

Muon induced secondary electrons at the KATRIN experiment

Detector installation and setup & data analysis

Diploma Thesis of

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Duration: September 27th 2012 – September 27th 2013

I declare that I have developed and written the enclosed thesis completely by myself, and have not used sources or means without declaration in the text.

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1. Introduction

Ever since the beginning of the 19th century science in general but especially the field of physics has been undergoing an unbelievably quick and vast development. The possibilities arising from automated analysis through the use of advanced computation grids connected to the optimization of manufacturing processes for detectors leave the world - and even scientist - amazed. Nevertheless, with more and more phenomena well understood, the remaining tasks often require huge projects and large collaborations. One of these projects, and a magnificent one at that, is the KATRIN experiment. Working on the project is a liaison of 15 universities and research facilities with over 150 coworkers aspiring to find the absolute neutrino mass scale. So at first, a introduction covering the postulation and discovery of the neutrino as well as latest results from research is given.

Another important topic for this thesis are cosmic rays: Both the particle most significant for KATRIN, the neutrino, and the background inducing muon are generated in different interactions with the atmosphere. That is why a part of this introduction will be devoted to the description of air showers.

1.1. Neutrinos - the early years

The neutrino was not discovered in the conventional meaning but postulated by Wolfgang Pauli, then under the name of “neutron”, as a explanation for the spectrum of the beta decay showing a continuous energy distribution which did not concur with the idea of a two body decay [1].

$$p \longrightarrow n + e^- \quad (1.1)$$

Conservation laws of energy, momentum and angular momentum were violated. The neutrino solved this problem by being a carrier of different kinetic energies thus allowing for a continuous spectrum.

$$p \longrightarrow n + e^- + \bar{\nu}_e \quad (1.2)$$

To be compliant with the laws of conservation, the new particle needed to be of spin 1/2 and chargeless. The first experimental evidence for this particle was then given by Cowan and Reines [2] who observed the reaction of electron-anti-neutrinos and free protons in the large neutrino flux of a nearby nuclear reactor.

$$\bar{\nu}_e + p \longrightarrow e^+ + n \quad (1.3)$$

They then looked for two events: a pair of 511 keV photons from electron-positron annihilation as well as the γ from neutron capture some μs afterwards. Following the electron

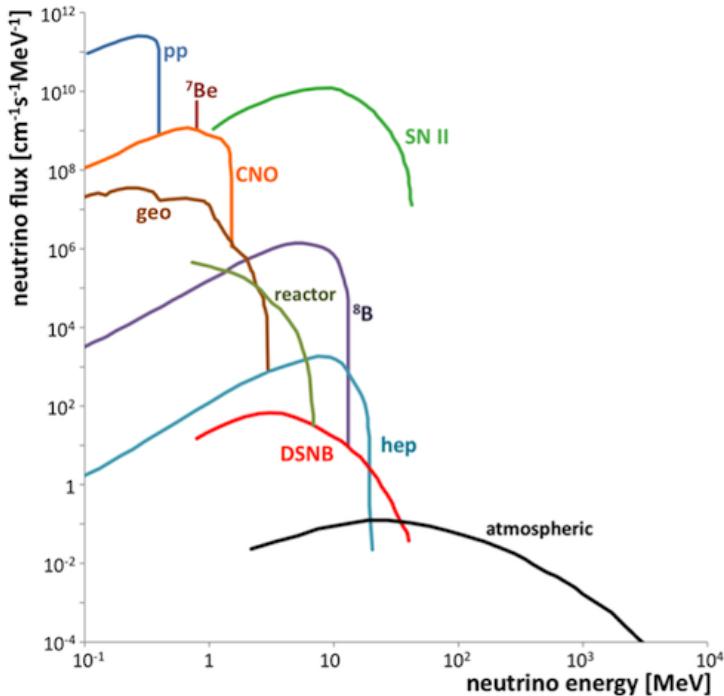


Figure 1.1.:

A graph for different neutrino sources both natural and artificial. In the upper left, solar reactions creating a large integral flux. In the upper mid, the supernovae type II. Peaking at around $10^5 \text{ s}^{-1} \text{ cm}^{-2} \text{ MeV}^{-1}$, geoneutrinos. Right of it reactor neutrinos and ${}^8\text{B}$, the β^+ decaying boron isotope. Following below are the diffuse supernovae background, another solar reaction, hep, and, last and least, the atmospheric neutrinos.

neutrino, both other known neutrino generations have been attested for in various experiments, the first ones to find evidence for ν_μ and ν_τ were to be Danby and Gaillard [3] and the DONUT experiment [4] respectively.

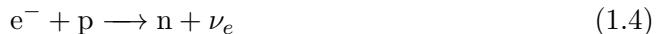
1.2. Neutrino sources

Next to the first indicator of neutrinos, the beta decay with its continuous spectrum, many other reactions produce neutrinos besides easily detectable products. An overview over natural sources creating the largest flux through earth as well as experimental sources is given below, figure

- **Primordial neutrinos**

Lingering around since the “Big Bang”, neutrinos with rather low, thermal energies form a cosmic neutrino background at $T_\nu \approx 1.95 \text{ K}$. These neutrinos decoupled shortly after the Big Bang when densities rapidly dropped and with it the weak force’s reaction rate that before kept an equilibrium between protons, neutrons electrons and neutrinos. This process of “freezing out” alone leads to a static number density of 336 cm^{-3} for the sum over all three neutrino flavors.

- **Supernovae neutrinos** Supernovae type II, which occur less often than the type I and only in stars with $M > 8M_\odot$, are known to produce large quantities of neutrinos. Inside the burned out collapsing star, the electrons’ degeneracy pressure leads to de-leptonization of the core by electron capture.



This process produces high energy neutrinos leaving the core and carrying away energy in the process - and large quantities of that: about 99 % of the energy released during a type II supernova cooling phase is carried away by neutrinos.

- **Solar neutrinos**

Our sun’s pp reaction chain equation (1.5) - dominant in its energy production -

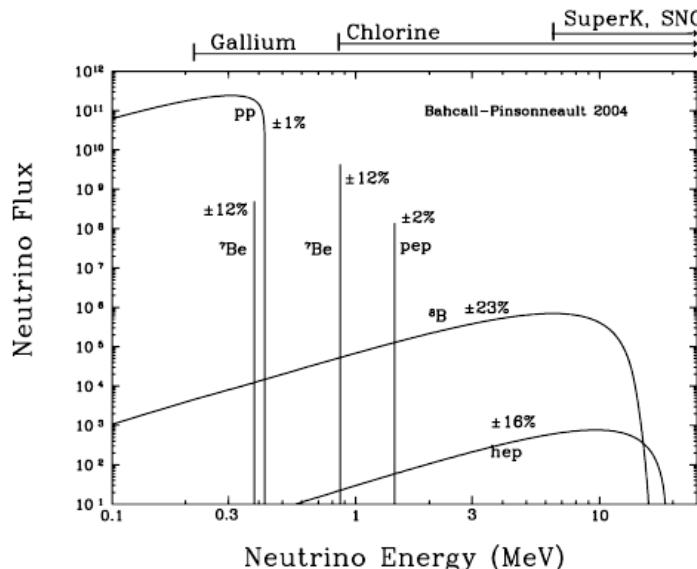
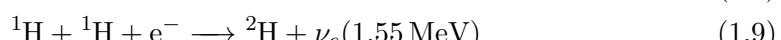


Figure 1.2.: The graph shows the theoretical solar neutrino flux in $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ over the neutrino energy - for line sources in $\text{cm}^{-2} \text{s}^{-1}$. Different processes are shown, the dominant pp process is visible in the upper left. CNO fluxes are dropped in this figure. On the very top, the sensitivities of different experiments are shown.

produces neutrinos in a continuous energy range (upper energy limit given) together with other, less dominant reactions.



Further on, electron capture processes add line spectra to the picture



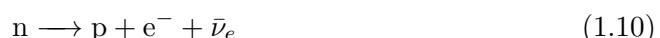
where ${}^7\text{Be}$ emits at two energies: mostly at 0.86 MeV (90 %) and another, lower energy line at 0.38 MeV (10 %) [5]. These reactions are responsible for the largest part of the solar neutrino flux through the earth. Predictions on this flux are shown in figure 1.2 together with other model calculations on flux expectations. Solar neutrinos were essential for oscillation research and by that for the proof that neutrinos are in fact massive (see chapter 1.4).

- **Atmospheric neutrinos**

As described in section 1.7 cosmic rays, consisting mostly of hadrons, which, in turn, are mostly protons, constantly impact onto the upper layers of the atmosphere. Here, they create air showers, cascades of the initially high energy particles into thousands of particles of lower energies. In that process, not only muons relevant considering background processes in KATRIN, but also neutrinos originate raising the flux through earth.

- **Reactor neutrinos**

Nuclear fission produces large quantities of neutrons that decay following



Three Generations of Matter (Fermions)			
	I	II	III
mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name →	u up	c charm	t top
Quarks	d down	s strange	b bottom
Leptons	e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
Bosons (Forces)	Z^0 weak force	W^\pm weak force	

Figure 1.3.: Particles stated in the standard model. On the upper left quarks, on the lower left leptonic particles. The very right row contains the bosonic force particles. Note the absence of the graviton.[9]

A fission reactor, in which many of these reactions concur, is hence a strong source of neutrinos, depending on the reactor's size of course. On an average GW reactor, around 6 neutrinos per fission reaction emerge. These sources are used in many experiments, among other things to prove the existence of neutrino oscillations (see chapter ??). The Daya Bay experiment for example was able to attest the disappearance of $\bar{\nu}_e$ in a baseline experiment [6].

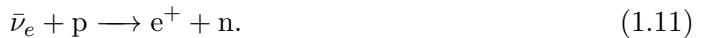
- **Neutrinos from β decays**

Very important for the KATRIN experiment are neutrinos from beta decays, more precisely the tritium beta decay. This is described in more detail in chapter 2.1.

1.3. Neutrinos in the standard model

During the second part of the 20th century, a model stating 16 particles has been developed to describe a huge portion of known phenomena - the standard model. It contains six quarks and six leptons (both made up of three particle generations) making up the matter as well as four types of Gauge Bosons. The latter are carriers of the standard model's interactions of the former particles, meaning all interactions of matter are based on the exchange of one or more of the Gauge Bosons. Lately, proof for the Higgs particle, a scalar boson, stated as a carrier of mass seems to have been found at CERN [7, 8]. It is the last particle to complete the standard model. For our universe, gravity, the graviton generated force, plays a major role for formation and stability of almost all larger structures. In particle physics however, it can mostly be neglected. Here, only the strong and weak as well as the electromagnetic interaction make for noticeable contributions to phenomena observed. That is why, in the standard model, gravity as well as its carrier, the graviton, are disregarded.

Most of what we can observe with our bare eyes or in basic experiments is attributable to the electromagnetic force or gravity, however, strong and weak interaction do play a major role when it comes to high energy physics. Here, the limited reach of the two is overcome by small distances between interacting particles. In case of the neutrino, detection and by that the study of its characteristics is even more difficult as it interacts only gravitationally and weakly. Now, as mentioned before, gravity is indeed long range, but very weak in force. And although weak interaction is a lot stronger compared to gravity, it is still weak compared to both electromagnetic and strong interactions. That is why the neutrino is considered elusive, detection efficiencies are low and only large scale detectors are able to detect statistically relevant amounts of neutrinos. One method used quite frequently is the Cherenkov radiation emitted by particles travelling through matter at speeds above the speed of light. The occurring cones of light, comparable to the supersonic cones planes cause in air, can be detected by standard photomultiplier tubes. The problem is that, as mentioned above, the volumes to be able to make dependable statements on directions and energies need to be large. This is why most experiments make use of “natural” detectors such as water [10] or even ice [11]. Other approaches are to catch neutrinos in reactions where those are required such as inverse beta decays in reactors



In the standard model, neutrinos are considered massless. Many experiments though have shown that the weightless neutrino is a wrong assumption. Most of these were experiments proving neutrino oscillations with both reactor neutrinos and solar neutrinos such as Kamiokande[12], the Daya Bay experiment [?] or SNO [13]. Important for those experiments is the known source location making baseline analysis possible.

Up till now, only the differences of the squared masses are known. This leads to different relations depending on how masses are distributed between the flavors, see figure 1.4, and how large they are absolutely, see figure 1.5. This problem is solved by the knowledge of one of the masses. KATRIN is on the verge of finding the ν_e ’s mass. Two mass schemes are possible: the normal and the inverted one. Normal means that the smallest number also describes the smallest mass state, i.e. $m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$. In the inverted scheme, the squared mass difference of eigenstates two and three is not directed upwards, but pushes the m_{ν_3} mass below the other two.

1.4. Neutrino Oscillations

If the neutrinos were without mass, its mass eigenstates would equal its flavor eigenstates. First doubts concerning this assumptions occurred as inconsistencies between the measured and the calculated solar ν -flux occurred at the Homestake mines [14]. As the count on ν_e was too low, the theory of neutrino oscillations emerged, stating that a mixture of flavors was possible as the flavors were made up of all three of the mass eigenstates. The mixture is described by the so called Pontecorvo-Maki-Nakagawa-Sakata matrix:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e,1}^* & U_{e,2}^* & U_{e,3}^* \\ U_{\mu,1}^* & U_{\mu,2}^* & U_{\mu,3}^* \\ U_{\tau,1}^* & U_{\tau,2}^* & U_{\tau,3}^* \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \quad (1.12)$$

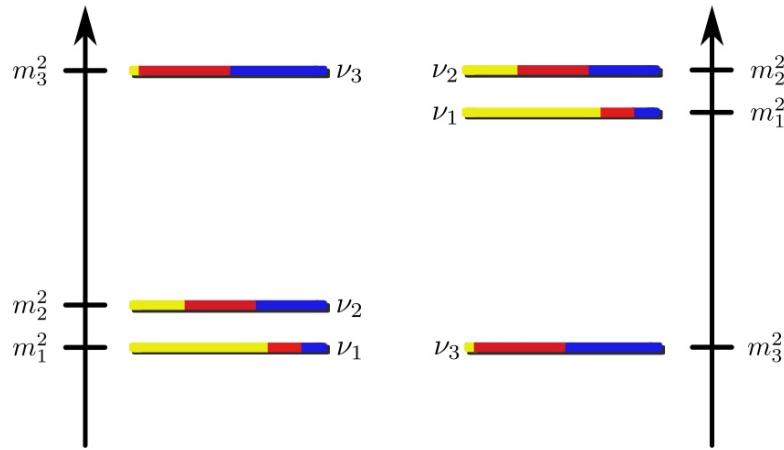


Figure 1.4.: The possible mass hierarchies for neutrinos. Left, the normal scheme with $m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$, on the right the normal scheme where $m_{\nu_1} < m_{\nu_2}$ is still true, though both $m_{\nu_3} < m_{\nu_1}$ and $m_{\nu_3} < m_{\nu_2}$. The colored bars represent the matrix elements for each flavor, i.e. the probabilities of measuring the mass eigenstate while detecting a pure flavor. Yellow stands for ν_e , red for ν_μ and blue for ν_τ .

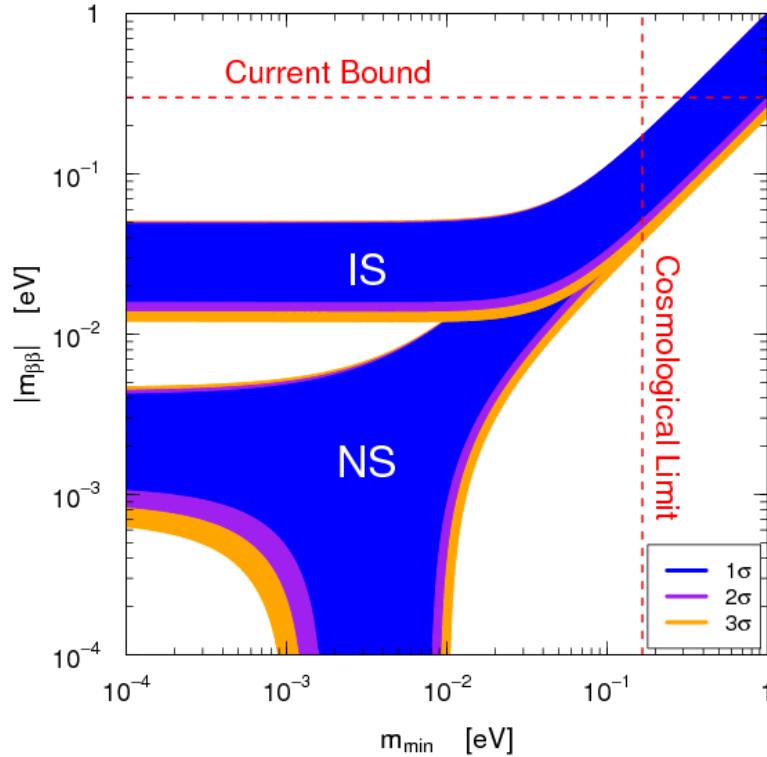


Figure 1.5.: The possible effective masses for neutrinos depending on the lightest neutrino mass m_{min} shown on the x-axis. Normal and inverted scheme are marked NS and IS. The current bound from $0\nu\beta\beta$ decay is displayed as well as cosmological limitations.

parameter	value
$\sin^2(2\Theta_{12})$	0.875 ± 0.024
Δm^2_{21}	$(7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2$
$\sin^2(2\Theta_{23})$	>0.95
Δm^2_{32}	$(2.32 \pm 0.12) \text{ eV}^2$
$\sin^2(2\Theta_{13})$	0.095 ± 0.010

Table 1.1.: Given are the latest known mixing angles and squared mass differences. For $\sin^2(2\Theta_{23})$, the lower limit is given.

Though mixing angles are known pretty well, there are still experiments being built that challenge the current error margins such as the LENA experiment which might be able to raise the precision of the mixing angle Θ_{12} by a factor of 10 and may even find the still unknown mixing angle Θ_{13} ([16]).

In this equation, the matrix U can be parametrized through a combination of three rotation matrices and a complex phase factor δ_D as well as two complex majorana phases δ_M

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_D} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\delta_{M1}} & 0 & 0 \\ 0 & e^{i\delta_{M2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.13)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$.

Now the pure eigenstate of a neutrino for $t=0$ can be described by three matrix elements and the corresponding mass eigenstates.

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}^* |\nu_1\rangle + U_{\alpha 2}^* |\nu_2\rangle + U_{\alpha 3}^* |\nu_3\rangle \quad (1.14)$$

The time evolution of this state now reveals the oscillations of the neutrino from flavor to flavor, as the time evolved states are not flavor eigenstates for every point in time.

$$|\nu_\alpha(t>0)\rangle = U_{\alpha 1}^* e^{-iE_{\alpha 1}t} |\nu_1\rangle + U_{\alpha 2}^* e^{-iE_{\alpha 2}t} |\nu_2\rangle + U_{\alpha 3}^* e^{-iE_{\alpha 3}t} |\nu_3\rangle \neq |\nu_\alpha\rangle \quad (1.15)$$

This means that the probability to find a state different from the initial one is non-zero for most times.

$$|\nu_\alpha(t)\rangle = \sum_{k=1,2,3} U_{\alpha k}^* \exp(-iE_k t) |\nu_k\rangle \quad (1.16)$$

for every state $|\nu_\alpha\rangle$. If the mass eigenstates in turn are expressed as a mixture of flavor eigenstates, one can extract the prefactor of the sums components as the transition probability for each single flavor:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle| = \left| \sum_{k=1,2,3} U_{\alpha k}^* \exp(-iE_k t) U_{\beta k} \right|^2 \quad (1.17)$$

Various baseline experiments have found results for all mixing angles except Θ_{23} for which a lower limit is known according to [15]

1.5. Indirect measurement of neutrino mass

One approach to get access to the neutrino mass is on indirect ways, i.e. using data that is affected by neutrinos but does not directly involve them. Two main techniques are to be indicated here.

First, the search for neutrinoless double beta decay, $0\nu\beta\beta$. The double beta decay $2\nu\beta\beta$ in which two neutrinos are emitted only occurs if the single β decay is prohibited by a heavier $^{A}_{Z+1}X$ core and follows the equation



Compared to this $2\nu\beta\beta$ decay the $0\nu\beta\beta$ decay can exist only if the neutrino is its own anti-particle, a so called Majorana neutrino. Then, if a nucleus double beta decays, the neutrino from one vertex can be absorbed in the second as an anti-neutrino with inverted helicity - or vice versa. As this change in helicity is only possible for a massive particle, the $0\nu\beta\beta$ decay would be further proof of a massive neutrino. Furthermore, as the probability for a helicity change is correlated to particle mass the rate, and with it the half life $t_{1/2}$, would depend on the effective Majorana neutrino mass square [17].

$$\Gamma_{0\nu\beta\beta} \propto \left| \sum U_{ei}^2 m(\nu_i) \right|^2 \quad (1.19)$$

Secondly, the problem can be approached by calculations using astrophysical data. For one, the formation of galaxies and other structures in the universe depends on the neutrino mass. In the formation, neutrinos wash out the structures as they act as hot dark matter. A galaxy's power spectrum's fluctuation is suppressed by massive neutrinos. Using long term spectroscopic galaxy surveys like SDSS[18] or studying the cosmic microwave background like WMAP [19] or Planck [?], a upper limit of 0.6 eV on $\sum_\nu m_\nu$ can be given. As the indirect methods for neutrino mass measurements depend at least to some point on model assumptions, the direct methods in the next section play a key role in finding standalone values or limits for neutrino mass.

1.6. Direct measurement of neutrino mass

Direct measurements of the neutrino mass require a reaction known to include neutrinos in its equation, usually the previously mentioned β decay. Advantageous for direct measurements is the only assumption made is the applicability of the relativistic energy-momentum-relation $E^2 = m^2 c^4 + p^2 c^2$. This makes the results mostly model independent. There are both spectrometric and calorimetric approaches. While the scale of spectrometers is getting bigger and bigger, calorimetric approaches seem to be a reasonable alternative, although the slow detector response - the detector material itself is decaying - requires for large arrays of detectors leading to extensive space requirements as well at some point. The luminosity of spectrometer experiments though is unachieved by any other. That is why the KATRIN collaboration is working on a setup to measure electrons from Tritium decay to determine the neutrino mass. Tritium is advantageous for several reasons listed below.

- A high luminosity is ensured by the short half life of $t_{1/2} = 12.3$ a. This makes small amounts of the emitter sufficient to ensure good statistical results.
- At the same time, the inverse of the cubic endpoint energy ($1/E_0^3$) defines the amount of electrons emitted in the endpoint region (up to 1 eV below the endpoint). Tritium's low endpoint energy of 18.6 keV, undercut only by one β emitter, rhenium, that has other disadvantages, ensures high luminosity at the detector.

- According to [20], as the tritium beta decay is superallowed, the matrix element $|M_{had}|$ is energy independent making corrective energy calculations unnecessary. This simplifies analysis procedures.
- Another simplification compared to different emitters is the easily calculable electron shell configuration. Excited states and their energies are accessible in theory for all decaying particles.
- As far as scattering is concerned, tritium is a well suited material as well. Its low atomic number makes for small cross sections for inelastic scattering. This reduces energy smearing inside the source volume.

These reasons make tritium the element of choice for KATRIN.

The above mentioned rhenium is used in the calorimetric approach. Experiments like MARE [21] use rhenium in bolometers as both emitter and detector. The lower endpoint energy of 2.47 keV guarantees a rather big fraction of electrons with energies near the endpoint, but this is largely compensated for by the much longer half life of $t_{1/2} = 4.32 \times 10^{10}$ a. Still, the mass of rhenium required to gain statistically relevant results remains below the tritium mass used in KATRIN. The MARE strategy is to split the radioactive material and use it in many small microbolometers. That is beneficial as readout is slow and the rate per bolometer is reduced by lowering the emitter mass. Thermistors then sample the temperature catching peaks induced by electrons from β decays scattering inside the solid source. The experiment set up by the Milano collaboration has set upper limits of

$$m_{\bar{\nu}_e} < 15 \text{ eV at 90 \% C.L..} \quad (1.20)$$

This limit shall be pushed to 0.2 eV according to [21].

1.7. Cosmic rays from the viewpoint of KATRIN

When high energy particles hit the upper parts of the atmosphere, a cascade of particles generated from the interaction with atmospheric molecules and atoms follows. Most primary particles are nucleons, most of which again are free protons (85%), i.e. Hydrogen ions, followed by α particles (15%). Helium nucleons' fluxes are already about an order of magnitude below the hydrogen ones, higher mass number nuclei show even lower rates, see figure 1.6 [22]. **(insert right side graphic from TODOR)** By different forms of interaction, roughly dividable into the three groups of electromagnetic, inelastic hadronic and nuclear phenomena, secondary particles are created [22, 24].

ToDo

- **Nuclear fragmentation**

For very high energy primary particles above the separation energy E_s according to

$$E_s \simeq E_b(N, Z) - E_b(N_F, Z_F) - E_b(N - N_F, N - Z_F) - \frac{Z_F(Z - Z_F)}{(A - F)^{1/3}} \quad (1.21)$$

it is possible to fragment a nucleous. The first three terms describe the binding energies of the nuclei involved, the last term accounts for the coulomb barrier. Of course, especially for higher order nuclei, more effects become relevant and one has to rely on empirical descriptions of the problem.

- **Inelastic hadronic interaction**

For high energies, quantum chromo dynamics describe the interactions of particles pretty well, while for energies below 1 TeV one has to rely on phenomenological descriptions. These interactions are prominent in the production of secondary particles like pions or kaons.

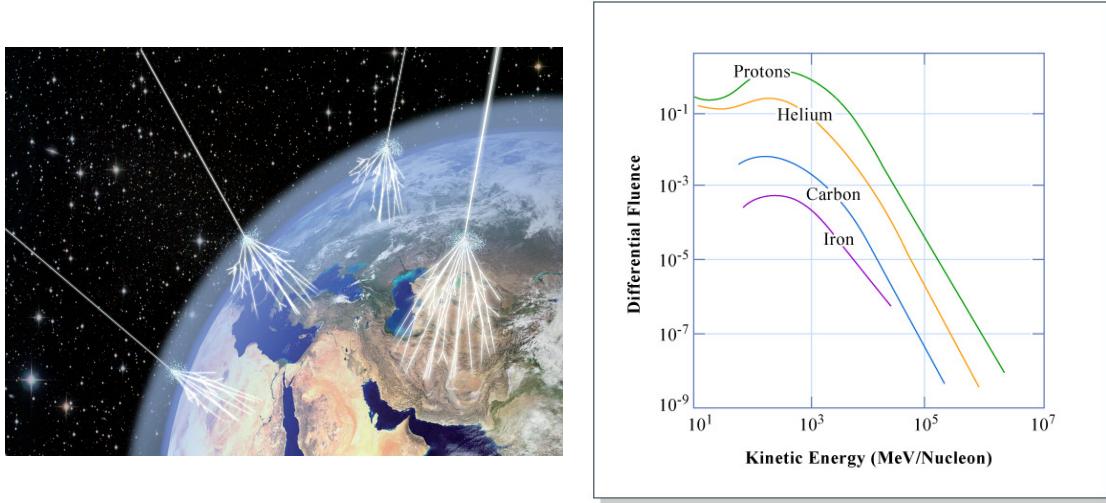


Figure 1.6.: On the left, an artistic impression of various cosmic rays hitting the atmosphere [23]. On the right, the measured composition for cosmic nuclei is shown: on top, the lightest particle, the proton. further down, all with orders of magnitude smaller rates, heavier ions, figure from [22].

- **Electromagnetic interaction**

The electromagnetic component is the main interaction channel for lighter, charged particles like muons or electrons but also for photons. As the propagation of muons is especially important here, these interactions will be described in some more detail.

- **Coulomb scattering**

If one charged particle passes another, it is deflected in its field according to

$$\tan \frac{\theta}{2} = \frac{zZe^2}{Mv^2b} \quad (1.22)$$

- **Ionization losses**

Through ionization and excitation of molecules, incident particles loose energy in a medium, in this case the atmosphere, according to

$$\frac{dE}{dx} = -\frac{N_a Z}{A} \frac{2\pi (ze^2)^2}{M'nu^2} \left[\ln \frac{2Mv^2\gamma^2}{W} I^2 - 2\beta^2 \right] \quad (1.23)$$

Z is the atomic, A the mass number of the medium, I the average ionization potential. N_a is Avogadro's number, ze the particle charge, v its velocity and M its mass. $\beta = v/c$ and $\gamma = 1/\sqrt{1 - \beta^2}$ and W the maximum energy deposit [25].

This is the effect used for muon detection in the KATRIN experiment, see 3.

- **Compton scattering & inverse compton effect**

Compton scattering is the photonic counterpart to ionization by charged particles. In the process, a photon interacts with bound electrons and excites or ionizes the corresponding atom. In the process the photon looses energy shifting it towards longer wavelengths.

The inverse compton effect, as the name suggests, describes a photon gaining energy from an atom's hull electron.

- **Bremsstrahlung & synchrotron radiation**

When charged particles are deflected in electric fields, photons are emitted and

the particle loses energy. The same is applicable for magnetic fields, where the effect is called synchrotron radiation and a time dependent energy loss occurs. The total energy loss for electric fields can be described by

$$\frac{dE}{dx} = \frac{4N_A Z^2}{A} \alpha r_e^2 E \ln(183Z^{1/3}) = \frac{E}{X_0} \quad (1.24)$$

where the radiation length has been introduced to describe the average matter necessary for a particular Energy loss.

– Electron-positron creation

A photon of sufficient energy ($2 \times 511 \text{ keV}$) can create a electron-positron pair either in the field of an atom's electron hull or in the field of its core. With higher energies, other particles can be created considering the known conservation laws. This process can be seen as the inverse bremsstrahlung, assuming the outgoing anti-particle to be its time inverted particle. The energy loss can be described similarly and scales with the incident particle's energy linearly.

– Cherenkov radiation

Much lower amounts of energy are lost in the creation of cherenkov light. The process is particularly important though as it makes for easily detectable particle indicators. Cherenkov radiation occurs when particles move through matter at speeds above the phase velocity of light c/n for a refractive index n . As the atmospheric refractive index is only slightly above 1, particles need to be super-relativistic to emit cherenkov light.

After cascading mostly through multiple intermediate particles, at sea level about 80 % of the cosmic particles are muons. These are super-relativistic due to their small masses though high energies. Even at these high speeds, the muons' average decay time of around $2.2 \mu\text{s}$ [26] is too small for many muons to reach the earth's surface from our reference frame's point of view. In the most common production height of 2 km [27], the non relativistic time of flight for a 90 % speed of light particle would be

$$t_{class} = 2 \text{ km} / 0.9 \cdot c = \quad (1.25)$$

meaning only time dilation from special relativity makes the muon flux as large as it is:

$$t_{rel} = t_{class} / \sqrt{1 - 0.9^2} \quad (1.26)$$

which, from our reference frame, prolongs the lifetime by a factor of around 5, being already enough to reach the surface from heights of 3 km. Most muons have even higher energies, making it possible for them to reach surface from greater heights and under non perpendicular angles towards it. For KATRIN, this poses a problem. A smaller flux would be advantageous, as muons may cause emission of electrons from the spectrometer vessels surface. Shielding against muons is difficult as it requires thick layers of dense matter due to the muons high energies and the low deposition in matter in relations to those. The fluctuation of energy deposition of a charged particle as the muon in matter can be described by the landau distribution that is parametrized as follows [24].

$$L(E) = \frac{1}{2\pi} \exp \left\{ -\frac{1}{2} \left(E - \hat{E} + \exp(-(E - \hat{E})) \right) \right\} \quad (1.27)$$

\hat{E} is the most probable energy deposition value. The analytic distribution is shown in figure 1.7. The muon modules show that distribution as expected, see 3 for details.

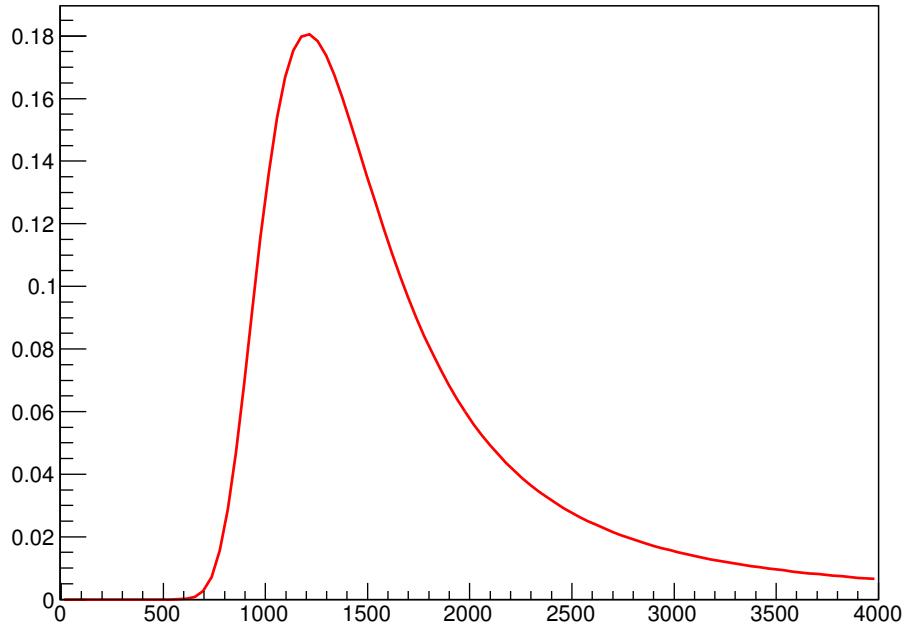


Figure 1.7.: Analytic landau distribution as implemented in the ROOT software. \hat{E} was set to 1200.

2. KATRIN experiment

The KATRIN experiment is on its way to measure the neutrino mass or set new upper limits at precisions never achieved before. It will reach a sensitivity of $200 \text{ meV}/c^2$ at 90 % C.L. excelling the previously best experiments of Mainz and Troisk by a factor of 10. Major challenges of the project are the requirement of ultra high vacuum, the exact knowledge of all magnetic and electric fields as well as external influences on those, the required high luminosity of the tritium source and the classification and reduction of background sources.

2.1. Measurement principle

A generally easy principle is used to find information on the neutrino mass. The energy of electrons from tritium decay is measured with high precision and compared to the standard model's presumption for a massless neutrino [28]



As the decay's energy is distributed between the constant neutrino's rest mass and the neutrino's and the electron's kinetic energies respectively, the decay electrons will show a continuous spectrum. The difference between the electron energy calculated by standard model presumptions and the extrapolated maximum electron energy from the spectrum is extracted. As all three mass eigenstates contribute to the electron neutrino's mass in any scenario (see 1.4, the difference will be a superposition of these. The knees occurring at each single eigenstates mass can not be resolved with the KATRIN spectrometer as the energy resolution is larger than the root of the squared mass differences. shown in figure 2.1. As all three flavors contribute to the electron neutrino's mass, what will be measured is the incoherent sum of all three as described in chapter 1.3.

A different light is shed on the simplicity of the task when considering the needed accuracy of $\Delta E < 0.93 \text{ eV}$ needed for the electrostatic filter to achieve the desired sensitivity [29]. And this is just one in a meshwork of requirements necessary. All components need to work as a whole in the end, not a single one may contribute to the background much more than expected.

2.1.1. MAC-E Filter

To measure the energy of electrically charged decay electrons at high precision, an electrostatic filter comes to mind. As the electrons are emitted isotropically, they will have

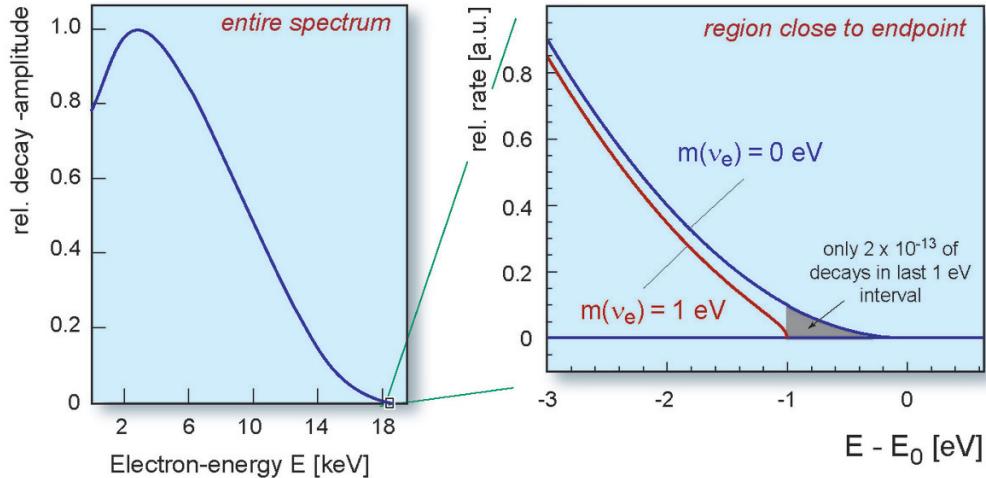


Figure 2.1.: Schematic energy spectrum for electrons from tritium beta decay. On the left, the entire spectrum with the peak at the energy most emitted - around 5 eV - can be seen. On the right, a zoom-in on the endpoint showing both the calculations for a massless and a 1 eV neutrino. As described in the graph, rates in this region are extremely low and extrapolation through advanced software tools needs to be applied.

momentum components both parallel and perpendicular to the source-detector axis (defined as the z-axis). To make statements on the overall energy, the momentum direction needs to be well defined. In case of an electrostatic filter, it needs to be parallel to the electric field to be analyzed. At the same time, a high luminosity is a major requirement for good statistics for the KATRIN experiment. To satisfy all these requirements, several techniques are combined in the MAC-E filter - magnetic adiabatic collimation with electrostatic filter [30].

Magnetic fieldlines connect the source and the detector. Electrons from tritium decays are guided from source side to detector in cyclotron motion around one of these field lines. This strongly raises luminosity as electrons with large angles towards the z axis will not necessarily hit the wall of the source but will be able to reach the detector.

Adiabatic motion in the magnetic field is defined by the allowance of momentum direction changes at constant momentum value. That is given if the magetic field change is small within each cyclotron orbit. If so, the magnetic momentum μ correlated to E_{\perp} (the energy perpendicular to the magnetic field B) as follows remains constant

$$\mu = \frac{E_{\perp}}{B} = \text{const} \propto \frac{p_{\perp}^2}{B}. \quad (2.2)$$

Collimation in a MAC-E filter is based on the above adiabacity. Magnetic field strengths drop over several orders of magnitude from B_{max} at the solenoid magnets to B_{min} in the analysis plane (see figure 2.2). Considering equation 2.2, this means that the energy perpendicular to the magnetic field must drop over the same order of magnitude for μ to remain constant. This leads to a parallelization of momentum vector and B-field direction.

Electrostatic filtering occurs exactly at that point of minimal energies E_{\perp} in the analysis plane. Here, the momentum vector is mostly defined by its component parallel to the

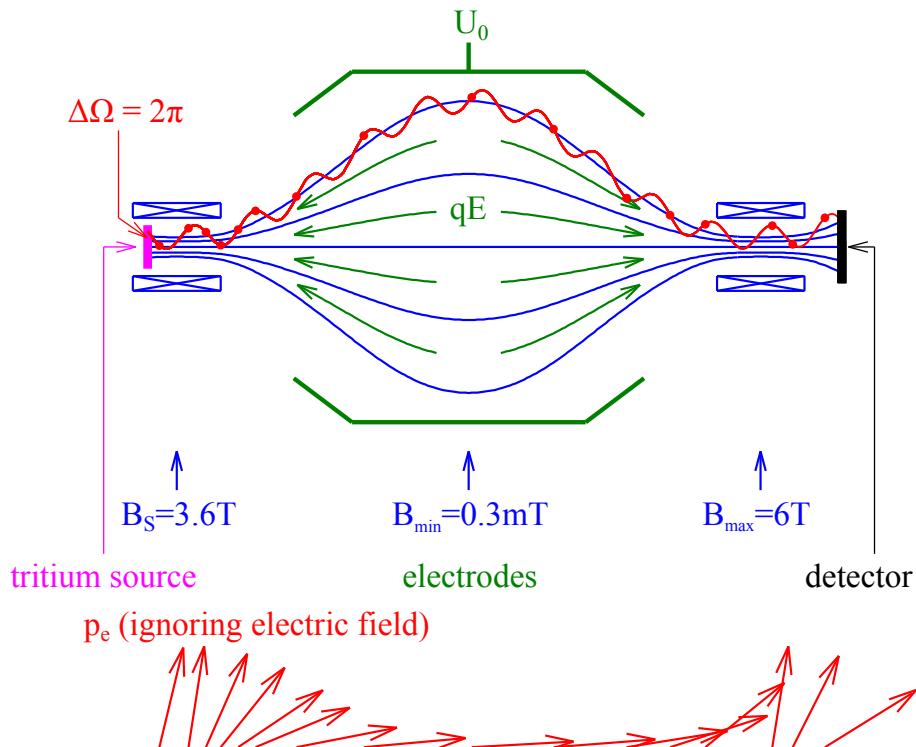


Figure 2.2.: Principle of a MAC E filter. In the upper part, magnetic fieldlines are plotted in blue together with fieldstrengths at the source (3.6 T) and inside the pinch solenoid (6 T). The accepted solid angle and a exemplary particle path are shown in red. The analysis plane is defined by the area of minimum magnetic fields B_{min} . Below, the momentum of an electron with a large starting angle towards the magnetic field lines is shown. It is tipping over as the field weakens. Meanwhile, the vessel voltage U_0 analyses the energy parallel to the electric field passing only electrons with large enough energies on to the detector [32].

magnetic field $E_{||}$. Setting the electrostatic filter to a fixed voltage U now reflects electrons with $E_{||} < U \cdot e$.

Most electrons are emitted at the source are non-parallel to the magnetic field lines and thus an energy $E_{\perp} \neq 0$. That means that it is very likely that electrons in the analysis plane have remaining energy E_{\perp} . This limits the filter resolution, with

$$\mu_{low} = \frac{E_{\perp min}}{B_{min}} = \frac{E_{\perp max}}{B_{max}} = \mu_{high} = \mu \quad (2.3)$$

the relative sharpness is given by the maximum transversal energy $E_{\perp max}$ that is still accepted in the filter. As for a

$$\Delta E = E_{\perp max} = E_0 \frac{B_{min}}{B_{max}} \quad (2.4)$$

Only in the edge case of $B \rightarrow 0$ in the analysing plane, the momentum would need to be exactly parallel to the field and the resolution would not be limited. After passing the analysing plane, the electrons are reaccelerated by the electric field and guided and focused onto a detector. To additionally dismiss electrons with large starting angles towards the magnetic field, the source field strengths are chosen to be smaller than the maximum field strength inside the solenoid. This ensures that electrons with long paths that are more likely to scatter will not be analyzed through the effect of magnetic mirroring [31]. With the chosen settings, this results in an angular acceptance of 50.77° . The main spectrometer reaches a resolution of 0.93 eV (see section 2.2.4 for more details).

2.2. Experimental Setup

The KATRIN experiment is made up of different sections all fulfilling their own important purpose in the whole setup. All begins at the windowless gaseous tritium source “WGTS”. Here, tritium decays isotropically emitting electrons. These are guided magnetically through the differential and cryogenic pumping sections “DPS” and “CPS” removing hydrogen ions and other residual gases in the process. At the same time, looking at the WGTS from the other direction, the rear section scans the activity of the source. For the electrons on their way to the detector, the path continues through the two spectrometers posing as a energetic high pass filter to the focal plane detector “FPD” registering them.

During the whole procedure, the electrons from the decay may not undergo energy changes as the knowledge of their kinetic energy after decaying is essential to the experiment. That is why the guiding needs to be adiabatic. This is guaranteed by spatially slowly changing and timewise very constant magnetic fields.

See figure 2.3 for a schematic overview of the whole experimental setup. It follows a more detailed description of the individual components.

2.2.1. WGTS and Rear Section

To generate tritium decay electrons, a gaseous tritium source is utilized (see figure 2.4). Advantages of the principle are the absence of solid state effects and a high luminosity [33]. In a solid, like tritium films, most electrons from decays inside the structure would interact with the solid itself. That could lead to energy shifts threatening the energy resolution. Another advantage of using a gaseous source is that not only the surface facing the detector emits electrons at the required spectrum, but the electrons from the whole volume covered by the magnetic flux tube hitting the detector can be analyzed. Furthermore, the emission of this kind of source is very homogeneous. Of course, new challenges arise from the decision to use gas instead of solids.

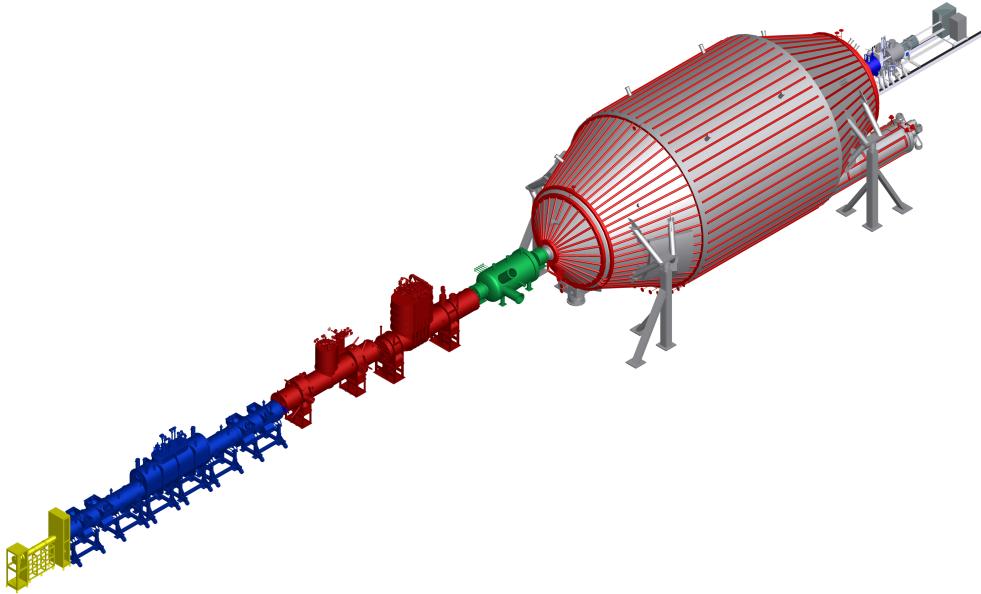


Figure 2.3.: The beam line of the KATRIN experiment with the different stages: Rear section (yellow) and WGTS (blue) on the very left, followed by the transport section (red) consisting of DPS and CPS. Energy analysis in pre- (green) and main spectrometer (grey-red) of the spectrometer section and electron detection at the detector section (grey-blue).

- The source's temperature needs to be very robust (max. ± 0.03 K at 30 K) to guarantee a rate stability of ± 0.1 % for the decay electrons [34].
- The spectrometers further downstream require for ultra high vacuum, for the main spectrometer in the order of 10^{-11} mbar. With the tritium pressure is in the order of 10×10^{-3} mbar and the source's need to be windowless - no electron transparent window is known to stand such pressure differences - the pressure must be reduced to desired values without any physical barrier.
- The tritium isotope contributions of the gas need to be known precisely, for that purpose a laser-raman-system has been developed [35].
- All devices used in contact with tritium have to undergo excessive testing in tritium environment to fault failure safety under the harsh conditions.

2.2.2. Transport and Pumping Section

In the DPS, pressure is actively reduced by seven orders of magnitude with the use of turbo molecular pumps. These as well need to be tested thoroughly to withstand the constant radiation by tritium decays [38]. The tritium gas is then processed to be reused in the tritium cycle. Further downstream, the CPS uses strongly cooled walls to freeze residual gas, always keeping the information carrying electrons away from those by magnetic guidance.

2.2.3. Pre-Spectrometer

The pre-spectrometer was built to reduce the flux to the main spectrometer by 7 orders of magnitude [41]. It works on the MAC-E filter principle from chapter 2.1.1. Being a lot smaller, its energy resolution can of course not compete with the main spectrometer one. Its purpose is to cut off the spectrum below energies of 18.4 keV, the electrons above that limit will pass and be further analyzed in the main spectrometer. Here, it is important that

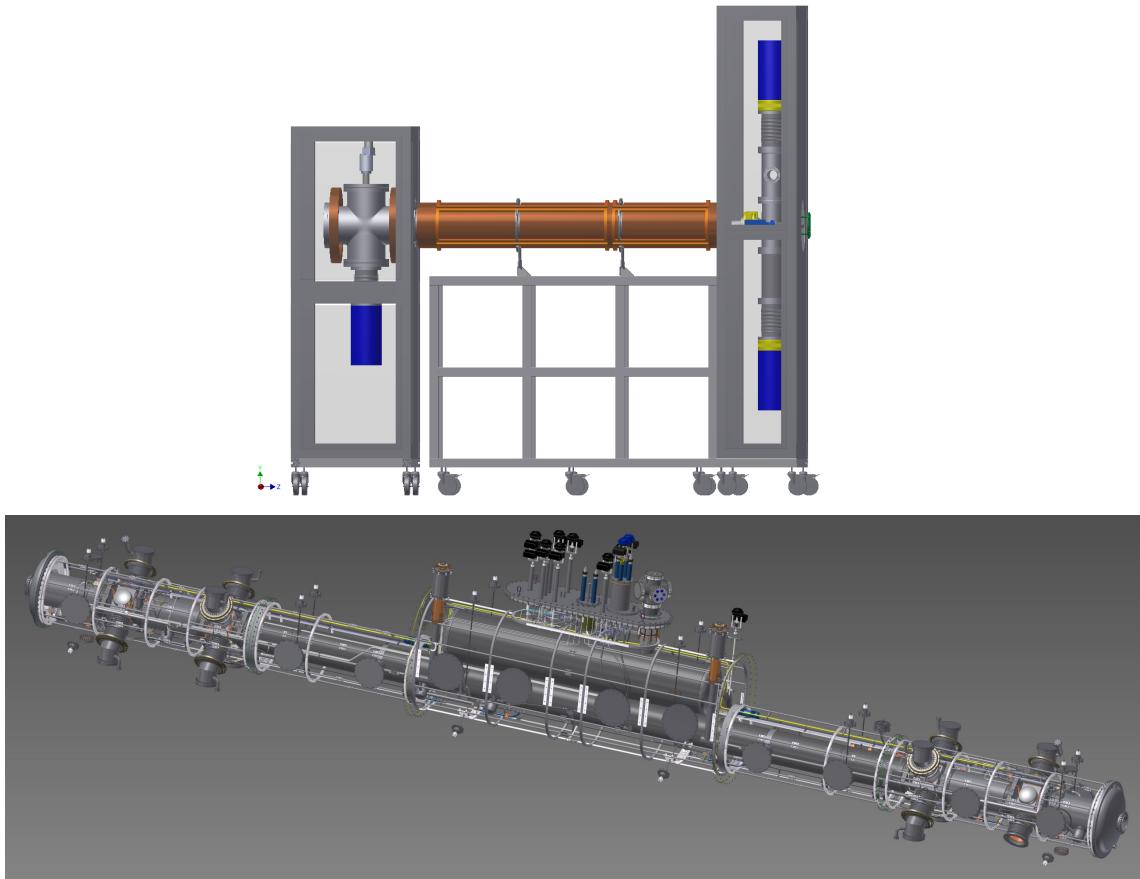


Figure 2.4.: On top, the rear section. In the model, there are two large attachments visible perpendicular to beam direction. The right one is the e-gun for calibration purposes. LEFT ONE!!!!. Also visible are the gray second containment boxes making for redundancy in radiation security. Below a model of the WGTS. The many pumping ports are clearly visible on the left and the right end, in the wider, middle section tritium is injected. Images from [36] and [37]

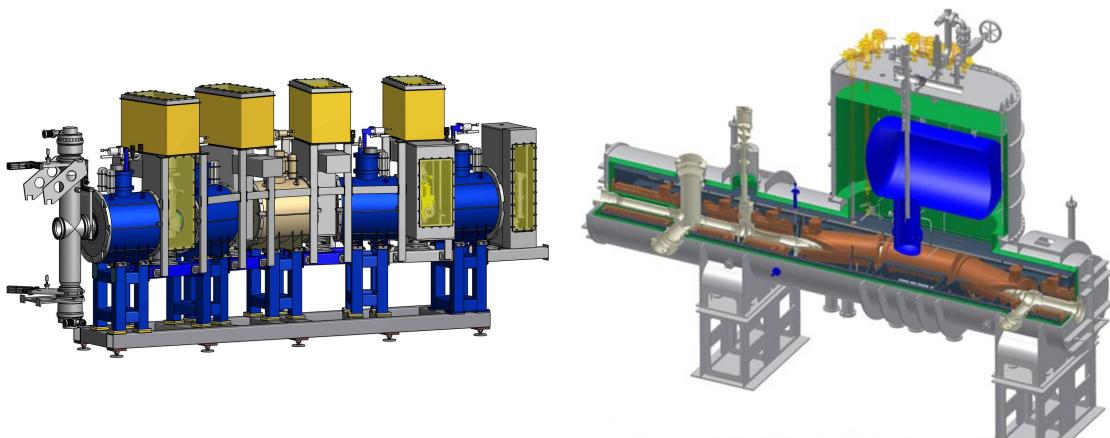


Figure 2.5.: Differential and cryogenic pumping sections, left the DPS with pumping ports all over the structure. All of the ports are isolated against the surroundings (yellow boxes) to protect against potential radiation leaks. On the right the CPS with its coolable wall structure to capture free particle as well as standard pumping ports [39, 40].

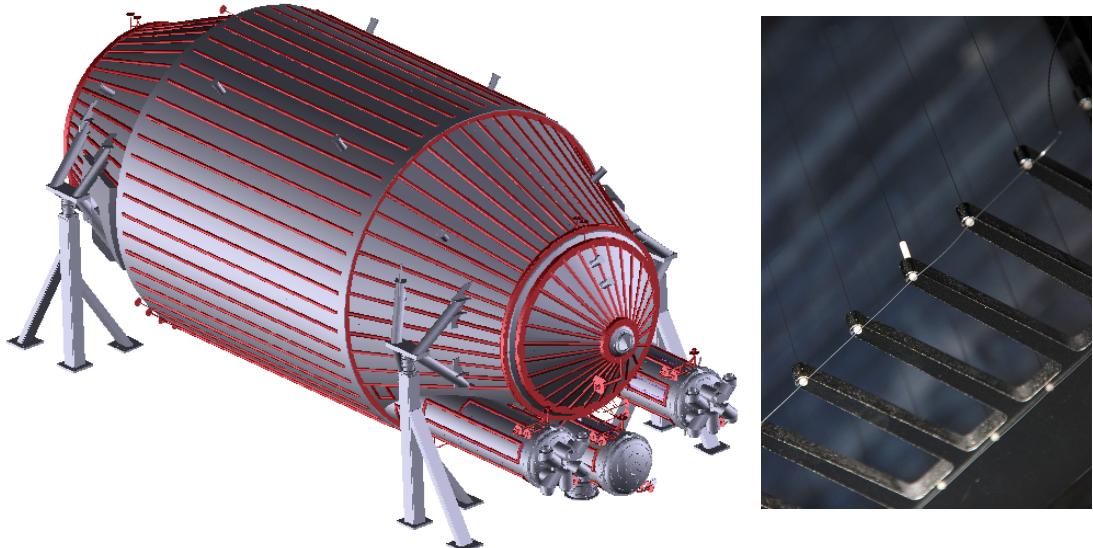


Figure 2.6.: On the left, the main spectrometer of the KATRIN experiment [45]. It is divided into a central, cylindric shape to which two flat cones, disengaging in the steep cones, are attached. Also visible in this image are the 3 large pump ports on the lower right and the three-legged holding structures. On the right a image of the comb structure of the inner electrodes with both layers of wires visible. The white structures on both top and bottom of the combs are the insulation of the wires [46].

the momentum is restored after analysis which requires for a symmetric setup. To shield against externally induced electrons, the pre-spectrometer has a single layer of wires as a inner electrode. It can be set to negative voltages in comparison to the pre-spectrometer hull which then reflects electrons with energies up to U_e .

2.2.4. Main Spectrometer

The largest component of all is the main spectrometer. With a diameter of 10 m and a length of over 23 m, it incorporates around 1400 m^3 that need to be evacuated to extremely high vacuum of $< 10^{-11} \text{ mbar}$. The main spectrometer, as the pre spectrometer, makes use of MAC-E filtering technique from 2.1.1. To do so, it features a uniquely designed electrode and a high voltage system [42]. A precision voltage divider was constructed to read out the high voltage applied to the vessel with the highest precision voltmeters, which operate in the order of 10 V [43]. Additionally, the voltage is fed to the monitor spectrometer from section 2.2.5 to ensure its long term stability.

The vessel is equipped with two layers of electrodes on a comb-like structure. This setup reduces the number of secondary electrons from the spectrometer walls entering the flux tube's volume. Keeping that count low, the rate of those electrons not reflected magnetically due to imperfect symmetries is reduced to the sub-eV level [44]. The layer made from thinner wires further to the inside shields the spectrometer volume from the one further towards the wall as cosmic rays may unleash electrons there as well. The main spectrometer as a whole is set to high voltage varied in the region below the endpoint of 18.6 kV. It constitutes the MAC-E filter from 2.1.1. The wire electrodes float on that voltage with a added more negative value to shield against electron background.

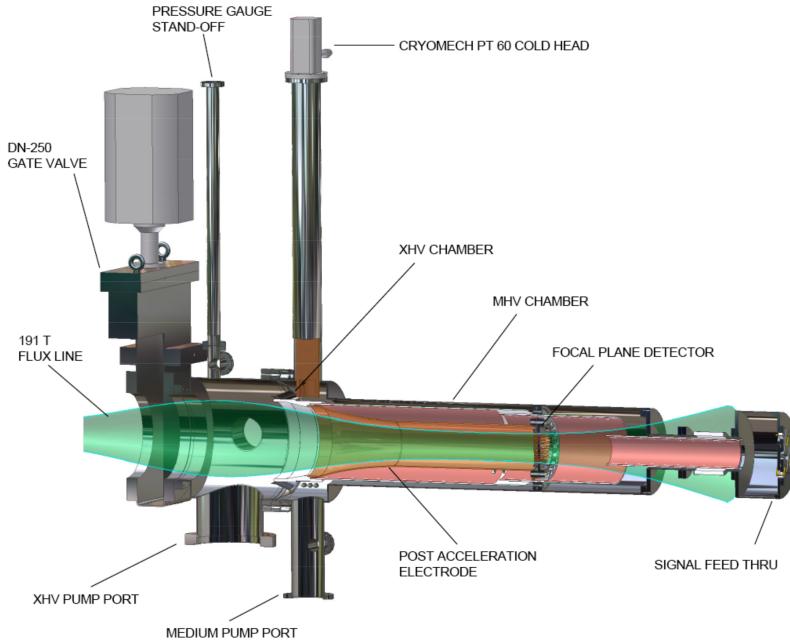


Figure 2.7.: The focal plane detector system including a flux tube (green). One can make out the different grade vacuum sections: extremely high vacuum (XHV) and medium high vacuum (MHV). The post acceleration electrode is visible left of the bronze colored actual detector and its signal feed trough on the very right. Multiple flanges and connectors are shown, not included in this picture are the calibration source holders [47].

2.2.5. Monitor spectrometer

The third MAC-E filter at KATRIN is the slightly modified Mainz spectrometer. It has been transported to Karlsruhe to work as a high voltage monitoring device. Here, electrons from ^{83m}Kr decays are detected and analyzed. The fact that the energy from these decays does not change over time (neglecting changes in the source material) can be used to detect shifts in the voltage of the MAC-E filter. For that purpose, the monitor spectrometer constantly measures transmission functions. The monitor spectrometer features two scintillation modules for muon detection that were used for a first inspection of muon induced background.

2.2.6. Focal Plane Detector System

The detector is located at the very north of the experiment. It is made up of a silicon wafer whose back-side is divided into 148 pixels attached to the readout electronics by pin connectors. The pattern is dartboard-like, multiple pixels with the same distance to the center form rings. Every pixel has the same surface area, making rates more easily comparable - that is for a magnetic flux through the wafer as homogeneous as in this experiment. The detector system is roughly divided into two chambers: one connected to the ultra high vacuum of the main spectrometer and one with a lower grade vacuum on the detectors readout side.

For background reduction, the detector system features both a passive shielding and an active veto system read out by the same data crate as the detector itself. It allows to discriminate against externally induced detector events. Due to the high magnetic fields from detector and pinch magnet, semiconductor readout electronics had to be used instead



Figure 2.8.: The detector wafer as installed in the FPD system. Note the “dartboard pattern” with the four pixel bullseye in the center. This is the detectors back side to which the electronics are attached, the front is plaid making for high detection efficiencies.

of conventional photomultiplier tubes. As it may be necessary to investigate electrons with energies below the detector threshold, especially for background investigations, a post acceleration electrode has been installed - also visible in 2.7 that can add to the electrons’ energies through an electric field of known strength.

2.2.7. Solenoids, LFCS and EMCS system

To achieve magnetic guidance as explained in chapter ??, a sophisticated system of superconducting solenoids, the low field correction system LFCS and the earth magnetic field compensation system EMCS have been installed [48]. These make sure that the path of flight is kept away from the wall and can be considered adiabatic, that penning traps are avoided as far as possible, that the earth magnetic field is compensated for and, most importantly, that the field drop to the analysis plane is of the order of (**order?**) so the spectrometers resolution will achieve desired values.

ToDo

2.2.8. Background sources

Different sources contribute to the background of electrons arriving at the detector. Background due to stored electrons is probably the largest source of detector background [49]. Penning traps cause electrons with energies in a certain range to be caught in a potential cup. Discharges of those traps due to scattering processes with either residual gas or due to excessive filling of the trap can cause high-rate events at the detector. This can be both dangerous for the detector itself as it is may inhibit data taking. Stored electrons can be both from external sources as from within the spectrometer. Decays of residual gas or wall absorbed molecules can contribute to the background. One large background source is radon, a neutral particle enabling it to move freely inside the vessel. Radon alpha decays, but shakeoff-, conversion- and auger electrons can be guided to the detector from inside the flux tube [50, 51]. Another large background source are cosmic rays interacting with the vessel hull and producing electrons like that. This background is reduced mainly by two factors, the symmetry of the magnetic field and the wire electrodes shielding the flux

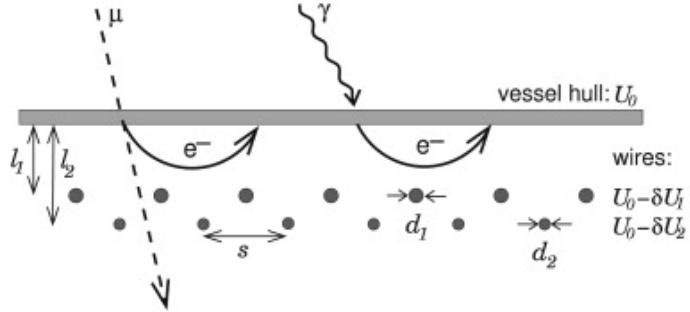


Figure 2.9.: A graph of the wire electrodes installed inside the main spectrometer. Both layers of electrodes with different distances to the spectrometer wall are visible, the inner being smaller in diameter than the outer one.

tube up to a certain threshold energy. To if the fields, both electric and magnetic, were perfectly symmetrical and parallel, only particles generated within the flux tube would be guided towards the detector. But through inhomogeneities and alignment errors, electrons may enter the flux tube even if generated externally, e.g. at the spectrometer wall through $E \times B$ drifts. To keep this from happening, the wire electrodes, were installed. They shield the flux tube against electrons with energies up to $E_e = eU_{\text{wire}}$ depending on the wire electrodes voltage U_{wire} .

3. Muon detection system

The need for low background rates at the main detector requires for a good knowledge of background sources. Despite magnetic reflection and wire electrodes, cosmic ray and particularly cosmic muon induced background may be an issue for the KATRIN experiment. To gather and assess muon related data, scintillator modules have been installed at both the monitor spectrometer and the main spectrometer. While the monitor spectrometer is equipped with only two rather small modules, at the larger main spectrometer, 8 modules have been installed at different positions enabling the user to cover different regions of the vessel (see figure ??). This freedom is enlarged by installing the detection system on three independently movable trolleys. The modules have been connected to the DAQ one trolley per card, meaning modules one and two connect to card three, modules 3 through 5 to card six and modules 6 through 8 to card nine (3.1)

All connections from modules to DAQ are made of coaxial cabling of equal length. This ensures comparable timestamps which are assigned only after the analogue signals arrive at the DAQ. High voltage is provided by two supplies, one on the east and one on the west side of the main hall. All devices of the muon detection system are connected to two multiplugs that are both overcurrent protected and feature mains filters. These multiplugs have been modified 3.6 to connect to a ground other than the outlet's. To ensure a common potential for all of the devices and the surrounding appliances this connection was made to the trough below the main vessel.

(insert photograph of multiplug)

ToDo

3.1. Data aquisition crate

The Data acquisition crate, short DAQ, is the central part of event recording and by that the interface between hardware muon modules and software based ORCA machine. It was

Module	1A	1B	2A	2B	3A	3B	4A	4B
Card	3	3	3	3	6	6	6	6
Channel	0	14	3	7	0	14	3	7
Module	5A	5B	6A	6B	7A	7B	8A	8B
Card	6	6	8	8	8	8	8	8
Channel	9	23	0	14	3	7	9	23

Table 3.1.: Assignment of module sides to cards and channels

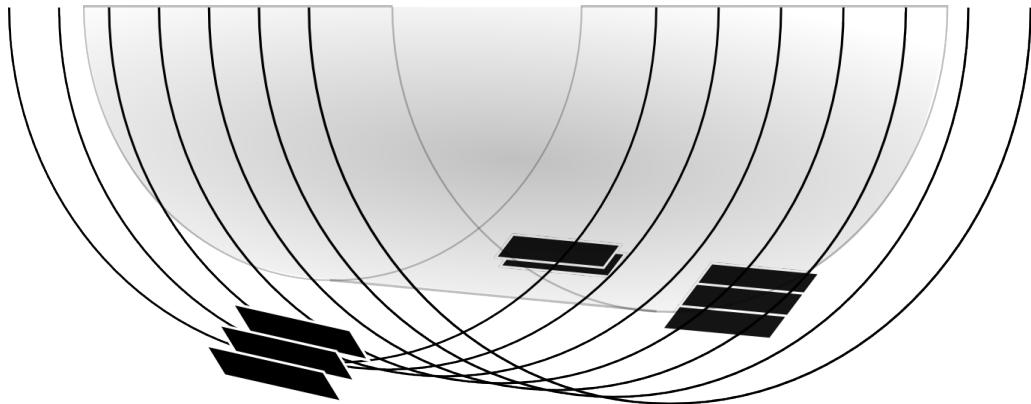


Figure 3.1.: An overview over the module positions in relation to the main spectrometer and its LFCS system.

V0	I0	I1	V1	Ramp Up	Ramp Down
1.5 kV or 1.6 kV	2000 mA			50 V	100 V

Table 3.2.: High voltage settings as used for the muon modules. Modules XX and XX are set to 1.6 kV.

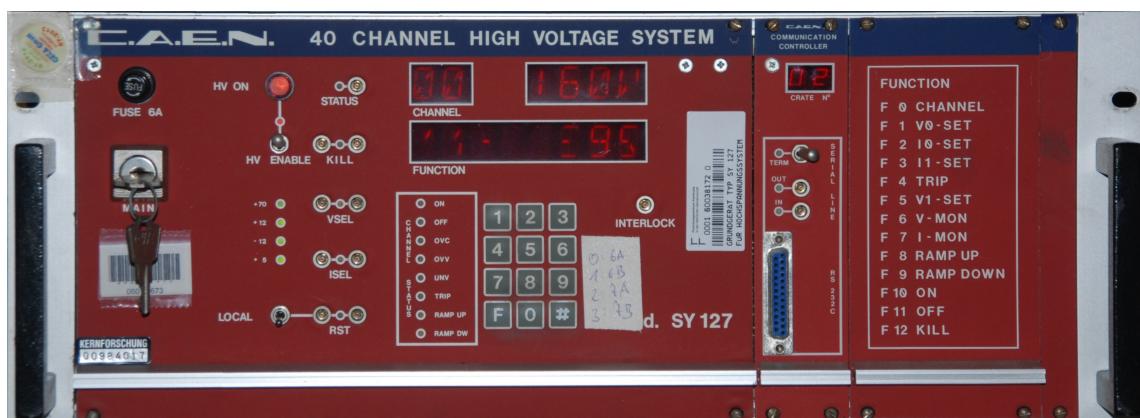


Figure 3.2.: A photograph of one of the two high voltage supplies used to power the muon modules photomultipliers. On the right side, the codes for setup are visible, see table 3.2 for the settings used.



Figure 3.3.: A image of the data acquisition crate's front panel. From left to right, the three FLT cards and the SLT card with its ethernet connection are visible.

Figure 3.4.: FLT back panel card with channel numbering scheme. Readout groups are 0,1,2,3,4,5,6,7 with 14 as the sum channel,

developed for the Pierre-Auger-Observatory in the first place, but was then distributed to many different experiments due to its large flexibility and the There are two types of DAQs used in KATRIN: the standard one and the mini DAQ used at the monitor spectrometer. The latter features only 4 FLT plus one SLT slot which is sufficient for the monitor spectrometer, but not for the main detector. Here, the larger model with up to It features first and second level trigger cards in version 4 that are described in detail in the following sections 3.1.1 and 3.1.2. The Linux based system runs from an external hard drive connected to the second level trigger card via USB. Here, a screen and keyboard can be connected for network setup, then, access via secure shell is possible. The DAQ can be connected to and controlled by the ORCA software 3.

3.1.1. First level trigger cards

The FLT cards directly receive the signal output of the photomultiplier tubes via coaxial cabling. They then do first parts of data analysis to reduce data flow to the ORCA machine. In this case, only events with occur simultaneously on both sides of any module are passed on. This reduces the rate from (**look up non veto rate**) to around 250 Hz. The FLT cards are made up of a large main card and a smaller connector card entered at the back side. Every card has 28(**28?**) channels. These are sectioned into three groups if the card is operated in veto mode. then, every group consist of one sum channel that can be read out in coincidence with any other or multiple other channels from the group (see figure 3.4). In case of the muon modules, 1-fold coincidence is used; one side of each module is the sum channel, the other an arbitrary channel in the respective group.

(**channel numbers**)3.4

ToDo

ToDo

ToDo

Figure 3.5.: FLT back panel card with channel numbering scheme. Readout groups are 0,1,2,3,4,5,6,7 with 14 as the sum channel,

Figure 3.6.: Added extension of the earthing contact to connect to any ground needed

3.1.2. Second level trigger cards

Only one second level trigger card is installed on each DAQ. all the Signals from the FLT cards are stacked here and passed on to the the ORCA machine. Networking runs directly through the SLT card. Other connections, such as USB, a display port, and also the CAT 5 connectors for synchronization to a clock can be attached to the back panel card.

3.2. Orca control

The ORCA software (Object-oriented Real-time Control and Acquisition) [52] is the central software for data acquisition. It is able to control lots of different devices via various kinds of interfaces with Ethernet connections being the most common.

3.2.1. Software Gains and Thresholds

All data registered by the DAQ is amplified and cut off at certain, software set values. Theses can be entered for every channel of every card separately. Gains can vary from 0 to 4095 (12 bit), thresholds can be set to any value up to the maximum bin used. Depending on the filter settings, ore more precisely with rising shaping length, bin values will be shifted towards higher absolute values 5.3. Scripting of the values is possible and reasonable for large numbers of readout channels such as at the FPD.

3.2.2. Run control

Runs are the basic element of data storage, every time data is recorded, a run is created. Inside every run can be a number of subruns (at least there is one) that will in turn contain data classes such as KaLi::KLVetoEvents, the most used event class in case of the muon modules. Runs and Subruns are started and stopped via the "Start Run", "Stop Run", "Start SubRun" and "Stop SubRun" buttons. While, from Run control, Runs can be set to end after a certain timespan and even repeat, Subruns can only be used on the go. This is different if scripting is utilised. 3.2.3.

3.2.3. Scripting

Scripts are useful for repetitive tasks or such that require short interaction only at certain points in time. One example for scripting is the ramping of LFCS coils that has been used to check the rate dependence on the LFCS currents. In that case, the script sends the values to be set to the ZEUS server, which passes them on to the (**company name**) boxes which in turn set the desired values at the power supplies. As this was supposed to be a stability measurement, every LFCS setting was kept constant for half an hour after which the script changed the currents. Scripting makes it possible to take these 5 h runs without human interaction making it much more comfortable A.2. Of course, much more sophisticated tasks can be handled through scripts as well.

Figure 3.7.: Data storage object in ORCA. Marked is the dropdown for setting paths for data, logs and ...

3.2.4. File handling

All runs created are first saved to the local disc of the iMac machine as ORCA specific .orca files. Sorting in folders for year and month can be applied to quickly find what you are looking for. They are then uploaded to servers of the IPE via cronjobs, a feature of the Linux based MacOS. The crontab is set to upload only files from "/home/..../data/" **(add dirs)** - the folders in the data storage object should be set to that 3.7. Scripts on the servers convert the files to the .root format. Using the ROOT based KaLi software, the user can then access and analyse 4.1 this data from anywhere he has Internet access.

To Do

3.2.5. Orca Fit

The Orca Fit function uses external servers to fit data aquired by the DAQ in user defined ways. Besides linear or gaussian fits, landau fitting can be used. This way, the user can receive an impression of the goodnes of the data via R^2 values.

3.3. Scintillator modules

The central part of the detection system are the eight scintillator modules. They are made of the synthetic material BC-412 which is utilized in applications requiring large area coverage [53]. These have previously been used at **(From Where?)**. Every scintillator cuboid is read out by two sets of four photomultiplier tubes. Photons arriving at the short ends of the module are guided to the photomultiplier tubes via non-scintillating material which, away from that, exhibits similar optical properties. All other sides of the scintillator are covered in reflective foil to push detection efficiency to the maximum. Of the eight photomultiplier tubes per scintillator module installed, 4 are read out via one FLT channel. The background of low energy events can be reduced significantly by recording only events occuring on both sides of the module at once. Only coincident signals should be recorded by the DAQ, though, on some occasions, quite a lot of single side signals occur. To account for those, every dataset is first analysed by a search algorithm (4.2.2) to filter them.

To Do

3.4. Photomultipliers

Photomultipliers work on two fundamental principles: photoemission and secondary emission. Each Photomultiplier tube is made up of a layer of bialkali metal where photons from scintillation ionize the layers' atoms leaving electrons with their initial energy less the ionization energy.

$$E_{e^-} = E_{phot} - E_{ion}$$

The electron is then accellerated and guided by the electric field from dynode to dynode (see figure 3.8), cascading to more and more electrons, as each electron's energy rises by $e \cdot U_{acc}$ between each pair of dynodes.

3.5. Gains, Thresholds and Acceleration Voltages

To achieve the best possible event detection, the photomultipliers' acceleration voltages as well as the software gains and thresholds in Orca had to be adjusted. The focus here was to obtain landau peaks with equal height and width, as the rates throughout the modules

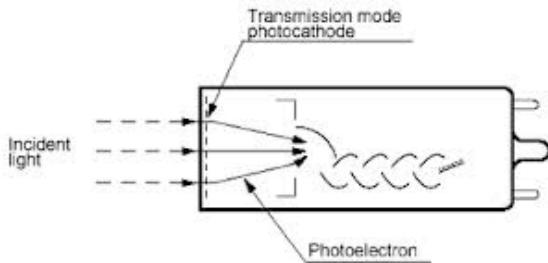


Figure 3.8.: Schematic view of a photomultiplier tube with incident photons and photoelectrons emerging. Note the nested dynode structure for cascading purposes.

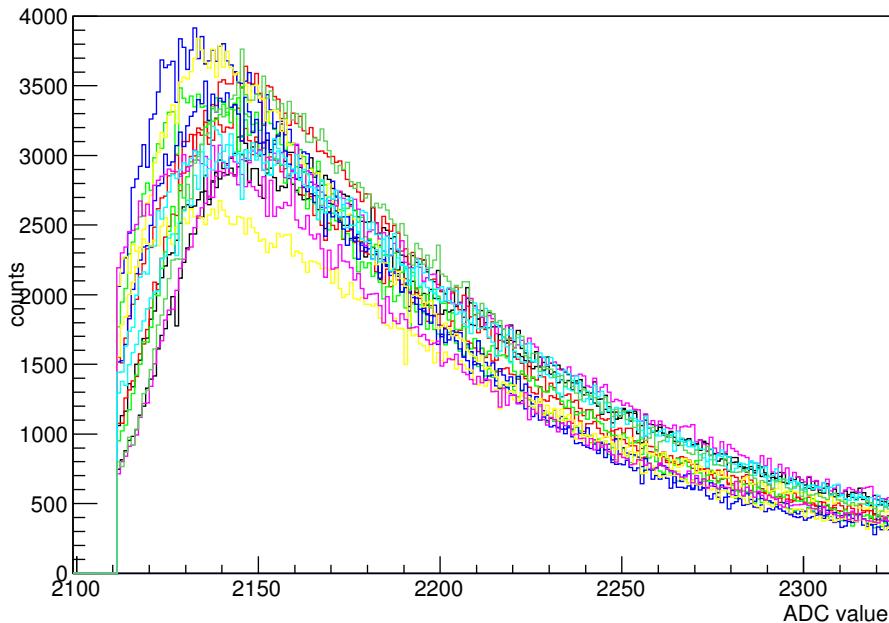


Figure 3.9.: The landau peak at acceleration voltages around 1200 V. All channels show similar width and height. Note that the thresholds had to be set pretty close to the peak position as noise was a huge issue under the conditions.

can be considered equal over large time intervals compared to the inverse rate. At first, the acceleration voltages were kept low to limit the signal peaks' heights to around 2 V. Carefully setting the mentioned parameters, one achieved the following, well aligned curves. A problem remaining at the time though was that the electronic noise set in pretty close to the peak position, only slightly shifted to lower energies. This meant that thresholds had to be set close to the peak bin as well, losing low energy events in the process, observable in figure 3.9. This showed in rates of around 150 Hz that did not compare too well to literature values. The high energy region though was well fittable with landau distributions.

ToDo

(mv co)

Later in the commissioning process, it got clear from the handbooks that the photomultiplier tubes had to be operated at acceleration voltages of 1.5 kV and above. To keep the signals' height as small as possible, most of the tubes were limited to this minimal voltage, whereas the sides (**which ones**) were set to 1.6 kV over showing lower rates than the others. Following this procedure, the tubes seemed much more stable and comparable, as all the gains and thresholds could now be set to the same values of (**enter values**) and respectively, while still showing aligned peak positions 3.10. This is a huge advance to before

ToDo

ToDo

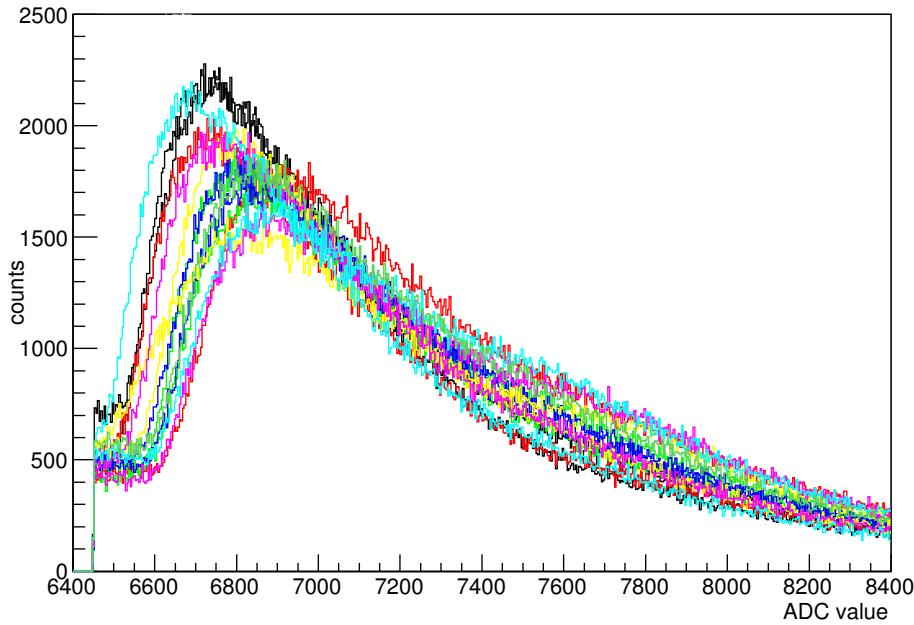


Figure 3.10.: Landau peaks after raising acceleration voltages to 1.5 kV or else 1.6 kV.
 Note that this pattern was achieved solely by raising two module's side's acceleration voltages to 1.6 kV leaving gains and thresholds at the same low level for all channels.

when gains varied by a factor of up to almost four as it reduces potential non-linearities in amplification. Also, gains are left at lower values to begin with, leaving a larger part of the signal in all amplification to the photomultiplier tubes known for their linear behaviour and relatively low noise.

4. Analysis software

To analyse the data recorded by DAQ and ORCA software, completely new data structures fit to the needs of muon detection and coincidence analysis have been created. Methods have been implemented to further investigate data stored inside those structures. A cmake file has been created making it possible to install the program on any machine used for analysis. All the sources including the main programs are available on the svn repository (**move program(s) to svn repository**). Doing so, external programs can be modified ToDo for custom analysis that shall include muon data making it very modular.

4.1. Data structure

All data from the IPE-servers arrives converted from ORCA-specific formatting to .root files compatible with CERN's analysis software ROOT. Hence, ROOT Methods are used to extract data from these structures, while most of these methods are implemented as part of the KaLi package in Kasper, which constitutes for a complete and closed data transfer protocol. Through those structures, data specified by the user will be cached locally and can be analysed afterwards.// For analysis with the classes described here, all data is transferred from the cached files to runtime storage. Here, the newly written class **event** with the following members comes into play.

event private class members

- fADCValue
- fTimeSec
- fTimeSubSec
- fPanel
- fSide

For each member, corresponding set- and get-methods have been implemented making them accessible to the programmer. Furthermore, the operators "<", "<=", ">", ">=", "==" and "-" have been overloaded to compare the timestamps of the event class. This

was useful especially since ADCValues are merely used for plausibility checking of the data but not for quantitative analysis. Doing so, events and the classes derived can easily be compared and searching becomes cleaner and clearer.

Derived from the base event class are two more storage classes:

panelEvent storing a second ADCValue

coincidentEvent additional member

- fADCValue2

and the common timestamp of events activating both panel sides and **coincidentEvent** storing ADCValues of simultaneous events in multiple modules and the number of modules involved:

coincidentEvent additional members

- std::vector fADCValues
- fnPanels

Every ORCA-run then utilizes the class **run** storing the data of the .root files in vectors of events. Recorded events should already be filtered - only simultaneously occurring events on the two sides of the same module should be recorded. As, under conditions not known, single sided events are recorded as well, a software workaround is needed. All events of one side of the modules are scanned to find whether a corresponding event with the same timestamp exists on the other side. If so, a coincidentEvent is created and pushed back into the run's vector of coincident events corresponding to the module it occurred in. Now, the user can decide on which modules to analyse with the setPanels() function. This can be done sequentially for multiple sets of modules without newly reading the run's data, as all the primary data is stored inside the event vector.

run class members

- std::vector events
- std::vector detectorEvents
- std::vector eventsByPanels
- std::vector coincidentEvents
- std::vector selectedPanels

4.2. Search Algorithms

To analyse data, at various points searches for events with a particular timestamp have to be performed. This was simplified by the time-sorted recording of events. A first implementation to search for coincident events was done on the base of average frequency and its standard deviation. This algorithm proved as fast and stable, though well applicable

Figure 4.1.: An illustration of the search algorithm utilising the average rate of the run analysed. Based on that, a guess is made (marked in). If that guess is wrong, the algorithm increments the guess in units of the rates standard deviation.

Figure 4.2.: All modules are stepped through, the one with the earliest time stamp is incremented. Then, all times are compared to each other.

only for two sets of timed events. That is why an advanced incremental method has been created. The number of modules is now limited only by the physically available memory and the speed is even higher.

4.2.1. Frequency Search

As this algorithm was built to run on only two sets of data, it simply walks through one set incrementally and looks for corresponding data in the other. Latter is not done in a "dumb" way by incrementing through the second set as well, but by calculating the average frequency of events inside the set and performing an intelligent guess on that basis. If the guessed event shows a different timestamp, the algorithm will keep going forward or backward in time in steps of the frequency's standard deviation until the timestamp searched for is in between two steps. Lastly, simple incrementation is used to find out whether an event at the desired point in time exists or not.

4.2.2. Incremental Search

While the frequency search increments solely one dataset, the incremental search steps through all the event trees, incrementing the one with the smallest timestamp. It then compares all events to each other, writes out the coincident ones, if any, and goes on incrementing the next smallest stamp. This assures the finding of all coincident events while keeping the speed very high.

4.3. Member Functions of the class **run**

Constructor **run()**

Whenever a new instance of "run" is created, the constructor is called. Arguments to be passed are a `KaLi::KLRIdentifier`, basically a string distinctively naming the run to be analysed, such as "myo00000001", `KaLi::KLDataManger`, a class handling the download of the files from IPE-servers and a toggle variable telling the constructor which data to read via the member function `getRun()` and what member functions to call afterwards:

Toggle Choices

- **0:** Data is downloaded and both muon data and detector data are stored
- **1:** Data is downloaded and only detector data is stored
- **2:** Data is downloaded and only muon data is stored
- **3:** Data is read from local file system, only muon data is stored

Destructor run()

The destructor deletes all the contents of the vectors of events and inherited classes and clears them afterwards before deleting the member RUN which in fact frees all the memory reserved by the KaLi classes.

getRun()

This sets the member KaLi::KLRUN through the KaLi::KLDataManager and then returns its KaLi::KLRUNEvents - these include all recorded events meaning also both the relevant KaLi::KLEnergyEvents and KaLi::KLVetoEvents. The getRun() function is used for example in the constructor to read the run's data.

getLocalRun()

It is not always possible to read data from the file servers, example given were files too big leading to timeouts at least in older KaLi versions. That is why the getLocalRun() function was introduced reading data from the local filesystem via the KaLi::KLRUNIdentifier. The path to the files needs to be adapted in the source code (**environment variable?**).

ToDo**detectCoincidences()**

After calling the member function channelCoincidences(), panelCoincidences(nPanels) is returned where nPanels defines, how many modules have to show coincidences for the counter to increment.

channelCoincidences()

This **always** clears the vector eventsByPanels before filling it according to the current selectedPanels settings. To do so, it loops over all entries of selectedPanels, calling loopOverSides() of the current module.

loopOverSides()

Analysing only one of the modules for coincident events between the two sides, the function runs through all the events of one panel side using the operators "<" and "==" overloaded for the class run to compare event times. For the search itself, the "A" side's index is incremented step by step while the "B" side's index is pushed up as long as its event time is smaller than A's. Every time that condition changes, it checks whether the events occurred at the same time - pushing a coincidentEvent with both the events ADCValues and the timestamp into the vector for the corresponding module if so - and then going on incrementing A's index.

ToDo**panelCoincidences()**

As mentioned above, the first algorithm to search for coincidences between different panels was based on the average event frequency and its standard deviation, soon being replaced by a simpler, more efficient incremental algorithm: This features a storage for the smallest timestamp in a group of events. (**change code to overl.ops**) This is set to the smallest timestamp of the first event of all the modules analysed. Now, all the events are compared to the smallest one. This has the advantage, that one does not need to cross check every event with every other one but can simply compare every event to the smallest in a linear way. If simultaneous events are found, they are pushed back into the coincidentEvents vector together with the timestamp and their ADC values, nPanels is risen by one. Subsequently, the index of the smallest event storage is incremented and the new smallest event in the

- **default/1:** Size of events returned
- **2:** Size of eventsByPanels returned
- **3:** Size of coincidentEvents returned
- **4:** Size of detectorEvents returned

changed pool is searched for via the member function `findSmallest()`. This is repeated until all the event storages have reached their last entry. The return value is the number of events fulfilling the requirement passed through `nPanels` to `panelCoincidences`: if it is zero, every coincident event with two or more modules involved is counted, for every other number, only the number of event with exactly this number of modules is counted.

findSmallest()

Setting the smallest event's timestamp through references, the `findSmallest` function requires only the steppoints of the different modules and returns the one with the smallest timestamp.

TOFHist()

Setting the modules to be analysed to one and two, this function was designed to analyse monitor spectrometer data. This also reflects in the fact, that both muon data and detector data are expected to be stored within the same mosxxxxxxxx run file. The function then runs `channelCoincidences()` and `panelCoincidences()` before shifting through all the muon events searching for following detector events in a certain time interval.

TOFMuonDet()

In contrary to the `TOFHist` function, this one reads muon and detector data from different files as it is designed for the needs of the main spectrometer. Here, two DAQs record muon and electron detections to `myoxxxxxxxx` and `fpdxxxxxxxx` files respectively. That is why the function reads a muon run and requires a guess as to where corresponding detector data is located. It then loads on detector run after the other to check whether there's events inside a time window after each muon event. If so, a histogram is filled with the data acquired to inspect it for cumulation at particular times.

determineEfficiency

Efficiencies of modules can be determined through three of them located coextensively in front of each other. Then, all events recognised in both the uppermost and the lowest module have to - leaving geometrical inaccuracies unaccounted for - pass the middle module as well. By comparing the counts one can determine an efficiency for the module:

$$\%_{\text{eff}} = \frac{\wedge_{68}}{\wedge_{678}} \quad (4.1)$$

getSize()

The `getSize()` function returns the size of one of the vectors storing events or one of the inherited classes depending on the passed integer "what":

(**default nonsense, reimplement**)

ToDo

readVetoEventData(), readDetectorData() and readMOSDetectorData()

Depending on the toggle choice in the constructor, either one of the two or both of the functions are called. While the readDetectorData() function reads all recorded KaLi::KLEnergyEvents (only the FPD records those), the readVetoEventData() function reads all the KaLi::KLVetoEvents from cards three, six and nine. This can never interfere with veto data recorded directly around the FPD vor active vetoing of detector signals, as cards 15 and 16 are used here. For analysis of monitor spectrometer data, a function readMOSDetectorData() has been implemented reading all energy events of card one independent of channel, while of course single channels can easily be excluded. The pulser usually active at the monitor spectrometer creating KaLi::KLEnergyEvents at constant frequency is standardly excluded from analysis. All the member functions reading data require the passage of an instance of the KaLi::KLRunEvents, usually the member of the same class set in the getRun() function.^{4.3}

5. Comissioning measurements and analysis

While the moun detection system had still been under construction at the beginning of my thesis-work, first measurements were taken at the time with some modules under preliminary conditions to look into the behaviour of these modules. Step by step, the system was completed and is now up and running. In the building phase, several measurements and test have been conducted to ensure the capabilities of the system meet the requirements for the KATRIN experiment. Starting with the setup of acceleration voltages, gains and thresholds, Using data obtained by the muon modules and the detector as well as other subsystems' data, the muon induced background rates and both spatial and energy distribution can be obtained. Before actual measurements were done, the modules had to be set up and calibrated, meaning high voltage and signal cabling needed to be installed and high voltage power supplies had to be acquired.

5.1. Rate instability due to charging effects

During the preliminary measurements, it became obvious that the panels' rates were peaking over certain, short time intervals at some arbitrary frequency. It was not possible to set gains, thresholds and PMT voltages correctly as one had to be lucky to be able to identify the peak position in a calm period. It seemed there was some kind of electronic pileup. As this did not appear for all the modules it was not noticed until later into the commissioning process.

If the landau distributions (chapter 1.7) were not identifiable due to prevalent electronic noise, the measurement was rendered useless as a lot of noise triggered events were recorded. As a countermeasure, in cooperation with Sascha Wuestling, potential equalisation by connecting the modules to the trough below the main spectrometer has been established.

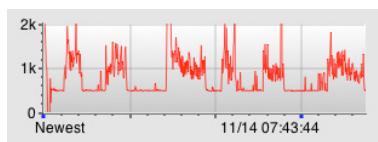


Figure 5.1.: Rate progression over the course of hours. Noticiable raise in the cumulative rate of all panels in certain intervals

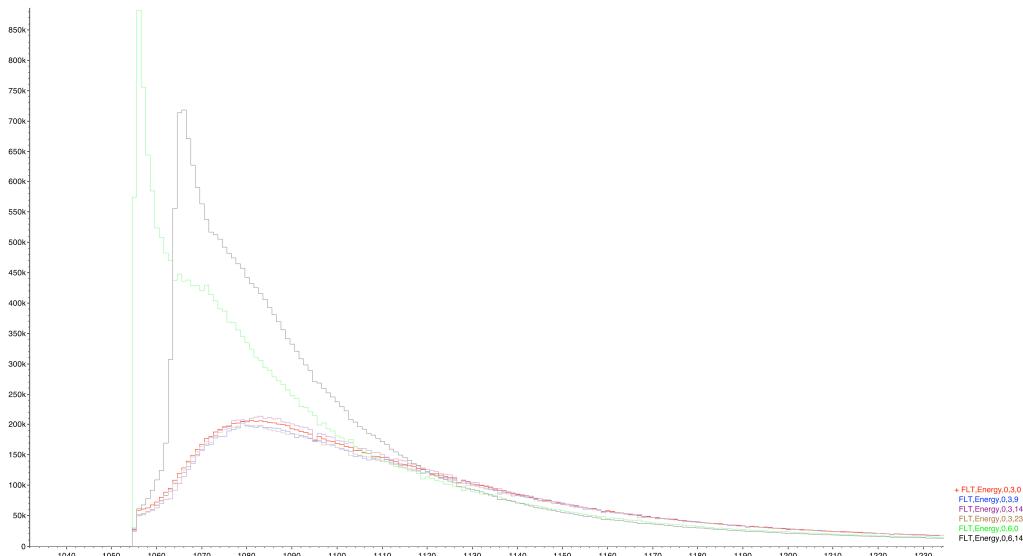


Figure 5.2.: Energy histogram of six channels, i.e. modules 6 through 8. Displayed are counts over ADC-Value. Two channels show a lot of noise at the low energy end of the histogram while four are developing nicely looking Landau Peaks.

After the installation of the grounding, the peaking did not occur any more so the issue seems to be resolved. Now, one could make a start on setting gains, thresholds and acceleration voltages 5.2.

5.2. Gain-, Threshold and Acceleration Voltage Settings

A first amplification - linear with acceleration voltage - of the scintillation photons occurs in the photomultiplier tubes. As signals at first seemed too high for the DAQ to handle at nominal values of the datasheet, these acceleration voltages were reduced to around 1200 V. After that, the software gains and thresholds in the ORCA software needed to be set. As the detection efficiencies 5.7 for the modules were not as high as expected, one assumption was that the acceleration voltages set lower than denoted in the user manual leads to loss of data in the low energy range. Consequently, the acceleration voltages were raised to 1.5 kV except for two channels, those of modules 2B and 6A, that were even ramped to 1.6 kV on account of showing lower overall rates as described in 3.5.

5.3. Finding the best filter settings

As the PMT tubes are directly, without any preamplifiers, connected to the DAQ, the signal lengths arriving at the latter are in the order of 20 ns. This poses a problem for filters as the sampling rates need to be high and anti-aliasing is inevitable. To find the best settings, a function generator has been set up to create events at known frequency and peak height. The pulser's signal form (**what form**) was chosen as closely to the actual shape as possible, which is the "pin diode" form.

To Do

In order to evaluate filter's figure of merit, the width of the resulting energy histogram, which should, assuming perfect pulser signals and perfect filters, be mono-energetic, was analyzed for each filter setting. For analysis, the width of the contributing ADC bins and their absolute position as well as the pulse height and the filter settings were noted.

On average, the boxcar filter at shaping lengths of 150 ns shows the most promising results, i.e. the sharpest energy resolutions for any signal height. This concurs with the settings

Panel/Side	1/A	1/B	2/A	2/B		
Card	3	3	3	3		
Channel	0	14	3	7		
PMT Voltage	1150	1150	1250	1150		
Threshold	2110	2110	2110	2110		
Gains	2350	2400	1200	2850		
Panel/Side	3/A	3/B	4/A	4/B	5/A	5/B
Card	6	6	6	6	6	6
Channel	0	14	3	7		
PMT Voltage	1150	1150	1150	1150	1150	1150
Threshold	2110	2110	2110	2110	2110	2110
Gains	2450	2400	2150	2550	2100	2400
Panel/Side	6/A	6/B	7/A	7/B	8/A	8/B
Card	9	9	9	9	9	9
Channel	0	14	3	7		
PMT Voltage	1150	1150	1150	1150	1050	1100
Threshold	2110	2110	2110	2110	2110	2110
Gains	3400	2100	2400	2500	3950	2900

Table 5.1.: **Gains, thresholds and voltages:** These are the settings found to be optimal for each panel side; furthermore, the table displays the card and channel each side is associated with in the DAQ card system

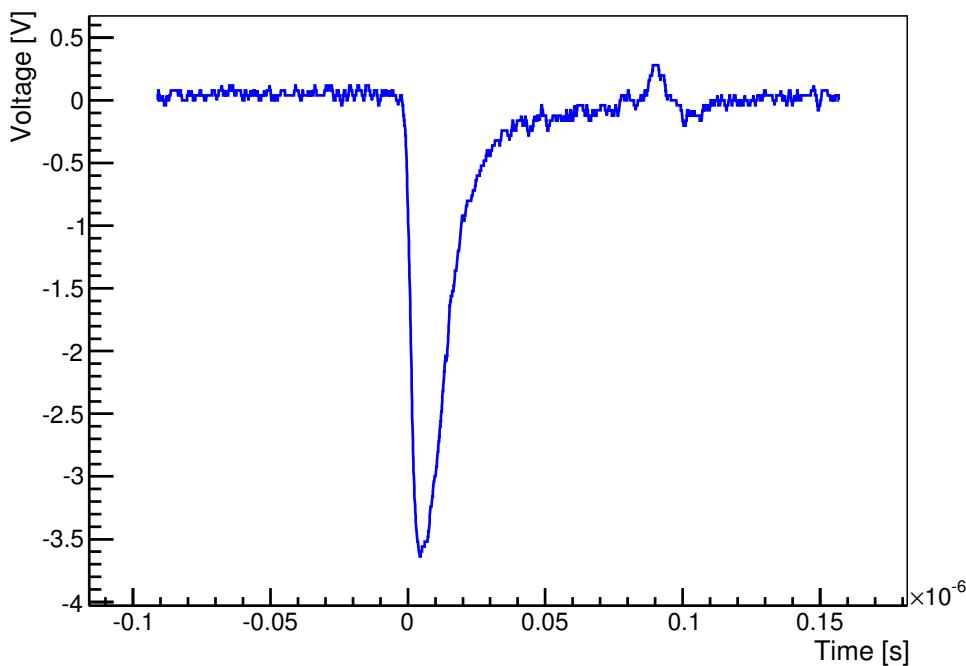


Figure 5.3.: Pulser shape on the left compared to actual signal shape on the right.

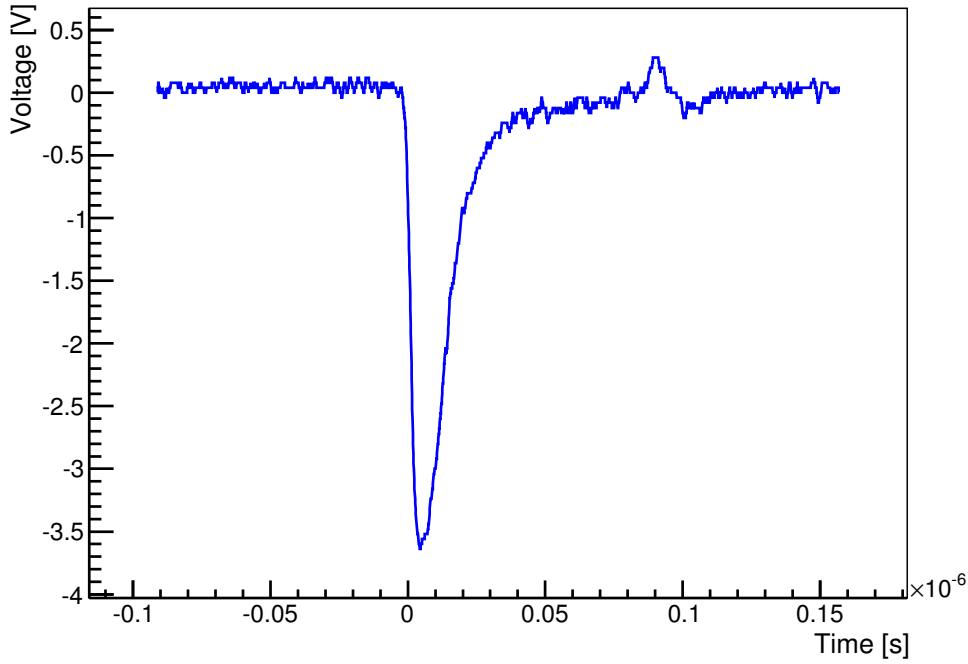


Figure 5.4.: Pulser shape on the left compared to actual signal shape on the right.

Voltage[V]	Boxcar length [ns]	width	position	threshold
1	50	33	2160	2100
	100	37	2140	4200
	150	13	2140	6300
	200	10	2141	8400
2	40	25	2160	2100
	100	78	2140	4200
	150	78	2140	6300
	200	77	2141	8400
3	59	25	2160	2100
	100	113	2140	4200
	150	110	2140	6300
	200	112	2141	8400
4	80	25	2160	2100
	100	145	2140	4200
	150	147	2140	6300
	200	149	2141	8400
5	94	25	2160	2100
	100	180	2140	4200
	150	185	2140	6300
	200	41	2141	8400

0 ns gap, 0 s shaping time

Table 5.2.: Energy resolution at different filter settings. A function generator was used to simulate pulses from the muon modules.

chosen for the active fpd veto; here slightly longer (around 30 ns) but comparable signals enter the DAQ's FLT cards showing best results at the same filter settings[54]. That is why, for any measurements after (**run & date**), the new filter settings were used, bringing up the need for new threshold and gain adaptions 5.2.

ToDo

5.4. Moun module's rates

A simple first check into the data was possible simply by comparing the rates measured to literature values. Here, a flux of around 1 per min and cm^2 through an area parallel to the ground is stated. Measured rates are in the order of 250 Hz. The muon modules' area is

$$315 \text{ cm} \cdot 65 \text{ cm} = 2.05 \text{ m}^2 \quad (5.1)$$

considering the 45° tilt of the modules towards the horizontal, this area reduces to an effective area of

$$A_{\text{eff}} = \sin(45^\circ) A_{\text{real}} = 1.45 \text{ m}^2 \quad (5.2)$$

Further taking into account detection efficiencies η discussed in 5.7, we receive an estimation of effective rate of

$$\Phi_{\text{est}} = \eta \frac{1}{\text{cm}^2 \text{ s}} A_{\text{eff}} = 225 \text{ Hz} \quad (5.3)$$

This compares well to measured rates of (**calculate actual rates**) 250 Hz.

ToDo

5.5. Modules in high magnetic fields

For there is the need of moving the muon modules as close to the spectrometer tank as possible to register mostly muons that indeed went through the vessel, they are aligned closely to the air coil system. This brought up the problem of photomultiplier tubes having to work in high magnetic fields. Photomultipliers, as mentioned before, use electrons cascading in electric fields to generate amplified signals. Additional magnetic fields can keep the electrons from reaching the dynodes stopping the cascade thus keeping single events from being registered. As rate decreases strongly under these conditions (**are there runs showing that? ask nancy**), a solution needed to be found. As a simple, yet efficient passive counter measurement, a layer of mu-metal was wrapped around the modules. Mu-metal is a magnetically highly permeable material (here, $\mu_r \approx$ (**find out permeability**)) that guides the magnetic field lines inside itself. In doing so, the remaining flux inside a mu-metal surrounded volume, and with it the field strengths, drastically reduces. To test the improvement the mu metal coverage produces, measurements with rising aircoil currents have been performed. Steps in the size of tenths of the maximum current of mostly 100 A, in some cases only 70 A, were used to record rates over half an hour at each value. During the first run, due to a slow control problem, the current was not raised between two steps. Although displaying the expected behavior - rates dropped much less than before - the measurement was repeated with the correct currents. Measurements show that the rate still drops at currents close to the maximum, though only to around 90 % of initial values, see figure 5.5. As, under normal measurement conditions, the coil currents are mostly around half the maximum value or less, the problem could be solved, as here, the reduction in rate is within the errors' order.

ToDo**ToDo**

5.6. Module Stability

If consistent factual statements on muon induced background are to be made, the modules need to work stable over the course of days, as rates are supposed to be comparable. For this reason, over the Christmas time 2012, a two-weekly measurement of half hourly runs

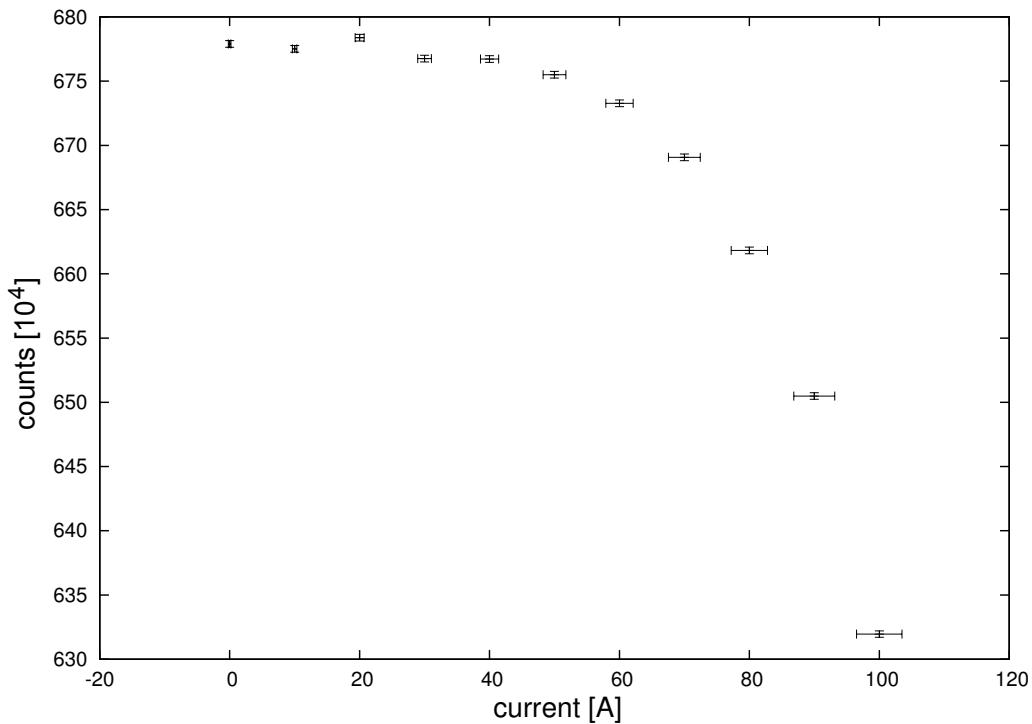


Figure 5.5.: Counts over air coil currents, with a maximum of 100 A. A clear decrease in rate is recognizable in the last 5 data points.

Coil #	1	2	3	4	5	6	7	EMCS h
Current [A]	10	10	14	25	42	39	54	50
Coil #	8	9	10	11	12	13	14	EMCS v
Current [A]	54	21	36	30	21	20	56	15

Table 5.3.: Runtime settings for air coils as proposed and for the commissioning measurements. These were kept static over the two weeks end 2012/beginning 2013

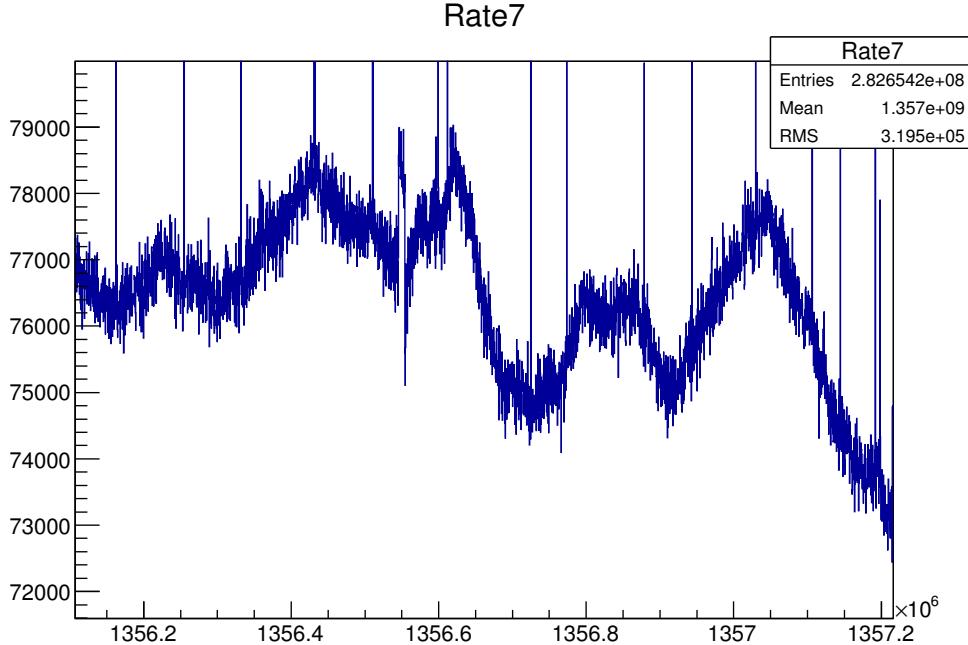


Figure 5.6.: Rate per five minutes over the course of about two weeks (21-12-2012 to 03-01-2013).

Figure 5.7.: Atmospheric density as a function of time over the course of two weeks the muon measurements took place. Note the

was taken, see table 5.3 for air coil settings used. Runs myo00000051 to myo00000675 contain the data of this measurement. The time slot was chosen for the lowly frequented spectrometer hall's sake to minimize external impacts on data taking. For analysis, a simple program to count events in variable time bins was written, creating a count histogram for all the runs in the measurement period. The result can be seen in figure 5.7. The observable fluctuation is well describable by fluctuations in atmospheric density, i.e. pressure Δp and temperature ΔT and in muon production height Δh [55].

$$\frac{\Delta I}{I} = -(\alpha_\mu \Delta p + \beta \Delta h - \gamma \Delta T) \quad (5.4)$$

where α is a barometric coefficient in $0.215\% \text{ mmHg}^{-1}$, β a decay coefficient in $5\% / 10 \times 10^3 \text{ m}$ and γ a temperature coefficient in $0.1\% \text{ K}^{-1}$. If one looks at the data from [56] the fluctuations, only available on a daily basis, are comparable to the ones visible in the data of the stability measurements. To make graphs more comparable, the data has been analyzed again, now with daily binning. It has to be kept in mind that the weather data was obtained from a weather station in Rheinstetten, about 20 km from KIT campus north, and represents only the lowest atmospheric layer while muons are generated mostly in the upper layers of the atmosphere.

5.7. Module Efficiency

The runs used for stability measurements, as well as any other run including modules six, seven and eight, can be used to check muon module seven for efficiency. For tests on other modules, the geometry would need to be changed so that the one to be checked is in between at least two other modules. For analysis, the function `determineEfficiency()` 4.3 has

been written. The principle is the following: considering the small change in momentum direction high energy muons achieve through interaction with matter, one can assume straight-lined paths. From that follows, that if two parallel planes, that can be used to describe the scintillating volumes, are hit, any other, also parallel plane, in between those two will be hit as well. Keeping this in mind, one can analyse data for events registered in both modules 6 and 8 and cross check whether a event has been detected in module 7 as well. The quota of events in all three modules compared to those detected in 6 and 8 - including the triple events - shows the efficiency of module 7. It shows that during the measurement period end of 2012, the efficiencies were at (**rerun**) 94 % which is less than one would expect at a scintillator thickness of 5 cm for muons perpendicular to the largest module surface, even more for any other. For that reason, the filter settings were checked and changed to the boxcar filter with a gap of 150 ns from the before used (**exact name**) filter. However, the expected efficiency increase was not observable, the average efficiencies before and after are within the margin of error of the other. To examine the problem further modules 3, 4 and 5, that are located next to each other, were used for efficiency measurements as well considering they are stacked in an upright way. Using the program on those three modules resulted in even lower efficiencies of $(50 \pm 3)\%$. This raises the question whether this is not an effect of signal filtering, but a previously not considered physics effect. One thing coming to mind is deviation of the muon track from linear forms. This feature would comply with the seemingly lower efficiency at the upright stacked modules, where, at equal bending radii, the ratio of muons traveling around the middle module is higher due to the lower total area in stacking direction. This thesis should be tested. This can be done both by simulating the cosmic muons including magnetic fields and empirically by varying the distance between the single modules. The latter is difficult not only because the modules are heavy and not made for lifting (no designated carrying structures), but also because movement always means potential danger to the photomultiplier tubes and their connection to the scintillators. Furthermore, if all coils and solenoids were to be turned off simultaneously at some point, one could collect data then and see how efficiencies change during that (there have been runs taken when that was still the case, but only few modules were working properly at that point). If the dependence on module distance turns out to be true, but the efficiencies are still below expected values at the lowest possible distances, a possible improvement would be to use pre-amplifiers before signals arrive at the DAQ. These would widen the signals timewise leading to a more easily detectable signal for the filters.

5.8. Photo Multiplier Tube Test with Sr source

With sets of four photomultiplier tubes being read out over one cable, and, consequently, via one channel, the test of individual PMTs is not trivial. Nevertheless, a method using a MBq ^{90}Sr source to trigger events was used to check functionality. Of course, all tubes were able to see the source at any position but rates were expected to rise as the distance to any of the tubes shrank. A source holder was constructed from acrylic glass to shield the user from radiation and to attach the source to the modules, as a large dependence of rate on the position was found when the source was simply duct taped to the modules. As the foil mantling of the modules absorbs a non negligible part of the radiation emitted from the source, it had to be ensured that the number of layers was equal for all measurements. This was given only below the modules as the foil has been folded around them at the ends in a gift wrapping way. Thus, the source was pretty far away from the photomultiplier tubes making it more difficult to distinguish between them. A first measurement was to check for exactly this distinguishability. (**insert measurement for small steps over PMTs positions**).

As one can see a rise in rate at the positions the tubes are located at, it was decided that

ToDo

ToDo

ToDo

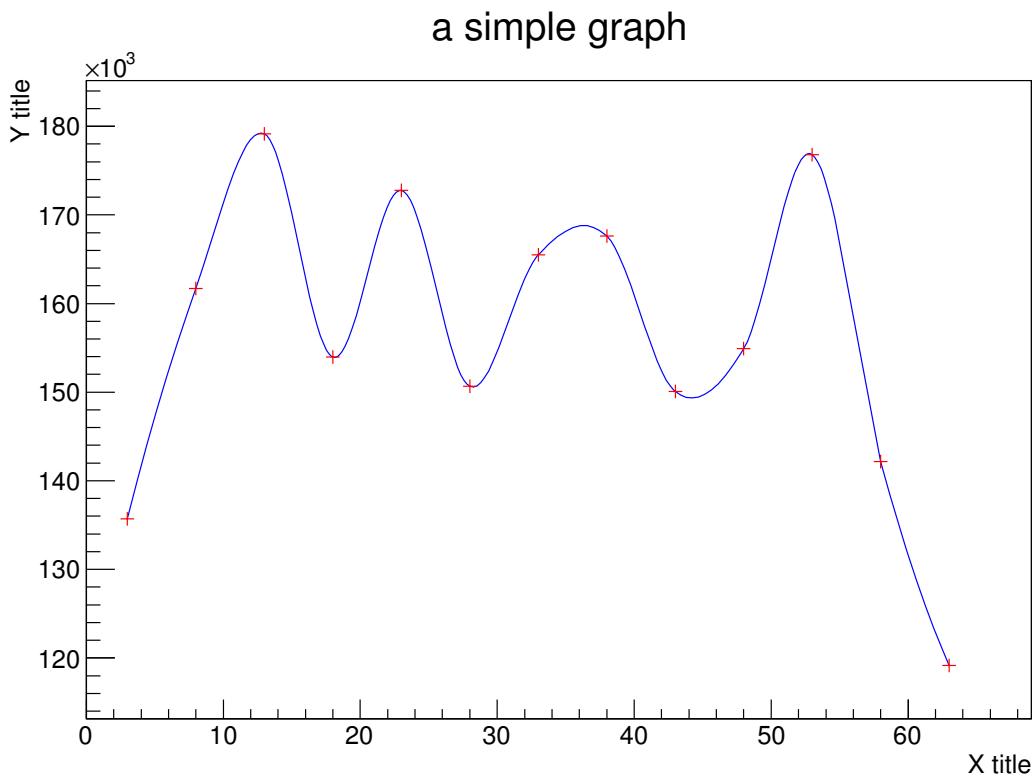


Figure 5.8.

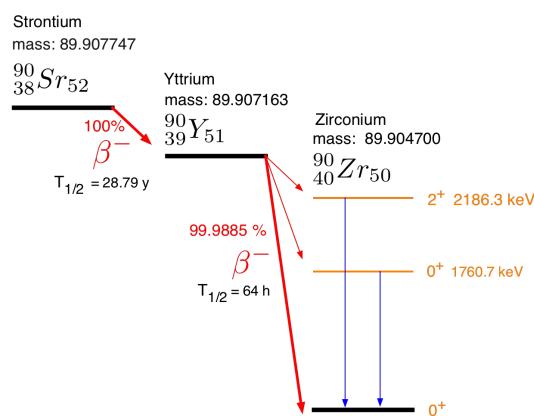


Figure 5.9.: Decay scheme of ^{90}Sr : first a lower energetic decay to ^{90}Y emitting $544\text{ keV}/c^2$ electrons, from that most probably a higher energetic decay to ^{90}Zr ground state ($2.29\text{ MeV}/c^2$ electrons) or, with low probability, to one of two of its excited states.

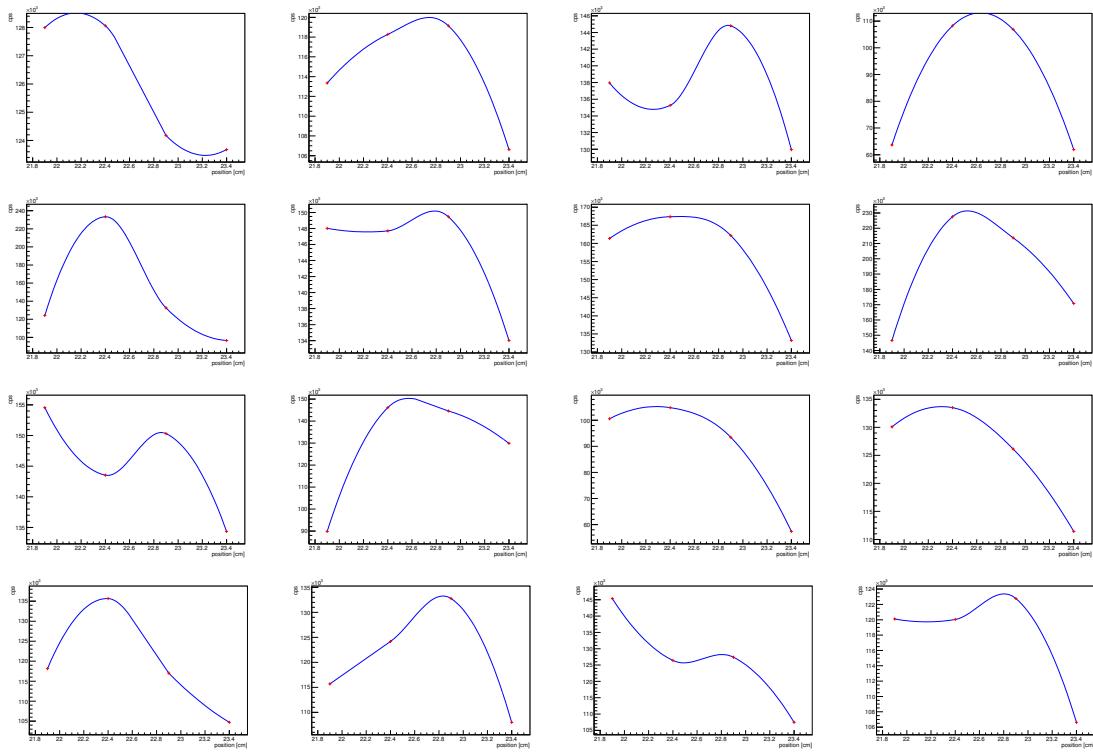


Figure 5.10.: Measurements with source at four different positions. All modules

Figure 5.11.: With the old firmware installed, one can see a difference of $\approx \mu\text{s}$ between events recorded. As the signals occur simultaneously and the DAQs are synchronised, this difference should vanish.

four measurements per module and side were sufficient, especially as all measurements can afterwards be compared to each other. The tube positions at **(n,n,n,n cm)** were used as measurement positions as well. For each side, a run has been taken containing five minute subruns for every position. Figure 5.10 shows the result of these measurements. One can see that the gerneral shape of each side compares very well to the others. Exceptions are **(which ones different?)** showing slight, but acceptable deviations off the norm.

ToDo

ToDo

5.9. Synchronisation of moun module and FPD DAQs

Measuring time differences between detector signals and muon events on a μs scale requires exact synchronization of the two different DAQs. For this purpose, a clock has been designed sending signals at two frequencies: one at 1 Hz and one at 10×10^6 Hz internally converted to a 20×10^6 Hz signal by the DAQ. Those signals can be synchronized to the timestamps of GPS satellites if a GPS antenna is connected. This has not yet been done as relative synchronization between the two crates is sufficient for the purposes of finding correlations between muon and detector events. As the cable length for signal transmission is pretty extensive - around 50 m - it was decided to use optical fibers instead of CAT 5 cabling. As two signals need to be transmitted, paired **(connection type name)** fibers were used. The clock itself has optical outputs, the DAQ though needs converters from optical to electrical signals and a modified SLT back panel card to receive the converted signals via Cat5 cabling.

To test the setup, the muon DAQ was moved to the detector platform. Both crates were fed by a pulser signal. Runs at different frequencies were recorded to test both the

ToDo

Figure 5.12.: With the old firmware installed, one can see a difference of $\approx \mu\text{s}$ between events recorded. As the signals occur simultaneously and the DAQs are synchronised, this difference should vanish.

Figure 5.13.: Time differences between events after firmware upgrades. Differences between the event times are within one 50 ns bin

synchronization and the detection of events. To synchronize timestamps to an external signal, the FLT cards drop down menu needs to be set to (**look up**) and the SLT needs to be set to (**lookup too**). At first, manually triggered signals were used in minute runs to check the timestamps equality. Several runs were taken, all showing that the events were shifted by several μs .

ToDo
ToDo

In close cooperation with the IPE it was found that this was merely a problem of firmware versioning as well as software settings in ORCA resolving the problem quickly. After installing the latest firmware, more runs were taken now displaying the desired behavior: Following the manually triggered events, runs with fixed frequency events were recorded, raising the frequency to up to 10 kHz. Doing so, different recording modes and filter settings were applied - see table 5.4. All the tests worked fine including starting one DAQ's run way ahead of the other. Those events recorded in both run files were always well synchronized.

Afterwards, the muon DAQ was moved back to its original position and the optical fibers were stowed in wire-ways guiding it from the detector platform down to the basement where the muon detection system is located. Another problem occurred here, as signal transmission was impaired by a kink at one of the turns, but was quickly resolved by smooth rewiring. Concluding, it can be said that the clock runs continuously without any problems throughout all the measurements - including main spectrometer commissioning measurements.

5.10. Coincidence Search between Muon- and Detector Events

If one wants to actually detect background induced by muonic events detected by the muon modules, those events need to be correlated to detector events time wise. For this purpose, the analysis code's class run was extended by the member functions TOFHist()4.3 and TOFMuonDet()4.3, where the former is used for monitor spectrometer analysis and the latter for the main spectrometer. The biggest difference is that, for the main spectrometer, runs by two DAQs leading to different starting times and different lengths are created that need to be compared. Here, the necessity for synchronization from chapter 5.9 becomes clear.

5.10.1. Monitor Spectrometer

Measurements at the monitor spectrometer are easily manageable due to the fast accessibility of all the components and the collection of data in a single run-file through the mini-crate. For measurements, high voltage supplies have been added to the (**name of the rack**) **ToDo** rack and the readout electronics were connected to a second FLT-card inserted into the mini-DAQ and operated in veto-mode. Gains and thresholds were easily set as only four sides had to be adjusted - compared to the 16 main spectrometer channels. The PMT tubes were operated at 1.5 kV. The detector gain and threshold settings for the 5 pixel detector have been kept, although the detector position was shifted to the position at which the center pixel exhibited maximum rate and the pairs of east-west and top-bottom

ToDo

Settings	fpd run	myo run
Pulser voltage 250mV, freq (sampling) 100000, waveform: needle negative		
as before, but 300sec runs	4174	710
as before, but 300sec runs and energy+trace mode (sync)	4175	711
5 random pulses within 60sec run	4176	712
pulser frequency: 1 Hz, 60sec run	4177	713
pulser frequency: 10 Hz, 60sec run	4178	714
pulser frequency: 100 Hz, 60sec run	4180	715
pulser frequency: 1 kHz, 60sec run	4181	716
pulser frequency: 10 kHz, 60sec run	4182	717
Pulser:		
Pulser voltage 150mV, Freq (sampling) 1000, waveform: Pin diode negative		
5 random pulses within 60sec run	4184	719
increased thresholds from 500 to 1000 (both) pulser frequency: 1 Hz, 60sec run	4185	720
pulser frequency: 10 Hz, 60sec run	4186	721
pulser frequency: 10 Hz, 300sec run	4187	722
pulser frequency: 100 Hz, 300sec run	4188	723
pulser frequency: 10 Hz, 300sec run	4189	724
Removing Cat5 cables from synchronization clock and installing fiber optic cables + converter boxes		
pulser frequency: 0.2 Hz, 60sec run	4190	725
5 random pulses within 60sec run, both energy mode	4191	726
pulser frequency: 1 Hz, both energy mode, 60sec run	4192	727
pulser frequency: 10 Hz, both energy mode, 60sec run	4193	728
pulser frequency: 10 Hz, both energy mode, 300sec run	4194	729
pulser frequency: 100 Hz, both energy mode, 300sec run	4195	730
pulser frequency: 10 Hz, both energy+trace (sync) mode, 300sec run	4196	731

Table 5.4.: All settings including run numbers tested with the two DAQs from detector system and muon modules. In the leftmost column, pulser settings and run lengths are described. In front of the different parts the pulser settings kept constant for the following measurements are described.

Run	solenoid source	solenoid detector	inner aircoil	outer central aircoil	outer aircoil	emcs x	emcs y
mos00159395	0	25	0	-4	-4	2	-19.5
mos00159396-							
mos00159398	0	50	0	-8	-8	2	-19.5
mos00159399	0	50	0	-7	-7	2	-19.5
mos00159400	0	50	0	-6	-6	2	-19.5
mos00159401	0	10	0	-2	-2	2	-19.5
mos00160713-							
mos00160717	0.1	12.5	0	-2	-2	0	0
mos00160718-							
mos00160730	0.1	12.5	0	-2	-2	0	0
mos00161105-							
mos00161107	0.1	12.5	0	-2	-2	0	0
mos00161108-							
mos00161110	0.1	25	0	-2	-2	0	0

Table 5.5.: Measurements at asymmetric magnetic fields. The source side magnet was turned off for all measurements leaving the flux tube entering the spectrometer walls.

Figure 5.14.: Flux tube at asymmetric magnetic fields. Electrons from processes at the walls are guided directly towards the detector as the largest part of the flux tubes surface ends in the monitor spectrometer's vessel's wall

pixels showed comparable count rates. Furthermore, the recording mode was switched from histogram-mode to energy-mode as the timestamps for every single event were needed for analysis. Several hourly runs were taken under different magnetic field compositions. Both asymmetric magnetic field (see table 5.5 and figure 5.14 and non-axially-symmetric field (see table 5.6 and figure 5.15 configurations were investigated.

The TOFHist function (chapter 4.3) has been used to analyze the data. It browses through all the muon-events detected and finds any detector event in a definable timespan after the muon-event. This can be more than one detector-event per muon-event. In all of the settings, a clear peak is visible at around 7 μ s. As for count rates, they are a lot higher in the asymmetric magnetic field setup as secondary electrons are guided from their point of origin to the detector instead of mostly being magnetically shielded. In this setup, only the reflection through the rise in magnetic field on the electrons' paths takes its toll on the rate. A graphic of the flux tube configuration as well as the histograms for all of the settings can be found in the A, figures (**reference figures.**) The exact values are:

ToDo

(**Do analysis for every measurement, insert peak positions + stdev**)

ToDo

Figure 5.15.: Flux tube at non axially symmetric fields. Although no direct guidance from the wall to the detector is given (the flux tube never touches the wall in this configuration), by adding a magnetic component perpendicular to z-direction, the probability for entrance into the flux tube rises strongly.

Run mos00...		2 Horizontal loops	solenoid source	solenoid detector	inner aircoil	outer aircoil	outer cent. aircoil	EMCS x	EMCS y
161111-161125	0	25	25	6.8	7	5	0	-14	
161126-161129	+50	12.5	12.5	3.5	-3.5	2.5	0	0	
161130-161133	+25	12.5	12.5	1.75	-1.75	1.25	0	0	
161134-161149	-25	12.5	12.5	1.75	-1.75	1.25	0	0	
161150-161155	-50	12.5	12.5	3.5	-3.5	2.5	0	0	
161156-161158	0	12.5	12.5	3.5	-3.5	2.5	0	0	

Table 5.6.: Measurements in energy mode at non axially symmetric magnetic field. Both solenoid and air coil currents have been changed, though always by a multiplication factor for all of them so that the ratio remained the same.

Average Standard Deviation

Figure 5.16.: Time difference histogram for asymmetric magnetic fields.

Figure 5.17.: Flux tube at non axially symmetric fields. Although no direct guidance from the wall to the detector is given (the flux tube never touches the wall in this configuration), by adding a magnetic component perpendicular to z-direction, the probability for entrance into the flux tube rises strongly.

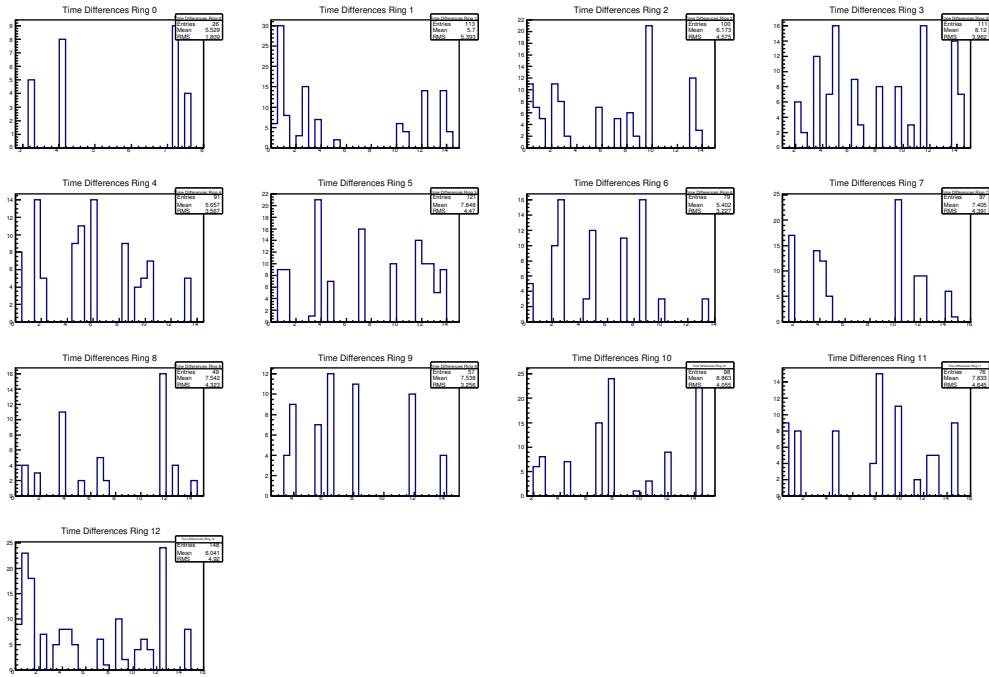


Figure 5.18.: Time differences of muon events followed by a detector event. From left to right and top down for every single detector ring, 0 being the innermost and 12 being the outermost ring. No clear indication of a time of flight for electrons induced by muons visible.

5.10.2. Main Spectrometer

Monitor-spectrometer results suggested that the time of flight was well measurable, even if on bigger scale, at the main spectrometer. So, during commissioning measurements, already parallel to first measurements “M1”, some runs with asymmetric magnetic field have been taken with switched polarity or turned off pre spectrometer magnets compared to standard setup. The data was analysed for each single ring of the FPD. Search parameters were the time slot from 0 s to 15 μ s though remains inconclusive at the moment, see 5.18. Analysis for every single pixel was not possible due to far too low statistics, though it might be more conclusive as less different paths contribute to a single pixel. On the other hand, after the non-central alignment of the detector has been fixed using different settings for the LFCS-system, under asymmetric magnetic fields, the fields should be rotationally symmetric around the z-axis disregarding small deviations. Assuming this, the path lengths for every pixel of one ring should be very comparable.

The failure to find a clear runtime for electrons induced by muonic events might be due to the combination of muon module position and the magnetic field setup as the wall area covered by the flux tubes and the volume surveilled by the muon modules did not overlap very much. Furthermore, due to the very low magnetic field at the wall compared to the volume inside the detector and pinch magnet, most of the induced electrons are magnetically reflected as the maximum polar angle towards magnetic field lines θ_{max} is defined by

$$\frac{B_{min}}{B_{max}} \approx \frac{3\text{ G}}{4\text{ T}} = \sin^2(\theta_{max}) \quad (5.5)$$

meaning only angles satisfying the inequation

$$\theta < \arcsin \sqrt{\frac{B_{min}}{B_{max}}} = \arcsin \sqrt{\frac{3\text{ G}}{4\text{ T}}} = 0.004^\circ \quad (5.6)$$

Figure 5.19.: Flux tube as proposed in [57]

Figure 5.20.: Flux tube in field configuration M12.8

ToDo will be able to reach the detector. All others will be reflected and fly back to the wall to be absorbed in the conducting wall material. (**set real field values**) As a result, compared to the monitor spectrometer, where the ratio is a lot greater, less of the muon induced electrons arrive at the detector making long measurements a requirement for good statistics. This leads to detector rates of only around 2 cps, depending on the inner electrode voltages. At high inner electrode voltages, the rate increases strongly to 150 cps which is probably due to field emission from the electrodes. Here, the rate of events actually analysed can be reduced by using energy cuts and excluding pixels with either known problems - for example the two defective pixels - or such covered by the misaligned flapper valve. The relevant energies were 25.6 keV to 30.6 keV including the PAE voltage of (**add PAE voltage**). To raise the overall acceptance of the muon induced events, these measurements were repeated with the main vessel on high voltage of 18.6 kV accelerating all the electrons towards the FPD. Following that presumption, for measurements (**Name measurements**), the setup was changed. The fluxtube was widened for its outer parts to hit the spectrometer wall in regions around combs n and n (**which combs**). This raises the probability of the muons detected being those inducing secondary electrons at the vessel as well. Also, the LFCS setup was changed in such fashion that the magnetic field at the spectrometer wall is higher by a factor of two, directly resulting in a higher angular acceptance of electrons. The resulting flux tube is shown in figure 5.19.

ToDo (**flux tube including modules for horizontal and vertical view**) (**If data will be taken add to analysis.**)

ToDo All measurements that have been taken with the main spectrometer for muon induced background analysis are listed in ??.

Figure 5.21.: Rate trend over inner electrode voltages

measurement setting	myo		fpd	
	start	end	start	end
A1	5159	5164	939	949
	5166	5172	950	977
B	5255	5256	1052	1055
A2	6306	6307	1090	1096
	6308	6311	1097	1104
	6312	6315	1105	1112
	6316	6321	1113	1124
	6322	6327	1125	1136
	6328	6333	1137	1148
D	6401	6404	1226	1229
	6405	6408	1230	1233
	6409	6412	1234	1237
A3	7111	7134	1301	1325

Table 5.7.: Main spectrometer runs taken for the search of muon induced background events. The runs are split into groups of same magnetic field settings. The individual settings are listed in 5.8. All group members have different inner electrode voltages, refer to appendix for those as well.

Measurement setting	IE[V]	PS I [T]	PS II [T]	Pinch [T]	Det [T]	LFCS [A]		EMCS h [A]	EMCS v [A]
						#1 - #13:	100 A; #14: 0 A		
A1, A2, A3	-700	0	0	5	3.5	#1 - #13:	100 A; #14: 0 A	50	9
B	0	0	0	5	3.5	#1 - #3:	0 A; #4: 50 A; #4 - #13: 100 A; #4: 0 A	50	9
C	-600	0	0	5	3.5	#1 - #3:	0 A; #4: 50 A; #5 - #13: 100 A #14: 0 A	40	9

Table 5.8.: Magnetic field settings for the individual groups from table 5.7

6. Simulation of muon induced background

To compare the data acquired to theoretically expected values, a Geant4 simulation of cosmic showers has been set up including the geometry of the main spectrometer as well as the muon modules. Using this software, any number of incidenting muons can be simulated and the effect on the main spectrometer and the muon modules can be evaluated. It was especially relevant to achieve estimations on which amount of the muons travelling through the main spectrometer would be registered by the muon modules. This would then make it possible to estimate the overall rate and probabilities for muons incidenting to also induce electrons entering the spectrometer.

6.1. Geant4

The Geant4 package is a powerful tool for simulation of particles. It has loads of possible interactions already integrated making it easy for the user to set up and run simulations. After setting up geometry and detectors, the user starts a run. Each run may consist of one or more events. During a single run, a loop of processes is called:

- Primary Generator Action
- Run action
- Event action
- Stacking action
- Tracking action
- Stepping action

For user interaction, for each item above, classes with the addition 'user' to the base classes name can be called before or after the standard action class. An example is the class G4UserEventAction invoked before and after each call of G4TrackingAction. It contains two member classes, namely BeginOfEventAction and EndOfEventAction that let the user decide what to do at this point. Through those, it is possible to change behaviour of the simulation or extract data needed. In this case, for every event, if more than one module has been hit, the copy numbers of those are pushed back to a vector of event data. Running the simulation, one can either interactively enter commands or write those to a .mac file, by default the vis.mac file, which are then sequentially executed.

Figure 6.1.: Dependance of muon rate on zenith angle.

6.2. Geometry setup

To set up a geometry, the class G4VUserDetectorConstruction is used. B1DetectorConstruction inherits from that as a base class and additionally contains all of the geometrical parameters needed for the setup such as radii of the main spectrometer cones or positions and extent of the muon modules. Every shape generated is made up of both a logical volume G4LogicalVolume and a physical volume G4PhysicalVolume. The logical volume describes the intrinsic properties of the geometric object added: its shape, its size and its material. The physical volume accepts a logical volume as input providing position and alignment of the previously defined. Inside the detector construction class, all of the materials used in the simulation need to be defined as well. These are the components of the air outside and inside the spectrometer including pressures and constitution, the stainless steel of the spectrometer wall and the scintillator material of the muon modules. The main spectrometer geometry was already (**written by who?**) existant but had to be modified as many border volumes were implemented. These were very flat volumes covering any area of the main spectrometer not needed for this simulation. Additionally, the muon modules have been added as sensitive volume. Keeping in mind that one wants to not only distinguish whether a module has been hit, but also which one. That is why the logical volume for every module is the same whereas the physical volume is a copy of the first at different world coordinates making them identifiable via their individual copy number.

ToDo

6.3. Muon generator

Muon generation was realised through the primary generator action. The angular distribution suggested by Henrik Arlinghaus [58] was implemented. The angular rate dependance is shown in 6.1. The energy was set to (**reasonable value**) disregarding the actual anergy distribution as this was mainly about flight paths that are not strongly dependant on energy at high energies. Starting positions were spherically distributed, with the direction towards the origin, which is in the center of the main spectrometer. Positions were then randomly moved in a volume surrounding the spectrometer to account for the non-point like structure of the detection system as a whole, while the distribution describes a single point in space.

ToDo

6.4. Hit counter

For comparing the simulation to real data, of all the events generated, those hitting modules were counted. Each event containing at least one hit is written into a file for further analysis. To do so, the functions (**exact names**) are used handing the information up from function to function. This made it possible to compare the rates of the single modules, showing that the generator works fine. furthermore, it allowed for an estimation of muons hitting the modules compared to the total of inciding muons.

ToDo

6.5. Visualisation - the vis.mac file

To display results of the calculations made, the tracks of all particles can be displayed as well as the geometry setup itself. This can be done interactively after running the program, though the faster approach is to use *.mac files, standardly the vis.mac file. Here, different parameters can be changed and simple visualisation settings like viewing angles and zooms can be chosen.

7. Conclusion

The whole muon detection system has been set up at the main- and readopted at the monitor spectrometer. Both systems are able to take data at rates that compare well to literature values.

It was shown that the muon induced electron rate is well shielded by axially symmetric magnetic fields and that, under circumstances differing from those, this rate increases strongly.

8. Outlook

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Appendix

A. First Appendix Section

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Figure A.1.: A figure

Figure A.2.: Scripting task through the example of a LFCS current ramping script. All currents are incremented in tenths of the maximum current for the individual coil.

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non-axially symmetric magnetic field

solenoid source	solenoid detector	inner aircoil	outer aircoil	outer cent. aircoil	emcs x	emcs y
25	25	7	-7	5	0	-14
mos00159753- mos00159754	Two horizontal loops at 100 A					
mos00159755- mos00159758	Two horizontal loops at -100 A					
mos00159759- mos00159771	No current in horizontal loops - background measurement					
mos00159772- mos00159773	Two horizontal loops at 100 A					

solenoid source	solenoid detector	inner aircoil	outer aircoil	outer cent. aircoil	emcs x	emcs y
12.5	12.5	3.5	-3.5	2.5	0	0
mos00160661- mos00160666	Two horizontal loops at 50 A					
mos00160667- mos00160682	No current in horizontal loops - background measurement					
mos00160684- mos00160687	Two horizontal loops at -50 A					

solenoid source	solenoid detector	inner aircoil	outer aircoil	outer cent. aircoil	emcs x	emcs y
6.2	6.2	1.7	-1.7	1.2	0	0
mos00160688- mos00160691	Two horizontal loops at 25 A					
mos00160692- mos00160706	No current in horizontal loops - background measurement					
mos00160707- mos00160711	Two horizontal loops at -25 A					

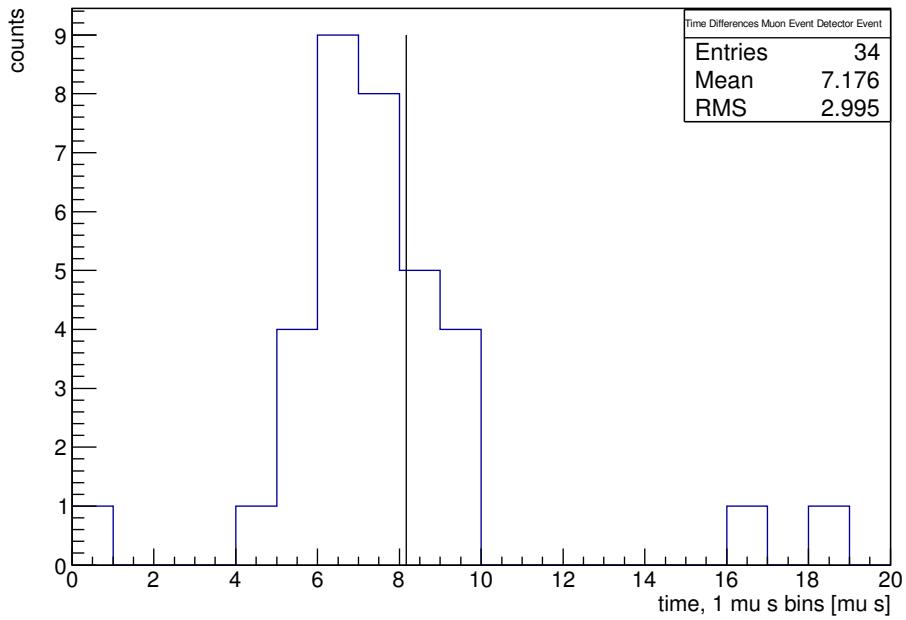


Figure A.3.: Two horizontal loops at 50 A current. For all settings see 5.6, line 1.

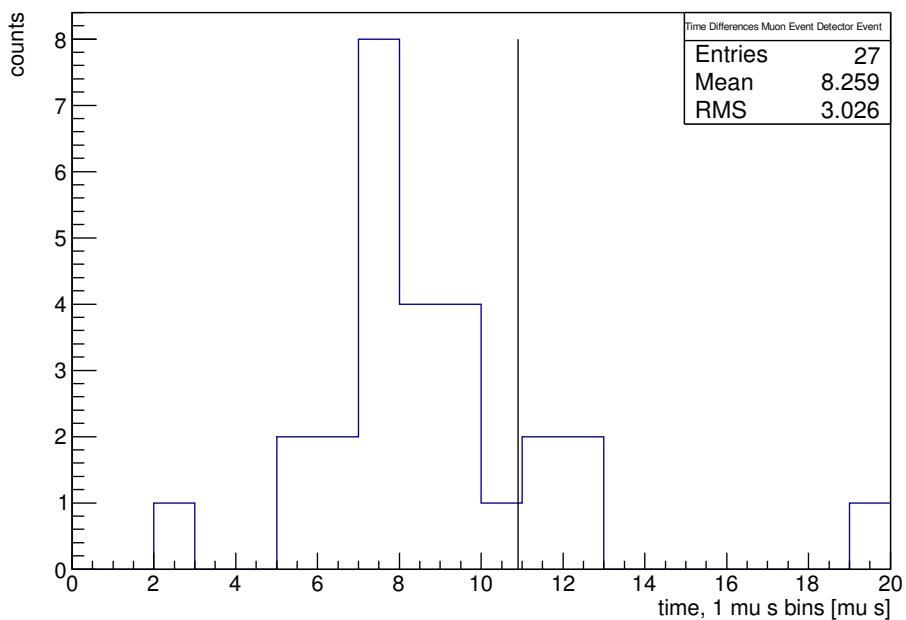


Figure A.4.: Two horizontal loops at -50 A current. For all settings see 5.6, line 3.

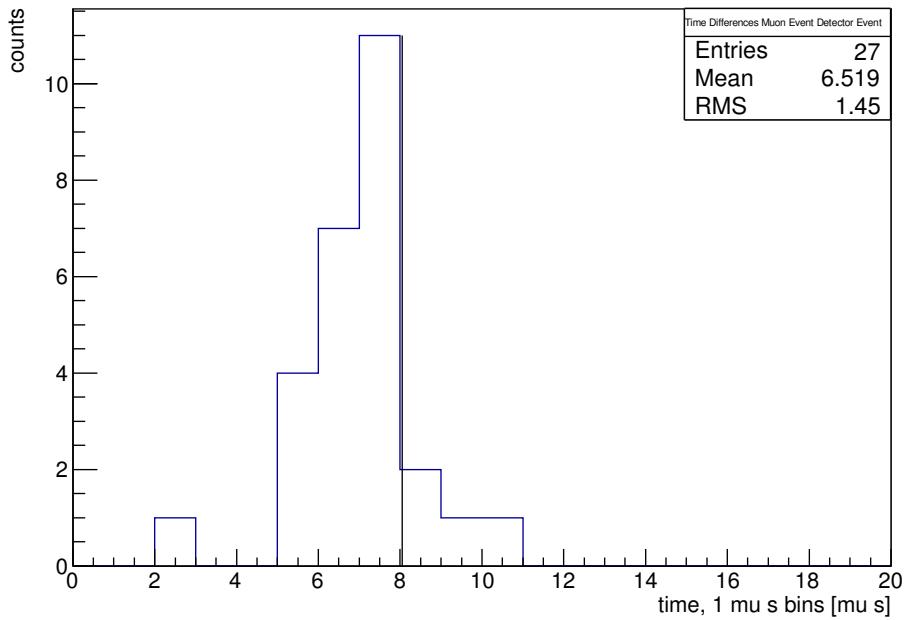


Figure A.5.: Two horizontal loops at 25 A current. For all settings see 5.6, line 2.

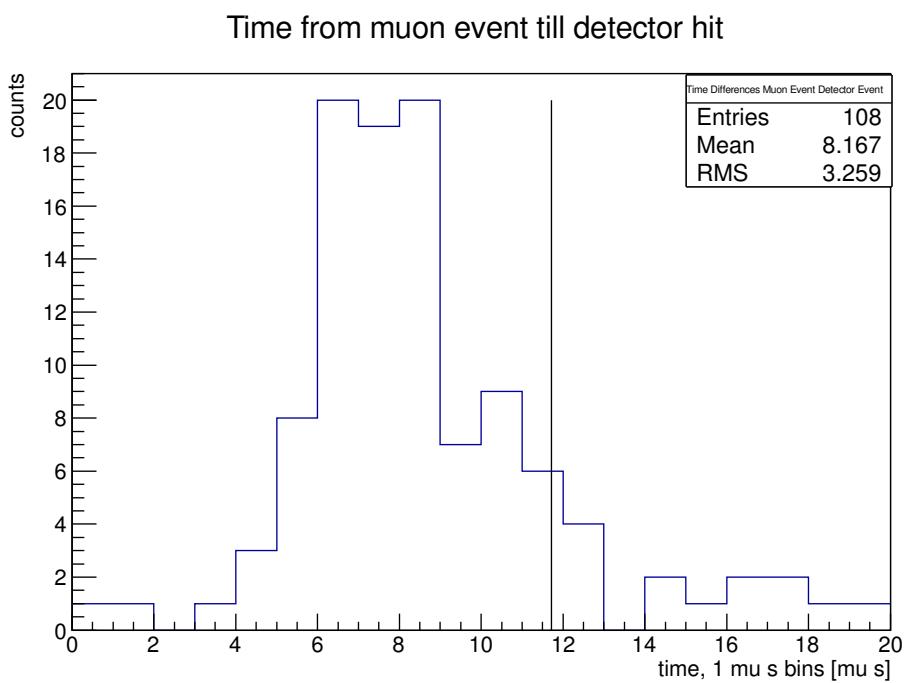


Figure A.6.: Two horizontal loops at -25 A current. For all settings see 5.6, line 4.

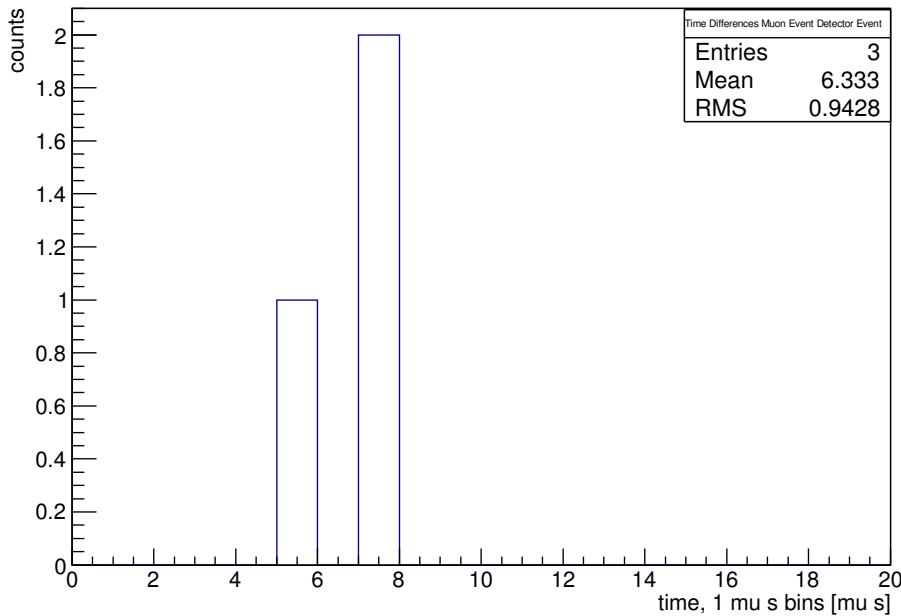


Figure A.7.: Two horizontal loops at 0 A current. For all settings see 5.6, line 1.

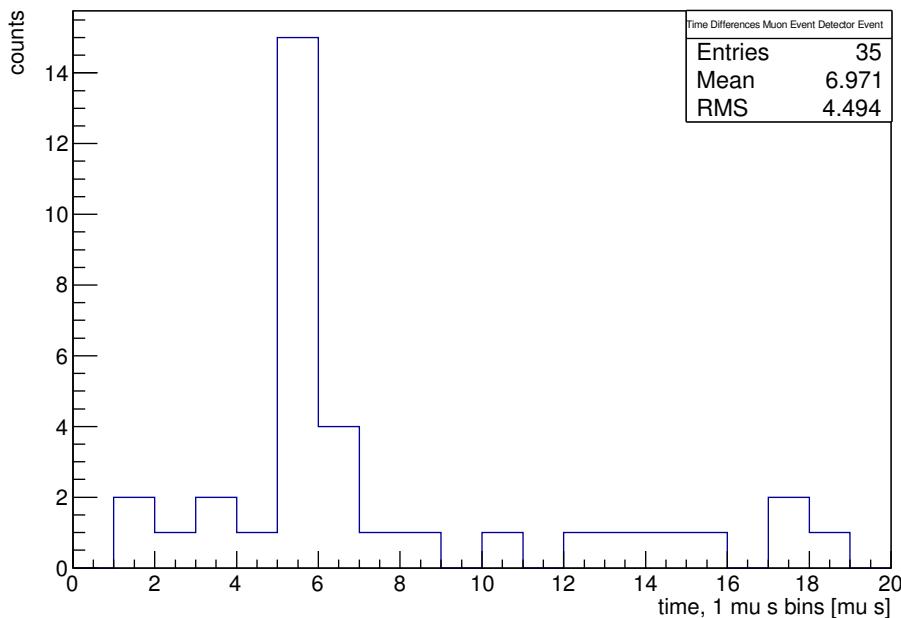


Figure A.8.: Two horizontal loops at 0 A current. Both solenoids at 25 A for a comparison of the background at different field widening. For all settings see 5.6, line 1.

Date	T _{low} [K]	T _{high} [K]	p _{low} [kPa]	p _{high} [kPa]	p _l / T _l	p _h / T _h
21.12.12	274.95	281.25	1010.10	1018.20	3.67	3.62
22.12.12	278.55	282.15	1009.50	1020.60	3.62	3.62
23.12.12	282.85	287.25	1009.50	1013.70	3.57	3.53
24.12.12	277.05	287.15	1007.40	1013.50	3.64	3.53
25.12.12	276.05	288.35	1004.00	1010.30	3.64	3.50
26.12.12	281.25	282.85	1010.40	1016.40	3.59	3.59
27.12.12	280.75	283.25	1004.80	1014.70	3.58	3.58
28.12.12	279.65	281.85	1016.20	1029.50	3.63	3.65
29.12.12	276.05	284.55	1014.90	1026.00	3.68	3.61
30.12.12	279.05	282.85	1015.90	1024.60	3.64	3.62
31.12.12	277.05	283.15	1011.60	1024.40	3.65	3.62
01.01.13	274.45	281.45	1008.10	1016.90	3.67	3.61
02.01.13	272.25	279.15	1017.50	1033.00	3.74	3.70
03.01.13	273.65	280.45	1033.10	1038.30	3.78	3.70

Table A.1.: Temperature and pressure data from the weather station in Rheinstetten. Daily high and low were given, included are the ratio of pressure and temperature for both the high and the low values. This ratio is proportional to the air's density . Bare in mind that this data is only for the low atmospheric layer and the station is also around 20 km away from the KATRIN muon modules.