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12 Sector Single Ring Permanent Magnet Lens On Axis B Field Measurements

Brandon Dos Remedios

TRIUMF

Abstract: The constructed 12 sector single ring permanent magnet lens differs from its corresponding theoretical model and OPERA model and thus needed to be measured, to find its true on axis B field. It was measured from -51.2 cm to 50.8 cm, relative to its midpoint, with a resolution of 1 cm in 3 trials. The theoretical model function was fit to the average of this data yielding parameters of $B_0 =$ -13200 G, $R_1 =$ 2.90 cm, $R_2 =$ 6.15 cm, $l =$ 5.10 cm and the OPERA data was fit with a scaling function, yielding a scaling factor of 1.15.

4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3 · Tel: 604 222-1047 · Fax: 604 222-1074 · www.triumf.ca

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1 Introduction

The 12 sector single ring permanent magnet lens is a physically constructed arrangement of 12 trapezoidal magnets, formed into a single focusing ring, meant for the magnetic focusing of ion beams. Specifically, this ring was made to focus hydrogen anion beams for the newest in construction ion source I2 of the 520 MeV cyclotron at TRIUMF. The 12 sector was designed as an alternative focusing lens to that of powered solenoids, providing focusing without requiring any electrical power[1]. The constructed permanent magnet however, differs from its expected theoretical and its OPERA model[2] meaning that the B field must be physically measured to find its true magnitude. This short report contains the measurement procedure, plotted data, and measurement analysis for on axis, in direction of axis, B field measurements for the constructed 12 sector magnet lens, including the least square fitted parameters for the theoretical function to the data, and the scaling factor for the OPERA model's data to the measurements. For this report, the B_z field is considered to be the B field in the direction of the magnet's axis, and the magnet's axis is considered to be the z axis.

Figure 1: Picture of the physically constructed 12 Sector magnet lens.

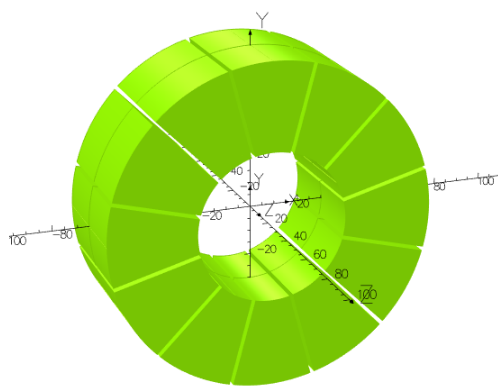

Figure 2: OPERA model of 12 Sector showing beam axis as the z axis, which was the axis measured upon.

2 Material and Methods

The tools used were the Lakeshore 460 Gaussmeter, the Lakeshore MMZ-2512-UH 3-axis probe, the Lakeshore zero gauss chamber, measuring tape for distance along the axis, and multiple jigs to stabilize the probe at a constant position during B field measurements. These jigs included a non-magnetizable plastic tube and a non-magnetizable brass tube, which both could sit in the ring of the 12 sector magnet lens and hold the probe at some stable position, near to the magnet. Also included, was a aluminum tripod jig which stabilized the probe on top of the tripod for measurements further away from the ring, for which neither tube was suitable.

The 12-sector magnet was zip tied to a table for safety and such that it maintained a stable position during measurements. This table was located in TRIUMF around I3, meaning that there was some non constant ambient field of about 1 Gauss. The table was aligned such that the beam axis was along the minimal field of 0 Gauss. The probe was zeroed before every set of trials using the zero Gauss chamber. Within each measurement in each trial, the probe was moved to an appropriate position along the magnet's axis, as measured by the measuring tape, and stabilized by either the tubes or the tripod. The probe was then checked for alignment to ensure that the z direction pointed along the beam axis after it's placement. Then after readjusting it was remeasured, before recording the B field reading from the Gaussmeter. The probe was measured from its tip to the surface of the magnet, meaning that raw measurements were off by 1.8 mm due to the hall plate's distance from the tip, and an additional 0.3 mm due to the magnet being slightly over 50 cm in length, which are both already accounted for in the positional data in this report. 3 trials were taken along the beam's axis, each from -51.2 cm to 50.8 cm at 1 cm intervals. The mean of the 3 trials at each position along the axis was then taken, rounded to 3 significant figures.

3 Data and Observations

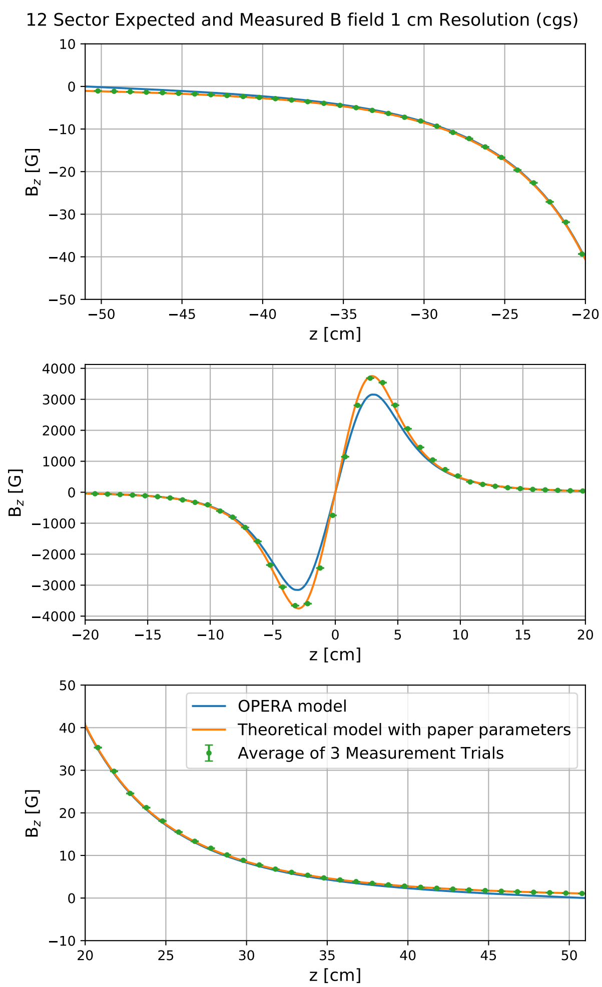

Figure 3: Average of 3 Trials plotted with theoretical model from report, using the parameters described there[1], and plotted with the OPERA model's data for the on axis B field.

As seen in figure 3 the averaged measurements' overall shape matches both models well, deviating only slightly from the theoretical function and only greatly in magnitude from the OPERA data by some scaling factor. This is to be expected, as the true magnetic remanence strength for the constructed 12 sector's magnets is unknown, so the OPERA model would potentially not match.

4 Uncertainty

Briefly addressing uncertainty, for distance along the beam axis, the tape measure used to measure the probe's location had a 1 mm resolution, so the 95% confidence interval was approximated to be 2 mm, with the uncertainty being caused by human error.

For uncertainty of the B field magnitude at each point, the Gaussmeter's reading would fluctuate up and down around the reading, depending on the distance from the origin, with magnitude of fluctuation decreasing further from the origin. For uncertainty from this fluctuation, the 95% confidence interval was recorded for each measurement, to be the approximate range between the maximal and minimal magnitude for the point, and was approximately the same across all 3 trials. The ambient magnetic field was also a factor, especially further from the origin, however fluctuation seemed to be dominant so uncertainty from the ambient field was ignored. However, uncertainty was approximated by how the Gaussmeter seemed to be fluctuating so there is not a lot of confidence its estimation, and thus it was opted to disclude its effects in the fitting.

5 Analysis

5.1 Fitting the Theoretical Function

$$\begin{aligned} F(s) &= \frac{1}{\sqrt{s^2+1}} - \log\left(\sqrt{s^2+1}+1\right) \\ B_z(z) &= \frac{B_0}{2}\left[F\left(\frac{z+\frac{l}{2}}{R_1}\right) - F\left(\frac{z+\frac{l}{2}}{R_2}\right) - F\left(\frac{z-\frac{l}{2}}{R_1}\right) + F\left(\frac{z-\frac{l}{2}}{R_2}\right)\right] \end{aligned} \tag{1}$$

This theoretical model equation for the 12 sector's on axis field, obtained from the paper[1] was fit via least squares, to the average of the 3 measurement trials, to find the parameters which would best fit the measured data. In this equation B_0 is magnetic remanence strength, R_1 is the inner radius of the 12 sector, R_2 is the outer radius of the 12 sector, and l is the length of the 12 sector in the z direction[1]. The resulting fitted parameters and plotted fitted theoretical are shown below.

B_0	-13200 G
R_1	2.90 cm
R_2	6.15 cm
l	5.10 cm

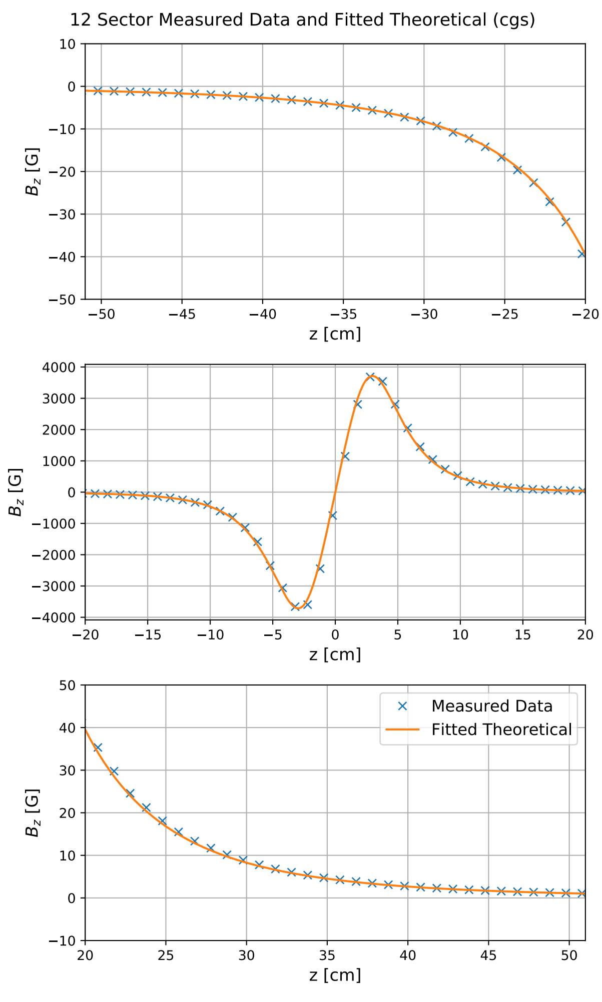

Figure 4: Theoretical model function using least squares fitted parameters, with measured data.

5.2 Scaling OPERA Model

As stated previously, the OPERA model data seemed to be off by some scaling factor for the remanence strength. To find the size of this scaling factor, a buffer from the the OPERA model was taken of B_z at each of the measurement points, and a function was made that outputted the OPERA B_z, for a certain point on the z axis, multiplied by some constant scaling factor parameter. This function was then least squares fit to the measured data, giving a fitted parameter of a scaling factor of 1.15. The scaled OPERA data is plotted below.

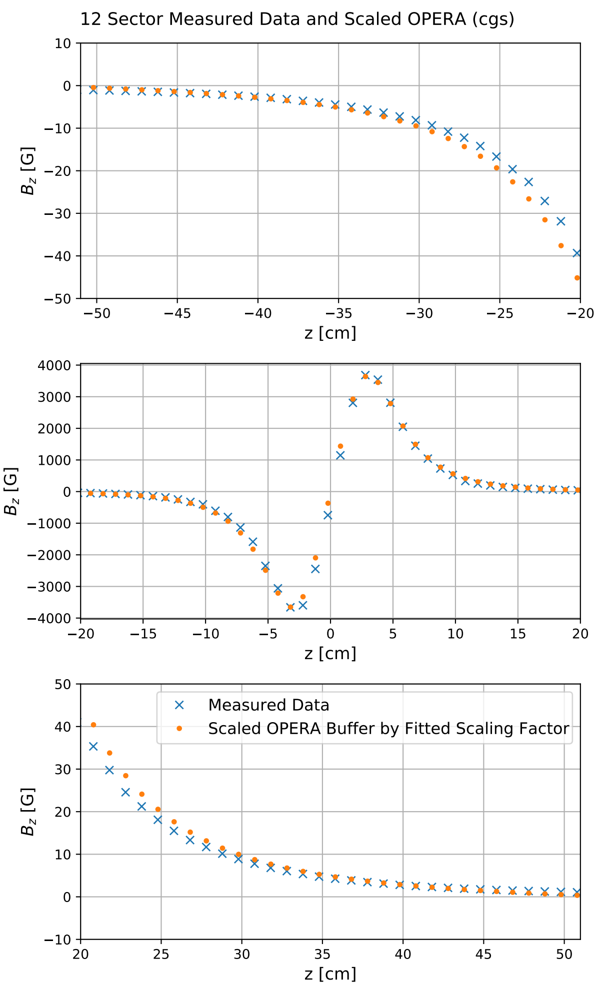

Figure 5: Scaled OPERA data by scaling factor 1.15, with measured data.

6 Suggestions

For further or similar experimental measurements there are multiple suggestions to improve on the procedure here. The ambient magnetic field of about one Gauss, experienced during the measurements of this report, made little difference nearer to the origin, but created some discrepancy at the fringes where field from the magnet was small in magnitude. It would be best to avoid taking measurements within stray magnetic field, to avoid this discrepancy, especially if the far field is of interest. Further, better recording of fluctuation, possibly by using a Gaussmeter built in function to trigger maximum and minimum, if one exists, would lead to a more accurate uncertainty measure and thus would likely be usable in a weighted least squares fitting. Finally higher resolution within the -10 cm to 10 cm interval would be a good idea, as B field varies much more rapidly in that area, so higher resolution (in comparison to sections further away) may capture that change better, for the fits.

7 Conclusion

The on axis B field of the constructed 12 sector magnet lens seems to match the shape of the theoretical and OPERA data quite well, but does deviate from them, especially in terms of magnitude for the OPERA data. Fitting these functions to the data, the least squared fit parameters of the theoretical are B_0 = -13200 G, R_1 = 2.90 cm, R_2 = 6.15 cm, l = 5.10 cm and the OPERA data requires a scaling factor of 1.15.

References

[1] K. Jayamanna, R. Baartman, I. Bylinskii, T. Planche, R. Simpson, and M. Corwin, in *International Particle Accelerator Conference (9th), Vancouver, BC, Canada, 2018*, p. 1513-1515

[2] R. Simpson, *trapezoid42UHRounded.opc*, OPERA model of 12 sector, Internal Resource, TRIUMF, Apr. 2017

8 Appendix

8.1 Relevant Files and Descriptions

12prongmagnet_data.csv

Contains all 3 trials' measurements from -51.2 cm to 50.8 cm every 1 cm, with estimated 95% confidence interval for both distance and B field magnitude.

trapezoid.csv

Contains higher resolution OPERA buffer data of B_z across z, for plotting (-51 cm to 51 cm in OPERA model)

matching512.csv

Contains OPERA buffer data of B_z at and only at measurement points, for fitting the OPERA scaling factor.

trapezoid42UHRounded.opc

Original OPERA model of trapezoid magnet with appropriate symmetries for full 12 sector model[2].

12prongstretchedair52.opc

Same OPERA model as trapezoid42UHRounded.opc just with air stretched to -52 cm to 52 cm to accommodate measurements reaching out beyond original -40 cm to 40 cm span.

ndfeb42uh.bh

B-H curve for OPERA models.

12 Sector Magnet Analysis.ipynb

Jupyter notebook containing all analysis in report including measurement averaging, theoretical function fitting, scale factor fitting, and generation of all plots. Uses all csvs mentioned above.