Ambient Magnetic Field Compensation for the ARIEL (Advanced Rare IsotopE Laboratory) Electron Beamline

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Summary

TRIUMF's Advanced Rare IsotopE Laboratory (ARIEL) facility is under deployment and it aims to expand Canada's capabilities to produce rare isotopes as well as to deliver greater beam time for experimenters. This project requires the construction of a new beamline from the cyclotron in addition to the existing meson producing beamline and an electron beamline, which will have its source in a 300kV electron gun.[1] The Beam Physics group is focused in overcoming the challenges the project presents.

One of the challenges the electron beam line posed on the Beam Physics group was overcoming the possible complications that an ambient 3 Gauss magnetic field from the cyclotron would present to the alignment of the beam. This was approached by performing magnetic field surveys in the experimental hall where the beamline would be located and analysing the data as well as making predictions based on simulations to arrive at solutions that would attenuate or eliminate the stray field.

The ambient magnetic field was successfully reduced to 1(±0.1) Gauss eliminating the need for previously considered shielding.

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Abstract

The e-Hall presented an ambient magnetic field of 3 Gauss, which would affect the alignment of the electron beam unless it was compensated for or eliminated. A potential solution evaluated involved the use of Helmholtz coils along the beam path to create a region of uniform magnetic field in combination with shielding the beam using high magnetic permeability steel.

Shielding was considered given the lack of homogeneity and uniformity of the stray magnetic field. Placing steel with a high magnetic permeability on the floor along the beamline would cause the field lines to be directed through the metal and become more homogeneous as they emerge and pass through the Helmholtz coils. Alternatively, degaussing the e-Hall was also considered.

Even though the magnetic field was not completely eliminated through degaussing due to magnetic hysteresis, the results were satisfactory. We effectively reduced the ambient 3G field to approximately 1G. The current intensity of the ambient field is not expected to affect the alignment of the electron beam.

Initial measurements

Measurements were taken in the e-Hall along the beam path and at beam height (approximately 34 inches) using a magnetic probe and a gaussmeter precise to 0.01G. Only the vertical and horizontal components were measured (y and x respectively) following the convention dictating the z-axis as the beam direction.

Markings were put on the floor every 10 inches to indicate where to take measurements and due to irregularities in the concrete's flatness it was necessary to check and re-adjust the levelling of the probe regularly. To ensure the measurements for the vertical and transversal components of the magnetic field were taken accurately, one laser projecting a straight line along the beam path and a laser pointing at the location where the measurement was to be taken were used. The data collected was plotted using Matlab as shown in Figure 2 . The same procedure was repeated to take measurements with the cyclotron off (Figure 3).

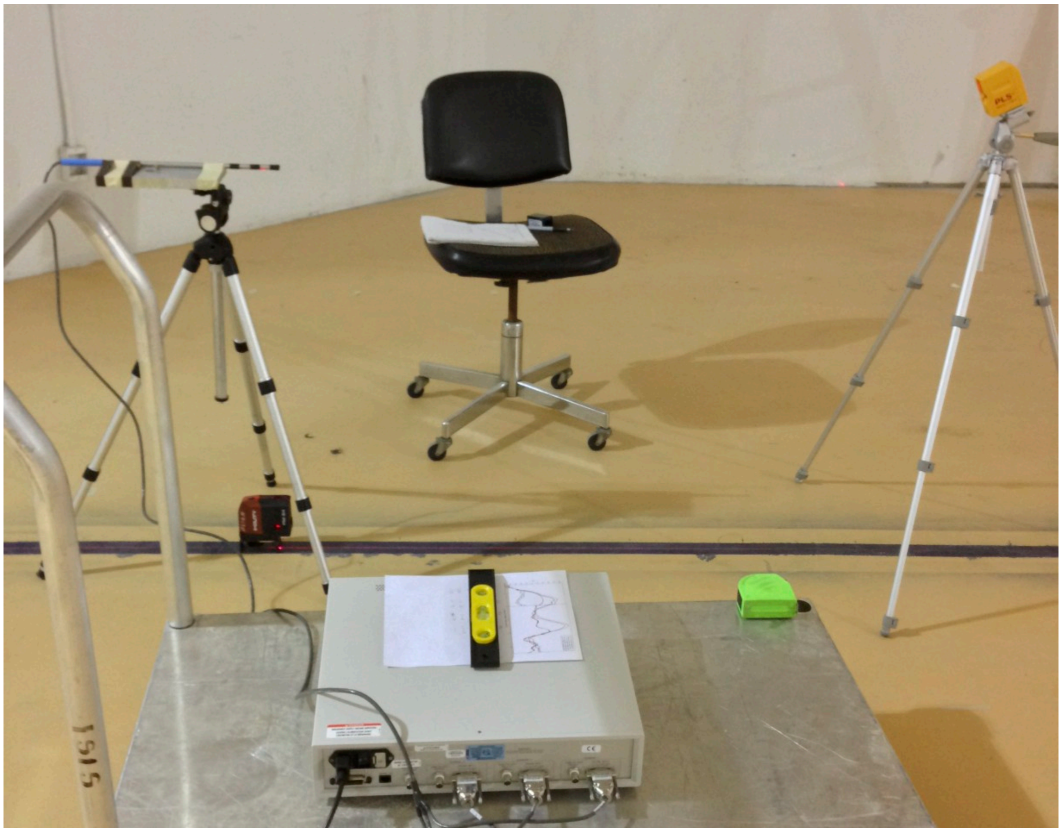

Figure 1: Set up used for taking measurements showing gaussmenter, probe, a laser shooting directly above the beamline onto the probe and a laser projecting a strainght line along the beam path.

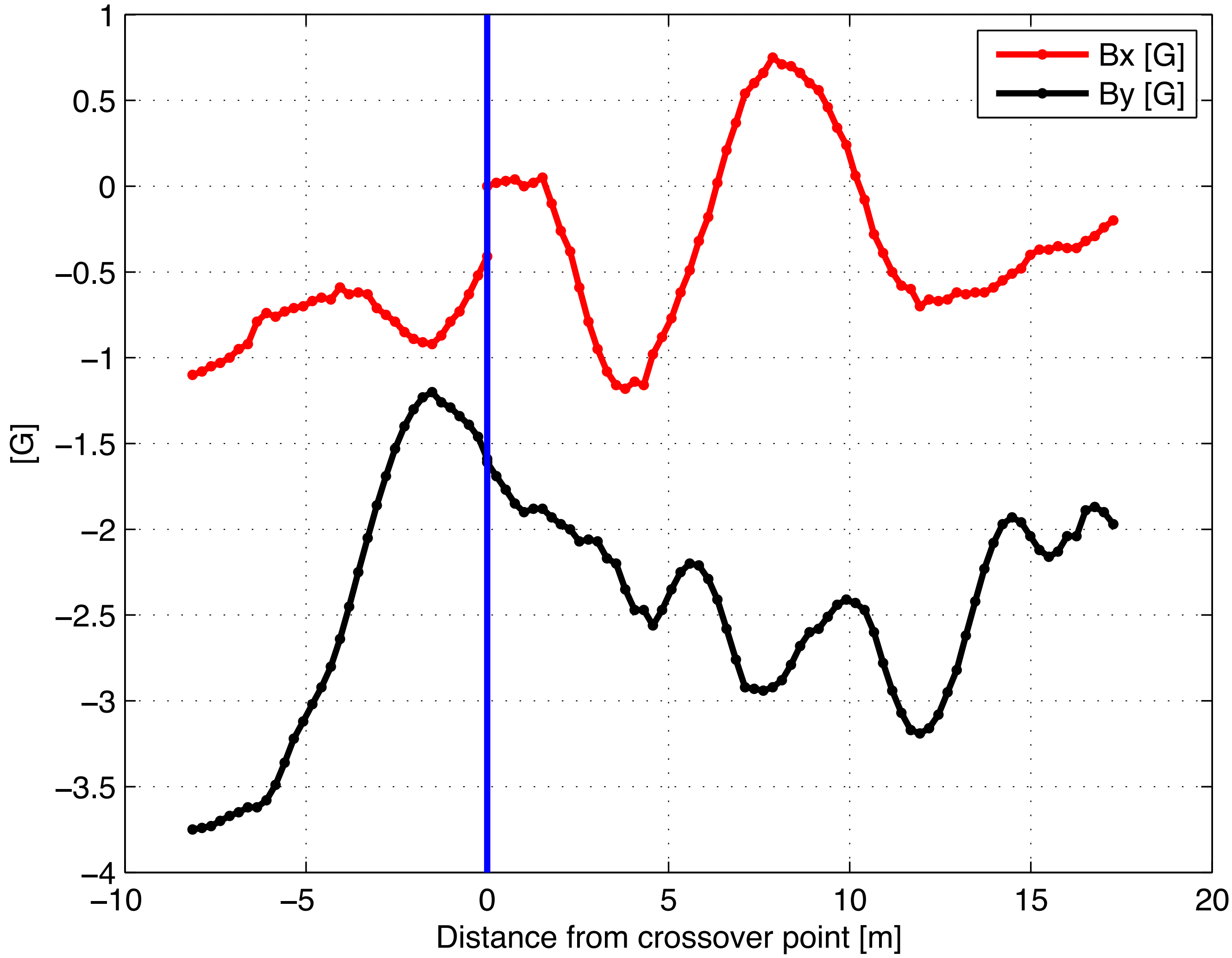

Figure 2: Vertical and Horizontal components of ambient magnetic field along beam path

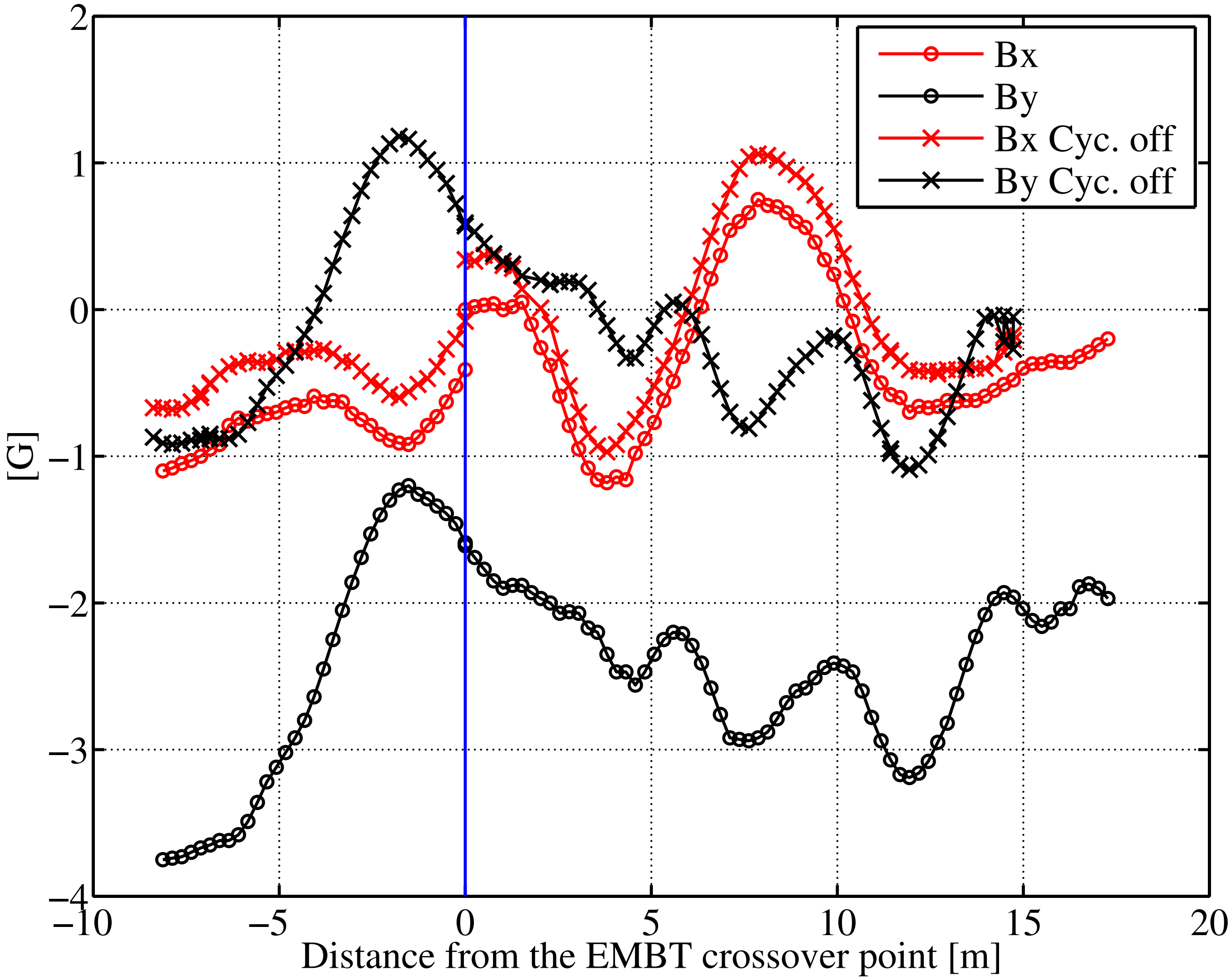

Figure 3: Vertical and Horizontal components of ambient magnetic field along beam path. Graph includes data points taken with cyclotron on and off.

Shielding

Introduction

It was clear from measurements that the magnetic field along the beam path fluctuated dramatically. This is due in great part to the rebar inside the concrete that makes up the floor of the e-Hall. Placing steel was predicted to help in making these variations less pronounced.[2] A more uniform magnetic field would mean the Helmholtz coils could compensate more effectively for the stray field.

3D Models

Using OPERA simulation code the cyclotron was modelled to be a 10m diameter coil. The electron beamline lies24 inches below the cyclotron plane and 34 inches above the e-Hall floor. The rebar is simulated using random cylinders made of steel to exemplify their effect.

Simulations were carried out to determine the effect of structural steel in the floor on the cyclotron's stray magnetic field. Additionally, scenarios including the steel shielding were also simulated and show the effect of different μ_r and thickness combinations as well as different area coverage.[3] The models illustrate the need to have a large as possible area covered as well as a high $\mu_r \times$ thickness combination.

The values were calculated using the equation for field attenuation for a cubic shielding box[4]:

$$s = \frac{4}{5}\mu\frac{d}{a} \quad (1)$$

where d is the material thickness, a is the length and μ represents magnetic permeability.

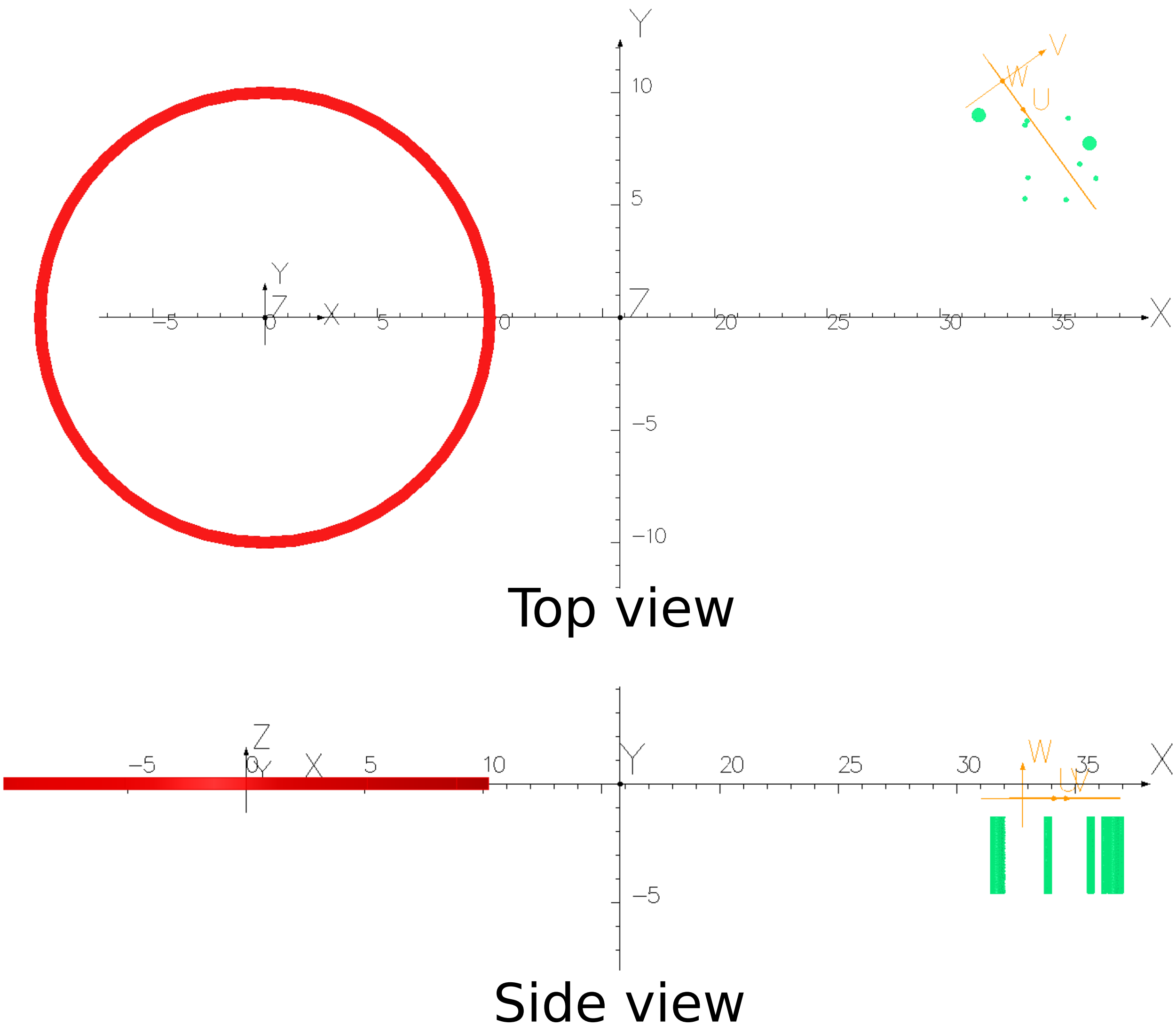

Figure 4: OPERA model showing the cyclotron in red, rebar steel in green. The orange axis represents the beam axis

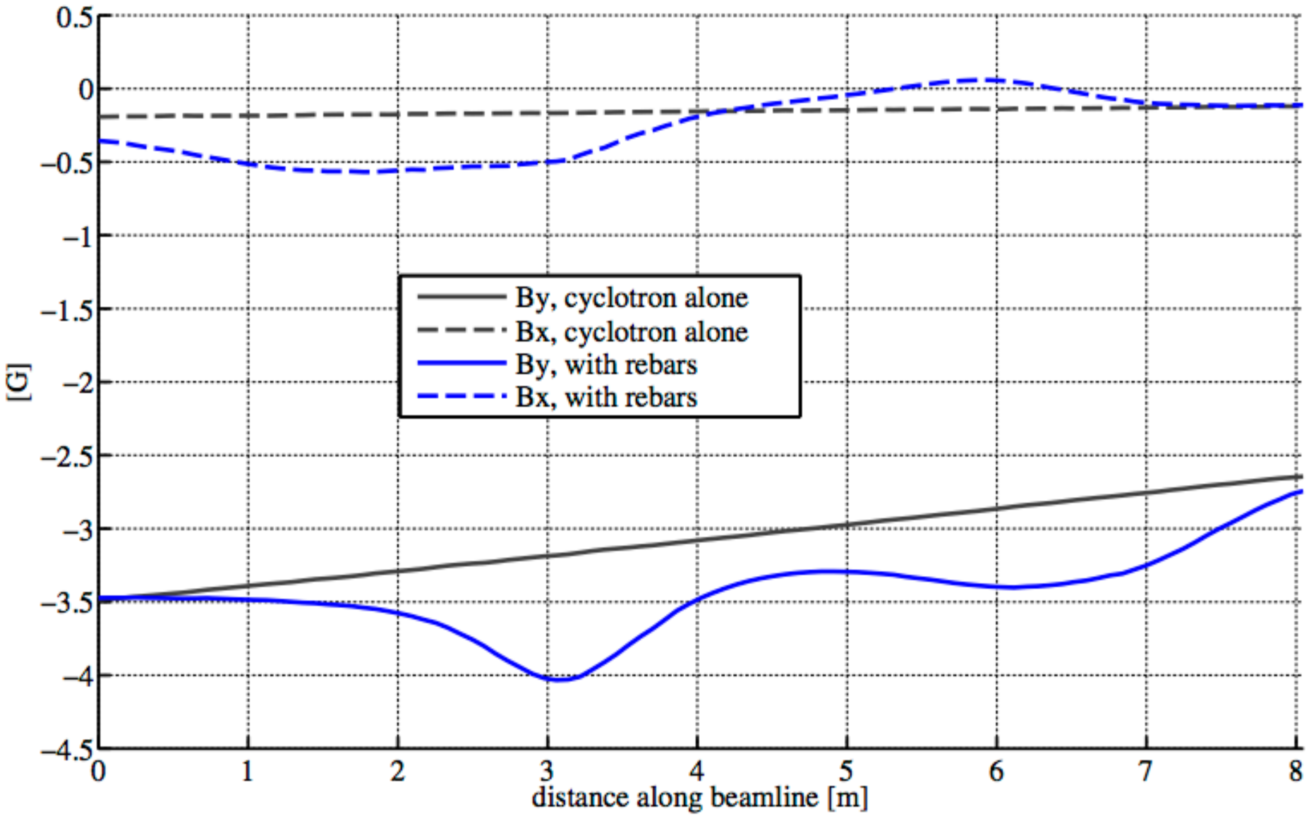

Figure 5: Effect of steel rebar on x and y components of cyclotron's stray magnetic field

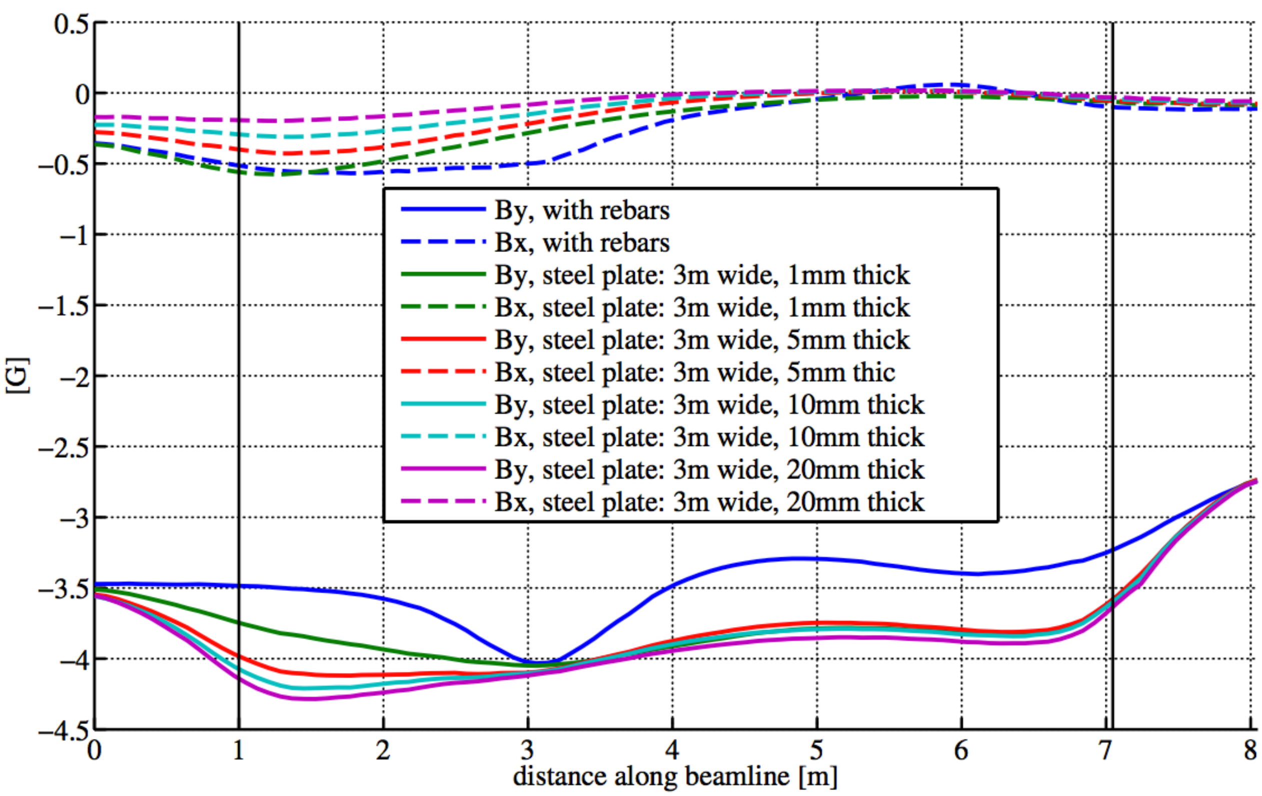

Figure 6: Effect of shielding 3m wide with μ_r = 1000 and varying thicknesses

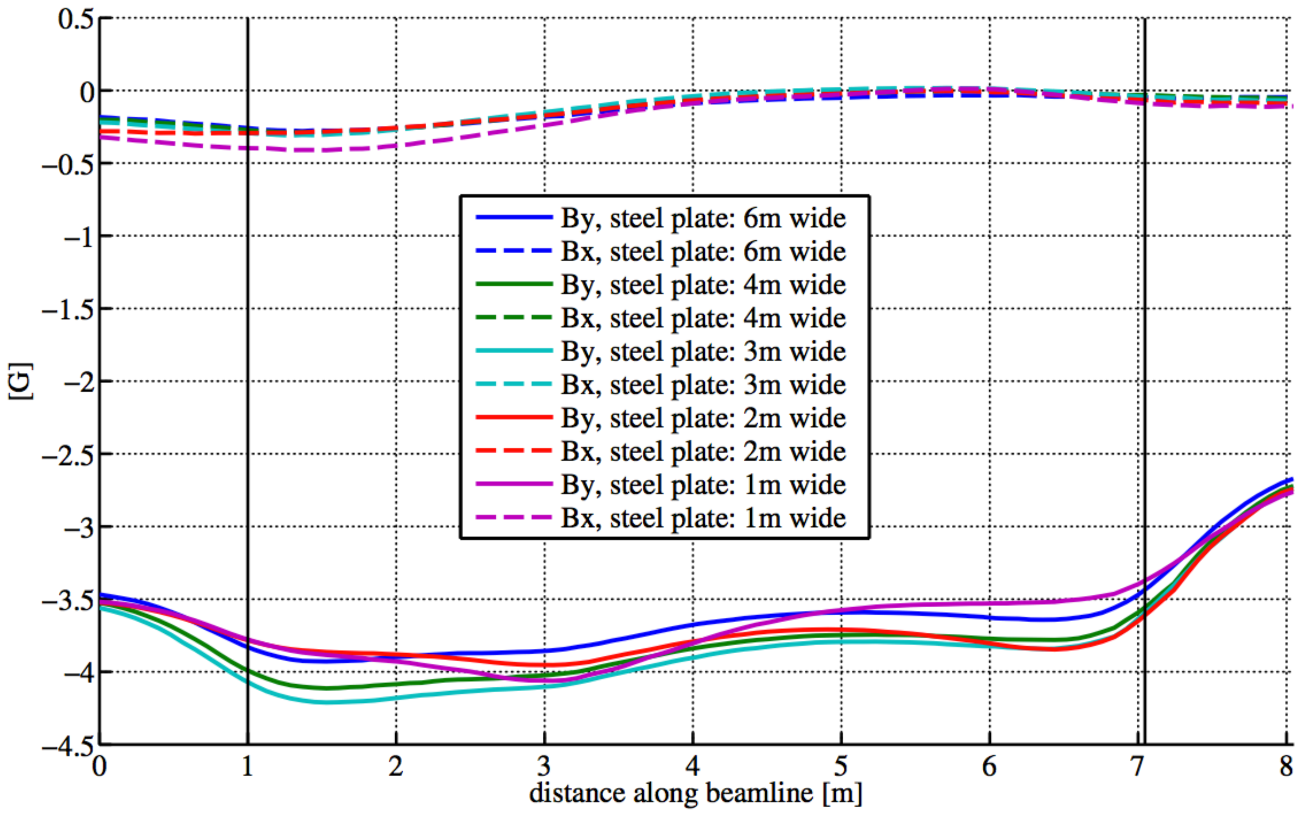

Figure 7: Effect of varying width of shielding with μ_r = 1000, thickness = 10mm

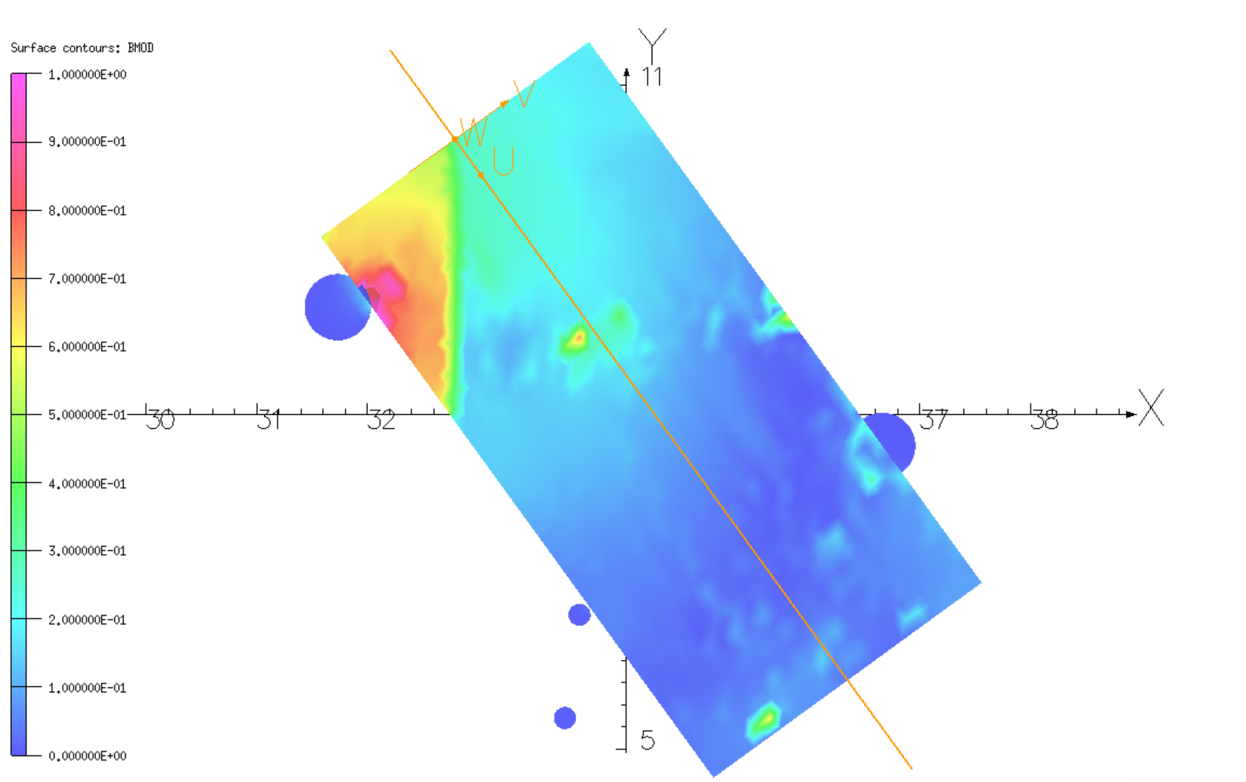

Figure 8: Field variation in Tesla throughout 2mm thick steel plate with μ_r = 5000

Opera

Material Requirements

Minimum μ_r × thickness	10 m
Minimum thickness of steel	3mm
Minimum μ_r	1000
Area to cover	A minimum of 1.5 m: on both sides of the beamline (transversally and longitudinally)

Table 1. Requirements for shielding material, μ_r stands for magnetic permeability[5]

Helmholtz Coils

Use of Helmholtz Coils to Attenuate Magnetic Field Around Electron Beamline

The geometry of Helmholtz coils being such that their radius is equal to the distance between them and including a current of the same magnitude and direction in each coil allow for a homogeneous field to be produced mid-plane between the coils. To increase the area of uniformity, the coils can be extended in one direction and create a uniform field along a straight line, in this case the beam axis. The ratio for coil width and separation between the coils is √3 : 1. And the magnetic field along the beam axis can be described by[6]:

$$B_0 = 2\sqrt{3}\,\frac{\mu_0 I}{2\pi h} \tag{2}$$

For current ±I inside the coils and the distance between the coils, separation between the coils, h, and μ_0 being the permeability of free space.

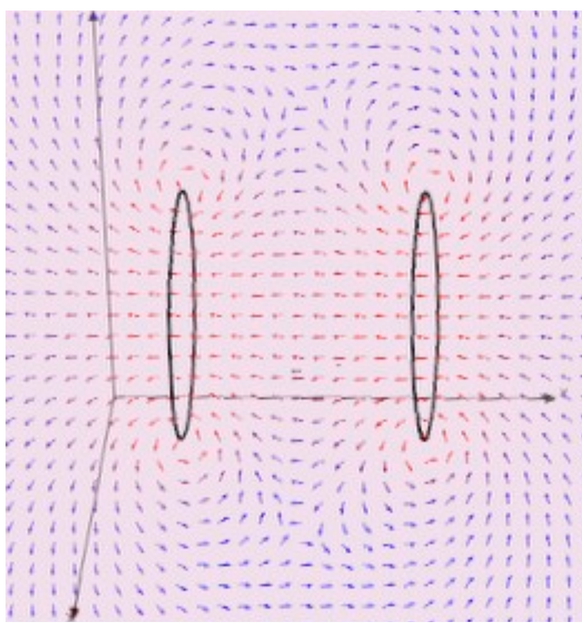

Figure 9: Model showing magnetic field around circular wires in Helmholtz coils

Simulation and Modelling

A simulation was done in OPERA for Helmholtz coils with total current of -296A in each coil. The model revealed that the effect of the structural steel in the floor dominates over the effect of the cyclotron.

The coils are modelled in red and added onto the previous model shown in Fig 7. and Fig. 11.

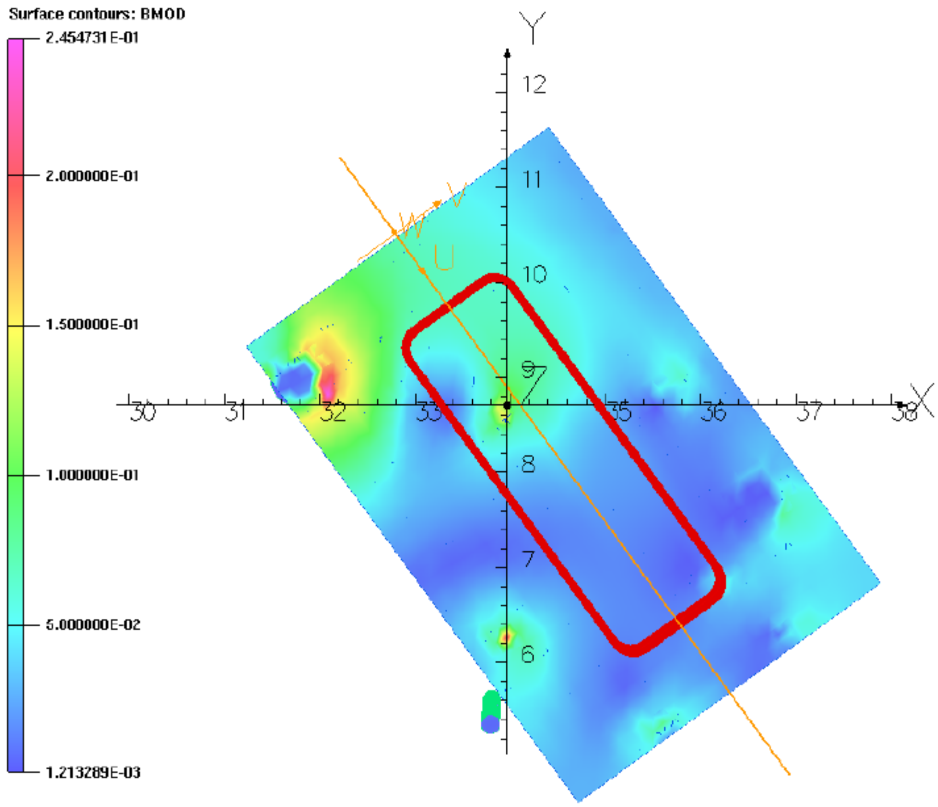

Figure 10: Field variation in Tesla using steel shielding and Helmholtz coils

Matlab plots form data gathered through 3D modelling for x and y components of the magnetic field show the Helmholtz coils being the field closer to zero.

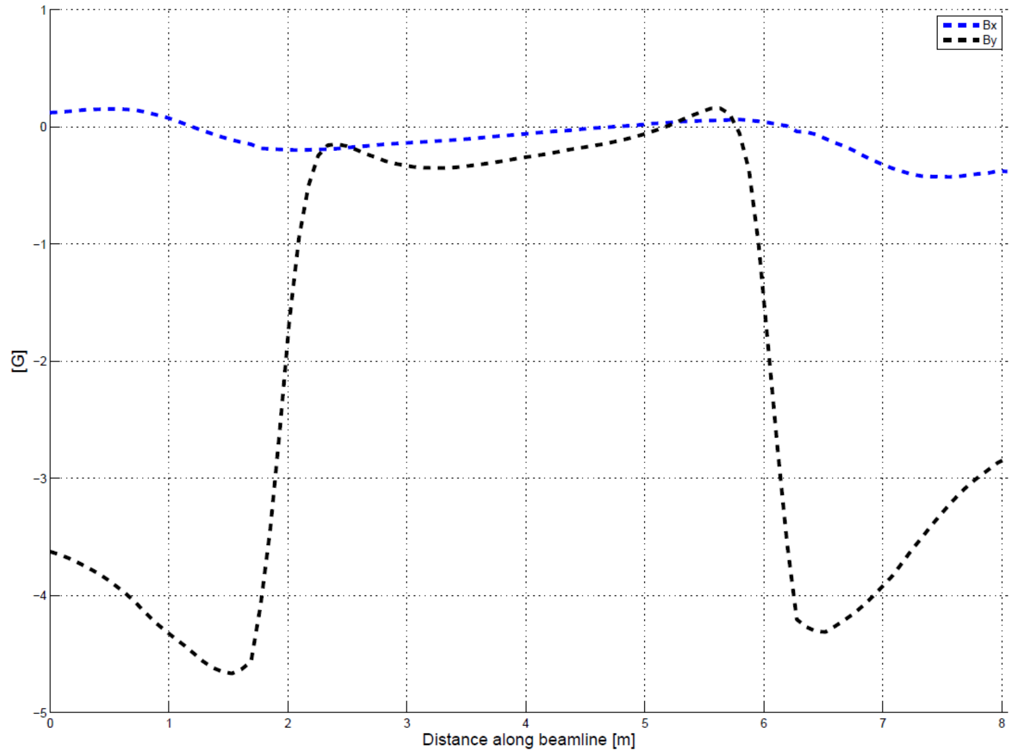

Figure 11: Bx and By components along beam axis under the effect of Helmholtz coils

A simulation ran without the effect of the cyclotron and with a recommended current of 500A showed the effect of the Helmholtz coils dominates over the rebar. A Matlab plot of the vertical component along the beam axis shows the potential of the Helmholtz coils to produce a uniform field.

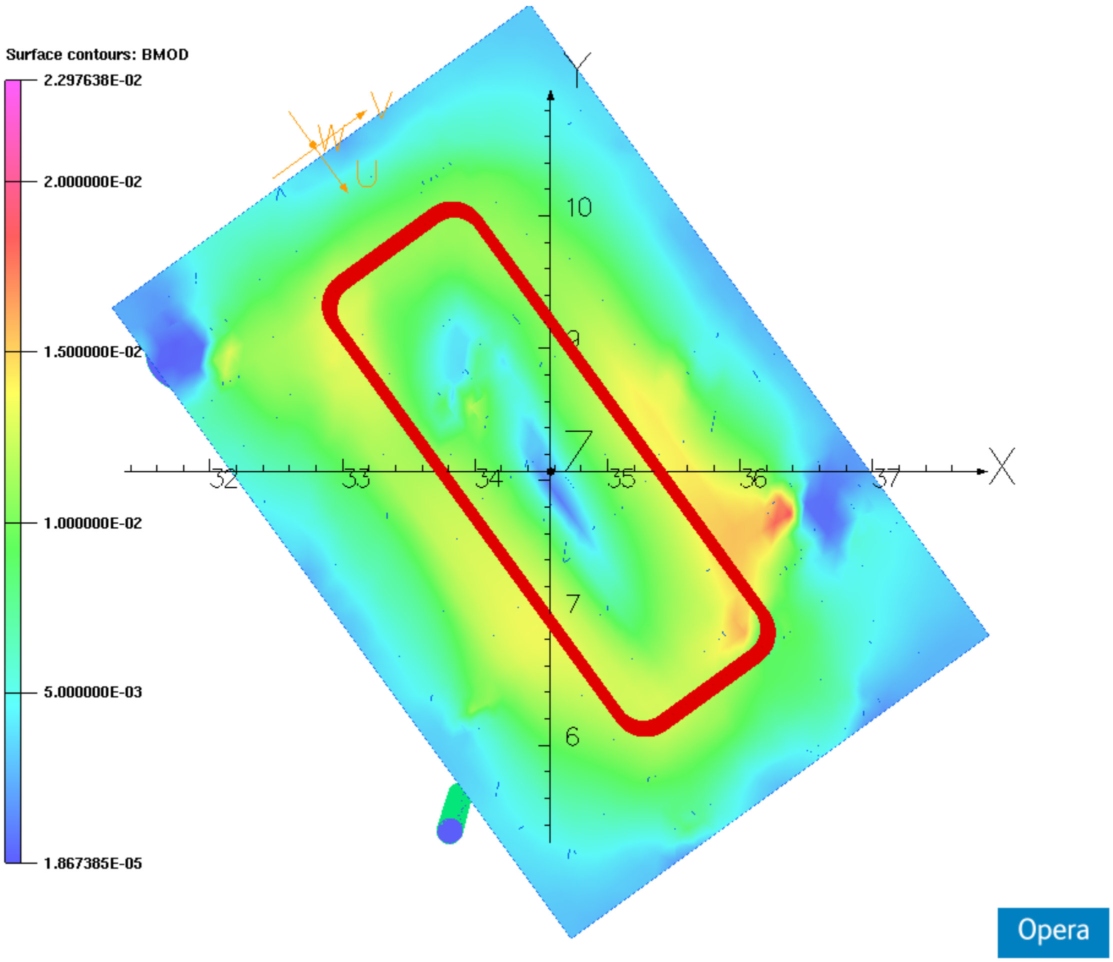

Figure 12: Variation of magnetic field in Tesla around area with rebar using steel shielding, Helmholtz coils and with the cyclotron off

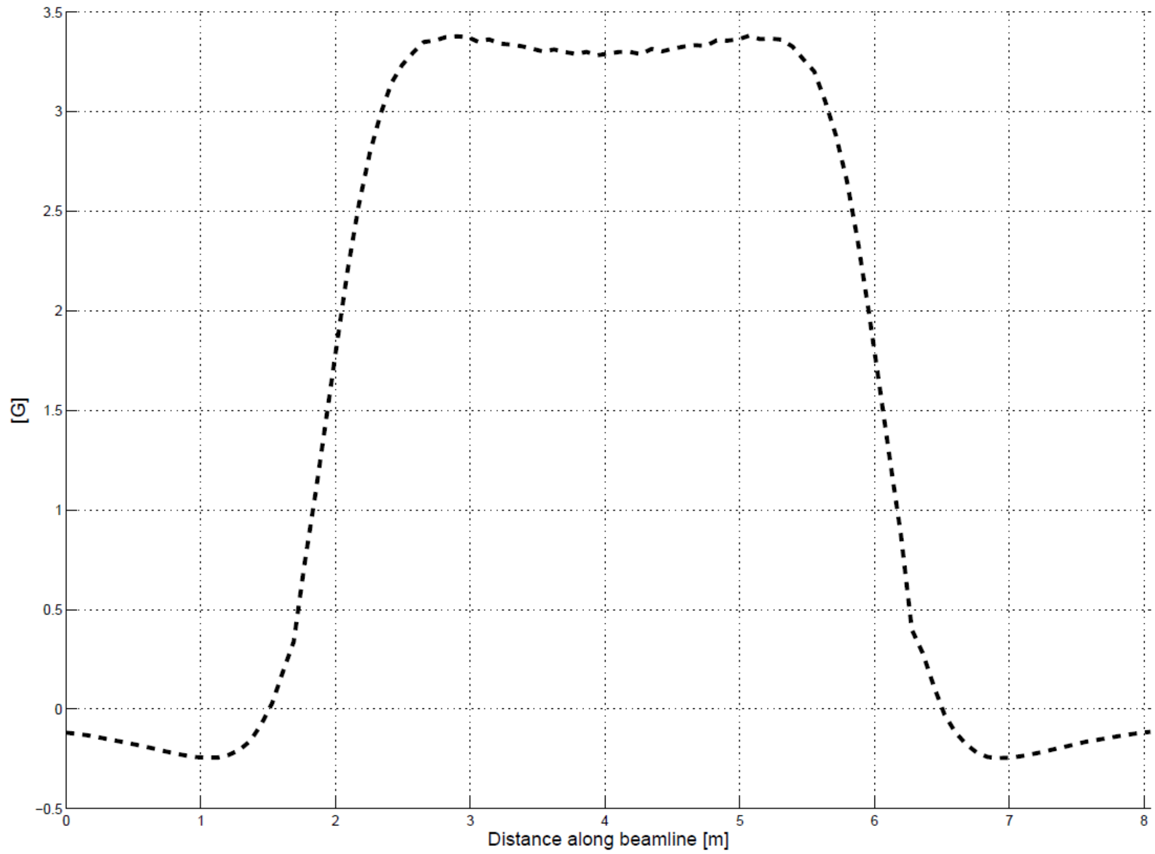

Figure 13: Variation of vertical component of magnetic field along beamline axis without the effect of the cyclotron and with Helmholtz coils

Degaussing

Initial Consideration for Degaussing the e-Hall Floor

The e-hall remained relatively empty and stripped of equipment before the new components were brought down for installation. This opened the opportunity for a large-scale degaussing attempt to affect the entire floor as opposed to restricting it to a limited area around the electron beam axis. Degaussing a limited area near and over the beam path would be ineffective due to a leak magnetic field from the non-degaussed surroundings affecting it.

Method and Materials

The method for degaussing the floor was chosen to be two coils, one on top of the other (in order to increase the number of turns) with an alternating current through the wires, supplied by a power supply, of approximately 30A and at a low frequency of approximately 4 Hz. We performed several trials and the specifications for the current and frequency were changed but the main setup remains as described above. The coils were attached to wheels so that their elevation from the floor would not exceed 1 inch. As the coil was slowly swept across the e-Hall the small magnetic field created would penetrate the rebar in the floor and reduce the ambient field observed in previous data plotted in Figures 2 and 3.

Figure 14: Degaussing set up

Initial Testing

To evaluate the performance of this method, a small test area was chosen where the magnetic field was measured. It was later degaussed and measurements were taken again. The measurements were taken using the same setup and equipment described the previous in section. Colour maps for this initial test area show the variation in the magnetic field after sweeping the coil and indicate the necessity to degauss a larger area to experience more drastic results.

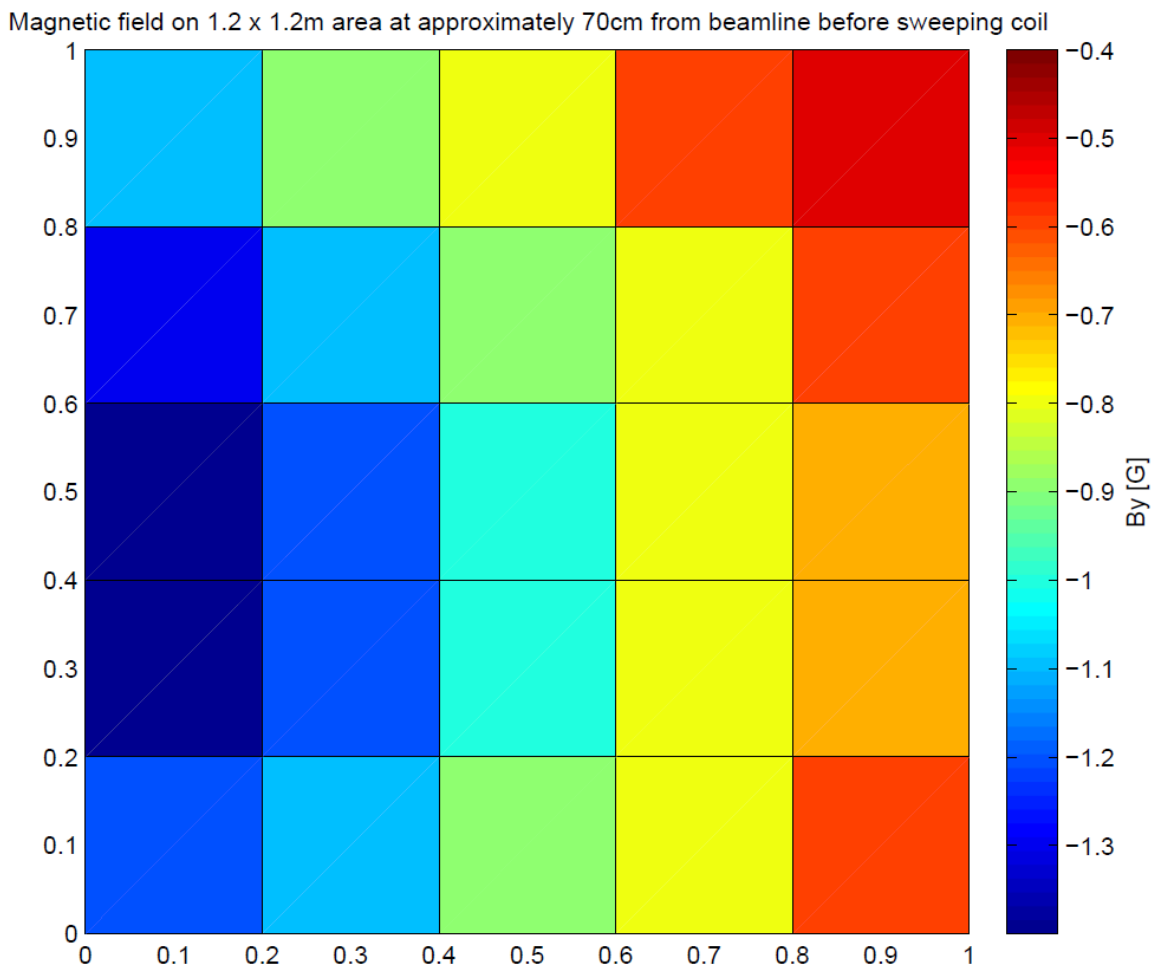

Figure 15: Colour map of vertical component of magnetic field (By) around test area to be degaussed measured at beam height (34 inches)

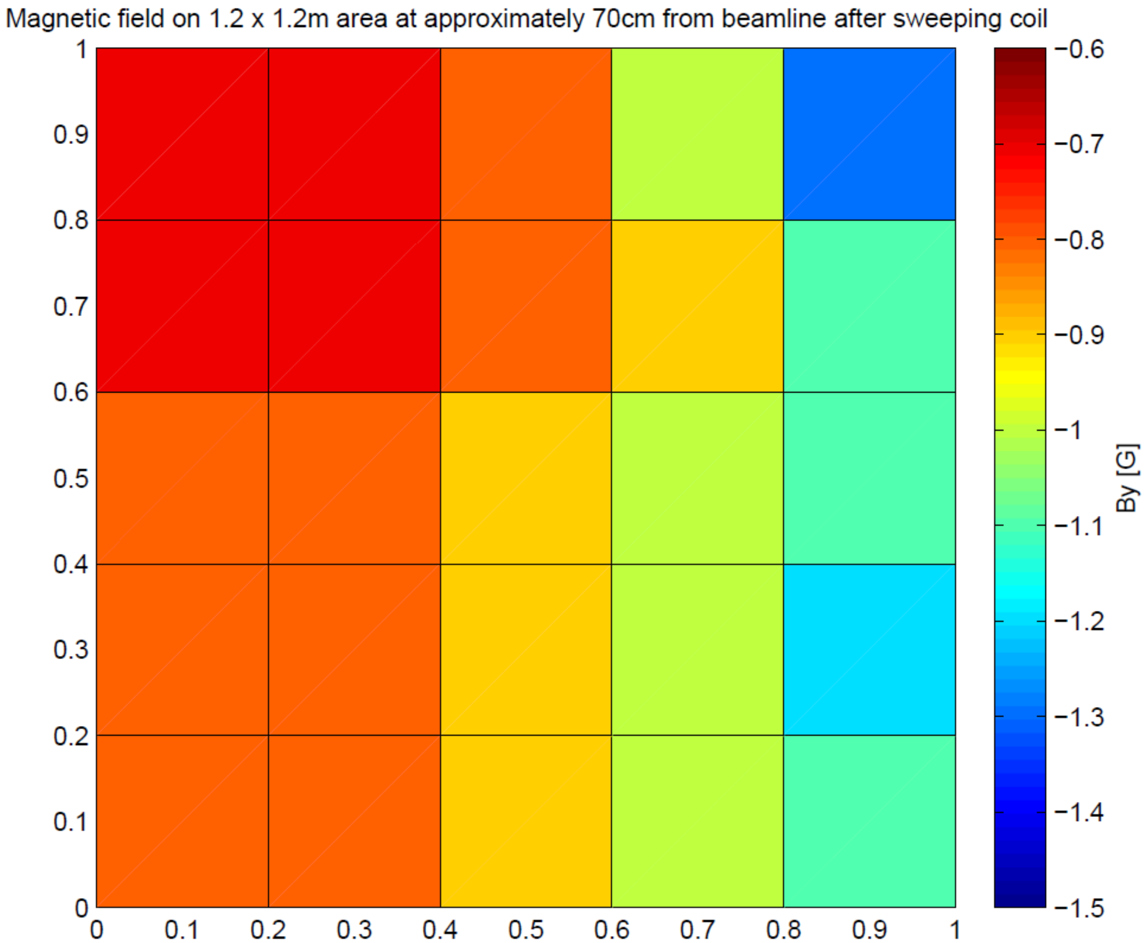

Figure 16: Colour map of vertical component of magnetic field (By) around test area after degaussing measured at beam height (34 inches)

First Degaussing Attempt

After degaussing the entire e-Hall I took more measurements and plotted them against the previous data (Figure 17). Even though some improvements were visible, there were still areas that showed peaks. The data proved the effectiveness of degaussing and so we decided to sweep the coil one more time using a lower frequency.

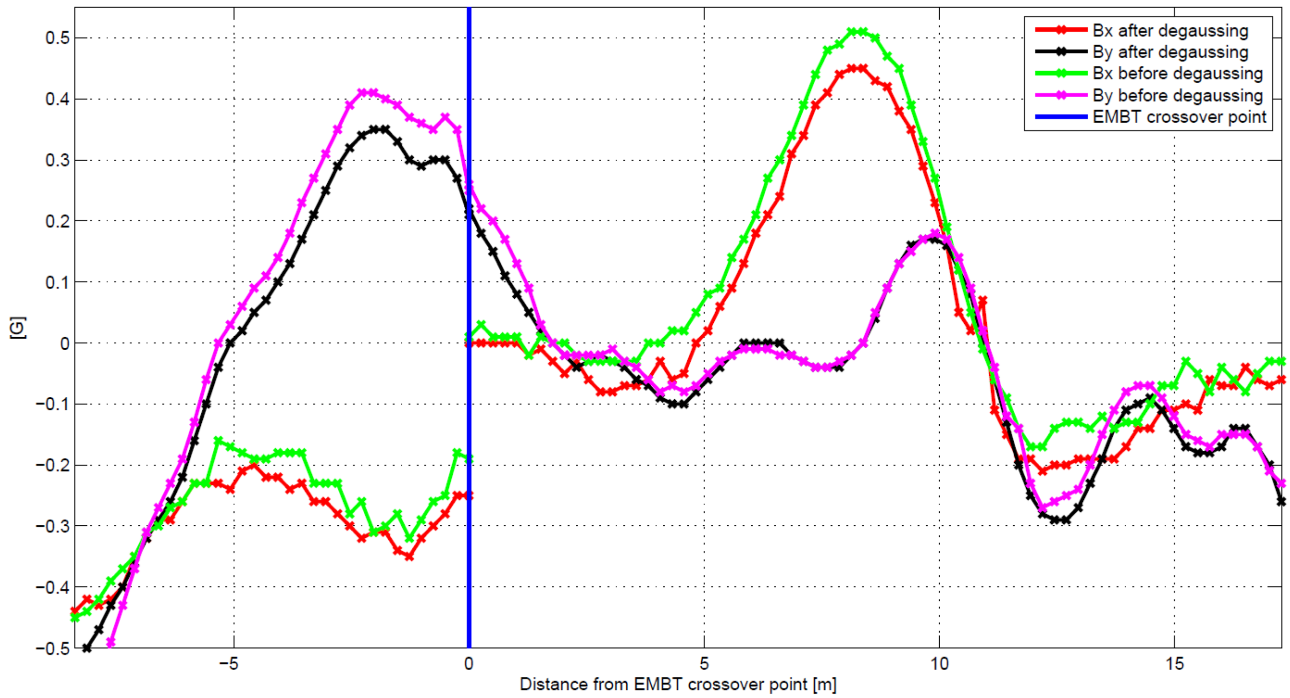

Figure 17. Comparison between vertical and horizontal components of magnetic field before and after degaussing showing marginal improvement.

Introduction of New Infrastructure in the e-Hall

As we approached installation and assembly dates for components in the e-Hall a steel frame was constructed with the purpose of supporting cables and piping connecting cryogenic modules to the linear accelerators. This structure posed a potential inconvenience to the ambient magnetic field as well as for the process of degaussing. I studied the potential effects the steel frame would have on the vertical component of the magnetic field along the beam axis. A simulation was carried out using OPERA modelling the frame as hollow steel columns and the data was plotted using Matlab.

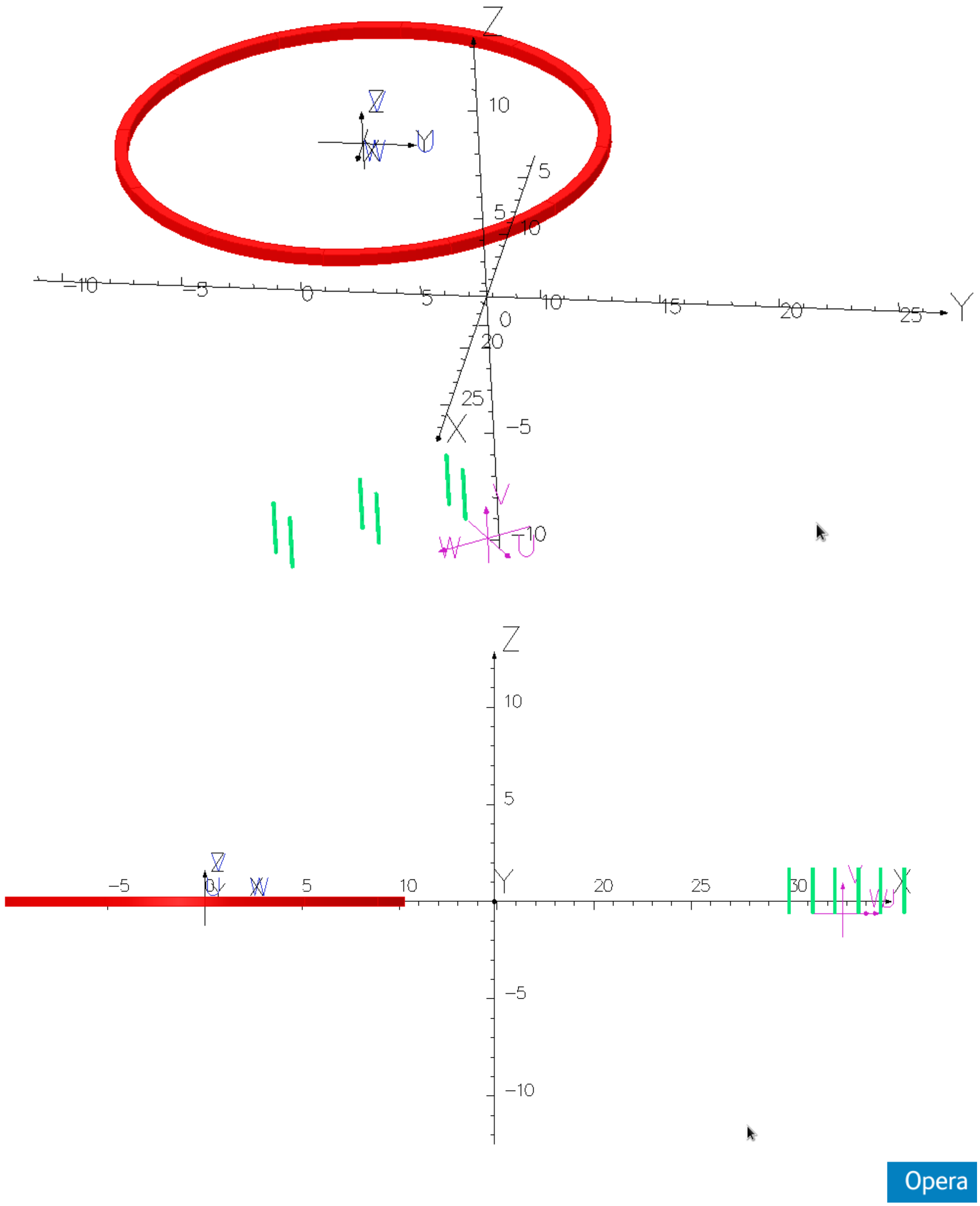

Figure 18: Steel columns (in green) added onto previous model

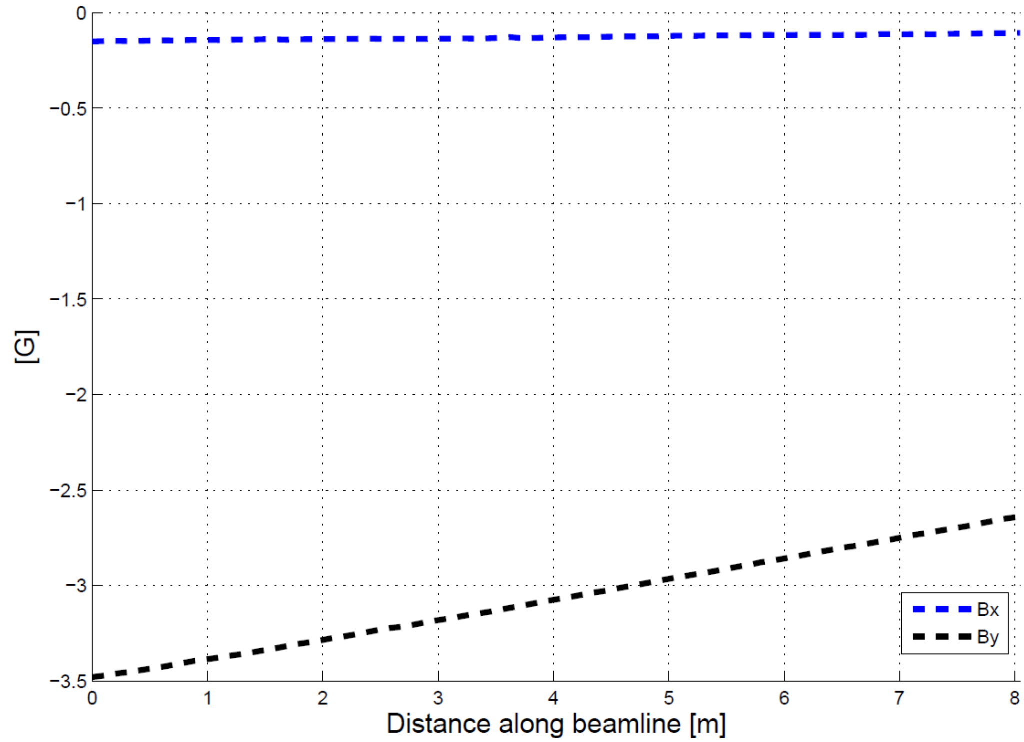

Figure 19: Effect of steel structure on vertical and horizontal components of magnetic field along beam axis assuming μ=100 for steel.

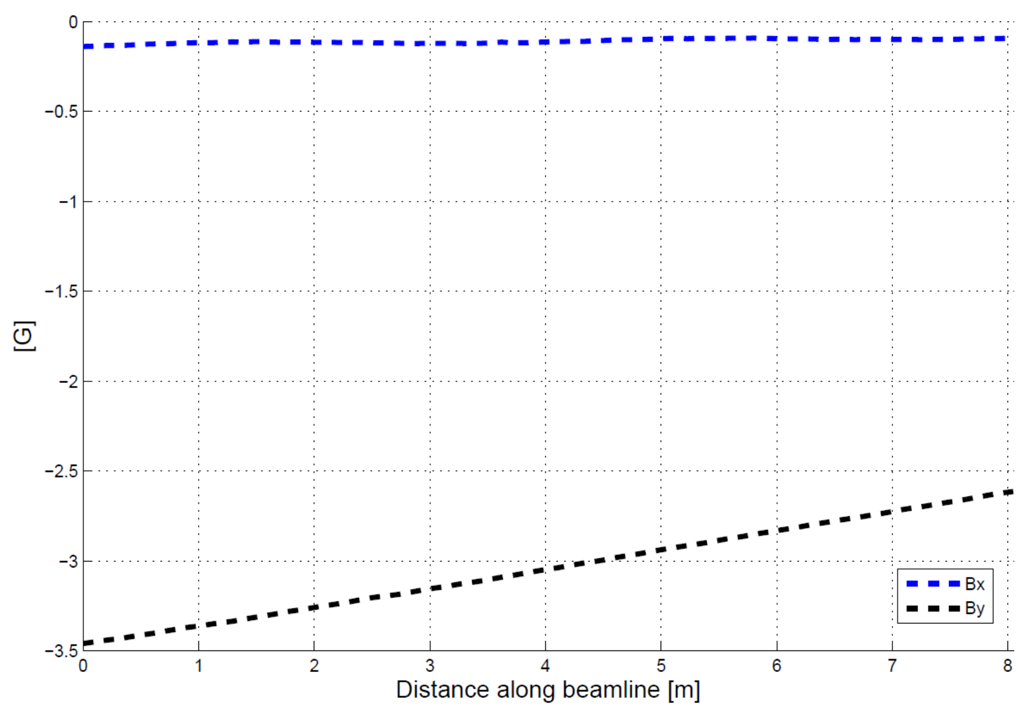

Figure 20: Effect of steel structure on vertical and horizontal components of magnetic field along beam axis assuming μ=1000 for steel.

The effects from the steel frame were not alarming and we do not expect the structure to interfere with the alignment of the electron beam.

Final Degaussing Results

Following the same procedure described previously, the final degaussing campaign was carried out with an alternating current of 80 A peak-to-peak and at a low 0.25Hz frequency. The results were plotted against the initial measurements and show remarkable improvement, there is only a fluctuation of ~1.1G on By and ~0.9G on Bx.

Figure 21: Effect of the degaussing coils seen on fragments of iron following the field lines around rebar in the concrete

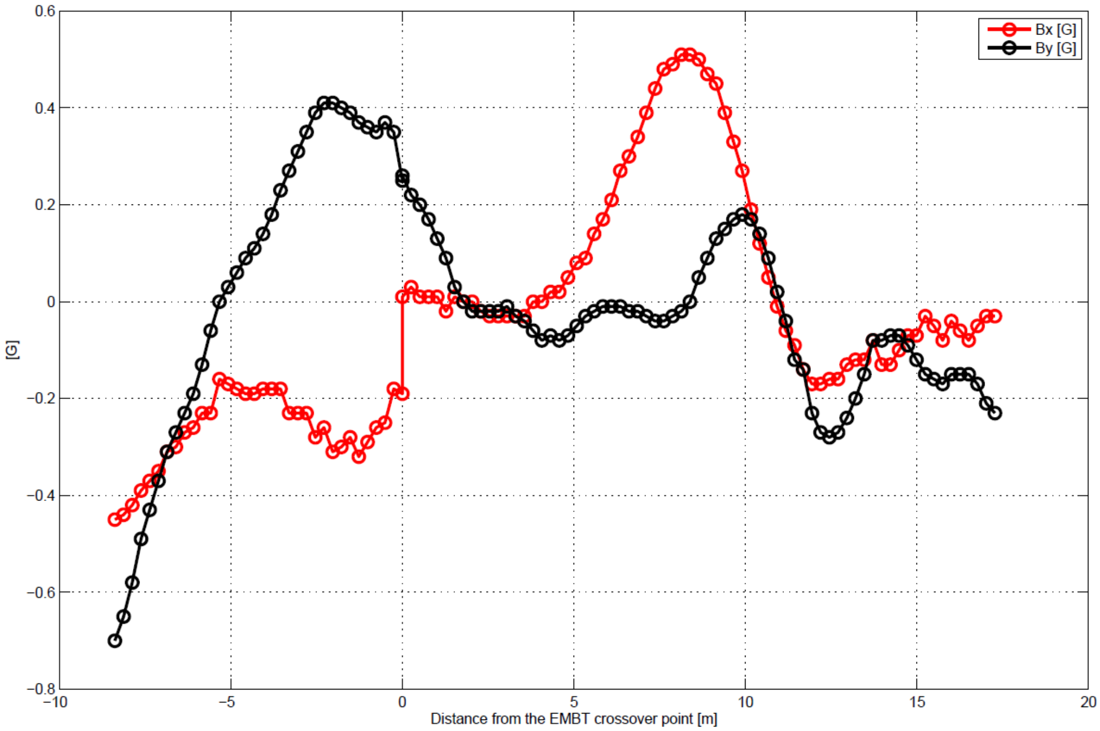

Figure 22: Vertical and horizontal components of magnetic field along beam line after degaussing. Bx fluctuates between -0.45 and 0.5 G while By varies between -0.7 and 0.4G showing improvement from Figure 17.

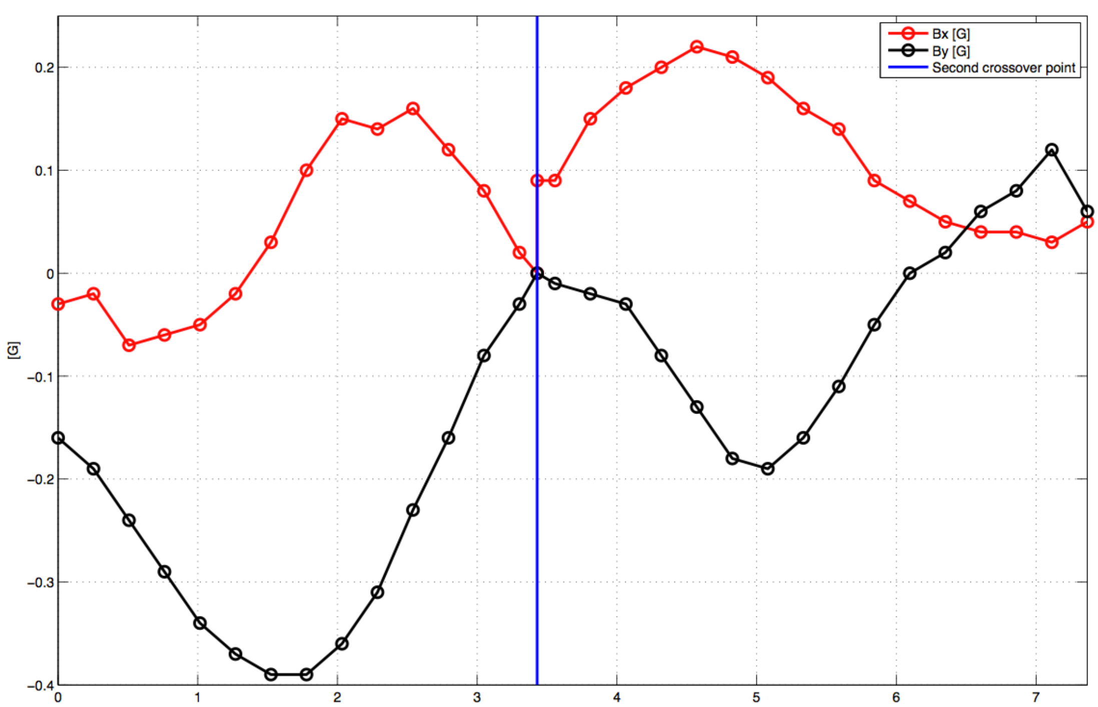

Figure 23: Vertical and horizontal components of magnetic field for beam dump after degaussing

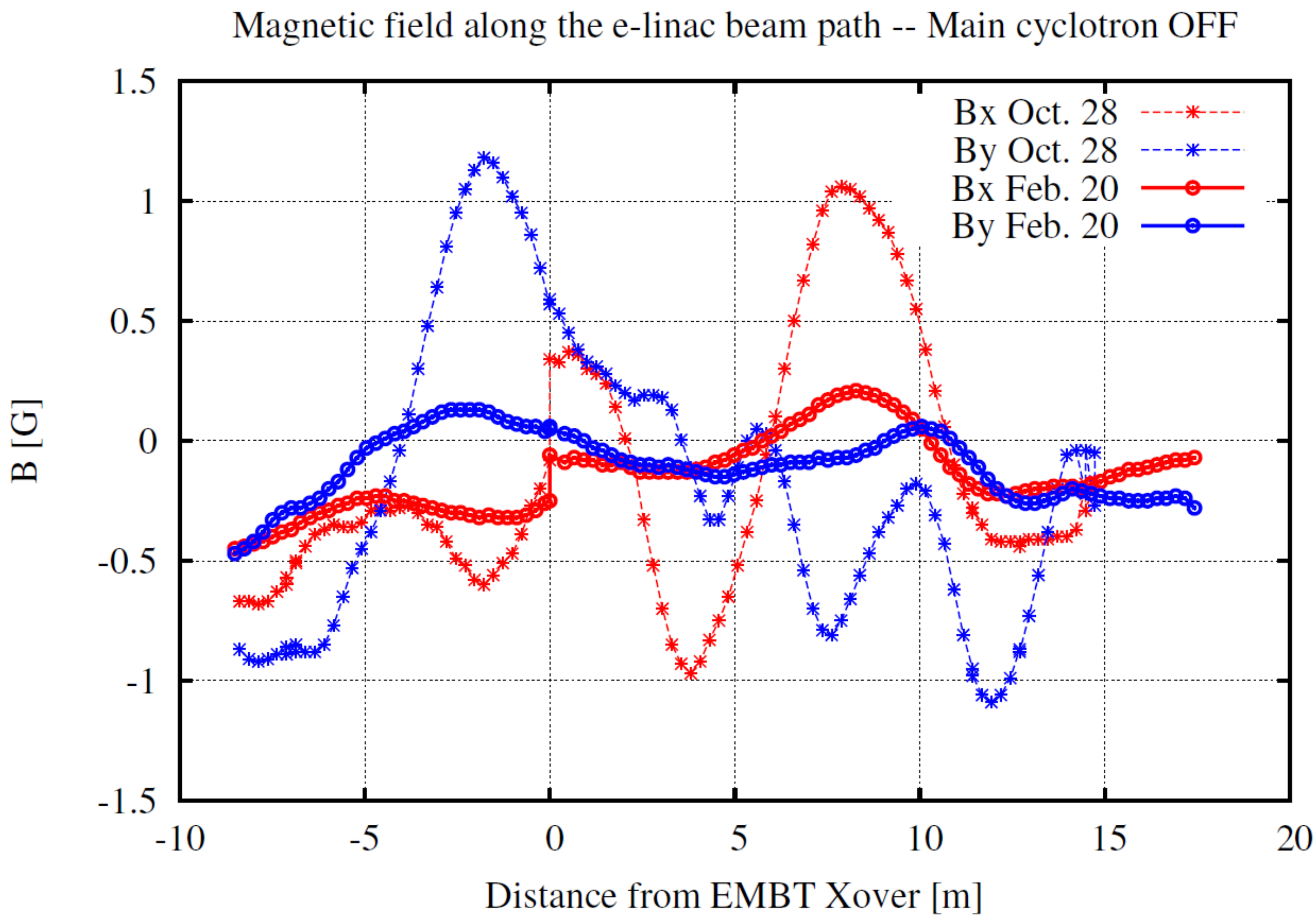

Figure 24: Magnetic field along beam line before and after final degaussing campaign showing significant improvement.

Conclusion

Even though due to magnetic hysteresis, it is not possible to completely eliminate the stray magnetic field, the results indicate that we have successfully reduced the ambient field from 3(±0.6) G to a fluctuation between -0.45 and 0.23G on Bx, and between -0.47 and 0.13G on By . Our work degaussing has been effective enough that previous methods considered to attenuate the magnetic field such as shielding are no longer required. The ambient magnetic field is under control and should not present a challenge for the alignment of the electron beam.

Acknowledgments

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[1] Merminga, L. et al. *ARIEL: TRIUMF'S ADVANCED RARE ISOTOPE LABORATORY*. Vancouver: TRIUMF.
[2] Planche, T. (2013). *Cyclotron Stray Field Compensation Part 1: Floor Plates Requirements*. Vancouver: TRIUMF.
[3] Planche, T. (2013). *Cyclotron Stray Field Compensation Part 1: Floor Plates Requirements*. Vancouver: TRIUMF.
[4] Thomas Planche, private communication
[5] Planche, T. (2013). *Cyclotron Stray Field Compensation Part 1: Floor Plates Requirements*. Vancouver: TRIUMF.
[6] Baartman, R. (2010). *Magnetic field compensation for E-Linac*. Vancouver: TRIUMF.