MAGNETIC AND ENGINEERING ANALYSIS OF AN ADJUSTABLE STRENGTH PERMANENT MAGNET QUADRUPOLE*

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Abstract

Magnetic and engineering analyses used in the design of an adjustable strength permanent magnet quadrupole will be reported. The quadrupole designed has a pole length of 42cm, aperture diameter 13mm, peak pole tip strength 1.03Tesla and peak integrated gradient * length (GL) of 68.7Tesla. Analyses of magnetic strength, field quality, magnetic centerline, temperature compensation and dynamic eddy currents induced during field adjustments will be presented. Magnet sorting strategies, pole positioning sensitivity, component forces, and other sensitivity analyses will be presented. Engineering analyses of stress, deflection and thermal effects as well as compensation strategies will also be shown.

INTRODUCTION

We describe magnetic and mechanical analyses of an adjustable strength permanent magnet (PM) quadrupole [1, 2]. This quadrupole achieves variable strength as well as centerline (CL) adjustment in x and y by means of magnet retraction. The basic method of adjusting the strength is shown in Figure 1. All magnets are retracted the same amount. When the magnetic centerline needs to be adjusted then the method shown in Figure 2 is used (the shift is highly exaggerated for clarity). For example, in order to move the centerline right, the left and right magnets are shifted the same amount to the right. The magnetic centerline shift is smaller than the physical magnet shift. Therefore, if strength and centerline need to be adjusted this quadrupole will require independent control of at least three magnet retractions. In order to keep the field quality high, the symmetric retractions shown in Figures 1 and 2 are preferred and all four magnets will need to be retracted.

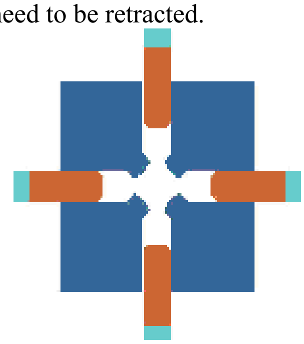

Figure 1: Method of achieving strength adjustment by uniformly retracting all four magnets in a PM Quad.

In both Figures 1 and 2, we also show temperature compensating steel on the backs of the magnets [2]. The configuration shown in Figure 1 would be used to correct temperature dependent strength changes such as dB_r/dT and component expansion. In order to compensate for vertical centerline shifts caused by component expansion, the method shown schematically in Figure 3 can be used. As the temperature increases the upper magnet with compensator becomes stronger than the lower one. This is equivalent to moving it down so the vertical centerline shifts downward.

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The remainder of this paper first describes the particular design optimization used for a 42cm long, 13mm aperture quadrupole having 1.03Tesla pole tip field. Then we describe mechanical FEA, sensitivity, temperature and eddy current analyses.

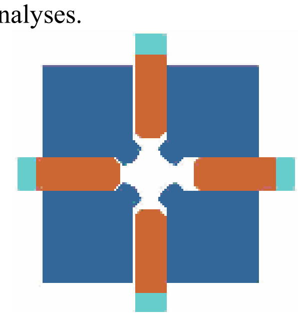

Figure 2: Method of shifting the horizontal magnetic centerline to the right by shifting a pair of magnets. (Highly exaggerated for illustration purposes.)

Figure 3: Method of correcting for temperature dependent vertical centerline shifts by using asymmetric vertical magnet temperature compensating steel

DESIGN OPTIMIZATION

The overriding criterion for this design was a desire to minimize shifts of the magnetic centerline as the strength is adjusted. This was achieved by choosing thin magnets, 10.4mm nominal, to increase the ratio of magnet shift/centerline shift. We call this the 'mechanical advantage' of the design. A large 'mechanical advantage' means that large physical magnet shifts are needed to make small magnetic centerline shifts. It allows more flexibility in the mechanical design of the retraction system. For this choice of magnet thickness the 'mechanical advantage' was 15. If the magnets are thick, ca. 20mm, the quadrupole has a smaller transverse extent but the 'mechanical advantage' drops to about 7. Interestingly, we found that adding temperature compensating steel to the back favorably changed the

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forces on the poles during strength adjustment, see Figure 4. Notice that a 10.4mm thick magnet gives a very flat pole force vs. retraction over a wide retraction range. After we established the magnet thickness we determined the tuning curve. The strength tuning curve is shown in Figure 5. When all the magnets are retracted 25mm the strength is 29% of nominal. There is some non-linearity, but this can be easily corrected.

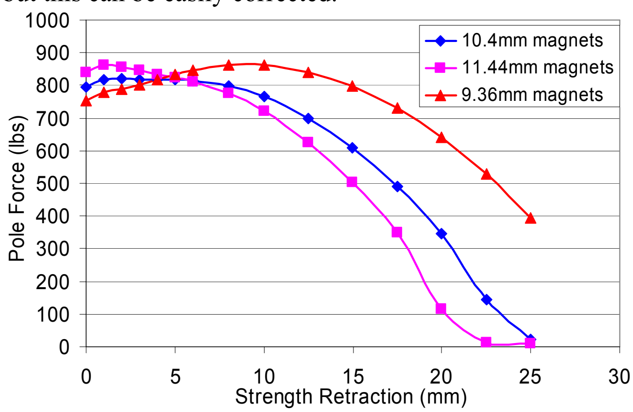

Figure 4: Pole force for three magnet thicknesses vs. Strength Retraction.

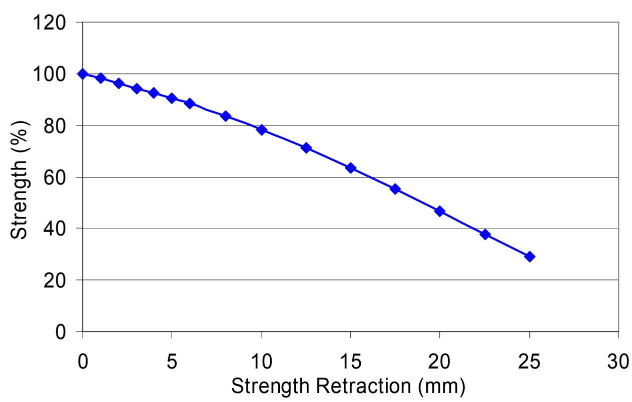

Figure 5: Strength tuning curve for 10.4mm thick magnets, 13mm aperture, 1.03T pole tip field.

The mechanical advantage does depend on strength. This has a significant implication for how accurately the initial magnet retractions need to be determined. If they differ (due to fabrication tolerances) then there will be a false magnetic centerline shift as the strength is adjusted. This is illustrated in the centerline tuning curve shown in Figure 6.

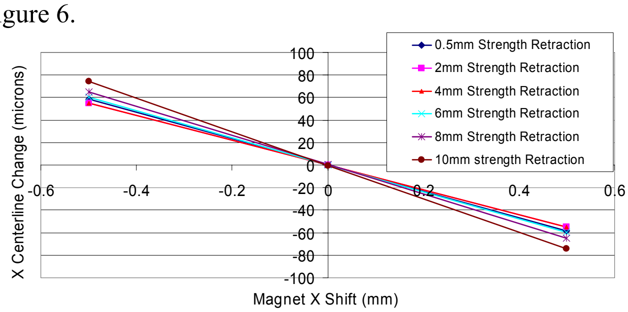

Figure 6: Magnetic centerline tuning curves for different strength retractions (0-10mm).

On this design, a 10mm retraction reduces the quadrupole strength by 21%. If a pair of magnets have a starting retraction that is incorrect by 0.25mm then as the strength is reduced from 100% to 79% the magnetic centerline will shift 10 microns.

Field quality was calculated using 2D FEA. The pole tips were hyperbolic with nubs [3] and the estimated field quality was 0.05% 8-pole at 80% aperture. All other 4n poles thru the 20-pole were less than 0.5%. No detailed pole tip optimization beyond this was performed.

MECHANICAL FEA

Mechanical FEA was performed using MSC NASTRAN. All designs were deflection limited with Von Mises stresses at least 50X below yield. For this analysis we used the as-built 3D CAD models. The quadrupole uses 4 arrays of 6 magnets with stainless steel magnet clamps and bolts to hold the pole to a rigid aluminum strongback. As long as the quadrupole has four fold symmetry, neither pole nor magnet deflections will change the magnetic centerline. The largest magnet array deflection occurred at peak strength. Average magnet deflections would be about 12 microns. This would be highly repeatable and was acceptable. For the poles, the worst-case deflection occurred at the pole axial center. The deflection between zero load and full magnetic load was calculated to be 4.6 microns. As noted earlier, see Figure 4, the pole force should remain reasonably constant when the strength is reduced 20%, so then the pole deflection should be about 10X smaller or 0.5 microns, which was quite acceptable.

SENSITIVITY ANALYSES & SORTING

We performed 2D sensitivity analyses of pole positioning errors, magnet strength deviations, angle deviations as well as forces and torques on magnets caused by assembly tolerances. The sensitivity to pole position errors is shown in Figure 7. A 200 micron pole shift gave a 5 micron centerline shift during adjustment from 100% to 80%. Pole induced CL shifts are approximately 40X smaller than the pole position errors.

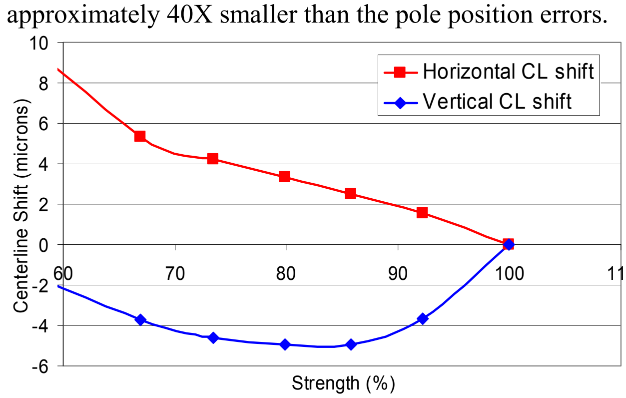

Figure 7: Pole positioning sensitivity. One pole was displaced 200 microns horizontally.

For the magnets, it is well known that PM designs will require magnet sorting. On this PM quad we needed to know the sensitivity of the CL to individual magnet

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strength and angle errors as the quad strength is adjusted. The analyses left three magnets in Figure 1 at their nominal values and only changed the strength or angle of a single magnet. The sensitivity to angle vs. strength retraction is shown in Figure 8. Similar analyses were performed for the sensitivity to magnet remanence differences. The sensitivities were 1micron/% and 1micron/degree. Centerline offsets are ignored.

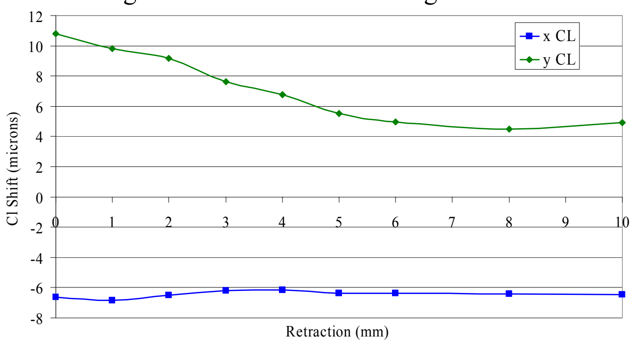

Figure 8: Magnet angle sensitivity. Angle of one magnet was changed by 5 degrees. Sensitivity is approximately 1 micron/degree.

Care is taken during magnet assembly to insure that the magnets are centered in the slot between poles. However, if they are not perfectly centered then there is a small strength dependent centerline shift which is strongest during the first 5% change. The sensitivity is about 0.03 microns/micron magnet miscentering or 0.5 microns for a 12 micron miscentering.

Once the magnet strength and angle sensitivities were analyzed we wrote a sorting code that minimized the centerline shifts as a function of quadrupole strength. We used a 'brute force' approach because there were only 24 magnets in the quadrupole. The sort cost function gave higher weight to end magnets. After sorting, the predicted strength dependent CL shift was about 0.1 micron. Therefore, we expected pole and magnet assembly errors to dominate strength dependent CL shifts. The resulting sort was used during assembly [1].

TEMPERATURE ANALYSES

We originally performed 2D analyses of the effects of temperature compensating steels. The final quadrupole needed room for magnet clamps so the compensators could only fill about 90% of the axial length at the back of the magnets. Therefore we allowed room in the design for 25% thicker compensator. When we started assembly we needed a better estimate and performed 3D FEA of the as-engineered device. This analysis gave considerably different predictions. We traced this difference to axial flux channelling. Partial volume compensators were carrying the indirect flux in the non-magnetic clamping region as well as the direct magnet leakage flux. This elevated the magnetic field in the compensators, which reduced their permeability. The net impact of 3D partial volume effects and compensator non-linearity was a 50% to 70% reduction in the effectiveness of the compensator. If the magnet remanence has a dB_r/dT=-0.1% then the best a reduced volume compensator could do was to reduce d(GL)/dT from –0.1%/degC to –0.05%/degC. In addition, mechanical expansion of the entire quadrupole increased the clear aperture with temperature. This effect was about –0.03%/degC leading to a total d(GL)/dT of –0.08%./degC. This prediction is consistent with the measured d(GL)/dT on the assembled quad [1].

EDDY CURRENT ANALYSIS

The FEA code we used, MagNet from Infolytica Corp, has 2D and 3D transient solvers with motion and current induced eddy currents. We performed 2D transient eddy current analyses caused by magnet motion. The magnets moved 9.31mm in 40 msecs. This is a –20% strength change. We chose a very fast move to see how long it took for the magnetic field to reach equilibrium. A plot of the magnet retraction vs. time and magnetic field at 80% aperture is shown in Figure 9. The exponential rise time (after the initial oscillation) is 50 msecs. Field change between 180 msec and 200 msec is 0.014%. This shows that the PM quad field could be changed very rapidly should that be needed.

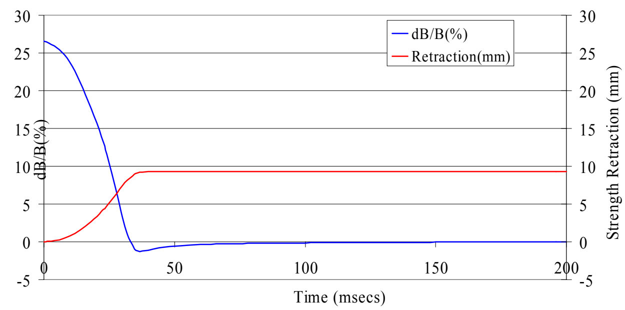

Figure 9: Eddy Current analysis of peak field change vs. time (dB/B) for a rapid field adjustment.

CONCLUSION

We have performed magnetic and engineering analyses of an adjustable strength PM quadrupole. Strength and centerline tuning curves were analyzed. Sensitivity analysis was described. Eddy current calculations indicate that it should be possible to rapidly change the field strength (20% in 0.2 secs) should that be needed. Three dimensional partial volume effects complicated the use of temperature compensating steels. In the future, we will include 3D FEA of temperature effects rather than rely on 2D analysis.

The measured performance of this quadrupole is described in [1]. The magnetic centerline required little calibration and was highly repeatable.

REFERENCES

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[2] S. Gottschalk, et al, Particle Accelerator Conference 2001, p. 3218
[3] J. Volk, et al, Particle Accelerator Conference 2001, p. 217