Studies on a Time Projection Chamber

- Summer Student Programm 2008 -

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Abstract

I studied the influence of different material to the magnetic field of a large bore solenoid magnet (it will be used for a time projection chamber). With the help of a structure the magnet will be moved up and down and also rotated. The calculations were done to decide which material to use for the structure. The material should have a minimal influence to the magnetic field. To do the calculations a FEM-Software was used. Also I tested a new time projection chamber prototype.

Contents

1 Introduction

During the Summer Student Program I worked for the group FLC (Research & Developement for a Linear Collider detector) and my subgroup was TPC, which is working on a concept for a Time Projection Chamber (TPC). This Time Projection Chamber is part of the ILD (International Linear Collider Detector) concept, which is one of three detector concepts for an International Linear Collider (ILC). The ILC will be a linear electron-positron collider reaching energies up to 1 TeV and will run a scientific programme which is complementary to the one of the LHC (Large Hadron Collider). The advantage of the ILC in comparison to the LHC is that it will be able to do more precise measurements due to the well known initial state. From the three detector concepts two will be selected to be implemented and used for the ILC. These two detectors will be used with a push-pull method. This method just needs one beamline and so the costs are not that high as if one would use two beamlines. At the moment it is under investigation, if it is possible to move the detectors in general and in a reasonable time to gain a high luminosity (as intended in the the push-pull method). During my work the field cage of a new prototype (Large Prototype) arrived at DESY. Until that time I have done calculations of the magnetic field for the PC-MAG. The PC-MAG is a large bore solenoid magnet in which the Large Prototype later on will be tested. After the arrival of the Large Prototype I helped to test it. In the following I will give a short overview of the general principle of a TPC and then I will present the results of my studies.

2 Time Projection Chamber

A Time Projection Chamber consists of a gas filled sensitive volume, usually with a central cathode that divides the volume into two identical halves. On both sides are anodes with readout systems. The cathode is at a potential that results in a field strength of some 100 $^{\mathrm{V}}/_{\mathrm{cm}}$ while the anode is at ground potential. In 4π-detectors at high energy experiments, the drift volume is usually cylindrical and the beam pipe goes trough the rotation axis of the TPC with the interaction point being at the center.

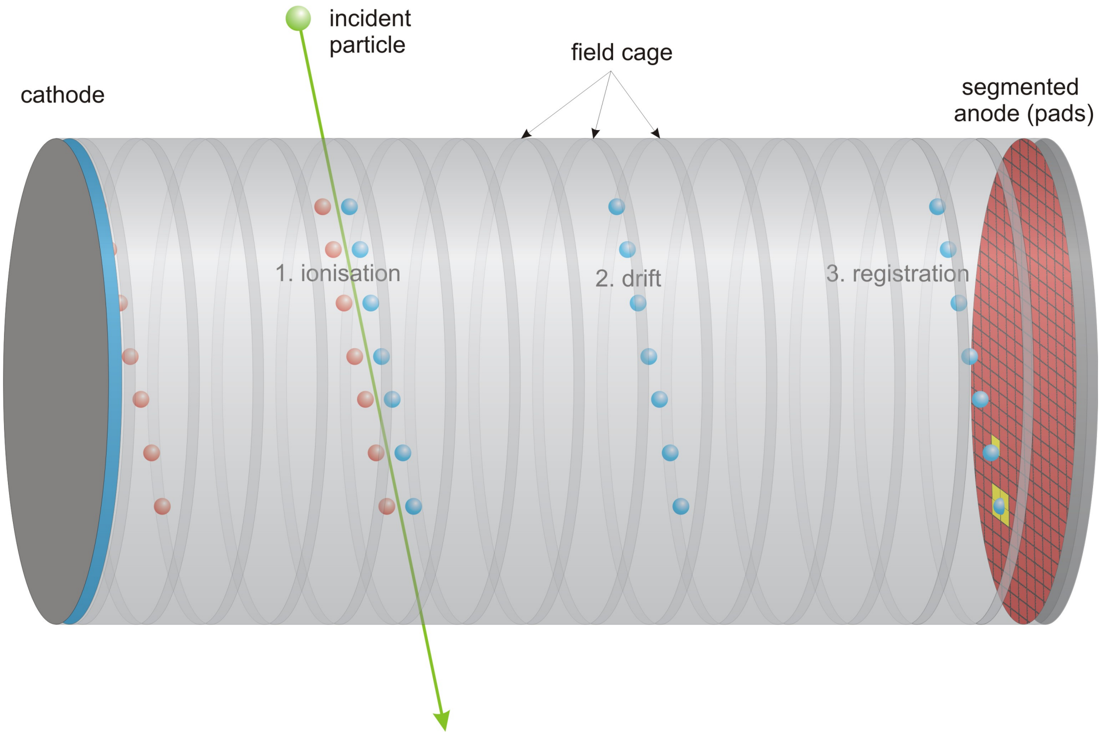

Figure 1: Sketch of a Time Projection Chamber and its working principle (figure from [1]).

Figure 1 shows a sketch of one half. When the incident charged particle crosses the sensitive volume it ionizes the gas molecules. In the electric field between the cathode and the anode, the produced electrons and ions are being separated and drift to opposite ends of the TPC. In front of the anode is a gas amplification device which creates an electron avalanche and operates in proportional mode. The amplification is necessary because the amount of primary electrons is too small to create a measurable signal. Behind the amplification region is a segmented readout system, that measures the produced charge. With the information of the produced charge and the time between the collision and the detection it is possible to reconstruct the tracks of charged particles crossing the chamber. The choice of the detector gas has an influence on the energy deposition and on the behavior of charged particles in the detector volume. In most cases noble gases are chosen as the main component of the detector gas because of their low ionization energies. Since in the amplification process photons with energies above the ionization potential are emitted, so-called *quencher gases* are added to the gas mixture to avoid fake events. These quencher gases have a high cross section for photons in the right energy range and therefore "catch" the emitted photons. The absorbed energy is then transformed in elastic collisions, vibration and rotation states or in decomposition into simpler radicals. Another import point is the possibility of adding a magnetic field parallel to the barrel axis (z-axis, see figure 1), so that the incident charged particles are forced on a curved trajectory (a helix in three dimensions). By measuring the trajectory the transverse momentum of the particle can be determined. Using the transverse momentum and the z information it is possible to calculate the total momentum of the incident particle. Another positive effect of the magnetic field is, that it limits the transversal diffusion, so that a better spatial resolution and two track separation can be achieved. The magnetic field for the Large Prototype will be produced by the PC-MAG. In the following I give some general information about the PC-MAG and then I introduce the model I used to calculate the magnetic field of the PC-MAG.

3 PC-MAG

The PC-MAG (Permanent Current Magnet) is a superconducting large bore solenoid magnet with a diameter of 86 cm and an active length of about 1 m. The maximum magnetic field is about 1.2 T at a current of 520 A. For the Large Prototype the magnet will be operated at 430 A with a maximum magnetic field of 1 T. The PC-MAG is part of the EUDET infrastructure for detector development towards ILC and is located at the DESY testbeam area since 2006. The Magnet was designed and previously used for the Japanese-American Collaborative Emulsion Experiment (JACEE)[4]. There it was used in balloon experiments in the position and spectra of cosmic rays at energies in the region of 1-1000 TeV. This resulted in a lightweight design and a total weight of the magnet of less than 500 kg. The inner volume of the PC-MAG has a bottleneck shape because of the liquid He tank in the small end (see figure 3). This tank has a volume of 260 l and, once cooled, keeps the coil at liquid Helium temperature for about one week. The coil itself is a closed circuit and has to be excited and deexcited through a secondary circuit. For that reason in an emergency case the current can not be extracted faster than within a few minutes without quenching and thus damaging the coil. The coil consists in total of 3342 windings in 4 layers over the full length and additional 4 layers at the ends (see figure 3). It has no flux return yoke (because it had to be lightweight for the balloon experiments). The

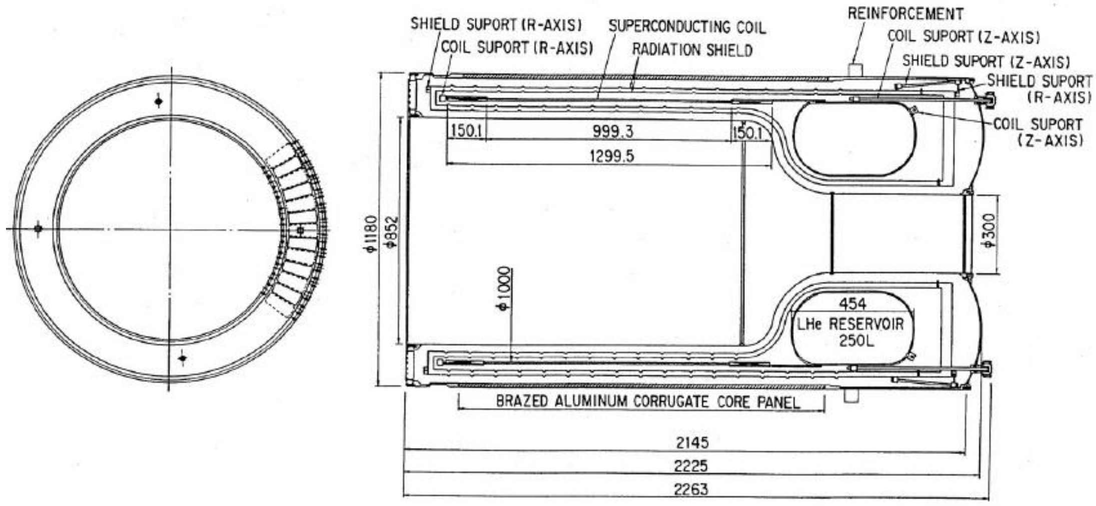

Figure 2: Sketch of the PC-MAG.

additional layers at the ends are needed to provide a higher field homogeneity in the center of the coil. The overall low field homogeneity will be exploited to test the Large Prototype at different levels of field homogeneity, in order to simulate some effects which will be also appearing at the ILC later on.

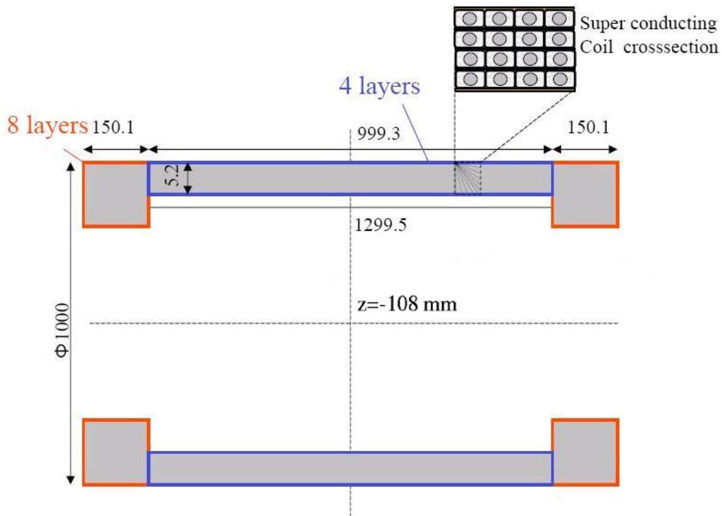

Figure 3: Sketch of the layers of the PC-MAG.

4 Coil Model with CST

4.1 Complete Coil Model

To calculate the magnetic field of the complete coil one has to sum up the field of 3342 closed current loops. These loops would be placed according to drawings of the magnet at 680 different z-positions with 8 different radii to represent the coil with its up to 8 layers of windings. The first and last 78 z-positions have 8 layers and the central part has 4 layers. The real coil has only 3342 windings which is most likely due to the need of transitions from 8 layer to the 4 layer part, but this could not be reconstructed from the drawings. Another issue is that a real coil has no closed loops, but some small tiltings in the current instead. This effect is assumed to be negligible since the coil windings go in one direction for one layer and in the other direction for the next layer. So there is no current flow in one direction and no influence on the magnetic field at distances from the windings which are large compared to the pitch between the layers. The number of windings is fixed, as well as their relative position. The pitches between the winding are always the same. This leaves the model only with four free parameters:

- The length, which is equivalent to the pitch in z direction.
- The radius of the innermost layer.
- The pitch between the different layers.
- The current.

4.2 First Coil Model

For the field calculations presented in this work the program CST STUDIO SUITE was used. This software uses the finite element method (FEM). With the help of this program all models and components were designed. After the components have been modeled, a fully automatic meshing procedure was applied before the simulation engine started. To ensure that the accuracy of the resulting field is good but also the calculation takes not too much time the number of meshcells was set to be about $2 \cdot 10^6$. In the first model all possible symmetries (rotational symmetry and mirror symmetry) were used which result in a flat model of the magnet shown in figure 4. This model consists of 43 current paths with a distance to the center of 500 mm and 10 current paths with a distance of 495 mm. These 10 current paths together with 10 current paths of the larger distance represent the coil with 8 layers of windings. Each current path represents 31.5 windings. To gain a magnetic field of $B = 1\,\mathrm{T}$ the current has to be $I = 430\,\mathrm{A}$. That means that the current in each current path of the model has to

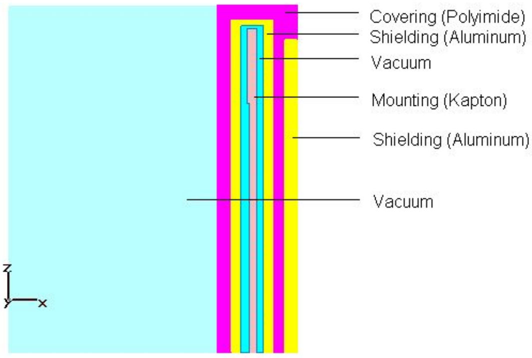

Figure 4: Flat model of the PC-MAG and used components.

be $I = 13565\,\mathrm{A}$. The gap between two paths is about 15.4 mm. Figure 5 shows the resulting magnetic field.

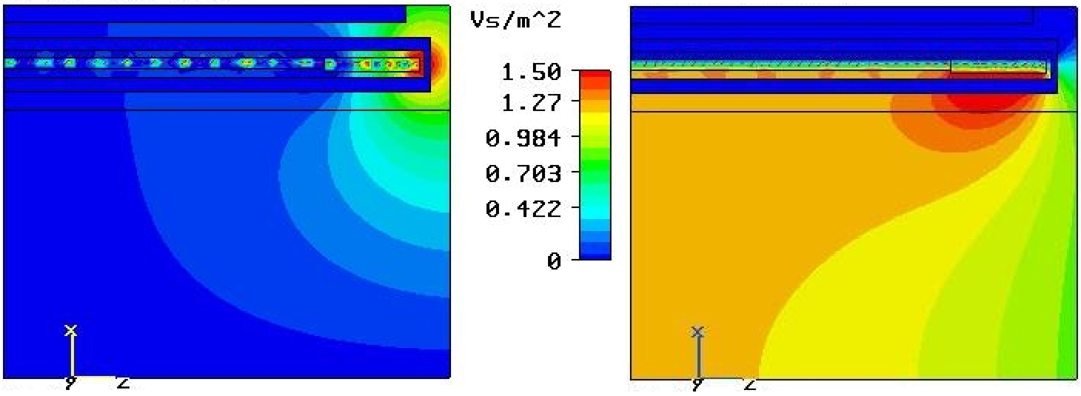

Figure 5: Resulting magnetic field B_X (left) and B_Z (right).

It is planned to build some supporting structure beneath the magnet to move it up and down and also to rotate it. Because of the beam is fixed, that structure enables to produce tracks all over the sensitive volume of the TPC. The question is how does the structure influence the magnetic field inside the sensitive volume. To get a first impression of the order of influence there was a ring of iron put in front of the magnet within the simulation. This means in case of the flat model a block was placed in front of the plane structure characterizing the magnet. The resulting magnetic field is shown in figure 6.
To compare the field intensities the data were extracted from CST as ASCII-files and then used in the data analysis program Origin. The results are shown in figure 11. The center of the magnet is at the position $x = 0\,\mathrm{mm}$ and $z = -108\,\mathrm{mm}$. This is just because one wants to be able to compare results with former calculations. The dashed lines in the first two plots, showing the x- and z-component of the

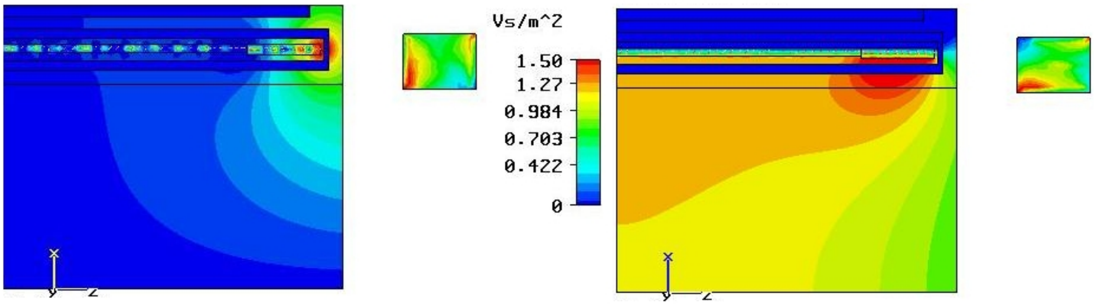

Figure 6: Resulting magnetic field B_X (left) and B_Z (right) with ring of iron in front of the magnet.

field, represent the resulting field with the iron ring in front of the magnet. Due to the fact, that the z-component is much larger than the x-component, the difference of the field intensity, in case of the x-component, is normalized to the z-component. The results show a maximum influence of about 0.5 % for the x-component and 1.25 % for the z-component. The change of the field is not constant over the sensitive volume and so the iron ring would have an influence on the tracks of charged particles crossing the TPC. In the end we decided to create a better model because of the influence of the iron ring is much too large (the aim is to keep the influence below 0.01 %) and this model reduces the magnet too much.

4.3 Second Coil Model

The second model is based on the First Coil Model, but it is a three dimensional model. The center of mass of the PC-MAG (z =-687.7 mm) is not equal to the center of the coil (z =-108 mm) concerning the z-position. The structure to move the PC-MAG is symmetric to the center of mass. That means that there is no more rotational symmetry that can be used to calculate the magnetic field. But there is still one mirror symmetry remaining used in this second model (see figure 7). All material, besides the current paths, used in the first model was left out, because the permeability of this material is 1 and so there is no magnetization of this material. Just the structure consisting of magnetizable material was added for calculations. The structure (see figure 8) consists of two spindles with gearboxes (to move the magnet up and down) and a gearing (to rotate the magnet).
The spindle has a radius of 16 mm and a length of 900 mm. The gearboxes are cuboids of the size 100 mm x 100 mm x 110 mm. The calculations were done for different types of material used for these components to get to know the influence to the magnetic field of every component. With the results of these calculations we want to decide which material to choose for building the structure. Of cause

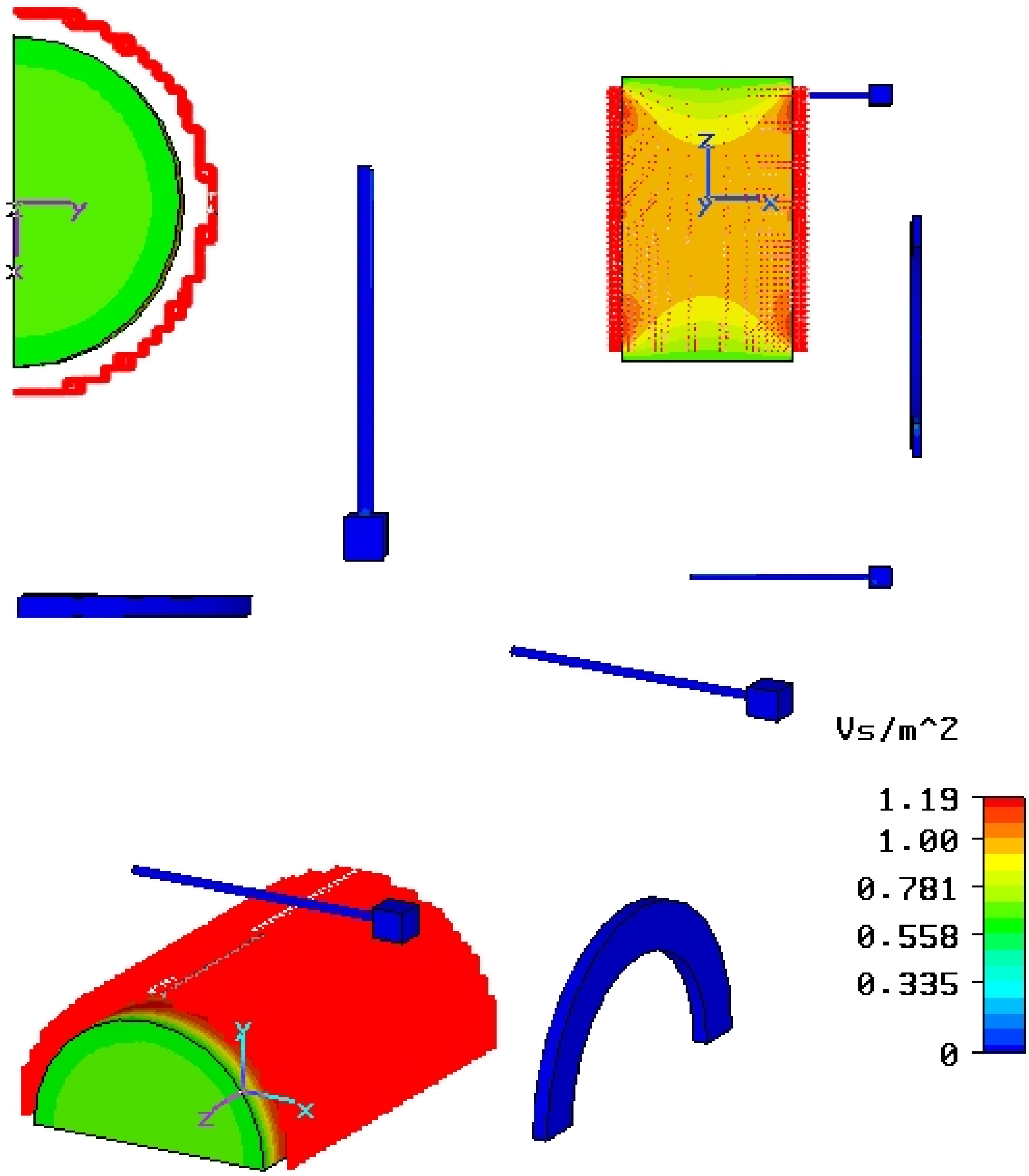

Figure 7: Field of the second model: front view, bottom view and perspective view. Spindles, gearboxes and gearing consists of steel-1010.

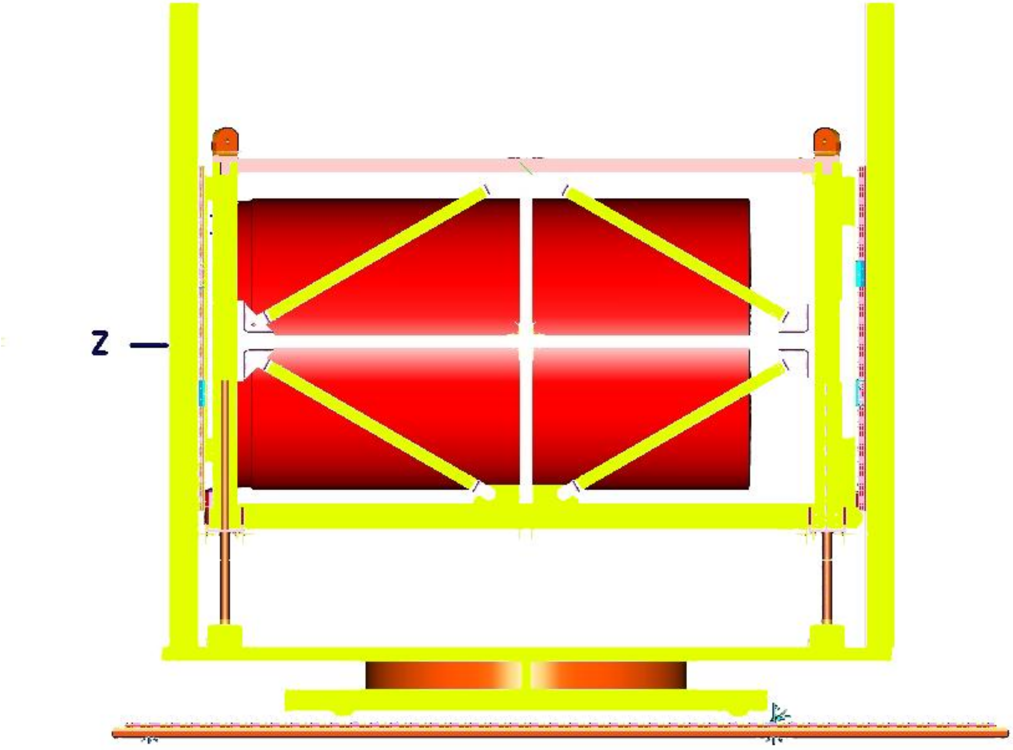

Figure 8: Sketch of the structure holding the PC-MAG. The gearing and the spindles are orange.

the influence of the structure should be as small as possible, but on the other hand non-magnetizable materials are much more expensive. Also the structure has to be able to carry the PC-MAG. In the following the used materials are introduced. First of all there is steel. For the calculations there was used the material *steel-1010* (a standart steel often used in the industry) taken from the library of CST. Characteristics concerning the permeability are shown in figure 10. On the other hand there is stainless steel. Due to the fact that stainless steel has a much lower permeability than steel the permeability was set to 1. For calculations with iron the library of CST was also used. At last aluminum was used. Aluminum has a permeability of 1 and so it does not influence the calculations.
At the beginning of the calculations the field without any structure was calculated (figure 13). These data can be compared to the measured data presented in [5]. As shown in figure 12 the magnet was placed in a standart container made of steel. This may be the reason for small differences but all in all the data show a good agreement with the calculated data. After verifying the model with measured data the influence of the hight of the PC-MAG was investigated. Therefore the

field was calculated for the lowest, meaning the TPC is in the closest position to the spindles and the gearing, and the highest position, meaning a maximum distance between the TPC and the components, of the PC-MAG. The distance between the lowest and the highest position is about 800 mm. In addition the size of the gearing was varied. This was done to characterize two different possibilities of the gearing design. On one hand the gearing can be made completely out of steel and on the other hand the gearing can be made out of stainless steel only where the balls of the ball bearing are made of steel. These two possibilities leads to two different thicknesses of the gearing (50 mm and 12 mm respectively). The results (see figure 14) show that the change of the field varies in the order of one magnitude concerning these two possibilities. Also the height has a significant influence considering the thicker gearing. The influence is lost considering the thinner gearing. Following the influence of the spindles was investigated while the height of the TPC was set to the lowest position. Therefore the material of the spindles was set to aluminum instead of steel. The results (see figure 15) show that the spindles have also an influence of a factor of two. Additionally it is shown that steel and iron nearly have the same influence. Up to this point the conclusion would be to use a gearing made of stainless steel. At last it was tried to investigate the influence of stainless steel without assuming that it has a permeability of 1. In the library of CST there is now stainless steel and so materials with a constant permeability of 1.3 and 20 respectively were created. Calculations result in a non expected behavior shown in figure 16. It was expected to see a bigger difference between the two materials. Also the change of the field should not be bigger than in case of steel (see figure 14). That is why these results are disputable. It is planed to repeat these calculations analytical to verify these results. All in all it could be shown that the second model can be used to calculate the magnetic field of the PC-MAG and also estimates concerning the influence of different materials around the magnet can be done. However, the calculations with CST have to be validated.

5 Field Cage Tests

After the field cage passed some inspections concerning the accuracy of components finally it reached the TPC laboratory. Following there had to be done a number of tests.

5.1 Checking the resistances

One of the first tests concerning the field cage was to check all the resistances. By doing this, one gets to know if all the connections between the field strips and the resistances are working well. Also the value of the resistances proofs that they were not damaged after they were attached to the field cage.

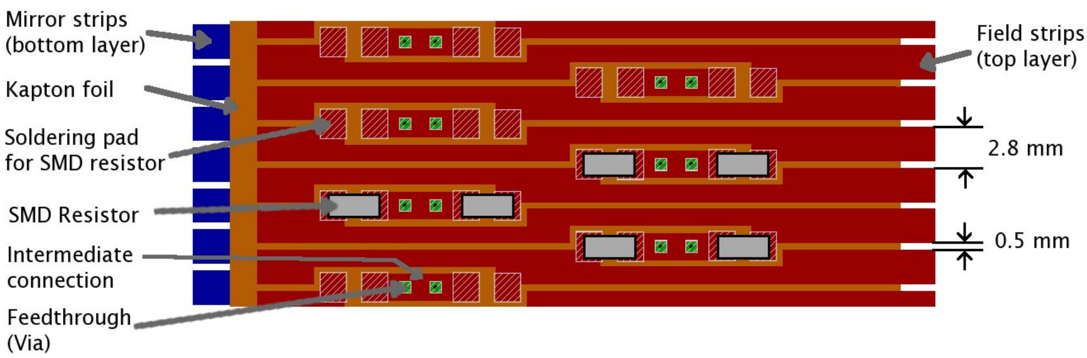

Figure 9: Sketch of the layout of the foil. There are two alignments like this on the foil.

Between every strip two resistances are connected in parallel. Figure 9 shows the layout of the foil with only one of the two parallel resistances. A resistance connects a strip to a via while the via is connected to a mirror strip on the backside of the foil. To protect the strips from scratches we contacted the soldering of the resistances for our measurement. That means that the value we measured is due to:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \qquad R_1 = R_2 = 1\,\mathrm{M}\Omega$$

$$R = \frac{1}{2}R_1 = 0.5\,\mathrm{M}\Omega$$

After cleaning the inner part of the field cage all resistances worked well and the measurement worked out (typical value):

$$R = (0.4999 \pm 0.0002)\,\mathrm{M}\Omega$$

This result is a first hint of a constant gradient of the electric field. But there were fluctuations in the order of $100\,\Omega$. The maximum of these fluctuations was in the middle of the foil. This is due to the large number of field stripes connected via the resistances. This causes an antenna effect. To get rid of this effect the surrounding copperfoil was grounded. This reduced the fluctuations and lead to the result given above.

5.2 Outlook

After the first test of measuring the resistances follows a low voltage test were a voltage of about 200 V will be supplied. The voltage between two stripes will be measured to get a more precise impression of the field gradient, but the antenna effect will also have an influence on this measurement. It is also planed to check the parallelism of the field stripes. Therefore a structure was build and a x- y-table was connected to this structure. This x- y-table enables a precise movement of a camera or a mirror mounted on that table. After some more tests (like a test of the gas tightness) the TPC will be ready to take some data. Therefore the TPC will be inserted into the PC-MAG and tracks will be produced with a e^--beam produced by the ring accelerator DESY III.

6 Acknowledgment

I want to thank my supervisor Klaus Dehmelt for his help and the time he spend to me. Also I want to thank him, Takeshi Matsuda and all other members of the TPC group for having a lot of nice discussions. Thanks to Jeannine Beck for a bike lock, Ralf Diener for the logo and Alexander Kaukher for making nice pictures. Finally thanks to all DESY organizers (Andrea Schrader, Joachim Meyer and others),lecturers and summer students for a wonderful and profit time we had in Hamburg.

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A Plots

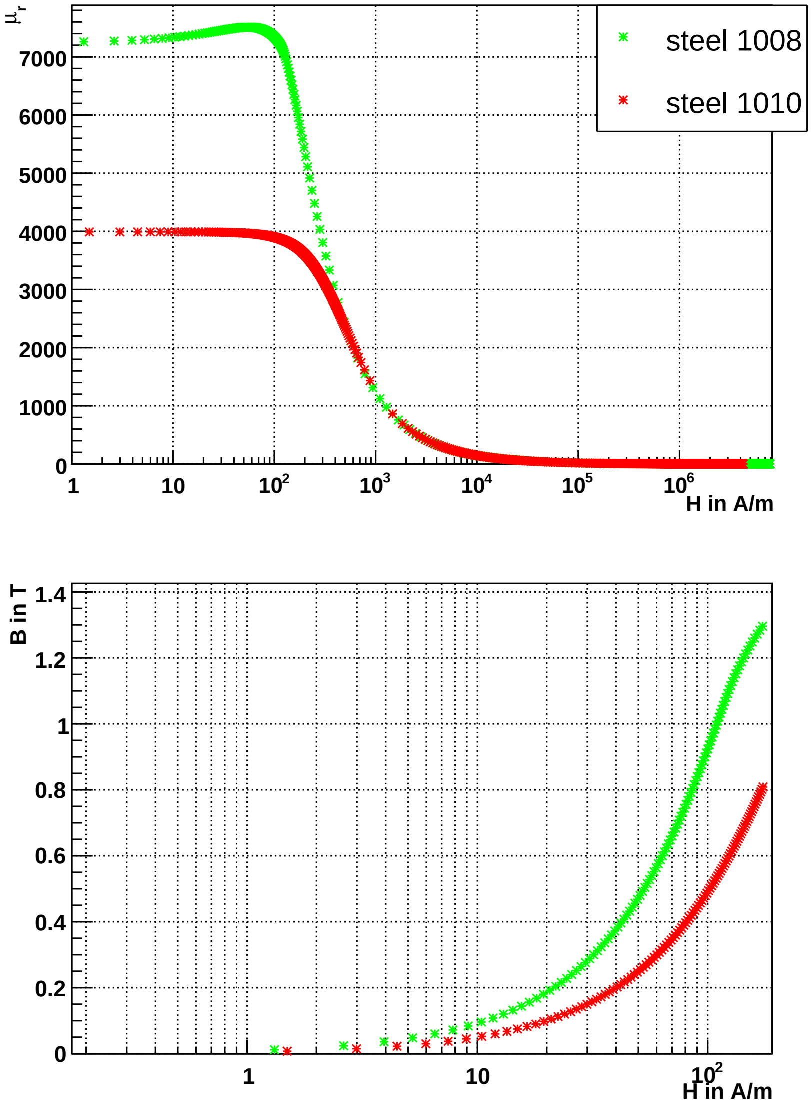


Figure 10: Characteristics for two different types of steel. The lower plot shows a detailed area of the H-field.

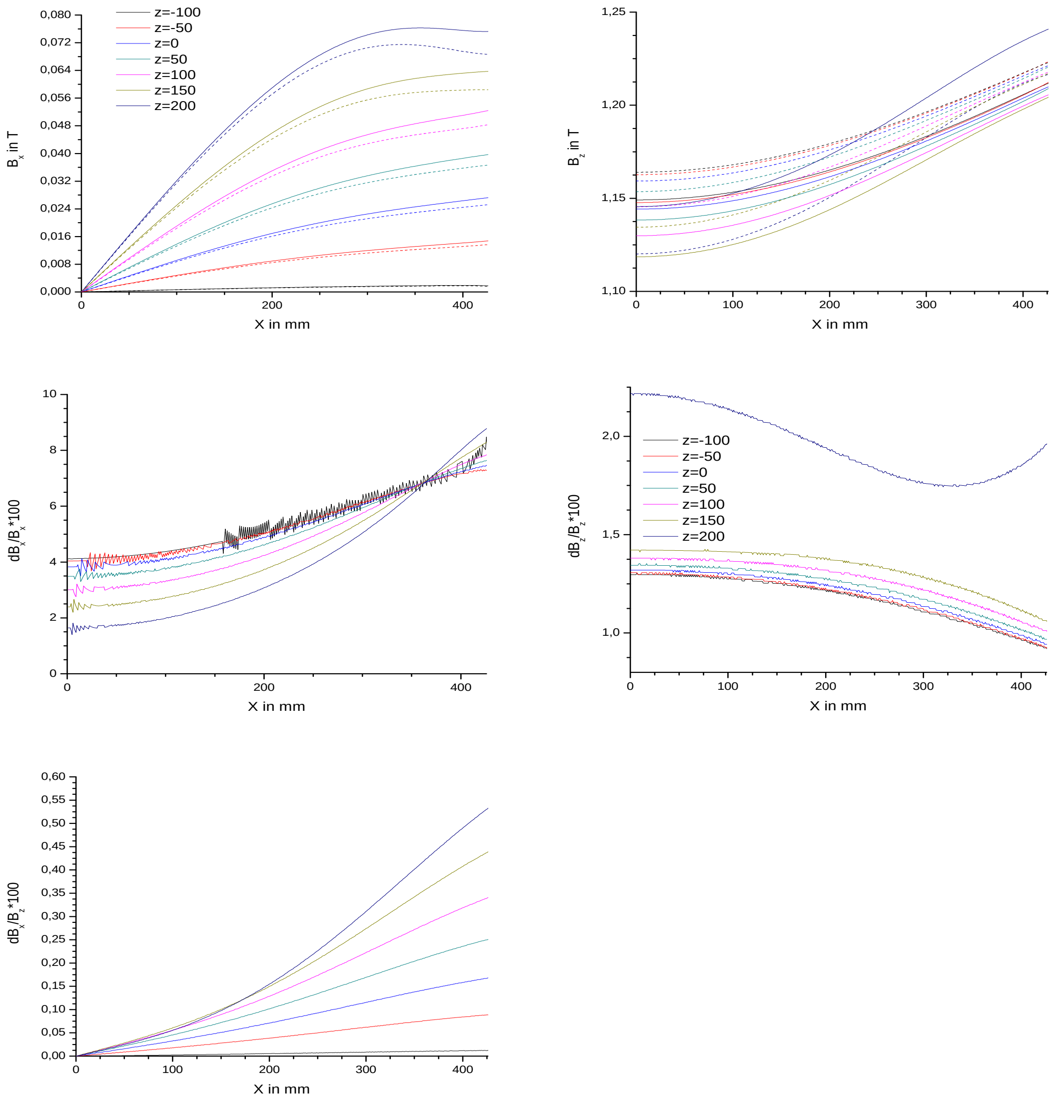


Figure 11: Resulting magnetic field B_X (left) and B_Z (right) with a ring of iron in front of the magnet.

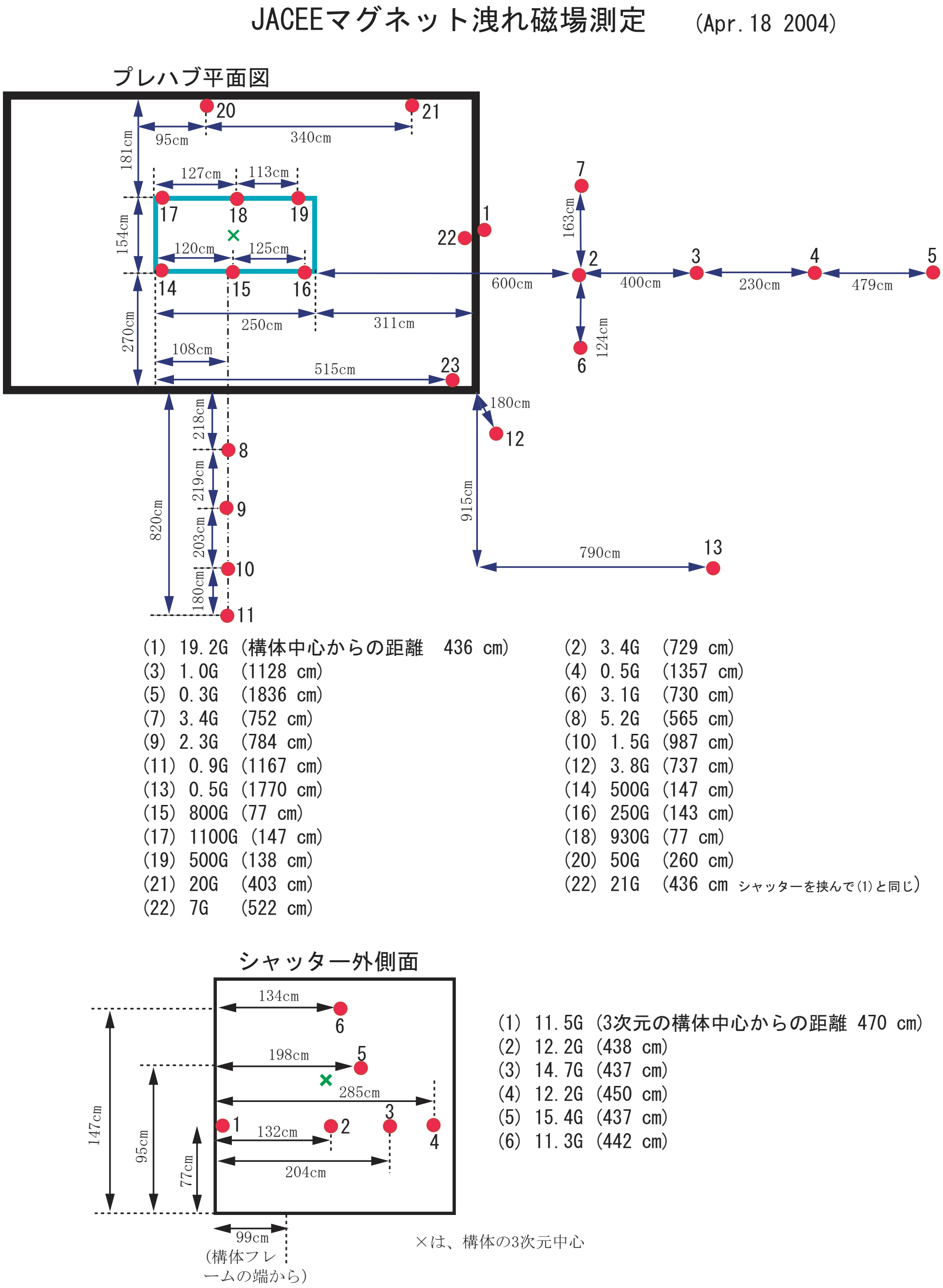
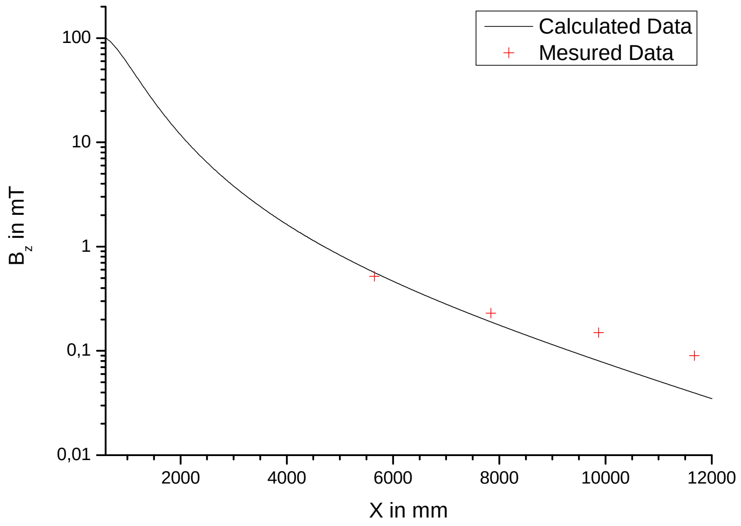


Figure 12: Results of the field measurement taken from [5].



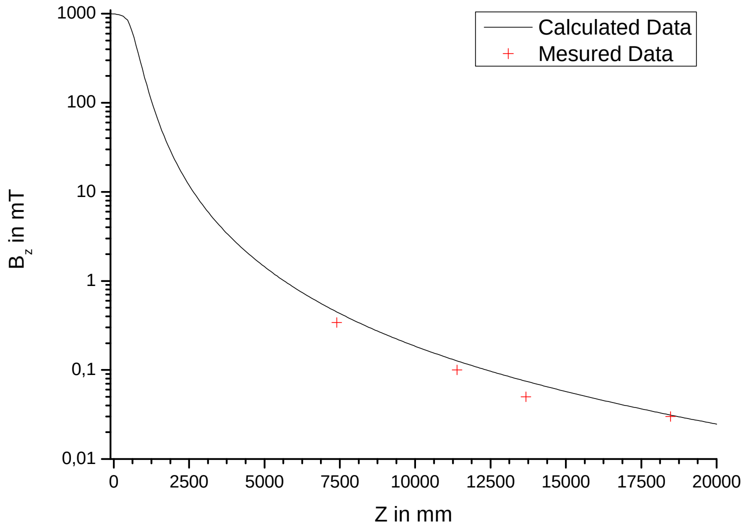


Figure 13: Calculated field going from the center of the magnet in x-direction (top) and in z-direction (bottom). The center position of the magnet is at $x = 0\,\mathrm{mm}$, $z = -108\,\mathrm{mm}$. Measured Data are taken from [5].

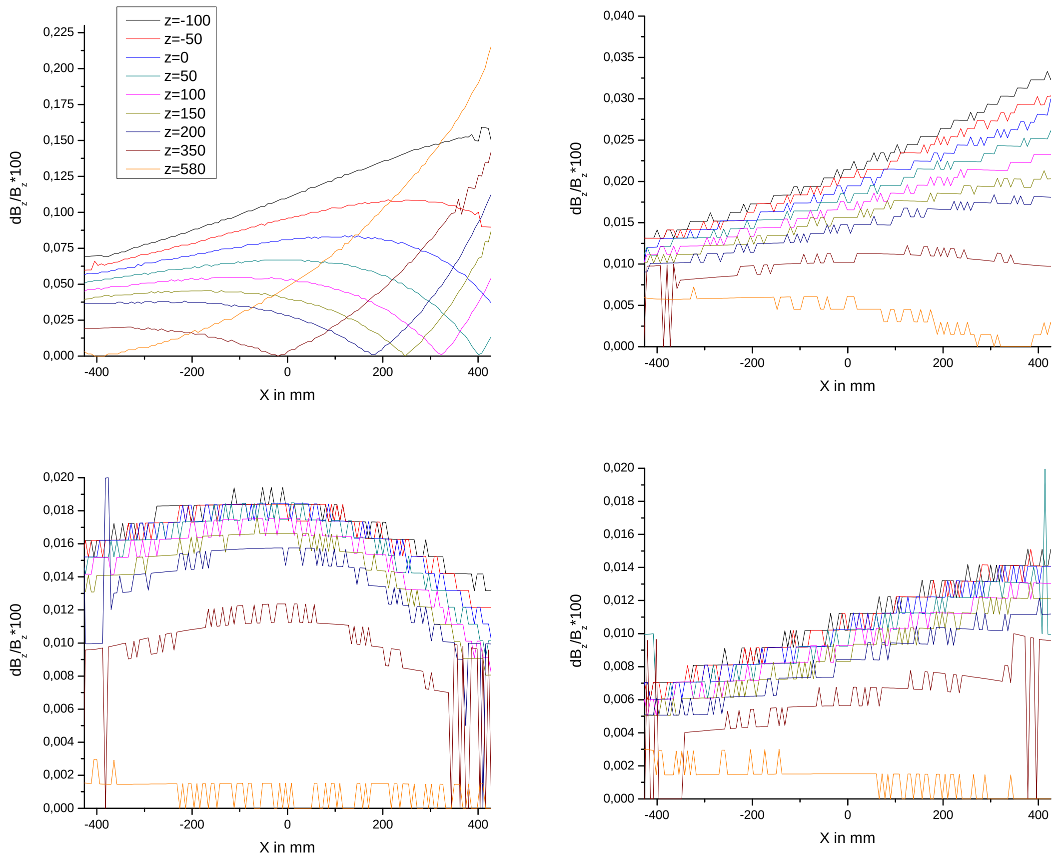


Figure 14: Comparison between a gearing made of steel (top) and a gearing made of stainless steel beside the balls of the ball bearing (bottom). On the left side the TPC is at the lowest position and on the right side it is at the highest position.

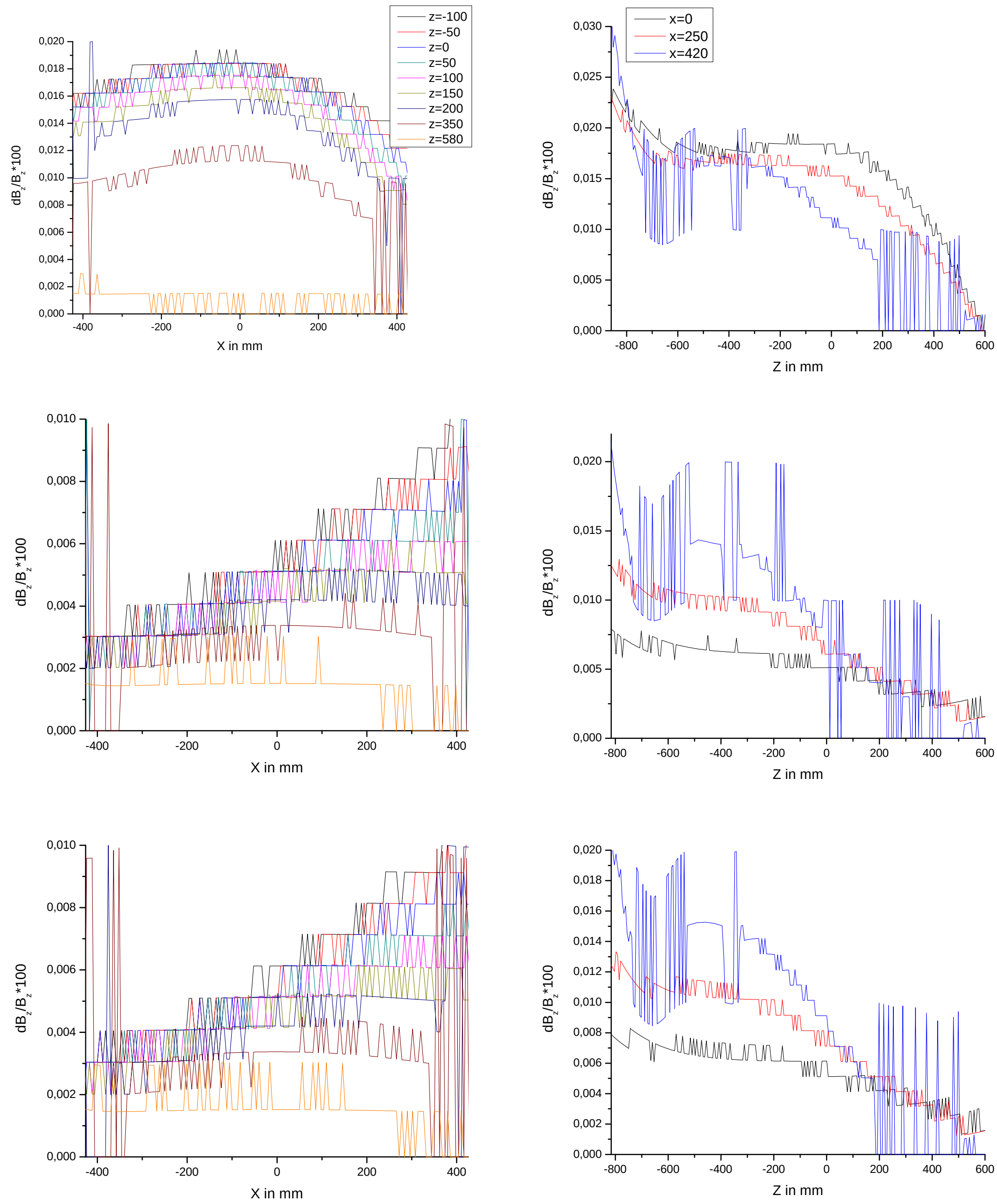


Figure 15: Resulting magnetic field B_X (left) and B_Z (right) for different material of the gearboxes and gearing. Spindles consist of aluminum beside on top - there they consist of Steel-1010. Top: Steel-1010 Middle: Steel-1010 Bottom: Iron

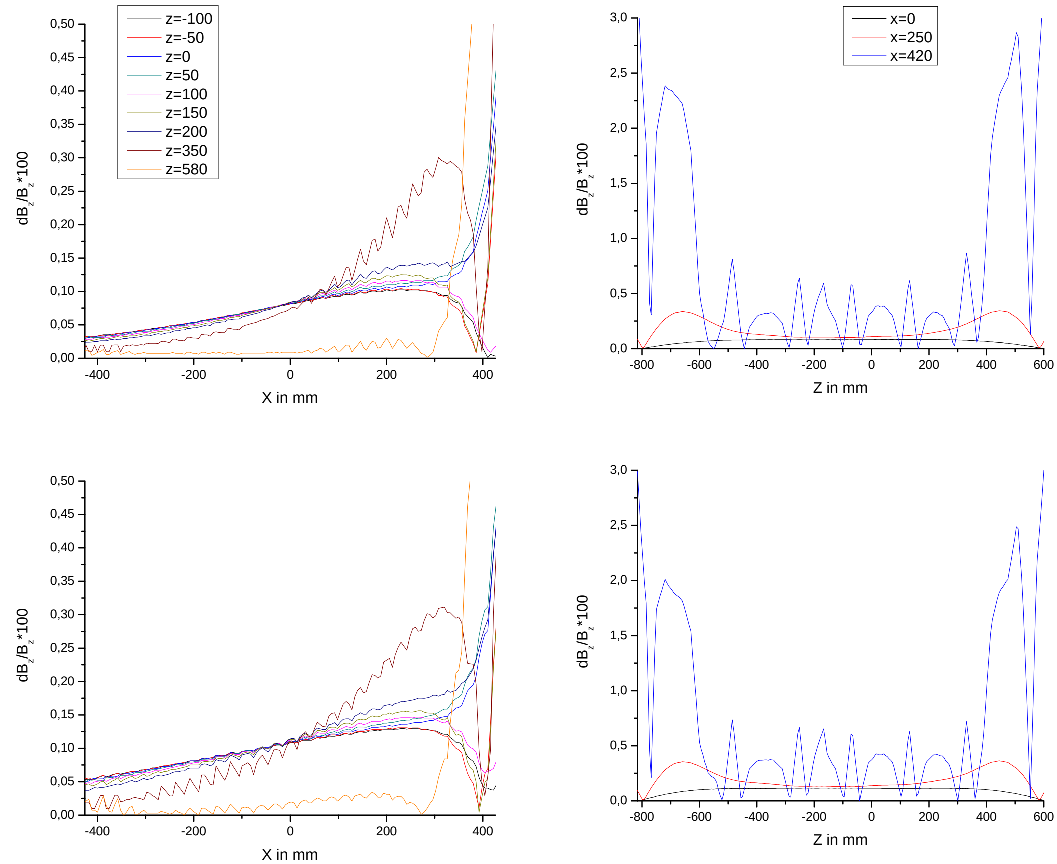


Figure 16: Resulting magnetic field B_X (left) and B_Z (right) for a material with constant μ. Top: $\mu = 1.3$ Bottom: $\mu = 20$