# Magnetic guides and applications

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**Abstract.**

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## 1. Introduction

In this paper we report on the recreation of a real atomic-physics experiment in which a cloud of neutral atoms is decelerated, trapped, and cooled down with the use of magnetic fields. In our case, atoms are represented by steel balls and we use permanent Neodymuim magnets to decelerate and eventually trap them. The second recreated experiment is one of magnetic transport which is simulated by a deflection experiment with the same materials. Such emulation allows us to macroscopically visualise the behaviour of microscopic objects – atoms.

This method is possible because of the fact that steel balls are affected by magnetic fields when they enter it. If placed correctly, the balls are trapped. The magnetic field induces a magnetic dipole moment in the steel balls and this magnetic moment seeks to align itself to the field lines and tends to move towards the region of higher magnetic field.

The equation describing the behaviour of the potential energy ($U$) of a magnetic dipole is given as:

$$U = -\mu \cdot B, \tag{1}$$

where $\mu$ is the magnetic dipole moment and $B$ is the magnetic field [1]. The magnetic moment (steel ball) will lower its potential energy by moving to the region of higher magnetic field (closer to the magnet). A reduction of potential energy is what the system strives for and this mechanism allows us to manipulate it.

## 2. Experiments

In our project, we wanted to carry out experiments in the same precise way they are carried out in atomic physics given our circumstances.

An electromagnetic release mechanism was used to eliminate human error which we observed when the ball was released by hand. Using this method enabled us to have the same initial conditions in terms of the initial velocity.

It was measured using the parabolic drop method in which the ball is ejected from the end of the table onto a sheet of millimetre paper covered with indigo paper and the distance of the mark is measured with respect to the edge of the table. With the known height of the table ($h = 75.8\,\mathrm{cm}$), and using the equation for the initial velocity of a horizontally shot projectile:

$$v_0 = \sqrt{\frac{D^2 g}{2h}}, \tag{2}$$

where $D$ is the horizontal distance measured and $g = 9.81\mathrm{m/s}^2$ the gravitational acceleration of Earth. The ball was dropped 20 times and the results were statistically evaluated. The measured initial velocity was $v_0 = (1.2 \pm 0.1)\,\mathrm{m/s}$.

In order to achieve higher velocities, we introduced an accelerator system. It consists of two identical parts which were 10 cm apart. The parts themselves included a

**Figure 1.** Photograph of experimental setup with the release mechanism, accelerator system, and deceleration and trapping magnets in separate panels.

magnetic sphere and two non-magnetic steel balls in that order. We fixed the magnetic ball and the steel ball to our rail letting only the last to move and be launched. When the magnetic ball was hit by the incoming steel ball, its kinetic energy is transformed into magnetic energy. This energy is transferred through the system and amplified due to the change in the magnetic field configuration when the steel ball attaches to the spherical magnet. The last ball in the chain is then launched with the increased kinetic energy which manifests itself as an increase in the velocity. After the two stages, the final velocity of the steel ball is $v_f = (1.91 \pm 0.04)$ m/s, again measured by the parabolic drop method.

### *2.1. Deceleration experiment*

In order to trap the ball, we included a system which reduced its velocity. We carefully carried out experiments to see if there is any connection between the position of the decelerator and its efficiency. We chose the zero point to be the beginning of the second accelerator and then four other positions: 10 cm, 15 cm, 20 cm, and 25 cm away from our zero point in the direction of the ball's velocity. We tested all positions for their effects and results are shown in figure 2. We concluded that the first position is the most effective. It is followed by the fourth position, but with a slightly larger standard deviation. The second and the third position roughly offer the same effect, but due to

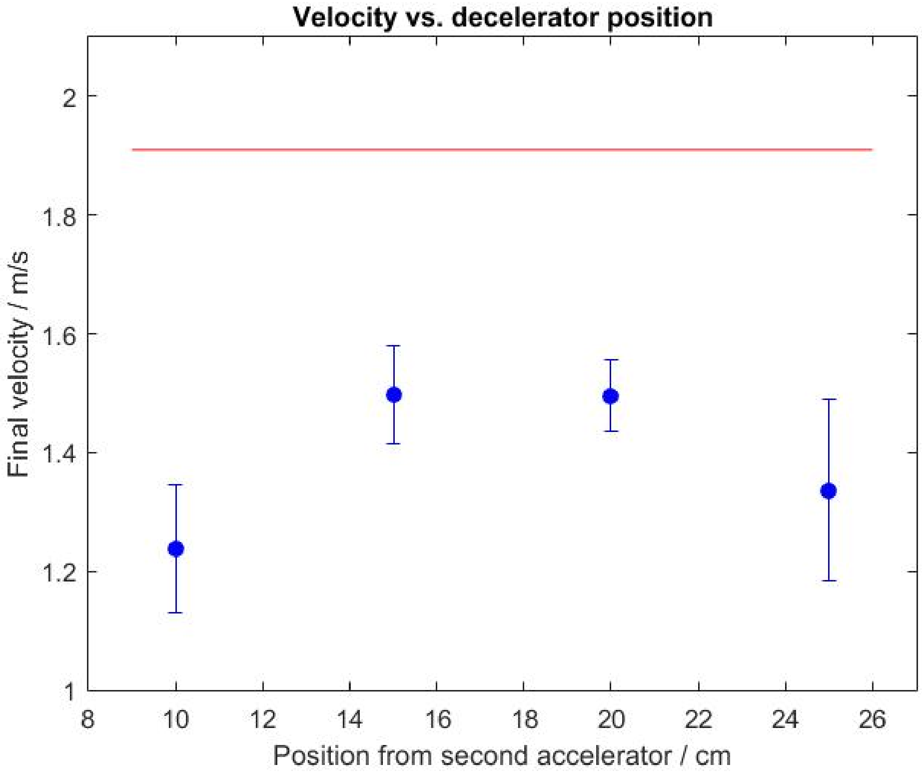

**Figure 2.** Graph of the velocity after deceleration with respect to the decelerator position. The red line at the top represents the accelerated ball's velocity without any deceleration applied.

their smaller efficiency, they are not used.

The first position offers such effectiveness because its proximity to the acceleration system which cancels the full acceleration effect. The fourth position shows the effects that friction along the rail not amplified by the magnetic field influences the final velocity. The larger standard deviation furthers this hypothesis.

For the trapping system, we decided to install the following configuration: we put the decelerator in the first position in order to cancel the accelerating effect and we put our trapping mechanism at the fourth position to eventually trap the ball.

### *2.2. Trapping experiment*

We chose one configuration of magnets which was the most efficient in trapping the ball without the use of the acceleration stage. It is shown in figure 3. The setup was placed 40 cm away from the start of the rail in a N-S-N-S configuration. The ball enters the magnetic field that is generated by the magnets which results in it being attracted to both sides. The rail stops the transversal motion of the ball. However, the attraction of the magnets causes higher friction which results in the ball decelerating and eventually stopping in-between the magnets.

Introducing the acceleration system and adding velocity made it impossible to trap

**Figure 3.** Configuration of magnets for trapping without the acceleration stage.

the ball using this configuration of magnets. Therefore, we had to use the strongest magnet we had to trap the ball. As mentioned in the previous section, we installed a decelerator at 10 cm distance from the start of the second accelerator, and put the magnet 10 cm further down the rail 16 mm above it with supports. The high-velocity projectile was successfully trapped with this setup by attracting it to the strong magnet.

### *2.3. Deflection experiment*

Our next experiment focused on deflection of the steel ball with the help of a strong magnet. We excluded the acceleration stage from this experiment because we observed that lower velocities provide a greater measure of control of reproducible conditions. Three parameters could be varied: initial velocity of the ball, the transversal and the longitudinal position of the magnet.

We excluded varying the initial velocity because higher values resulted in uncontrollable motion of the ball while transferring from the rail to the table. The longitudinal position provided no measurable effect to the deflection because it only delayed the magnet-ball interaction. Therefore, only the transversal position of the magnet was varied.

The photograph of the experimental setup is on figure 4. The deflection from the straight path was measured with a millimetre paper overlaid with an indigo paper so

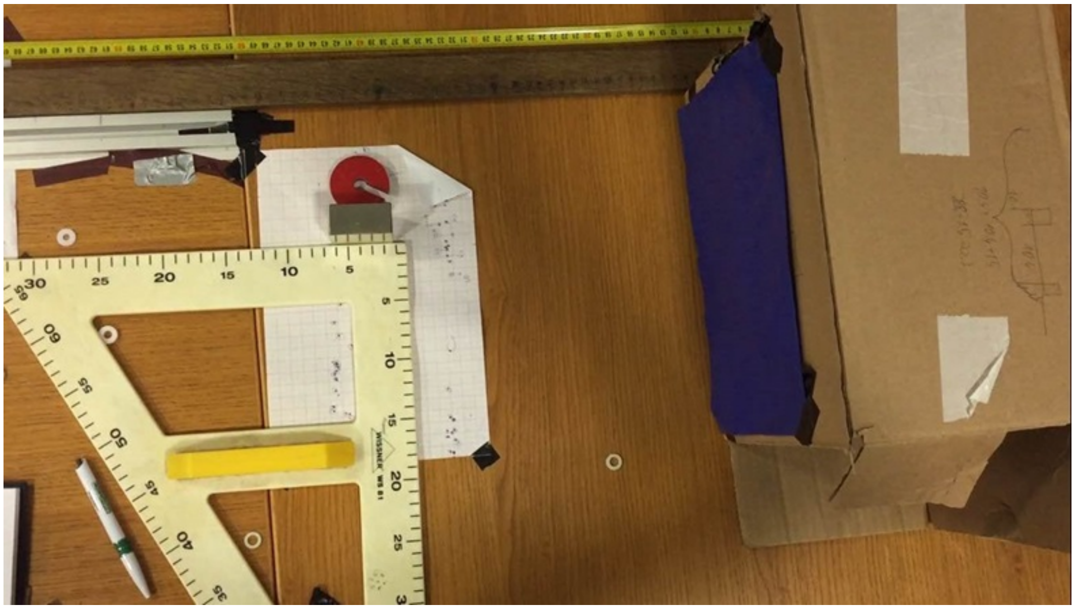

**Figure 4.** Photograph of the experimental setup for deflection. The rail, magnet, and the indigo paper position are shown.

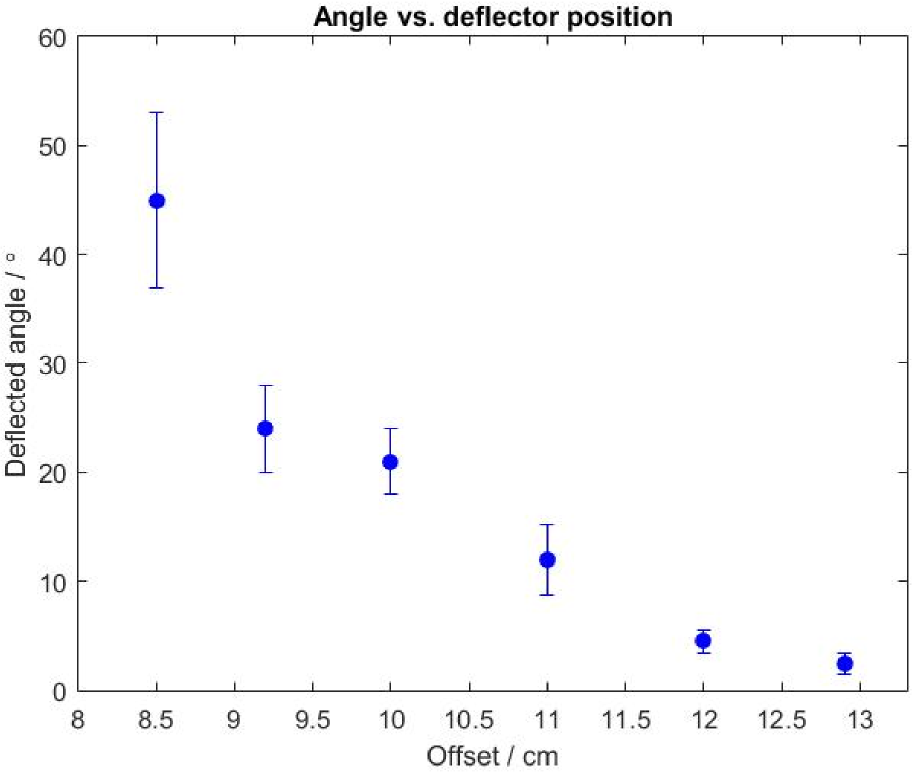

**Figure 5.** Graph of the deflection angle with respect to the transversal magnet position.

that the impact of the ball can be measured. The transversal position of the magnet was measured with the millimetre paper put underneath it.

We observed that the closest the magnet could be to the rail is 8.5 cm. Closer than that point, the ball would fly to the magnet and stick which resulted in no further motion or deflection. As we increased the distance, the angle of deflection decreased up to the maximum distance of 12.9 cm after which no measurable effect could be observed.

What figure 5 shows is that the angle of deflection grows as the magnet is put closer to the rail. This is because the magnetic field is then stronger and affects the ball more. One other aspect which needs to be considered is that the scatter of the values is greater for smaller transversal distances. This is due to the fact that smaller perturbations of velocity induced through disturbances such as friction and the rail-table transition have a greater influence when the magnetic field is higher. When the magnet is farther away, the small perturbations of velocity aren't so influential and the scatter is smaller.

In conclusion, the behaviour of the deflection is as expected and the observed effects of data scatter can be explained as above.

## 3. Simulation and visualisation of magnetic fields

Along with the experimental part, theoretical and simulation computations were made with the use of the COMSOL Multiphysics software. The achieved goal was to visualise magnetic fields and effects caused by permanent magnet configurations – models of the devices used in experiment – and qualitative results were obtained. Two configurations were modelled: trapping without an acceleration stage and deflection. Approximated response of the steel ball to the magnetic field was also computed by taking the gradient of the magnetic induction field. As the final results, the images obtained are presented in Appendix 1.

## 4. Conclusion

To conclude, we emulated experiments from atomic physics with macroscopic objects – permanent magnets and steel balls.

We performed deceleration experiments with various configurations of magnets, both with and without an acceleration stage. The measured effect of velocity reduction was a 40 % reduction in the velocity. This experiment was followed by trapping with a fixed configuration. Without the acceleration stage, the trapping was performed with a single stage placed on the side of the rail. With an acceleration stage, the trapping was only possible with a very strong magnet placed above. In both cases, the trapping effect was longitudinal – the ball was stopped in the forward direction with magnetic fields, but its lateral motion was stopped with other methods. This is a limitation that macroscopic handling of this phenomenon imposes.

Another experiment which we emulated was the magnetic transport – moving trapped atoms with magnetic fields. This was done by deflecting a moving steel ball with a strong magnetic field. The results observed agree with expectations and we can explain the observed scatter.

Our simulations focused on visualisation of magnetic fields and provided qualitative descriptions of observed effects.

## Acknowledgements

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At last, we would like to thank Matilda and Jelena for the impeccable organisation of S3++.

## References

[1] J. D. Jackson, *Classical Electrodynamics* (Third Edition), Wiley, (1998.)

## Appendix A. COMSOL visualisations

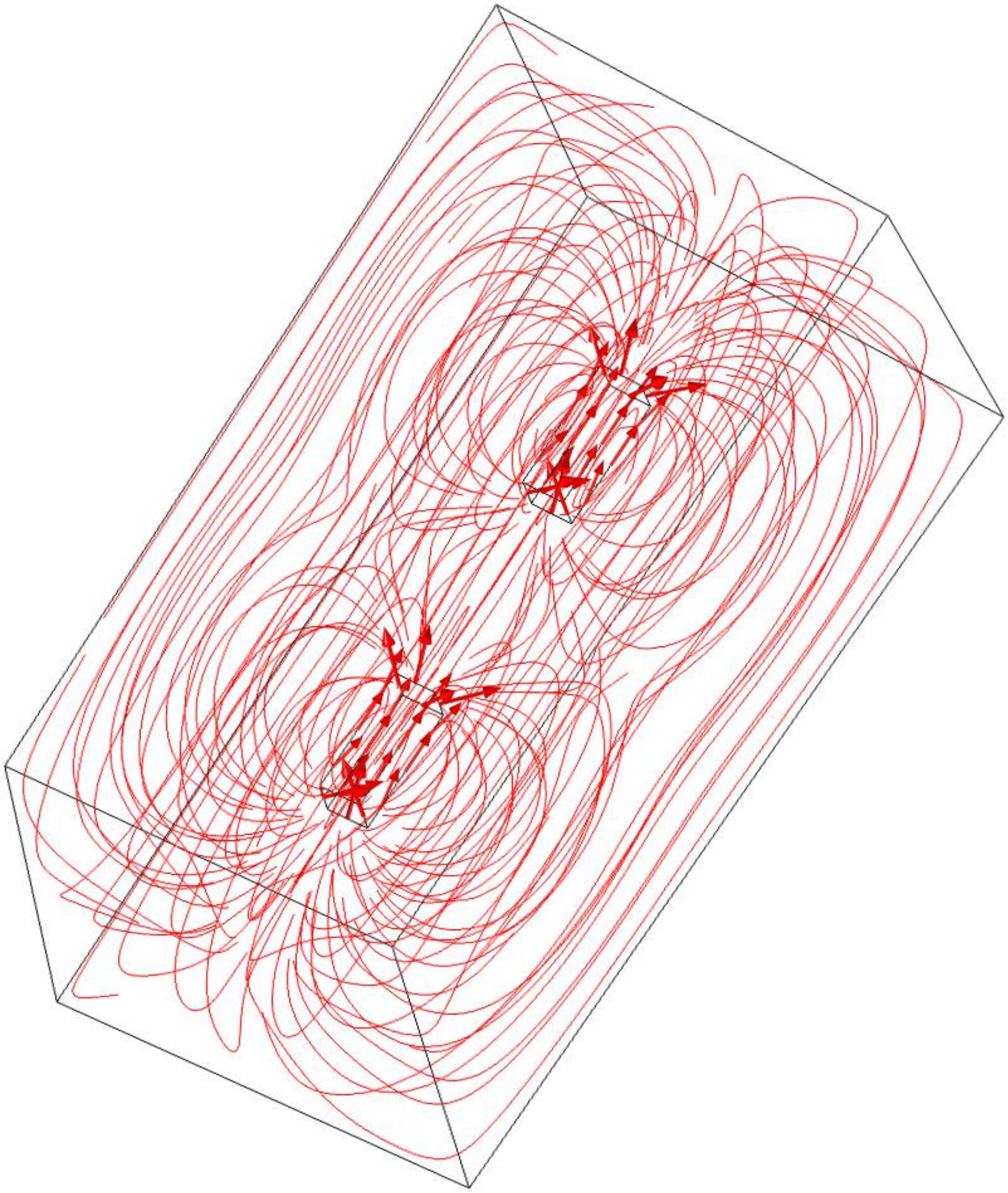

**Figure A1.** 3D view of the magnetic trap with the streamline visualisation technique of the magnetic field.

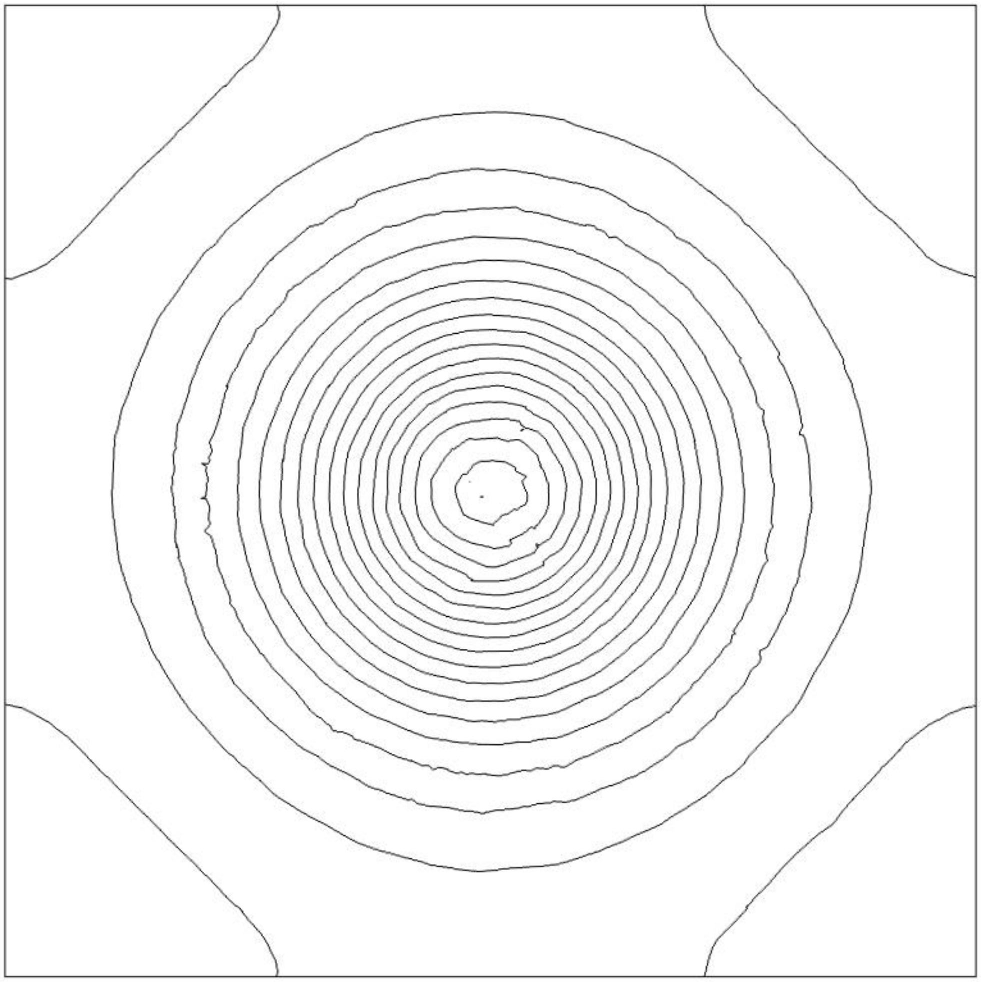

**Figure A2.** Contour plot of the magnetic field strength in the plane perpendicular to the axis connecting the centres of the two magnets. The maximum in the middle shows the trapping position of the ball.

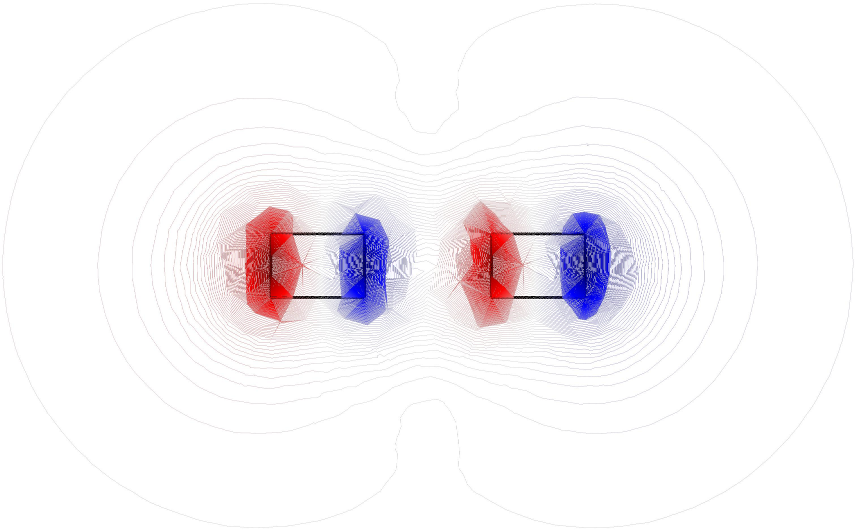

**Figure A3.** Contour plot of the magnetic field strength in the plane containing the two magnets. The blue-red hues denote the south-north magnetic poles, respectively.

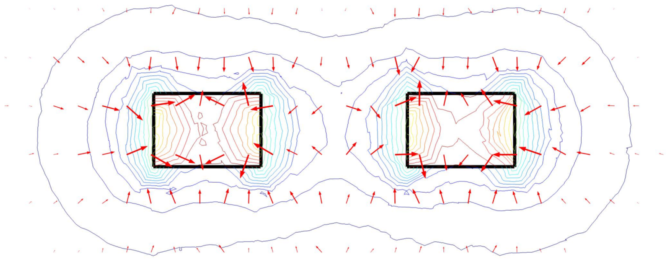

**Figure A4.** Magnetic field potential in the same plane as in figure A3 with an arrow plot of the force field exerted on the steel ball.

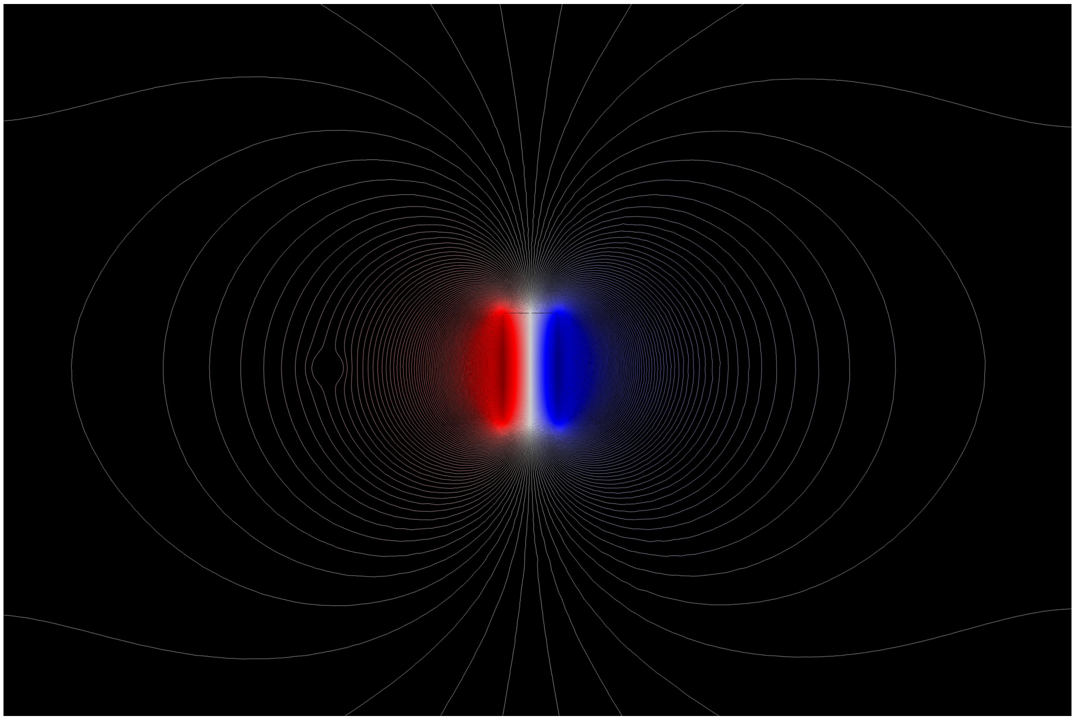

**Figure A5.** Contour plot of the magnetic field produced by the deflector. The round disturbance in the field lines on the left signifies the position of the magnetic ball. The different density of the field lines from each side signifies that the ball will be attracted towards the magnet.

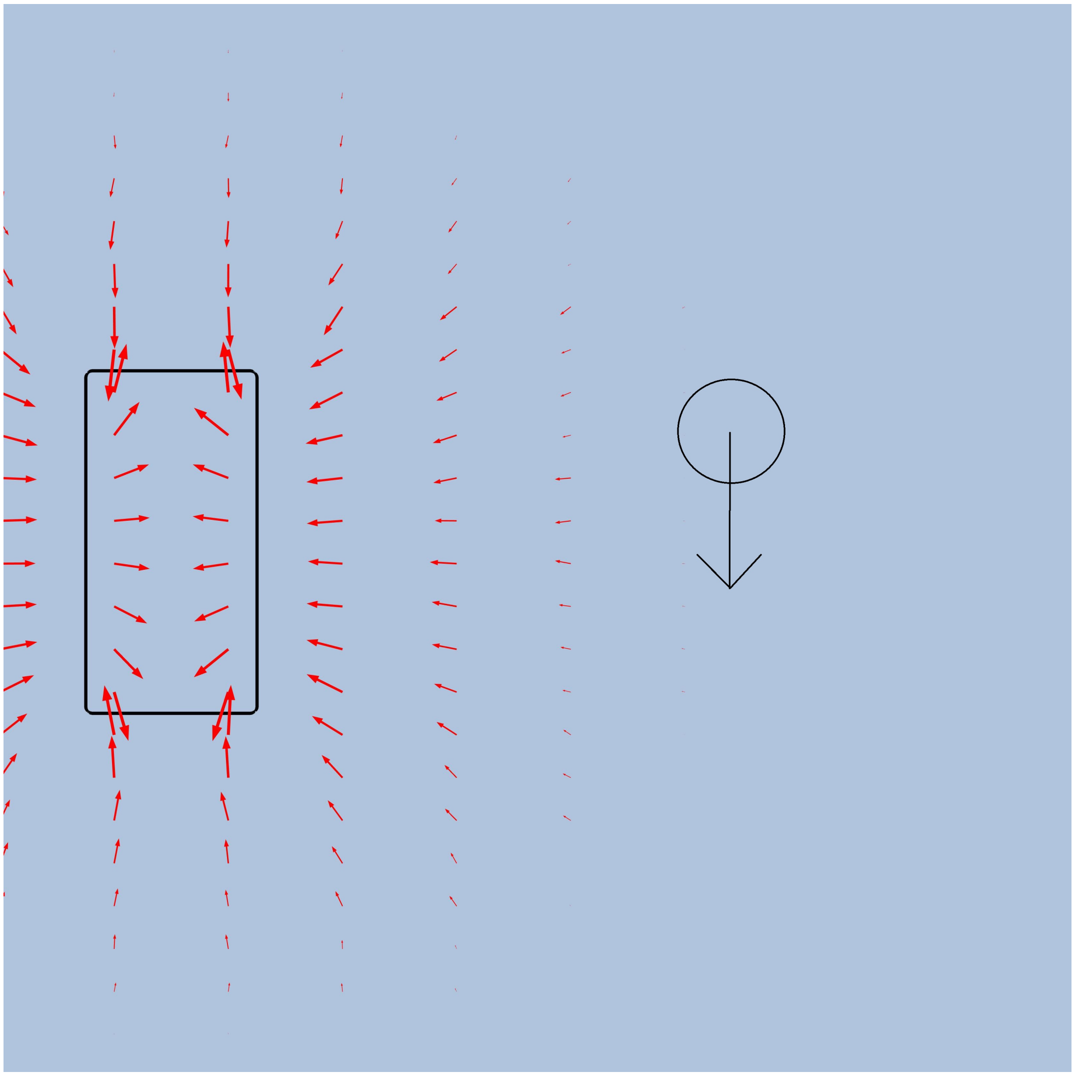

**Figure A6.** Arrow plot of the force field with the ball's velocity indicated.