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TPC track distortions: correction maps for magnetic and static electric inhomogeneities

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Abstract

Inhomogeneities of the magnetic and electric fields in the active TPC volume lead to displacements of cluster coordinates, and therefore to track distortions. In case of good data taking conditions, the largest effects are expected from the inhomogeneity of the solenoidal magnetic field, and from a distortion of the electric field arising from a high voltage misalignment between the outer and inner field cages. Both effects are stable over the entire HARP data taking. The displacements are large compared to the azimuthal coordinate resolution but can be corrected with sufficient precision, except at small TPC radius. The high voltage misalignment between the outer and inner field cages is identified as the likely primary cause of sagitta distortions of TPC tracks. The position and the length of the target plays an important rôle. Based on a detailed modelling of the magnetic and static electric field inhomogeneities, precise correction maps for both effects have been calculated. Predictions from the correction maps are compared with laser data.

1 Introduction

In an earlier memo [1], it has been quantitatively argued that in case of good data taking conditions (beam intensity not too high, beam well centred on the target, beam focus near the target), inhomogeneities of the electric and magnetic fields inside the active TPC volume are dominated by

- the inhomogeneity of the solenoidal magnetic field, and
- the inhomogeneity of the electric field caused by a 2.4% misalignment of the high voltages between the outer and inner field cages [2].

Both effects are stable and unchanged during all HARP data taking. The displacements of clusters arising from both effects were estimated to be large compared to the azimuthal coordinate resolution of the TPC, thus demonstrating the need of calculating corrections with adequate precision.

In this memo, we present the results of calculations of displacements which are now based on a careful and detailed modelling of field inhomogeneities.

The pertinent corrections are presented in terms of matrices of numbers, called 'correction maps'.

The displacements predicted by the correction maps are compared to laser data.

This memo uses the same conventions as the earlier one. The standard HARP coordinate system (x, y, z) is employed: looking downstream in the $+z$ direction, the $+x$ coordinate points to the left, and the $+y$ coordinate points up. Also a cylindrical coordinate system $(r, r\phi, z)$ is employed. Again, the $+z$ axis points to the downstream direction. The $+r$ axis points radially outwards. Looking downstream, the $+r\phi$ axis points to the clockwise direction. Dimensions along the $r\phi$ axis have the same unit length as the r and z coordinates.

2 Correction algorithm

The driftvector $\vec{v}$ of electrons in the electric field $\vec{E}$ and magnetic field $\vec{B}$ of the TPC is given by the Langevin Equation:

$$\vec{v} = -\frac{\mu}{1+(\omega\tau)^2}\left(\vec{E} - \frac{\omega\tau}{|\vec{B}|}(\vec{E}\times\vec{B}) + \frac{(\omega\tau)^2}{|\vec{B}|^2}\vec{B}(\vec{E}\cdot\vec{B})\right) , \tag{1}$$

where the electron cyclotron frequency is

$$\omega = |(e/m)\vec{B}| ,$$

and the electron mobility (= velocity per unit electric field strength in the absence of a magnetic field) is:

$$\mu = (|\vec{v}|/|\vec{E}|)_{|\vec{B}|=0} = |(e/m)\tau| .$$

Here, τ is the average time between successive collisions of the electron with gas molecules; e and m are the electric charge and the mass, respectively, of the electron. The value of $\omega\tau$ is for the HARP TPC 3.28 ± 0.07, based on a measurement made for the ALEPH TPC [3] which had the same gas mixture as the HARP TPC.

2.1 Magnetic field inhomogeneity

We investigate the distortions in the pad plane arising from an inhomogeneity of the solenoidal magnetic field. We assume, in cylindrical coordinates, a perfectly aligned electric field $\vec{E} = (0, 0, E_{\mathrm{z}})$ and a (nearly) parallel magnetic field $\vec{B} = (B_{\mathrm{r}}, B_{r\phi}, B_{\mathrm{z}})$ with small transverse components $|B_{\mathrm{r}}|, |B_{r\phi}| \ll| B_{\mathrm{z}}|$ arising from unavoidable imperfections in magnet construction.

Using Equation 1, we obtain for the components of the electron velocity vector:

$$
\begin{aligned}
v_{\mathrm{r}} &\simeq \frac{-\mu}{1+(\omega\tau)^2}\,(\pm\omega\tau\frac{B_{r\phi}E_{\mathrm{z}}}{|B_{\mathrm{z}}|} + (\omega\tau)^2\frac{B_{\mathrm{r}}E_{\mathrm{z}}}{B_{\mathrm{z}}})\\
v_{r\phi} &\simeq \frac{-\mu}{1+(\omega\tau)^2}\,(\mp\omega\tau\frac{B_{\mathrm{r}}E_{\mathrm{z}}}{|B_{\mathrm{z}}|} + (\omega\tau)^2\frac{B_{r\phi}E_{\mathrm{z}}}{B_{\mathrm{z}}})\\
v_{\mathrm{z}} &\simeq -\mu\, E_{\mathrm{z}}\ . \qquad (2)
\end{aligned}
$$

Here, and in all subsequent formulae, whenever there is a double sign the upper sign refers to the magnetic field orientation $\vec{B} = (0, 0, B_{\mathrm{z}})$ with $B_{\mathrm{z}} > 0$, and the lower sign to the opposite magnet polarity (the HARP data taking convention was that $B_{\mathrm{z}} > 0$ refers to positive beam polarity).

With the angles $\alpha^{\mathrm{m}}_{\mathrm{r}} = B_{\mathrm{r}}/B_{\mathrm{z}}$, $\alpha^{\mathrm{m}}_{r\phi} = B_{r\phi}/B_{\mathrm{z}}$ and the drift length L ($L > 0$), the distortions in the pad plane are approximately (here, but not in the calculation of the correction maps, we neglect a small deviation from a straight line):

$$
\begin{aligned}
\Delta_{\mathrm{r}} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\pm\omega\tau\alpha^{\mathrm{m}}_{r\phi} + (\omega\tau)^2\alpha^{\mathrm{m}}_{\mathrm{r}})\\
\Delta_{r\phi} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\mp\omega\tau\alpha^{\mathrm{m}}_{\mathrm{r}} + (\omega\tau)^2\alpha^{\mathrm{m}}_{r\phi})\ . \qquad (3)
\end{aligned}
$$

The overall negative sign appears because the drift is upstream, i.e. in the direction $-z$.

Because of the rotational symmetry of the set-up, $\alpha^{\mathrm{m}}_{r\phi}$ equals zero and the displacements reduce to:

$$
\begin{aligned}
\Delta_{\mathrm{r}} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\omega\tau)^2\alpha^{\mathrm{m}}_{\mathrm{r}}\\
\Delta_{r\phi} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\mp\omega\tau\alpha^{\mathrm{m}}_{\mathrm{r}})\ . \qquad (4)
\end{aligned}
$$

We note that the distortions due to small transverse magnetic field components are in the (uncritical) r coordinate larger by a factor of $\omega\tau$ than those in the (critical) $r\phi$ coordinate.

With Equations 2 it is possible to calculate the overall displacement in the r and $r\phi$ coordinates for any starting point in an (r, z) grid, thus producing correction maps. The grid granularily has been taken as 1 cm × 1 cm. The overall displacement is the integral of the displacements calculated for steps of 10 ns in the drift time.

All numerical results of correction maps are given for positive beam polarity ($B_z > 0$). For negative beam polarity, the radial corrections remain unchanged whereas the azimuthal corrections change sign.

Figure 1 shows the inhomogeneity of the magnetic solenoid field as used in track reconstruction and Monte Carlo simulation, and for the calculation of the correction maps for magnetic field inhomogeneity. The magnetic field was calculated with the OPERA package [4].

Figure 2 shows the resulting overall displacement in the radial and azimuthal directions for every starting point in (r, z) inside the active TPC volume. One concludes that the displacements at small radius are relatively small, and the dominant effect of the magnetic field inhomogeneity shows up at large radius. Looking downstream and concentrating on the critical azimuthal coordinate, the overall effect is to displace clusters in the anti-clockwise direction, by typically one to two millimetres, strongly depending on the point of origin inside the active TPC volume. The effect on the track sagitta is to increase the sagitta for positive tracks (which bend anti-clockwise) and decrease it for negative tracks, independently of the magnet polarity. Positive tracks are systematically shifted to smaller momentum, negative tracks to higher momentum.

The correction for this effect by using the correction maps is straightforward and uncritical.

The magnetic-field correction maps are also available as matrices of numbers [5].

2.2 Static electric field inhomogeneity

We assume a perfectly aligned magnetic field $\vec{B} = (0, 0, B_z)$ with $B_z > 0$, and a (nearly) parallel electric field $\vec{E} = (E_r, E_{r\phi}, E_z)$ with $E_z > 0$ and with small transverse components $|E_r|, |E_{r\phi}| \ll| E_z|$. The latter arise from the 2.4% high voltage misalignment between the outer and inner field cages [1, 2].

From Equation 1, we obtain for the components of the electron velocity vector:

$$\begin{aligned} v_r &= \frac{-\mu}{1+(\omega\tau)^2}\,(E_r \mp \omega\tau E_{r\phi}) \\ v_{r\phi} &= \frac{-\mu}{1+(\omega\tau)^2}\,(E_{r\phi} \pm \omega\tau E_r) \\ v_z &= -\mu\, E_z\, . \end{aligned} \tag{5}$$

With the angles $\alpha_r^e = E_r/E_z$, $\alpha_{r\phi}^e = E_{r\phi}/E_z$ and the drift length L ($L > 0$), the distortions in the pad plane are approximately (here again, but not in the calculation of the correction maps, we neglect a small deviation from a straight line):

$$\begin{aligned} \Delta_{\rm r} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\alpha^{\rm e}_{\rm r} \mp \omega\tau\alpha^{\rm e}_{r\phi}) \\ \Delta_{r\phi} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\alpha^{\rm e}_{r\phi} \pm \omega\tau\alpha^{\rm e}_{\rm r})\,. \end{aligned} \quad (6)$$

Because of the rotational symmetry of the set-up, $\alpha^{\rm e}_{r\phi}$ equals zero and the displacements reduce to:

$$\begin{aligned} \Delta_{\rm r} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,\alpha^{\rm e}_{\rm r} \\ \Delta_{r\phi} &\simeq -L\,\frac{1}{1+(\omega\tau)^2}\,(\pm\omega\tau\alpha^{\rm e}_{\rm r})\,. \end{aligned} \quad (7)$$

We note that the distortions due to small transverse electric field components are in the (critical) $r\phi$ coordinate larger by a factor of $\omega\tau$ than those in the (uncritical) r coordinate, just opposite to the case of the magnetic field inhomogeneity.

All numerical results of correction maps are given for positive beam polarity ($B_{\rm z} > 0$). For negative beam polarity, the radial corrections remain unchanged whereas the azimuthal corrections change sign.

Because of the great importance of distortions from the electric field inhomogeneity, we state in Table 1 the parameters which have been used for the electric field modelling [2]. It turned out that the high voltage misalignment between outer and inner field cages is larger than thought originally [1].

The high voltage at the membrane of the inner field cage is in absolute terms lower by 2.4% than the nominal value. This causes a distortion of the electric field which is shown in the $E_{\rm z}$ and $E_{\rm r}$ components in Fig. 3. The electric field was calculated with the POISCR package [6].

Figure 4 shows the resulting overall displacement in the radial and azimuthal directions for every starting point in (r, z) inside the active TPC volume. Concentrating again on the critical azimuthal coordinate, one notes that the displacements are unpleasantly large, up to $\sim$ 20 mm, and strongly dependent on the radius and on the point of origin inside the active TPC volume (the strong radial dependence has been ignored in the earlier memo [1], only the average over radius was taken into account). The effect is most prominent at small radius, where near the target position displacements of order 10 mm are expected. The displacement at large radius is one order of magnitude smaller.

Looking again downstream, the overall effect on the azimuthal coordinate is to displace clusters in the anti-clockwise direction. Because the displacement is much stronger at small radius, the sagitta for positive tracks (which bend anti-clockwise) is increased, and for negative tracks decreased, independently of the magnet polarity. Positive tracks are systematically shifted to smaller momentum, negative tracks to higher momentum.

Table 1: TPC parameters relevant for the electric field.

Item	Value
Upstream end of coil cylinder	-750 mm
Downstream end of pad plane	-500 mm
Anode wires plane	-495 mm
Cathode wires plane	-490 mm
Nominal target position	0 mm
Inner field cage high voltage membrane	+286 mm
Radius of inner field cage electrodes	53 mm
Outer field cage high voltage membrane	+1067 mm
Radius of outer field cage electrodes	392 mm
Downstream end of coil cylinder	+1502 mm
Driftlength along outer field cage	1557 mm
Driftlength along inner field cage	776 mm
Measured high voltage at outer field cage membrane	-17.302 kV
Measured high voltage at inner field cage membrane	-8.421 kV
Nominal high voltage at inner field cage membrane	-8.623 kV

The effects of the magnetic and electric field inhomogeneities have the same overall effect on the distortion of track sagittas.

Another distinct feature is the strong dependence of the displacements on the longitudinal position inside the active TPC volume, especially around the nominal target position. This suggests that the position and the length of the target plays an important rôle. The higher upstream the track, the less it will be affected. Therefore, tracks from thin targets will generally be less affected than tracks emerging at the downstream end of long targets. This may shed some light on observations on TPC track distortions reported recently [7].

The correction for the displacements caused by the electric field inhomogeneity by using the correction maps, is also straightforward but critical because of the sheer size of the effect at small radius – in the worst corner, we would like to apply a correction which has a 1% error, impossible to achieve (see below).

The electric-field correction maps are also available as matrices of numbers [5].

The systematic precision of the calculated displacement corrections depends mostly on the $(\omega\tau)^2$ term, which has a 4% error. The second important error contribution comes from the error on the 2.4% high voltage misalignment between the outer and inner field cages, where it is hard to state a reliable systematic error. Yet, an overall error of 10% on the displacement corrections seems realistic. This renders the calculated distortion corrections good enough not to deteriorate significantly the azimuthal precision of the TPC, except at small radius.

Figure 5 shows a magnified view of the drift path of an electron under the influence of both the magnetic and static electric inhomogeneities. The correction maps, however, ignore the details of the drift path and give for each starting point the overall displacements at the arrival point only.

3 Crosscheck against laser data

The TPC is equipped with optical fibres which emit at the high voltage membrane electrons into the TPC volume, through photoeffect by short pulses of laser light. The fibres are located at well-known positions. During their drift through the TPC volume, the electrons sample the magnetic and electric field inhomogeneities across the whole TPC length. Therefore, the clusters produced by laser pulses serve directly as cross-check of the validity of the displacements in the correction maps, for starting points at the far end of the TPC.

The laser data are an important tool to ascertain the validity of the corrections for TPC track distortions.

Figure 6 shows the position of the optical fibres together with the predicted displacements from both the magnetic and static electric inhomogeneities, for positive beam polarity. The most prominent feature is a systematic distortion in the azimuthal coordinate.

A first look at laser data was already presented in December 2001, with indications of distortions from field inhomogeneities [8].

Figure 7 shows, for run No. 18138 which has positive beam polarity, the reconstructed position of laser clusters together with the geometrical position of the optical fibres. The data can be directly compared with the predictions shown in Figure 6. Here, as well as in all subsequent plots, we show laser data taken outside the spill gate. Since cosmic tracks lead to negligible displacements, all possible beam-related effects, although expected to be small in comparison [1], are absent.

Figures 8 and 9 show the difference in radius and in the azimuthal coordinate, respectively, between the geometrical fibre positions and the positions of reconstructed clusters. While the radial displacements from the magnetic and electric field inhomogeneities have opposite sign and tend to cancel each other, the azimuthal displacements have the same sign and add up. Fig. 9 supports the calculations presented in this memo.

More detailed work on laser data is in progress.

4 Summary

The problem of TPC track distortions due to magnetic and static electric field inhomogeneities has been adressed in a quantitative way. Correction maps have been calculated which permit corrections to the data to be applied in an easy manner, with satisfactory precision except at small TPC radius. The high voltage misalignment between the outer and inner field cages is identified as the likely primary cause of sagitta distortions of TPC tracks. The position and the length of the target plays an important rôle.

References

[1] F. Dydak, ‘On distortions of TPC coordinates: inhomogeneities of electric and magnetic field’, HARP memo 03-001, revised on 10 June 2003, available at *http://cern.ch/dydak/TPCdistortions.ps*

[2] L. Linssen, email of 23 June 2003 sent to Yu. Nefedov, after relative calibration of the high voltage units used for the outer and inner field cages. We thank L. Linssen for her careful cross-check of all numbers relevant for the high voltage misalignment between the outer and inner field cages.

[3] S.R. Amendolia *et al.*, Nucl. Instr. Meth. Phys. Res. **A244** (1986) 516.

[4] The solenoidal magnetic field was calculated by E. Boter and L. Linssen in an iterative process with the OPERA program, until satisfactory agreement with the measured field map was achieved. The field was then parametrized by Yu. Nefedov and made part of the official HARP software.

[5] Until inclusion of the relevant code into the official HARP software, the correction maps are available on request to *iouri.nefedov@cern.ch*.

[6] Ch. Iselin, program POISCR, program T604 in the CERN Program Library.

[7] A. Blondel and S. Borghi, presentation at the 29 April 2003 Analysis Meeting.

[8] M. Campanelli and G. Prior, presentation at the December 2001 Collaboration Meeting.

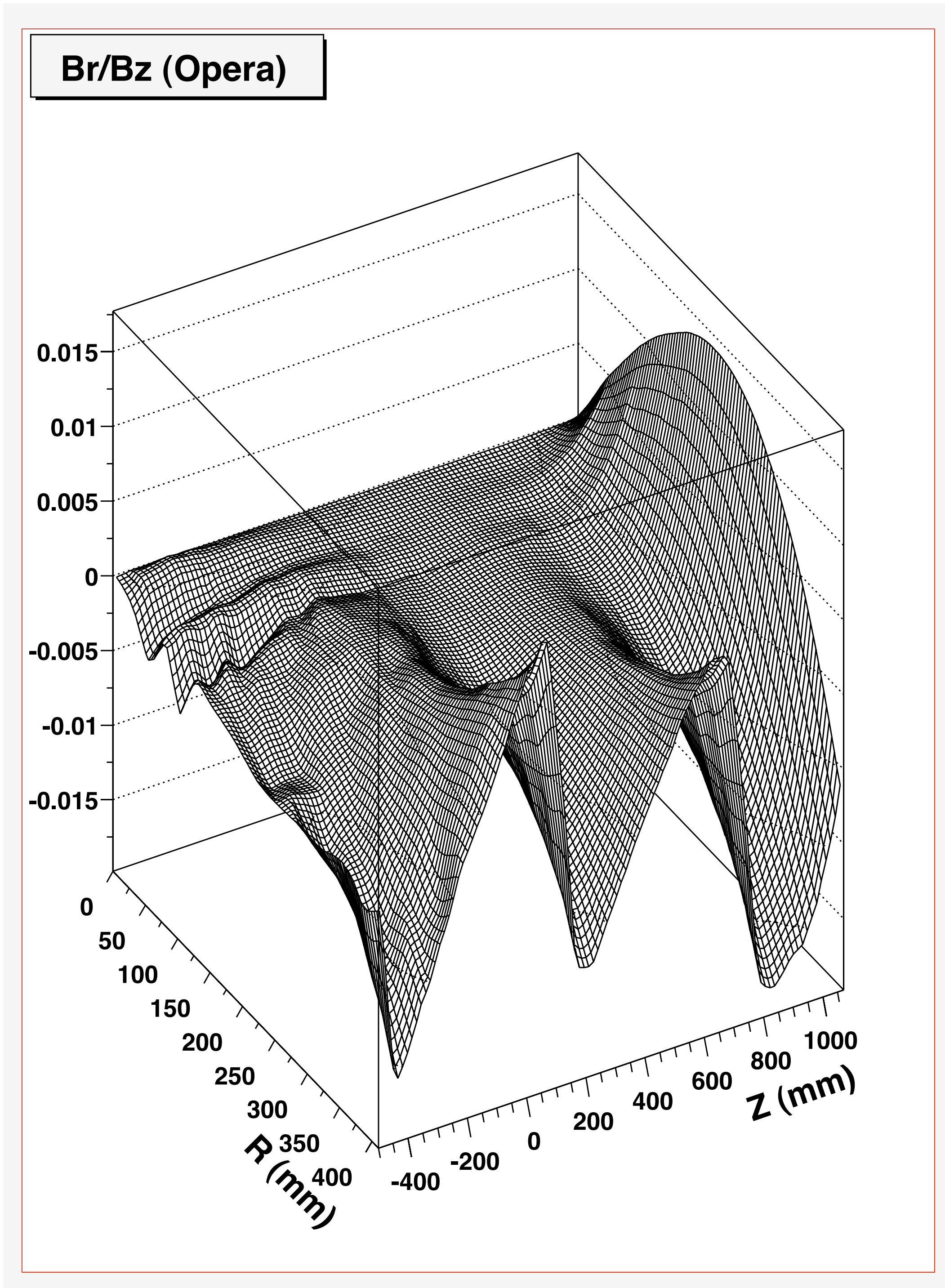

Figure 1: Inhomogeneity of the solenoidal magnetic field.

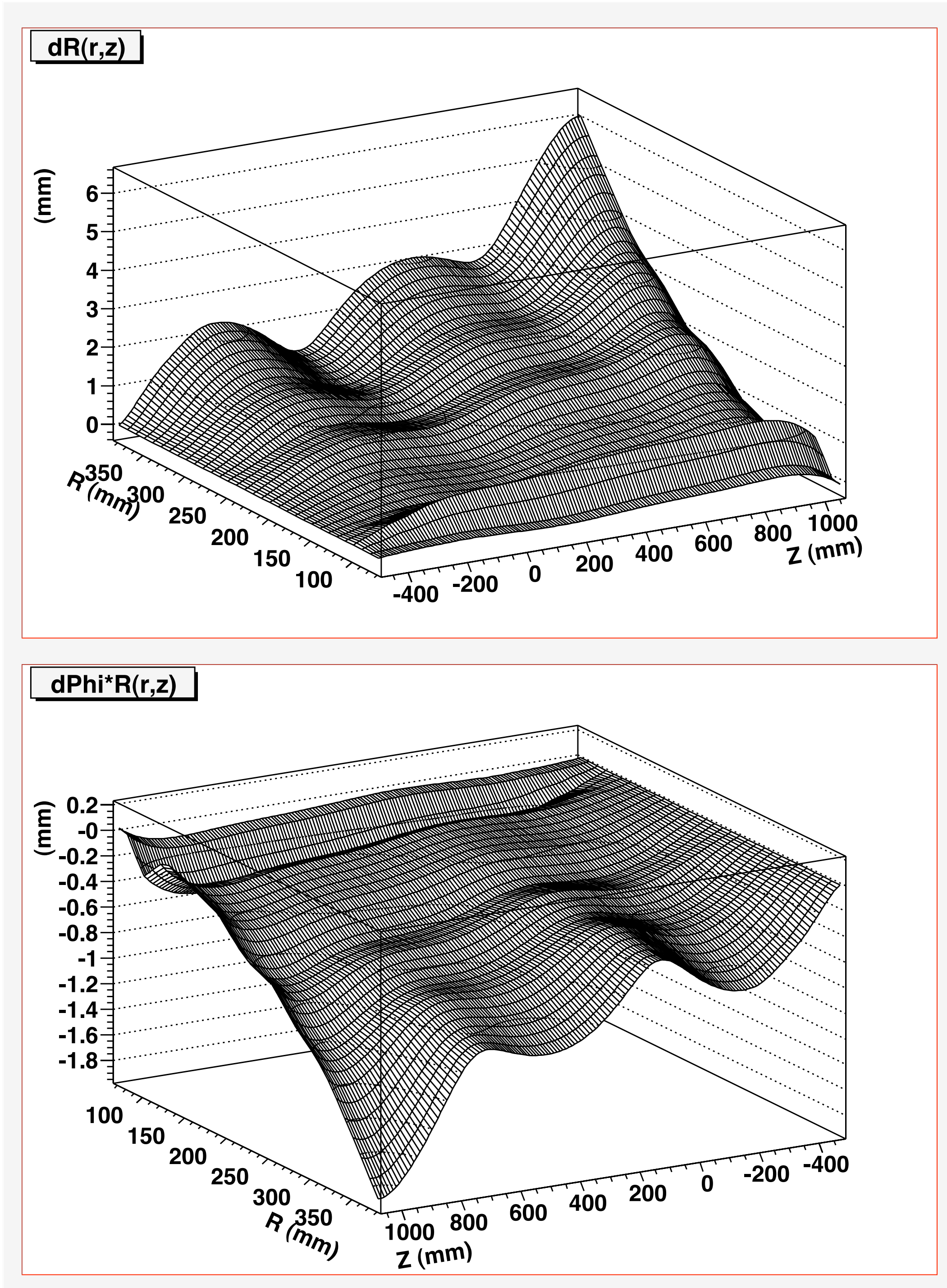

Figure 2: Radial (top) and azimuthal (bottom) displacements due to the magnetic field inhomogeneity.

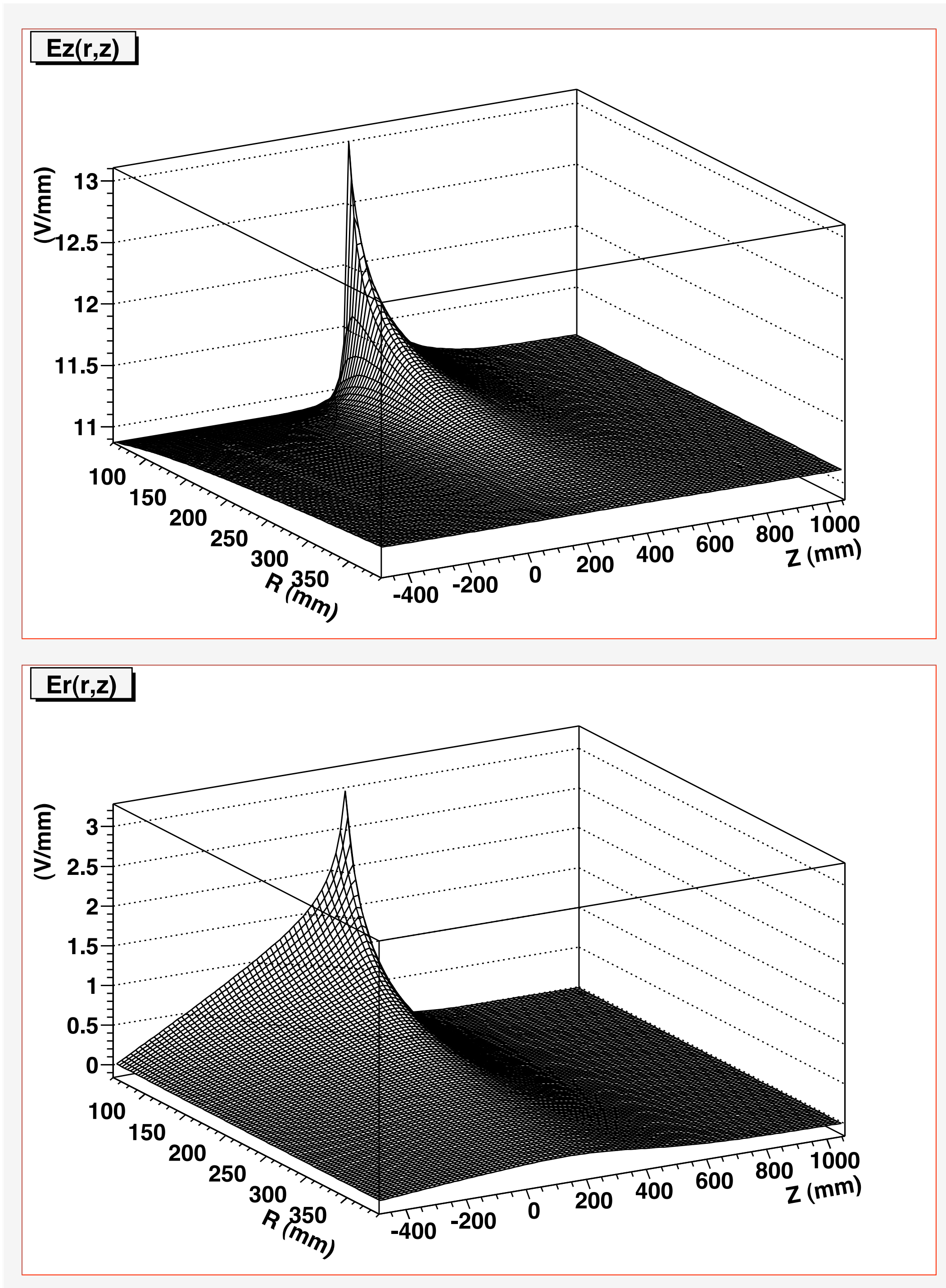

Figure 3: Inhomogeneity of the electrical field.

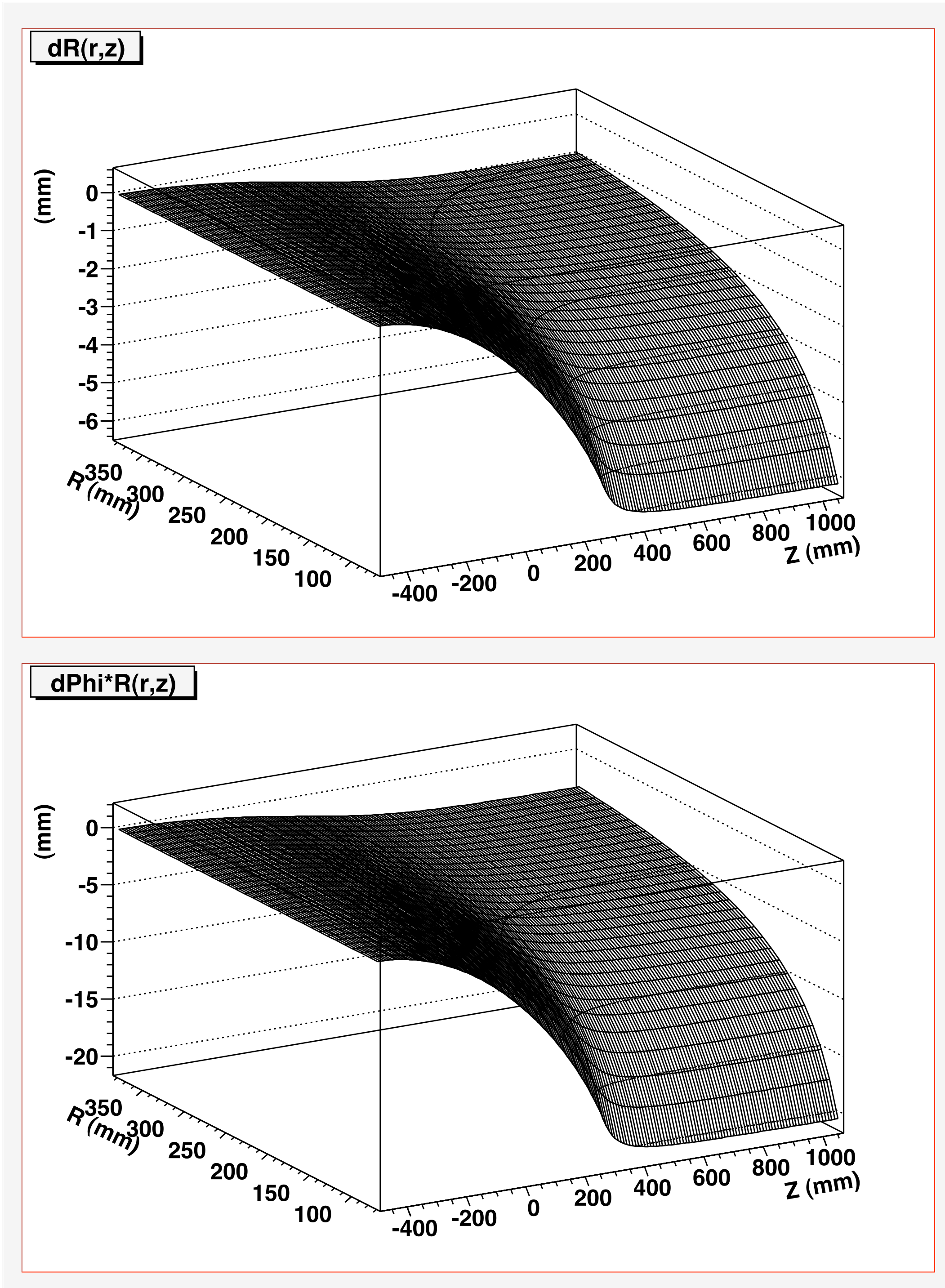

Figure 4: Radial (top) and azimuthal (bottom) displacements due to the electric field inhomogeneity.

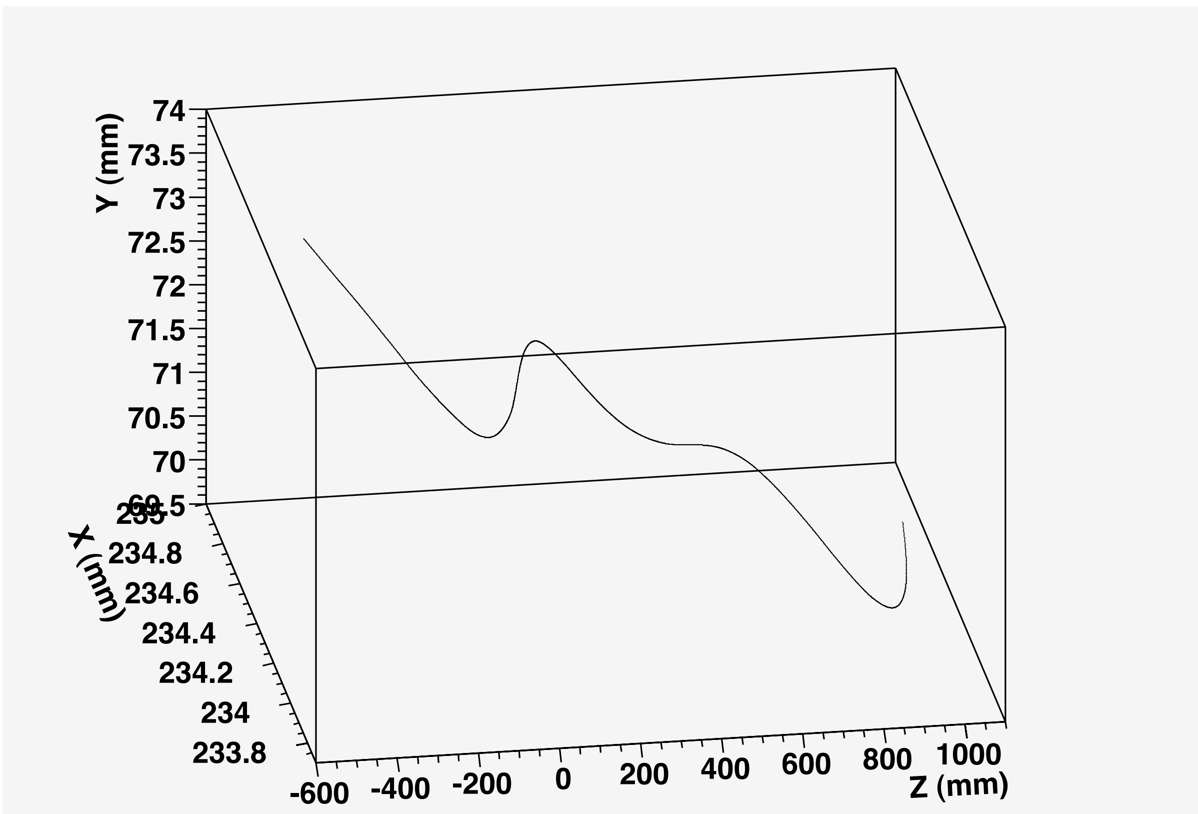

Figure 5: Drift path of an electron from the far end of the TPC (right) to the cathode wire plane (left); beware of the strongly magnified transverse dimensions.

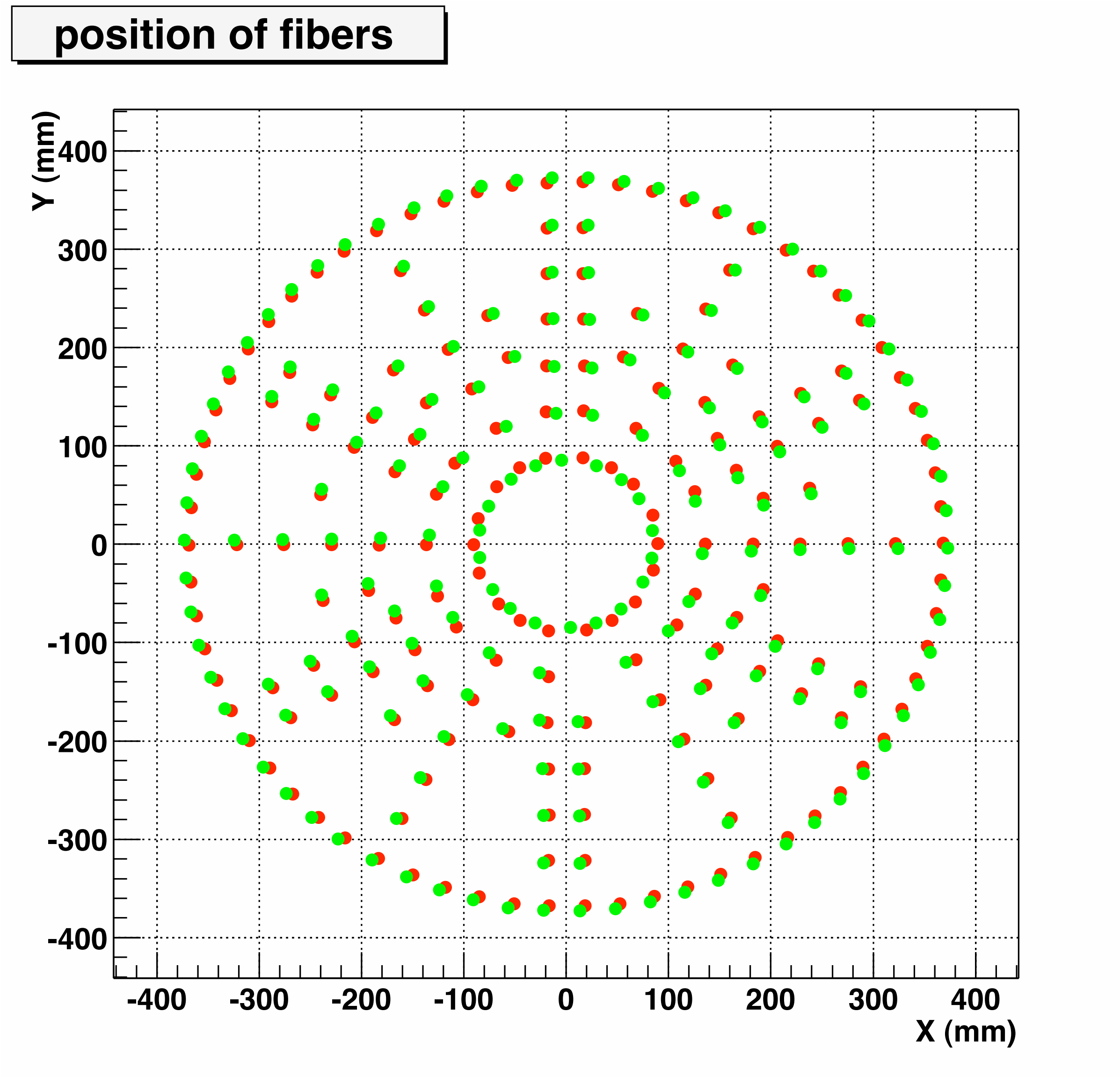

Figure 6: Looking upstream: positions of the optical fibres (black) and the predicted displacements of clusters (grey) from both magnetic and static electric inhomogeneities, for positive beam polarity.

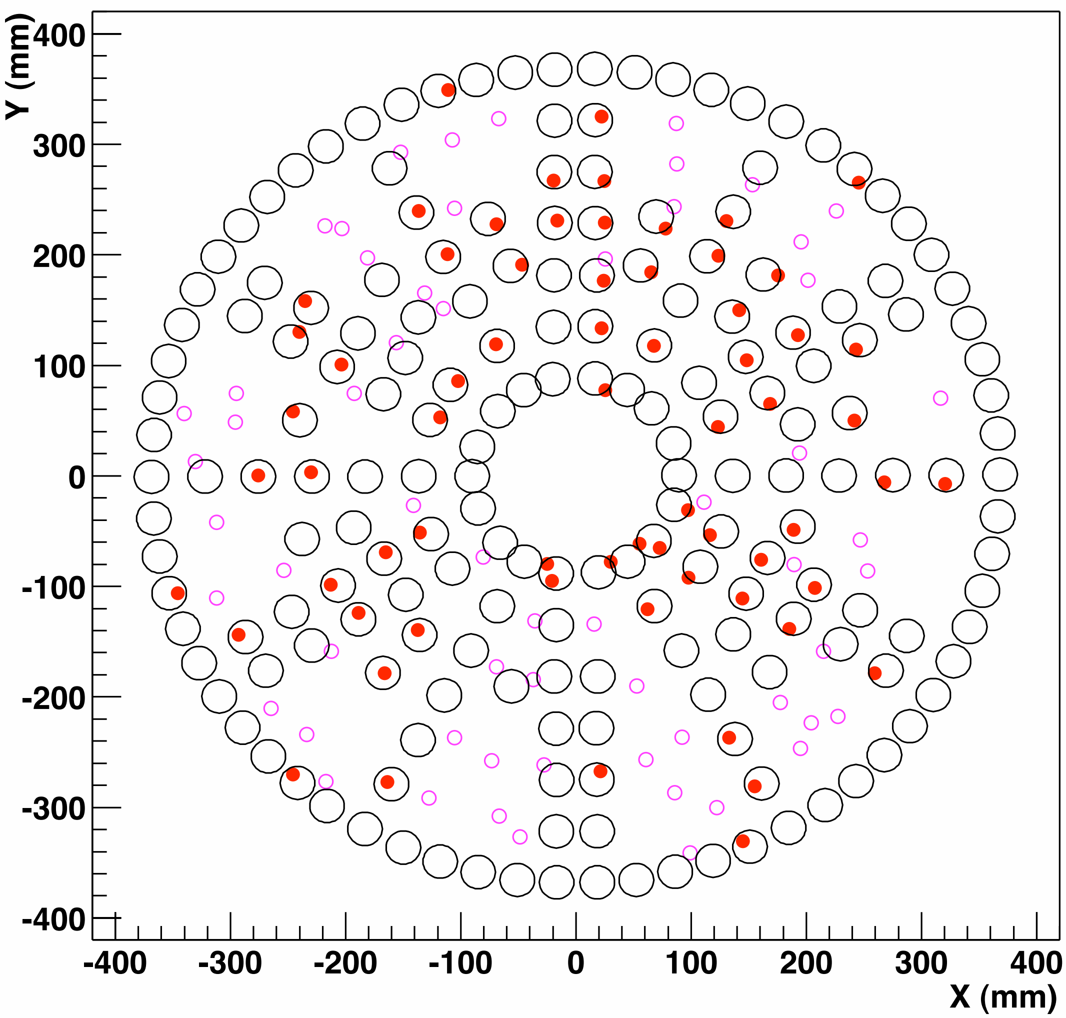

Figure 7: Looking upstream: reconstructed laser clusters (dark dots) inside a 15 mm radius around geometrical fibre positions; open dots mark laser clusters with distance larger than 15 mm to fibre positions; positive beam polarity.

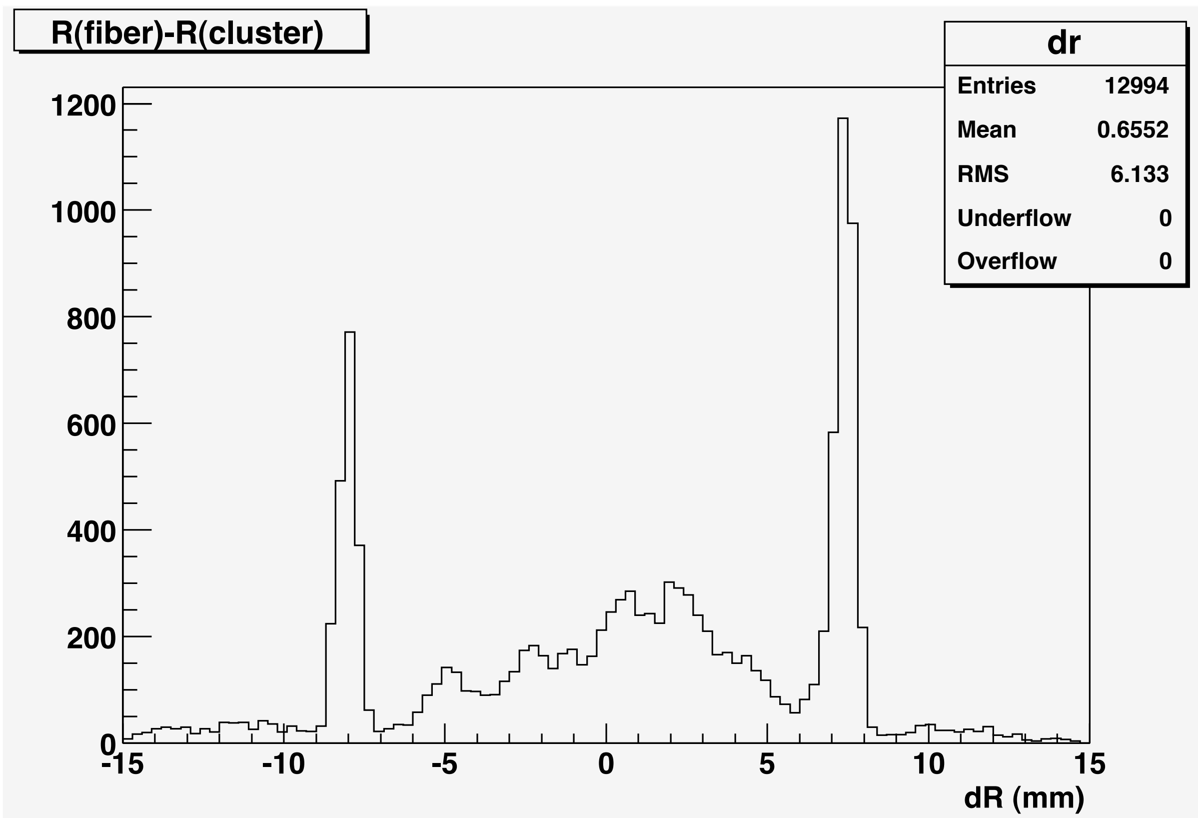

Figure 8: Difference in radius between geometrical fibre and reconstructed cluster positions (the peaks arise from the radial granularity of the pads); positive beam polarity.

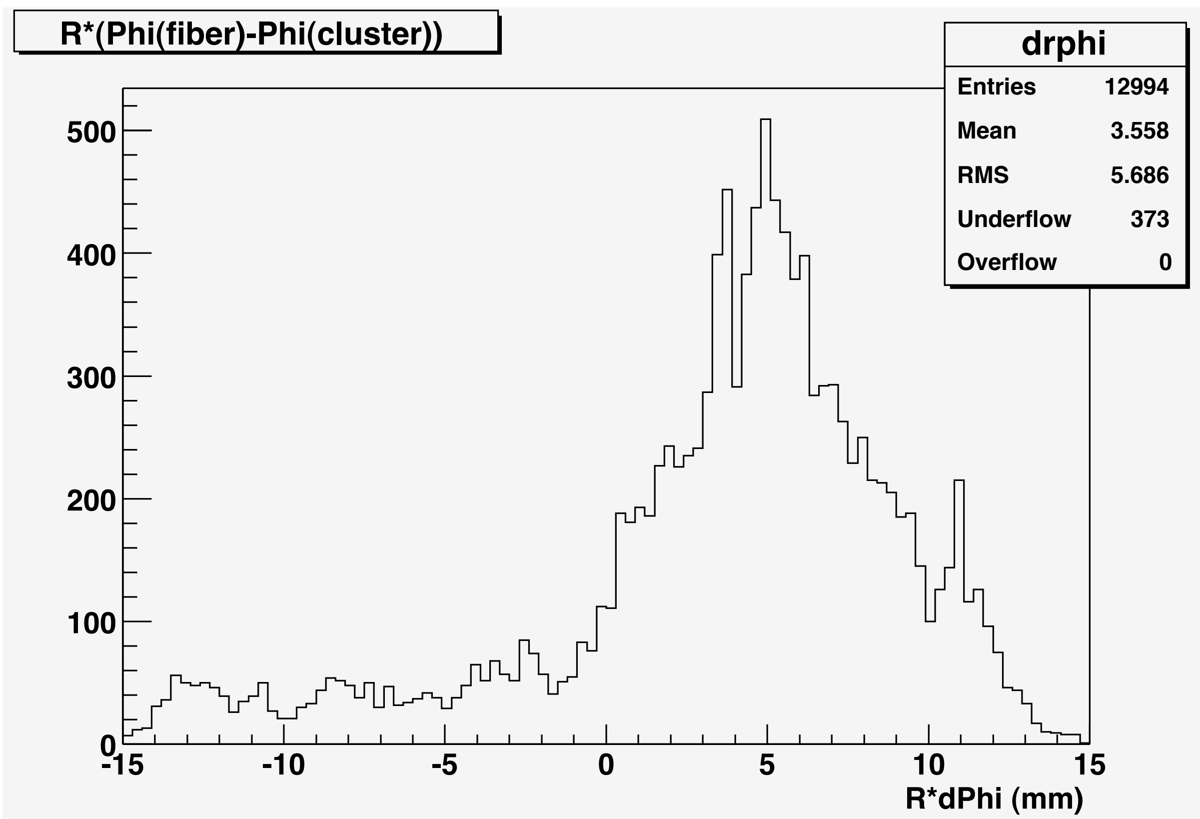

Figure 9: Difference in the azimuthal coordinate between geometrical fibre and reconstructed cluster positions; positive beam polarity.