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Lorentz angle measurements in silicon detectors

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Future LC experiments are using silicon detectors in high magnetic fields. Therefore a good knowledge of the Lorentz angle is needed for design and operation of silicon detectors. We present measurements of the Lorentz angle between 77 K and 300 K up to fields of 9 Tesla.

1 Introduction

Future Linear Collider experiments need stronger magnetic fields for momentum measurements, because of the higher particle momenta. In high fields the drifting ionization generated by traversing particles are deflected significantly by the Lorentz force $e\vec{v} \times \vec{B}$, where $\vec{v}$ is the drift velocity and $\vec{B}$ the magnetic field. As advantage of such a deflection one can consider the increased charge sharing between the readout strips, which can improve the resolution for a given readout pitch. On the other hand the charge sharing worsens the double track resolution and the signal-to-noise ratio. The drift mobility of electrons is larger than the hole mobility [1–4], so a considerably larger Lorentz shift for electrons than for holes is expected. Therefore, the p-side of silicon detectors, where the holes are collected, shows much less of an effect of the magnetic field, than the n-side, where the electrons are collected.

Typical position resolutions of silicon strip detectors are in the order of μm, while the Lorentz shifts in a 4 T magnetic field reaches 200 μm for electrons in a 300 μm thick detector. Therefore, these shifts have to be accounted for. For strip detectors the resolution is mainly determined by the strip pitch and the Lorentz effect is just a nasty side-effect, which has to be calibrated away. In order to reduce the alignment effects from the Lorentz shift one should use the p-side as $r-\phi$ side for the measurement of the momentum and use the n-side for the $r-z$ measurement. In case the $r-z$ strips are perpendicular to the magnetic field ("90 degree strips"), then the large Lorentz shifts of the electrons are along the strips and do not influence the measurements at all.

In this note we study the Lorentz angles of both electrons and holes in magnetic fields up to 8 T and temperatures between 77 and 300 K. This is done before and after irradiating a detector with 21 MeV protons up to a fluence of $10^{13}/\mathrm{cm}^2$, which equals $\approx 2.8 \cdot 10^{13}/\mathrm{cm}^2$ 1 MeV equivalent neutrons.

2 Experimental setup

The Lorentz angle Θ_L under which charge carriers are deflected in a magnetic field perpendicular to the electric field is defined by:

$$\tan(\Theta_L) = \frac{\Delta x}{d} = \mu_H B = r_H \mu B \tag{1}$$

where the drift length corresponds to the detector thickness d and the shift of the center of charge is Δx (see figure 1). The Hall mobility is denoted by μ_H, the conduction mobility by μ. The Hall mobility differs from the conduction mobility by the Hall scattering factor r_H. This factor describes the influence of the magnetic field on the mean scattering time of carriers of different energy and velocity[5]. The Hall scattering factor has a value of 1.15 (0.7) for electrons (holes) at room temperature and decreases (increases) towards 1.0 with decreasing temperature [6]. The mobility μ increases with temperature proportional to $T^{-2.42}$ for electrons and $T^{-2.2}$ for holes [7].

The Lorentz angle can be measured by injecting charges at the surface on one side and observing the drift through the detector by measuring the position of this charge on the opposite side (see figure 1). Charges were generated by injecting light with a wavelength of $\lambda = 650$ nm, which has an absorption length of 3 μm at 300 K and 10 μm at 77 K. Alternatively an infrared laser with a wavelength of 1060 nm was used, which has an absorption length of 300 μm at room temperature. This laser penetrates the detector and so mimicks a minimal ionizing particle. With the red laser one type of carriers immediately recombines at the nearest electrode, whereas the other type drifts towards the opposite side. This allows to measure the Lorentz angle for electrons and holes separately by either injecting laser light on the n- or p-side.

For our measurements the JUMBO magnet from the Forschungszentrum Karlsruhe[8] was used in a $B = 10$ T configuration with a warm bore of 7 cm. A flow of cold nitrogen gas through the warm bore allowed the detectors to be cooled to temperatures between 77 and 300 K. The sensors are double sided “baby” detectors of approximately 2x1 cm from the HERA–B production by Sintef. They have a strip pitch of 50 micron on the p–side and 80 micron on the n–side; the strips on opposite sides are oriented at an angle of 90 degree with respect to each other. The x- and y-directions are taken to be along the strips, while the E-field is in the z-direction. The B-field, perpendicular to the electric field, has to be in the x-y plane, but cannot be oriented along the x- or y-direction, since then the Lorentz shift would be along one of the strips, i.e. unmeasurable. Therefore, the detector is rotated 45 degrees, so that the

B-field direction is at an angle of 45 degrees with both the x- and y-axis, as shown in fig. 2. The sensor is glued on the hybrid together with a pitch adapter and a 128 channel Premux charge sensitive amplifier[9] on each side. The connections are made by standard wirebonds. All signals are digitized for every laser pulse and averaged over a few 100 pulses. The signal position is computed using either a Gauss-fit or the center of gravity:

$$\bar{x}(PH) = \frac{\sum PH_i x_i}{\sum PH_i}. \tag{2}$$

Here PH_i is the pulse height of the strip i and x_i its position.

As can be seen from figure 3, the pulse on one side hardly moves, since the ionization has only to drift from the small penetration depth to the nearest electrode, while the pulse on the opposite side originates from ionization, which drifted through the whole detector and shows a clear Lorentz shift. The signal position is plotted as a function of the magnetic field in figure 4, which shows that the Lorentz shift is linear with the magnetic field up to 9 T.

In order to better understand the drift in the detector simulations were performed with the Davinci software package by TMA[10]. The inhomogeneous electric field in the sensor was taken into account by following the charge in small steps, calculating the mobility at each position and integrating the Lorentz shift using eq. 1 with a Hall scattering factor of 1.15 and 0.7 for electrons and holes, respectively. These are the values expected for sensors at room temperature, when the scattering by phonons dominates over the scattering by impurities[5].

For bias voltages at least a factor two above the depletion voltage the mobility is practically constant in the detector, while for just depleted detectors the electric field change from zero to the maximum field at the pn-transition, in which case the mobility decreases from its low field value to the value determined by the saturation of the drift velocity at high fields (see Fig. 5. The corresponding mean trajectory of the ionization becomes non linear at low bias voltages, as shown in figure 6.

3 Results

Instead of the Lorentz angle the shift in a 300μm thick detector is plotted for a 4 T magnetic field, which is the one of interest for future experiments. The dependence on temperature and bias voltage is shown in figures 7 and 8 together with the simulations from the Davinci software package by TMA[10], as mentioned above.

For holes the temperature dependence is well described, but for electrons the Lorentz angle first falls below the simulation for decreasing temperature, as expected for a decreasing value of the Hall scattering factor r_H at lower temperatures[6]. However, below $T = 160$ K the Lorentz angle for electrons rapidly increases and is a factor two *above* the simulation at liquid nitrogen temperature. The simulation was done with a temperature independent Hall factor of 1.15 (0.7) for electrons (holes), which is certainly wrong[6]. Therefore, the most likely interpretation of the deviation between simulation and data would be the temperature dependence of the Hall scattering factor, since the drift mobility at low temperatures is well known[6] and the electric field dependence is well described by the simulation, as shown in figure 8. However, then a Hall scattering factor around two is needed. Such a large r_H is expected for Coulomb scattering on impurities[5] like the space charge in a fully depleted detector. However, this has to be verified with numerical simulations.

Before irradiation the detector depletes fully with a bias voltage of 40 V, while after radiation with $1.0 \cdot 10^{13}$ 21 MeV protons per cm^2 the depletion voltage has increased to 100 V. This implies that the bulk is inverted from n-type to p-type material, as expected[11]. The bulk damage of 21 MeV protons is about 2.8 times the damage by 1 MeV neutrons. The decrease of the Lorentz shift for the irradiated sample below 100 V in figure 8 is due to the reduced effective thickness of the partially depleted detector. Numerical results on the Lorentz angles and Lorentz shifts have been summarized in tables 1 and 2 before and after irradiation, respectively.

Figure 9 shows the signal from the 1060 nm infrared laser on the irradiated detector. As mentioned before, this laser has an absorption length of about 300 μm at room temperature, so it traverses the detector. It can be seen that the signal on the p-side hardly moves with the magnetic field, as expected for a dominant contribution of holes by the charge integrating amplifier, while the n-side shows a Lorentz shift corresponding to roughly half the Lorentz shift of the red laser. This is expected for ionization distributed in the detector, so the average drift length is half of the detector thickness.

4 Conclusion

The Lorentz angle has been measured for electrons and holes separately in magnetic fields up to 9 Tesla. At the typical 4T magnetic fields at future colliders the Lorentz angle in a 300 μm thick detector is typically 30 degrees for electrons and 7 degrees for holes. For minimum ionizing particles this causes a broadening of the pulse. The effect of the large Lorentz angles for electrons do not influence the measurements, if the strips on the n-side are perpendicular to the magnetic field, so the Lorentz shift is along the strip. Alternatively, one can reduce the Lorentz shifts somewhat by overdepleting the detector. In the foreseen CCD- or CMOS-type pixel detectors the drift distance is usually so small, that the Lorentz shifts have no effect.

For the non-irradiated detector the Lorentz angles of holes agree with simulations at all temperatures, but for electrons the Lorentz angle agrees only at room temperature. Below $\approx$ 160 K the angle increases rapidly to twice the expected value. A possible explanation could be a Hall scattering factor of ≈ 2 instead of ≈ 1. This rise is most likely due to a change of scattering mechanism at low temperature, e.g. from phonon scattering to Coulomb scattering on the space charge, although numerical simulations have not yet confirmed this idea.

After irradiation with protons to a fluence of $10^{13}/cm^2$, which equals $\approx 2.8 \cdot 10^{13}/cm^2$, the

Lorentz angle for holes is hardly changed at room temperatures, at least if the bias voltage is raised to obtain full depletion again. However, for electrons the angle decreases about 25% at room temperature. At lower temperatures radiation damage increases the Lorentz angles, both for electrons and holes.

5 Acknowledgements

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	Electrons (280 K)		Holes (270 K)		Electrons (77 K)		Holes (77 K)	
Bias / V	Θ	$\Delta x[\mu m]$	Θ	Δx $[\mu m]$	Θ	$\Delta x[\mu m]$	Θ	Δx $[\mu m]$
40	33°	192	6.5°	34	79°	1539	46°	309
100	30°	170	7.2°	38	71°	852	32°	184
200			5.9°	31	56°	449		
300			4.8°	25	45°	295		

Table 1
The Lorentz angle (Θ_L) and displacement Δx for a 300 μm thick detector in a 4 T magnetic field as function of bias voltage at room temperature and nitrogen temperature.

	Electrons (280 K)		Holes (260 K)		Electrons (77 K)		Holes (77 K)	
Bias / V	Θ	$\Delta x[\mu m]$	Θ	Δx $[\mu m]$	Θ	$\Delta x[\mu m]$	Θ	Δx $[\mu m]$
50	21°	117	8.5°	45	65°	630	45°	297
100	23°	127	8.0°	42	73°	970	48°	329
150	23°	126	7.6°	40	69°	785	37°	228

Table 2
As in table 1, but now for a detector irradiated with 21 MeV protons up to a fluence of $10^{13}/\mathrm{cm}^2$.

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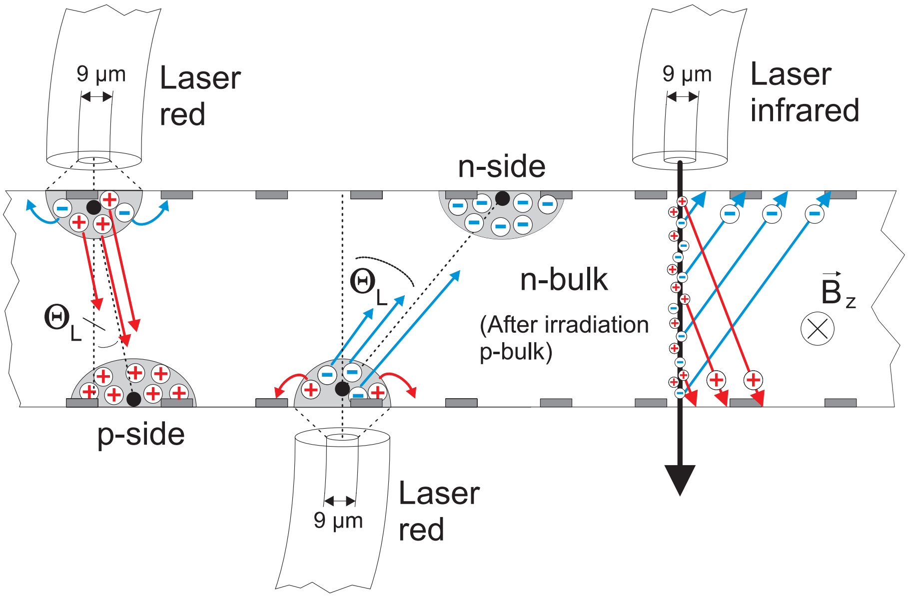

Fig. 1. The detectors have three lasers connected to them. The red lasers have a penetration depth of a few μm, so with a laser pulse on the n-side or p-side one can measure the drift from electrons and holes, respectively. With the infrared laser one can simulate a through going particle.

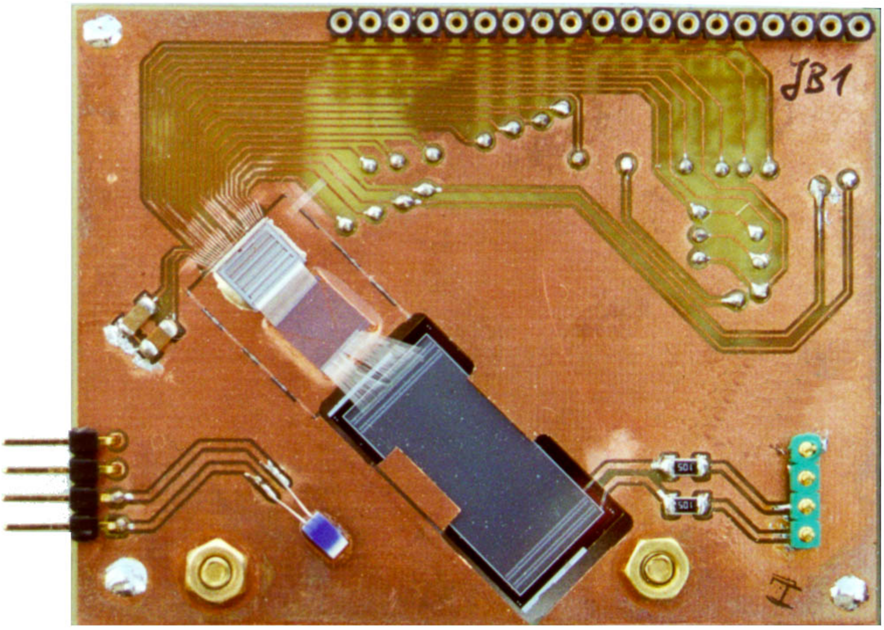

Fig. 2. The detector mounted at an angle of 45° on the hybrid in order to be able to measure the Lorenzt shift on both sides of the detector. The pitch adapter and the Premux128 chip with the 128 charge sensitive amplifiers can be clearly seen. The strips are parallel to the edges of the detector and oriented at an angle of 90° with respect to each other on the p- and n-side. The magnetic field is directed from the bottom to the top of the hybrid.

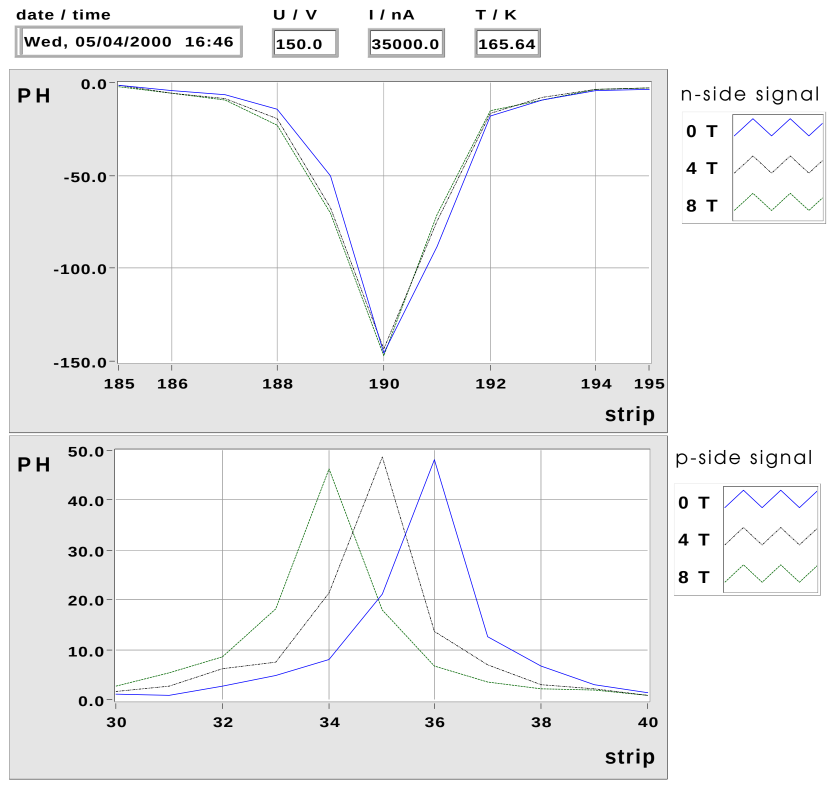

Fig. 3. Laser pulse position in different magnetic fields. Light is injected from the n-side resulting in an almost stable pulse position on that side and a clearly moving position on the p-side, if the magnetic field is increased to 8 T in steps of 4 T.

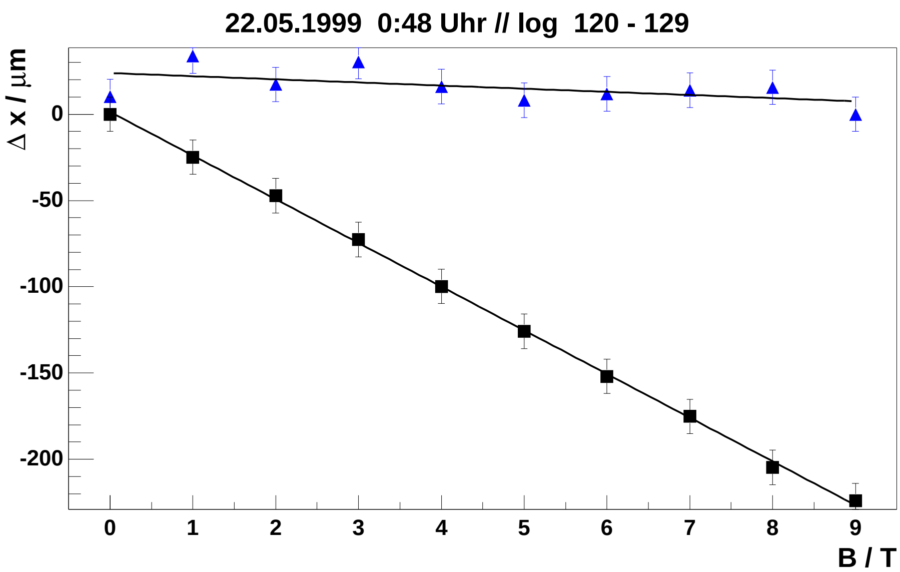

Fig. 4. The Lorentz shift versus magnetic field. The red laser pulse on the n-side side hardly penetrates, so the electrons are immediately absorbed by the neighbouring strips on the n-side and the holes drift through the detector to the p-side. Therefore an appreciable shift is only seen for the holes.

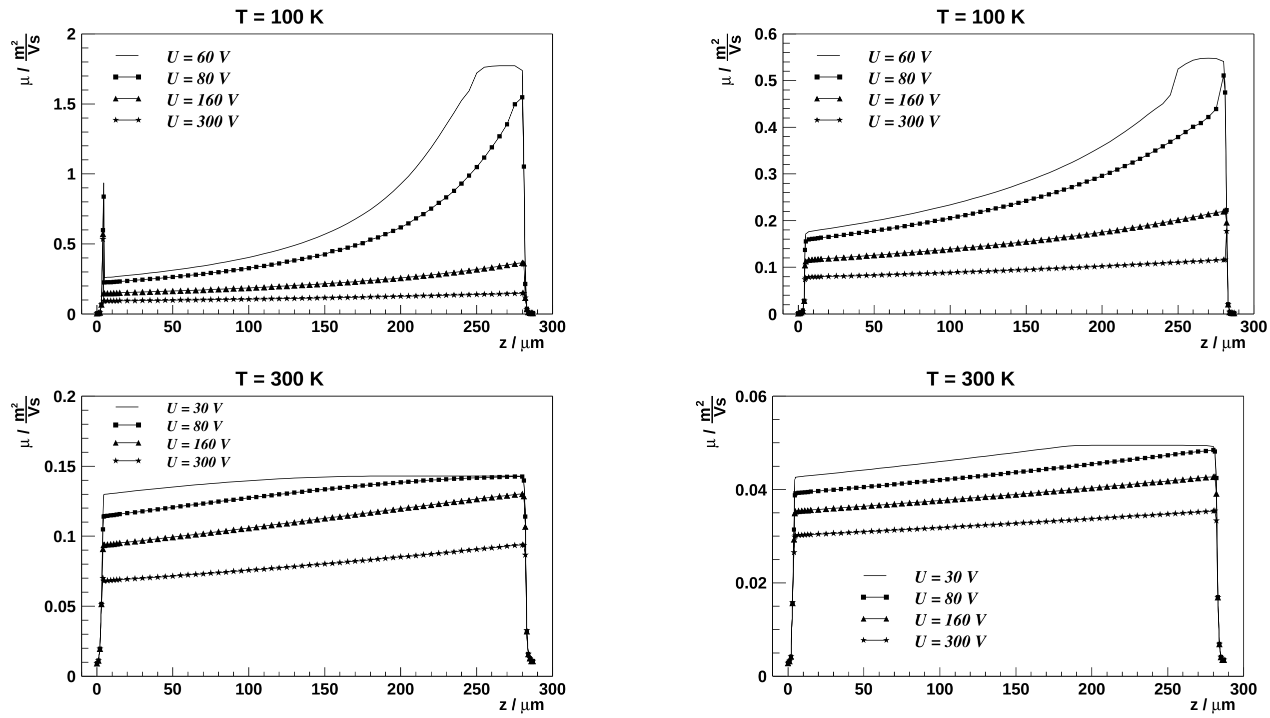

Fig. 5. Mobilities of electrons (left) and holes (right) for a detector with a full depletion voltage of 80 V. The top row is for a temperature of 100 K, the lower row for 300 K. From [3].

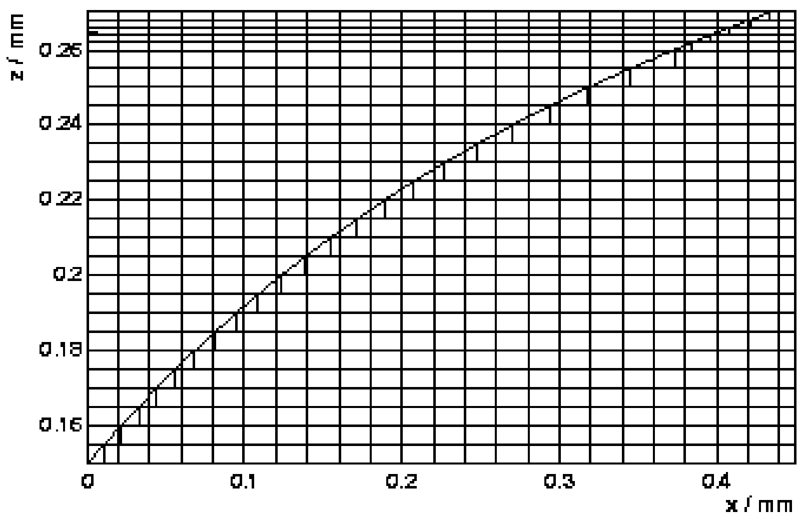

Fig. 6. Mean trajectory of charge in a just depleted detector at a temperature of 80 K in a 4 T magnetic field. From [3].

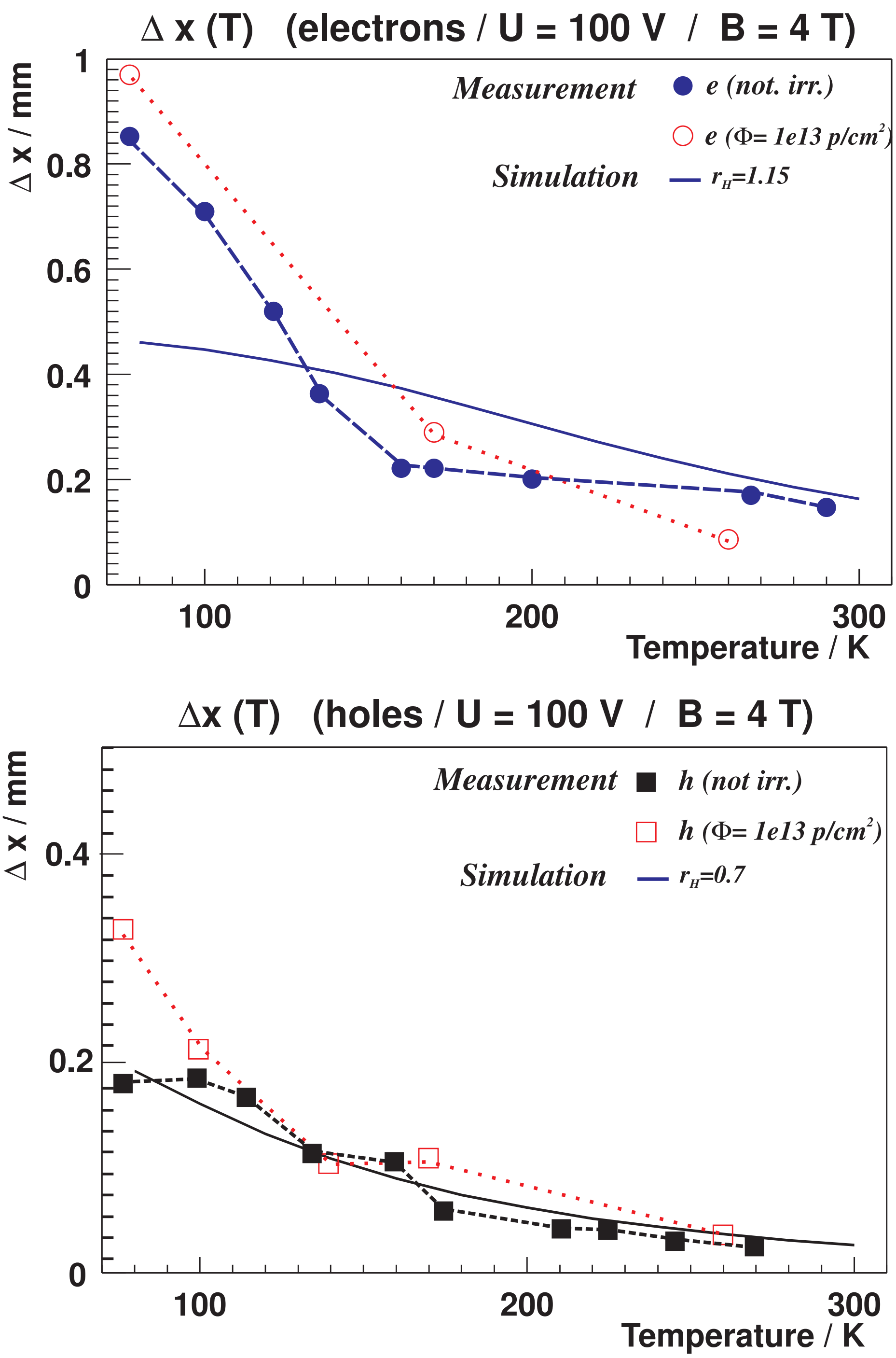

Fig. 7. Lorentz shift for electrons (top) and holes (bottom) for 300 μm detector in a 4 T magnetic field as a function of temperature. Data for an unirradiated detector and a detector irradiated with protons of 21 MeV to a fluence of $1.0 \cdot 10^{13}$ p/cm^2 are shown. For comparison, the temperature dependence from the Davinci simulation program with a constant Hall scattering factor of 1.15 (0.7) for electrons (holes) is shown by the full lines.

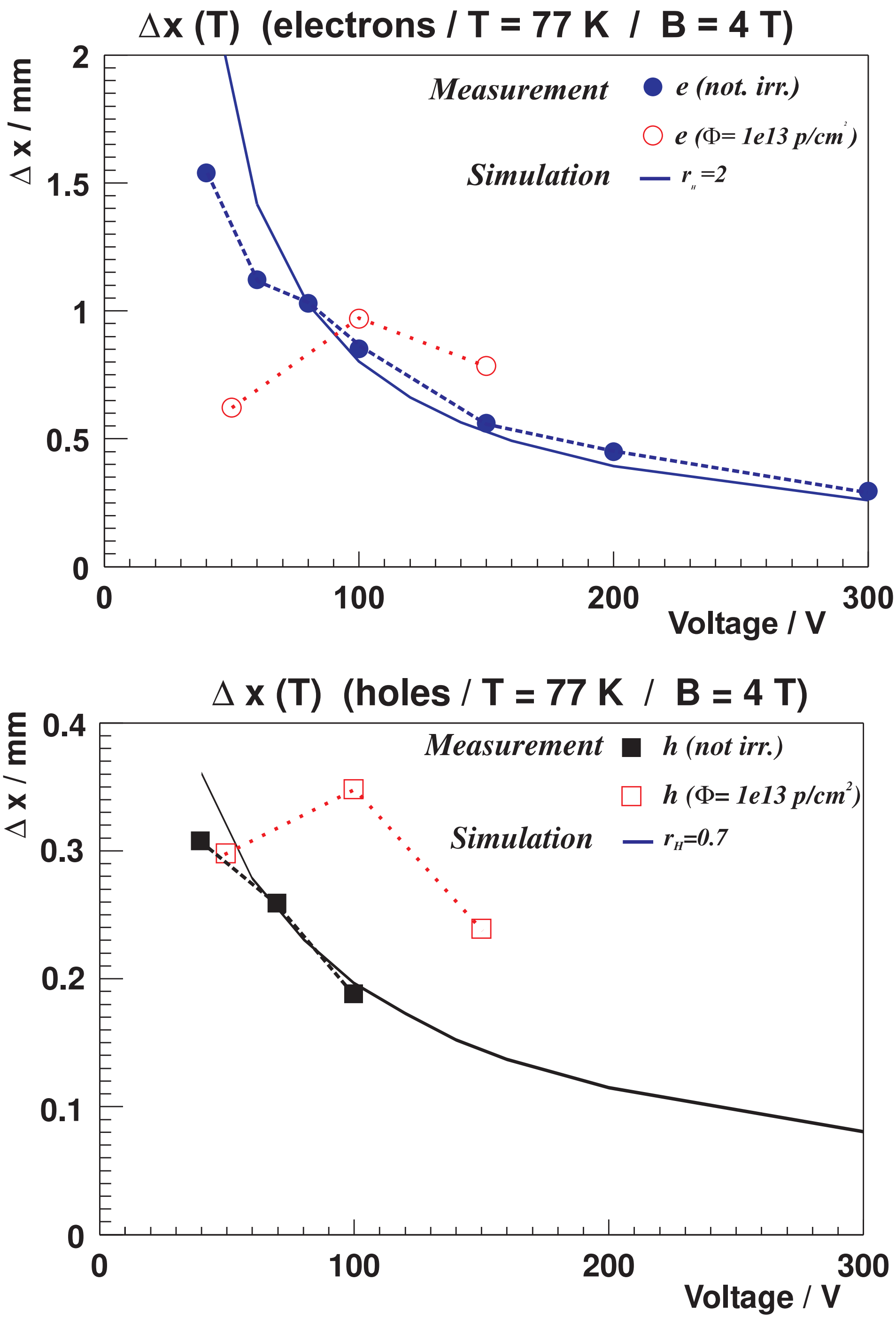

Fig. 8. Lorentz shift for a 300 μm detector in a 4 T magnetic field for electrons (top) and holes (bottom) versus bias voltage at a temperature of 77 K. Both, data for an unirradiated detector and a detector irradiated with protons of 21 MeV to a fluence of $1.0 \cdot 10^{13}$ p/cm^2 are shown. For the latter the full depletion voltage has increased from 40 to 100V. For comparison, the temperature dependence from the Davinci simulation program with a constant Hall scattering factor of 2.0 (0.7) for electrons (holes)is shown by the full lines.

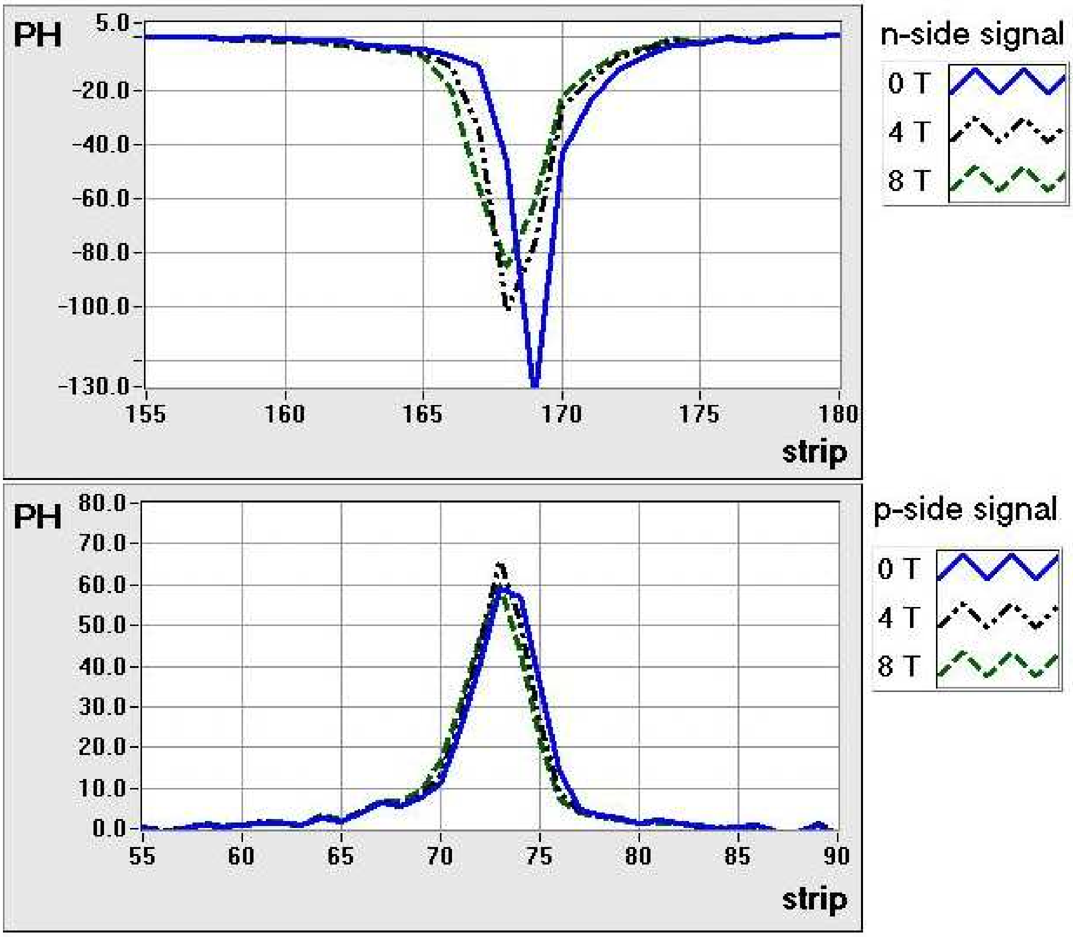

Fig. 9. Pulse shape of the infrared laser shining through the irradiated detector (10^{13} p/cm^2). The n-side signal is mainly dominated by electrons, the p-side signal by holes, as is apparent from the displacement as function of the magnetic field.