PERFORMANCE OF AN ADJUSTABLE STRENGTH PERMANENT MAGNET QUADRUPOLE*

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Abstract

An adjustable strength permanent magnet quadrupole suitable for use in Next Linear Collider has been built and tested. The pole length is 42cm, aperture diameter 13mm, peak pole tip strength 1.03Tesla and peak integrated gradient * length (GL) is 68.7 Tesla. This paper describes measurements of strength, magnetic CL and field quality made using an air bearing rotating coil system. The magnetic CL stability during -20% strength adjustment proposed for beam based alignment was < 0.2 microns. Strength hysteresis was negligible. Thermal expansion of quadrupole and measurement parts caused a repeatable and easily compensated change in the vertical magnetic CL. Calibration procedures as well as CL measurements made over a wider tuning range of 100% to 20% in strength useful for a wide range of applications will be described. The impact of eddy currents in the steel poles on the magnetic field during strength adjustments will be reported.

INTRODUCTION

An adjustable strength permanent magnet (PM) quadrupole has been built and tested. The measured magnetic CL (CL) stability during –20% strength adjustment was 0.2 microns. The quadrupole uses linear retraction of magnet assemblies to vary strength and/or CL [1]. The device is shown in Fig. 1. As can be seen, there are four independent magnet assemblies that are retracted by motors. This is an alternative to rotating magnets of Volk [2], sliding magnets used by Kashikin [3], rotating rings built by Halbach [4] and the outer rotating ring slices built by Iwashita [5]. We measured magnetic performance with an air bearing rotating coil system, [6]. The basic properties of this Quadrupole are summarized in Table 1. This quadrupole was designed to address the stringent 1.4 micron CL stability requirements during BBA of the Next Linear Collider [7, 8].

Table 1: PM Quad Properties

Quantity	Value
Maximum GL	68.7 Tesla
Minimum GL	7 Tesla
Maximum Pole Tip	1.034 Tesla
Minimum Pole Tip	0.1 Tesla
Aperture Diameter	13 mm
Pole Length	42 mm
Centerline Stability	0.2 microns
Centerline Adjustment Range	> 100 microns
Centerline Adjustment Resolution	55 nanometers
Strength Resolution	0.0022%

The most important observation that we made was that the poles must be equally powered to insure CL stability during BBA. This was accomplished by defining the zero positions of the assemblies. Once this ‘pole symmetrization’ operation was performed we achieved highly repeatable, stable CLs.

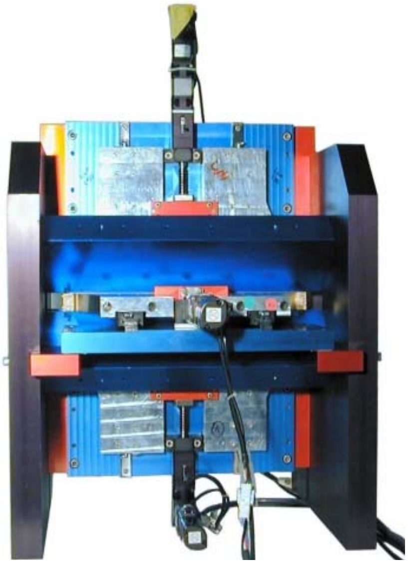

Fig. 1: Adjustable Strength PM Quadrupole

MECHANICAL DESIGN & ASSEMBLY

The basic goal of the mechanical design was to minimize deflections and insure highly repeatable performance. Individual magnets were clamped, see Fig. 2. The center clamps are stainless steel with clamping force supplied by compression of Belleville washers. Angle and strength sorting used the method described in [9]. Temperature compensating steel was placed at the back of each individual magnet [9].

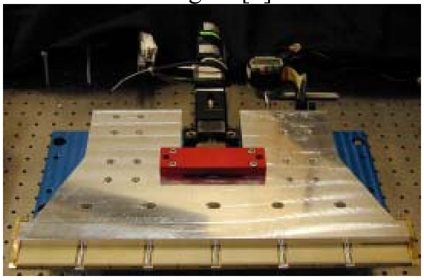

Fig. 2: Magnet Assembly

There were four arrays of six magnets, Fig. 2. Magnet arrays were positioned by custom linear actuators. Measured motion repeatability was below the 1-micron resolution of external micrometers. Linear rails were indicated into location. After alignment checks and adjustments, we bolted and pinned components.

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*Work supported by Dept. of Energy Grant DE-FG03-01ER83305

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Contributed to Particle Accelerator Conference (PAC 05), 16-20 May 2005, Knoxville, TN

Work supported in part by Department of Energy contract DE-AC02-76SF00515

MAGNETIC MEASUREMENTS

We used an air bearing rotating coil system, [6]. The measurement system was placed on a steel topped optical table that was equipped with pneumatic isolation mounts to minimize CL shift caused by floor vibrations. A graphite coil holder was carefully threaded thru the quadrupole. A low EMI servo amplifier that is controlled by a Galil Ethernet motion controller rotates the coil.

We acquired 256 data points per coil revolution. One revolution of data is acquired in the + direction, read out of a Metrolab PDI5025, then acquired in the – direction, read again, etc. Coils are labelled A, B, AB (bucking). The standard acquisition protocol was A(+), A(-), 5*(AB(+),AB(-)),5*(A(+),A(-), 5*(B(+),B(-)).

POLE STRENGTH SYMMETRY

After we built the quadrupole, debugged the measurement system and performed initial tests we found that the magnetic CL shifts were larger than expected, 5-10 microns. The shift was linear with field strength and had different rates of change for the x and y CLs. While this quadrupole has four motors so CL shifts are easily corrected, we wanted to understand the reason for such large shifts. We found that we needed to insure that all four poles are equally powered, which we call 'pole symmetrization'. This was accomplished by simply redefining the zero positions of each magnet assembly. After that, the CL shifts became quite small.

Fig. 3: Systematic Centerline Shift Method

In any quadrupole the field sensor null-point defines a magnetic CL. This does not mean that the zero locations of the magnet assemblies can be set arbitrarily. We used the method shown in Fig. 3 to systematically shift the magnetic CL. When the field strength changes, the slope of the CL tuning curve changes as well, Fig. 4.

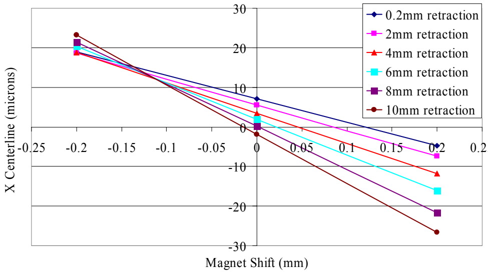

Fig. 4: X CL vs Magnet Shifts for Different Strengths

At full strength (0.2mm retraction here) the slope is small, while at 78% strength (10mm retraction) the slope is steeper. Notice that if an incorrect magnet assembly offset is chosen then as the strength changes the CL will shift. It is only when the magnet assembly offset is correct that the magnetic CL does not shift. In Fig. 5 we show two sets of CL measurements. One set shows performance only using pole symmetrization. There is a large 2 micron CL shift between 100% and ca. 95%. Once the strength is reduced, pole symmetrization achieves around 0.25 micron rms CL shift. Further improvements were made by using all four motors to adjust the CL. Then the stability is limited by the scanner repeatability.

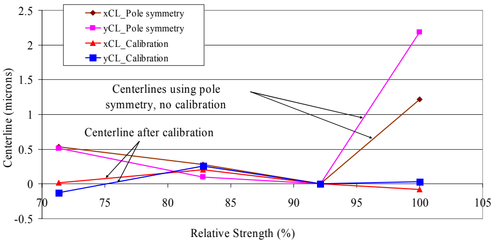

Fig. 5: Centerline Measurements

CALIBRATION PROCEDURES

After pole symmetrization, the calibration is straightforward. Retract all magnet assemblies the same amount and determine the integrated quadrupole. The tuning curve is shown in Fig. 6. A Hall probe was also used for strength calibration and no inconsistencies were observed between the two techniques. Note that there is some nonlinearity which agrees with FEA predictions [9]. This is easily corrected. There is a practical lower limit on the strength of 20%.

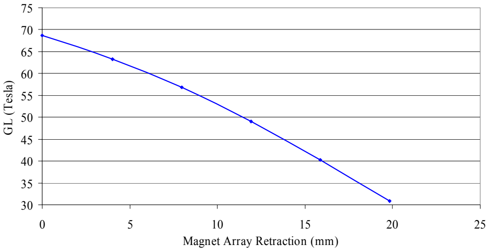

Fig. 6: Tuning Curve

Centerline calibration results are shown in Fig. 4.

TEMPERATURE SENSITIVITY

Our measurement lab is temperature controlled to about +-0.2 degC. If the temperature changes then the vertical CL shifts by about 7 microns/degC as is seen in Fig. 7. No shifts are observed for the horizontal CL. The vertical CL shift is caused by expansion of the quadrupole components, which is about 12 microns/degC. In addition, the steel air bearing supports expand at a different rate, about 5.5 microns/degC. The difference between these two expansion rates determined the CL shift.

We used temperature-compensating steel in this quadrupole. The particular location that we chose (backs of magnets) didn't work as predicted by 2D FEA. The most likely reason was 3D partial volume effects, [9]. Even if passive temperature compensation had been successful, it can only make the strength temperature independent at one value. We think that it is much better to use a thermocouple to measure the temperature and then change the strength and vertical CL by moving the magnets. The servo controller would automatically adjust the strength and CL in the background. This is far more flexible because in actual usage there are other components that are temperature sensitive.

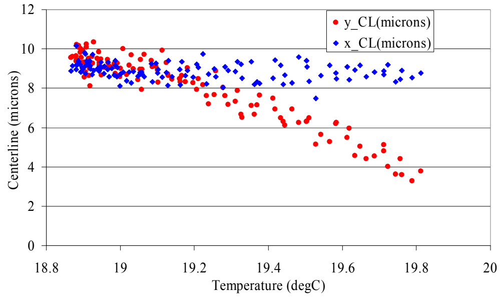

Fig. 7: Vertical Centerline Shift

We also performed experiments in which we rapidly changed the lab temperature by 5 degC. Due to differences in thermal diffusion rates CL stabilization took 24 hours. This will be a general concern for any beamline that has components with different thermal diffusion rates and it is not unique to PM quads. If the magnetic CLs need to be stable at the one-micron level then the rate of change of the beamline temperature also needs to be kept small.

HYSTERESIS AND CENTERLINE REPEATABILITY

We made measurements of strength hysteresis by adjusting the strength from 100% to 77% to 100% a total of 10 times. Results are shown in Fig. 8. We could not detect any hysteresis at the 0.03% strength repeatability of our scanner. Hall probes may be required for this measurement. We also measured CL repeatability for a BBA procedure that reduces the strength to ca. 77% and then increases it back to 100%. This sequence was repeated 10 times. The results are shown in Fig. 9. The CL repeatability was <0.2 microns at all strengths and the standard deviation was 0.09 microns.

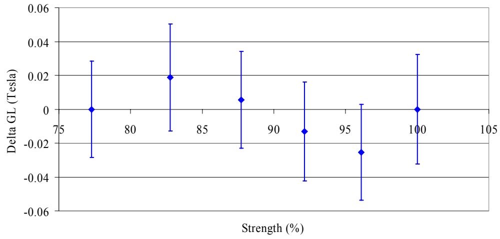

Fig. 8: Strength hysteresis measurements.

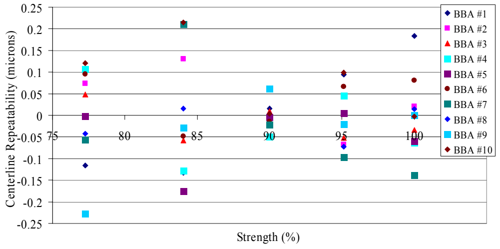

Fig. 9: Centerline repeatability measurements.

EDDY CURRENT MEASUREMENTS

We used a Group 3 DTM141 Hall probe to measure eddy currents for a BBA type of sequence. Results are shown in Fig. 10 for the fastest field changes. The initial 23% change took 2.3 seconds and 5% took 0.92 seconds. The fastest Hall probe update rate for this meter was about 3 readings/second. We did not detect any eddy currents. This simply means that the eddy current decay time is less than 0.3 seconds.

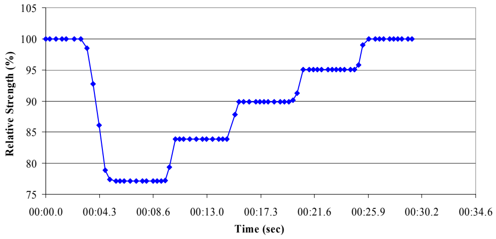

Fig. 10: Eddy Currents Measurements

CONCLUSION

A variable strength, adjustable CL PM quadrupole has been built and tested. It has demonstrated a magnetic CL stability and repeatability of 0.2 microns with –20% strength changes. This performance exceeds the original requirements of the Next Linear Collider. Long term tests exceeding 10,000 strength adjustments have shown no performance degradation.

Temperature effects were identified as being very important for micron level control of the magnetic CL. Both EM and PM quadrupoles will need to provide some means of compensating for temperature induced CL shifts. This particular quadrupole can achieve this by correcting the vertical CL as the temperature changes without using movers.

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