LCLS-TN-12-3

PPM Phase Shifter Tuning Studies*

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Abstract

This note describes the tuning adjustments for a pure permanent magnet (PPM) phase shifter. Various errors are studied and then the virtual shims to correct the errors are studied. Finally, an error is introduced in the simulation and the virtual shim to correct it is introduced, and the gap dependence of the correction is studied. We find that the error can be corrected at a fixed gap, but for most errors, a gap dependence to the correction remains.

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Contents

1 Introduction

A pure permanent magnet (PPM) phase shifter design was proposed in a previous note[1]. In this note, we analyze the tuning of the phase shifter. We start with an overview of tuning using virtual shims (block motions). Then we discuss typical errors in the phase shifter and the error fields they produce. This is followed by an analysis of the sensitivities of the virtual shims. These sensitivities are important since they tell us how to move the blocks to correct measured errors in the real device. The final section contains a study in which an error is introduced in the simulation and a virtual shim is used to correct it. We find that the correction works well at one gap, but in general does not work at all gaps.

2 Tuning Overview

When a phase shifter is measured in the lab, it will contain error fields which affect the electron beam. The errors are corrected by moving the magnet blocks, a process called virtual shimming. In this section, we present a qualitative look at virtual shims and the fields they produce. We start, however, by reviewing the phase shifter design we will study, and its baseline behavior.

This note studies the phase shifter design presented in the note referenced above. The block sizes are shown in figure 1. Also shown in the figure are the z-positions of the blocks. We will use

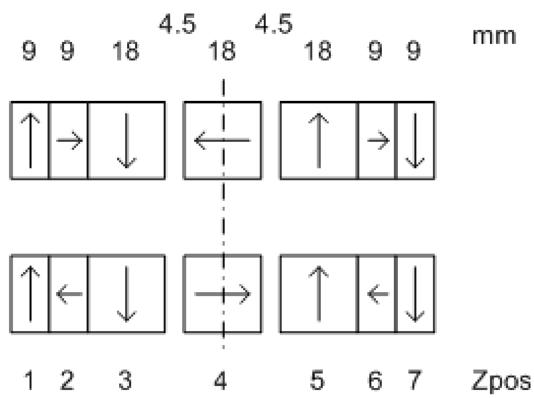

Figure 1: The dimensions of the magnet blocks and their magnetization directions are shown. The z-positions of the blocks are also indicated.

the z-position to identify which blocks we are moving when we make a virtual shim. The blocks are 25 mm high and 66 mm wide. The gap for most cases studied is the smallest gap, 10 mm. With this gap, the fields in the phase shifter are shown in figure 2. The horizontal field is zero. The peak vertical field is approximately 1 T when the gap is 10 mm.

Simulated trajectory changes of an electron beam are studied below when we make a virtual shim. In all cases, we study the effect on an 8.5 GeV electron beam. The horizontal trajectory with no field errors is given in figure 3. The vertical trajectory is straight at zero.

Virtual shims are magnet block motions which cause changes to the field in the phase shifter. One way to introduce a horizontal field B_x is to move upper and lower vertically magnetized blocks in opposite directions horizontally. This is shown in figure 4. The effect can be understood using superposition. The shifted blocks are the same as unshifted blocks plus extra charges which are equivalent to the shift. The extra charges near the beam position produce the desired B_x.

[1] Z. Wolf, "A PPM Phase Shifter Design", LCLS-TN-11-2, July, 2011.

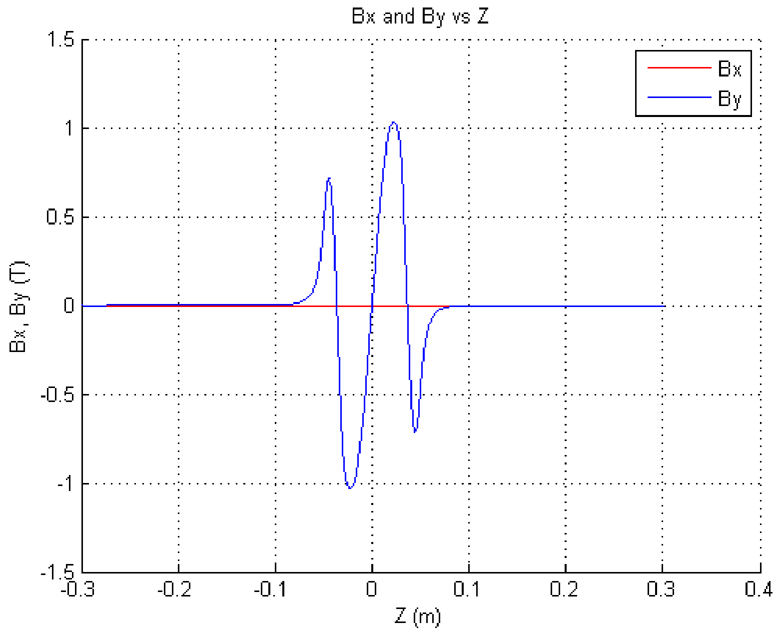

Figure 2: Fields in the phase shifter with no errors.

Block rotations also produce B_x. This is illustrated in figure 5. In this case, the rotated blocks can be thought of as the superposition of unrotated blocks plus new charges that cancel the unrotated block charges and add the charges from the rotated blocks. The new charges near the beam largely cancel each other. It is only at the extreme edges where charges exist without compensating opposite charges close by. These uncompensated charges are indicated in the figure and produce B_x.

The vertical field can be changed by moving vertically magnetized blocks vertically, both toward the gap, or both away from the gap. This is illustrated in figure 6. In this case, the blocks are moved toward the gap. The fields are the same as the fields from blocks at the original positions, plus charges that cancel the original blocks charges and place charges at the new block positions. These new charges increase the vertical field B_y.

Virtual shims change the trajectories. Vertical and horizontal motions of the vertically magnetized blocks give slope changes to the beam. Motion of the horizontally magnetized blocks give displacements to the beam. This will be studied below. The sensitivity of the effect on the beam to the block motion is determined. This information will be used to straighten the trajectories in the phase shifter.

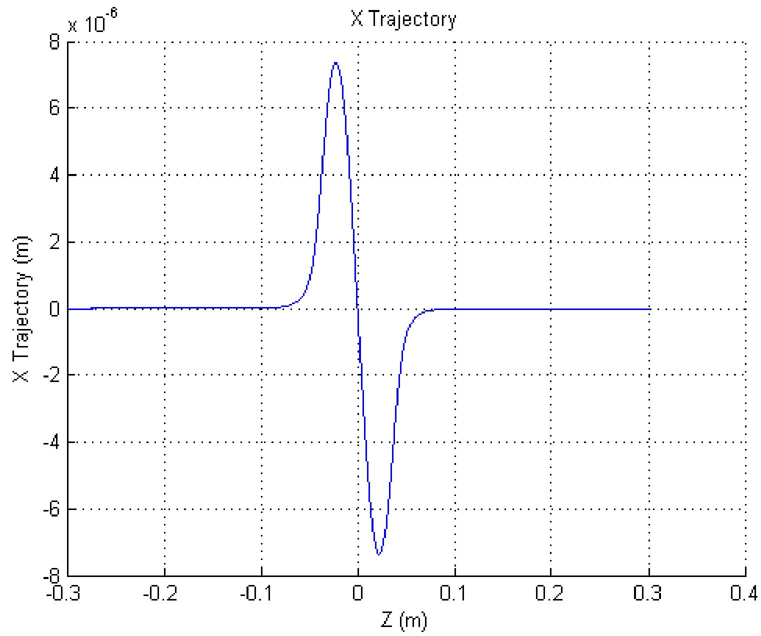

Figure 3: Horizontal trajectory of an 8.5 GeV electron beam with no field errors in the phase shifter.

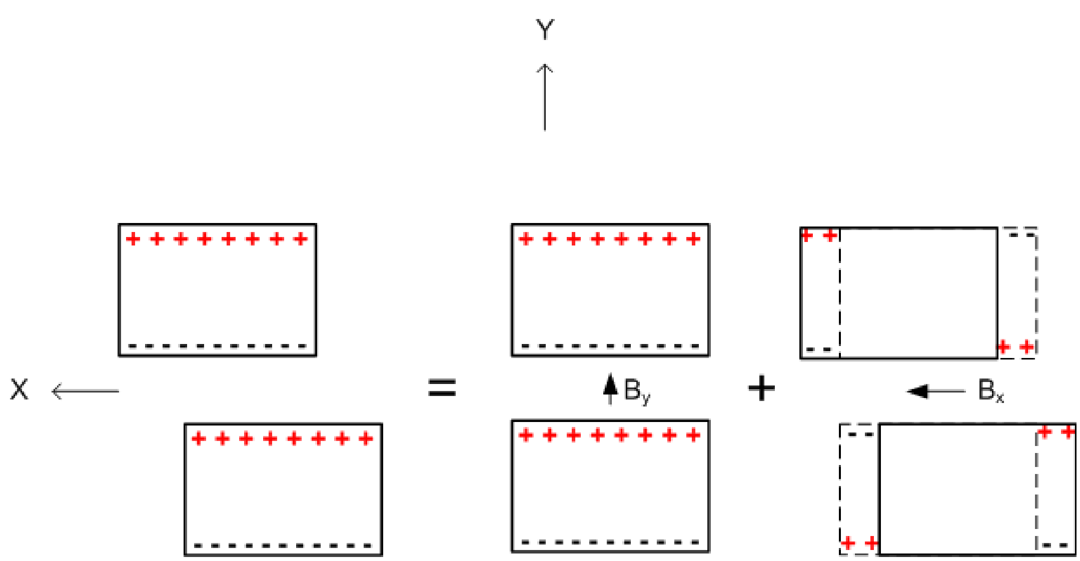

Figure 4: A horizontal field is produced when upper and lower vertically magnetized blocks are shifted horizontally in opposite directions.

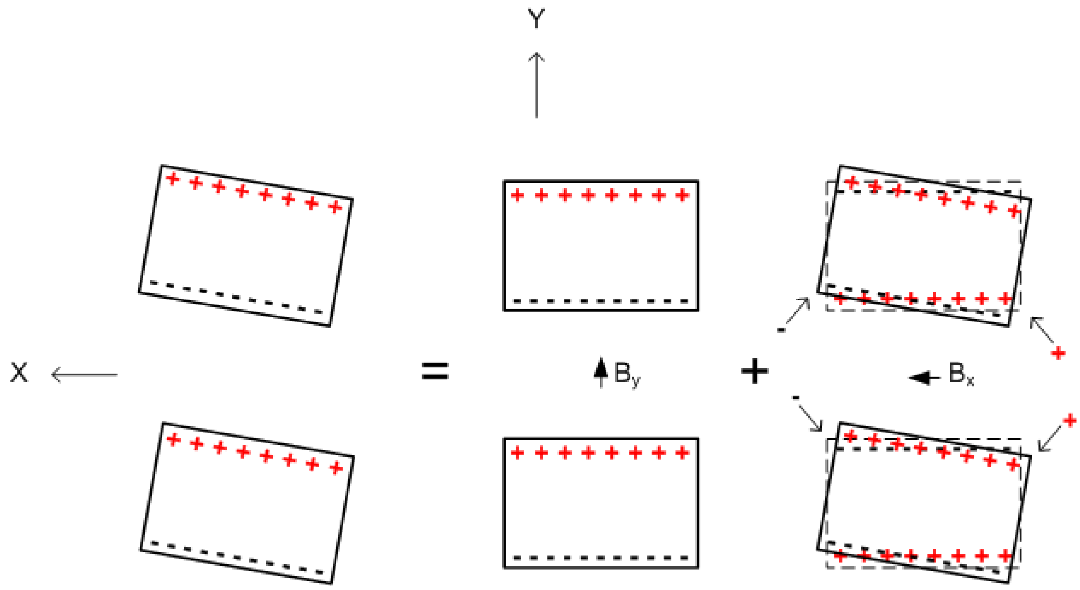

Figure 5: Block rotation produces a horizontal field B_x.

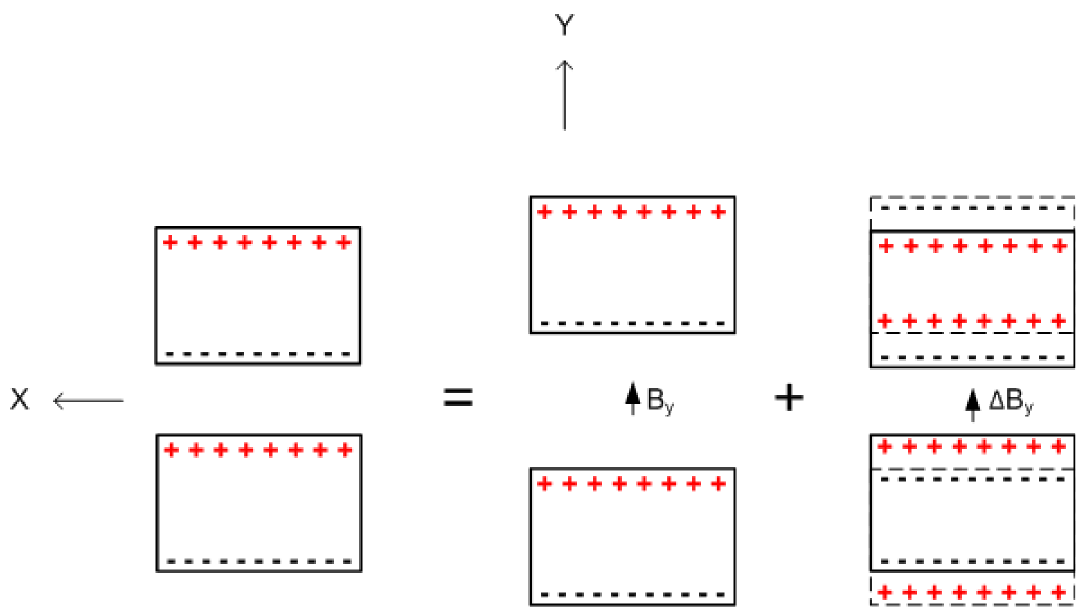

Figure 6: A vertical field change is introduced when vertically magnetized blocks are both moved toward the gap or away from the gap.

3 Typical Errors And Their Signatures

In this section we simulate typical errors in the phase shifter. Block magnetization errors, magnetization direction errors, block translations, and block rotations are considered. The field errors and the effect on the trajectories, as well as the gap dependence are considered. Only a sample of errors is presented, but it illustrates their general behavior.

In all plots with a z-coordinate, $z = 0$ is the center of the phase shifter. The phase shifter is 0.099 m long and extends from $z = -0.0495$ m to $z = +0.0495$ m. Increasing z is in the beam direction. The y-coordinate is up. The x-coordinate makes a right handed system.

3.1 Block Magnetization Error

Consider the effects when the remnant field in the upper block at z-position 3 is 1% too large. This is a vertically magnetized block 18 mm wide. Figure 7 shows the change in B_y resulting from the magnetization error. The maximum value of the field error is approximately 30 G.

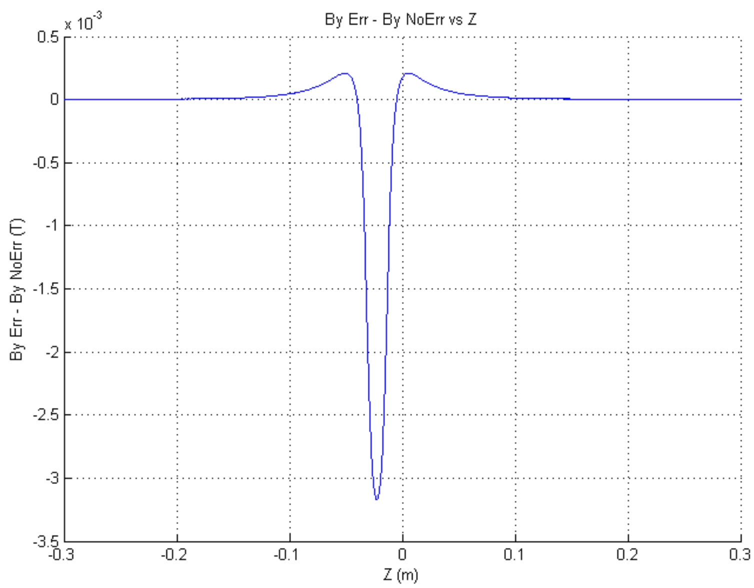

Figure 7: Change in B_y when the upper block at z-position 3 has a magnetization error of 1%.

Figure 8 shows the effect of the field error on the horizontal trajectory. The trajectory slope change from the error is -1.42×10^{-6}. The first integral of the B_y field is -4.07×10^{-5} Tm.

The gap dependence of the first field integral resulting from the 1% magnetization error is shown in figure 9. The magnitude of the first integral is largest at small gap and decays with increasing gap.

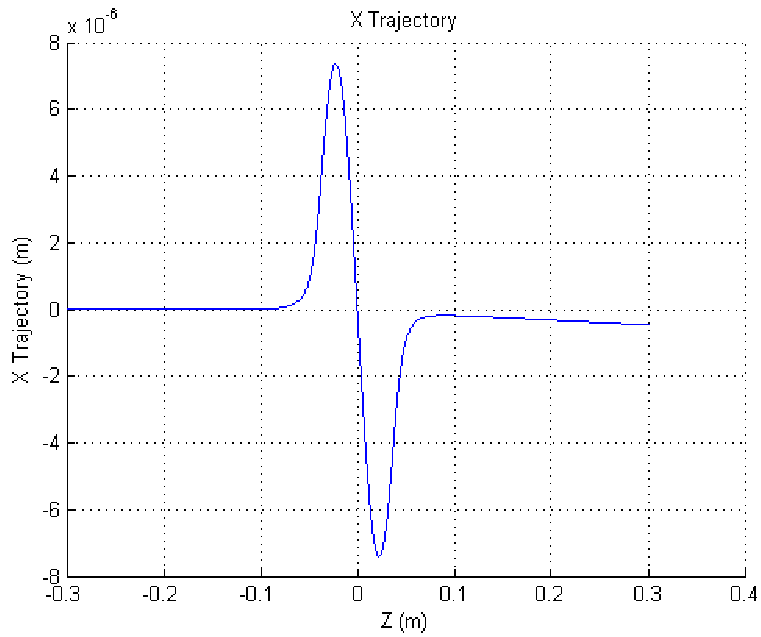

Figure 8: The upper block at z-position 3 has its remnant field increased by 1%. This figure shows the resulting x-trajectory.

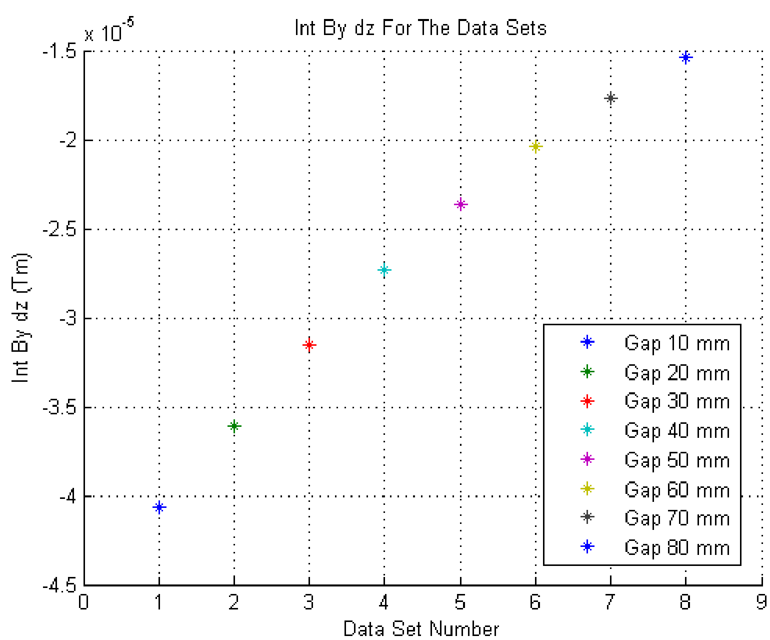

Figure 9: Gap dependence of a 1% error in the magnetization of the upper block at z-position 3.

3.2 Magnetization Direction Error

Suppose the magnetization direction of the upper block at z-position 3 is rotated by 20 mrad about the z-axis, in the positive sense from the x-axis toward the y-axis. A horizontal field is introduced as shown in figure 10. The maximum of the error field is approximately 10 G.

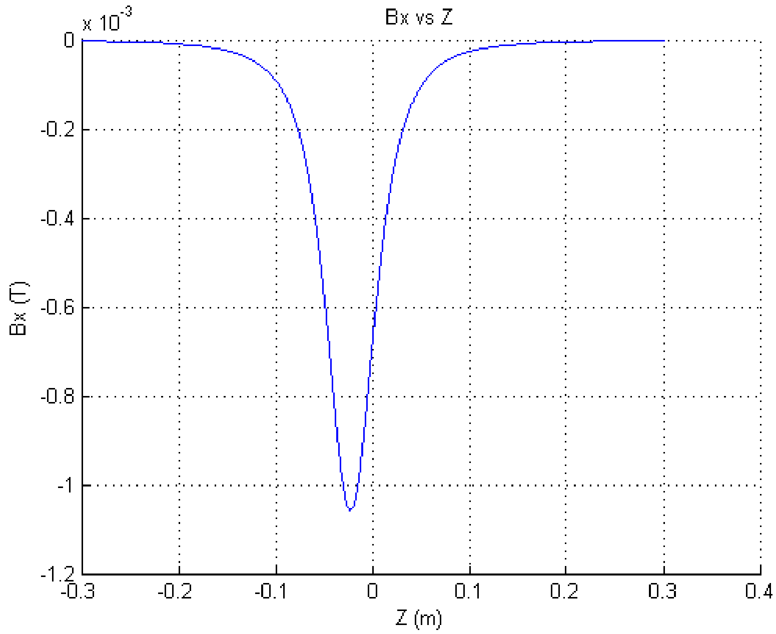

Figure 10: Horizontal field resulting from the magnetization direction of block 3 being rotated by 20 mrad.

The horizontal field affects the vertical trajectory as shown in figure 11. The slope of the exit trajectory is 2.80×10^{-6}. The first integral of the horizontal field is -8.01×10^{-5} Tm.

The gap dependence of the first integral of the horizontal field is shown in figure 12. The first integral is largest at small gaps and decays with gap.

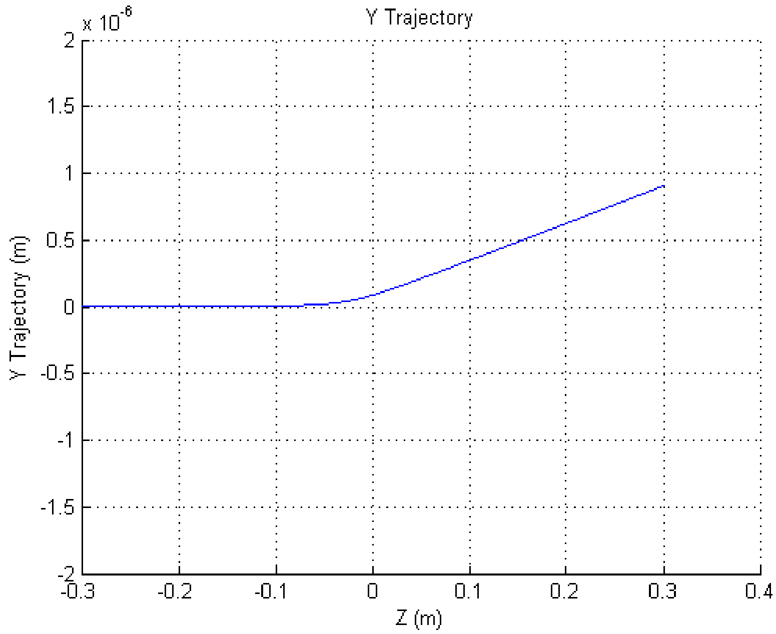

Figure 11: The horizontal field from the block rotation changes the vertical trajectory.

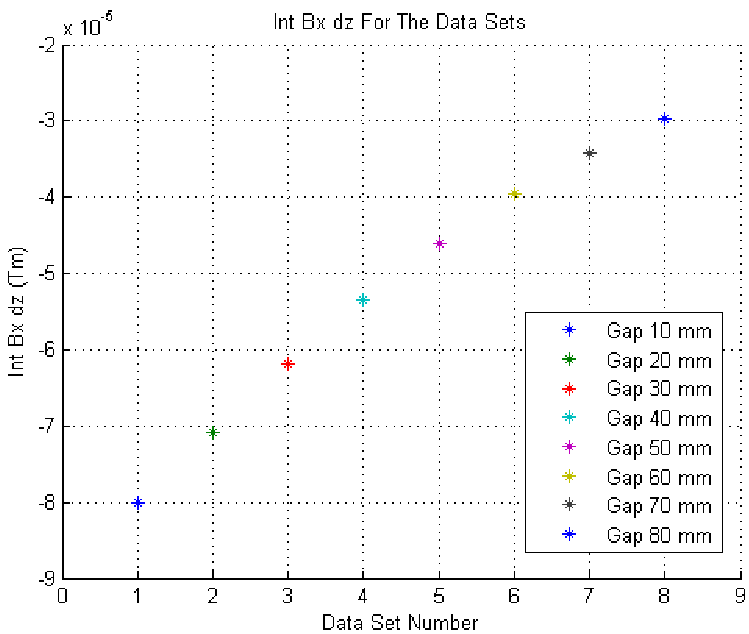

Figure 12: The direction of the magnetization of the upper block at z-position 3 has been rotated by 20 mrad. This plot shows the gap dependence of the first integral of B_x.

3.3 Block Translated Horizontally

When the upper block at z-position 3 is moved toward +x, a horizontal field results. This is shown in figure 13. The maximum value of the error field is approximately 30 G.

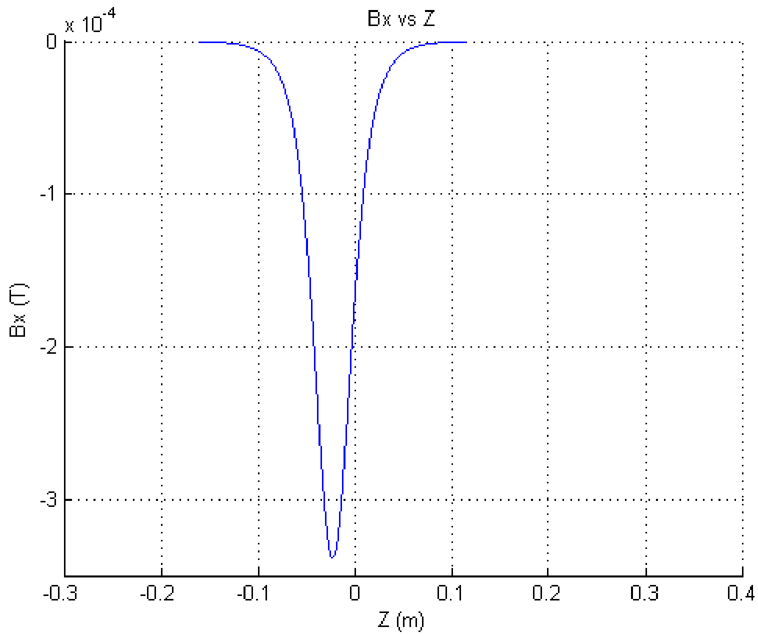

Figure 13: Horizontal field resulting from moving the upper block at z-position 3 by 200 microns in the +x direction.

The horizontal field changes the slope of the vertical trajectory as shown in figure 14. The trajectory slope change is 6.26×10^{-7}. The first integral of the horizontal field is -1.79×10^{-5} Tm.

The gap dependence of the first integral of the horizontal field is shown in figure 15. The first integral peaks at a gap larger than the minimum, and then it decreases at large gap.

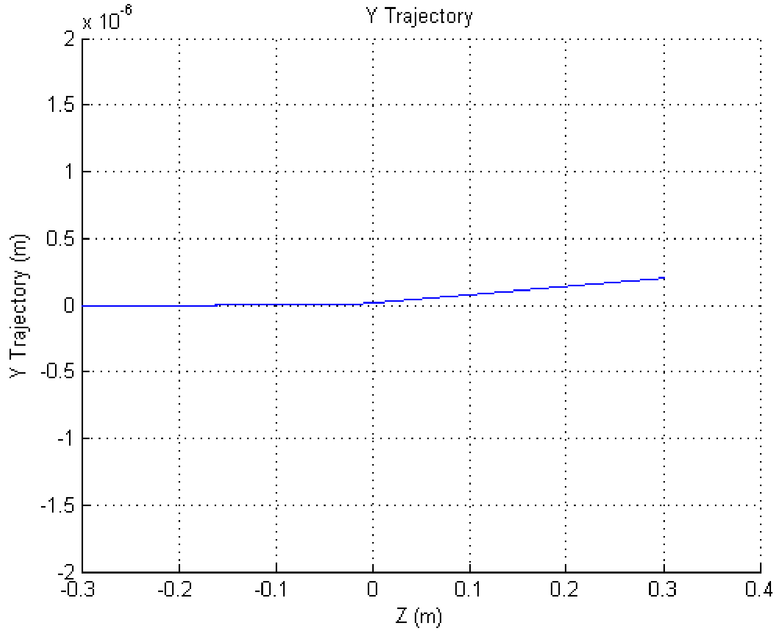

Figure 14: Vertical trajectory resulting from the horizontal field which comes from moving the upper block at z-position 3 by 200 microns in the +x direction.

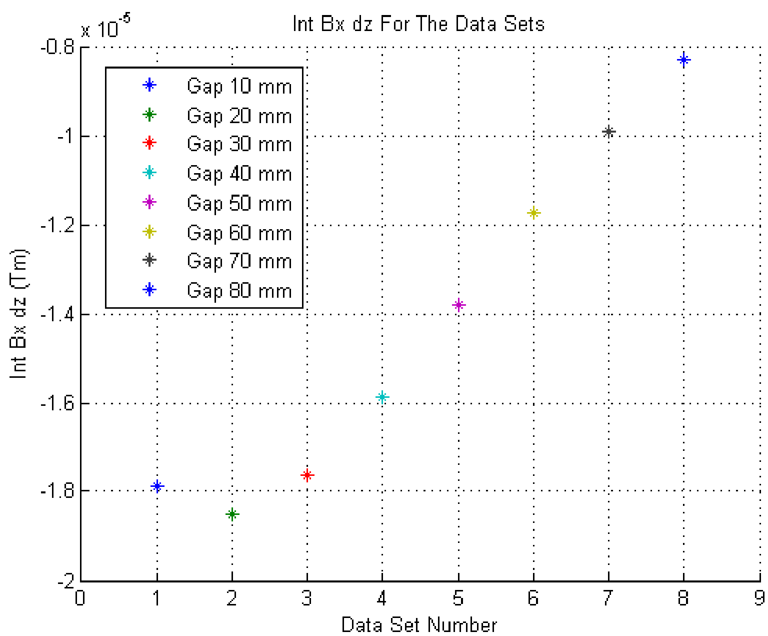

Figure 15: Gap dependence of the first integral of B_x when a 200 micron displacement along +x is introduced in the top block at z-position 3.

3.4 Block Translated Vertically

When the upper block at z-position 3 is moved toward +y by 200 μm, the vertical field changes. This is illustrated in figure 16. The maximum value of the error field is approximately 60 G.

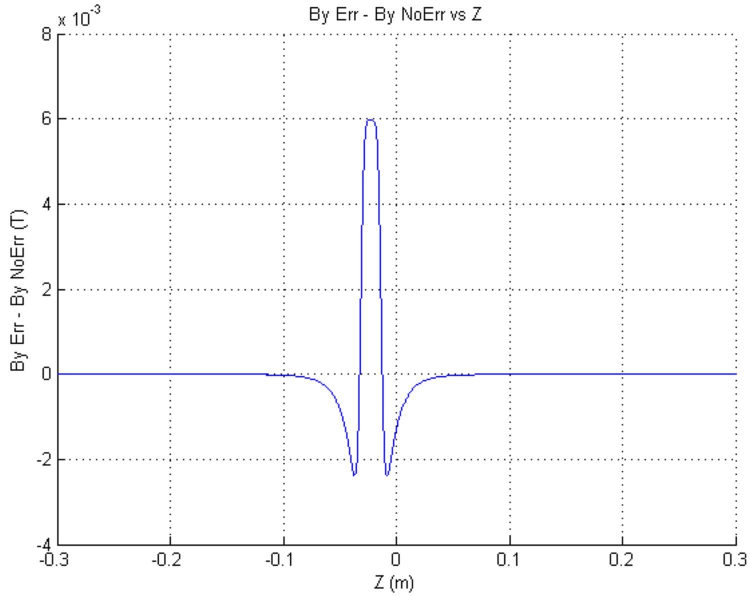

Figure 16: This figure shows the change in the vertical field when the upper block at z-position 3 is moved vertically by 200 microns.

The change in vertical field affects the horizontal trajectory as shown in figure 17. The slope of the exit trajectory is now 6.28×10^{-7}. The first integral of B_y is 1.80×10^{-5} Tm.

The gap dependence of the first integral of B_y is shown in figure 18. The field integral increases slightly as the gap is opened past minimum, then it decreases as the gap is opened further.

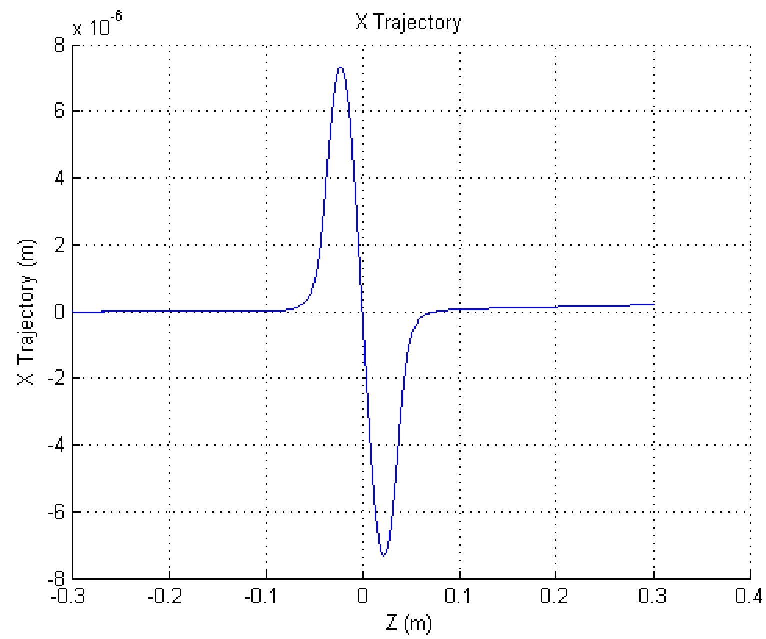

Figure 17: X-trajectory when the upper block at z-position 3 is moved vertically by 200 microns.

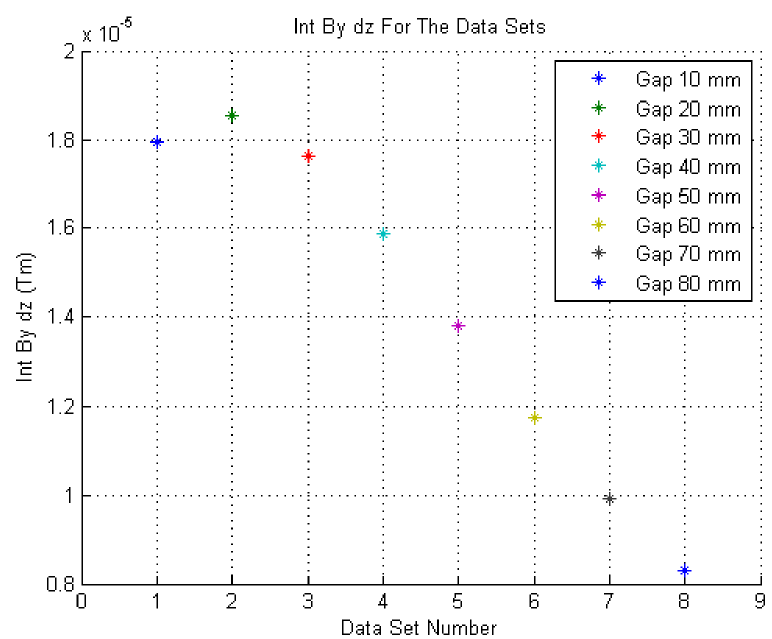

Figure 18: First integral of B_y as a function of gap. The upper block at z-position 3 has been moved vertically by 200 microns.

3.5 Block Rotated

When the upper block at z-position 3 is rotated about its center along the z-axis in the positive sense from the x-axis toward the y-axis, a horizontal field is created. This is illustrated in figure 19 for a rotation angle of 20 mrad. The maximum value of the error field is approximately 60 G.

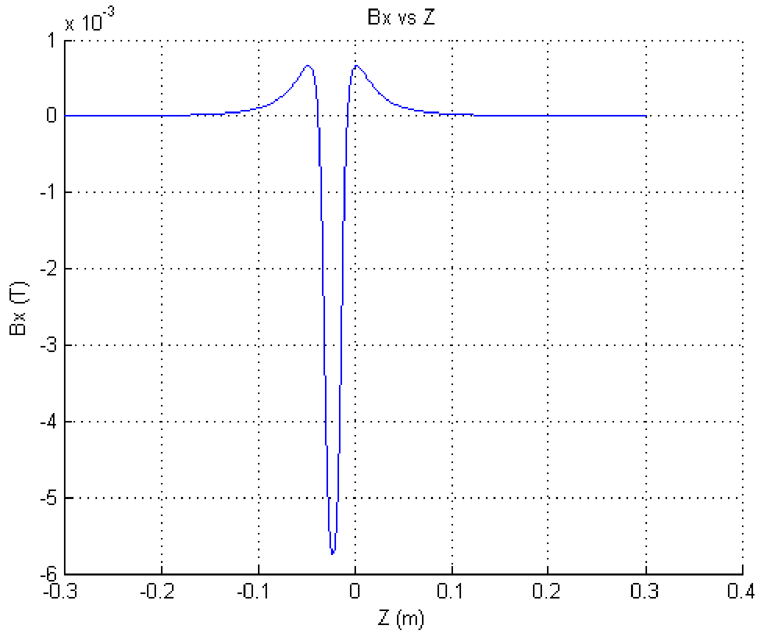

Figure 19: Horizontal field resulting from rotating the upper block at z-position 3 by 20 mrad about the block center along a line parallel to the z-axis.

The horizontal field changes the slope of the vertical trajectory. This is illustrated in figure 20. The slope of the exit trajectory is 1.75×10^{-6}. The first integral of B_x is -5.01×10^{-5} Tm.

The gap dependence of the first integral of B_x is shown in figure 21. The first integral is largest at small gap and then decreases as the gap is opened, up to a point when the first integral changes sign.

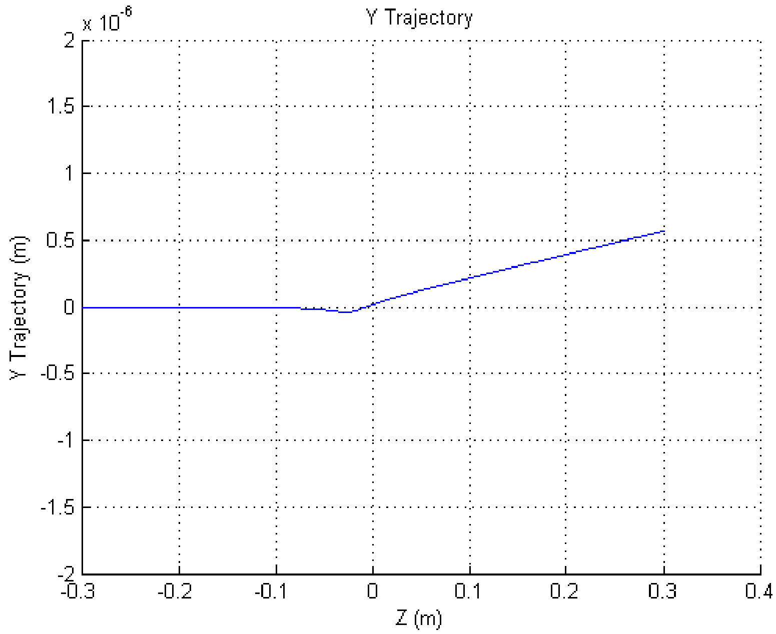

Figure 20: The vertical trajectory gets a slope change because of the horizontal field resulting from the block rotation.

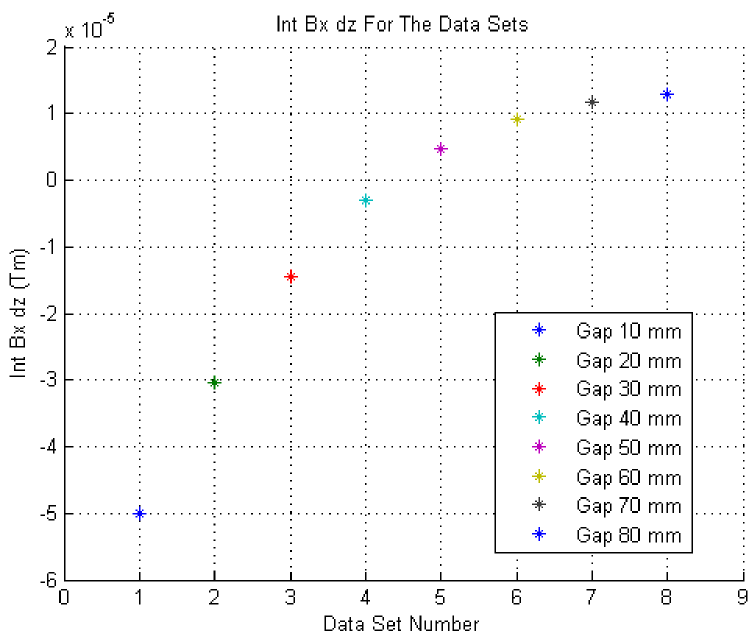

Figure 21: First integral of B_x as a function of gap when the upper block at z-position 3 is rotated 20 mrad about its center and about the z-direction.

4 Virtual Shims For Error Correction

In this section the effect of block motions, virtual shims, on electron trajectories is studied. In all cases, the electron energy is 8.5 GeV. The electron enters the phase shifter at $x = 0$, $y = 0$, and with zero slope. The phase shifter gap for these studies is 10 mm.

4.1 Horizontal Trajectory Slope Changes

4.1.1 9 mm Vertically Magnetized Blocks Moved Vertically

When the 9 mm thick vertically magnetized blocks at z-position 1 are both moved either away from the gap or toward the gap, the slope of the horizontal trajectory changes. This is illustrated in figure 22 where both the upper and lower blocks are moved into the gap by 600 μm. The slope change is positive, consistent with the vertical field becoming stronger. The exit trajectory slope goes from zero to 1.87×10^{-6}. The first integral of the horizontal field goes from zero to 5.35×10^{-5} Tm. The horizontal field remains zero. The vertical trajectory remains at zero.

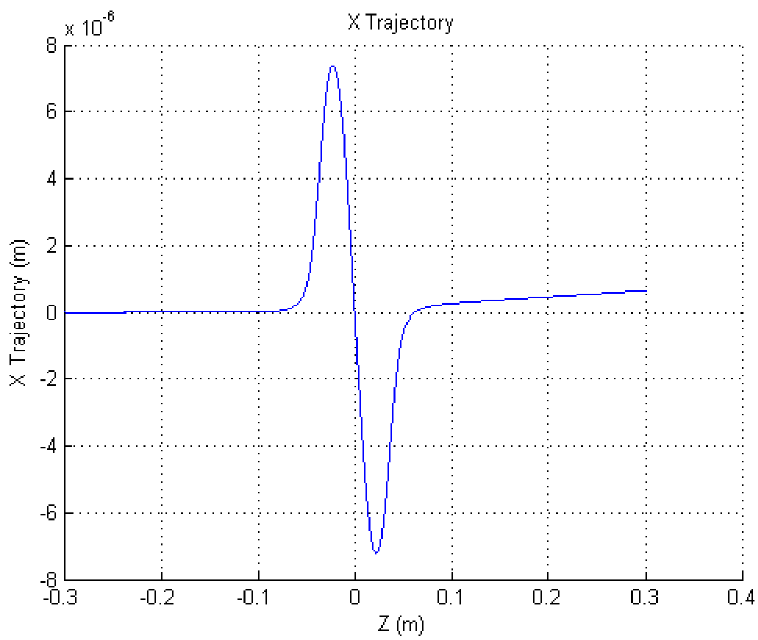

Figure 22: Horizontal trajectory when the blocks at z-position 1 are moved into the gap both by 600 μm.

The slope change as a function of block motion is plotted in figure 23. The fitted slope, the sensitivity of the virtual shim, is -3.14×10^{-9} 1/micron of block motion. Note that both the upper and lower blocks are moved by the indicated amounts, so the gap change is twice the indicated amount. The magnitude of this slope change sensitivity also applies to the blocks at z-position 7 since they have the same thickness, but the sign of the sensitivity is reversed since the field direction is reversed.

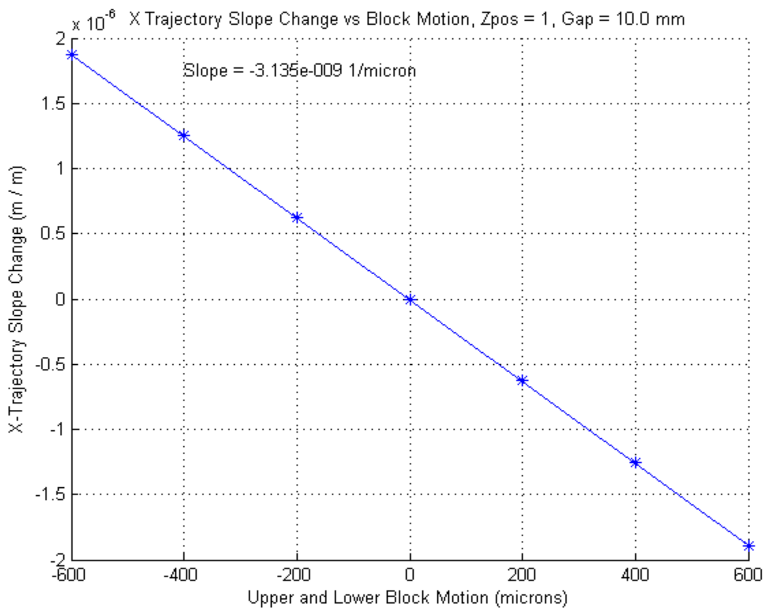

Figure 23: The upper and lower blocks at z-position 1 are moved vertically. The two blocks are either moved away from the gap (+ move), or toward the gap (- move).

4.1.2 18 mm Vertically Magnetized Blocks Moved Vertically

When the 18 mm thick vertically magnetized blocks at z-position 3 are both moved either away from the gap or toward the gap, the horizontal slope of the trajectory changes. This is illustrated in figure 24 where both the upper and lower blocks are moved into the gap by 600 μm. The slope change is negative, consistent with the vertically down field becoming stronger. The exit trajectory slope goes from zero to -3.74×10^{-6}. The first integral of the horizontal field goes from zero to -1.07×10^{-4} Tm. The horizontal field remains zero. The vertical trajectory remains at zero.

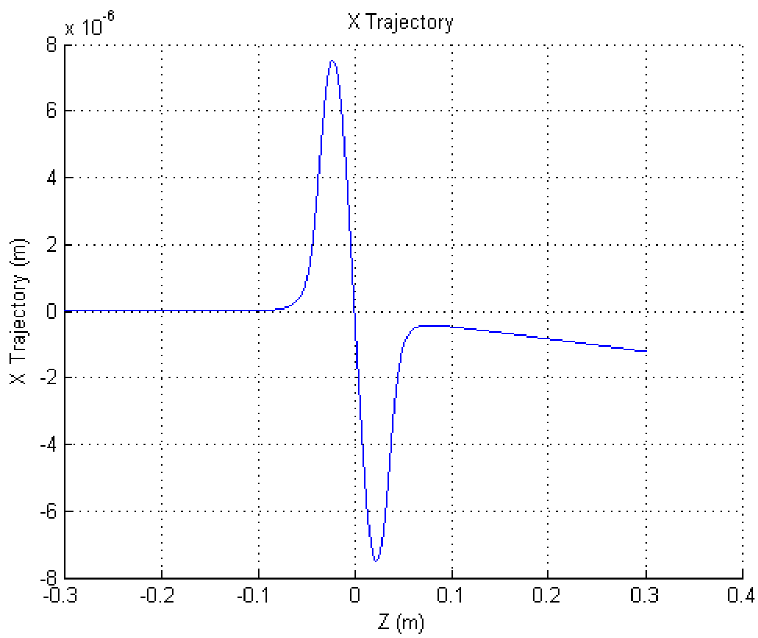

Figure 24: Horizontal trajectory when the blocks at z-position 3 are moved into the gap both by 600 μm.

The slope change as a function of block motion is plotted in figure 25. The fitted slope is 6.27×10^{-9} 1/micron of block motion. Note that each of the upper and lower blocks is moved by the indicated amounts, so the gap change is twice the indicated amount.

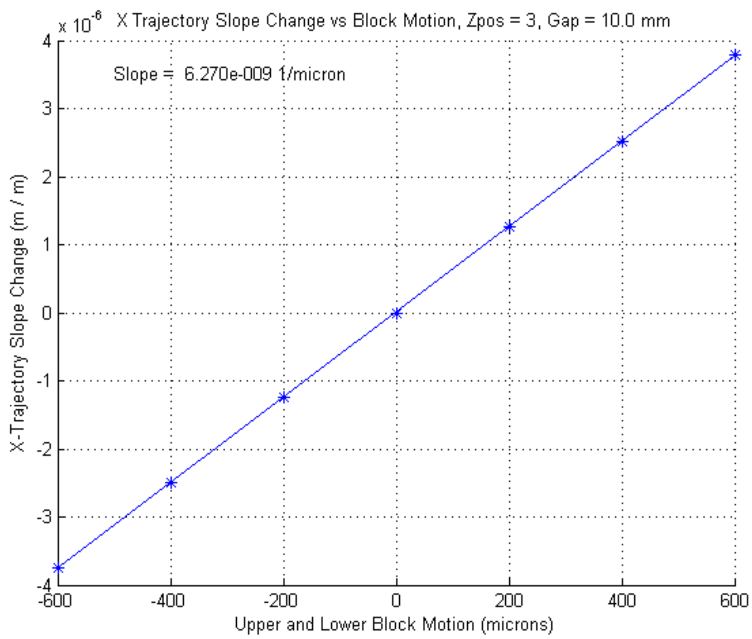

Figure 25: The upper and lower blocks at z-position 3 are moved vertically. The two blocks are either moved away from the gap (+ move), or toward the gap (- move).

4.2 Vertical Trajectory Slope Changes

4.2.1 9 mm Vertically Magnetized Blocks Moved Horizontally

When the 9 mm thick vertically magnetized blocks at z-position 1 are moved in opposite directions horizontally, a horizontal field is created. This is illustrated in figure 26 where the upper block is moved by 600 μm in the +x direction, and the lower block is moved by 600 μm in the -x direction.

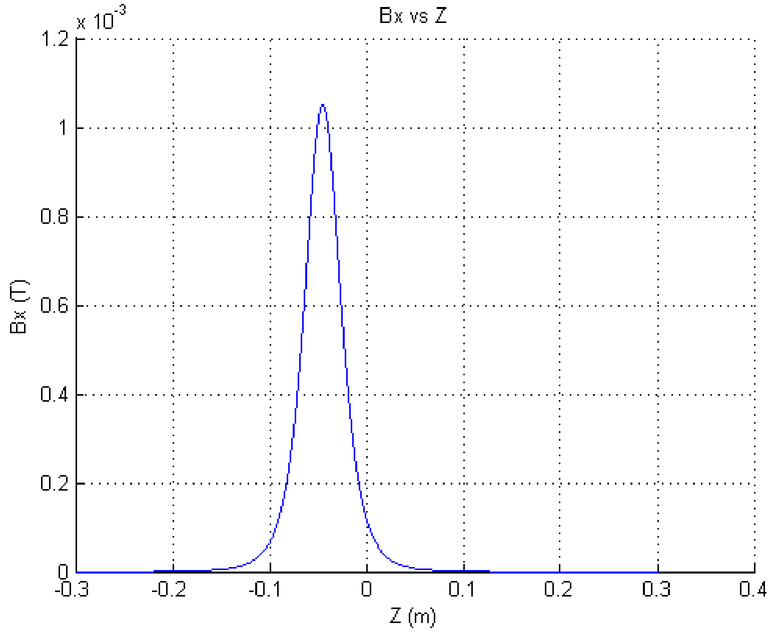

Figure 26: A horizontal field is created when the upper block at z-position 1 is moved by 600 μm in the +x direction, and the lower block is moved by 600 μm in the -x direction.

The horizontal field makes a slope change to the vertical trajectory. This is illustrated in figure 27. The slope of the exiting vertical trajectory is -1.88×10^{-6}. The first integral of the horizontal field goes from zero to 5.37×10^{-5} Tm. The horizontal trajectory remains unchanged.

The slope change as a function of block motion is plotted in figure 28. The fitted slope is -3.14×10^{-9} 1/micron of block motion.

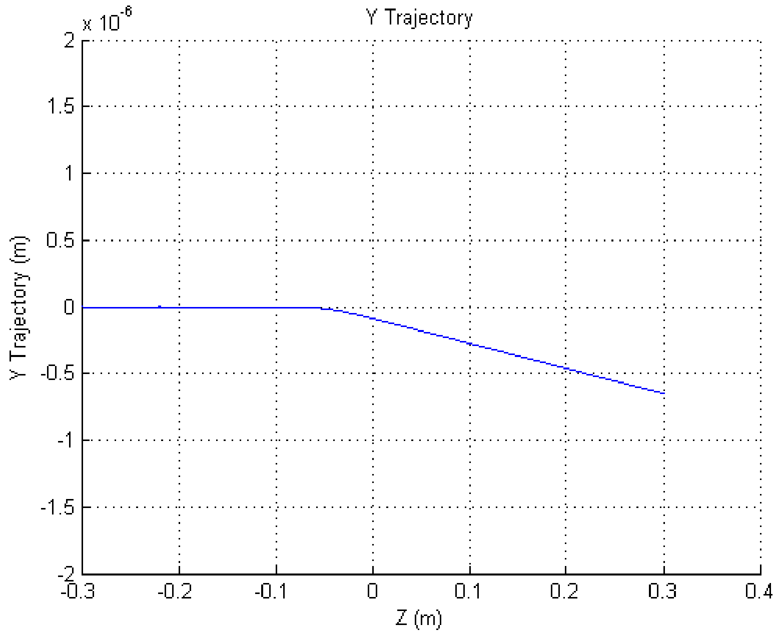

Figure 27: The horizontal field from the opposite horizontal block motions of the blocks at z-position 1 produce a slope change to the vertical trajectory.

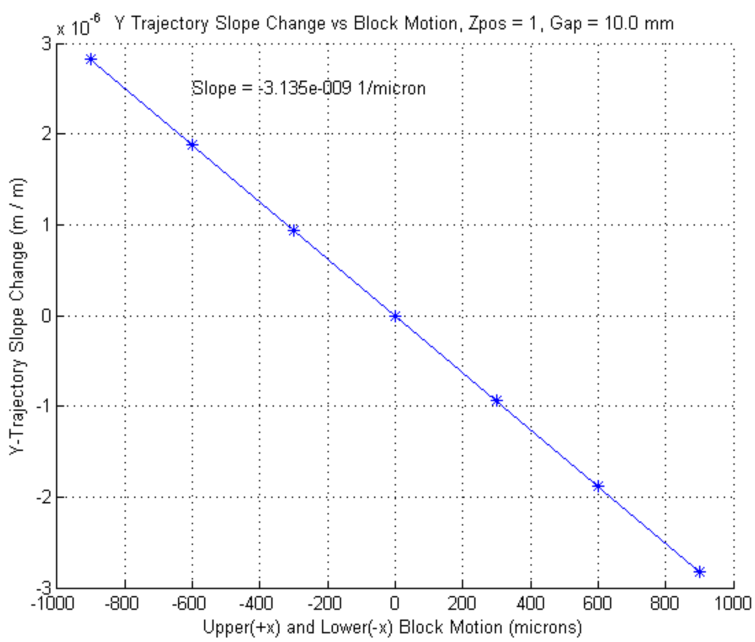

Figure 28: Vertical trajectory slope change as a function of upper (+x) and lower (-x) horizontal block motions.

4.2.2 9 mm Vertically Magnetized Blocks Rotated

When the 9 mm thick vertically magnetized blocks at z-position 1 are rotated about their center through the same angle, a horizontal field is created. This is illustrated in figure 29 where both the upper block and the lower block are rotated by 20 mrad in the positive direction, which moves points on the x-axis toward points on the y-axis.

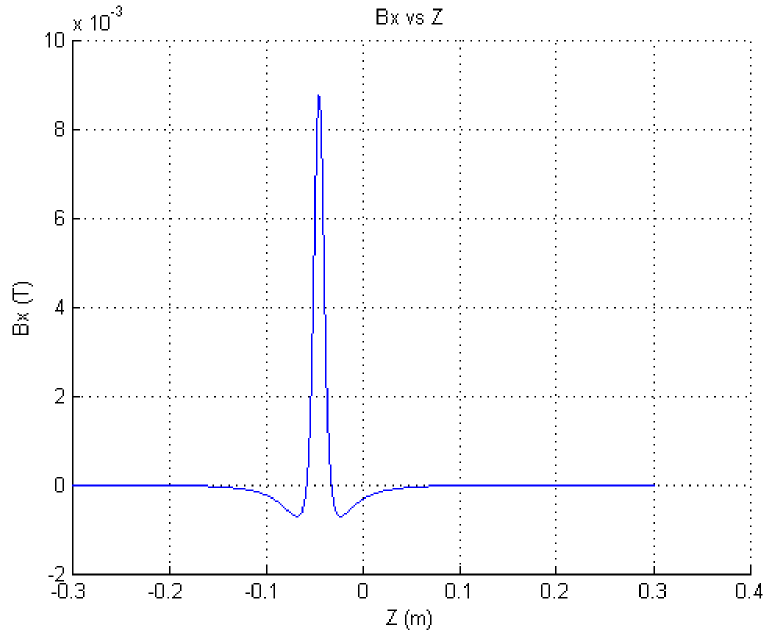

Figure 29: A horizontal field is created when the upper and lower blocks at z-position 1 are rotated by 20 mrad in the positive direction, where points on the x-axis are moved toward the y-axis.

The horizontal field makes a slope change to the vertical trajectory. This is illustrated in figure 30. The exit slope of the vertical trajectory is -1.75×10^{-6}. The first integral of the horizontal field is 5.01×10^{-5} Tm.

The slope change as a function of block rotation is plotted in figure 31. The slope changes by -8.77×10^{-8} 1/mrad of block rotation.

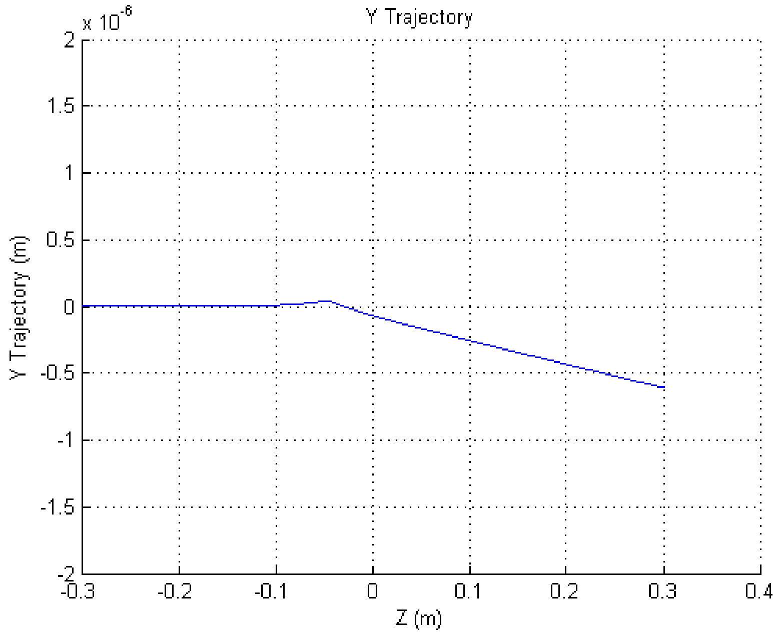

Figure 30: The horizontal field from the block rotations at z-position 1 produces a slope change to the vertical trajectory.

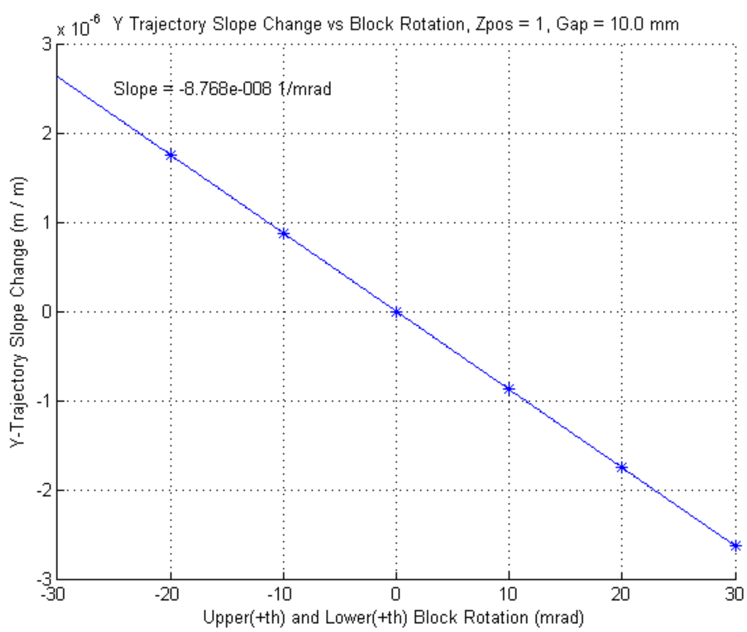

Figure 31: Vertical trajectory slope change as a function of upper (+th) and lower (+th) block rotation.

4.2.3 18 mm Vertically Magnetized Blocks Moved Horizontally

When the 18 mm thick vertically magnetized blocks at z-position 3 are moved in opposite directions horizontally, a horizontal field is created. This is illustrated in figure 32 where the upper block is moved by 600 μm in the +x direction, and the lower block is moved by 600 μm in the -x direction.

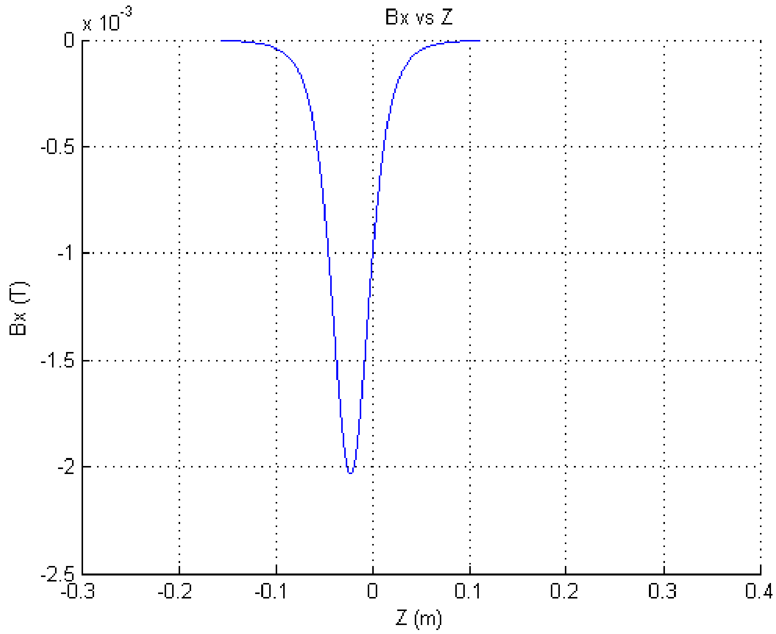

Figure 32: A horizontal field is created when the upper block at z-position 3 is moved by 600 μm in the +x direction, and the lower block is moved by 600 μm in the -x direction.

The horizontal field makes a slope change to the vertical trajectory. This is illustrated in figure 33.The slope of the vertical exit trajectory is 3.76×10^{-6} for the 600 microns of block motion. The first integral of the horizontal field goes from zero to -1.07×10^{-4} Tm. The horizontal trajectory remains essentially unchanged.

The slope change as a function of block motion is plotted in figure 34.The fitted slope is 6.27×10^{-9} 1/micron of block motion.

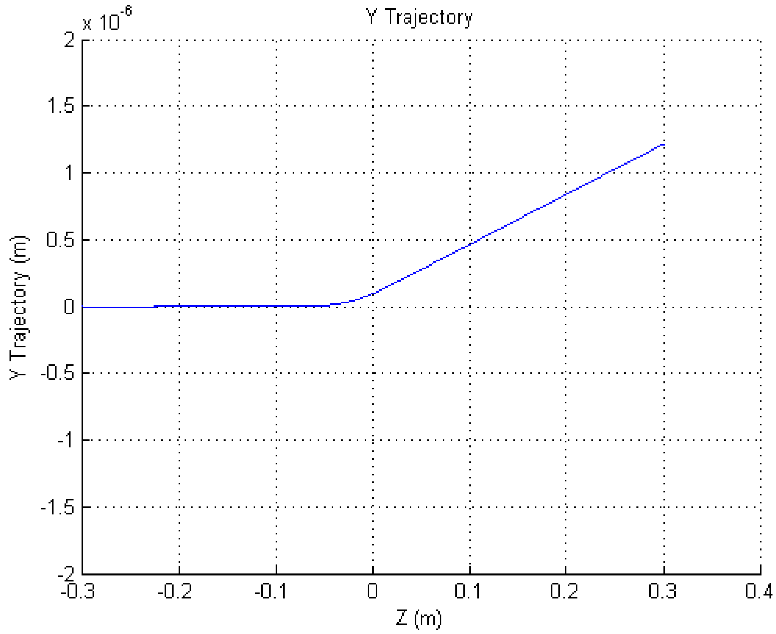

Figure 33: The horizontal field from the opposite horizontal block motions at z-position 3 produces a slope change to the vertical trajectory.

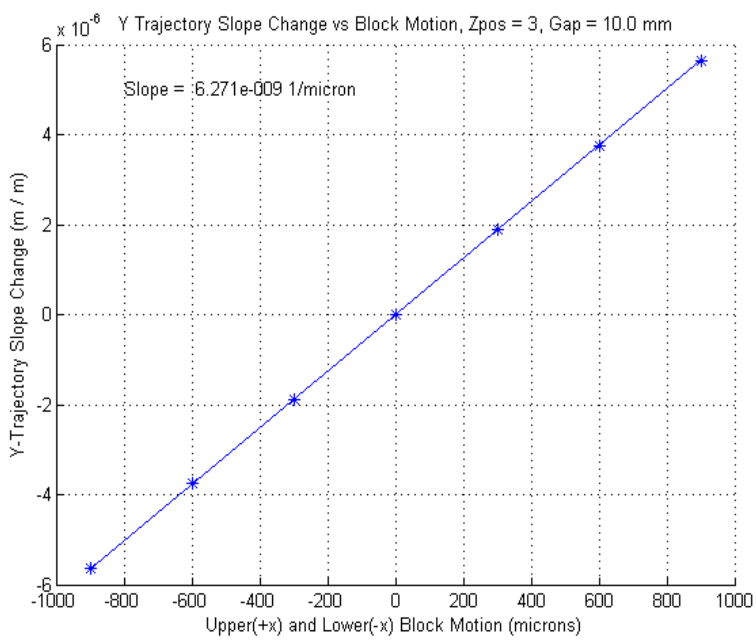

Figure 34: Vertical trajectory slope change as a function of upper (+x) and lower (-x) horizontal block motions at z-position 3.

4.2.4 18 mm Vertically Magnetized Blocks Rotated

When the 18 mm thick vertically magnetized blocks at z-position 3 are rotated about their centers through the same angle, a horizontal field is created. This is illustrated in figure 35 where both the upper block and the lower block are rotated by 20 mrad in the positive direction, which moves points on the x-axis toward points on the y-axis.

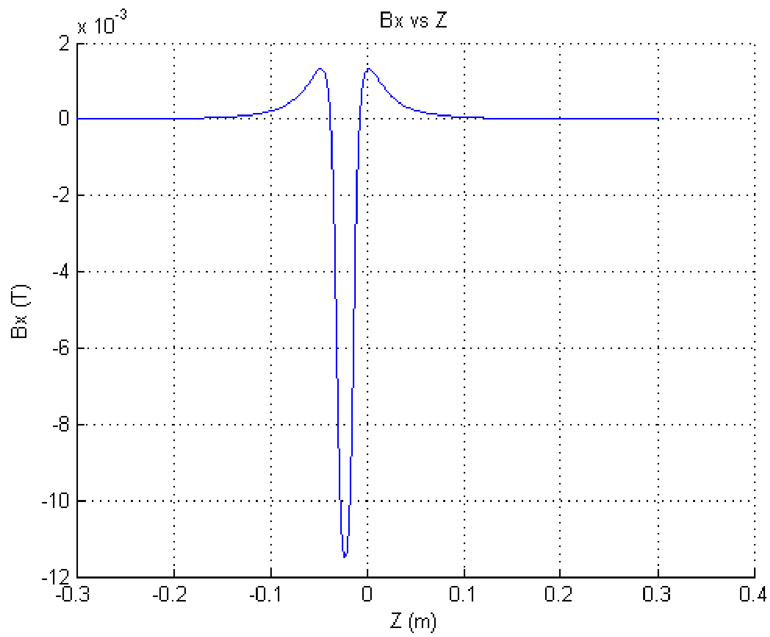

Figure 35: A horizontal field is created when the upper and lower blocks at z-position 3 are rotated by 20 mrad in the positive direction where points on the x-axis are moved toward the y-axis.

The horizontal field makes a slope change to the vertical trajectory. This is illustrated in figure 36. The exit slope of the vertical trajectory is 3.50×10^{-6}. The first integral of the horizontal field is -1.00×10^{-4} Tm.

The slope change as a function of block rotation is plotted in figure 37. The fitted slope is 1.75×10^{-7} 1/mrad of block rotation.

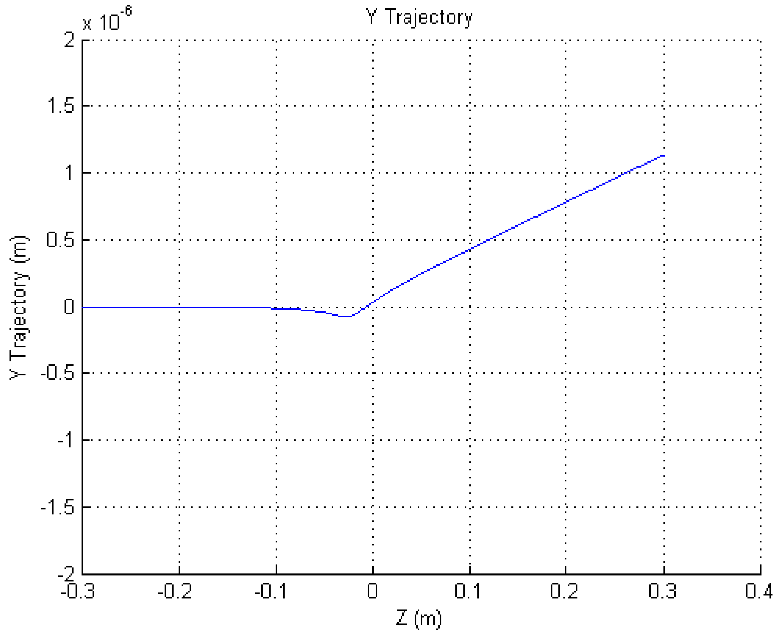

Figure 36: The horizontal field from the block rotations at z-position 3 produces a slope change to the vertical trajectory.

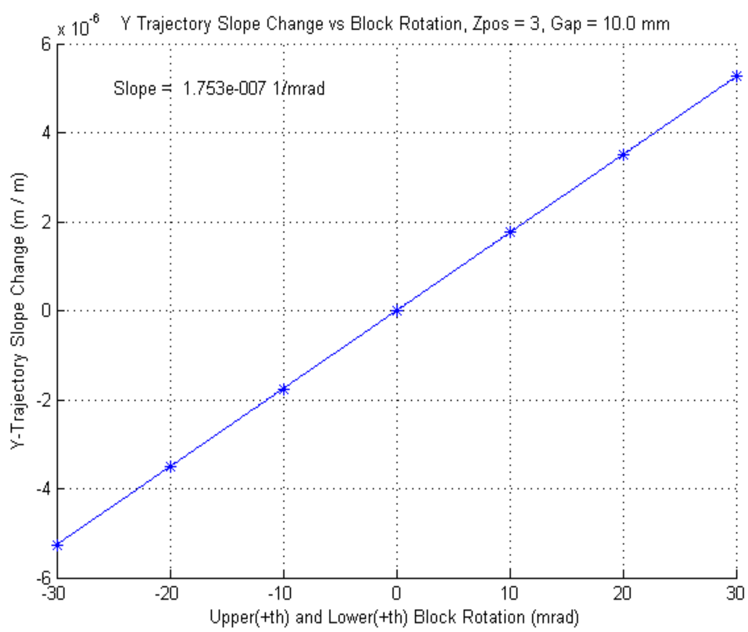

Figure 37: Vertical trajectory slope change as a function of upper (+th) and lower (+th) block rotation.

4.3 Horizontal Trajectory Offsets

4.3.1 18 mm Horizontally Magnetized Blocks Moved Vertically

Moving horizontally magnetized blocks vertically produces equal and opposite vertical field integrals at the ends of the block. The introduces equal and opposite slope changes to the horizontal trajectory, which produces an offset. The effect is fairly small, however, because much of the charge on the face of the block is away from the beam, and also the blocks are fairly short. When the blocks at z-position 3 were moved away from the gap by 900 microns, the offset to the horizontal trajectory was only 0.26 micron. The second field integral of the vertical field was 7.35×10^{-6} Tm^2. This effect is fairly small, so an alternate method to introduce an offset to the horizontal trajectory is introduced next.

4.3.2 Spacer Dimension Change

When the 4 spacers in the phase shifter are changed, the horizontal trajectory receives an offset. This is shown in figure 38. In this figure, all 4 spacers have been increased in thickness by 3 mm. The vertical trajectory remains at zero.

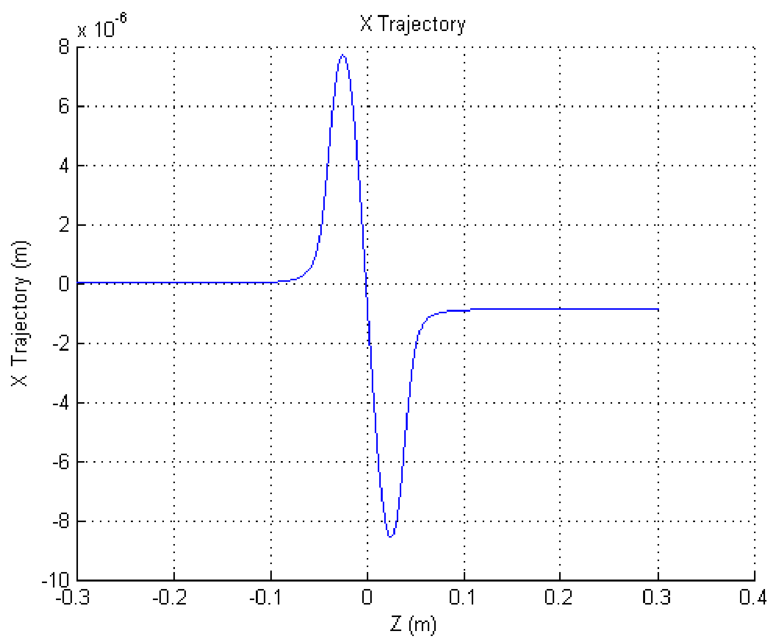

Figure 38: The horizontal trajectory gets an offset when the spacer thicknesses change. In this figure, all 4 spacers have been increased in thickness by 3 mm.

Figure 39 shows the horizontal trajectory offset as a function of spacer thickness change. All 4 spacer thicknesses are changed. The fitted slope is -2.89×10^{-7} m/mm, representing the change in offset position in meters per millimeter of spacer change of the 4 spacers.

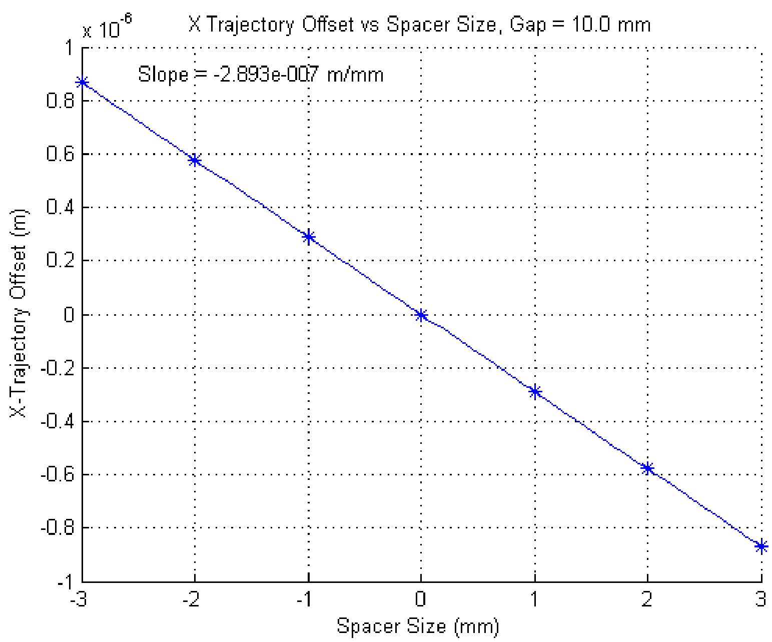

Figure 39: Horizontal trajectory offset as a function of spacer thickness change. All 4 spacers are changed.

4.4 Vertical Trajectory Offsets

Moving a horizontally magnetized block horizontally introduces equal and opposite horizontal fields at the ends of the block. The effect is to introduce two equal and opposite slope changes to the vertical trajectory, which produces an offset. Because much of the magnetic charge on the face of a horizontally magnetized block is away from the beam, and the block is short, the offset introduced from this block motion is fairly small. We only consider the case of moving the center 18 mm thick block, which produces the strongest effect. Even though the effect is small, we consider it because it is an easy way to introduce small offset corrections to the vertical trajectory. Large corrections can be made by making two slope changes using the methods previously described.

4.4.1 18 mm Horizontally Magnetized Blocks Moved Horizontally

When the 18 mm horizontally magnetized blocks in the center of the phase shifter are moved horizontally in opposite directions, equal and opposite horizontal fields are produced. This is illustrated in figure 40. The equal and opposite horizontal fields introduce a vertical offset to the beam. This

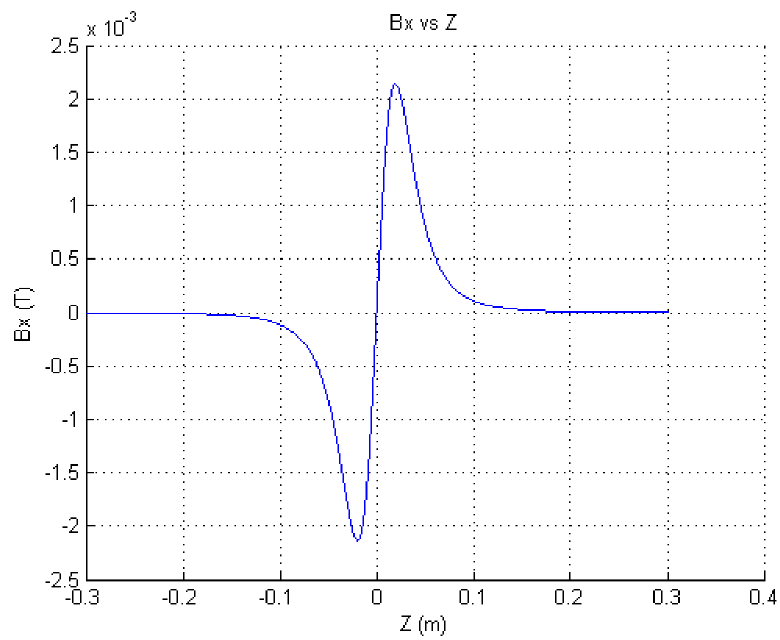

Figure 40: Equal and opposite horizontal fields are created when the upper block at z-position 4 is moved by 900 μm in the +x direction, and the lower block is moved by 900 μm in the -x direction.

is shown in figure 41.

The vertical offset as a function of block motion is shown in figure 42. The fitted slope is 2.76×10^{-10} m/micron, representing the trajectory offset in meters per micron of block motion of the upper and lower blocks.

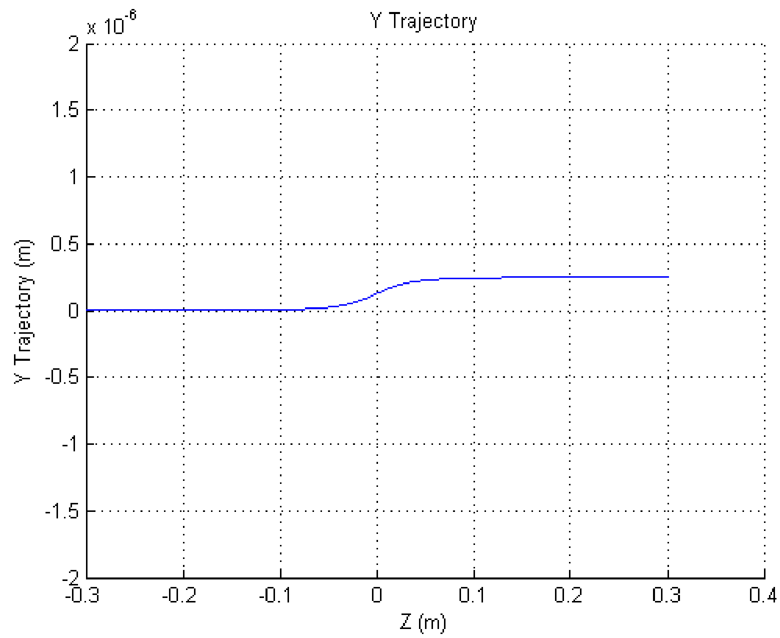

Figure 41: The horizontal fields from the horizontal block motions at z-position 4 produce a vertical offset to the trajectory.

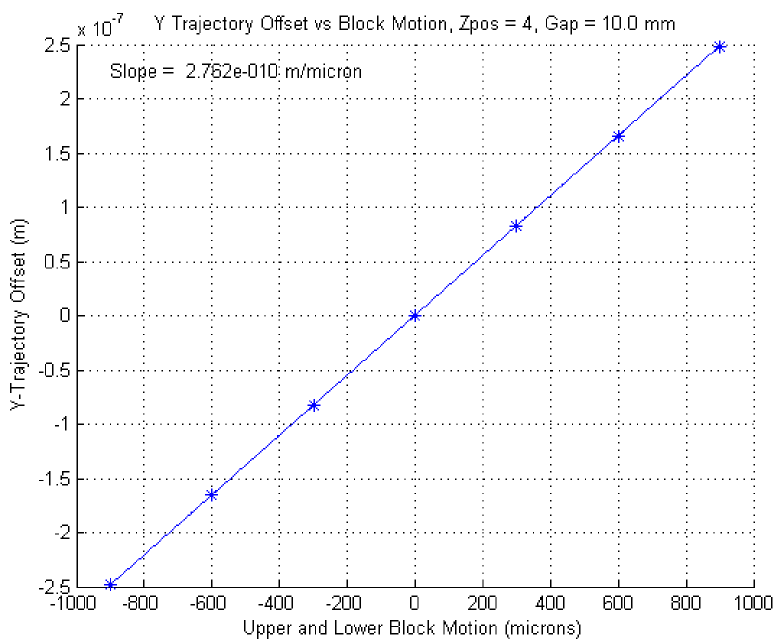

Figure 42: Vertical trajectory offset as a function of upper (+x) and lower (-x) horizontal block motions at z-position 4.

5 Tuning Simulations

In this section, an error is introduced into the phase shifter, and virtual shims are used to correct the error at 10 mm gap. The corrected phase shifter is then studied at different gaps. It will be seen that the virtual shims studied in the previous section work well at 10 mm gap, but the correction does not work as well at other gaps.

5.1 Block Magnetization Error Corrected By Vertical Block Motion Virtual Shim

When the magnetization of the upper block at z-position 3 is increased by 1%, the trajectory of figure 8 results. The slope of the exiting trajectory is -1.42×10^{-6}. When a virtual shim is applied by moving the blocks at z-position 3 away from the gap, the trajectory is corrected. The sensitivity of the virtual shim at 10 mm gap is 6.27×10^{-9} 1/micron, which is the slope change per micron of block motion. The required virtual shim is then to move both the upper and lower blocks away from the gap by $\left(1.42 \times 10^{-6}\right) / \left(6.27 \times 10^{-9} \text{ 1/micron}\right) = 226$ microns. This fixes the trajectory when the gap is 10 mm. The trajectory at 10 mm and other gaps is shown in figure 43.

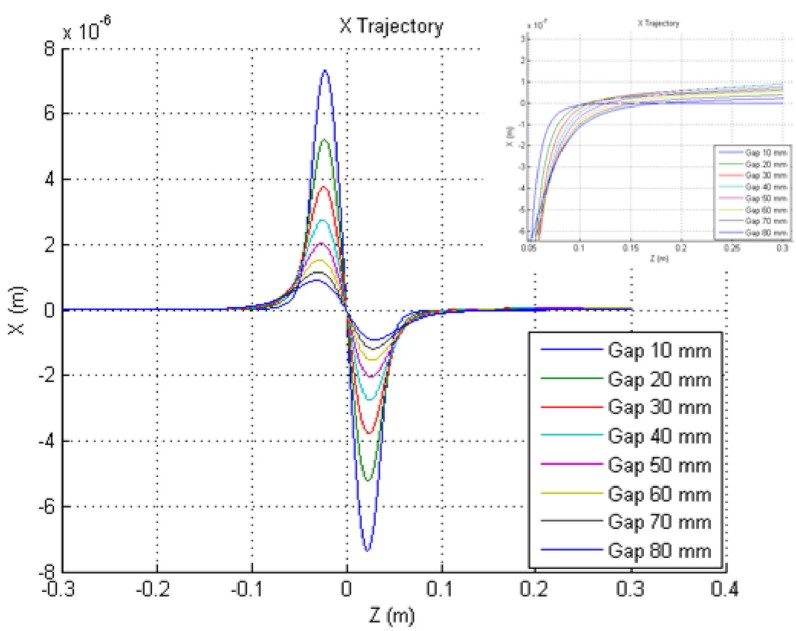

Figure 43: The virtual shim fixed the 1% block magnetization error at 10 mm gap, but the trajectory still has an exit slope at other gaps.

Figure 44 shows the first integral of B_y as a function of gap. There is a first integral of approximately 9 μTm at a gap of 40 mm, and the field integral is smaller at both smaller and larger gaps.

Suppose now that each magnet array is measured independently. The error can now be localized to the upper block at z-position 3. We apply a correction to the upper block at z-position 3 by moving it away from the gap by $2 \times$ (226 microns) = 452 microns. With this localized correction, the first integral of B_y as a function of gap is shown in figure 45. Note that the gap dependence of the first integral is almost identical to the case when the complete phase shifter is measured and

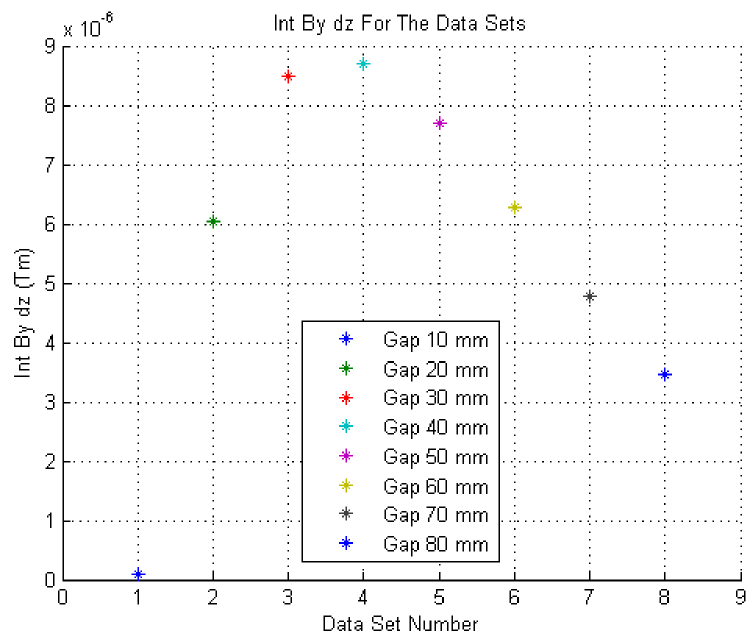

Figure 44: The upper block at z-position 3 has its remnant field increased by 1%. A virtual shim was applied as a correction in which both the upper and lower blocks were moved away from the gap by 226 microns. This fixed the trajectory at 10 mm gap, but the trajectory still has errors at other gaps.

where both the upper and lower blocks are moved.

Now suppose that the 1% magnetization error in the upper block at z-position 3 is corrected using a virtual shim at z-position 5. This could happen if the position of the error could not be determined, which might happen since the fields are large, and this is a small fractional change. The fields at z-position 5 are the opposite as at z-position 3, and the virtual shim must account for this. Both the upper and lower blocks at z-position 5 must be moved *into* the gap by 226 microns. At z-position 3, the virtual shim was to move the blocks away from the gap by 226 microns. With the virtual shim at z-position 5, the first integral of B_y as a function of gap is shown in figure 46. Note that the gap dependence of the first integral is almost identical to the cases illustrated above. This shows that the exact location of the virtual shim does not affect the first field integral. Field changes from the error and from the shim act independently. A very small additional second integral results from having the shim at the wrong location, but it was on the order of 1 μTm and can be neglected.

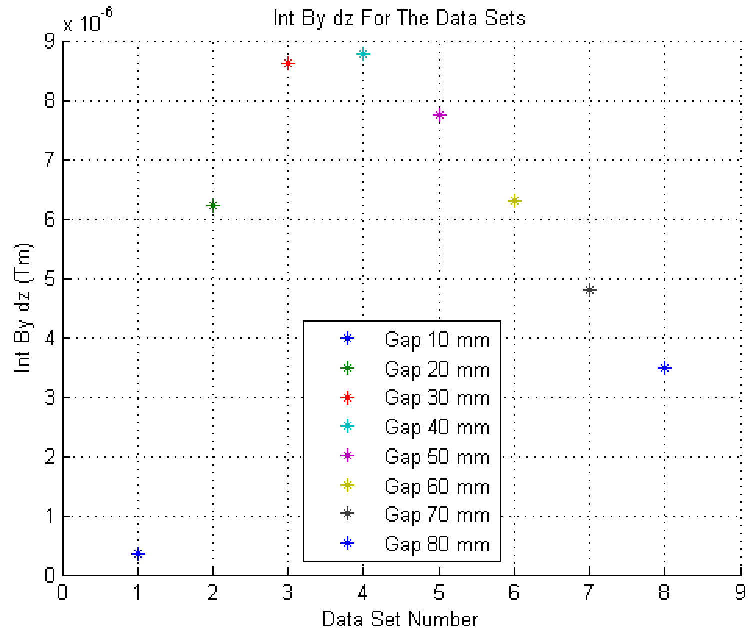

Figure 45: The upper block at z-position 3 has its remnant field increased by 1%. A virtual shim was applied as a correction in which only the upper block was moved away from the gap by 452 microns.

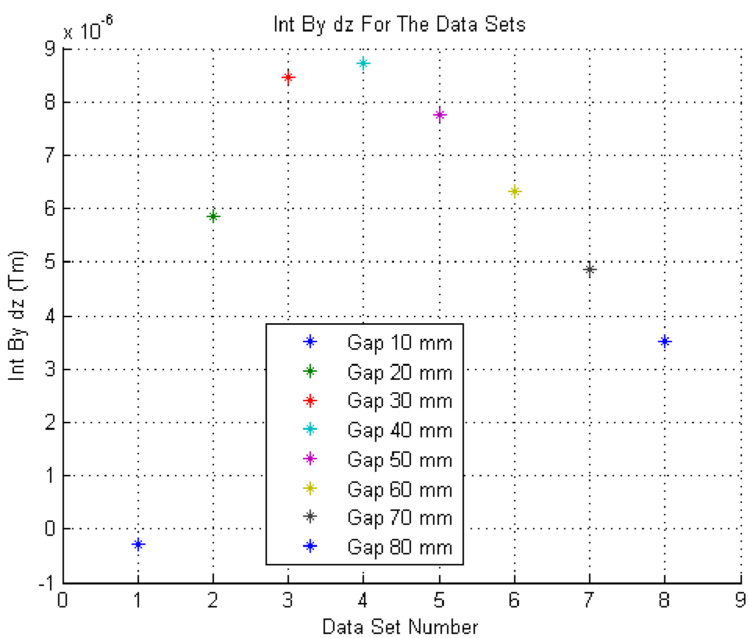

Figure 46: The upper block at z-position 3 has its remnant field increased by 1%. A virtual shim was applied as a correction in which both the upper and lower blocks at z-position 5 were moved into the gap by 226 microns.

5.2 Magnetization Direction Error Corrected By Block Rotation Virtual Shim

When the magnetization of the upper block at z-position 3 is rotated by 20 mrad, the trajectory of figure 11 results. The slope of the exiting trajectory is 2.80×10^{-6}. When a virtual shim is applied at 10 mm gap by rotating the upper and lower blocks at z-position 3 about their centers along the z-axis, the trajectory is corrected. The sensitivity of the virtual shim at 10 mm gap is a slope change per mrad of block rotation of 1.75×10^{-7} 1/mrad. The required virtual shim is then to rotate both the upper and lower blocks by $-\left(2.80 \times 10^{-6}\right) / \left(1.75 \times 10^{-7}\ 1/\text{mrad}\right) = -16$ mrad. This fixes the trajectory when the gap is 10 mm. The trajectory at 10 mm and other gaps is shown in figure 47.

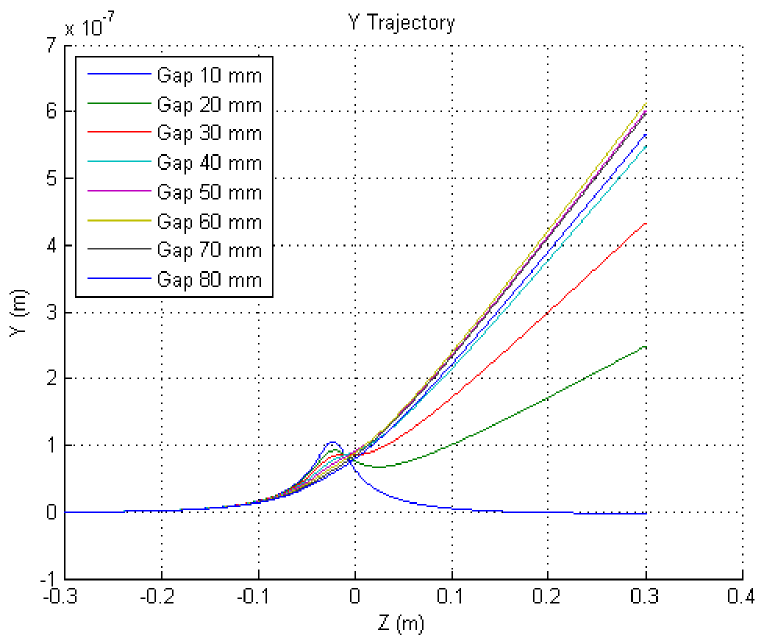

Figure 47: The magnetization direction error is corrected by the virtual shim at 10 mm gap, but errors persist at other gaps.

Figure 48 shows the first integral of B_x as a function of gap. The first integral of B_x peaks at approximately 54 μTm at a gap of 60 mm. Note that the first integral remains large at large gaps.

Suppose now that each magnet array is measured independently. The error can now be localized to the upper block at z-position 3. We apply a correction to the upper block at z-position 3 by rotating it by $2 \times (-16 \text{ mrad}) = -32$ mrad. With this localized correction, the first integral of B_x as a function of gap is shown in figure 49. Note that the gap dependence of the first integral is almost identical to the case when the complete phase shifter is measured and where both the upper and lower blocks are rotated.

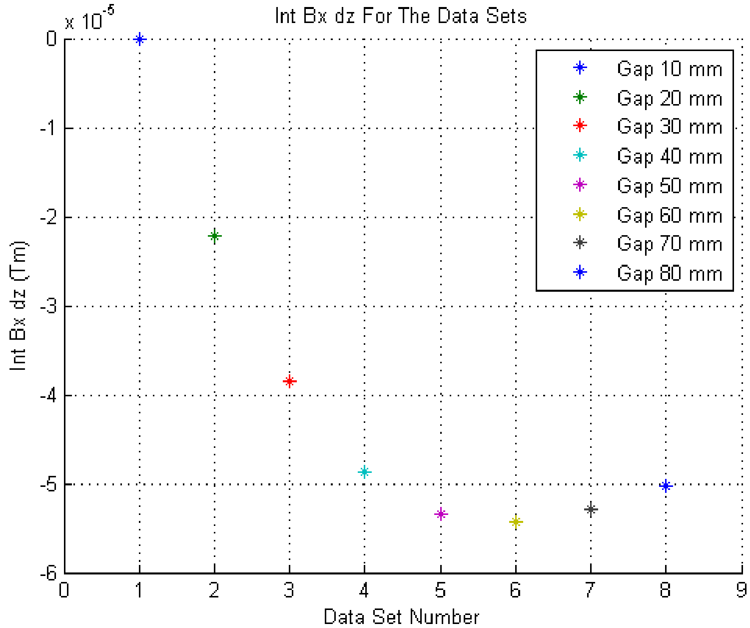

Figure 48: First integral of B_x at different gaps after a 20 mrad magnetization direction error is corrected by block rotation.

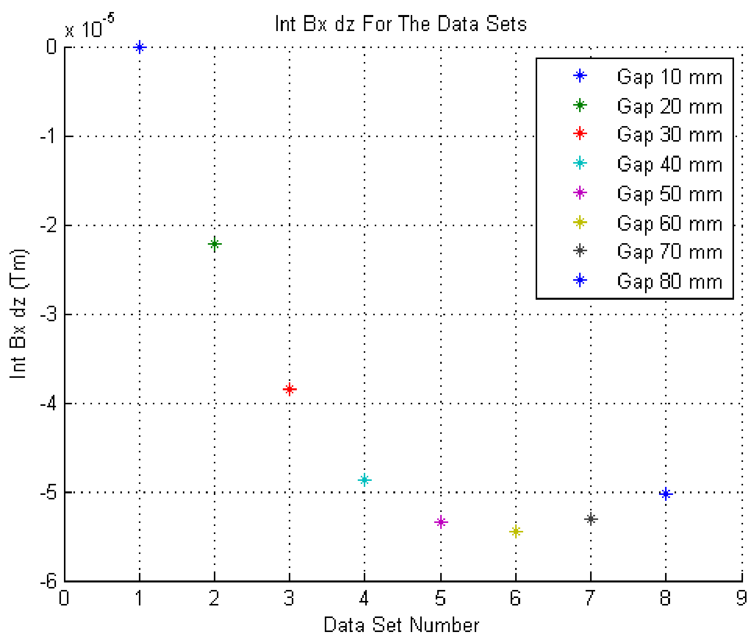

Figure 49: First integral of B_x at different gaps after a 20 mrad magnetization direction error is corrected by block rotation of only the block with the error.

5.3 Magnetization Direction Error Corrected By Horizontal Motion Virtual Shim

As noted above, correcting block magnetization direction errors with block rotations leaves a large gap dependence to the first integral of B_x. In this section, we see if correcting the error with horizontal block translations has a smaller gap dependence. As noted above, when the magnetization of the upper block at z-position 3 is rotated by 20 mrad, the trajectory of figure 11 results, and the slope of the exiting trajectory is 2.80×10^{-6}. When a horizontal block motion virtual shim is applied at 10 mm gap by translating the upper and lower blocks at z-position 3 in opposite directions, the trajectory is corrected. The sensitivity of the virtual shim at 10 mm gap is a slope change per micron of block motion of 6.27×10^{-9} 1/micron. The required virtual shim is then to translate both the upper and lower blocks by $\left(2.80 \times 10^{-6}\right) / \left(6.27 \times 10^{-9} \text{ 1/micron}\right) = 447$ microns. This fixes the trajectory when the gap is 10 mm. The trajectory at 10 mm and other gaps is shown in figure 50.

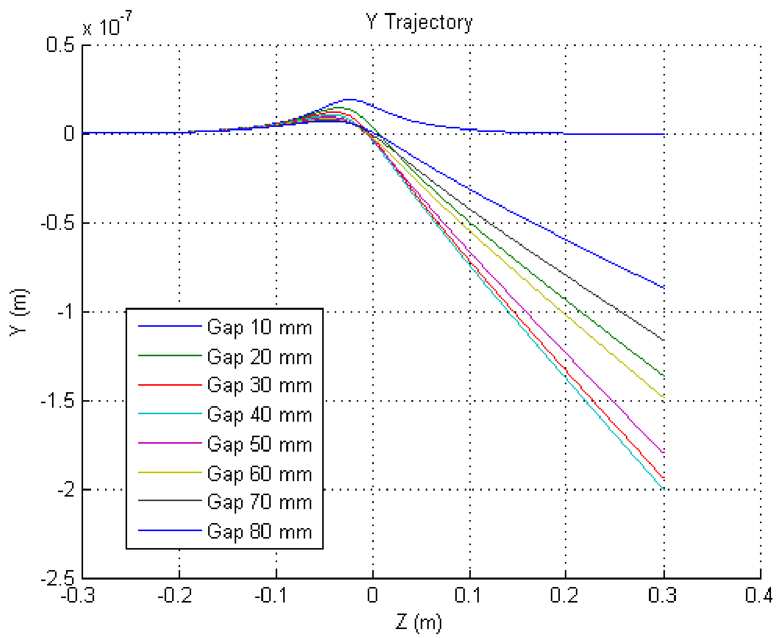

Figure 50: The magnetization direction error is corrected by the virtual shim at 10 mm gap, but errors persist at other gaps.

Figure 51 shows the first integral of B_x as a function of gap. The first integral of B_x peaks at approximately 18 μTm at a gap of 40 mm. Note that the first integral is much smaller than when the magnetization error was corrected by using block rotations as the virtual shim.

Suppose now that each magnet array is measured independently. The error can now be localized to the upper block at z-position 3. We apply a correction to the upper block at z-position 3 by translating it by $2 \times (447 \text{ microns}) = 894$ microns. With this localized correction, the first integral of B_x as a function of gap is shown in figure 52. Note that the gap dependence of the first integral is almost identical to the case when the complete phase shifter is measured and where both the upper and lower blocks are translated.

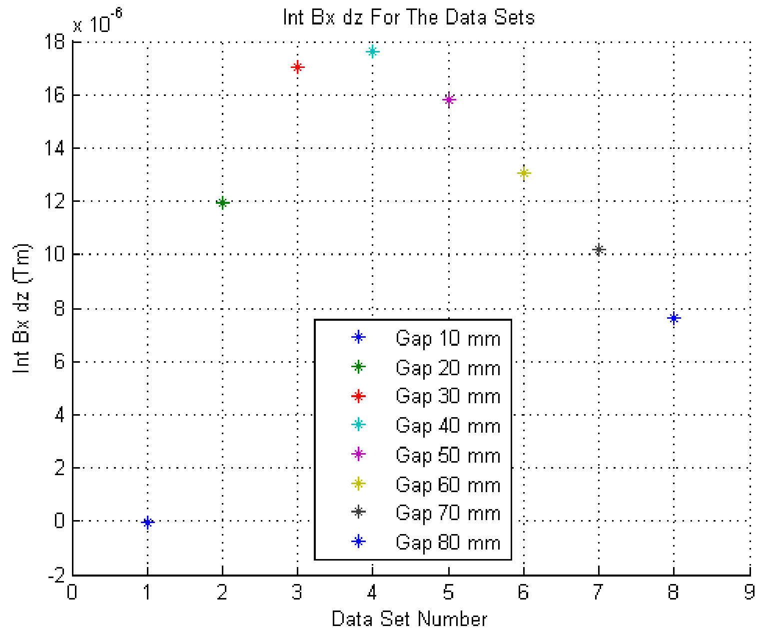

Figure 51: First integral of B_x at different gaps after a 20 mrad magnetization direction error is corrected by block translation.

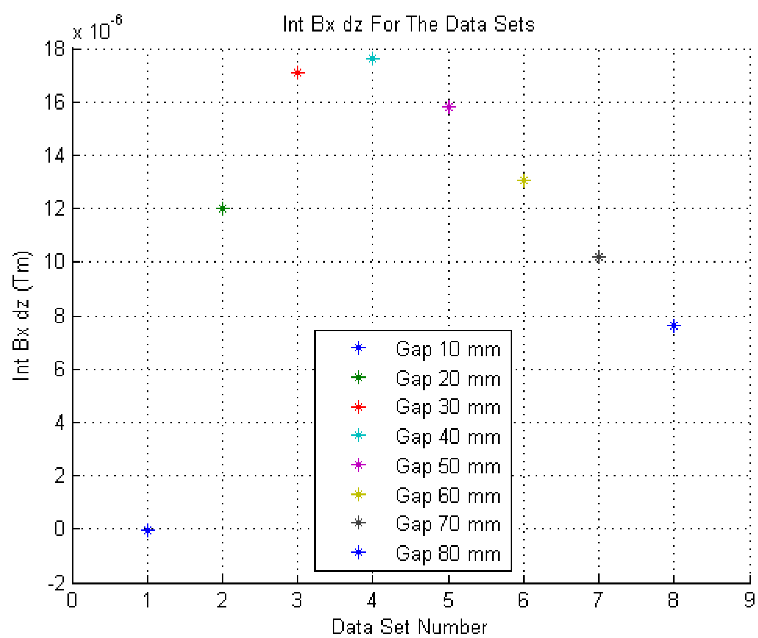

Figure 52: First integral of B_x at different gaps after a 20 mrad magnetization direction error is corrected by translation of the block with the error.

5.4 Block Translated Horizontally Corrected By Horizontal Motion Virtual Shim

When the upper block at z-position 3 is translated horizontally by 200 microns, the trajectory of figure 14 results. The slope of the exiting trajectory is 6.26×10^{-7}. When a virtual shim is applied at 10 mm gap by horizontally translating the upper and lower blocks at z-position 3, the trajectory is corrected. The sensitivity of the virtual shim at 10 mm gap is a slope change per micron of block motion of 6.27×10^{-9} 1/micron. The required virtual shim is then to translate both the upper and lower blocks by $-\left(6.26 \times 10^{-7}\right) / \left(6.27 \times 10^{-9} \text{ 1/micron}\right) = -99.8$ microns. This fixes the trajectory when the gap is 10 mm. The trajectory at 10 mm and other gaps is shown in figure 53. The trajectories are very small, so the shim essentially works at all gaps.

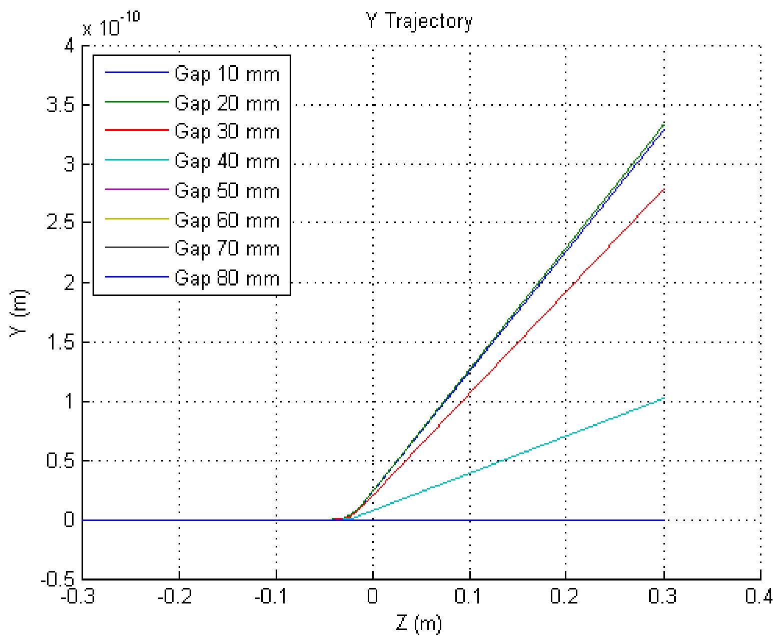

Figure 53: The y-trajectory at different gaps when the upper block at z-position 3 is translated by 200 microns and this error is corrected by a virtual shim at at gap of 10 mm.

Figure 54 shows the first integral of B_x as a function of gap. The first integral is essentially zero at all gaps.

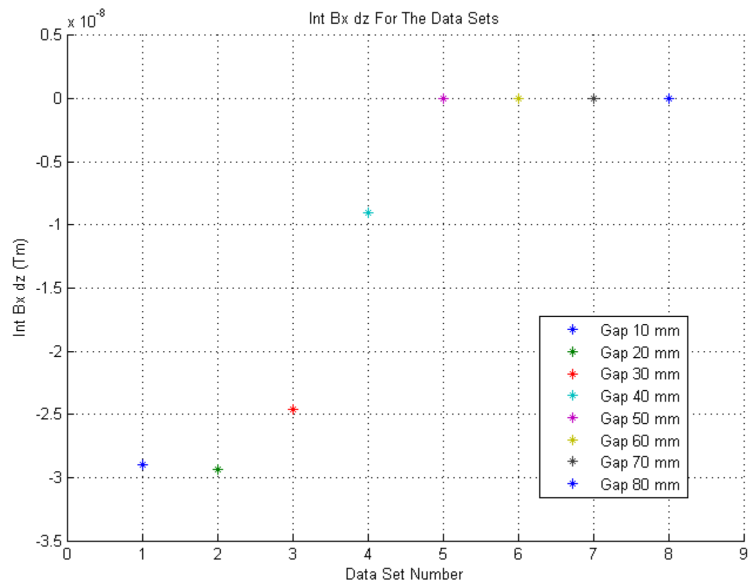

Figure 54: First integral of B_x at different gaps when the position error of the upper block at z-position 3 is corrected by a virtual shim.

5.5 Block Translated Vertically Corrected By Vertical Motion Virtual Shim

When the upper block at z-position 3 is translated vertically by 200 microns, the trajectory of figure 17 results. The slope of the exiting trajectory is 6.28×10^{-7}. When a virtual shim is applied by vertically moving the upper and lower blocks at z-position 3 toward the gap, the trajectory is corrected. The sensitivity of the virtual shim at 10 mm gap is a trajectory slope change per micron of block motion of 6.27×10^{-9} 1/micron. The required virtual shim is then to translate both the upper and lower blocks by $-\left(6.28 \times 10^{-7}\right) / \left(6.27 \times 10^{-9} \text{ 1/micron}\right) = -100$ microns. This fixes the trajectory when the gap is 10 mm. The trajectory at 10 mm and other gaps is shown in figure 55. The exit trajectory errors are very small, so the shim essentially works at all gaps.

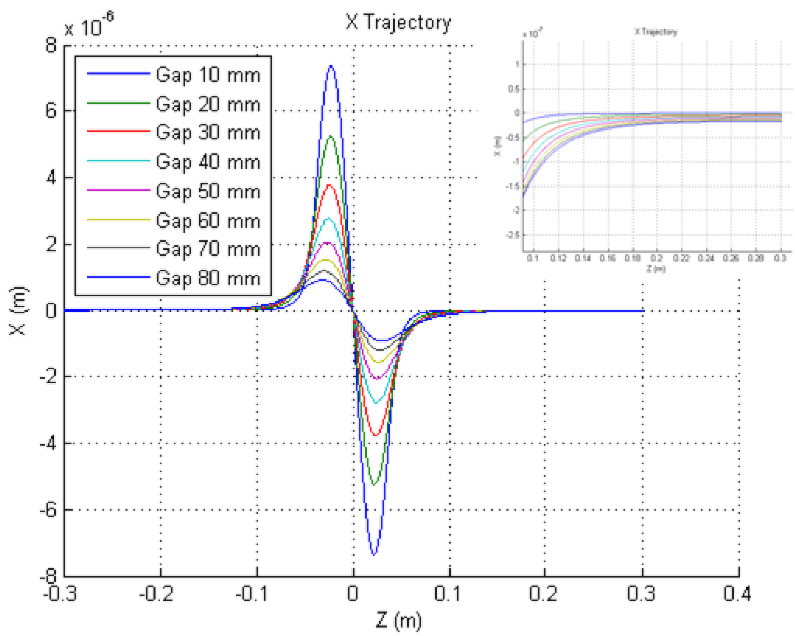

Figure 55: X-trajectory at different gaps when a position error in the upper block at z-position 3 is corrected by a virtual shim.

Figure 56 shows the first integral of B_y as a function of gap. The first integral is essentially zero at all gaps, indicating that the shim works at all gaps.

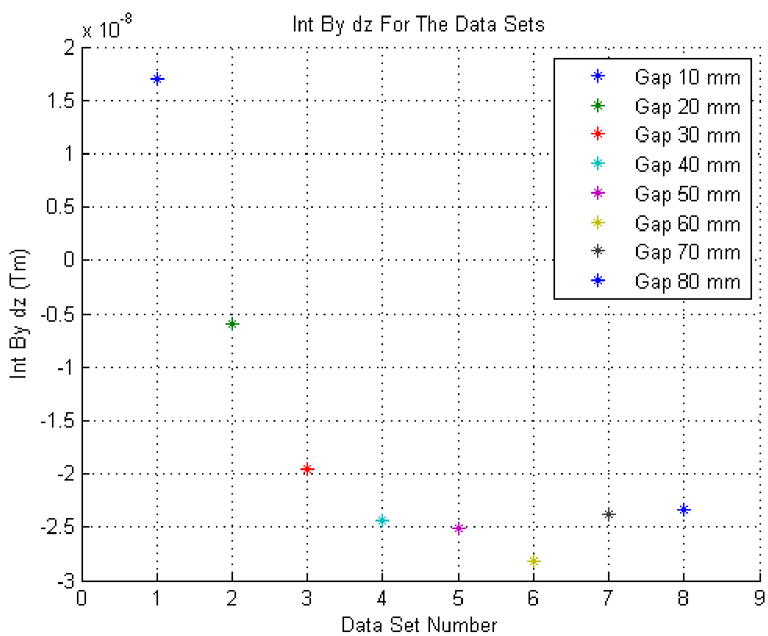

Figure 56: First integral of B_y at different gaps when the position error of the upper block at z-position 3 is corrected by a virtual shim.

5.6 Block Rotated Corrected By Block Rotation Virtual Shim

When the upper block at z-position 3 is rotated by 20 mrad, the trajectory of figure 20 results. The slope of the exiting trajectory is 1.75×10^{-6}. When a virtual shim is applied at 10 mm gap by rotating the upper and lower blocks at z-position 3 to counter the horizontal field, the trajectory is corrected. The sensitivity of the virtual shim at 10 mm gap is a slope change per mrad of block motion of 1.75×10^{-7} 1/mrad. The required virtual shim is then to rotate both the upper and lower blocks by $-\left(1.75 \times 10^{-6}\right) / \left(1.75 \times 10^{-7} 1/\text{mrad}\right) = -10$ mrad. This fixes the trajectory when the gap is 10 mm. It also fixes the trajectory at all other gaps. Figure 57 shows the first integral of B_x as a function of gap. The first integral is zero at all gaps.

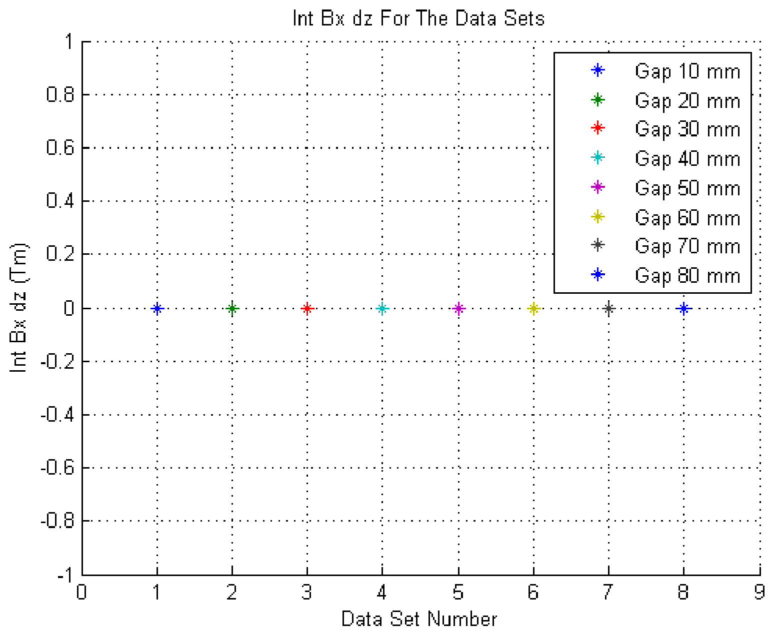

Figure 57: The first integral of B_x as a function of gap when a 20 mrad rotation of the upper block at z-position 3 is corrected by a virtual shim consisting of rotating the upper and lower blocks at z-position 3 by -10 mrad.

5.7 Discussion

It is interesting that identifying the block with the error and applying a virtual shim to only that block does not correct the phase shifter better than when a virtual shim is applied to both the upper and lower blocks. This was demonstrated explicitly for block magnetization errors and block magnetization direction errors. This also applies to block translation errors and block rotation errors since the virtual shims in these cases applied to both upper and lower blocks corrected the single block error almost perfectly. Of course translating or rotating the block with the error in this case would also perfectly fix the phase shifter. The reason for the upper and lower block correction working so well is linearity. When moving two blocks, both the upper and lower block corrections have the same strength, so the effect of correcting only the upper block by twice as much is the same as correcting using two blocks.

It is also interesting that the virtual shim does not need to be at the location of the error. This was demonstrated for block magnetization errors. Field changes from block errors and from virtual shims act independently. The first integrals do not change with shim location. Small second field integrals result, but they are negligible.

The procedure to tune a phase shifter proceeds as follows. First the blocks should be sorted to combine strong and weak blocks together to minimize magnetization magnitude errors. The blocks should be further sorted to combine blocks with opposite magnetization direction errors. These errors have the largest gap dependence and care should be taken to minimize these errors at the outset. Magnetization direction errors are best corrected by block translations since the gap dependence was minimized in this case. After assembly, the magnet arrays should be mechanically measured and shimmed to eliminate as many block translation and rotation errors as possible. At this point, the phase shifter should be magnetically measured. There is no need to magnetically measure individual arrays. All error fields decayed at sufficiently large gap, so the field integrals at large gap should be relatively small. The phase shifter should be shimmed at minimum gap and the field integrals should be made to go to zero. The field integrals are then zero at minimum gap and small at maximum gap. They will have excursions in between. Care must be taken to have small enough initial errors so that the excursions at intermediate gaps will be within tolerance.

6 Conclusion

This note studied errors in the phase shifter, virtual shims to correct the errors at 10 mm gap, and the gap dependence of the corrections. Virtual shim sensitivities were determined at 10 mm gap. Most errors are corrected satisfactorily at all gaps. Block magnetization direction errors, however, still have a significant first integral at large gap even when they are corrected at 10 mm gap. It will be important to sort the blocks and to include the magnetization direction error in the sort.

Acknowledgements
I am grateful to Yurii Levashov and Heinz-Dieter Nuhn for many discussions about this work.