Master Thesis in Experimental Subatomic Physics

# "Development of a motor - controller for an infrared laser test stand for silicon detectors"

"Entwicklung eines Motor - Controllers für einen Infrarotlaserteststand für Siliziumdetektoren"

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# Introduction

There are only two ways to live your life. One is as though nothing is a miracle. The other is as though everything is. Cilbert E = White

Gilbert F. White

Since the beginning of mankind, we have been in search of the smallest building blocks comprising our earth, galaxy and even the whole universe. In a run of approximately 2,500 years a lot of discoveries have been made. From Leucippus' and Democritus' atomism over Kopernikus' heliocentrism to the well-established quantum field theories nowadays, we have a huge amount of different particles to describe nature. They are so many that a term exists to summarize them: Particle zoo. The elementary particles contain six quarks and six leptons plus all their antiparticles and, additionally, twelve interacting particles as well as the Higgsboson. Interaction among each other is caused by four forces. Three of them are combined in the standard model, which describes today's physics at the best. As of this writing there are many questions which are still open, just to name a few: How is mass created, why occur leptons in exactly three families, why is the matter-antimatter ratio asymmetric, will the universe collapse one time...?

Experiments have always been a very important part of physics. On the one hand to discover phenomenons and laws and on the other to confirm them. According to the progress physics made, the laboratories have been changed analogously and became more and more complex. Mankind arrived at facilities, which require years or even decades only for development plus large space to build them as well as great financial ressources.

One of these facilities will be  $FAIR^1$  that will hold among others the  $PANDA^2$ -experiment. In this, antiproton-proton annihilation processes will be studied, which provide a wide range of physics topics. Usually, a detector consists of many subdetectors due to some parameters of interest such as energy, momentum, vertices, tracks and others. Each detector fulfils a special function to identify particles which are being produced at the collision point of the antiproton-proton annihilation. The experiment possesses a great luminosity and, as a result of many produced particles in the annihilation processes, high requirements are imposed on the detector.

As the innermost detector, the MVD<sup>3</sup> has to particularly withstand vigorous influences and strains. It is a vertex detector and its purpose will be the identification of primary and secondary interaction points. Therefore a high spatial resolution is required, which many single silicon and pixel detectors will provide.

The aim of this thesis is the development of a laser test stand, which includes a positionable laser head via a xy-table. Compared with the existing system using a radioactive source, a laser has been implemented. This is why time and location, the radiation impinges on time, the sensor can be characterised exactly. For that reason, it is possible to shift the laser in very small increments across the sensor. It is intended for prototype testing and quality assurance of sensors and sensor modules that will be used in the MVD.

<sup>&</sup>lt;sup>1</sup>Facility for Antiproton and Ion Research

<sup>&</sup>lt;sup>2</sup>Antiproton Annihilation at Darmstadt

<sup>&</sup>lt;sup>3</sup>Micro Vertex Detector

# Part I Physical background

# 1 Quantum Chromodynamics

Alle Elementarteilchen sind aus derselben Substanz, aus demselben Stoff gemacht, den wir nun Energie oder universelle Materie nennen können; sie sind nur verschiedene Formen, in denen Materie erscheint.

Werner Heisenberg

Physics at FAIR means hadron physics and furthermore nuclear, atomic, plasma, applied and even bio physics. Fundamental particles are either fermions, the building blocks of matter, or bosons, the carriers of forces. On the level of fermions, matter is divided into leptons and quarks with an half-integer<sup>4</sup> spin and in regard to the level of bosons the gauge bosons with an integer spin. According to the standard model, the elementary substructure is as follows:

• Quarks: 
$$\begin{pmatrix} u \\ d \end{pmatrix}$$
,  $\begin{pmatrix} c \\ s \end{pmatrix}$  and  $\begin{pmatrix} t \\ b \end{pmatrix}$ .  
• Leptons:  $\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ ,  $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$  and  $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$ 

as well as their antiparticles and the

• gauge bosons:  $(g), (\gamma)$  and  $(W^{\pm}, Z^{0})$ 

The Higgs particle  $(H^0)$ , a quantum excitation of the Higgs field, is as much a part. Due to its coupling to all particles, except for photons and gluons, the Higgs boson gives them mass. It is a boson with no spin, electric or colour charge. Gauge bosons are particles that mediate the fundamental forces. Leptons appear in three different generations. Each generation consists of a charged particle and a belonging to it neutrino. Quarks are bound into hadrons by the strong force. Hadrons, consisting of quarks and gluons, are all particles liable to the strong force, theirselves distinguished into baryons (qqq) with half-integer spin and into mesons  $(\bar{q}q)$  with integer spin. The most famous representative of a baryon is the proton (uud) that is also the only known stable among them. Together with neutrons (udd) they form nuclei. Hadrons can decay via strong, electromagnetic and weak force. In this order their relative strength decreases:

 $<sup>^{4}</sup>$ Half-integer particles are subject to the Pauli exclusion principle: Two or more identical fermions cannot simultaneously have equivalent quantum numbers

Interaction Property	Strong	Electromagnetic	Weak	Gravitational
Acts on:	Colour charge	Electric charge	Weak charge	Mass / Energy
Particles experiencing:	Quarks, gluons	Electrically charged	Quarks, leptons	All
$\hookrightarrow$ Particles mediating:	8 gluons	$\gamma$	$W^{\pm}, Z^0$	Graviton (?)
$\rm Mass \ [GeV/c^2]$	0	0	80.4, 91.2	-
Relative strength $\alpha_{s,em,w}$	1	$10^{-2}$	$10^{-15}$	$10^{-41}$
Range [m]	$\approx 1\mathrm{fm}$	$\infty$	$\approx 1\mathrm{fm}$	$\infty$
$J^P$ of the mediating particles	1-	1-	1	-

Table 1: Fundamental forces and their mediating particles as well as coupling constants with strengths relative to the strong force [GREINER 00]. Mass unit is  $1 \text{ eV} / c^2 \equiv 1,783 \cdot 10^{-36} \text{ kg}$ , the electric charge  $e = 1,602176565 \cdot 10^{-19} \text{ C}$  and  $J^P$  is a notation for quantum numbers where J is the total angular momentum  $J = |L \pm S|$  and P parity L and S is spin-orbit interaction and Parity is space mirroring ( $\pm$ ). The mediating particle graviton is currently still hypothetical.

Strong interaction is realised by gluon exchange and described by the QCD<sup>5</sup> [PDG 99]. On the contrary to other forces, the strong coupling constant  $\alpha_s$  increases by distance (figure 1).



Figure 1: Coupling constants:  $\alpha_1$  for the strong force,  $\alpha_2$  for the electromagnetic force and  $\alpha_3$  for the weak force. Distance in energy and electromagnetic charge units according to  $1 \text{ cm} = \frac{1cm}{\hbar c} = 51 \text{ MeV}^{-1}$  with  $\hbar = 6,62606957 \cdot 10^{-34} \text{ Js.}$ 

Coupling constants describe the strength of the mediating particles for coupling to appropriate charges. The coupling constant of the strong force is given by:

$$\alpha_s\left(q^2\right) = \frac{12\pi}{(33 - 2n_f)\log\left(q^2/\Lambda^2\right)} \tag{1.1}$$

with  $\Lambda$  as a scaling parameter,  $N_f$  for number of quark flavours and  $q^2$  for four-momentum transfer.

 $<sup>^5 {</sup>m Quantum \ Chromodynamics}$ 

It can be seen that the coupling constant is not constant at all. This is due to a vacuum polarisation: Quarks are clouded by gluons and quark-antiquark pairs, so their colour charge is partially elevated. This is called anti-screening. In very small distances the coupling constant becomes so small that quarks can be seen asymptotically as free (for small  $q^2$ )<sup>6</sup> [DUCKECK 00]. At distances higher than 1 fm confinement<sup>7</sup> has effect on the colour states. The phenomenological potential of the strong force is represented by:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(q^2)}{r} + kr$$
(1.2)

with  $k \approx 1$  GeVf $m^{-1}$  and r for  $q\overline{q}$  distance

It offers both: A linear, and an inverse relationship with distance. The first represents the confinement. By separating quarks from each other, the energy of the gluon field increases and immediately a new pair  $(q\bar{q})$  of quark-antiquark occurs (figure 2).



Figure 2: Confinement ensures separation of quarks is not possible. By exceeding a distance of about 1 fm, a new quark-antiquark pair emerges due to the increasing energy of the gluon field.

Therefore it is not possible to isolate quarks. The mediating particles of the strong force, the gluons, carry colour-anticolour, so they couple among each other.

## 2 FAIR

FAIR is the new international particle accelerator facility in Darmstadt. It comprises many particle accelerators as well as storage rings and uses the already existing GSI<sup>8</sup>-accelerators as pre-accelerators (figure 3). Main part is a double ring accelerator (SIS<sup>9</sup> 100/300<sup>10</sup>) with a circumference of 1.100 m for protons and ions. At first, protons will be linearly accelerated to 70 MeV in the p-Linac (heavy ions in the Unilac) and then injected to the accelerator SIS  $18^{11}$ . After achieving 2 GeV, the protons will be extracted to the SIS 100, where they are speeded up again, now to 29 GeV (heavy ions up to 2.6 GeV<sup>12</sup>). At lower intensities, the heavy ions can achieve an energy of about 34 GeV/u using the SIS 300 [SMYRSKI 11]. The beams will be delivered to a lot of experimental stations. In bunches of 50 ns the protons from the SIS 100 beam hit a Ni, Ir or Cu target producing antiprotons [KNIE 08]. Afterwards, they are ejected to the CR<sup>13</sup>, collected and injected to the HESR<sup>14</sup>. This procedure will be

<sup>&</sup>lt;sup>6</sup>Uncertainty principle:  $\triangle x = \frac{h}{\triangle q}$ 

<sup>&</sup>lt;sup>7</sup>Only colour neutral states are allowed

<sup>&</sup>lt;sup>8</sup>Gesellschaft für Schwerionenforschung

<sup>&</sup>lt;sup>9</sup>Schwerionensynchrotron

 $<sup>^{10}\</sup>mathrm{Rigidity}$  of 100 Tm and 300 Tm

<sup>&</sup>lt;sup>11</sup>Rigidity of 18 Tm

 $<sup>^{12}</sup>$  Unified atomic mass unit: u =  $1.66053892\cdot 10^{-27}~\mathrm{kg}$ 

<sup>&</sup>lt;sup>13</sup>Collector Ring

 $<sup>^{14}\</sup>mathrm{High}$  Energy Storage Ring

repeated until  $10^{10}$  antiprotons have been accumulated. The HESR improves the quality of the beams evoking energy sharpness and focusing. Two technical modes can be chosen, a high luminosity mode with luminosities up to  $L = 2 \cdot 10^{23} \frac{1}{\text{cm} \cdot \text{s}}$  and a high resolution mode with a relative momentum resolution up to  $\frac{\Delta p}{p} \leq 10^{-5}$ .



Figure 3: The new accelerator facility FAIR (red) in Darmstadt. It is connected to the already existing GSI (blue), which will then serve for pre-accelerating. FAIR increases the intensity of protons and heavy ions by up to two magnitudes.

Luminosity is the ability of a particle accelerator of producing the required quantity of particles N per time and area of interactions  $[cm^{-2}s^{-1}]$ . It is given by:

$$\frac{\mathrm{l}N}{\mathrm{d}t} = \sigma \cdot \mathcal{L} \tag{2.3}$$

 $\sigma$  is the cross section of a certain interaction and given in 1 b=10^{-28}\,\mathrm{m^2}

The special feature of FAIR will be antiproton- and ion beams in a never been before achieved intensity<sup>15</sup> and brilliance<sup>16</sup> [FAIR 14]. Intensity is important to increase the probability of producing rare reactions and their products. For example, heavy elements, which occur in supernova explosions, can appear. Highest brilliance is necessary to determine the mass of

<sup>&</sup>lt;sup>15</sup>Energy per area per time

<sup>&</sup>lt;sup>16</sup>Energy sharpness

short-lived or unstable nuclei [GSI 14]. Also high beam/collision energies will be available, thus highly compressed matter can emerge. Another asset of FAIR is the possibility of operating up to four programs in parallel.

Four major topics will become operational. One is PANDA, besides CBM<sup>17</sup>, the most crucial. Two more are APPA<sup>18</sup> and NuStar<sup>19</sup>. The observation of particles with more than one strange quark, so-called multistrange hyperons, is one goal of CBM [FAIR 09].

Compared to other existing facilities, for example  $\text{RHIC}^{20}$ , having a too high beam energy, that is why  $\text{QGP}^{21}$  can only be produced with less baryonic densities. This part will be fulfilled by CBM. In comparison to positron-electron colliders (like  $\text{BES}^{22}$ ), which can only produce  $1^{--}$ -states, FAIR can produce pairs of hadrons with charm-quarks directly and in all quantum numbers.  $\bar{P}$ ANDA's task is to detect and measure all these particles.

# 3 PANDA

One of the central aspects of FAIR is the  $\bar{P}ANDA$ -experiment investigating objects in the invariant mass range up to  $\sqrt{s} = 5.4 \text{ GeV}/c^2$ . Main focus are studies related to the strong force at medium energy, among others, charmonium spectroscopy for precision measurements of mass, decay branchings and widths, more exotic multiquark states, glueballs and charmed hybrids (in nuclear matter).

At full luminosity,  $\bar{P}ANDA$  will collect thousands of charmonium and open charm states per day in  $\bar{p}p$ -annihilations. Due to fine scans, measurements of mass widths with a precision of 10% or better will be feasible [FIORAVANTI 14].

The circumstance that only 5% of the nucleon mass is created by valence quarks is another part of  $\bar{P}ANDA$ 's investigations. Probably their masses result from the quarks kinetic and interaction energy. Quarks themselves receive their mass from the Higgs boson, but most of the proton's mass is produced by strong interaction, glueballs even get their mass only by strong interaction. Hence, they might be a useful hint for the understanding of mass production. The whole glueball spectrum should be accessible to  $\bar{P}ANDA$  [WIEDNER 14].

By reason of continuous chiral symmetry breaking, some hadronic properties change, if they are being produced in hadronic matter [TPR 05]. Yet, only light quarks were analysed.  $\bar{P}ANDA$  will extend this program to heavier quarks. Furthermore, existing GSI-studies like the study of Generalized Parton Distributions (GPD) as well as the electromagnetic form factors  $|G_E|$  and  $|G_M|$  of the proton in the time-like region will be carried on.

Another investigation objects are hyperons respectively their CP<sup>23</sup> violation that is accessible by hyperon decay products. The asymmetry between matter and antimatter in the universe must have its origin in CP violation.

The  $\bar{P}$ ANDA-detector has to cover a wide performance spectrum. To verify the wide range of physics goals, the detector has to fulfil many requirements: High interaction rate  $(2 \cdot 10^7 \frac{1}{s})$ , solid angle coverage  $(4\pi)$ , good particle identifaction  $(p, e, \mu, K, ...)$ , high momenta resolution  $(\approx 1\%)$  and a momentum range up to 8 GeV/c, a very high vertex resolution and a modular design for different experiments [BRINKMANN 07].

<sup>&</sup>lt;sup>17</sup>Compressed Baryonic Matter

<sup>&</sup>lt;sup>18</sup>Atomic, Plasma Physics and Applications

<sup>&</sup>lt;sup>19</sup>Nuclear Structure, Astrophysics and Reactions

 $<sup>^{20}</sup>$ Relativistiv Heavy Ion Collider

<sup>&</sup>lt;sup>21</sup>Quark gluon plasma

<sup>&</sup>lt;sup>22</sup>Beijing Spectrometer

<sup>&</sup>lt;sup>23</sup>Charge symmetry & Parity symmetry

The detector (figure 4) is divided into two regions: The Target Spectrometer, designed for transverse momentum  $p_t$ , consisting of four main stages:

- Target system: Pellet beam target, cluster beam target or nuclear targets
- Tracking system: Micro Vertex Detector, Central Tracking Detector, Gas Electron Multiplier Stations and Forward Mini Drift Chamber Stations
- Electromagnetic Calorimeter
- Particle Identification: DIRC<sup>24</sup>, TOF<sup>25</sup> and the Muon Chambers

and the Forward Spectrometer for forward tracks consisting of Forward RICH and a Hadronic Calorimeter as well as of Muon Chambers.



Figure 4: PANDA-detector provides two different magnetic field sections: Target and Forward Spectrometer. The Target Spectrometer consists of the Target system, the Tracking System with the MVD and Central Tracking Detector, the Electromagnetic Calorimeter and the Particle Identification Detector with DIRC, TOF and the Muon Chambers.

To obtain a high momentum resolution, the detector possesses two sections with different magnetic field strength: The Target Spectrometer with a magnetic field of 2 T and the Forward Spectrometer with a magnetic field of 0.3 T. The Target Spectrometer is designed for interactions producing trajectories with large angles, the Forward Spectrometer for small ( $\pm$  10° horizontally and  $\pm$  5° vertically). Both parts fulfil complete detection possibilities [SCHWARZ 12]. A Micro Vertex Detector will be placed in the Target Spectrometer around the collision point.

Compared to  $e^+e^-$ -colliders, where only quantum numbers of the photon are available,  $\bar{P}ANDA$  can create all quantum numbers for  $q\bar{q}$  resulting in the complete spectrum of charmonium states.

 $<sup>^{24}</sup>$ Detection of Internally Reflected Cherenkov light

 $<sup>^{25}\</sup>mathrm{Time}$  Of Flight

## 3.1 Target system

Mainly, there will be two different target systems: A cluster target and a pellet target.

**Cluster Target** Substance will be hydrogen, but can be replaced by deuterium or heavier gases. Under certain conditions, condensation can occur that creates nano particles, the clusters. They contain  $10^3$  to  $10^5$  atoms and will be bound by Van der Waals-forces. A cooled gas produces cluster-jets, which are formed to a supersonic beam and led into the antiproton beam.

**Pellet Target** A jet of liquid hydrogen will be led as well into the beam and will be frozen on their way. The pellets consist of frozen hydrogen mircospheres, the pellets. They are produced at 1 m above the collision point and fall down by 60 m/s. Their size is about 20  $\mu$ m to 40  $\mu$ m. Such a pellet will have approximately 100 interactions while passing the beam [BÜSCHER 14].

In both cases the target material will traverse the beam vertically. For this purpose a pipe crosses the beam line. Due to their lack of momentum in beam direction, the targets can be regarded as fixed.



Compared with each other, the pellet target yields a higher maximum density and a better pointlike interaction zone. The cluster target has an adjustable and homogenous target density plus a better time structure, instead. The target consists of two modes:

- High luminosity up to  $L = 10^{32} \frac{1}{\text{cm}^2 \text{s}}$  and  $\frac{\Delta p}{p} = 10^{-4}$  for  $10^{11} \,\bar{\text{p}}$
- High precision with  $L = 10^{31} \frac{1}{\text{c}m^2 \text{s}}$  and  $\frac{\Delta p}{p} = 10^{-5}$  for  $10^{10} \,\bar{\text{p}}$

[PELIZÄUS 07]. Antiprotons that do not hit the target material recirculate in the ring about 500.000 times per second. To guarantee beam intensity and energy, the bunches pass a cooler at every recirculation which compensates certain losses [ORTH 14].

## 3.2 Tracking system

The purpose of the tracking systems is the reconstruction of particle trajectories. Specifically, a trajectory in particle physics represents the direction and magnitude of charged particles

momenta. A very important requirement is a good spatial resolution. In order to achieve this, tracking system detectors are mostly segmented very finely. Together with a few parameters (depending on observed particles and experiments), traversing particles can be identified. The tracking system for PANDA contains four subsystems.

## 3.2.1 Micro Vertex Detector

The Micro Vertex Detector is the very first detector at the collision point. It is designed for the tracking of charged particles and for a very precise determination of secondary decay vertices of short-lived particles, especially optimized for D-mesons and hyperons. Furthermore, a maximum acceptance<sup>26</sup> as close as possible to the vertices is an important aspect and will also increase the resolution of the particles' transverse momentum. Additionally, energy losses of slower particles will be detectable in a small part.

Annihilations using fixed targets cause particle momenta, above all, in forward direction. Therefore, a highly precise resolution is needed especially in this direction. Simulations exhibits that four track points are an ideal number for reconstructing the trajectory [SCHNELL 14]. The detector will provide 3D information of hits according to track and time information. The vertex resolution owns a spatial resolution of  $< 100 \text{ }\mu\text{m}$  as well as a time resolution of  $\leq 6,43 \text{ } \text{ns}.$ 

Figure 6: Micro Vertex Detector as the closest detector to the collision point. Starting from there, traces with different angles to each other can be viewed.

A huge challenge is the hardness protection, which will be 10 MRad in 10 years [WÜRSCHIG 07]. The MVD has a length of 40 cm and a radius of 15 cm [BIANCO 12]. It is meant to cover an angle of about 3° to 150° in the polar region and comprises an inner and an outer part, each consisting of two barrels. The inner part is made of hybrid pixel sensors and the outer part of double-sided strip silicon detectors. In forward direction six discs are planned of which four are pixel detectors and the other two are a combination of pixel and strip detectors (figure 7). Upon the pixel detectors rectangular cells with a size of  $(100 \times 100) \text{ µm}^2$  will be placed and read out individually. Double-sided silicon detectors are semiconductors with readout strips on both sides, which can also be read out individually. By reducing the necessary amount of readout channels, they are of a great advantage. All together 200,000 strip channels will be implemented. Two different layouts are being considered, one for the barrel design and the other for the forward discs.



 $<sup>^{26}</sup>$ Spatial coverage



Figure 7: Micro Vertex Detector of PANDA as part of the target spectrometer. *Left* - The MVD consists out of four barrels [circled] around the collision point and six discs [pictured squared] in forward direction. Pixel detectors are orange and strip detectors green. *Right* - The discs and mechanical stuff highlighted.

The spatial resolution is given by the pitch<sup>27</sup>: It is 45  $\mu$ m for the barrel layout and 70  $\mu$ m for the disc layout. Finally, the spatial resolution amounts to 90  $\mu$ m, because of two pitches: 2.45  $\mu$ m [SCHNELL 14].

A compromise between interaction rate (pixel sensors) and resolution (double-sided strip detectors) is necessary. Actual simulations enable a momentum resolution of

 $\sigma(p) = 1.4\% = \sigma(p_t)$ , a primary vertex resolution<sup>28</sup> of  $\sigma_z \leq 70 \ \mu\text{m}$  and a vertex resolution<sup>29</sup> of  $\sigma_{x,y} \leq 35 \ \mu\text{m}$  as well as  $\sigma_z \leq 100 \ \mu\text{m}$  for a beam direction in z [CALVO 13]. In the ideal case, the MVD influences transmitting particles as little as possible in order to have no effect on subsequent detectors.

The tracking system consists of one more part, the Straw Tube Tracker. It is a cylindrical detector and key part for obtaining momentum of charged particles. Straw tubes are drift tubes and therefore filled with gas, which will be ionised by traversing particles. Electrons produced in this way drift to a wire in the center and the opposing charged ions towards the wall according to an applied voltage. As gas, argon, quenched with 10% CO<sub>2</sub>, will be deployed. Crucial is the circumstance that electrons will cause an avalanche of ionisation. This happens proportionally to the initial charge and can be read out as a signal.

Figure 8: The straw tube tracker detects traversing particles due to their ionisation of the gas atoms inside. The so-produced electrons and ions will be pulled towards the wire and wall. Through a cascade of electrons, caused by an avalanche effect of the freed electrons, signals can be obtained.



 $^{27}\text{Distance between strips}$   $^{28}\bar{\rm p}{\rm p}\mapsto\pi^{+}\pi^{-}$ 

 $<sup>^{29}\</sup>bar{\rm pp} \mapsto D^+D^-$ 

The design is planning layers parallel to the beam axis with interleaved skewed layers. These are arranged with an angle relative to the beam axis of about  $\pm$  3°, so 3D reconstructions of trajectories are possible. The Straw Tube Tracker has an outer diameter of 418 mm. The drift tubes are 15 cm long with a diameter of 1 cm, all together 4636 straws will be used.

Furthermore, two more devices play a role for the endcap and the forward detector. On the one hand a Gas Electron Multiplier station, which operates as a first forward tracking detector. This is done by a large area of planar detectors. Current calculations predict three or four such discs and will provide a resolution better than 100 µm plus unambiguous particle identification. The Straw Tube Tracker cannot detect all particles due to angular reasons. Particles emitted at angles below 22° will be tracked by the Gas Electron Multiplier Station. On the other hand, behind the Gas Electron Multiplier Station, a forward mini drift chamber station analyses momenta of charged particles deflected by the dipole magnet. It consists of three pairs of planar stations: One in front, one behind the dipole magnet and one more inside the magnet gap. The position resolution is expected to be 0.1 mm and 1% of momentum resolution per detection layer [SMYRSKI 14].

### 3.3 Electromagnetic Calorimeter

The tracking system is directly followed by the EMC<sup>30</sup>, measuring energy losses  $\frac{dE}{dx}$  of traversing charged particles. A particle entering such a crystal causes a particle shower, which results in an alternation of  $e^+e^-$ -pairs and Bremsstrahlung. The measured light is proportional to the deposited energy. With the view of determining deposited energy a resolution of  $\frac{\sigma_E}{E} \leq \frac{1.54\%}{\sqrt{E/\text{GeV}}} + 0,3\%$  will be supported. Usually, the shower takes place in several scintillators that is why they are combined in clusters.

Due to high count rates that demand fast response, scintillators will come into action. As scintillator material, lead tungstate<sup>31</sup> of a second generation (PWO-II), has been chosen for its fast response of less than 20 ns and great radiation hardness [NOVOTNY 14]. For the EMC crystals of Lead tungstate will be used with a size of 2 cm x 2 cm x 20 cm. All crystal's openings refer to the middle where the target is located.



Figure 9: Electromagnetic Calorimeter of the Target Spectrometer for obtaining energy losses  $\frac{dE}{dx}$  of traversing particles, especially designed for high count rates. Therefore it consists of 15552 PbWO4 crystals as scintillators which measure the deposited resolution with a resolution of  $\frac{\sigma_E}{E} \leq \frac{1.54\%}{\sqrt{E/\text{GeV}}} + 0, 3\%$ .

In total 15552 PbWO4 crystals will be implemented as a cylindrical barrel, which are split as follows: 11360 crystals for the barrel layout, 592 crystals for the backward endcap layout and

 $<sup>^{30}</sup>$ Electromagnetic calorimeter

 $<sup>^{31}\</sup>mathrm{PbWO}_4$ 

3600 crystals for the forward FSC<sup>32</sup>. In between there is a gap of about 680 µm. Presumably, LAAPDs<sup>33</sup> are chosen for the crystal's readout. The operating temperature is -25 °C at which the light output of the crystals reaches its maximum.

# 3.4 Particle Identification

Particle Identification covers a momentum range of 200 MeV/c to 10 GeV/c. Charged particle identification is done in combination with  $\frac{dE}{dx}$  measurements of the EMC and trajectories of the Tracking System. The following systems are involved:

• DIRC: Covering the tracking system. It measures 3D information consisting of x, y and time of internally reflected<sup>34</sup> cherenkov photons, which are caused by particles traversing quartz<sup>35</sup> slab radiator bars.

Figure 10: The DIRC-detector detects particles which create Cherenkov light. It offers 3D information containing x, y and time with a resolution of 100 to 200 ps.



A mirror is attached at one end of the radiators that reflects the photons backwards to the readout system, which contains many APDs or PMTs [ZIMMERMANN 2011]. The photon detection amounts to 100 - 200 ps. DIRC is splitted into two detectors: One into the Target Spectrometer as a barrel and the other into an endcap disc in the Forward Spectrometer. The barrel has a radius of 50 cm and an expansion volume depth of 30 cm consisting of 80 radiators. They have the following sizes: A length of 2500 mm , a width of 33 mm and a height of 17 mm. The forward disc is made of four pieces, 2 cm thick, with a diameter of 2 m [SCHWIENING 11].

- TOF: A TOF is useful to identify particles. By measuring the time of flight for a certain distance via two signals the mass of a particle can be reconstructed if their momentum is determined by the Straw Tube Tracker. The time resolution is foreseen as 200 ps or better. The two signals could be generated by the MVD and by a scintillator out of the tracking system [ZIMMERMANN 2011].
- Muon Detection System: Cross sections of muons in final states are small compared to background muons. Therefore a very good signal to background ratio is necessary. Meaningful are tracking detectors which will be placed in the clearances of the segmented yoke of the magnet. Together they form a system of altering tracking chambers and absorber films. Muon detection is done corporately with the EMC, Cherenkov and TOF.

<sup>&</sup>lt;sup>32</sup>Forward spectrometer calorimeter

<sup>&</sup>lt;sup>33</sup>Large area avalanche photodiodes

<sup>&</sup>lt;sup>34</sup>Refractive index with:  $n > \sqrt{2}$ 

 $<sup>^{35}</sup>$ Synthetic fused silica

In closing, the interaction of all detectors can be represented as follows:



Figure 11: Subdetectors of PANDA and their purposes. The tracking system (MVD, SST and GEM) offers tracking and vertex information and provides momenta, too. Particle will be identified by the EMC, DIRC, RHIC, TOF and Muon system measuring energy loss, momenta and velocity of particles.

# Part II Fundamentals

# 1 Semiconductor

In general conductors are materials, which can transfer energy. Considering radiation detection semiconductors are of peculiar interest. Semiconductors' conductivity lies between conductors and insulators. Semiconductors are widely used for detecting ionising radiation (charged particles or photons). Radiation causes free charge carriers which travel to the electrodes. Their amount is formed to a signal whose height represents the intensity of the radiation. Semiconductors themselves are classified into four types: Organic, ternary compounds, binary compounds and certain intrinsic materials. The main aspect for the ability of conducting electrons is the specific resistance:

$$\Rightarrow \rho = \frac{R \cdot A}{l} \tag{1.4}$$

To categorise material with respect to conductivity, three types are common (Tab. 2):

Conductors	$\rho < 100 \frac{\Omega \cdot mm^2}{m}$
Semiconductors	$100 \frac{\Omega \cdot mm^2}{m} < \rho < 10^{12} \frac{\Omega \cdot mm^2}{m}$
Insulators	$10^{12} \frac{\Omega \cdot mm^2}{m} < \rho$

Table 2: Classes of conductors

All conductors are usually classified into these. To cast a material into one of these categories, the magnitude of the (isotropic) specific resistance  $\rho$  was used for a long period. This works quite fine as long as the material is homogenous and the material is subject to DC operation.

### 1.1 Electronic band structure

By a quantum mechanical treatment of solid state semiconductors, it turns out that electrons cannot assume every energetic state. Instead, they can only be in specific discrete states. All of them can be described by the electronic band structure. In case of two atoms, which come closer to each other, their energy levels degenerate and split up. Energy levels are eigenstates and belong to specific states. Atoms possess several discrete energy levels represented as follows:

$$E_n = -\frac{Z^2}{n^2} E_R \tag{1.5}$$

for a hydrogen-like atom with  $E_R = hcR_{\infty} = 13,6 \text{ eV}$ when needed, fine and hyperfine structure and lamb shift have to be added

By increasing the number of participating atoms, the level density increases heavily. When atoms are so close to each other that their energy levels overlap, so-called bands come into play. Electrons inside those bands cannot be assigned to single atoms anymore. Mainly in solids, atoms are spaced so closely to cause this situation. The overlap integral is given by:

$$S_{\mu\nu} = \int \phi_{\mu}^{*}(\vec{r}) \,\phi_{\nu}(\vec{r}) \,d\vec{r}$$
(1.6)

with 
$$\phi_i = \sum c_{ri} \chi_r$$
  
where  $\phi_i$  is a molecular orbital,  $\chi_r$  atomic orbitals and  $c_{ri}$  a corresponding term;  $r = 1...n$ 

being a quantity that indicates how much wave functions overlap each other. Furthermore, the width of different energy levels is not similar due to the fact that electrons close to the nucleus experience a higher attraction leading to smaller bands. If bands exist, a valence band and a conduction band will occur, first are still occupied.



Figure 12: Electronic band structure. The higher the number of lattice atoms the more the energy levels overlap and finally smear out to a so-called band. Electrons can jump more easily from the valence into the conduction band due to decreasing distance (green arrow).

The probability an energy state is occupied by an electron with a given temperature is provided by:

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$
(1.7)

k for the Boltzmann constant

using the Fermi energy:

$$E_F = \frac{\hbar^2}{2m} \left(3\pi^2 n\right)^{\frac{2}{3}}$$
(1.8)

with the reduced Planck's constant  $\hbar = \frac{h}{2\pi}$ , the particle density  $n = \frac{N}{V}$  (N = amount, V = volume) and the particle mass m

Expression 1.7 can be separated for electrons and holes, in cases  $E_F$  lies in the band gap which should satisfy  $E_G \ge 6kT$  [LUTZ 01]. Therefore, f(E) splits into

$$f_n(E) \simeq e^{-\frac{E-E_F}{kT}} \tag{1.9}$$

for electrons and for holes into:

$$f_p(E) \simeq 1 - f_n(E) \tag{1.10}$$

The Fermi energy (not to be confounded with the Fermi level which indicates a probability of 50% of occupation for an energy level under equilibrium conditions) is the highest energy a particle can have in a system that stays in its ground state. In case of semiconductors the highest band completely filled is the upper band limit of the valence band. The density of states for electrons in the conduction band is given by

$$\rho(E) = \frac{8\pi\sqrt{2}}{h^3} m^{3/2} \sqrt{E}$$
(1.11)

If states are initially occupied of a certain energy (for example  $E_c$  for the conduction band), then:

$$\rho(E) = \frac{8\pi\sqrt{2}}{h^3} m^{3/2} \sqrt{E - E_c}$$
(1.12)

with  $E_c$  as the lowest energy in the conduction band, m for the electron mass (for  $E < E_c$  it turns to zero)

is applied. Valence electrons are located in the most distant orbitals and can form bonds. Conduction and valence electron wave functions are described by the Bloch function:

$$\Psi_{nk}\left(r\right) = e^{i\vec{k}\vec{r}}u_{nk}\left(\vec{r}\right) \tag{1.13}$$

with **k** as a wave vector and **n** as a band index

The Bloch functions are eigenstates of the Schrödinger equation:

$$-\hbar^2 \frac{\partial^2 \psi}{\partial x^2} = \hbar^2 k^2 \psi \tag{1.14}$$

for  $\psi = e^{i(kx-\omega t)}$  and  $k = \frac{n\pi}{L}$  with n = 1,..n and L for a geometric length

with a periodical potential. Only electrons in the conduction band cause conductivity. Most of the conductors are metals (except for graphite and for a few chemical compounds), in which the Fermi energy usually lies at the lower edge of the conduction band, lacking the need of an excitation to participate in conduction.



Figure 13: Various conductor classes. In conductors, the valence and conduction bands overlap in which area the Fermi energy lies. Therefore valence electrons can contribute to conductivity. In semiconductors, the Fermi energy is above the valence band, which is separated from the conduction band by a band gap. Semiconductor's electrons can jump therefor example because of light and temperature influences. Insulators have a much higher band gap, so for them it is mostly not possible to lift electrons into the conduction band.

It is important to know which bands are occupied. Unoccupied (in lack of free charge carriers) and fully occupied (in lack of free available states) bands do not contribute to the charge transport.

#### 1.2 Band gap

Since the valence and conduction band do not merge in semiconductors, there is an open area between, called band gap. It's dimension represents an energy  $E_G$ . In semiconductors the Fermi energy is not located inside the conduction band, therefore a certain energy is necessary to shift electrons out of the valence band into the conduction band. This is, for example, possible by light absorption  $E_{\gamma} > E_G$  or thermal excitation. At T = 300 K few semiconductors possess intrinsic conductivity, so they can conduct on their own. This means, electrons of the valence band can be lifted up into the conduction band due to thermal influences. The energies of band gaps depend slightly on temperature and result out of the atoms' vibrations which rise with temperature. The dependence of a semiconductor to become conductive is provided by Eq. 1.7. The band gap energy is given by the Varshni relation [DONNELL 91]:

$$E_G(T) = E_G(0) - \frac{\alpha T^2}{T+\beta}$$
(1.15)

where  $E_G(0)$  is the bandgap at 0K,  $\alpha = 4,73 \cdot 10^{-4} \text{ eV/K}$  and  $\beta = 636 \text{ K}$  are material constants

At room temperature silicon has a band gap of 1.12 eV and at 0 K a bang gap of 1.17 eV [SZE 07]. Additionally the band gap can be expressed by the energy bands:

$$E_G = E_C - E_V \tag{1.16}$$

In insulators the band gap is too high (> 4 eV) hence electrons cannot jump into the conduction band. Additionally, insulators do not have free charges. Thus, they are not able to conduct currents. Furthermore, band gaps can be direct or indirect ones. In addition, because silicon is a so-called indirect semiconductor, phononic excitations are necessary to bridge an electron from the valence into the conduction band.

Figure 14: Direct and indirect band gap as open area between the valence and conduction band. If the wave vector  $\vec{k}$  is equal for both, then there will be a direct band gap transition, otherwise there will be an indirect band gap transition.



This is due to the fact that the minima of the conduction band is displaced with respect to each other in k-space from the maximum of the valence band. Their energy bands are defined by a certain lattice momentum  $\vec{k}$  from  $\vec{p} = \hbar \vec{k}$ . If they coincide, then it will be a direct band gap transition, otherwise it will be an indirect one. The main principle is the opportunity to

crystallise, especially to mono crystals. Mono crystals are arranged in a way that a sample of lattice is periodic repeatable. Lack of deviations or defects alter their properties beneficially according to optic and electric properties. The structure of crystals is described by lattice and basis. The latter is the smallest unit, which is repeated multiply to build up a single crystal, whereas the lattice specifies how the basis is arranged. In  $\mathbb{R}^3$ , this is done by fourteen different so-called "bravais lattices".

### 1.3 Silicon

As material for semiconductors, silicon is predominantly used. After oxygen, silicon is the material that is the most prevalent on earth and to a great extent thermally stable. In contrast to other materials, for example germanium and GaAs, which are significantly more conductive, it is easily possible to cover silicon with an insulating oxide layer. Silicon is the most resistant material against radiation damage and is widely used in sectors like computer (Wafer) and energy industry (Photovoltaic), therefore a huge knowledge about it is available. It is important that silicon is produced highly pure to ensure free charge carriers do not contribute to conductivity, mostly done by the Czochralski-method or float-zoning developed at Bell Labs.



Figure 15: Single crystal structure of silicon. It will build up a tetrahedron for symmetry reasons.

As part of the fourth group in the periodic system, silicon possesses four valence electrons. It has 2 s and 2 p electrons, which then hybridise to 4 sp<sup>3</sup> orbitals. If silicon is surrounded by other atoms with four valence electrons, for example, silicon, too, then it will build homopolar bonds in different directions, achieving that electrons will not be shifted or even transported. For symmetry reasons, the structure will be a tetrahedron and for simplifying reasons, only the planar structure will be considered from now on. It resembles as follows:

Figure 16: Crystal lattice of Silicon. All valence electrons participate in bonds. This is due to nature's ambition to achieve noble gas configuration.



# Doping

High-purity silicon is completely nonconductive (at T = 0 K). When temperature increases, bonds will eventually break and liberate electrons contributing to conductivity. Another possibility to gain conductivity is doping. Doping describes the procedure of adding a very small amount (1 to 100 ppm) of different atoms, like arsenic or gallium, to the pure lattice (figure 17). By doping with new atoms, two scenarios are arising:

- n(egative) type: Atoms with five valence electrons, one more than silicon, provide an additional respectively a quasi-free electron.
- p(ositive) type: Atoms with three valence electrons, one less than silicon, lack the possibility of achieving noble gas configuration, so one bond is missing, also called a "hole".

The n-types are called donors, because of their additional electron, and the p-types are called acceptors, because of their missing electron. By applying a voltage to the crystal, the holes act very similar to real charges. The kind of doping has a consequence for the type of major and minor charge carriers. In n-type the major charge carriers are electrons and minor charge carriers are holes. In case of p-type, it is vice versa.



Figure 17: Doped silicon. On the left side a n-type semiconductor (doped with arsenic) is shown, and on the right side a p-type semiconductor (doped with gallium).

Semiconductors without any additional doping are called intrinsic semiconductors. Doping produces new energy levels due to a shift of the Fermi energy. In n-type there are new levels closer to the conduction band, and in p-type closer to the valence band.



Figure 18: New energy levels are added due to impurity of the lattice. For n-type, the electrons can jump onto extra levels below the conduction band, and for p-type, the holes move into the new level above the valence band.

Doping changes electric properties, above all the conductivity. At room temperature, the average mobility (see 1.4 Carrier drift velocity) of electrons in intrinsic silicon (doping  $10^{16}/cm^3$ ) is  $1400 \frac{cm^2}{Vs}$  and  $450 \frac{cm^2}{Vs}$  for holes [URI 05].



Figure 19: Electron drift mobility versus donor density (phosphorus) and hole drift mobility versus acceptor density (boron) at a given temperature of T = 300K on silicon.

In general electrons are faster than holes (Eq. 1.20).

#### 1.4 Carrier drift velocity

The motion of a carrier depends on several aspects. When an electric field is applied to the crystal, the electrons stop moving randomly, following the electric field's direction. They move to the positive electrode, and holes to the negative one. The higher the potential the faster their movement according to  $\langle v \rangle \propto E$ . The electron mobility  $\mu$  is defined as

$$\langle \vec{v} \rangle = \mu E , \qquad (1.17)$$

which indicates the speed of an electron moving in an electric field. The force a charge feels is given through the electric field by:

$$F = qE \tag{1.18}$$

On the basis of the definition of force  $\vec{F} = \frac{d\vec{p}}{dt} \triangleq \frac{d(m \cdot \langle \vec{v} \rangle)}{dt}$  it now appears:

$$\frac{\mathrm{d}\left(m\cdot\left\langle \vec{v}\right\rangle\right)}{\mathrm{d}t} = qE \tag{1.19}$$

$$\langle \vec{v} \rangle = \frac{qE}{m^*} \cdot \tau \tag{1.20}$$

 $m^\ast$  is the effective mass

Time t is set to  $\tau$ , which shall represent the time for travelling until an electron collides with an atom. This collision time can be expressed as:

$$\tau = \frac{\mu m}{e} \tag{1.21}$$

[KASAP 05]. The reason why the electrons' velocity differs from the holes, is for the most part that electrons possess less effective mass. It is figured out in Eq. 1.20 that velocity depends on the effective mass inversely. Electrons can only receive energy for conducting, if they are very close to the Fermi energy [FÖLL 14]. The corresponding velocity is given by:

$$\Rightarrow v_F = \left(\frac{2E_F}{m}\right)^{1/2} \tag{1.22}$$

#### **1.5** Carrier concentration

Under equilibrium conditions there is a hole p for every free electron n. Using the law of mass action yields for the charge carrier concentration:

=

$$n = p = n_i$$

$$\Rightarrow n \cdot p = n_i^2$$
(1.23)

specifying:

$$n_0 = N_c e^{(E_F - E_c)/k_B T} \qquad p_0 = N_v e^{(E_v - E_c)/k_B T} \qquad (1.24)$$

with the effective densities of state  $N_c$  and  $N_v$ 

Assuming Eq. 1.23 is true, then:

$$\Rightarrow n_i = N_c e^{(E_i - E_c)/k_B T} \tag{1.25}$$

$$= N_{\nu} e^{(E_{\nu} - E_{i})/k_{B}T} \tag{1.26}$$

Rearranging yields:

$$N_c = n_i e^{(E_c - E_i)/k_B T} (1.27)$$

$$N_v = n_i e^{(E_i - E_v)/k_B T} (1.28)$$

In silicon at room temperature T = 300 K, the effective density of the conduction band amounts to  $N_c = 2.82 \cdot 10^{19} \frac{1}{cm^3}$  and for the valence band to  $N_v = 1.83 \cdot 10^{19} \frac{1}{cm^3}$  [ZEGH-BROECK 11]. Putting Eq. 1.28 and 1.27 into Eq. 1.25 offers [LEE 03]:

$$n_{0} = n_{i}e^{((E_{c}-E_{i})+(E_{F}-E_{c}))/k_{B}T}$$
  
=  $n_{i}e^{(E_{F}-E_{i})/k_{B}T}$  (1.29)

$$p_{0} = n_{i}e^{((E_{i}-E_{v})+(E_{v}-E_{c}))/k_{B}T}$$
  
=  $n_{i}e^{(E_{i}-E_{c})/k_{B}T}$  (1.30)

This implies for the conductivity [FÖLL 14]:

$$\sigma = q \left( n_o \cdot \mu_e + p_0 \cdot \mu_h \right) = \frac{1}{\rho}$$
(1.31)

By means of the electric Field  $\vec{E}$ , the drift current density can be achieved:

$$\vec{j} = \vec{j_p} + \vec{j_n}$$

$$= \sigma \vec{E}$$

$$= q (n_o \cdot \mu_e + p_0 \cdot \mu_h) \vec{E}$$
(1.32)

From 275 K to 325 K measurements for intrinsic silicon were taken and put into an empirical fit [MISIAKOS 93]:

$$n_i = 9,15 \cdot 10^{19} \left(\frac{T}{300}\right)^2 \exp\left(-\frac{6880}{T}\right) \frac{1}{\mathrm{c}m^3} , \qquad (1.33)$$

which looks as follows:



Figure 20: Empirical fit from Eq. 1.33 represented in a range from 275 K to 325 K for the concentration of free charge carriers in intrinsic silicon.

At room temperature the concentration is  $n_i = 1.00369^{10} \frac{1}{\text{cm}^3}$ , according to Eq. 1.33.

#### **1.6** P-N Junction

Even doped semiconductors are not charged in their initial situation. By connecting a p- with a n- type, diffusion stimulates a current close to the junction caused by a difference between the concentration of charge carriers in both types as a result of thermal energy (figure 21). Electrons are going to merge with holes and vice versa (recombination). Electrons, abundant in the n-type region, are more present than within the p-type region, so they begin to spread to the p-type region. This behaviour is expected for holes as well but to the n-side. Both are going to drift towards the opposite junction zone, causing a surplus of electrons in the p-zone as well as a surplus of holes in the n-zone. All this results in building up an electric potential, called diffusion voltage, which opposes the charge carrier motion:

$$V_d = \phi_n - \phi_p \tag{1.34}$$

with  $\phi_{n,p}$  for the potential field of the n- and p-region

A p-n junction is the arising region by combining two semiconductors being still neutral electrically, therefore lacking any free charge:

$$n + N_A = p + N_D \tag{1.35}$$

with  $N_A$  for the number of ionised acceptors and  $N_D$  for ionised donors

The conduction band possesses different energy levels for both zones, which is usually lower in the n-zone than in the p-zone and the same for the valence band. Donotors create new conduction energy levels for electrons below the initial conduction band, and acceptors new conductive energy levels for holes above the initial valence band (figure 18).



Figure 21: By connecting a p-type region with an n-type region a so-called p-n junction will emerge. Free charge carriers will move to the opposite region to recombine building up a space charge region. This causes a potential difference of approximately 0.7 V for silicon. Further charge carriers cannot recombinate any more.

Connecting a p- with a n-zone entails a deflection of their energy bands merging to each other (figure 22). Distinctive for the p-n junction is that the Fermi level is adjusted at the same height on both sides of the boundary layer in consequence of a thermodynamic equilibrium. Free electrons in the n-zone prefer to stay close to the conduction border, so they cannot move into the energetic higher conduction band of the p-zone, vice versa the holes. The p-n junction is conductive or nonconductive depending on an applied voltage. Therefore the height of the potential barrier depends on it, too.



Figure 22: The p-n junction, seen in the band model. By connecting the p- with the n-zone the Fermi level of the p-zone aligns with the Fermi level of the n-zone. The energy bands of both regions will bend within the p-n junction. Electrons can be lifted into the conduction band due to thermal reasons.

Additionally, the depletion width can be influenced in this way relative to the sign of current (figure 23). If the n-zone is filled up with further electrons, they will travel towards the p-region (forward biasing). The p-n junction becomes narrow. If the n-zone is connected to a positive voltage, the electrons will not drift towards the p-zone, but will be pulled away from the junction zone (reverse biasing) widening up the p-n junction zone. No current is flowing and this state will be called "dynamic equilibrium". Dynamic because of a permanent generation of minority carriers due to thermal excitations. The so-called generation rate is given by:

$$G_{th} = \frac{n_i}{\tau_g} \tag{1.36}$$

#### $\tau_G$ for generation lifetime

With this definition, the recombination rate is obtained through:

- $R = \frac{p}{\tau_{r,n}}$  for n-material
- $R = \frac{p}{\tau_{r,p}}$  for p-material,

where the lifetime is also subject to other parameters [ROSSI 06].



Figure 23: Left - In case of a forward biasing voltage, the electrons spread to the opposite region because of a different kind of doping causing a narrow p-n junction. Right - In case of reverse biasing voltage, the charge carriers are pulled outwards resulting in a wide p-n junction.

This mechanism can be used to make sure that the current is passing in one direction only. This construction constitutes a diode. A voltage that decreases the junction zone is called a forward biasing voltage. Without any external voltage, the junction builds up a potential of about 0.7 V for silicon. If there is a lack of charge carriers in the p-n junction, it is called a depletion zone. If the zone extents through the whole volume, it will be called further a full depletion zone.

### 1.7 Depletion width

To get an analytical expression of the depletion width, a Poisson equation in one dimension has to be solved:

$$\frac{\partial^2\left(\phi\right)}{\partial x^2} = -\frac{\rho}{\varepsilon_0} \tag{1.37}$$

with  $\rho$  for space charges and  $\varepsilon_0 = 8.854187817 \cdot 10^{-12} \frac{F}{m}$  for the vacuum permittivity

The Poisson equation describes the presence of space charges. In the absence of space charges  $(\rho = 0)$  the Poission equation Eq. 1.37 simplifies to the Laplace equation:

$$\Delta \phi = 0 \equiv \vec{\nabla} \cdot \vec{E} \left( r \right) \tag{1.38}$$

with  $\vec{\nabla}$  for the spatial-partial derivation operator

Thus,

n-side: 
$$E_n(x) = \frac{qN_D}{\varepsilon_0\varepsilon_r}x_n$$
 (1.39)

p-side: 
$$E_p(x) = \frac{qN_A}{\varepsilon_0\varepsilon_r}x_p$$
 (1.40)

is obtained. Right at the junction they merge into each other as follows:

$$E(x) = \frac{qN_D}{\varepsilon} x_n = \frac{qN_A}{\varepsilon} x_n \tag{1.41}$$

The depth of one region is thereby:

$$x_n = \varepsilon \frac{E_n(x)}{qN_D} \tag{1.42}$$

$$x_p = \varepsilon \frac{E_p(x)}{qN_A} \tag{1.43}$$

This results the in the total depletion width:

$$x_n = \sqrt{2\varepsilon \frac{\phi N_D}{q \left(N_D + N_A\right) N_A}} \tag{1.44}$$

$$x_p = \sqrt{2\varepsilon \frac{\phi N_A}{q \left(N_D + N_A\right) N_D}} \tag{1.45}$$

For the complete zone under equilibrium conditions,

$$x = x_n + x_p$$
  
=  $\sqrt{\frac{2\varepsilon\phi}{q} \cdot \frac{(N_A + N_B)}{N_D N_A}}$  (1.46)

is achieved. In case of asymmetric doping, for example  $N_A \gg N_D$ , Eq. 1.46 simplifies to:

$$x = \sqrt{\frac{2\varepsilon\phi}{qN_D}} \tag{1.47}$$

[LUTZ 01]. The depletion width depends on the applied voltage and the doping concentration. The broader the depletion zone the more charges will be concentrated at both electrodes. This can be seen as a capacitance according to:

$$C = \frac{\varepsilon_0 \varepsilon_r}{x} A \tag{1.48}$$

#### **1.8** Silicon detector

Silicon detectors have a massive influence on high energy physics detector design due to their excellent ability tracking charged particles. Compared to gas detectors, silicon detectors share the same principle of detection via ionisation, but exhibit a lower ionisation energy threshold and a higher spatial resolution. Particles, especially charged particles, traversing matter will certainly knock off electrons from atom shells producing a track according to their passage. Silicon detectors are based on semiconductors. The use of them as a spatially resolving system was first done by E. Belau et. al. in 1983 [BELAU 83].

Prerequisite is a P-N junction operated in reverse biasing at full depletion lacking free charge carriers. Irradiated with light, electron-hole pairs will be generated in the space-charge region and separated by the electric field. A traversing particle can force an electron to jump from the valence band into the conduction band, when its energy is sufficient high. This energy is composed of the band gap energy and, as a consequence of the indirect band gap (see "1.2 Band gap"), of the phonon creation energy. The ionisation energy of silicon amounts to 3.6

with A for the area of the capacitance

eV [SPIELER 05]. At T = 300 K, the band gap energy is 1.12 eV, therefore the necessary energy part for phonon creation must be the missing part. At the same time, the wrested electron in turn leaves a hole in the valence band, which will be occupied by an electron next to it. This procedure will be repeated as a chain reaction. An electron now being in the conduction band will be dragged to the positive electrode according to an applied electric field. Holes will move in opposite direction to the negative electrodes. Typically, particles will ionise many atoms while traversing.



Figure 24: Traversing charged particle ionises an atom. The liberated electrons are pulled to the positive electrode and leaves a hole, which is filled by a nearby electron causing a chain reaction of such displacements.

The depletion width depends on the doping concentration according to Eq. 1.46. If the pand the n-zone have a similar doping concentration, then the depletion zone is quite thin and only located at the frontier of both. The p-strips  $(\rightarrow p^+)$  have a higher doping concentration than the n-bulk, therefore the depletion width increases and extends widely into the n-bulk. However, the complete n-bulk has to be depleted to measure traversing particles.

#### 1.8.1 Construction of Si-detectors

For tracking purposes silicon detectors are mainly built in two ways: Pixel detectors and strip detectors, the major distinction being the spatial resolution versus the required readout channels. The former possesses usually a better spatial resolution and the latter less readout channels. Strip detectors consist of a high-ohmic n-type bulk and parallel strips of p-regions above, creating the p-n junction. Furthermore, segmented aluminum electrodes are attached on one side on the surface. The distance in between is called pitch determining the spatial resolution. In case of one-sided strip detector the complete back is covered with an aluminum contact.



Figure 25: Charged particles will cause a current flow in two directions according to an applied electric field between the  $n^+$ -backside-electrode and the  $p^+$ -strips. One main aspect of a silicon detector is the pitch (distance from strip to strip).

An electric field applied between the  $p^+$ -strips and the  $n^+$ -backside-electrode depletes the bulk of free charges and causes charge carriers to move to their adequately nearest readout electrodes for detection. Holes will move to the  $p^+$ -strips and electrons to the  $n^+$ -back. Crystal defects at edges can cause large leakage currents. A guard ring made of a  $p^+$ -strip surrounds the surface absorbing these currents. Additionally, more features are implemented. A bias ring ensures that all the electrodes have the same potential. With respect to readout purposes, two different coupling methods exist:

- DC: Strips are connected directly to an amplifier. Sensor-manufacturing is easier, but amplifier-manufacturing is more complicated. Furthermore, leakage currents will flow through the connected electronics.
- AC: Strips are connected indirectly to an amplifier via series capacitors. Attaching capacitors onto sensors is not that trivial. In case the bias-voltage collapses, capacitors will protect the electric inputs of HV-supply. Leakage currents do not flow into the amplifier.

These two methods determine the design. DC-coupling possesses an alternating structure of strips and insulating layer. The insulating layer has repetitive notches, wherein the strips are being implemented. In case of AC-coupling, there will be a continuous insulating layer (figure 26) and capacitors will be integrated. The insulating layer is made of  $SiO_2$  and typically 100-200 nm thick representing a dielectric. Complications will occur if gaps exist in the dielectric ("pinholes") allowing large leakage currents to flow. Furthermore, readout chips are bonded directly to the channels. Today's standard is the use of AC-coupling [LIST 07].



Figure 26: A strip detector with several features (AC-coupling).

The bias line is attached perpendicular to the strips and consists of a  $p^+$ -implant, too. To connect the bias-voltage, there are several options: One method is to use built-in resistances of poly-crystalline silicon between the bias line and  $p^+$ -strip, another option is to see the  $p^+$ -bias line, the n-bulk and the  $p^+$ -strip as a p-n-p field-effect transistor. Then, by applying a negative voltage, one p-n junction is in forward direction and the other in back direction. The latter is build up by the bias line and the n-bulk. An increasing of the voltage extends the depletion width of the p-n junction in back direction. If this depletion width reaches to the strips the corresponding voltage will be called punch through bias.

Figure 27: The bias line, providing the bias voltage, ensures all strips respectively all electrodes possess the same potential. Readout can be done in two ways: DC- and ACcoupling. The latter has enforced nowadays.



#### 1.8.2 Tracking

Silicon detectors may exhibit a one-sided or a two-sided strip layout. Coordinates of traversing particles are measured in one dimension perpendicular to the strips. Two sided-strip sensors have the advantage of measuring both coordinates simultaneously but also have the disadvantage of being more expensive. By using double-sided microstrip detectors the back has to be segmented, too, but perpendicular to the topside providing two-dimensional measurements. In between each  $n^+$ -strip a floating  $p^+$ -strip is implemented due to isolation reasons, so-called  $p^+$ -stops. They help avoiding fixed oxide charges at the Si-SiO<sub>2</sub>-transition which in turn collect electrons of the n-bulk causing a short circuit between the electrodes.



Figure 28: Measuring two coordinates goes hand in hand with a better tracking capability. Therefore both sides are segmented with electrodes which are perpendicular to each other.  $p^+$ -stops between the strips avoid a short circuit due to fixed oxide charges.

Compared with pixel detectors strip detectors can create fake events appearing through multiple simultaneous tracks.



Figure 29: The tracking of a strip detector (left) compared to a pixel detector (right). Pixel detectors lack of the circumstance measuring fake events (so-called Ghosts) emerging by simultaneous tracks.

*n* hits lead to *n* x-coordinates and *n* y-coordinates, therefore there are  $n^2$  combinations. The number of ghosts  $n_{gh}$  can be offered by  $n_{gh} = n^2 - n$ . To obtain the trajectory of an ionising particle its hit positions has to be detected within the n-bulk. In the first order the position resolution is determined by the geometry of the electrodes and even more by the electrode pitch, than the electrode widths. The differences between measured and real positions have a Gaussian distribution according to:
$$\sigma^{2} = \int_{-p/2}^{p/2} \frac{x^{2}}{p} dx$$
  
=  $\frac{p^{2}}{12}$  (1.49)

by integrating from the middle of a strip to the middle of a neighbour strip [SPIELER 05]. The position resolution then is:

$$\sigma = \frac{p}{\sqrt{12}} \tag{1.50}$$

The spatial resolution is limited by charge collection of transverse diffusion and knock-on electrons. The simplest case will occur if only one channel responds, being just a digital information. If more than one strip responds some aspects will have to be considered: Lorentz-angle (in case of a magnetic field), diffusion (a space-charge cloud spreads activating adjacent strips), skewed passing and capacitive charge division between neighbouring strips.



Figure 30: If a particles traverses skewed then several electrodes will collect the charge. Taking into account the height of the amplitude and position of the collected charge the trajectory can be reconstructed.

Diffusion extending the space charge cloud is offered by:

$$\sigma_D = \sqrt{2Dt} = \sqrt{2\left(\frac{kT}{e}\mu\right)t}$$
(1.51)

with  $\mu$  for the charge carrier mobility, T for the temperature, e for the elementary charge and k for the Boltzmann constant

[KRAMMER2009]. Capacitive charge division occurs in cases the pitch exceeds the space charge cloud decreasing the position resolution. One solution for further improving position resolution is implementing additional strips without readout connection of these intermediate strips. Charges are still measured by all electrodes, but non-connected strips transfer their charges to neighbouring connected strips. The increased capacitive smeared hit width increases the position resolution. Condition is, that the amplitude h of collected charges is measured instead of only the binary hit information of the strips. Determining the centre of gravity of measured charges yields the position of the particles:

$$x = x_1 + \frac{h_2}{h_1 + h_2} (x_2 - x_1)$$
(1.52)

for two strips, positioned at  $x_1$  and  $x_2$ . In case of a magnetic field the Lorentz force:

$$F_L = qvB$$
  

$$F_L = q\mu EB$$
(1.53)

has to be taken into account considering the drift velocity v of the charge carriers.



Figure 31: A magnetic field will distract the charge carriers due to the Lorentz force. Then the Lorentz angle has to be considered.

The force acting is then:

$$F = \mu_H B \tag{1.54}$$

with the hall mobility  $\mu_H$ 

comprising the Lorentz force  $F_L$  and the electric force  $F_E$ .

#### 1.8.3 Signal production

Of interest is the deposited energy, which is, ideally, proportional to the total charge measured. Not the charge itself is measured, but the current is. The charge is the time integral of the current so a charge-sensitive preamplifier produces an output pulse of a certain voltage which is proportional to the collected charge. Then, this output will be shaped and bandpass filtered increasing the signal-to-noise ratio (SNR). Finally, a multichannel analyser receives or ADC all shaped and amplified pulses (corresponding to the deposited energy) and generates a histogram of number of pulses with their amplitudes in each channel [REDUS 07].



Figure 32: The electrodes measures currents which will be converted into charges by a preamplifier. Afterwards, this output will be shaped and bandpass filtered. Lastly, a multichannel analyzer or ADC generates a a histogram.

Important aspect is a as high as possible SNR leading to two conflicting requirements:

- High signal: Low ionisation energy given by a small band gap
- Low noise: Few charge carriers as a result of a large band gap

For one thing the noise is given by the leakage current: Thermally produced  $e^-h^+$ -pairs, their number rising with the depletion width respectively with the applied voltage. The time for detecting particles is limited by the drift velocity  $\langle \vec{v} \rangle$  of the charge carriers and, additionally, by the read out. Assuming a bias voltage of 100 V and typically 300 µm bulk thickness, and an electric field in the center is  $E \approx 1.5 \cdot 10^5 \frac{V}{m}$  and the drift velocity for electrons  $\langle \vec{v} \rangle = \mu E = 21,000 \frac{m}{s}$  (see "1.5 Carrier drift velocity"). Thus, the electrons need approximately 7 ns to reach the electrodes. Holes, in comparison, need approximately 23 ns.

For another thing noise is also given by the amplifier, which is dominant.

## 2 Laser

Lasers have been a very useful tool since their development and, nowadays, they can be found everywhere, from supermarkets (barcode) over entertainment (data discs) to science labs (measurements, research) and to many others. Lasers signify Light amplified stimulated emission of radiation. This term describes the principle very well and will be covered below. Lasers are a technical device, precisely light sources with definite properties. They differ from other light sources in the following aspects: High intensity and brilliance<sup>36</sup>, coherence<sup>37</sup>

 $<sup>^{36}</sup>$ Energy per wavelength range:  $B \sim \overline{E/\left(\frac{\Delta\lambda}{\lambda}\right)^{-1}}$ 

 $<sup>^{37}\</sup>mathrm{Fixed}$  phase relation

and low divergence.

At first, light is introduced. It is of a dual nature<sup>38</sup> depending on the observation's context. Photons are electromagnetic radiation with no mass and no electric charge. Furthermore, their velocity amounts to the speed of light and their energy corresponds to  $E = h\nu$ . The power density distribution of laser beams with good beam quality form Gaussian profiles. Laser beams have a transversal profile of a Gaussian curve and a longitudinal Lorentz profile.



Figure 33: Profile of a laser beam, which is described transversely by a Gaussian and longitudinally by a Lorentz profile. The radius depends on the distance to the beam waist.

The radius of a Gaussian beam propagating along the z-direction is:

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \tag{2.55}$$

starting from the beam waist  $\omega_0$ . Gaussian beams possess a position at which they have their narrowest cross sectional area. The Rayleigh range:

$$z_R = \frac{\pi \omega_0^2}{\lambda} \tag{2.56}$$

describes the distance a laser beam needs to double the cross sectional area seen from the beam waist along the optical axis. The following single components are important for operating: Active laser medium, optical pumping respectively population inversion and optical cavity.

Atoms are polarisable. The light field induces an electric dipole moment within the atom with which the light acts in turn. In homogeneous fields, a dipole experiences only rotations, but in inhomogeneous fields a force acts, too. This can be understood as a momentum transfer. In virtue of throwing power, net momentum is not transferred to the atom, because it emits a photon in the same direction as the absorbed one. A time varying dipole moment with the according quantum is  $m = 0, \pm 1$  and implies an absorption or emission of electromagnetic radiation.

## 2.1 Population inversion

Population inversion is a necessity for lasers. Of peculiar interest are the parameters  $\Omega$ , s and  $\gamma$ , which will be explained in detail now by assuming a laser intensity of  $I = \frac{1}{2} \varepsilon_0 E_0^2 c$ . In

 $<sup>^{38}\</sup>mathrm{Wave-particle}$  duality

a two-state quantum system according to laser influences, the Rabi-frequency  $\Omega$  represents the fluctuation of a state becoming populated or unpopulated:

$$\Omega = -\frac{eE}{\hbar}\hat{\epsilon} < e|\vec{r}|g>$$
(2.57)

In other words,  $\Omega$  is the measure for the coupling strength between a laser field and an atom. Atomic electron transitions might take place and depend on the light field's frequency. Therefore it is necessary to obtain an expression for frequencies deviating from it:

$$\Omega' = \sqrt{|\Omega|^2 + \delta^2} \tag{2.58}$$

with  $\delta = \omega_L - \omega_{eg}$  for laser detuning. The transition linewidth  $\gamma$  yields the quantity of emitted photons per second:

$$\gamma = \frac{s_0}{2(1+s_0)} \tag{2.59}$$

For spontaneous transitions  $\gamma$  simplifies to  $\gamma = 1/\sigma$  with the lifetime  $\sigma$ . s is a saturation parameter and describes the measure of population density :

$$s = \frac{s_0}{1 + (2\delta/\gamma)^2}$$
(2.60)

by means of the on-resonance saturation parameter [RIEGER]:

$$s_0 = \frac{I}{I_s}$$
(2.61)  
with  $I_s = \pi hc \left(3\lambda^3 \tau\right)^{-1}$ 

In case of a partial or of a full saturation, the transition spectral line changes according to  $\Delta \omega_s = \Delta \omega_0 \sqrt{1+s_0}$  because of altering the occupation number. Laser intensities with  $I \gg I_s$  can create maximal equal population between ground state and excited state. A laser works by having more atoms in excited than in ground states. This is called population inversion, enabled by so-called three-level lasers in which a third energy level exists. A transition from the highest level, the third, into the second is much faster than from the second into the first, the lowest. The frequency of monochromatic light can be represented as:

$$\omega_{eg} = \frac{E_e - E_g}{\hbar} = \omega_L , \qquad (2.62)$$

which lasers can produce very well.

#### 2.2 Active mediums

Active mediums ensure atomic electron transitions producing light. If a photon strikes an atom with a definite wavelength, it will displace an electron further away from its orbital known as excitation. After a determined decay time, the atom falls back to the ground state. Rising and falling is associated with light absorption and emission. Last can be done in two ways: Spontaneous and stimulated emission. Stimulated emission was described as an inversion of absorption by Albert Einstein in 1916, and twelve years later, experimentally discovered by Rudolf Ladenburg.

The capability of an atom to absorb or to emit electromagnetic radiation is given by the transition dipole moment:

$$\mu_{jk} = e \left\langle e | \varepsilon \cdot \vec{r} | g \right\rangle \tag{2.63}$$

with  $\varepsilon \cdot \vec{r}$  for the electronic dipole moment operator, e for the excited state, g for the ground state and  $\varepsilon$  for a plane wave  $\varepsilon = E_0 \hat{\epsilon} \cos(kz - \omega t)$ , where  $\omega$  represents the laser field

 $\mu_{jk}$  describes the interaction between the electric field and the dipole moment<sup>39</sup>. Of peculiar interest is material suited for stimulated emission. Contrary to spontaneous emission, stimulated emission can be determined very well, whereas only average values are obtained for spontaneous emission. Another aspect is the circumstance that spontaneous emission has no preferred direction for emitting photons, but spontaneous emitting atoms also take part in exciting atoms which can be stimulated then.

The atom is described quantum mechanically:

$$i\hbar\frac{\partial\psi\left(\vec{r},t\right)}{\partial t} = \mathcal{H}\psi\left(\vec{r},t\right) \tag{2.64}$$

using  $H(t) = H_0 + H'(t)$  with  $H_0$  for the undisturbed atom and H'(t) for the interaction with the light field. A solution for  $\psi(\vec{r}, t)$  is given in its eigenfunction of  $H_0$  by

$$\psi\left(\vec{r},t\right) = \sum_{k} c_{k}\left(t\right) \phi_{k}\left(\vec{r}\right) e^{-i\omega t}$$
(2.65)

 $\phi_n\left(\vec{r}\right)$  are eigenvalues of  $E_n$  and  $\omega_k = E_k/\hbar$ 

Initially, only some atoms are located in excited states. This can be expressed by:

$$|c_k| \ll 1$$
 (2.66)  
for k > 1

The ground state is given by:

$$c_1(0) \mid = 1$$

which only means that it is populated. First order offers:

$$\frac{\partial c_j(t)}{\partial t} = -\frac{i}{\hbar} \mathcal{H}'_{j1}(t) e^{i\omega_{j1}t}$$
(2.67)

 $|c_j(t)|^2$  is the probability of the system transitioning to the state j in the time t. The transition rate is given by Fermi's golden rule according to

$$P_{1\to j} = \frac{\partial}{\partial t} |c_j(t)|^2 = \frac{2\pi}{\hbar} |\mathcal{H}'_{j1}|^2 \frac{\partial n}{\partial E_j}$$
(2.68)

#### $\frac{\partial n}{\partial E_i}$ for the density of final states

Fermi's golden rule can be applied for spontaneous emission only. It calculates the transition rate per unit time from one energy eigenstate  $|i\rangle$  of a quantum system into another energy eigenstate  $|f\rangle$  due to perturbation. The force exerted of laser light on atoms is in general:

$$\mathcal{F} = \frac{\partial \underline{p}}{\partial t} = \frac{1}{i\hbar} [\underline{p}, \mathcal{H}] = -\underline{\nabla} \mathcal{H} = e \left\langle \vec{\nabla} \varepsilon \left( \vec{r}, t \right) r \right\rangle$$
(2.69)

 $<sup>^{39}\</sup>mathrm{Measure}$  of the charge distribution. It is present if center of opposite charges differ

Forces out of a Hamiltonian's gradient are conservative [SAVAGE 08]. The time averaged force is:

$$F = \frac{s\hbar}{1+s} \left( -\delta \left( \Re \frac{\partial \ln \Omega}{\partial z} \right) + \left( \Im \frac{\partial \ln \Omega}{\partial z} \right) \frac{\gamma}{2} \right)$$
(2.70)

Light exerts two kinds of forces on atoms: Dipole forces and throwing powers. Dipole forces are all forces according to the incoherent scattering via spontaneous emission:

$$F = \frac{\hbar k \delta s}{1+s} \tan\left(kz\right) \tag{2.71}$$

Throwing powers are all forces according to induced and permanent dipole moments caused by interacting with the light field. The average throwing power acts in the incident photon's direction and looks as follows [SCHIPPERS 12]:

$$F = \hbar k \gamma \frac{s}{2(1+s)} \tag{2.72}$$

#### 2.3 Optical resonator

The emitted wavelengths are much smaller than a housing could realistically be. As consequence, many modes would be produced influencing the laser beam in its properties. To amplify wavelengths, two mirrors are placed along an optical axis in such a manner only desired respectively only wavelengths along the optical axis experience resonance, all others will leave the housing. At the moment the wavelengths are a multiple of the distance between the mirrors, they begin to interfere constructively and destructively according to  $n\lambda = 2L$ . This results in a selection of wavelengths.



Figure 34: Lasers operate by having more atoms in excited states than in ground states. If an excited atom absorbs an additional photon, it will emit both photons in the direction of the last one. This is called stimulated emission. Both photons will have the same frequency.

To create a beam, one of the mirror's reflectivity has to be less than the other allowing radiation to emit. The measure of transmission is important. On the one side to gain a high intensity (less transmission) and on the other side to reduce losses (high transmission) due to scattering, diffraction and spontaneous emission [BAUER 14].

## 3 Interaction of radiation with matter

Radiation interacts with matter of a wide scope. It provides significant information about ionisation, scattering and energy deposition. Besides, the energy range is an important issue. The intensity loss of electromagnetic radiation is, in general, described by Beer–Lambert's law:

$$I(x) = I(0) e^{-\mu x}$$
(3.73)

where  $\mu = \sigma n$  is the linear attenuation coefficient, with  $\sigma$  for a certain cross section and  $n = \rho \frac{N_A}{A}$  for the atom density with  $N_A = 6, 21 \cdot 10^{22}$  for the Avogadro constant

depending on the type of material, for example, especially on its thickness and atomic number. The loss can be understood as an elimination of the photons by interacting. This is valid for all electromagnetic processes relative to interacting with matter, but the Compton-effect. All processes are distinguished by scattering: Elastic scattering<sup>40</sup> and inelastic scattering<sup>41</sup> plus coherence. In general, five processes occur:

- Elastic scattering
- Photoelectric effect
- Compton effect
- Pair production
- Photonuclear interactions

which can be classified into

- Photon scattering: Compton effect and elastic scattering as well as
- Photon disappearing: Photoelectric effect, pair production and photonuclear reactions.

Considering semiconductors, only ionising processes are of current interest. Ionising characterises cases in which electrons are being removed from neutral atoms resulting in an ion pair: The positive charged atom and the negative charged electron. This is true for three major mechanisms: Photoelectric effect, Compton effect and pair production.

 $<sup>{}^{40}</sup>E_{kin, \, before} = E_{kin, \, after}$ 

 $<sup>{}^{41}</sup>E_{kin,\,before} \neq E_{kin,\,after}$ 



Figure 35: The photoelectric effect, Compton effect and pair production seen in a energy range. The photoelectric effect is dominant from up to 100 keV, the Compton effect dominates from 100 keV to 10 MeV and the pair production above 10 MeV.

Above all, the photon energy  $E_{\gamma}$ , together with the atomic number Z, is the most relevant aspect. This fact determines significantly in which manner a photon interacts with the atoms (figure 35). Lines show regions in which adjacent effects are of similar probability.

#### 3.1 Photoelectric effect

The photoelectric effect is a major contribution of Einstein to quantum physics. He discovered that the quantity of electrons emitted from metal due to light depends on intensity. Additionally, the electron's speed rises with the frequency, and no electron is ejected until a certain frequency threshold is reached. Einstein showed that this phenomenon will only occur if light is seen as particles.

A photon undergoes an interaction with an absorber atom, then photon disappears and transfers all its energy to the atom. In consequence, the electron is ejected from the bound shell of the atom:

$$E_e = E_\gamma - I \tag{3.74}$$

The photon will wrest an electron (figure 36) from an atom only, if its energy exceeds the electron's binding energy I.



Figure 36: An electron will absorb an incident photon leaving the atom. A higher electron can now switch to an energy level below by emitting a photon.

In light atoms, I is in the order of 1 keV. Photons of this energy come into play in a region where the Compton-effect prevails. I is offered by:

$$I = Z^2 \cdot 13.6 \,\mathrm{eV} \tag{3.75}$$

and decreases from shell to shell outwardly, using the energy difference between energy level n and energy level m (m>n):

$$\Delta E = E_n - E_m = h\nu = 13.6 \,\text{eV} \cdot \left(\frac{1}{m^2} - \frac{1}{n^2}\right) \tag{3.76}$$

with an energy level according to  $E_n = -13.6 \text{ eV} \cdot \frac{1}{n^2}$ . In case of ionising m is  $\infty$  and with an electron in the ground state n is 1, Eq. 3.76 leads to:

$$\Rightarrow \Delta E = -13.6 \,\mathrm{eV} \tag{3.77}$$

If two electrons are involved for the K-shell, the ionisation energy will decrease due to Coulomb repulsion:

$$I = (Z - 1)^2 \cdot 13.6 \,\mathrm{eV} \tag{3.78}$$

Photoelectric effect is predominant for

- respectively low photon energies  $E_{\gamma}$  and
- for high atom numbers Z.

This process takes place in a wide range up to E = 500 keV and is mostly dominant up to E = 100 keV. The photoelectric effect ( $\gamma \rightarrow e^-$ ) can be seen virtually as an inversion of Bremsstrahlung ( $e^- \rightarrow \gamma$ ). The removal of an electron can ionise itself other atoms (electron impact ionisation). If energy exceeds the K-shell binding energy of the electron, the cross section will be dominant by ionising via K-electrons. Therefore the atom may emit a photon itself due to having an excited atom and an unoccupied state. Of particular interest is the determination of the cross-section for the photoelectric effect. This process is as follows:

$$h\nu + |i\rangle \to |j\rangle + e$$
 (3.79)

To approach Fermi's golden rule is used:

$$P_{if} = \frac{2\pi}{\hbar} |H_{if}|^2 \frac{\mathrm{d}n}{\mathrm{d}E_f} \tag{3.80}$$

An explicit calculation evokes many troubles. The cross section in the energy region of  $E \approx 100 \text{ keV}$  looks as follows:

$$\tau = \frac{Z^4}{E_\gamma^3} \quad [cm^2/atom] \tag{3.81}$$

and in general:

$$\tau = \frac{Z^n}{E_{\gamma}^m} \quad [cm^2/atom] \tag{3.82}$$

in the K-shell [ATTIX 08]. The so-called inner photoelectric effect is responsible for the conversion of light into solar electricity.

#### 3.2 Compton effect

Compton effect describes the increase of the wavelength  $(\lambda_0 \to \lambda)$  of a photon due to scattering by an electron at an angle  $\vartheta$ . Contrary to the photoelectric effect in this process, the photon is not absorbed by the electron, which acts as nearly free. It is also an ionisation incident. The electron receives energy from the photon and leaves the atom. The Compton effect is the dominant process in the energy region of 500 keV to 10 MeV. The wavelength shift of the electron is given by:

$$\lambda - \lambda_0 = \frac{h}{m_e c} (1 - \cos \vartheta)$$
  
=  $\lambda_C (1 - \cos \vartheta)$  (3.83)

with  $\lambda_C$ , the Compton wavelength by scattering perpendicularly at a particle with rest mass m

Hence, it is an incoherent process. The incident photon is deflected through an angle  $\vartheta$  with respect to its initial direction. The energy of the scattered photon is:

$$h\nu = \frac{h\nu_0}{1 + \frac{h\nu_0}{mc^2} (1 - \cos\vartheta)}$$
(3.84)

and for the electron [BLUMENTHAL 70]:

$$E_e = h \left(\nu_0 - \nu\right)$$
  
=  $h\nu_0 \frac{(1 - \cos\vartheta)}{1 + h\nu_0 \left(1 - \cos\vartheta\right)}$  (3.85)

At 180° the energy transfer between photon and electron is the highest. The scattered photon has  $E = \frac{1}{2}mc^2$  then. The cross section of the Compton effect for polarised radiation through an angle  $\phi$  is given by the Klein-Nishina formula:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_e^2}{4} \left(\frac{\nu}{\nu_0}\right)^2 \left(\frac{\nu_0}{\nu} + \frac{\nu}{\nu_0} - 2 + 4\cos^2\phi_{pol}\right) \tag{3.86}$$

and the cross section for unpolarised radiation:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_e}{2} \left(\frac{\nu}{\nu_0}\right)^2 \left(\frac{\nu_0}{\nu} + \frac{\nu}{\nu_0} - \sin^2\vartheta\right) \tag{3.87}$$

 $\nu$  can be achieved by dividing Eq. 3.84 by h.



Figure 37: Klein-Nishina cross section: Compton scattering is dependent on energy and angle. This image represents the abundance of a photon scattered at a certain angle. It is also obvious that  $\theta$  decreases with increasing photon energy. Forward scattering is also prevalent at high energies. In case of polarised compton-scattered radiation the electron has to be polarised. The image above shows the case for unpolarised radiation.

The cross section is split into one part for scattered fraction<sup>42</sup> and into another for transferred<sup>43</sup>:  $\sigma = \sigma_s + \sigma_{tr}$ . In addition it is proportional to Z. The special character of the Compton effect lies in its extensive independence of Z. Literature makes not quite clear if the Compton effect represents an elastic or inelastic process. It should be elastic, because the kinetic energy does not change. If the kinetic energy changes, a part of the kinetic energy will be converted into inner energy, because an electron has no degree of freedom left. Therefore it might be an elastic process.

#### Thomson scattering

Thomson scattering is the low-energy limit of Compton scattering. It works fine as long as the photon energy is much smaller than the electron energy (valid for  $h\nu \ll m_e c^2$ ). It is a

 $<sup>^{42}</sup>$ Part of the photon's energy that is not transferred

<sup>&</sup>lt;sup>43</sup>Part of the photon's energy that is transferred

non-relativistic process, so  $v_e$  has to be different from c. The cross section is given by:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = r_e^2 \sin^2 \theta$$

$$\Rightarrow \sigma = \frac{8\pi}{3} r_e^2 \qquad (3.88)$$

with  $r_e$  for the classical electron radius

(can be pulled out of the mass-energy equivalence, though an electron has probably no radius)

#### 3.3 Pair production

Pair production can convert a photon into an antiparticle-particle pair in the vicinity of a particle at an energy threshold of  $2mc^2$ . It relies on the conversion of energy into mass or vice versa according to Albert Einstein's famous formula:

$$E = \sqrt{\left(mc^2\right)^2 + p^2 c^2} \tag{3.89}$$

The existence of antiparticles was predicted previously at first by Paul Dirac. If the photon energy exceeds twice the rest energy of the electron 1.022 MeV, pair production is possible in the field of a nucleus as follows:

$$E_{thr} \ge 2m_e c^2 + 2\frac{m_e^2}{m_{nucleus}}c^2 \tag{3.90}$$

A further particle is necessary for momentum conservation reasons. If a photon has just only the threshold energy, the antiparticle-particle pair will be at rest. Since a photon possesses a momentum a violation of the momentum's conservation would follow. For that reason a particle has to absorb the photon's momentum. Pair production at electrons can be neglected due to the high energy threshold of  $4mc^2$ . The photon must have at least the energy of the combined particle's rest mass. If exceeded, the additional energy portion will take place in the kinetic energy. Newly generated particles can move in opposite direction at an angle of 180 degrees, this means that they have a zero total momentum. Otherwise they spread at an angle of less than 180 degrees resulting in a very small combined momentum.



Figure 38: In the vicinity of a particle a photon can produce a antiparticle-particle pair if its energy is sufficient. The newly generated particles will leave in opposite direction if they possess some kinetic energy.

This process is dominant in the energy region from 10 MeV and higher. The conversion length  $X_0$  can be expressed by:

$$X_{pair} = \frac{9}{7}X_0\tag{3.91}$$

The quantity, which describes the energy loss through a given mean length, represents the radiation length  $X_0$  approximately as follows:

$$X_0 = \frac{716.4}{Z \left(Z+1\right) \ln\left(\frac{287}{\sqrt{Z}}\right)} \frac{g}{cm^3}$$
(3.92)

with Z for the atomic number and A for the nuclei mass number. This equation is often given in  $cm^{-2}$ , which is available by dividing the density

This quantity is very useful for high energy electrons due to Bremsstrahlung and for high energy photons due to  $e^+e^-$ -pair production.  $X_0$  offers the mean length in which an electron loses all its energy, but of 1/e, and is simultaneously the length of 7/9 for pair production of an high energy photon. It should only be used when measurements are not available [GUPTA 10].

The inversion of pair production is called annihilation. Two particles (antiparticle and particle) will eliminate each other. The cross section of pair production is represented by [MÜLLER 12]:

$$\kappa = 4Z^{2} \alpha r_{e}^{2} \left[ \frac{7}{9} \left( \ln \left( \frac{2E_{\gamma}}{m_{e}c^{2}} - f(Z) \right) \right) - \frac{109}{54} \right]$$
(3.93)  
with  $f(Z) = (Z\alpha)^{2} \left\{ \left[ 1 + (Z\alpha)^{2} \right]^{-1} + .. \right\}$ 

In the closing, the cross section of a photon beam's attenuation finally goes by:

$$\sigma = \tau + \sigma + \kappa \tag{3.94}$$

due to the circumstance that photonuclear reactions have less probability

#### 3.4 Bethe equation

Charged particles traversing matter cause ionisation and/or excitation effects, also called hard and soft collision, thereby losing a specific energy (also called stopping power). If released electrons ionise atoms in turn, they will be called  $\delta$ -electrons or "knock-on"-electrons. The sum of all single energy losses of charged, heavy particles along a direction x is described by a formula discovered by Niels Bohr.

Due to statistical processes, the Bethe equation represents the mean energy loss of particles through matter. The whole energy loss can be obtained either with a Gaussian or with a Landau distribution (figure 40) depending on the absorbers' thickness. A lot of specific effects have been added, like behaviour in relativistic and quantum mechanic (Bethe), in high energies (Fermi), proportionalities to  $Z^3$  (Barkas & Andersen) and  $Z^4$  (Bloch) and shell corrections. Sternheimer made adjustments relative to density corrections, yielding:

$$\frac{\mathrm{d}E}{\mathrm{d}x} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \cdot \left[ \ln\left(\frac{2m_e c^2 \gamma^2 \beta^2 T_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \qquad (3.95)$$
with  $\beta = \frac{v}{c}, \ \gamma = \frac{1}{\sqrt{1-\beta^2}},$ 

 $\rho$  for the target density, Z as the mass number, z for the incident charge  $\delta$  for density corrections, C for shell corrections, material dependent mean ionisation potential I and  $T_{max}$  for a single maximum energy transfer

by taking into account that ionisation probabilities increase with increasing incident particle velocity [LEO 94]. This equation works very fine in an energy range of  $0.1 < \gamma\beta < 100^{44}$ . For the mean ionisation potential several expressions due to material dependencies exist, the most common is  $I = 10eV \cdot Z$ . The maximum energy transfer in one collision is approximately  $T_{max} = 2m_e (c\beta\gamma)^2$ . Shell corrections consider the probability of collisions with electrons of different shells. For the most part inner atomic shells are negligible. An adjusted equation of Berger & Seltzer is suitable for electrons and positrons. The energy loss depends on velocity of incident particles, on their charge and on the target density. The curve can be split into three sections:

- A negative slope proportional to  $(1/\beta)^2$  due to the fact that slow particles experience more electric forces of atoms until they reach approximately  $\beta \gamma \approx 3.5$ .
- A positive, logarithmic slope considering relativistic cases in which Lorentz transformations increase the transversal electric field according to  $E_{\gamma} \rightarrow \gamma E_{\gamma}$ .
- At high energies a Fermi plateau (energy loss saturation) emerges as a result of polarisation effects. Electric fields become shielded far from particle paths via  $\delta/2 \approx \ln(\hbar\omega/I) + \ln(\beta\gamma) - 1/2$ .

Usually, energy loss is normalised to  $-\frac{1}{\rho}\frac{dE}{dx}$  with  $\rho$  for the absorber density.



Figure 39: Energy loss of positively charged muons traversing copper dependent on the velocity  $\beta\gamma$ . Three specific regions play a role. The curve exhibits a minimum at  $\beta\gamma \approx 3.5$ . Particles there are important for detector design due to a similar behaviour.

 $<sup>^{44}\</sup>beta\gamma=p/Mc$ 

The total energy transfer to an electron is represented by:

$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$
(3.96)

with M for the traversing particle mass

#### 3.4.1 Minimum ionising particle

The energy loss in the equation possesses a most prominent part at  $\beta \gamma \approx 3.5$ , where particles often have a very similar mean energy of  $E = 3m_pc^2$  according to E = pc. Then their energy loss is roughly:

$$-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \approx (1-2)\frac{MeV}{gcm^{-2}} \tag{3.97}$$

Particles in that range care called MIPs<sup>45</sup>. The minimum  $\beta \gamma \approx 3.5$  includes  $\beta = 0.96$  and  $\gamma = 3.6$ . The  $\beta$ - and  $\gamma$ -dependence is used for identifying particles. Particles with different mass, but same momentum, have different  $\beta$  and  $\gamma$ . Out of this the energy loss curve varies in a function of  $\beta \gamma$  for different masses. MIPs are very useful for designing detectors due to their lowest energy ionising matter relative to their term. Relativistic particles are often ionising minimally.



Figure 40: Left - Energy loss of pions with 500 MeV in silicon of different thickness. Most probable energy loss and mean energy loss rate differ from each other. The behaviour of the curve acts like a Landau distribution. Right - Energy loss of kaons, protons, pions and electrons in response to their momentum. For different  $\beta$  and  $\gamma$  the functions are unlike each other.

## 4 Positioning

Positioning is the mechanism of moving an object to a desired position through several optional parameters, for example acceleration, velocity, path and steps. Essential aspects are

 $<sup>^{45}\</sup>mathrm{Minimum}$  ionising particle

the quantity of axis and the travel range, additionally, possible carry load. Another relevant issue represents the kind of engine (stepping motor, linear motor,..). Of importance here is the understanding of linear motors, famous for achieving high velocities and accelerations.

Figure 41: Two-dimensional projection of a standard rotating motor. The stator becomes planar and forces an object into a specified onedimensional direction, now. A turn is equal to a pole pair length.

Linear motors can be seen as a two-dimensional projection of a typical rotating motor. Therefore a linear motor does not force objects into a rotating movement. Eventually, the only distinction is the planar assembly of the stator, which contains the electric field windings. It keeps an object above the surface. The linear motor function is caused by its specified change of polarity of magnets attached upon the stator. The movement is caused by an electric field within the moveable object. One (electrical) turn is adequate to a pole pair length. The field varies only in one direction.



Figure 42: The Lorentz force is the reason for the movement. It is perpendicular to the current and magnetic field. By changing electrical parameters of the field, the movement's behaviour can be influenced.

The magnetic field protrudes perpendicularly from the pole pairs to the object. The current runs across the stator, so, thanks to Lorentz force, the object travels to a certain direction:

$$\vec{F_L} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{4.98}$$

By changing the electric field, velocity and breakpoints can be defined. Two dimensions are realized by two axis/motors. Furthermore, two parameters are of particular interest:

- Position repeatability: A device can consistently return to the identical position. In case of a motion in direction x it is  $\pm \Delta x$ . The repeatability has to be distinguished by unidirectional and bidirectional. Unidirectional repeatability is the capability to return to the same position from the same direction, contrary to bidirectional repeatability, which describes the same, but from different directions.
- Position accuracy: The maximal permissible deviation between the desired position and the actual location, also expressed in  $\pm \Delta x$ .



Figure 43: Illustration of the two parameters and their interaction.

Therewith positioning depends on repeatability and accuracy. Joint, it describes the ability of returning to the same position with a differing error. Additionally, two more parameters are of interest:

- the smallest possible step a system can shift and
- the position resolution of the encoder: The smallest shifted increment the system can detect.

#### 4.1 MNR-effect

Magnetoresistive effect is the change of a resistivity in presence of an external magnetic field discovered by William Thomson in 1856. This includes the anisotropic magnetoresistive effect, which is explained in the following. On the one side, magnetic fields exist as a result of a moving charge, and on the other side, in case of particles with spin, as their consequence. Classically considered, an electron along an orbital motion around a proton represents a current. On the basis of that a magnetic moment is:

$$\vec{\mu} = \frac{q}{2m_q} \cdot \vec{L} \tag{4.99}$$

Quantisation of the orbital angular momentum L, according to  $L = n \cdot \hbar$ , leads to:

$$\mu = \frac{q}{2m_q} \cdot n\hbar , \qquad (4.100)$$
  
with  $\hbar = \frac{\hbar}{2\pi}$ 

which is known as Bohr magneton  $\mu_B$  and describes an electron magnetic dipole moment. Particles with a spin  $\vec{s}$  have a magnetic moment out of this as:

$$\vec{\mu_s} = g\mu_B \frac{\vec{s}}{h} \tag{4.101}$$

with the gyromagnetic g-factor g

For electrons it is:

$$\vec{\mu_e} = g_e \mu_B \frac{\vec{s}}{h} \tag{4.102}$$

with the Landé g-factor  $g_e$ 

Magnetic dipole moments (for example  $\mu_e$ ) are the measure of the magnetic polarity of charges and their amount. In presence of a magnetic field, a torque is exerted on them:

$$\vec{T} = \mu \times \vec{B} \tag{4.103}$$

If all magnetic moments are aligned in one direction, their magnetic fields will build up an external measurable magnetic field. In such a case, a body is so-called magnetised. The alignment can occur in presence of an external magnetic field. The magnetisation is:

$$\vec{M} = \frac{1}{V} \cdot \sum_{i=1}^{n} \vec{\mu_i}$$
(4.104)

with the sum of all magnetic moments in a certain volume [BETTNER 99]. If all magnetic moments are aligned in such a way on their own respectively without an external magnetic field, the body will be called ferromagnetic. An external magnetic field  $\vec{B}$  can change the magnetisation respectively the direction of magnetisation via:

$$\vec{M} = \frac{\chi}{1 + \chi \cdot N} \cdot \vec{B} \tag{4.105}$$

#### with $\chi$ as magnetic susceptibility and N as demagnetisation factor

The AMR-effect takes place in ferromagnetic materials in which the specific resistance  $\rho$  changes by a varying angle  $\theta$  between magnetic field line and the current's direction. This change makes up a few percent only and is already usable in case of weak magnetic fields. Therefore it can be utilised for very sensitive measurement methods.

The AMR-effect assumes an anisotropically specific resistance. By applying an external magnetic field, the magnetisation direction will change. The specific resistance depends on the angle between the direction of the flowing current  $\psi$  and the direction of magnetisation  $\phi$  according to:  $\theta = \phi - \psi$ . The resistance is given by:

$$R(\theta) = \rho_{0,n} \frac{l}{wt} + \Delta \rho \frac{l}{wt} \cos^2 \theta$$
  
=  $R_{0,n} + \Delta R \cos^2 \theta$  (4.106)

# for a body with the width l, the thickness t in a time t $\rho_{0,n}$ and $\triangle \rho$ are material constants

 $\Delta R$  describes the possible resistance changing by a magnetic field, and  $R_{0,n}$  represents the resistance crosswise to the magnetisation [HAUSER 98]. Ohm's law offers:

$$V_x(\theta) = \rho_{0,n} \frac{l}{wt} \cdot I + \Delta \rho \frac{l}{wt} \cos^2 \theta \cdot I$$
  
=  $R + \Delta R \cos^2 \theta$  (4.107)

assuming a current in direction x. Additionally, a voltage  $V_y$  is generated, the so-called planar hall effect (not to be confounded with the common hall effect), but is not used because of its very small amount.

# Part III Approach

La science, mon garçon, est faite d'erreurs, mais d'erreurs qu'il est bon de commettre, car elles mènent peu à peu à la vérité.

Jules Verne

Purpose is the development of a laser test stand for silicon detectors. Using this, sensor boards can be characterised via measurements of leakage currents, charge distributions and capacitances, noise, position resolution and so forth. The laser test stand includes a xy-table, a laser driver & head, a TTL-device and a readout system. Additionally it includes power supplies, a laser beam attenuator and a mechanical setup for the sensor boards. The xy-table consists of a controller (Hydra-controller), two linear axis and sensors measuring the position. A laser provides the capability to inject charges very precisely into a sensor. Due to a small spot size of the laser's beam, the collected charge inside the sensor can be measured by a readout system. The location radiation impinges can be shifted even in the magnitude of nm. Furthermore the deposited energy of the photons respectively their created charge can be varied by the laser's intensity. By triggering the laser time response studies are possible.

A program is written for the laser test stand to control the xy-table and laser driver. This contains several settings concerning the movement of the xy-table and firing the laser. On this basis it is possible to move the table in very small increments, manually and automatically, absolutely and relatively. In case of automatic motion four modes are available. Besides, the time for each movement can be adjusted, also, how often the laser fires at each position and the time between each shot, too. Further features are provided, too.

The MVD of the PANDA-experiment consists of silicon strip detectors, therefore the laser test stand will be answer quality assurance purposes as well.

A traversing MIP generates numbers of electrons, which can be calculated on the basis of its deposited energy. Out of figure 40 the most probable energy a MIP deposits in 300  $\mu$ m silicon is approximately:

$$\frac{\mathrm{d}E}{\mathrm{d}x} \approx 260 \,\frac{eV}{\mu m} \tag{4.108}$$

Integrating over the thickness yields:

$$\int dE = \int \frac{dE}{dx} dx$$

$$\int dE = \int_{0\mu m}^{300\mu m} 260 \frac{eV}{\mu m} \cdot dx$$

$$E = 78,000 \text{ eV} \qquad (4.109)$$

as deposited energy.

Using the mean energy for ionisation of a silicon atom I = 3.6 eV (at room temperature), the total amount of liberated electrons is:

$$n = \frac{E}{I} = \frac{78 \text{ keV}}{3.6 \text{ eV}}$$
$$\approx 21,66\overline{6} \tag{4.110}$$

It remains to be shown that, like MIPs, light releases a similar number of electrons, too. To produce the same charge production of a MIP, the laser energy has to be defined. To create  $\approx 22$ k electrons a laser with the same energy a MIP deposits (78 keV) is necessary. The energy of a laser puls is given by:

$$E = P \cdot t \tag{4.111}$$

with P for the peak power and t for the pulse width

Assuming a peak power of 256 mW and an average pulse width of 54 ps, the energy amounts to 86, 283 MeV. Apparently, the laser has to be attenuated to mimic a MIP. The attenuation factor is according to:

$$\frac{E_{Laser}}{E_{20k}} = 1106,192\tag{4.112}$$

The energy of one single photon is 1.19 eV, compliant with  $E = \lambda \cdot \nu$  and a wavelength of 1041,5 nm. Therefore 65546 photons are necessary. It is important to consider that a critical wavelength exists in which electrons cannot be lifted within a specific material:

$$\lambda_c = \frac{hc}{E_G} \tag{4.113}$$

requiring that a photon possesses at least the energy of the band gap. The absorption coefficient  $\mu$  (Eq. 3.73) depends on the frequency and is lower for higher frequencies. The absorption coefficient for silicon against the wavelength of light:



Figure 44: Absorption coefficient of light for silicon against the wavelength at room temperature.

The absorption coefficient is expressed in units of  $cm^{-1}$  and indicates how deep an impinging photon will penetrate the material before being absorbed by the lattice releasing an electron. At a laser wavelength of 1000 nm and a silicon thickness of 260 µm, light is absorbed to a portion of 55%, reflected to a portion of 31.625% and transmitted to a portion of 12.81% [SHAYAN 08].

## 5 Implementation

## 5.1 XY - Table

The xy-table consists of several components: The Hydra-controller, two linear axis and the AMR-sensor. The Hydra-controller receives commands of the user, administering them respectively passing them to the axis. For the most part it is a motion controlling matter, furthermore an adjustment of table settings. The signalling can be represented like:



Figure 45: Process flow of the xy-table system consisting of the NanoStar sensor board, the Hydra-Controller and the FCS 100-xy-table.

The NanoStar sensor boards measure the actual position in a very high resolution, passing this information to the signal conditioner which in turn sends it to the Hydra making use of it converting this data input into x-y coordinates. On this basis the table will be shifted as required.

The xy - table is a product of ITK Kassen GmbH of the Flatline series  $(\widehat{R})$ .

Position resolution:	$1 \mathrm{nm}$
Position accuracy:	50  nm
Velocity:	max. $50 \text{ cm/s}$
	min. $100 \text{ nm/s}$
Acceleration:	$1,000 \text{ cm/s}^2$
	$1 \ \mu m/s^2$
Travel range:	$100 \text{ x } 100 \text{ mm}^2$
Load:	3 kg



Figure 46: XY-Table of ITK Kassen GmbH.

## 5.2 Hydra CM 2-axes controller for linear motors

The hydra controller is the head of the xy-table, the

Power:	500 W
Current:	15 A per Phase (10 A
	continuously)
Processor freq.:	$400 \mathrm{~MHz}^{-1}$
Communication:	Ethernet, RS 232
	max. 115 kHz
Memory:	64 MB
Flash memory:	8 MB
Measue systems:	NanoStar (absolut)
	MiniStar (magnetic
	incremental)
	MicroStar (robust
	and measures absolute
	up to 25mm)
Programming:	ASCII



Figure 47: Hydra-controller

Its measurement systems include three digital highspeed measuring channels. Two of them are for evaluation of the position and the third is free for own measuring applications. Positioning of the axis can be done independently and simultaneously.

#### 5.3 Sensors

motion controller.

Hydra contains three types of sensors: NanoStar, MiniStar and MicroStar, all based on the AMR-effect. Therefore all measurements take place magnetically. Their behaviour is very similar to each other, so only the most precise system is considered:

Position measurement of the table is obtained by a selfdeveloped AMR-Sensor by ITK Kassen GmbH. Two external NanoStar-sensors have the task to detect magnetic structures on a scale. Structures are analysed and converted into an absolute position. At a velocity of 10 m/s even a precise positioning of about 100 nm is possible. Measured data is transmitted to Hydra via a speed of 20 kHz. Three sensors are placed upon a measuring tape that consists of three (12 x 0,22) mm<sup>2</sup> magnetic paths. Each of them represents a different accuracy. The middle consists of a specific arrangement of magnetic poles representing the absolute position. The others possess a phase shift to the middle and calculate the absolute position. An accuracy of up to 5 nm is possible.



Figure 48: MNR-sensor

## 5.4 TTL

As transistor-transistor logic-device, a Deditec USB-TTL-32 is used that connects a computer with the laser for triggering purposes. It possesses 32 inputs/outputs (1.5 V to 5 V by setting jumpers), which can be controlled in blocks of eight. Access time limits the maximum to 1 kHz.



Figure 49: Deditec USB-TTL-32

### 5.5 Laser

The laser system consists of two components: The laser driver and the laser head. As

- laser driver a PDL 800-D is employed and as
- laser head a LDH-D-C-1060 (both PicoQuant GmbH),

which can operate in pulsed or continuous mode.



Figure 50: Pulsed Driver PDL 800-D and laser head LDH-D-C-1060 (PicoQuant GmbH). Polarisation plane is represented by two groove marks.

Emitted light is linearly polarised. The laser head consists of a diode with a polarisation extinction<sup>46</sup> of 20 dB and has a wavelength of 1052 nm. Rotating the polarisation of the laser head can produce pulses of different shape and intensity.

#### 5.5.1 Triggering & Synchronisation

Triggering can be done internally or externally, the last via fast gate. In case of external triggering, the signals have to be less than  $\pm$  5 V, and connectors must be 50  $\Omega$ . The best values for triggering are signals with amplitudes of 1 V to 2 V and longer than 5 ns. The laser driver provides two special gating options, fast gate and slow gate, to allow suppression of the laser emission by an external signal (negative slope). Fast gate offers high pulse stability for fast (unit: [ms]) and periodic on/off signals as well as a slow gate that decreases settling times of the laser head to a minimum at slow (unit: [s]) on/off periods, requiring a high-active TTL signal. For both gates, in case of triggering, the laser fires only if desired.

The amplitude for synchronisation output corresponds to NIM<sup>47</sup> standards and is connected to the trigger input. Its pulse width amounts to 6 ns. Remoted interlock is supported, too.

<sup>&</sup>lt;sup>46</sup>Compares the optical power on the wanted axis to that which is on the unwanted axis, the orthogonal polarisation state, and is expressed in decibels: PER =  $10 \log_{10} \left(\frac{P_y}{P_x}\right)$  [FIBERCORE 14]

 $<sup>^{47}</sup>$ Nuclear Instrumentation Module: Fast logic standard is a current-based logic, with negative true (I=-16 mA, R=50  $\Omega$  & V=-0.8 V)

#### 5.5.2 Puls broadening

The puls shape depends on a few aspects: Increasing the laser intensity results in

- a higher amplitude and broader shape. Afterpulsing<sup>48</sup> can occur.
- shifting the peak to an earlier time
- another peak shift of the emitted beam wavelength

as side effects. Varying the repetition rate to higher rates causes the following results:

- different shape or pulse width per single pulse
- lower peak per single pulse
- lower energy per single pulse

The pulse widths are ranged between 50 and 500 ps with an optical power of more than 1 W and a pulse energy of approximately 50 pJ to 300 pJ.



Figure 51: A single beam pulse plotted as optical power against time.

<sup>&</sup>lt;sup>48</sup>Liberation of a photon during a subsequent gate pulse



Figure 52: Different optical power outputs against wavelength. Peak shifts, varying spectral distributions and amplitudes dependent on wavelength and intensity can be seen clearly.

#### 5.5.3 Optical Power

Optical power outputs are given for the repetition rates from 2,5 Mhz to 80 Mhz (given and constant intensity setting):

Repetition frequency	Max. optical power
	(10%  calibr. error):
80 Mhz	20.2 mW
40 Mhz	11.5 mW
20 Mhz	5.4 mW
10 Mhz	2.8 mW
5.0 Mhz	1.4 mW
2.5 Mhz	0.66 mW

Table 3: Optical power outputs from 2.5 Mhz to 80 Mhz

The device possesses two master oscillators and a belonging frequency driver that divides the two frequencies by 1, 2, 4, 8, 16 and 32. On this basis, twelve repetition (Int 1 & Int 2 on the interface) rates can be chosen from 31,25 kHz to 80 Mhz. The average optical output power is increasing very linearly with the repetition rate. In table 5.5.3 the optical power is cited, but the laser output power is not given for all frequencies. Therefore a fit is made:



Figure 53: Fit for the optical power output to gain values for lower repetition rates.

The fit yields the equation  $f(x) = 0,25454 \frac{mW}{Mhz} \cdot x + 0,31154 \text{ mW}$ . With the help of this, the following optical powers are achieved for low repetition rates:

Repetition frequency:	Max. optical power
	(10%  calibr. error):
1 Mhz	$0.56608 \mathrm{mW}$
$0.5 \mathrm{~Mhz}$	0.43881  mW
0.25 Mhz	$0.37517 \mathrm{mW}$
0.125 Mhz	$0.34335 \mathrm{mW}$
0.0625 Mhz	$0.32744  \mathrm{mW}$
0.03125 Mhz	0.31949  mW

Table 4: Optical power outputs from 31.25 kHz to 1 Mhz

#### 5.5.4 Spot size

Since the laser beam is guided via a fibre with an attenuator in between, the spot size depends on several devices. Fibres (more precise optical fibres) are waveguides to transmit light consisting of extreme transparent glas. The light is guided by virtue of different refractive indices of core and cladding on basis of total reflection ( $n_{core} > n_{cladding}$ ). The core is the transparent fibre's component. At the end, a collimator ensures that the incident light is aligned parallelly. Subsequently, a microfocus optic transforms a collimated laser beam into a micro spot of the magnitude of µm. The following components are used:

Microfocus optic:	5M-M30-37-S	$Sch{\ddot{a}}fter + Kirchhoff GmbH$
Fibre collimator:	60FC-4-A18-03	${ m Sch\"after} + { m Kirchhoff~GmbH}$
Optical fibre:	H1060	Thorlabs

Table : Optical devices for light guiding, collimating and focusing.

with the following quantities:

- Numerical aperture of outgoing fiber: NA = 0.14
- Numerical aperture of collimator: NA = 0.18
- Focal length of collimator: 18.4 mm
- Focal length of microfocus optic: 30 mm respectively effective working distance from the housing edge: 26.7 mm

Essential quantity is the numerical aperture<sup>49</sup>, which should match all devices. Another aspect is the  $MFD^{50}$  that can be calculated as follows:

$$MFD = \frac{2\lambda}{\pi \cdot NA \cdot 0.82} \tag{5.114}$$

#### with NA of the fiber

Thus, the MFD amounts to 5833.833 nm. The spot of the microfocus optic is an image of the mode field on the basis of which the spot size is obtained via:

$$\phi_{spot} = \frac{f'_{micro-focus}}{f'_{collimator}} \cdot MFD \tag{5.115}$$

yielding a spot size of  $9.512 \ \mu m$ . The spot size specifies the accuracy of positioning the beam relative to measuring individual charge deposits at the strips.

#### 5.6 Mechanical setup

The xy-table as well as the sensor boards are attached to a plate. The sensor boards have a base plate the holders of which can be adjusted to the varying geometries of the different sensor boards. The ground plates are also attached to a ground base plate inside the light tight box 5.8.



Figure 54: Technical view of the xy-table's ground plate (blue - right) and the ground plate for the sensor modules (blue - left)

<sup>&</sup>lt;sup>49</sup>Resolution respectively capability of focusing light:  $NA = n \cdot \sin \alpha$  (n as refractive index and  $\alpha$  as half angle of beam spread. <sup>50</sup>Mode field diameter: Distribution of the irradiance respectively the optical power per unit area

The laser head is secured to a holder (figure 55) and mounted in it in a way that it rests on a circle with a centered orifice. The head can be pulled out at any time.

Positioning in z direction is possible via a Misumi XSB60 system. It is attached to the xy-table by an angle.

Travel range:	$\pm$ 21 mm
$\hookrightarrow$ Coarse thread:	18 mm
$\hookrightarrow$ Fine thread:	2.3 mm
Accuracy:	30 µm
Load:	2 kg
Dimension:	$60 \ge 40 \text{ mm}^2$



Figure 55: Misumi XSB60 Height positioning system.

## 5.7 Sensor board

The sensor board consists of a  $PCB^{51}$  with readout and voltage supply devices attached upon it. 385 channels on the p- and 385 n-side are read out by six Front End-Chips, each for 128 channels and three for each side. The sensor board has following properties:

Crystal growth	Lattice			n-side		
method:	structure:	Thickness:	Structure:	isolation:	Guard rings:	Biasing:
Float zoning	<111>	$(285 \pm 10) \ \mu m$	Double-sided,	P-spray	8	Punch through,
	•	'	front p-side &			from bias ring
			back n-side			to strips

with specific strip parameters like a strip length of 19320  $\mu m,$  a pitch of 50  $\mu m,$  a width of 30  $\mu m$  and 2.385 channels.



Figure 56: Sensor board (Spssdm50) with the laser head above. The sensor board is connected to a supply board. The n-side channels run sideways and the p-side channels perpendicular.

 $<sup>^{51}\</sup>mathrm{Printed}$  Circuit Board

## 5.8 Light tight box

To ensure light impinging the sensor emitted only by the laser, a box had been designed and built by the manufacture. It is covered inside with a very high absorbing material.



Figure 57: Light tight box. Due to a simple implementation of all devices, the xy-table is positioned with its origin of moving bottom right at the expense of ease of use. The xy-table, the sensor board and support board are placed upon the plate. Below, all other devices are installed: Laser driver, low & high voltage supply, Hydra-controller and a separate trigger source. The Hydra-controller is clamped to a steel strut laterally to render its LEDs visible. On the right the readout system.

The shelter of the light tight box possesses a remote interlock which communicates via RFID with a responder mounted to the box. The laser will only fire, if the shelter is closed. The box is separated into two regions: The upper part is utilized for the xy-table, laser head and sensor boards and, consequently, for measurements. The lower part consists of all the technical devices, like voltage supplies, Hydra-controller, laser driver and TTL. The attenuator for the laser beam is attached to the left in the upper part of the box.



Figure 58: The optical attenuator fans the light and due to a screw to adjust the damping factor by varying the space between the one end of the connection portion and between the device.

## 6 Program

The program's aim is the ability of shifting the table's location as desired. The motion is done by two linear axis of the table, they are connected to the Hydra-controller, which controls the total behaviour. The program is written in Borland C++ Builder 6 Professional. It concludes three classes:

- RS 232: Connection via PC and Hydra
- Hydra: Executing commands
- TTL: Laser triggering

and the xy-table program. Application programming interface is Windows Application Programming Interface (WinAPI).

## 6.1 RS 232

First of all, a connection between PC and Hydra is needed. The type of connection RS 232 which is embedded as a separate class written by Teunis van Beelen.

## 6.2 Hydra

This class contains all single commands, which can be used for the xy-table program as a Boolean data type. Commands are included in the header of Hydra (\*Hydra.h) in the form of

		Command	Data type	Variable	Description:
example:	bool	$set\_absolute\_x$	float	coordinatex	go absolutely
	bool	$get\_pos\_x$	float	х	to x-coordinate receive actual position of axis 1

which will look like: bool set\_absolute\_x(float coordinatex) Commands are distinguished by sending (set\_\*) and receiving (get\_\*). The data type differs for each command and has to be found out in the header.

## 6.3 TTL

The TTL-Device is used for sending trigger signals to the laser driver. This class is firmware of Deditec GmbH.

## 6.4 XY-Table

The program consists of various sections, which have their own functions. The first three are specifying several settings, such as mechanical behaviour of the table, laser pulsing and triggering and also device connection. The fourth is attented for controlling the table's motion and the fifth for reading the actual position of the table. The sixth, however is a mix of several features. Besides, it is possible to represent all units in inch, centimetre, millimetre, mikrometre and nanometre.

The program is designed as follows:

🗤 Table			
1. Table settings:	xy-table v1.0.0	3. Establish RS 232 Connection:	time on target s elapsed: 0 ; 0 ; 0 s
Step size:         Lin           ▲ x, r: 5         mm         x <sub>min</sub> : 0           ▲ y: 5         mm         y <sub>min</sub> : 0	nit ranges: mm X <sub>max</sub> ; <sup>100</sup> mm mm Y <sub>max</sub> ; <sup>100</sup> mm	4. Program control:	
Step holding time: St t. 500 ms v: 1	ep velocity: <sup>10</sup> mm/s	-> Connection necessary <-	
Movement: St Automatic Manual Pt	ep acceleration: <sup>10</sup> mm/s <sup>2</sup> Jlsing:		
Default Shots: 1	per step 10 ms		
2. TTL settings: 11 Ch 13 Ch 15 Vin 2 ChD Ch 12 Ch 14 Vin 1 ChD GND h 8 - 15 Set to high low	Output         Read:         CHS input/Output:           Ch 16 - 23         → input           Ch 24 - 31         → input           Ch 0 - 7         → input           Ch 8 - 15         → input           Set out         Input           Input         → input	5. Current positions: unit in cm mm um nm SAVE x:mm y:mm CALIBRATE axis 6. Receive data:	exit RESET © Hydra STOP motion
	Low after input Toggle High/Low Stop toggle Beam:	Hydra CPU Temperature Table Trigger delay Sensor Actual current Max current Motor off Delete	
Signal measure		Delete	

Figure 59: Program for controlling the xy-table and the laser. It consists of seven sections with specific features.

The program contains six different subsections which are as follows:

- 1. Table settings: This section includes all mechanical parameters of the table.
  - (a) Step size: The desired increment the table shall move in x and y direction. Values for both can be independent on some functions. Some require a fixed value for both which is then given by the x, r-input window.
  - (b) Step holding time: The waiting time between each single step.
  - (c) Step velocity & acceleration: The velocity and acceleration of the movement.
  - (d) Movement: Automatic or manual motion, selecting one of them which means only one can be chosen. If a control via the other mode is wanted, it will be necessary to disconnect ensuring that no undesirable influences will disturb a current process.
- 2. Pulsing: Two inputs are present: One for the amount of shots per step and one for the time in between. The laser fires in the middle of its hold point, therefore, the chosen time is divided into two halves, one for the time before firing, one for the time after.

All inputs will be checked for their validity due to the table parameters. For example it is not possible to enter a higher velocity than the table is able to perform. The inputs will be checked by pressing enter or by leaving the focus of the input window and, furthermore, be corrected into a certain value, if the input is wrong.

- 3. TTL-settings:
  - (a) Channels: Output-channels can be set into high/low.
  - (b) Output: Channels can be set to output in blocks of eight.
  - (c) Read: Channels can be set to input in blocks of eight.
  - (d) Toggle gate: Changes the time for toggling between high and low for channel 14.
  - (e) Low after input: By receiving a input signal the signal will be low.
  - (f) Toggle High/Low: Toggles certain times between high and low.
  - (g) Toggle Ch. 14: Starts toggling of channel 14.
- 4. Connection
  - (a) COM-Port: Defines the COM-Port one wishes to use (COM1, COM2,..).
  - (b) Connect/Disconnect: The program tries to connect to the Hydra-controller, if currently disconnected. Otherwise it disconnects. A connection procedure involves several responds: It checks if the Hydra-controller is available and on this basis that the linear axis responds and finally the TTL, device, too. If connected, the On Target Timer represents the time the position stays at the current location.
- 5. Program control
  - (a) Automatic cycle mode:

It is possible to move the table manually to a desired position and start an automatic motion, beginning from there on. By clicking the *Start* the table will move to its initial position, if considered. *Pause* provides the option to stop and continue a process and *Stop* will end it in any way. *Center* moves the table to x=y=50 mm.

Automatic c	ycle mode	:	inal		
• inear	Snake	sp	ITAI	ran	dom
			Enc	ł.	
	• linear x di	rection	x 99.9	99 mm	
from actual	🔿 linear y di	rection			
pos.					in
				_	om
<u> </u>	Stop	Move to	X: 50	mm	mm
Clast	0	Cantas	V 50	mm	um

Actual situations are displayed by Start-green / Pause-yellow / Stop-red - LEDs. For pulsing in each step "2. Pulsing." has to be regarded. Four modes can be chosen:

- i. Linear: A straight line will be driven to the edge in a number of steps set by the step size. This is possible from the actual position and from x or y = 0. Additionally, the end position can be specified.
- ii. Snake: First the table moves to its origin (x, y = 0), then it drives a straight line similar to i. By reaching the edge, it moves one step up, returns and moves one step up again. This process will be repeated until the table reaches the end or a defined position. Both endpoints x and y have to possess a certain value, for example x, y = 99.
- iii. *Spiral:* The table moves to a defined starting point and then begins to travel spirally outwards. The spiral is an Archimedes spiral. The distance between the circles can be defined.

iv. *Random:* A default movement function. By choosing the random function, the table will will start moving arbitrarily.

If a mode has been started, the elapsed time will be represented up right (*hours*, *minutes*, *seconds*).

(b) Manual movement: In case of manual motion every single motion has to be done manually, no process that involves more than one step is available.

Center will move the table to x=y=50 mm, too and *Home position* to x=y=0. The Button *Pulse*, surrounded by many circles, can fire the laser once (see "6.4 XY-Table 2. Pulsing"). The movement behavior within the coordinate system is displayed in subtle gray next to the arrow keys  $(\pm x, \pm y)$ .



One LED displays when the table has reached an outer border (*spacelimit reached*) and another when the table has finished the step (*ready*). In case of the latter, a movement is not possible until the LED flashes greenly. Manual movement provides two different behaviour: Absolute positioning and relative positioning. Using

- i. *Move to* will position the table to an absolute location, entered in the x-y input window on the right and the
- ii. Arrow keys will move the table relative to its actual position. The distance for each step is defined in "1. Table settings: (a) step size".

The origin of the xy-table's coordinate system is located bottom right (viewed from the front). This means x=0 is at the right edge and x=100 mm at the left. This circumstance is considered and adjusted in the program, therefore the table moves left by shifting the table manually to the left.

- 6. Current positions: Display the actual positions for x- and y-coordinate, refreshing automatically every 250 ms.
- 7. Receive data:
  - (a) Hydra: Receives error code of the Hydra-controller
  - (b) Table: Receives error code of both linear axis
  - (c) Sensor: Receives error code of the sensors Error codes for checking the controller, table and sensors included in the user manual.
  - (d) Max. current: Receives the maximum current, the motor can use [A]
  - (e) CPU-Temperature: Receives the current CPU-temperature [°C]
  - (f) Trigger delay: Receives the current trigger delay
  - (g) Actual current: Receives the actual current
  - (h) Motor off/on: Switches the motor on or off. When off, the table can be shifted externally. When on, the table will try to hold its position even under external influences

Furthermore, there are four special functions highlighted by graphics:

- Calibrate axis: Table will begin moving to find the motion range limits and a corresponding to it position origin
- Save position: Saves the position to the Hydra-controller, so the table can remember afterwards to start from there
- Reset Hydra: Resets the Hydra-controller. This means that the controller will power off, causing a connection loss, and will power on immediately
- Stop motion: Every actual motion can be stopped

Two queries are permanently executed for various matter:

• Position update: Every 250 ms the program will receive the actual table's position. Each time the position will be written respectively into a \*.txt. file (*position.txt*) as follows:

Number of turn:	0
X:	-9.99999997475243E-7
y:	-9.0000003183377E-6
	·
number of turn:	1
X:	-1.99999999495049E-6
y:	7.00000009601354E-6
number of turn:	2
X:	-2.99999989495029E-6
y:	7.00000097401294E-6

representing a shift only in x-direction of  $1 \ \mu m$ .

• Status timer: Every 100 ms the program will check the program's connection to the Hydra-controller respectively to the axis. Additionally, if the table is currently moving will be provided.

To make modifications within the program commands out of the Hydra-class have to be used.

## 7 Measurements

To ensure the system is working well, the table was shifted to the left in positive x-direction via 5  $\mu$ m steps (y-coordinate: 52.000 mm). The motion in x-direction corresponds to the n-side of the sensor board. At each position the laser was firing continuously with an intensity of approximately 50% at a frequency of 100 Hz. The charge distribution was measured at each position and data from the following five locations was taken off:

Number of steps:	x-position / [mm]:
4	87.015
7	87.030
12	87.055
16	87.075
19	87.090

## 7.1 Charge distribution



Figure 60: Charge distribution on different strips (from 179 to 186): The second curve (red) shows the charge distribution after a travel of 30 µm. Analogously the third (blue) after 40 µm, the fourth (pink) after 60 µm and the last (green) after 75 µm. All relative to the first charge distribution (black).

As one can see in figure 60, the position of the injected charge changes according to the motion of the table, whereas the shape of the charge distribution does not change. The table's motion corresponds to a response of different channels and, in turn, to the kind of response respectively the amplitude of collected charge.
#### 7.2 Change in the amplitude of charge

The charge amplitudes of four channels are plotted against the position of the table, beginning at 87.015 mm with step 4.



Figure 61: The charge amplitude for the channels 180 to 183 in dependence to the position of the table. The amplitude changes according to the location light impinges the sensor.

Figure 61 exhibits that the amplitude of the charge changes in dependence to the positioning of the table. At position 87.03 mm and at position 87.055 mm the laser is straight above channel 182. The travelled distance between both positions amounts to 25  $\mu$ m, which is the half of the pitch, therefore neither an increase or a decrease of the amplitude is expected. Channel 180 to 182 show a decrease of charges injected but channel 183 displays significantly an increase. This could be understood as leaving the laser the ranges of channel 180 to 182 but enters the sphere of action of channel 183.

Only four channels are considered because a fifth channel does not feature five track points, instead two different channels are sharing those.

## 8 Outlook

Future developments will be to set up the triggering of all components. It is crucial that the table only moves in case the laser has fired and not during the firing and so forth. Therefore one possible behavioural dependence is: Table moves  $\rightarrow$  stops  $\rightarrow$  triggers the laser  $\rightarrow$  laser fires  $\rightarrow$  laser triggers the readout system  $\rightarrow$  readout system measures  $\rightarrow$  readout system triggers the table  $\rightarrow$  the table moves. It is necessary to consider and figure out the time for each signal path. Moreover, the laser and its components have to be modified in a way that MIPs can be simulated.

Furthermore, the program will be embedded into the existing readout program, so it is not necessary to have two separate PCs. For the xy-table program itself, two features are planned: Selection of the COM speed and setting the limit ranges of the table according to the size of the sensors.

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## Selbstständigkeitserklärung (Justus-Liebig-Universität Gießen)

Hiermit versichere ich, die vorgelegte Thesis selbstständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt zu haben, die ich in der Thesis angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Thesis erwähnten Untersuchungen habe ich die Grundsätze gute wissenschaftlicher Praxis, wie sie in der "Satzung der Justus-Liebig-Universität zur Sicherung guter wissenschaftlicher Praxis" niedergelegt sind, eingehalten. Gemäß § 25 Abs. 6 der Allgemeinen Bestimmungen für modularisierte Studiengänge dulde ich eine Überprüfung der Thesis mittels Anti-Plagiatssoftware.

 $\operatorname{Datum}$ 

Unterschrift

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