparatus extending through the bore. Circumstances forced the set-up to be in lab without air conditioning and the liquid He to come from 250 l Dewars.

Making magnetic measurements on this superconducting magnet was not as straightforward as we had envisioned because the liquid helium came out of a 250 litre Dewar which lasted only about 6 hours and we did not pass the helium overnight, just the liquid nitrogen. So time and liquid He was spent every morning cooling the magnet back to 4.5 K. Then helium would run out during data-taking and the quad might increase in temperature a little and sometimes quench; the cryogenics system needed continual monitoring by a cryogenics technician.

IV. MAGNETIC MEASUREMENT SET-UP

Over the past several decades SLAC's MMG has developed accurate and precise magnet measurement systems based on rotating G10 rods in which multiple sets of thin wires are wound. When these long coils are rotated in a quad's aperture then voltages are induced, read out and processed to measure integrated strength and the multipole components. Since 2001 the MMG has further developed this technique so as to measure a relative magnetic center change to a ~0.02 µm uncertainty. Magnetic center measurements are sensitive to coil vibration, rotating part wear and environmental effects, namely temperature and relative humidity and support vibration. MMG evolved their apparatus to minimize mechanical noise and create environmental isolation [2].

A rotating coil was designed and made especially for the measurements of this prototype quad. It was based on a G10 rod of 41.275 mm diameter and 1061.7 mm length; 7 precisely placed machined grooves carry 6 sets of windings which each have 19 turns of AWG 36 *Litz* wire. The 6 coils are connected in various ways so that they measure the main quadrupole integrated strength component or buck out the quadrupole signal so that the smaller multipoles can be measured, or the dipole component which is a measure of the quad's magnetic center relative to the mechanical center of the rotating rod. In order to measure the magnetic center with sub-micrometer precision one has to find ways to connect shafts to the G10 rod ends and cause the rod to rotate without bowing, wobbling or vibrating relative to the geometric centerline of the quadrupole. As described in [2] a sapphire "Olive ring" bearing through which a shaft attached to the G10 rod at the non-drive end sits, meets these requirements. The other rod end is connected through a flexible coupling and mercury wetted slip rings to a microstepping motor and encoder.

Budget cuts meant we had to modify where our experiment was housed and we ran the magnet and measuring apparatus in a large lab without any air-conditioning. So the ambient temperature varied by several degrees during the day and this caused the temperatures of the supports under the rotating coil ends and under the cryostat to vary (we measured these temperatures with thermocouples); the supports were not optimized because of time constraints. So all these support structures made of different materials expanded and contracted at differing rates which affected the magnetic center measurements as will show in the results below.

V. BEAM BASED ALIGNMENT AND OPERATIONAL DETAILS

One of the goals of these measurements was to ascertain if this superconducting quad can meet the ILC's Beam Based Alignment (BBA) requirements on its magnetic center behaviour. During BBA the electron beam passing through the 300 quadrupoles in the main linac is used to precisely align all these quads, in small groups at a time, along the linac. The beam's emittance will grow if the quads are not aligned to within 10 to 20 µm. A BBA calibration process requires that each quadrupole's operating strength be lowered by 20% and returned in 2 or 3 steps to its original value, during which its magnetic center must not shift by more than +/- 5 µm. The quad's current is changed in this sequence: 100%-78%-80%-90%-100% of starting current. We planned to go 2% lower than 80% first so that the current's value is always approached from a lower value to avoid hysteresis effect, but we discovered it was not necessary. The operating strength of the quads increases with their position along the 11Km long linac.

We took care to change the currents during BBA with slow ramp rates, e.g. 0.2 A per second. When we started the measurement project we did standardization cycles when first powering up, but then we established it made no difference in the integrated strength whether we standardized or not and so we did not. Each set of coils had their own power supply (PS) and each PS suffered from RF noise that made them trip occasionally, or sometimes a ground fault caused a PS trip (but not a quench) and time was spent recovering.

VI. Magnetic Measurement Results

A. *Range of Integrated Strength of the Quadrupole*

Another goal of these measurements was to see if this design could produce integrated gradients between 2 T and ~35 T with the required field quality. This range of strengths is what is needed in a 500 GeV electron linac. We measured the integrated gradient at 9 currents between 10 and 100 A and the plot of ∫G.dl versus current was very linear. The ∫G.dl at 100 A was 34.706 T, just a little short of the predicted 34.723 T. The ∫G.dl per A values drop by 0.26% over the whole range, caused by parts of the steel yoke beginning to saturate.

B. *Harmonic Measurements of the Quadrupole*

The current needed to produce 2 T is 6 A and we needed to measure the harmonics at low, medium and high currents to check the field quality met the requirements across the whole range. We measured all the integrated harmonics up to n=15 (30-pole) at the radius of 1.9531 cm at 5, 35, 50 and 100 A and then scaled them to 3 cm and calculated them as a fraction of the integrated quadrupole strength. The values are plotted in Fig.2; the 5 amp values are significantly higher than the others and the allowed 20-pole is the only one above 10^{-3} at all 4 currents. But the ILC's beam will be much smaller than 30 mm wide and a more appropriate measure of field quality is the total non-linearity of the field at some radius, i.e. the sum of all the multipoles compared to the quad. The ILC requirement is that this ratio be less than 0.05% at 0.5 cm.

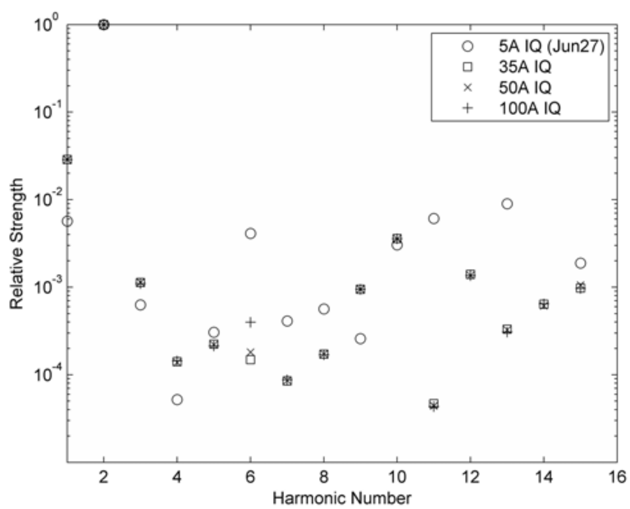

Fig. 2. Quad's harmonics were measured by rotating coil at 4 currents.

We measured this ratio at 14 currents between 2 and 80 A. Although the ratio below 10 A was higher than above 10 A, it was always less than 0.03%.and met ILC field quality specs.

C. *Magnetic Center Behaviour during BB Alignment*

The rotating coil apparatus measures the X and Y coordinates of the magnetic center relative to the mechanical center of the rotating coil which our analysis protocol defines as the origin. As previously mentioned the temperatures of all parts of the measuring apparatus varied during the center data-taking and there is a strong linear correlation between the rotating coil supports' temperatures and changes in the the Y coordinate, but the X coordinate moves much less. This effect was observed in room temperature quads [2] and was why we planned to do these measurements in a room with ambient temperature controlled to +/-0.1ºC. Instead the apparatus suffered temperature variations between 0.5 and 1.2ºC during a series of BBA current sequences. On a plot of magnetic center's Y coordinate versus various measuring coil support temperatures one can see the linear correlation between them, see Fig. 3. We call the slope of the linear fit the thermal correction coefficient for the Y coordinate data (e.g. -4.465).

The construction of the quad is symmetric in the X and Y axes, its magnetic properties should not differ between X and Y and so we take the behaviour of the X coordinate of the magnetic center during BBA as the representative behaviour of the whole quad and ascribe the larger variations in Y to thermal effects that cause the supports to change in height and cause an apparent change in the Y of the magnetic center.

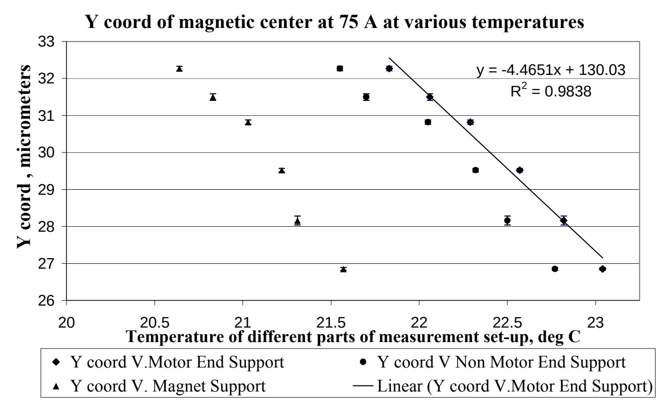

Fig. 3. To establish thermal behavior of measuring set-up: measured magnetic center six times at 75 A while various support temperatures also tracked.

Fig. 4. shows that the original Xs and corrected Ys vary by less than 2 µm during 5 consecutive BBA sequences at 75 A.

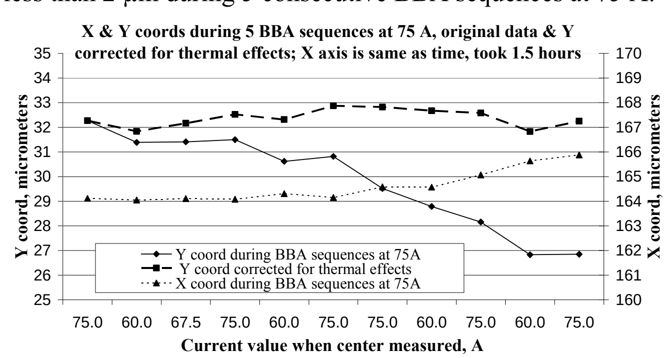

Fig. 4. Corrected Y coord = Y-(-4.465 x (Temperature-Temperature at start))

We tracked the X and Y coordinates of the quad's magnetic center during repeated BBAs at these starting currents: 5, 10, 20, 50, 75, and 100 A. We measured the temperatures of two parts of the measuring coil's supports, the magnet's support and ambient. The larger the variation in support temperature the larger the variation in Y. Table II summarizes the overall variations in X, Y and Y corrected for the temperature changes using the correction coefficient from the 75 A run.

TABLE II. SUMMARY OF MAGNETIC CENTER MOVEMENT DATA

BBA Current, A	ΔX micro-meters	ΔY micro-meters	ΔY(corr) micro-meters	Support ΔTemp ºC
5	4.83	5.38	3.27	0.66
10	0.96	1.39	0.8	0.48
20	0.48	1.74	1.40	0.55
50	0.36	4.06	0.8	1.24
75	1.83	5.44	1.04	1.21
100	0.98	2.37	1.34	0.54

Only at 5 A does the ΔX become over ~2 µm and the ΔY is more than expected from the 0.66 ºC ΔT; we believe these are real magnetic effects caused by persistent currents. The center stability still meets the +/- 5 µm ILC spec for a 20% BBA.

D. Inner and Outer Dipole Measurement Observations

We measured the integrated strengths of the inner and outer dipoles while the quadrupole was off. Fig.5 shows the OD transfer function starting from 0 A, going to +25 A and then stepping through small currents to negative currents, to -25 A.

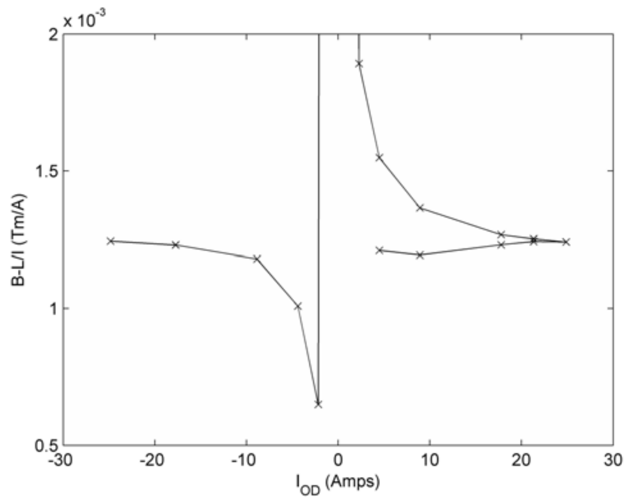

Fig. 5. Outer Dipole transfer function when ID and quad off.

∫ B.dl per A is not constant for the OD or ID. It is larger at smaller currents- this is caused by persistent currents, whose effect becomes more obvious when real current is small. Nor is the ∫ B.dl/A symmetric between positive and negative currents. We measured the multipoles up to n= 15 at various currents. The allowed sextupole and 10 pole were significant and above the multipole specs. They did not have any 12 or 20 pole components. The quadrupole current was set to 45 A and then the OD was run at 0 =>24.90=>-24.86=>-12.40=>-6.19=>0.2 A. The X coordinate of the magnetic center moved by 1.0027mm with the OD at 12.4 A. The quadrupole's strength per A is affected by less than 0.03% by the dipoles being on, this is as desired. The inner dipole (ID) causes a shift in the Y coordinate of the magnetic center: with the quad at +45 A and the ID at 12.58 A, the Y coord shifted by -0.978 mm. The X coord shifted a little too: 0.079 mm. It should not move at all. The OD and ID should be completely independent in their effects on the X and Y coordinates.

TABLE III. MAGNETIC MEASUREMENT RESULTS

Parameter	Nominal or Spec	Measured	Units	Comment
Integrated Quad Strength at 100 amps	34.723	34.706	Tesla	Reached maximum design strength
Effective Length	0.5787	N.A.	m	Estimated
Field non-linearity at 5 mm radius	0.05	<0.03	% of quad	From 5 A to 100 A
Multipoles/ quad at 30mm radius	< 10x 10^{-4} Storage ring magnet spec	Most OK. Not 20-pole	Fract of quad	From 5 A to 100 A Tighter than ILC Spec
Magnetic center stability for 20% BBA	+/-5	<2 total variation if thermally corrected	µm	From 10 A to 100 A
Outer Dipole coil integrated strength/A	0.00128	0.001254	T· m/A	Measured over -25 A to +25 A
Inner Dipole coil integrated strength/A	0.00125	0.00122	T· m/A	Measured over 0 to 18 A
OD/ID Strength	1.026	1.028		Excellent agreement
Liquid He temp	2	4.5	K	Ran at ~4.5 K

VII. CONCLUSIONS

A small, low gradient, combined function quadrupole-dipole superconducting magnet has been thoroughly and precisely measured; see Table III, with these conclusions:

This quadrupole design could be used in all positions in an ILC main linac as its integrated strength and field quality meet specs from 2 T to ~35 T. This quadrupole design could be used in the ILC main linac because its magnetic center meets stability specs for the Beam Based Alignment process.

Having some dipole windings in the same concentric volume did not work well, their multipole components were too large and they moved both the center's X and Y coordinates, instead of just X or Y. Dipole correctors sitting in their own space should be designed for the ILC's linac.

REFERENCES

[1] F. Toral, et al. "Fabrication and Testing of a Combined Superconducting Magnet for the TESLA Test Facility," *IEEE Trans. Appl. Supercond.* Vol. 16 pp. 231-235, June 2006.

[2] Cherrill M. Spencer et al, "A Rotating Coil Apparatus with Sub-Micrometer Magnetic Center Measurement Stability," *IEEE Trans. Appl. Supercond*. Vol 16, pp. 1334-1337, June 2006.

[3] M.Racine, S.J.St Lorant et al, "Performance of the Cryostat for a Prototype ILC DC Combined Function Superconducting Quadrupole-Dipole Magnet," Korea Institute of Applied Superconductivity and Cryogenics, Proceedings of the ICEC 22-ICMC 2008, pp. 495-500, 2009