CHAPTER 9:
SDD IN THE MAGNETIC FIELD

9.1 Introduction

Tracking detectors are routinely operated in high magnetic fields in order to obtain momentum measurements. Thus, it is important to understand the effects of the magnetic field on drift detectors and verify its functionality under these conditions.

The extremely high and relatively homogeneous magnetic field achievable with the E896 super-conducting dipole magnet provided a unique opportunity to study the effects of the magnetic field on the electron drift. A laser injection setup was assembled and drift measurements were taken for several different magnetic field values at the very end of the E896 April 1998 beam time.

9.2 Theoretical considerations on magnetic field effects

9.2.1 Effects of a perpendicular (transverse) field

A charged particle moving through a magnetic field ($\vec{B}$) is subject to the Lorentz force [ref. 9.1]:

$$\vec{F} = -e\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{9.1}$$

A $\vec{B}$ field perpendicular to the drift direction and the wafer plane causes a motion in the plane of the detector, perpendicular to the drift direction. The electron cloud is swept in the transverse direction, towards neighboring anodes.

With the $\vec{B}$ field perpendicular to the drift direction but parallel to the detector plane, the Lorentz force is perpendicular to the wafers. This configuration is similar to the standard Hall experiment [ref. 9.2], performed in conducting materials. The standard Hall effect is due to the perpendicular force that shifts the charge carriers towards the surface of the conducting material thus giving rise to an electric field that opposes the original force generated by the magnetic field. The direction and magnitude of this electric field are expressed in:

$$\overrightarrow{E_H} = -R_H \cdot \vec{B} \times \vec{j} \tag{9.2}$$

where R is know as the “Hall coefficient”. Assuming that the charge carriers are all of the same sign (electrons):

$$\vec{j} = -ne\vec{v} \tag{9.3}$$

Since, by definition, $\vec{E}_H$ is the force per unit charge due to the Hall effect, the Hall coefficient is given by:

$$R_H = -\frac{1}{ne} \tag{9.4}$$

This is for the simple case where all the charge carriers are of the same sign, and no anisotropies of the medium are considered. In semiconductors, this effect will be affected by several factors, such as the non-spherical band structure and the crystal lattice orientation. The ratio of Hall to conductivity mobility is a quantity of great interest in discussing the behavior of semiconductors, but it is an extremely difficult quantity to determine. In N-type silicon, previous experiments measured values around 1.2 to 1.3 [ref. 9.3, 9.4]. In a more recent experiment, using a STAR-1 prototype, the Hall coefficient was measured in a transverse magnetic field up to 4.7 T, and was found to be around 1.5 [ref. 9.5]. In this experiment, both drift mobility and Hall mobility were measured.

In Silicon Drift Detectors, the parabolic potential (section 3.3.1) that constrains the electron cloud in the center plane of the detector limits the motion in the perpendicular direction. Thus, the magnetic field only creates a small shift of the electron cloud position with respect to the center of the bulk. Unlike standard Hall experiments, in Silicon Drift Detectors, the perpendicular magnetic field does not give rise to an opposing electric field from charge accumulation due to the cathodes on the surface that collect the charges. Further details of the Hall effects in Silicon Drift Detectors can be found in reference [ref. 9.6].

9.2.2 Longitudinal Magneto-resistance

Considering only the macroscopic behavior of the electron cloud in drift detectors, a $\vec{B}$ field parallel to the drift direction, would only affect the initial part of the electron drift, when the electrons are moving towards the center of the detector, while $\left(\vec{B}\times\vec{v}_{drift}\neq 0\right)$. Once the electrons cloud is in the center of the detector cloud $\left(\vec{B}\times\vec{v}_{drift}=0\right)$, thus, the Lorentz force could be considered null. A small constant correction factor to account for the delay caused by the effects of the magnetic field in the drift time measurements would be sufficient. However, if we consider the electron dynamics in more detail, using quantum statistics instead of classical statistics, a longitudinal magnetic field (parallel to the drift direction) gives rise to an important effect called magneto-resistance that affects the overall drift velocity of the electrons in the semiconductor.

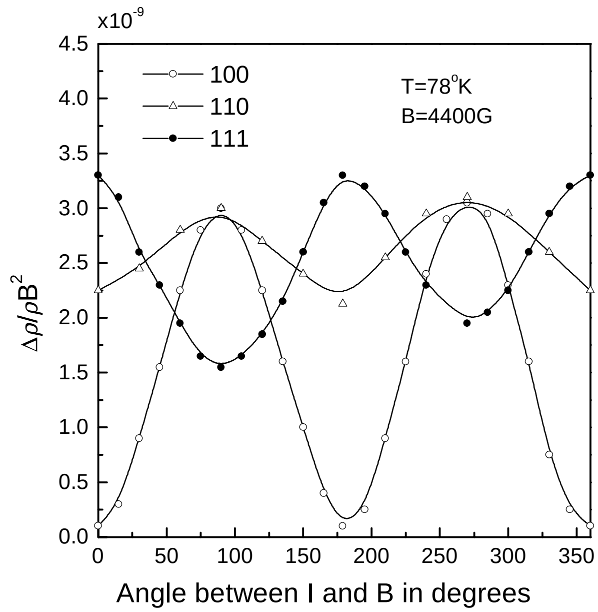

Figure 9.1: *Variations in $\Delta\rho/\rho B^2$ as B is rotated with respect to I in n-type silicon at 78°K.*

The magneto-resistance effect causes an increase in the resistance of a conductor when a magnetic field is applied. A naive explanation for this phenomenon is that when a magnetic field is applied, the path trajectory of electrons between successive collisions becomes helical, causing an increase in the path length and reducing the component of motion in the drift direction. Calculations show that, for an isotropic system, in which electrons obey classical Boltzman statistics [ref. 9.7], the magneto resistance should be maximum when the magnetic field is perpendicular to the direction of the electric field (transverse effect). If the direction of the magnetic field is the same than that of the drift velocity, the force produced by the magnetic field (longitudinal effect) should vanish, in accordance to the Lorenz force equation. However, in silicon it was experimentally verified that the longitudinal effect could be comparable to the transverse effect. In addition, it was found that the magnitude of the effect depends upon the crystalline orientation. Figure 9.1 shows a magneto-resistance measurement [ref. 9.8] on n-type silicon, as a function of the angle between the direction of the magnetic field and the direction of the electric field (drift field), for different crystal orientations.

A direct calculation of the energy band system can provide an unambiguous interpretation of the magneto-resistance effect, however such calculations are very complex. Another way of understanding this effect is to consider non-spherical Fermi-surfaces which lead to anisotropies in the tensor of the effective mass (m^*) or relaxation time (τ) [ref. 9.1].

Based on the Lorentz equation and Hall effect studies, the Magneto-resistance is parameterized by the following approximation:

$$\frac{\Delta\mu}{\mu} = -a^2 \cdot B^2 \tag{9.5}$$

or

$$\mu_B = \frac{\mu_0}{\left(1 + a^2 B^2\right)} \tag{9.6}$$

where "μ_B" is the electron mobility in the presence of a magnetic field and "μ_0" is the electron mobility without any field. Therefore, the drift velocity will be reduced by $\left(1 + a^2 B^2\right)$ with the increase of the magnetic field.

9.3 Experimental setup and results

In experiment E896, the silicon detectors were placed vertically inside the magnet, thus the electron drift and the magnetic field had the same direction. Two optic fibers were pointed at the surface of the first detector from a short distance. An infrared laser with a wavelength of *1060 nm* was used to ionize electrons on the detector. Data were recorded for 27 different magnetic field values between zero and *6.2 Tesla*. For each magnetic field, 100 events with laser signals and 50 "null" events with no laser injection were recorded. The "null" events were used for pedestal calculation and subtraction. The temperature was recorded for drift velocity correction purposes. All measurements were normalized to the same temperature of 32°C using equation 4.20 with an α=-2.42.

The laser hit position for each event was determined using the E896 analysis code described in chapter 7. For each magnetic field value, the average laser hit positions from 100 events were calculated. Figure 9.2 shows the average drift velocity calculated from the two laser hits, as a function of the magnetic field. The error bars are the RMS based on 100 events. As expected the drift velocity decreases with increasing magnetic field.

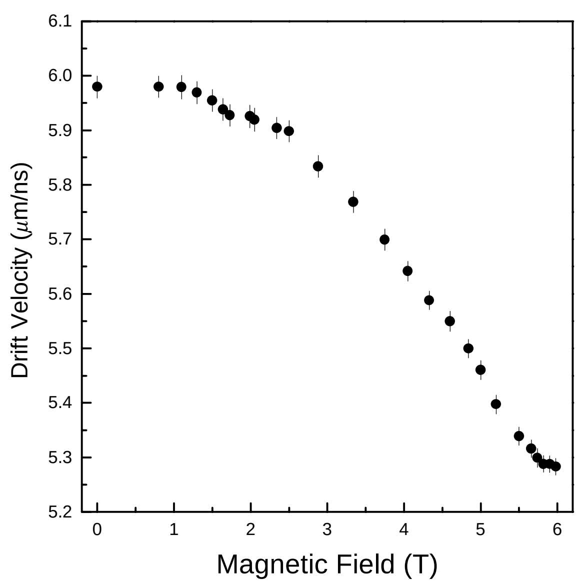

Figure 9.2: *Change in the drift velocity due to the magnetic field.*

In the transverse direction (anode direction), only a small deviation due to the magnetic field was observed, less than *0.2 mm*, for a drift distance of *25 mm*.

Thus the increase in the drift distance due to the transverse deviation is negligible, as expected.

9.4 Discussion

The increase of the drift time, as a function of the magnetic field, is thought to be the result of a longitudinal magneto-resistance effect. This effect is expected to be proportional to B^2 or higher order degrees. Considering that the orientation of the magnetic field should not affect the longitudinal magneto-resistance, terms to the power of odd numbers (B, B^3, …) are not expected.

Figure 9.3 shows the relative variation of the drift time, $(t_B-t_0)/t_0$, as a function of the magnetic field, which is equivalent to equation 9.5.

$$\frac{\Delta t}{t_{B=0}} = -\frac{\Delta v}{v_{B=0}} = -\frac{\Delta \mu}{\mu_{B=0}} = a^2 \cdot B_T^2 \qquad \textbf{(9.7)}$$

The solid and the dotted curves in figure 9.3 show the fit to the data, with the following results, respectively:

$$\begin{aligned} \frac{\Delta t}{t_{B=0}} &= (3.8 \pm .2)10^{-3} \cdot B_T^2 \\ \frac{\Delta t}{t_{B=0}} &= (1.8 \pm .2)10^{-3} \cdot B_T^2 + (1.5 \pm .4)10^{-4} \cdot B_T^4 + (2.7 \pm .3)10^{-6} \cdot B_T^6 \end{aligned} \qquad \textbf{(9.8)}$$

The coefficient obtained with the first expression is slightly smaller than the coefficient measured previously with the STAR-1 detector [ref. 9.5]. This difference is most likely due to purity variations between the silicon wafers used for STAR-1 detector and STAR-2.9 detector.

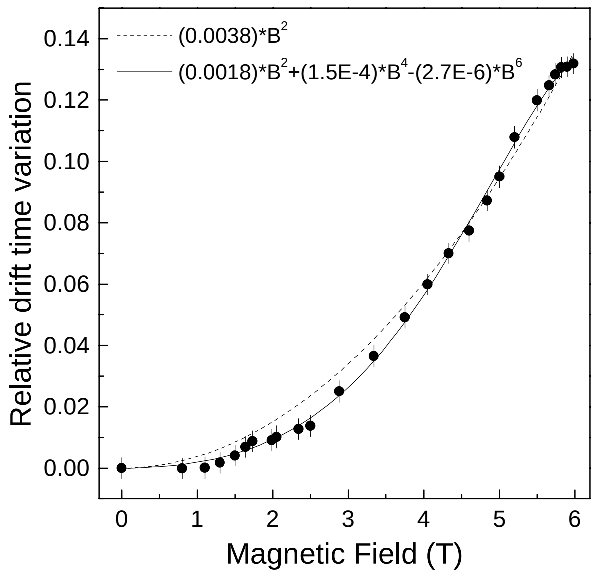

Figure 9.3: *Relative variation of the measured drift time (t_B-$t_{B=0}$)/$t_{B=0}$, as a function of the magnetic field, "B".*

As shown in figure 9.3, the higher order fit describes the data well. However, the coefficients of the higher order terms are much smaller, indicating that equation 9.5 is a good approximation in the large range of magnetic fields measured.

In summary, it has been proven that the magnetic field does not affect the standard operation of the drift detector. No significant distortions were seen in the shape of the signal with increasing magnetic field. A change in the drift velocity was measured, caused by a longitudinal magneto-resistance effect, which is expected to be proportional to B^2. In the STAR experiment at RHIC, the expected magnetic field is around 0.5 Tesla, parallel to the plane of the detector, but perpendicular to the drift direction. In this case, the transverse magneto-resistance should be predominant. The transverse shift expected for the maximum drift distance of *30 mm* is below *2.7 mm*. The longitudinal magneto-resistance will cause a decrease of the drift velocity of less than 0.1%, and is therefore negligible.