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Preparation of a High-precision X-ray Detector for Kaonic Atom Measurements at J-PARC and DAΦNE

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Abstract

The antikaon-nucleon interaction close to threshold is one of the most important unsolved problems in the field of low-energy QCD in hadron physics. This interaction can shed light on one of the most fundamental questions in physics, namely the creation of hadron masses.

Two experiments (E57 at J-PARC and SIDDHARTA-2 at DAΦNE) have been proposed to study the contribution of the strong interaction on the $1s$ ground state of kaonic deuterium. The $1s$ state of kaonic deuterium should be shifted and broadened due to the strong interaction between the strange quark in the kaon and the quarks in the nucleus. This shift and width will be determined with a newly developed X-ray detector system with a precision of 60 eV and 140 eV, respectively.

The X-ray detector system consists of 48 Silicon Drift Detectors (SDDs), which have been thoroughly tested at the Stefan Meyer Institute for Subatomic Physics. These test measurements included a stability analysis, a drift time measurement, a crosstalk probability evaluation and several tests on amplifier settings to achieve the best energy resolution.

Four SDD arrays have been tested in the E62 kaonic helium experiment at J-PARC to test the SDDs for the first time in a real beam environment. The obtained results confirmed the SDDs' excellent operation, and ensured their readiness to be used in the E57 and SIDDHARTA-2 experiments.

Zusammenfassung

Eines der wichtigsten, ungelösten Probleme im Gebiet der Niedrigenergie-QCD der Hadronenphysik ist die Antikaon-Nukleon Wechselwirkung nahe der Produktionsschwelle. Diese Wechselwirkung kann jedoch Licht auf eine der fundamentalsten Fragen der Physik werfen: die Frage der Erzeugung von Hadronenmassen.

Zwei Experimente (E57 am J-PARC Beschleuniger und SIDDHARTA-2 am DAΦNE Beschleuniger) wurden beantragt um den Beitrag der starken Wechselwirkung am Grundzustand von kaonischem Deuterium zu untersuchen.

Der Grundzustand von kaonischem Deuterium ist aufgrund der starken Wechselwirkung zwischen dem Strange-Quark im Kaon und den Quarks im Kern verschoben und verbreitert. Diese Verschiebung und Verbreiterung soll mithilfe von einem neu entwickelten X-ray-Detektorsystem mit einer Präzision von 60 eV beziehungsweise 140 eV bestimmt werden.

Das Detektorsystem besteht aus 48 Silizium-Drift-Detektoren (SDDs), welche am Stefan Meyer Institut für Subatomare Physik getestet wurden. Diese Testmessungen beinhalteten Stabilitätsmessungen, eine Bestimmung der Driftzeit, eine Evaluation der Crosstalk-Wahrscheinlichkeit und mehrere Tests an verschiedenen Verstärkerboards um die beste Energieauflösung zu erzielen.

Vier dieser SDD-Arrays wurden im Experiment E62 zur Messung von kaonischem Helium am J-PARC verwendet, um die SDDs erstmalig im Umfeld eines Beschleunigers zu testen. Die erzielten Resultate bestätigten den hervorragenden Arbeitsbetrieb der SDDs und unterstrichen, dass die SDDs bereit für den Einsatz in den Experimenten E57 und SIDDHARTA-2 sind.

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1 Introduction

Low-energy quantum chromodynamics (QCD) is still one of the less explored fundamental theories of the standard model. Especially the problem of bound state QCD is still vastly unexplored due to the immense difficulties of the experiments. Given that the kaon is the lightest meson including a strange quark, it is the perfect candidate to form exotic atoms with strangeness and thus more insight into the unsolved problem of the antikaon-nucleon interaction can be gained. It could also lead to an answer to the mystery of how hadron masses are generated.

Two experiments (the E57 experiment at the Japan Proton Accelerator Research Complex (J-PARC) and the SIDDHARTA-2 (Silicon Drift Detector for Hadronic Atom Research by Timing Application-2) experiment at the Double Annular Φ Factory for Nice Experiments (DAΦNE/DAFNE) at the Laboratori Nazionali di Frascati (LNF)) have been proposed to investigate these interactions in more detail. In these experiments the electron of a deuterium atom will be exchanged with a kaon and produce a highly excited kaonic deuterium atom. Losing its abundant energy via several mechanisms the kaon will come close enough to the nucleus to feel not only the electromagnetic force but also the strong interaction. Therefore, a deviation from the very well known electromagnetic value of the 1s ground state of kaonic deuterium will result in a shift and broadening of it, which can be directly measured in the experiment.

Even though the measurements of KpX at the High Energy Accelerator Research Organization (KEK) in Japan as well as the DEAR (DAΦNE Exotic Atom Research) and SIDDHARTA experiments at DAΦNE have already produced important results for the K^-p transition from $2p \rightarrow 1s$ state, and have put tight constraints on the theory of antikaon-nucleon interactions, the determination of the isospin dependent antikaon-nucleon scattering lengths a_0 and a_1 is still unsolved. This will only be possible by a combined analysis of the already determined K^-p interaction and the newly proposed K^-d experiments.

The challenges of these measurements are foremost the very low kaonic deuterium X-ray yield and the high-radiation environment in the accelerator. Therefore, the background of the accelerator must be studied precisely to be able to single out the kaonic deuterium K lines and to determine the energy shift and width with a precision of 60 eV and 140 eV, respectively, in the E57 experiment.

384 new Silicon Drift Detectors (SDDs) developed at Fondazione Bruno Kessler (FBK) and Polytechnico Milano will be used to measure the radiative X-ray transition of the $2p \rightarrow 1s$ state of kaonic deuterium. The SDDs must show a stable performance during the whole experiment to guarantee a summing of all channels, the energy resolution should be below 180 eV at 6 keV to enable the suggested precision of the shift and width, and the time resolution should be below 300 ns at a temperature of 100 K. Furthermore, they must withstand high count rates of up

to 20 kHz (which corresponds to the injection of the e^-/e^+ pairs at the DAΦNE collider, and a similar rate is expected for J-PARC). To ensure the required performance of the SDDs, several test measurements have been performed at the Stefan Meyer Institute in Vienna (SMI).

The E62 kaonic helium measurement of the $3d \rightarrow 2p$ transition has been performed at J-PARC in June 2018 with high precision Transition-Edge-Sensors (TES) to determine the shifts of the kaonic ^3He and ^4He atoms with a precision of 0.2 eV. Four newly developed SDD arrays have been used during the experiment in order to test their stable workings in real beam environments by measuring the L line of the $3d \rightarrow 2p$ transition. The very first preliminary results are presented here.

2 Kaonic Atoms

The strong interaction is one of the fundamental interactions with many questions about it remaining unanswered. One of the most prominent unsolved problems is the discrepancy between the quark masses and the resulting hadronic mass. How is it possible that the proton possesses a mass of almost 1 GeV even though the constituents of it (u and d quarks) have masses of only a few MeV each? Even though many experiments with hadrons have been performed more information is still needed. Therefore, it seems only reasonable to study atoms with a different composition than the one seen in everyday life - and exotic atoms with strangeness provide the perfect starting point.

Exotic atoms have already been postulated in the 1940s (e.g. [1]) and are formed if a negatively charged particle, like a π^- or a K^- , is stopped by an atom of a target and replaces one of the atom's electrons. As the kaon is the lightest meson containing a strange quark, it provides excellent features for exotic hadron spectroscopy at low-energies to discover unknown characteristics of the strong interaction.

2.1 Formation of Kaonic Atoms

To form a kaonic atom, a negatively charged kaon (K^-) replaces an electron from an outer shell via Coulomb capture of the atom. Due to the high mass of the kaon of 493.7 MeV/c² (taken from [2]) compared to the low mass of the electron with only 0.5 MeV/c² (taken from [2]) the exotic atom is formed in a highly excited state as

$$n_{K^-} \approx n_e \sqrt{(\mu_{K^-}/m_e)} \quad (2.1)$$

with n being the principal quantum number, m_e the mass of the electron and μ_K the reduced mass of the kaon (m_K) and the nucleus (m_N), $\mu_K = (m_K \cdot m_N)/(m_K + m_N)$. Therefore, the kaon will cascade down into lower energy states releasing the additional energy in form of Coulomb de-excitation, Auger electrons and X-rays. When it reaches an energy state near the nucleus, the kaon will feel not only the electromagnetic force due to its negative charge, but also the strong interaction originating from the quarks of the nucleus. This leads to an energy shift of the state. The electromagnetic value can be calculated from the Bohr energy given by

$$B_n = \frac{\mu c^2 \alpha^2 Z^2}{2n^2} \quad (2.2)$$

where B corresponds to the binding energy, n is again the principal quantum number, μ is the reduced mass of the system, $\alpha \sim (1/137)$ is the fine-structure constant and Z being the atomic number. In the case of kaonic deuterium the electromagnetic energy difference of the $2p \rightarrow 1s$ states is 7.8 keV. The cascading process for kaonic deuterium is shown in figure 1. The time it takes the kaon to reach the ground state is in the order of 10^{-9} s [3].

One can measure the energy shift ϵ induced by the strong interaction as the difference between the expected energy resulting only from the electromagnetic force and the measured energy of the photon:

$$\epsilon_{1s} = E_{2p \rightarrow 1s, \text{measured}} - E_{2p \rightarrow 1s, \text{em}} \quad (2.3)$$

At the end of the cascading process the kaon will be absorbed by the nucleus, broadening the width Γ of the state due to the short lifetime of the 1s state ($\Gamma = \hbar/\tau$, $\hbar$ being the reduced Planck constant and τ the lifetime of the state). This process can already happen at higher energy levels, the probability of absorption at higher energy levels increasing with the mass of the exotic particle (in our case the kaon) as particles with higher mass are closer to the nucleus ($r \sim 1/\mu_c$, μ_c being the reduced mass), thus absorption becomes more likely the heavier the particle.

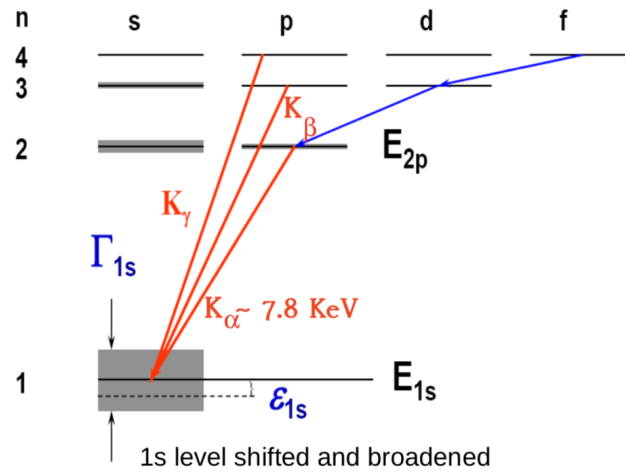


Figure 1: A schematic view of the kaonic deuterium cascading process. The transition of interest is the $2p \rightarrow 1s$ state. *Picture courtesy of the SIDDHARTA-2 collaboration.*

One of the main processes that can decrease the yield of kaons reaching the 1s state is the Stark mixing: An external electric field originating from other target atoms causes a mixing between rotational states of the same principal quantum number n . This can lead to an increased absorption of the kaon already in energy states with a high principal quantum number, and therefore decreases the kaon yield drastically. In general less than 1% of the kaons will reach the 1s state of kaonic deuterium before being absorbed by the nucleus (of course during the cascade the kaon might decay into pions) [4]. For more detailed information about hadronic atoms see e.g. [5].

2.2 $\bar{K}N$ Scattering Lengths

The first paragraph of this chapter is a brief introduction in QCD and chiral symmetry, and is based on the theory provided in [6].

“The strong interaction is governed by quantum chromodynamics (QCD) which is a color SU(3) gauge theory of quarks as fundamental fields and gluons as gauge fields,” stated by T. Hyodo and D. Jido in [6] *page 9*. For reasons of simplification, only the case where the three light quarks (u, d and s quark) are considered will be discussed. The chiral symmetry $SU(3)_R \times SU(3)_L$ of QCD is broken mainly due to two reasons: “The quark condensate is the vacuum expectation value of the $q\bar{q}$ operator. This is not invariant under chiral symmetry, since it mixes the left- and right-handed quarks (...). This is called spontaneous breaking of chiral symmetry (...). When the symmetry is spontaneously broken, Nambu-Goldstone theorem [7, 8, 9] ensures that the spectrum of physical particles must contain one bosonic massless particle for each broken symmetry,” explained in [6] *page 10*. The particles created are termed the Nambu-Goldstone (NG) particles and, in the case of the three light quark model, are the pseudoscalar mesons π , K, and η . However, quarks are not massless and another type of symmetry breaking, namely the *explicit symmetry breaking*, ensures that these NG particles have non-zero mass.

By introducing external fields into the Lagrangian an effective field theory can be constructed, which includes these symmetry breaking mechanisms (non-perturbative coupled-channel techniques based on driving terms from the chiral SU(3) effective Lagrangian).

In the chiral SU(3) effective field theory approach the $\bar{K}N$ scattering lengths a_0 and a_1 of the s-wave (dependent on the isospin $I=0,1$) can be determined at low energies. In case of the K^-d interaction, they take the following form:

$$\begin{aligned} a_{K^-p} &= \frac{1}{2}[a_0 + a_1] \\ a_{K^-n} &= a_1 \\ a_{K^-d} &= \frac{4[m_N + m_K]}{[2m_N + m_K]}Q + C \\ Q &= \frac{1}{2}[a_{K^-p} + a_{K^-n}] = \frac{1}{4}[a_0 + 3a_1], \end{aligned} \tag{2.4}$$

with a_{K^-p} being the scattering length of a K^- with a proton (p), K^-n of a kaon with a neutron (n) and K^-d the scattering length between kaon and deuterium (d) atom; m_N stands for the nucleon mass, m_K for the mass of the kaon, and C for a correction term for higher-order contributions from three-body interactions.

The first pioneering approach to connect the s-wave scattering lengths to the energy shift and width induced by the strong interaction was done by Deser *et. al* in [10] for pionic atoms (see equation 2.5 for the kaonic deuterium case).

The SIDDHARTA experiment at DAΦNE already successfully measured the kaonic hydrogen 1s shift and width [11], and the K^-p interaction is well understood due to these results as well as the theoretical calculations constrained by the experimental values ([12], [13]). In figure 2, taken from [13], an analysis with these constraints on the real and imaginary forward scattering amplitude is shown.

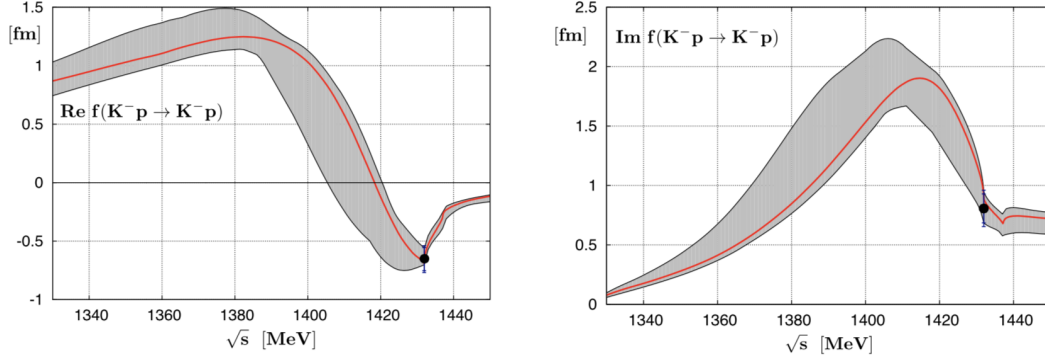


Figure 2: Real and imaginary part of the $K^-p \rightarrow K^-p$ forward scattering amplitude, where $\sqrt{s}$ denotes the meson-baryon centre-of-mass energy. The SIDDHARTA kaonic hydrogen data is shown by the dots including statistical and systematic errors [13].

For kaonic deuterium the correlation between these observables and the scattering lengths is given by the improved Deser formula [14]:

$$\epsilon_{1,s} - \frac{i}{2}\Gamma_{1,s} = -2\alpha^3 \mu_c^2 a_{K-d} (1 - 2\alpha \mu_c (\ln(\alpha) - 1) a_{K-d}). \quad (2.5)$$

Here, α denotes the fine structure constant and μ_c the reduced mass of the kaonic nucleon.

In table 1 theoretical values for the scattering length a_{K-d} , the energy shift $\epsilon_{1,s}$ and the width $\Gamma_{1,s}$ are given. The values show a big range going from $a_{K-d} = -1.42 + i 1.09$ up to $a_{K-d} = -1.58 + i 1.37$. Therefore, an experimental determination of $\epsilon_{1,s}$ and $\Gamma_{1,s}$ is needed to constrict theoretical parameters and possibly even resolve the discrepancy between theories.

Together with the result of the SIDDHARTA experiment the a_{K-d} measurement will allow to calculate the isospin dependent scattering lengths a_0 and a_1 . This is the goal for the E57 experiment at J-PARC and the SIDDHARTA-2 experiment at DAΦNE.

a_{K^-d} (fm)	$\epsilon_{1,s}(eV)$	$\Gamma_{1,s}$ (eV)	Reference
- 1.42 + i 1.60	- 670	1016	Weise <i>et. al</i> (2017) [14]
- 1.58 + i 1.37	- 887	757	Mizutani <i>et. al</i> (2013) [15]
- 1.48 + i 1.22	- 787	1011	Shevchenko [16]
- 1.46 + i 1.08	- 779	650	Meißner <i>et. al</i> (2011) [12]
- 1.42 + i 1.09	- 769	674	Gal (2007) [17]

Table 1: Calculated values for the K^-d scattering length and the expected experimental values for the energy shift and width of the kaonic deuterium 1s ground state.

2.3 Unsolved $\bar{K}N$ Potential Depth

There exist several theories about the potential depth of the antikaon-nucleon ($\bar{K}N$) scattering. The two most prominent theories, namely the phenomenological model (e.g. [18]) and the chiral unitary approach (e.g. [19]), differ substantially in their calculations about the depth of the potential of kaon-nucleon interactions for atoms with $Z \geq 2$. The first model gives a potential difference of 180 MeV, whereas the other assumes a potential depth of 50 MeV.

Furthermore, another theory (explained e.g. in [20]) suggests a difference between the scattering lengths of the kaonic helium isotopes ^3He and ^4He . To solve both open questions, the kaonic helium experiment E62 has been performed at J-PARC in June 2018, where the $3d \rightarrow 2p$ transition of both kaonic helium atoms has been studied with a high precision detector system.

3 Experimental Setup

Within the experimental test setup for SDDs at the SMI, the SDD array is mounted on an aluminium support structure inside a vacuum chamber with an insulation vacuum pressure of 10^{-7} mbar achieved with a forepump (Pfeiffer Vacuum MVP 055-3) and a turbo pump (Agilent Technologies TwisTorr 84 FS, in June 2018 exchanged to the turbovac T350 iX by Leybold). The cooling is done by a PCC PolyCold Cryotiger to reach temperatures between 150 - 170 K. Temperature sensors Pt100 are connected to the support structure and the line-driver to track the temperature gradient during and after cooling. To measure the temperature of the SDD chip a Pt100 is already integrated on the ceramic structure of the SDD and can be read out via the motherboard. The SDD is connected via a Kapton cable to the line-driver which transports the signal via a one-metre long broad-band cable to the amplifier board. The motherboard is stationed outside the vacuum chamber. A picture of the test setup can be seen in figure 3.

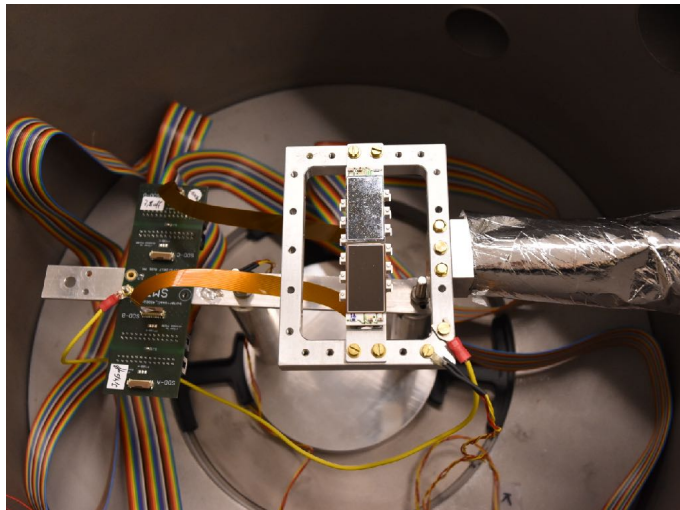


Figure 3: The kaonic deuterium test setup at the SMI.

A small window of 125 μm thick Kapton foil is set on top of the vacuum chamber to enable the irradiation of the SDDs by a radiation source. The distance from the source to the SDD is 12.8 cm. An Fe-55 source with an additional 5 μm thick Ti foil has been used for energy calibration of the SDDs. An example of an energy spectrum of SDD no. 11 (channel 1) taken during one afternoon with the Fe-55 + Ti source is shown in figure 4 with the four peaks clearly marked. Considering the thickness of the Kapton foil as well as the distance between SDDs and source, the efficiency for K_{α} Mn X-rays detection is roughly 10^{-4} per cell.

Several SDD arrays have been tested to examine their performances throughout the start of this master thesis until the test run in June 2018, even though most of the

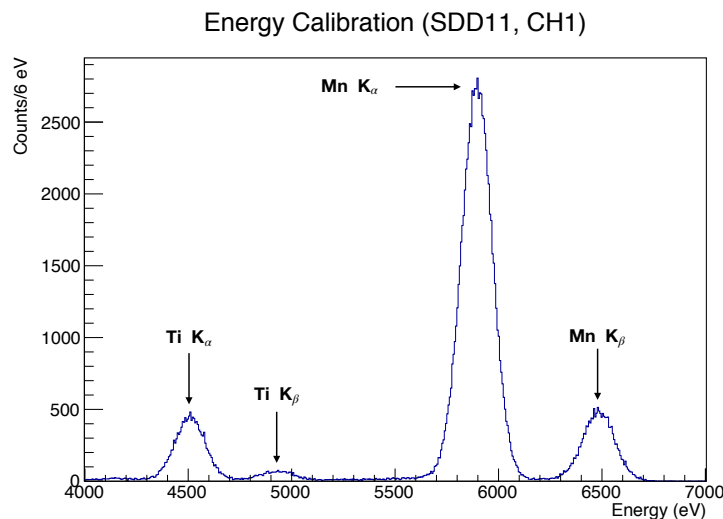


Figure 4: Example of an Fe-55 spectrum of channel 1 of SDD no. 11.

test measurements have been performed with two SDD arrays (no. 10 and no. 11), both in constant use from September 2017 until April 2018. From June 2018 until August 2018 SDD arrays no. 18 and 20 have been used for testing, as SDD no. 10 and no. 11 have been included in the VIP-2 experiment at Gran Sasso, and are running there successfully.

As lower temperatures should be reached at J-PARC, the cooling system has been replaced in April 2018 with a closed cycle cryocooler (with helium as cooling gas) to be able to cool the SDDs to temperatures between 70 - 80 K. For details on the workings of the two different cooling systems see chapter 3.1.2.

3.1 Silicon Drift Detectors

The principle of Silicon Drift Chambers (SDCs) was first proposed by Gatti and Rehak in [21]. When an X-ray hits the n-type silicon wafer an electron-hole pair is created. The electron is then forced by the created potential of the p^+ contacts, which are deposited on the n^+ bulk, to drift to the n^+ doped anode. A schematic picture of the working principle of a SDC is shown in figure 5.

SDDs use the same technique, however their arrangement is different. A small anode is stationed in the middle of the detector around which the p^+ contacts are arranged in a ring format to enforce a radial electric field. On the opposite side of the silicon wafer a non-structured p^+ area serves as the entrance window and collects at the same time the holes which have been produced by the incoming X-ray in the electron-hole reaction.

The electric field is generated by an applied bias voltage. A voltage can be applied

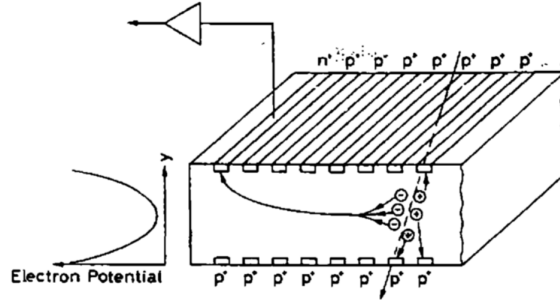


Figure 5: The working principle of a Silicon Drift Chamber [22].

to the back contact (which is the entrance window of the wafer) R_B , the outermost ring R_N and the innermost ring R_1 . The voltage of the drift rings between R_1 and R_N is produced by an integrated voltage divider [23]. The highest voltage is applied to R_1 , the lowest to R_N with typical values around $R_1 = -15$ V and $R_N = -90$ V, while $R_B = -70$ V.

For the SDDs used in the SIDDHARTA experiment a junction gate field-effect transistor (JFET) was directly implanted close to the anode to preamplify the detected signal. Figure 6 shows the structure of a SDD, including the path of the electrons and the applied bias voltages; underneath, the produced potential leading the electrons to the anode is presented.

3.1.1 Newly developed SDD units

The SDDs used for the E57 experiment as well as for the SIDDHARTA-2 experiment use a complementary metal-oxide-semiconductor (CMOS) preamplifier, called CUBE, instead of the usually used JFET [24]. The CMOS is stationed on the ceramic support structure of the SDD array and is electrically connected to the anode. This essential difference, compared to SDDs with integrated JFET preamplifier, makes the new SDDs easier to fabricate, more stable and almost independent to small changes e.g. variations of the bias voltage and additionally, the change from JFET to CMOS increases the latch-up performance of the new SDDs.

The ceramic carrier is then screwed onto an aluminium block to keep the assembly stable and will be used for cooling. Figure 7 shows the silicon wafer of the SDD array as well as the ceramic structure with the CUBE preamplifier.

One SDD array consists of 2×4 single SDD units. In the E57 experiment 48 SDD arrays (meaning 384 SDD cells) are needed to surround the cryogenic target cell. One SDD unit provides an active area of $8 \times 8 \text{ mm}^2$, which adds to a total active area of the whole detector of 245 cm^2 . The individual SDD cells are divided by a thin potential well, minimising crosstalk to under 1 % (see section 4.5 for a detailed crosstalk probability evaluation).

With only a margin of 1 mm on each side the dead area of the SDD is dramatically

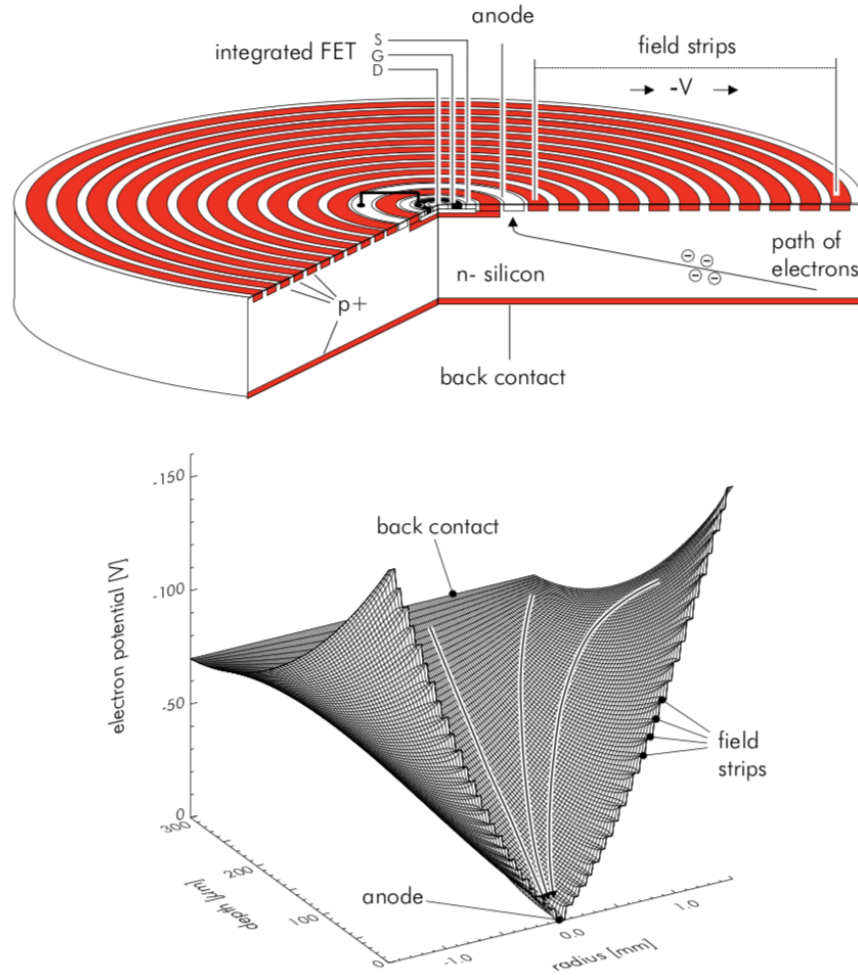
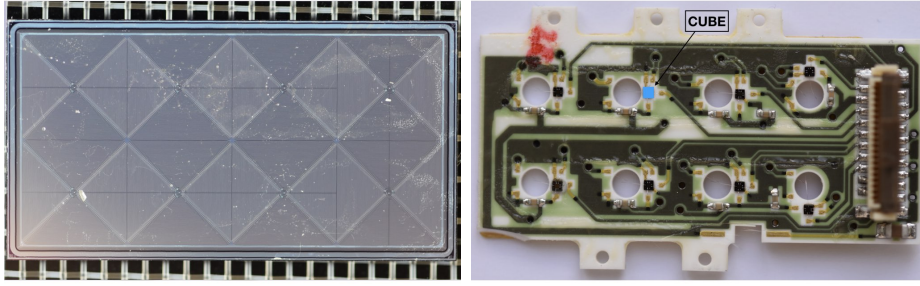


Figure 6: SDD structure and drift potential created by the applied bias voltage [23].



(a) View of the silicon wafer structure of one SDD array. (b) View of the ceramic structure with CUBE position indicated by the blue cube.

Figure 7: Silicon plate of one SDD array and back view of array with CUBE preamplifier.

reduced. A view of this is given in figure 8. This increase in total active area is an important improvement of the detection efficiency compared to the SDDs used in the SIDDHARTA experiment, where the active area only made up 20 % of the detector (compared to 80 % of the new SDD modules).

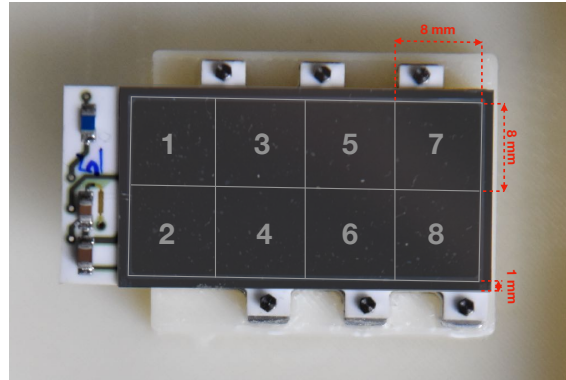


Figure 8: One SDD array with 2×4 SDD cells, each having an active area of $8 \times 8 \text{ mm}^2$ and a dead area margin of 1 mm around the 2×4 matrix. The numeration of the single SDD units is shown [25].

The SDDs are mounted on a ceramic support structure, which features three bulges on two sides to improve the positioning of the SDDs around the target cell and thus allows to keep the dead detector area at a minimum.

The newly developed SDDs need to meet some requirements, so that the kaonic deuterium experiment is feasible. Firstly, utmost stability is required to allow the summing of all 384 channels. Therefore, fluctuations of peak position and width of

only a few eV are acceptable, and the energy resolution at 6 keV should be better than 180 eV. Furthermore, the new SDDs must be able to deal with a count rate as high as 20 kHz (e.g. during injection of e^-/e^+ at DAΦNE, which will also be expected at J-PARC [26]). Finally, a drift time of 300 ns at low temperatures is needed to minimise the background further. This requires a decrease of the drift time compared to the previously used SDDs (800 ns) by almost a factor of 3.

3.1.2 Cooling System

For the cooling of the test setup a PCC PolyCold Cryotiger is used. For detailed information on the PCC Cryotiger see [27]. The cooling system consists of three main components: the cryocooler, an air-cooled compressor and two gas lines (the supply and return lines), that provide the link between cryocooler and compressor. A schematic overview of the cooling system is provided in figure 9. The fluid used is a flammable gas mixture and a proprietary refrigerant.

The cooling system is based on the Joule-Thomson effect: A gas is placed in a confined and isolated area with constant volume V_1 and constant pressure p_1 . It is separated by a porous material or a throttle from another confined area with volume $V_2 = 0$ and $p_2 = 0$. If a piston compresses the gas in the first chamber, it will pass through the material or throttle and expand on the other side (under the condition that $p_1 > p_2$), keeping the enthalpy of the system constant. Due to the ideal gas equation $pV = NkT$, where p denotes the pressure, V the volume, N the number of particles in the gas, k the Boltzmann constant and T the temperature, it is clear that if the pressure is reduced, also the temperature T will decrease, thus the gas is cooled. If V_2 is in contact with another material (in case of the Cryotiger it is in contact with the cold end) the gas temperature will increase as it will achieve a thermal equilibrium with the material, reducing the material's temperature. The heated gas will then be transported back into the first chamber where the process will take place again until a constant heat exchange is achieved. For more information refer e.g. to [28].

In the very beginning of the test measurements until September 2017, the cooling block has been connected with a $30 \times 2.5 \times 230 \text{ mm}^3$ copper cable to the support structure of the SDDs. With this configuration temperatures of just below 170 K were reached. As the cooling effect decreases with increasing length of the cooling cable, lower temperatures can be reached by connecting the SDD support structure directly to the cooling end. In this way temperatures of 150 K could be reached starting from September 2017 onwards.

As it was planned that the SDDs reach temperatures of $<70 \text{ K}$ (see e.g. [29]), the cooling system was changed from a simple cryotiger to a Gifford-McMahon cooling cycle, with He as the cooling fluid. This change was performed in May 2018 and temperatures as low as 100 K were reached. However, contrary to all expectations,

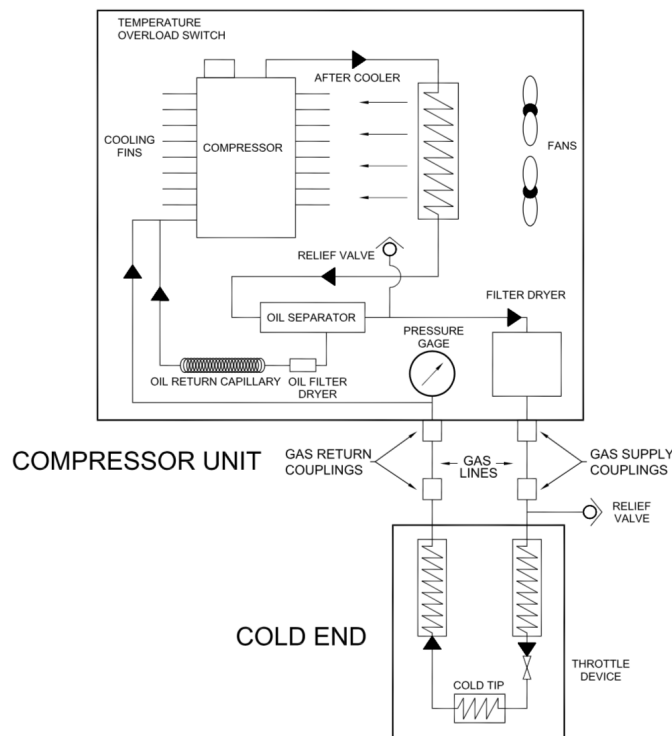


Figure 9: Cooling system for the test setup at SMI [27].

no signal output could be detected at these temperatures. The effect could be caused by several reasons: change of the R_1 potential, malfunction of the CUBE preamplifier or a small crack in the ceramic support structure. As the SDDs were fine after increasing the temperature again, the cooling system was changed back to a cryotiger with a Joule-Thomson system. Surrounding the SDDs with a superinsulation material allowed a cooling to temperatures of 120 K.

3.2 Motherboard and Line-Driver

The continuous improvement of the amplifier boards was one of the most crucial steps during this master thesis. As the amplifiers are mainly responsible for the energy resolution and stability, it was important to construct the boards in such a way, that the best energy resolution could be achieved, that the stability of the SDDs was hardly effected by the amplifier boards, and that the electronic crosstalk was negligible. Therefore, intensive studies with different amplifier boards have been performed with different SDD arrays. However, by the end of this master thesis not every detail about the amplifier boards has been understood, so further tests have to be done to achieve the best amplifier board setup for the kaonic deuterium measurement.

3.2.1 Motherboard

The CUBE preamplifier used to detect the small signal from one SDD unit is a charge amplifier, able to deal with very high event rates. When applying the bias voltage to the SDDs, the CUBE preamplifier sees a constant leakage current, and the integrated capacitance is constantly charged; the voltage is therefore increasing and a so-called ramp is created. If the SDDs see a signal, the current rises very quickly compared to the slow rise of the steady leakage current, resulting in a jump of the ramp. In figure 10 the rise of the ramp of SDD array no. 5 (Channel 3) can be seen by a detected cosmic event, for normal sized signals the difference is too small to be seen on the LeCroy WavePro 735Zi 3.5 GHz Oscilloscope. The difference of height on the ramp is proportional to the deposited energy of the detected signal.

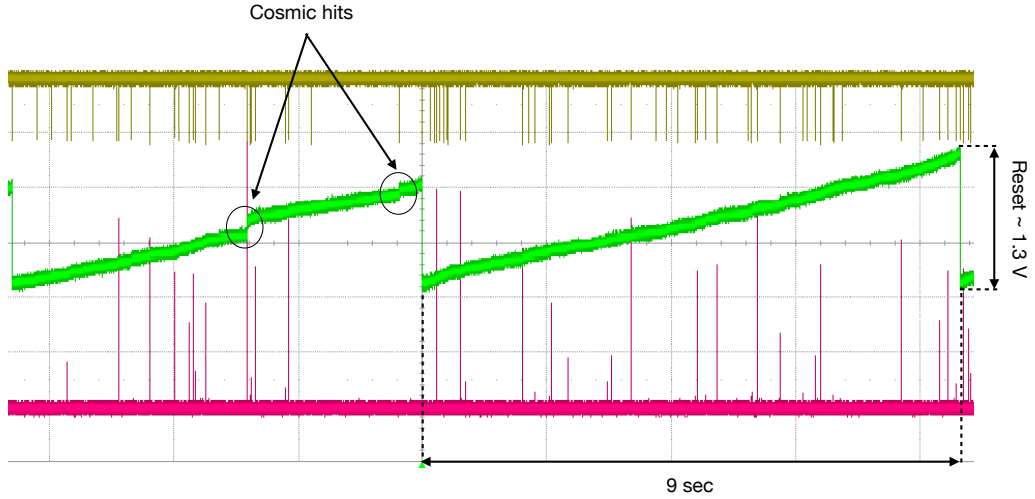


Figure 10: Ramp (green) of the CUBE preamplifier with a reset threshold at 1.3 V and a rise time of 9 s. The red line is showing the detected signals of the SDD channel with the corresponding trigger in yellow. As the trigger was on for all channels of the SDD array, trigger counts outnumber the detected signals.

When the supply voltage (+3.3 V) is reached, the CUBE saturates. To avoid a saturation, an individual reset threshold can be set for each SDD unit separately on the motherboard. To prevent an unstable situation after the reset, the signal output

is disabled for 20 μs . Additionally, to compensate differences between SDD channels the trigger threshold can be adjusted manually on the main board. The trigger condition is selected in a way that the trigger level corresponds to approximately 2.5 keV (far below the Ti K_α line), creating a so-called GATE, which is associated with a signal above threshold.

The motherboard is stationed outside the vacuum chamber. One amplifier board can boost the signals of two SDD arrays. The amplification is done in two steps: In the first step, a CR differentiation circuit is filtering out the low frequencies of the signal, thus changing the pulse height as well as the rise time. Afterwards, the high frequencies of the signal are filtered by an RC integration circuit. The CR-RC combination is responsible for the shaping of the signal and improves the signal-to-noise ratio of the amplifier (for more information refer to e.g. [22]).

3.2.2 Line-Driver

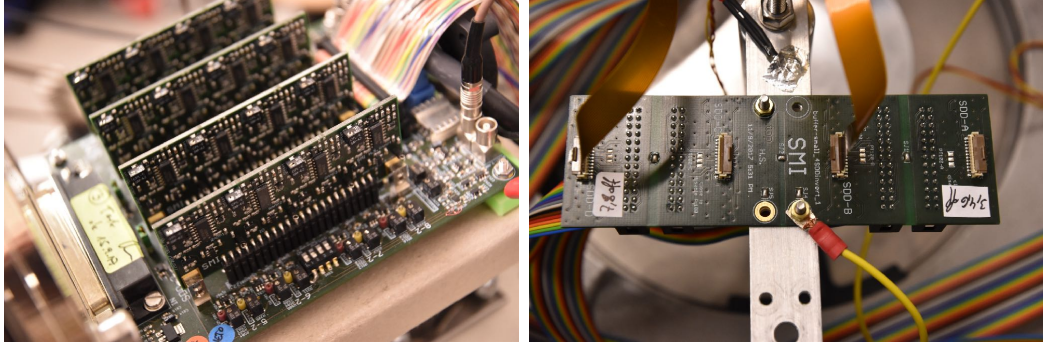
Due to the difficult structure of the E15 setup at J-PARC, which will be used for the kaonic deuterium experiment, the preamplified signal must pass a long distance before reaching the amplifier boards outside the magnet (see chapter 3.4.2 for more details). However, the CUBE preamplifier does not provide enough power to transport the signal to the amplifier boards without losses. Therefore, a special *line-driver* amplifier has been developed at the SMI in order to transport the output signal to the main amplifier. In order to maintain the signal shape, the line-driver is a 1:1 amplifier with enough power to overcome more than a 1 m long distance.

Signals of four different SDD arrays are collected separately at one line-driver element, which consists of four different 1:1 amplifier boards (one for every SDD array). All four line-driver amplifiers have a common ground to reduce signal fluctuations. Signals of non-working or badly working SDD units can be disconnected at the line-driver board, and are terminated directly after the CUBE preamplifier on the line-driver with 100 k Ω .

A picture of the motherboard and the line-driver is shown in figure 11.

3.3 Scintillator and SiPM

To perform a drift time measurement of the SDDs, the Fe-55 source is replaced with a Sr-90 source (a β -emitter), and a thin plastic scintillator is added on top of the entrance window (as shown in figure 12). As the Sr-90 source has a very high activity, the source is collimated by a 3 mm wide hole. The electrons emitted from the Sr-90 source will produce light in the scintillator (fluorescent mechanism) and can therefore be used as a start signal for the determination of the drift time of the SDDs. A 21 μm copper foil is placed beneath the scintillator in order to produce characteristic X-rays as the β -particles ionise the K shell of the Cu foil leaving a hole, which is then filled by another electron from the upper energy level resulting



(a) Motherboard

(b) Line-driver

Figure 11: Amplification boards used in the E57 experiment.

in an outgoing X-ray. This outgoing X-ray can be detected by the SDDs and thus the time between the signal seen by the scintillator and the signal detected by the SDDs can be determined. The results of this measurement are shown in section 4.4.

The term scintillator describes a specific type of material, which emits light when hit by radiation e.g. X-rays or other particles. The used scintillator of the type BC-408 produced by Saint-Gobain Crystals is a plastic scintillator with a polyvinyltoluene (PVT) base [30] and dimensions $40 \times 40 \times 1 \text{ mm}^3$.

This scintillator type has a refractive index of 1.58 and a maximum emission wavelength of 425 nm, thus emitting blue light [30]. It is sensitive to X-rays below 100 keV, beta particles as well as other charged particles [30]. As the scintillator is sensitive to β radiation, it has been used to generate a start signal with a Sr-90 source. The time difference of this start signal was compared to an X-ray signal from a Cu foil to calculate the drift time resolution of the detector (see chapter 4.4 for the results of this measurement).

To convert the photons of the scintillator to an electric signal, a Silicon Photomultiplier (SiPM) is connected to the light tube that collects and guides the light produced by scintillation to the SiPM. SiPMs are semiconductors operated via the principle of reversed bias p/n diodes. One SiPM consists of several micro-cells that are connected in parallel and work in Geiger mode [31]. This means, that the (reversed) bias voltage is higher than the breakdown voltage (i.e. it is higher than the voltage needed to operate the SiPM in avalanche mode). The SiPM used with the BC-408 scintillator has a size of $4 \times 4 \text{ mm}^2$ and was developed by FBK in Trento. The typical bias voltage for this SiPM is $V_{bias} = 31 \text{ V}$. An amplifier board developed at the SMI is connected to the SiPM readout and is operated with $V_{amp} = \pm 5 \text{ V}$.

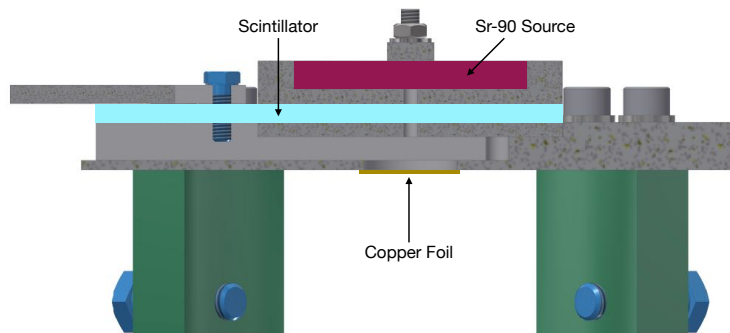


Figure 12: Schematic view of the drift time measurement setup with the Sr-90 source and the removable scintillator. The Cu foil has been added beneath the scintillator.

Picture courtesy of D. Pristauz-Telsnigg.

3.4 E57 Experiment at J-PARC

A rough estimation (with $c = 1$ and $\alpha = 1/137$) of the transition energy of kaonic deuterium can be achieved by calculating the Bohr energy levels from 2.2 for the first and second shell, and subtracting these values.

For kaonic deuterium the reduced mass is calculated from the kaon mass $m_K \approx 500$ MeV and the mass of the deuterium atom $m_d \approx 1900$ MeV: $\mu_{K^-d} \approx 395$ MeV.

Thus the binding energies equal to $B_1 \approx 10.5$ keV and $B_2 \approx 2.6$ keV, leading to a final electromagnetic energy value of the $2p \rightarrow 1s$ transition of

$$\Delta B_{2 \rightarrow 1} \approx 7.8 \text{ keV}.$$

Roughly around this energy the kaonic deuterium peaks is expected to occur, shifted due to the strong interaction.

3.4.1 MC Study of the K^-d reaction at J-PARC

The Monte-Carlo (MC) study of the E57 experiment has been performed during the PhD of C. Berucci and can be seen in more detail in her PhD thesis [32].

The MC study includes detailed background analysis as well as a degrader optimisation and trigger studies for an efficient kaonic deuterium measurement. For the background studies two sources have been included: correlated background, meaning direct results of K^- interactions like decay into pions, cascade products of kaonic

deuterium or nuclear absorption of the kaon, and uncorrelated background of particles lost in the accelerator. For the optimal stopping density gaseous deuterium with a 5 % liquid deuterium density (LDD) has been chosen as the kaon yield is higher for gaseous deuterium compared to the liquid case. For a kaon beam with a momentum of 0.7 GeV/c the best stopping rate has been achieved with a carbon degrader with a thickness of 40 cm [32].

With these parameters, mainly an efficient trigger system and a large X-ray detector area (total area amounts to 246 cm²), a signal-to-background ratio of 1:4 could be achieved. With a total of almost 800 K_α events in the experiment the shift and width can be determined with a precision of 60 eV and 140 eV, respectively. The simulated spectrum can be seen in figure 13. As theoretical input of the simulation the peak is assumed to be -800 eV shifted from the value obtained of quantum electrodynamics (QED) and an increase of the width due to nuclear absorption should amount to an increase of 800 eV [32].

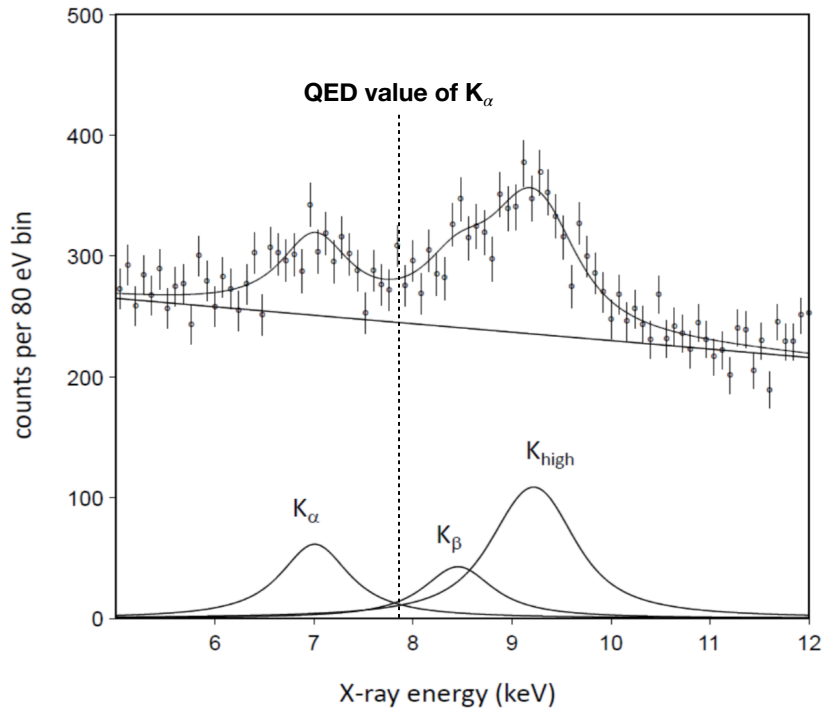


Figure 13: Simulated kaonic deuterium spectrum with a shift of the K_α peak of -800 eV compared to the QED value, which is given by the dashed line at 7834 eV, and an increase of the width of 800 eV. The achievable precision is 60 eV for the shift and 140 eV for the width [29].

3.4.2 E57 Setup

The kaonic deuterium experiment E57 will be performed at the K1.8BR kaon beam at the Hadron Hall at J-PARC, where the setup of the E15 experiment is built up. A schematic picture of the beam line is shown in figure 15.

When 50 GeV protons hit the production target, which is made of gold with a copper and stainless steel structure for cooling [33], secondary particles (mainly pions and kaons) are produced. They then enter the spectrometer beam line, where a set of triggers, counters and magnets will identify the incoming particles and distinguish between pions and kaons which can be seen in figure 14. Neither the neutron counter nor the beam swiping magnet of the spectrometer beam line shown in figure 15 will be used in the E57 experiment.

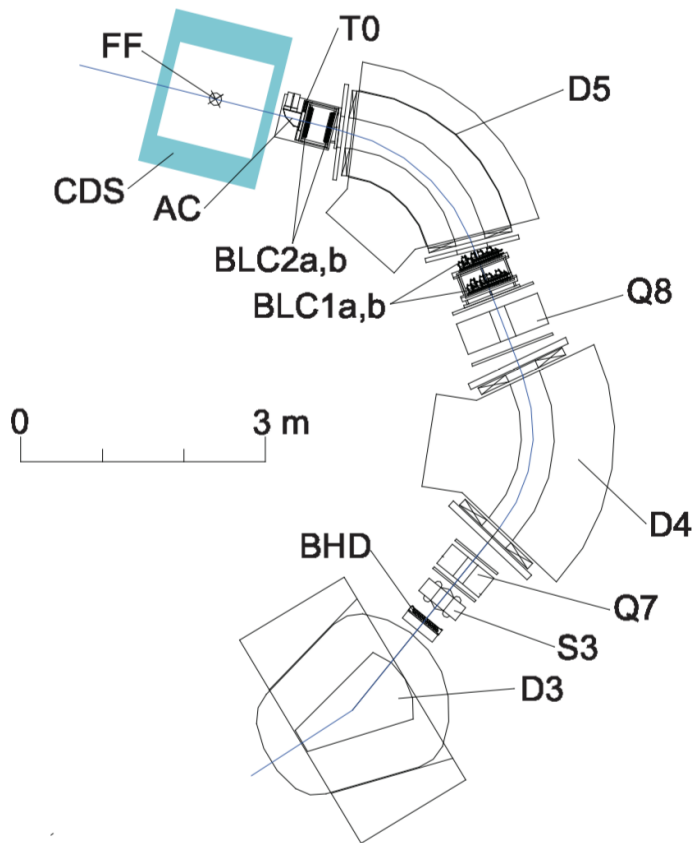


Figure 14: The beam line spectrometer consisting of dipole beam line magnets (D3, D4 and D5), quadrupole magnets (Q7 and Q8), a sextupole magnet (S3), trigger counters (BHD and T0), an aerogel Cherenkov counter (AC) for kaon identification, two beam line trackers (BLC1 and BLC2), and the cylindrical drift system (CDS) with the final focus (FF) point in the centre [34].

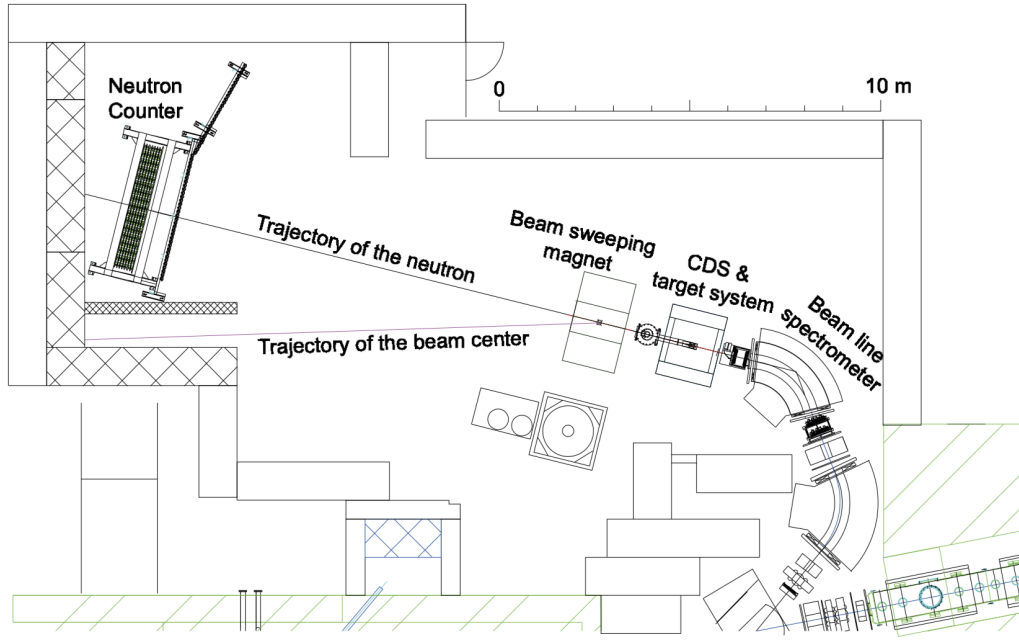


Figure 15: The kaon beam line K1.8BR at J-PARC where the E57 kaonic deuterium experiment will be carried out [34].

The six magnets are needed to keep the beam of secondary particles focused. The dipole magnet D5 is used together with the beam line detectors BLD1 and BLD2, which are defining the path of the kaon, to determine the kaon's momentum. The beam hodoscope detector and the T0 scintillator are responsible for the creation of the beam trigger. The aerogel Cherenkov counter identifies pions from the secondary particle beam (anticoincidence with trigger). The cylindrical detector (CDS) consists of three main parts: solenoid magnet with a strength of 0.7 T, with the final focus (FF) within the centre the magnet, as well as a cylindrical drift chamber (CDC) and a cylindrical hodoscope (CDH), both used for particle identification and background reduction. Additional detectors can be added if needed in various experiments. The coverage of the CDS amounts to a solid angle coverage of 59 % of 4π . All information about the K1.8BR secondary beam line is taken from [34].

The target cell, which is shown in figure 16, is placed at the final focus point. It is surrounded by 48 SDD arrays and is cooled down to 29 K, where it can withstand a pressure of 0.35 MPa. The length of the target cell is 200 mm with a diameter of 65 mm.

A dedicated MC study (seen in [32]) determined the optimal deuterium gas density to be in the order of 5 % of the LDD. This requires the walls of the cell to be thin enough for allowing K_α transition photons to pass through, but at the same time to be thick enough to withstand the high pressure. Therefore, the walls of the cell are made of two layers of 50 μm thick Kapton foil glued together, resulting in a total

thickness of $\sim 130 \mu\text{m}$ (foils plus glue). The target cell has been successfully tested to withstand pressures of 0.7 MPa at SMI.

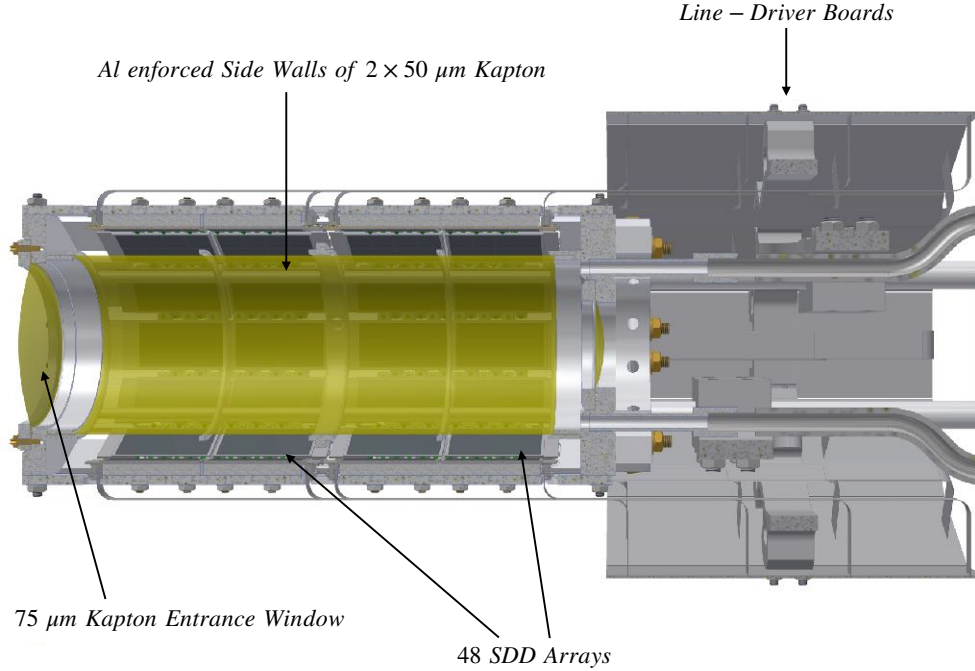


Figure 16: Drawing of the target cell for the kaonic deuterium measurement at J-PARC including the aluminium support structure, stationing of the line-driver boards and the SDD arrays. *Picture courtesy of D. Pristauz-Telsnigg.*

The support structure of the SDDs is connected to the cooling system of the target cell and therefore ensures the cooling of the detector arrays. Four SDD arrays are connected to one line-driver leading the detected signals outside of the vacuum chamber to 24 amplifier boards. Altogether twelve line-driver elements are needed for the experiment. A schematic picture of the setup is shown in figure 17.

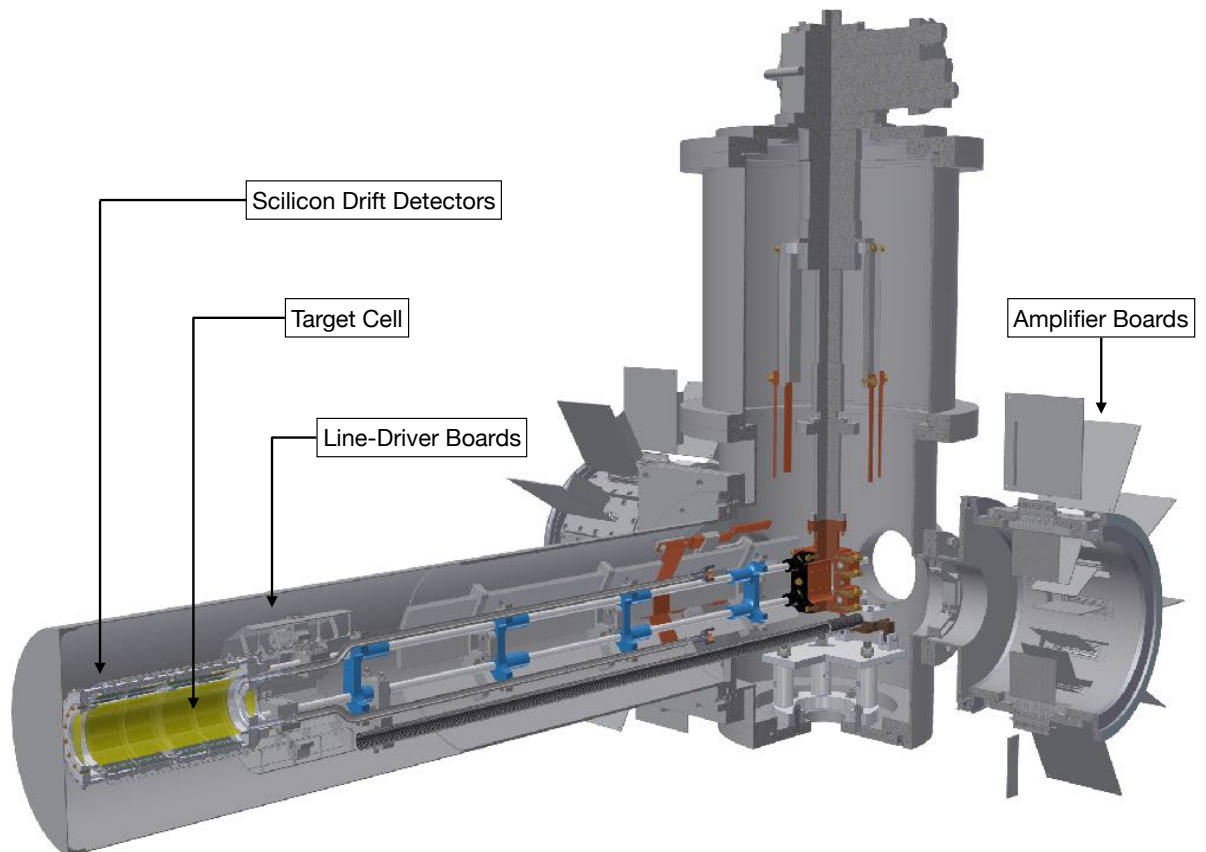


Figure 17: A schematic drawing of the E57 experiment target system.
Picture courtesy of D. Pristauz-Telsnigg.

4 Test Measurements at SMI

Several SDD arrays have been tested at SMI. The whole list of tested SDDs can be found in Appendix A. The performed test measurements include a stability measurement to check the SDD dependence on temperature fluctuations and on bias voltage settings, a drift time analysis as well as a detailed crosstalk evaluation.

4.1 DAQ system

For the data acquisition (DAQ) a VME crate of the type V1718 by CAEN is used as the master module. It can be operated via a USB port from a computer and has a transfer rate of ~ 30 MByte/s [35].

To convert the signal from analogue to digital the V785 ADC by CAEN is used with the VMEbus. It has 32 channels that can detect positive analogue signals with a risetime > 50 ns to analyse the peak maximum of the signal within a GATE window. The GATE input is common for all peak channels. The peak height of the analogue signals are then converted into digital ones and stored in a dual port data memory. The conversion time takes $5.7 \mu\text{s}$ for 32 channels [36].

For the drift time measurement, a TDC V1290N by CAEN has been added to the VMEbus system. It contains 16 Multi-Hit/Multi-Event time to digital conversion channels that are all independent of each other, and it has a resolution of 25 ps [37]. In figure 18 the used DAQ system is shown.



Figure 18: DAQ system used at the SMI consisting of a V1718 VME crate, a V785 ADC and a V1290 TDC by CAEN.

4.2 Energy Calibration

4.2.1 Development of Amplifiers

The first several months of this master thesis have been dedicated to optimise the motherboards for a good energy resolution of the SDDs. The important point of this was filtering out noise and other sources that contribute to a worse energy resolution or unstable working condition. Changes have been made to the motherboard as well as to the amplifier boards.

The modifications of the **motherboard** were foremost a gradual improvement of the logic to rule out coincidences between gate and reset signals. This was necessary as the reset signal caused high oscillations in the output signal, and thus often resulted in a gate signal where the output signals of all SDD channels were recorded. To bypass this problem, the reset can now only happen if the gate is closed again, i.e. when the signal is not higher than the gate threshold. However, as the high oscillations were still seen on all output signals of the channels, the output signals were gradually disabled for 20 μs to ensure that the output signals are again at zero after the reset.

The most important motherboard versions are:

- *Version 1*: old logic (gate and reset coincidences still possible), top plane still on ground
- *Version 4/7*: new logic (coincidence between gate and reset impossible), top plane not grounded for better resolution

The changes of the **amplifier boards** were mainly done to suppress oscillations on the signal output. These included changes to the base line resistor (BLR) before the feedback, different input capacitances as well as changes to the amplification. Furthermore, several tests with different shaping times have been performed: In general one would expect that a longer shaping time would result in a better energy resolution as the noise was averaged over a longer period. This was not the case, thus shorter shaping times have been preferred in the end. The different amplifier versions used for most test measurements are:

- *Version 2.0*: shaping time 800 ns, BLR = 2 k Ω , open input capacitance, amplification factor 100, compatible with motherboard V1
- *Version 2.1*: shaping time 1 μs , BLR = 6.2 k Ω , input capacitance = 470 pCi, amplification factor 100, compatible with motherboard V1
- *Version 3.0*: shaping time 800 ns, BLR = 15 k Ω , open input capacitance, amplification factor 80, compatible with motherboard V4 and V7
- *Version 3.1*: shaping time 1.8 μs , BLR = 22 k Ω , open input capacitance, amplification factor 80, compatible with motherboard V4 and V7

4.2.2 Energy Calibration of SDD No. 5

The first calibration tests were performed in August 2017 with SDD array no. 5 with only four working channels CH2, CH6, CH7 and CH8. The amplifier boards 2.0 and 2.1 have been compared with each other using the same motherboard of version 1. The temperature of the SDD array was at $T \sim 168$ K. As an X-ray source a Fe-55 source with an additional $5 \mu\text{m}$ Ti foil was used to see four energy peaks, which can be used for the energy calibration: Mn K_α , Mn K_β as well as Ti K_α and Ti K_β . The spectra were fitted with the same technique: The K_α peaks were fitted with two gaussian functions including the $K_{\alpha,1}$ and the $K_{\alpha,2}$ peaks using the same sigma but half the amplitude of $K_{\alpha,1}$ for the $K_{\alpha,2}$ peak, and with the mean shifted by the fixed eV value taken from [38]. For the two K_β peaks a single gaussian function was used. Additionally, the background was tuned to the best χ^2 with a cubic function. The full width half maximum (FWHM) of the Mn K_α peak was used as a reference value for the energy resolution.

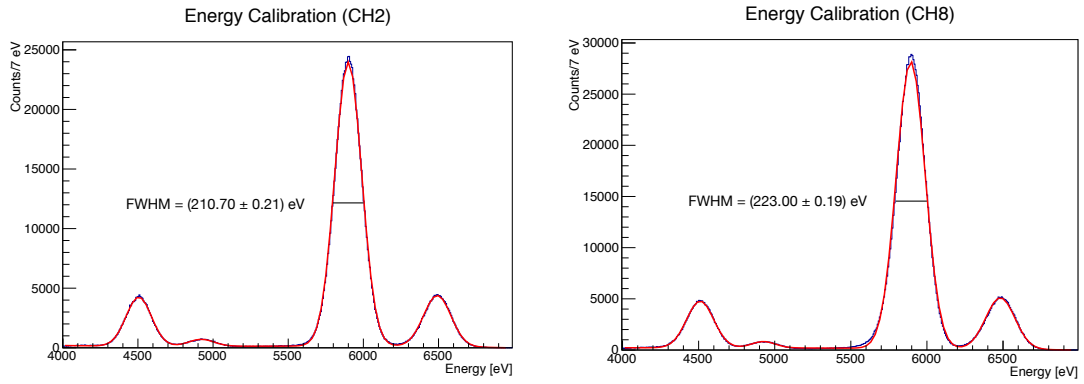
The first measurement was taken with amplifier board 2.1 over 3 days. The bias voltage was turned to the values $R_1 = -17.9$ V, $R_N = -91.0$ V and $R_B = -71.0$ V. The gate and reset thresholds as well as the ramp lengths for the well working four channels can be seen in table 2.

Channel No.	Gate threshold (V)	Reset threshold (V)	Ramp (s)
2	0.08	2.12	2.5
6	0.15	2.52	1.8
7	0.06	2.04	7.0
8	0.08	2.53	1.2

Table 2: Amplifier Board and Voltage Settings for Version 2.1

Representatively for this measurement, the calibration spectra of channel 2 and channel 8 can be seen in figure 19. The FWHM for all four working channels can be taken from table 3. With an energy resolution of $\text{FWHM} > 200$ eV for all channels this setup does not meet the necessary requirements ($\text{FWHM} < 180$ eV at 6 keV, see [26]) needed for a successful execution of the kaonic deuterium experiment.

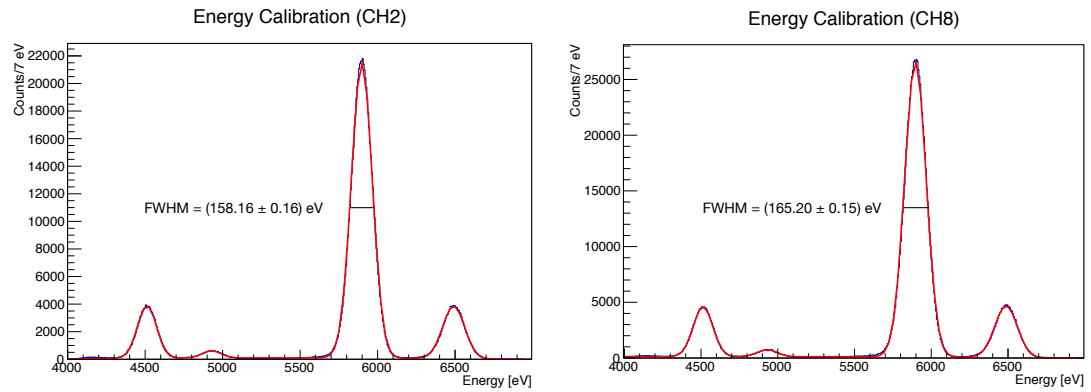
Another amplifier board version 2.0 was tested shortly afterwards. In general the setup remained the same, except for a different gate threshold of channel 6 and channel 7 (CH6=0.076 V and CH7=0.047 V). These thresholds proved to be too high to record the Ti peaks, thus for this comparison only CH2 and CH8 were used; the spectra of which can be seen in figure 20. The energy resolution has greatly improved with this amplifier version and is in acceptable range for the kaonic deuterium experiment. The improved energy resolution can be seen by the well defined gap between the Mn K_α and K_β peaks, which is not as visible in the spectra for V2.1 in figure 19.



(a) Energy calibration of channel 2 with FWHM = 210.70 eV.

(b) Energy calibration of channel 8 with FWHM = 223.00 eV.

Figure 19: Energy calibration spectra of CH2 and CH8 of SDD no. 5 with the amplifier board V2.1.



(a) Energy calibration of channel 2 with FWHM = 158.16 eV.

(b) Energy calibration of channel 8 with FWHM = 165.20 eV.

Figure 20: Energy calibration spectra of CH2 and CH8 of SDD no. 5 with the amplifier board V2.0.

To varify the good results of the test measurement with the amplifier board V2.0 another measurement has been performed, where also the gate threshold of channel 6 and 7 has been decreased to detect the Ti peaks. The duration of this was 10 days, and the data split into 8 hour intervals. The energy calibration has been evaluated, and representatively the results of one 8 hour interval are shown in table 3. The energy resolutions for all channels are below 160 eV, and fulfill the necessary requirement for a good energy resolution to determine the K^-d peak shift and width with a precision of 60 and 140 eV, respectively. In figure 21 the energy calibration spectra for channel 2 (which can also be seen in [39]) and channel 8 of this set of data are shown.

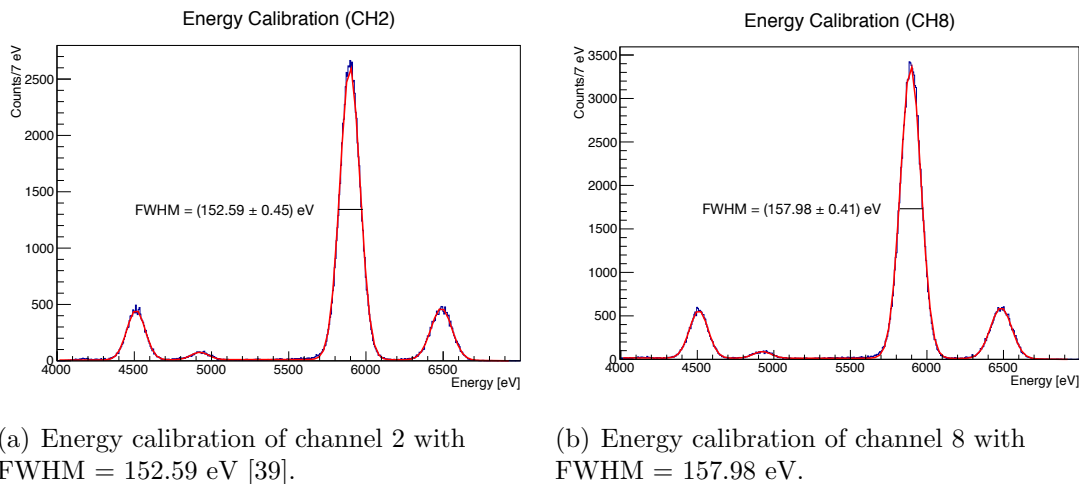


Figure 21: Repetitive measurement to determine the energy calibration spectra of CH2 and CH8 of SDD no. 5 with amplifier board V2.0 for an 8 hrs interval.

Table 3 lists the energy resolution (FWHM) of the Mn K_α peaks of all three test measurements. As can be taken from it, the energy resolution greatly improved with the amplifier boards V2.0 compared to the data taken with the amplifier boards V2.1. It can also be seen, that the difference between the energy resolution of the four SDD channels was smaller with the V2.0 measurement. The difference between channel 6 (FWHM = 208 eV) and channel 8 (FWHM = 223 eV) amounted to 15 eV for the measurement with the amplifier boards V2.1, whereas for the measurement with amplifier boards V2.0 it was only 5 eV (CH2 FWHM = 153 eV and CH8 FWHM = 158 eV). This might result from a better oscillation reduction with the amplifier V2.0 as channel 8 might be more sensitive to them.

Amplifier board	CH1 (eV)	CH6 (eV)	CH7 (eV)	CH8 (eV)
V2.1	210.79 ± 0.21	207.50 ± 0.18	209.71 ± 0.19	223.00 ± 0.19
V2.0 (1 st meas.)	158.16 ± 0.16	X	X	165.20 ± 0.15
V2.0 (2 nd meas.)	152.59 ± 0.45	156.30 ± 0.42	154.64 ± 0.46	157.98 ± 0.41

Table 3: Summary of the energy calibration measurements for two different amplifier boards of the same SDD array (no. 5) for the FWHM of the Mn K_α peak.

4.2.3 Energy Calibration of SDD No. 18

In August 2018 another energy calibration test was performed with SDD no. 18 to try and achieve the same energy resolution as the pervious year with SDD no. 5. Data has been taken with a LeCroy WavePro 735Zi 3.5 GHz Oscilloscope of channels 1,2 and 3 using a Fe-55 source with an additional Ti foil. For the analysis, only the Mn K_α peak was used.

4.2.3.1 Grounded and Ungrounded Line-Driver Tests

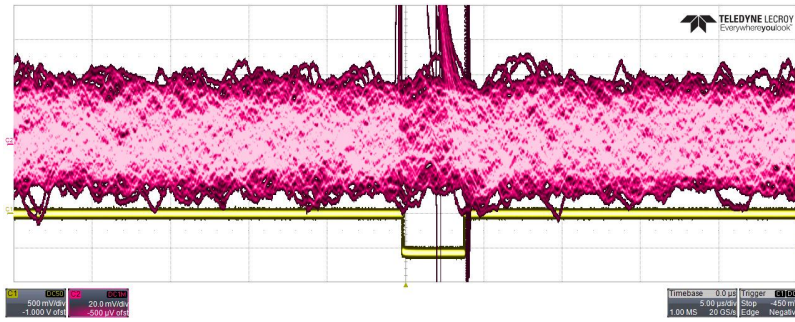
The first test was performed to analyse the energy resolution of the SDD array with the line-driver being once connected to ground and once without being grounded. Therefore, the noise of the spectrum was studied for channel 1 of SDD 18 at $T \sim 145$ K. Figure 22 a) shows the result of the line-driver not connected to ground, whereas figure 22 b) shows the same measurement with the line-driver connected to ground. In both figures the time axis was set to $5 \mu\text{s}/\text{div}$, the voltage axis for the gate (yellow line) to $500.0 \text{ mV}/\text{div}$ and the voltage axis for the noise (red line) to $20.0 \text{ mV}/\text{div}$.

The high reduction of the noise at $T \sim 145$ K by almost half suggested, that a better energy resolution of the SDD could be achieved if the line-driver was connected to ground.

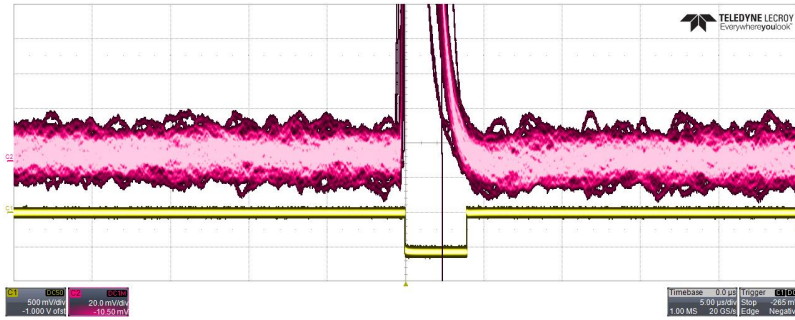
This was also proven by the analysis of the data for channels 1, 2 and 3, where the FWHM of the Mn K_α peak has been compared in table 4.

LD connected to ground	CH1 (eV)	CH2 (eV)	CH3 (eV)
No	323.12 ± 5.92	562.46 ± 53.30	404.77 ± 15.64
Yes	187.96 ± 2.68	187.38 ± 1.82	187.08 ± 1.81

Table 4: FWHM of the Mn K_α peak for CH1, CH2 and CH3 of SDD no. 18 with different line-driver groundings.



(a) Noise spectrum with line-driver not connected to ground.



(b) Noise spectrum with line-driver connected to ground.

Figure 22: Measurement of the noise spectra of the line-driver a) not connected to ground and b) connected to ground at $T \sim 145$ K.

4.2.3.2 Twisted Pair Cables, Grounding of Integrated Pt100 and Line-Driver Termination Resistor

For a possible further improvement of the energy resolution, the 1 metre long flat-band cable connecting the line-driver with the amplifier boards outside the vacuum chamber was exchanged with a twisted pair cable. Additionally, the Pt100, which is integrated on the SDD array, was short-circuited. A measurement was performed for channels 1, 2 and 3 of SDD no. 18 and the FWHM of the Mn K_α peaks evaluated (see row 1 of table 5).

Furthermore, another measurement had been done in which an additional termination resistor of 100 k Ω has been added to the line-driver directly after the CUBE amplifier. The FWHM of the Mn K_α has been analysed for channels 1, 2 and 3 and the results can be seen in row 2 of table 5.

LD termination resistor	CH1 (eV)	CH2 (eV)	CH3 (eV)
Open	177.97 ± 1.05	177.66 ± 0.93	177.08 ± 0.88
100 k Ω	180.40 ± 2.97	192.54 ± 2.83	179.10 ± 2.35

Table 5: FWHM of the Mn K_α peak for CH1, CH2 and CH3 of SDD no. 18 with and without a line-driver termination resistor.

4.2.3.3 Summary

If one compares all results of table 4 and 5, it can be said that the best energy resolution was achieved with a **twisted pair cable**, a **grounded Pt100** and an **open** line after the CUBE preamplifier. This was also the most stable measurement, as the FWHM of all three compared channels showed only little deviations and thus point towards the most stable setup.

The twisted pair cable and the grounded Pt100 resulted in a reduction of the FWHM of approximately 10 eV compared to the measurement with a normal flat-band cable and an ungrounded Pt100.

4.3 Stability Measurements of SDDs

4.3.1 Long-term Stability Tests

The stability tests of the SDDs were some of the most crucial experiments performed during the course of this master thesis. This is due to the fact that in the final experiment 384 SDD cells have to be summed up. If the SDDs would show fluctuations of more than a few eV, a more time consuming energy calibration would be necessary to guarantee the precise data analysis.

The first long-term study has been performed in August 2017 for almost seven days with SDD no.5 at a temperature of $T \sim 165$ K with a Fe-55 source plus an additional

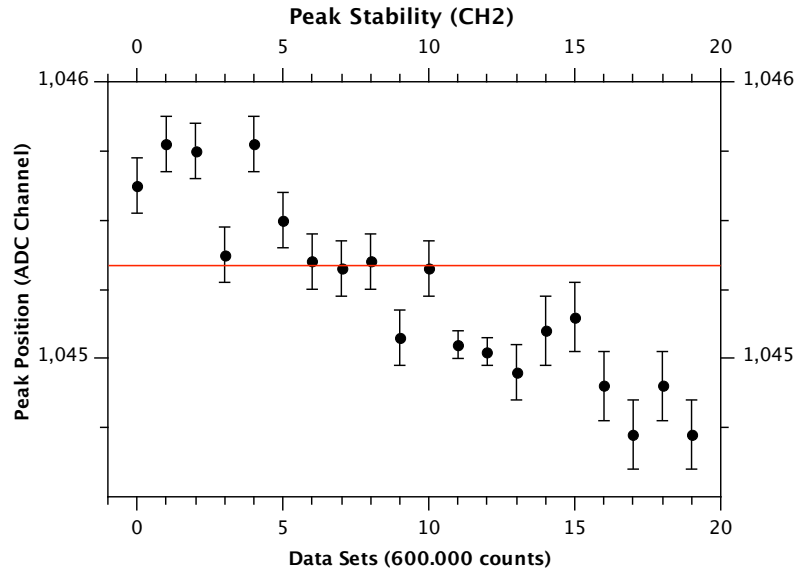
Ti foil. The data has been split up into sections of 600,000 data points, which corresponds to eight hour intervals. In figure 23 one can see the stability of both, the peak position as well as the width of the Mn K_α peak of channel 2. The strong decrease of the peak position results most probably from an outside temperature fluctuation. Unfortunately, there was no continuous temperature measurement during the data taking, therefore this cannot be guaranteed.

However, in general the SDD seems very stable. The peak stability shows a fluctuation of ± 0.5 ADC channel, which corresponds to ± 3 eV. It is even better when considering the stability of the width, where the fluctuations of ± 0.3 ADC channel mean a stability better than ± 1.8 eV. Refer also to [39] for the results of this measurement.

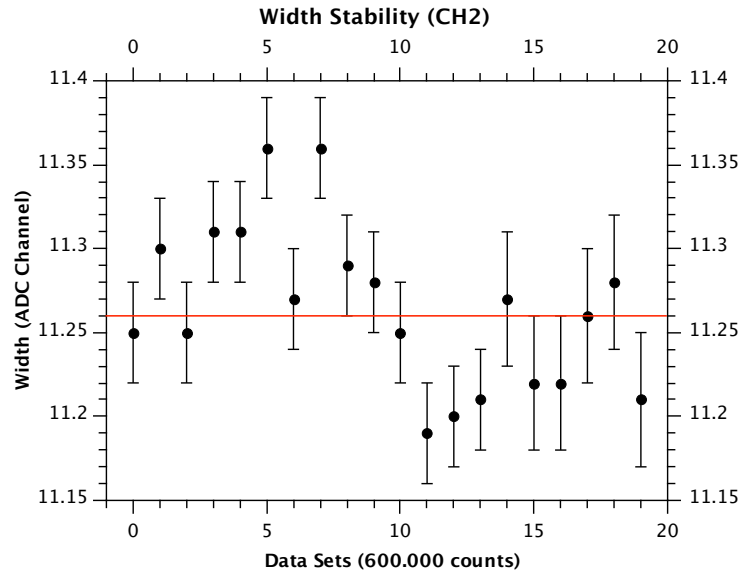
To verify the good results obtained in August 2017, another long-term study was performed in April 2018, this time with a Sr-90 source plus additional Cu foil (to create characteristic X-rays of Cu) and two different SDD arrays (no. 18 and no. 20). The duration of the data taking was 11 days, and the sample was divided into sets of 2,800,000 counts, which corresponds to twelve hour intervals. This increase in the duration of one data sample compared to the Fe-55 + Ti measurement was needed, as the detected hits with the Sr-90 source were mostly overflow events, and only ~ 0.5 % were actual detections of Cu K_α and Cu K_β X-rays. Therefore, a longer timespan was needed to obtain enough statistics for a good data analysis.

The results of this measurement can be seen in figure 24 for SDD array no. 20. The Cu K_α peak position was constantly decreasing during the first 5.5 days of data taking which might be explained by outside temperature variations. Considering only the fluctuations of the last eleven data points, where the system was stable, a ± 1 ADC channel fluctuation is seen, which corresponds to a range of roughly ± 6 eV and is more than expected from the previous measurement. This could be due to the SDD structure itself (e.g. different doping of the silicon wafer), intensified light admittance due to insufficient coverage, but most likely due to the high overflow rate (which is also expected in an accelerator environment). A similar result was achieved for the stability of the width, where the fluctuations are as big as ± 0.6 ADC channel corresponding to ~ 4 eV.

Comparing these results of both measurements, a decrease of the stability for both, peak and width, values was seen, which was expected from the SIDDHARTA measurement. Another measurement of this kind would provide additional data, and the stability of the SDDs could be determined with a better precision. However, there was no time to perform this study before the finishing of this master thesis as other tests were more urgent to perform due to the E62 experiment in June 2018.

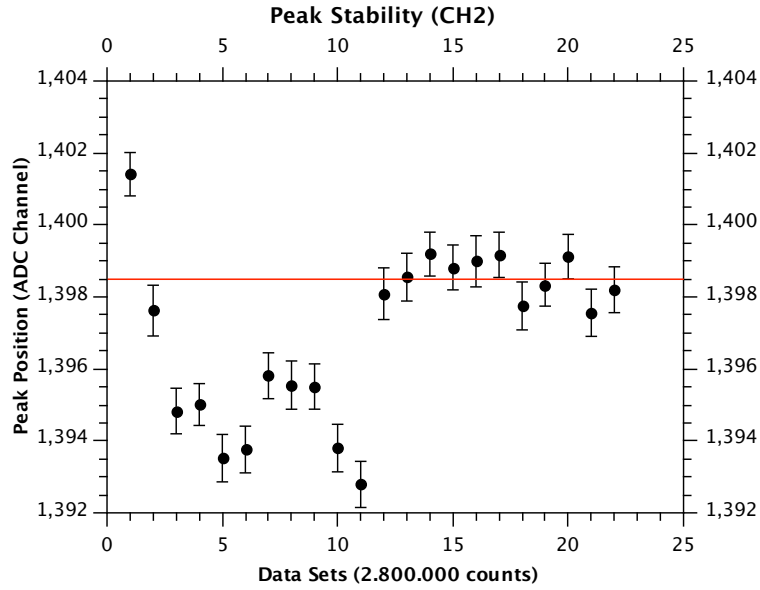


(a) Peak stability of SDD no. 5 (CH2). The fluctuations are in a 1 ADC channel range.

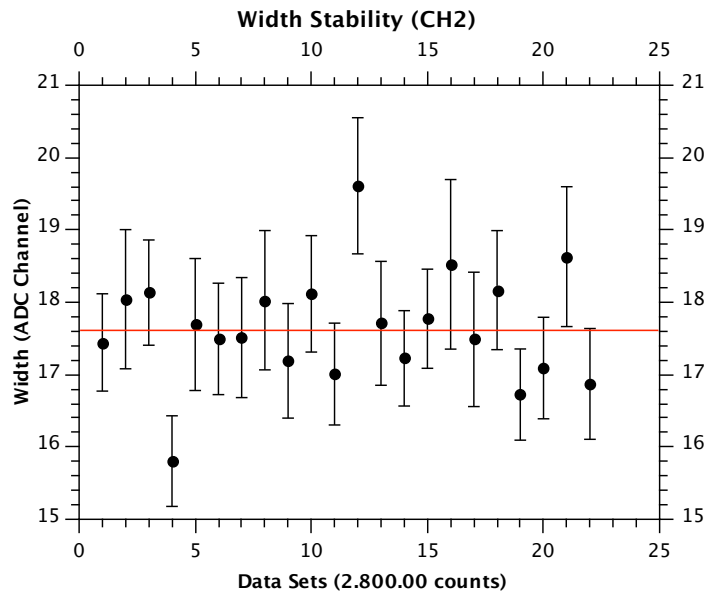


(b) Width stability of SDD no. 5 (CH2). The fluctuations are in a 0.6 ADC channel range [39].

Figure 23: Stability study of SDD no. 5 concerning the peak and width of one SDD channel. The red line indicates the average value of the data sets.



(a) Peak stability of SDD no. 20 (CH2). The fluctuations of the last eleven data points are in 2 ADC channel range.



(b) Width stability of SDD no. 20 (CH2). The fluctuations are below a 1.2 ADC channel range.

Figure 24: Stability study of SDD no. 20 concerning the peak and width of one SDD channel. The red line indicates the average value of the data sets, in case of the peak stability the red line corresponds to the average value of the last 11 data points.

4.3.2 Bias Voltage Dependence

The potential of one SDD cell is created by the applied bias voltage. Thus, it will vary for different combinations of R_1 , R_B and R_N . This combination will be different for different SDD arrays, as the doping of the Si wafer might show fluctuations. Hence, the perfect combination for the best energy resolution should be determined for every SDD array. This is important as four SDD arrays will be powered by the same bias voltage in the final experiment, and therefore arrays with similar bias voltage can be operated more stably ensuring a smooth data acquisition during the measurement.

4.3.2.1 Test Measurement with SDD No. 5

An Fe-55 and Ti spectrum has been measured (with the LeCroy WavePro 735Zi 3.5 GHz Oscilloscope) for different SDD bias voltage settings, and the Mn K_α peak for CH2, CH7 and CH8 of SDD 5 has been analysed:

1. At first, the R_1 has been changed in steps of 2 V between -14 V and -22 V for fixed R_B and R_N values ($R_B = -65$ V, $R_N = -90$ V). For the measured three channels the best energy resolution was achieved when R_1 was set to -16 V (see figure 25).

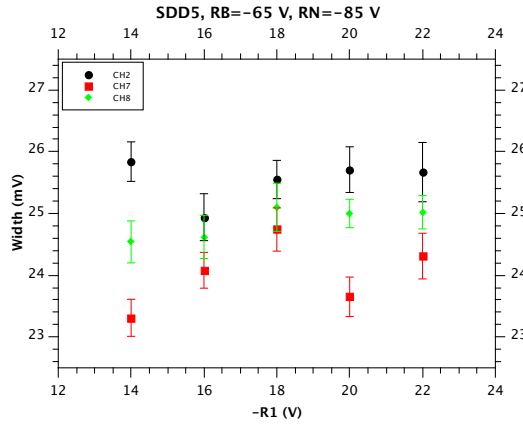
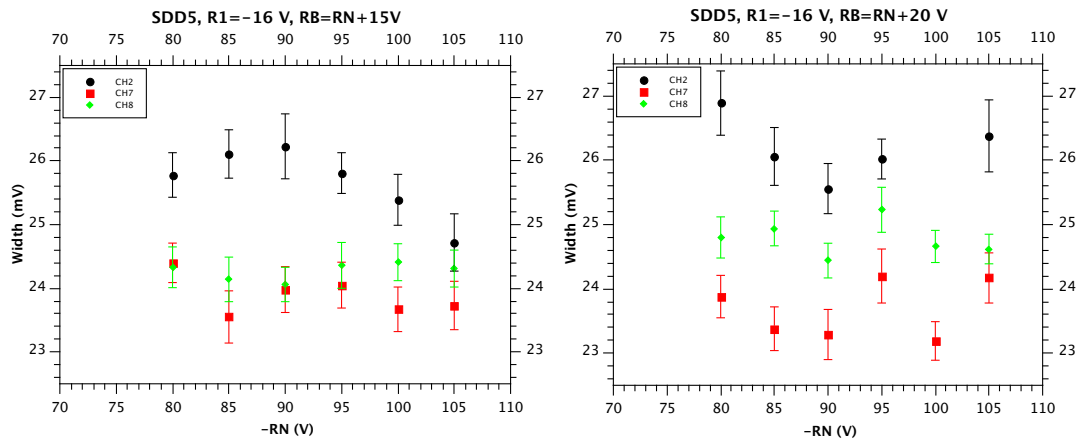


Figure 25: Variation of R_1 while R_B and R_N were kept constant at -65 V and -90 V, respectively. The best energy resolution was achieved for $R_1 = -16$ V.

2. With the R_1 fixed to -16 V, R_N was varied in steps of 5 V from -80 V to -105 V. This is shown in figure 26. The back voltage was kept either (a) 15 V or (b) 20 V higher than R_N . The bias voltage for the best energy resolution was chosen to be $R_N = -90$ V and $R_B = -70$ V. These results can also be seen in [39].



(a) Variation of R_N with R_B kept 15 V above the R_N value. (b) Variation of R_N with R_B kept 20 V above the R_N value.

Figure 26: Bias voltage configuration of three SDD channels with different R_B to R_N settings (with R_1 constant at -16 V). The best energy resolution was achieved with $R_B = -70$ V and $R_N = -90$ V [39].

3. Afterwards the first measurement was repeated in a range of $R_1 = -14$ V to -20 V with the configuration of $R_B = -70$ V and $R_N = -90$ V. In figure 27 the outcome of this measurement is shown. $R_1 = -18$ V resulted in the best energy resolution for the channels 2, 7 and 8. For channel 8 no data was taken at the value of $R_1 = -14$ V. However, it can be concluded from all previous measurements and the results of channel 2 and 7 that this bias voltage configuration would not have resulted in the best energy resolution of channel 8.

4.3.2.2 Test Measurement with SDDs No. 18 and No. 20

In August 2018, the voltage dependence was tested again for SDDs no. 18 and no. 20. This has been done by determining the energy resolution of each channel using an Fe-55 source with additional Ti foil and taking data with the DAQ system described in 4.1 for different bias voltage settings. Compared to the measurements performed with SDD no. 5 (which are discussed in section 4.3.2.1) slightly different settings have been used: Firstly, a different turbo pump has been installed (for more information on the type see chapter 3), and different amplifier boards have been used (motherboard V7 and amplifier boards V3.0). Thus slight variations of the results were expected.

Representatively for each setting the spectrum of SDD no. 18 channel 2 and of SDD no. 20 channel 2 is used as an example of the behaviour of the SDDs, and the FWHM of the Mn K_α peak is used as a reference for the energy resolution. In table 6 and 7 the FWHM of the Mn K_α peak of all working SDD channels for each bias voltage setting is given.

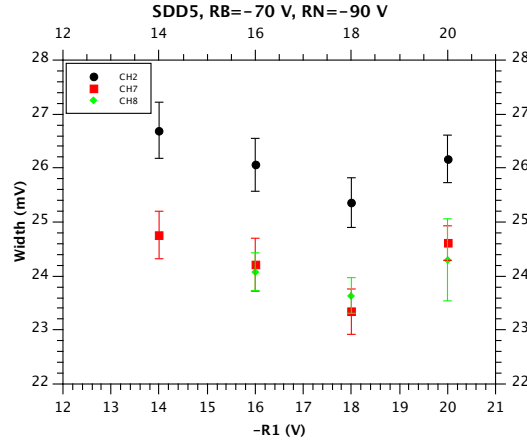
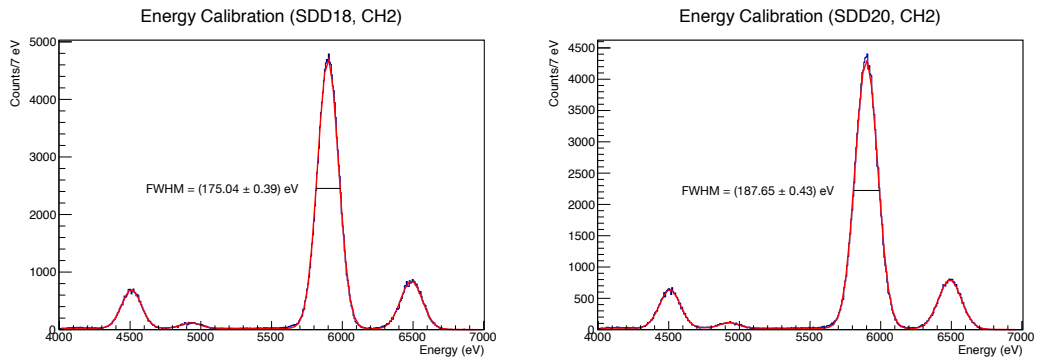


Figure 27: Repetition of the variation measurement of R_1 while R_B and R_N were kept constant at -70 V and -90 V, respectively. The best energy resolution was then achieved for $R_1 = -18$ V.

Three channels (channel 8 of SDD no. 18, and channel 11 and channel 14 of SDD no. 20) have been turned off as their ramps were less than a few ms long, and would have caused a reset frequency which would have been too high.

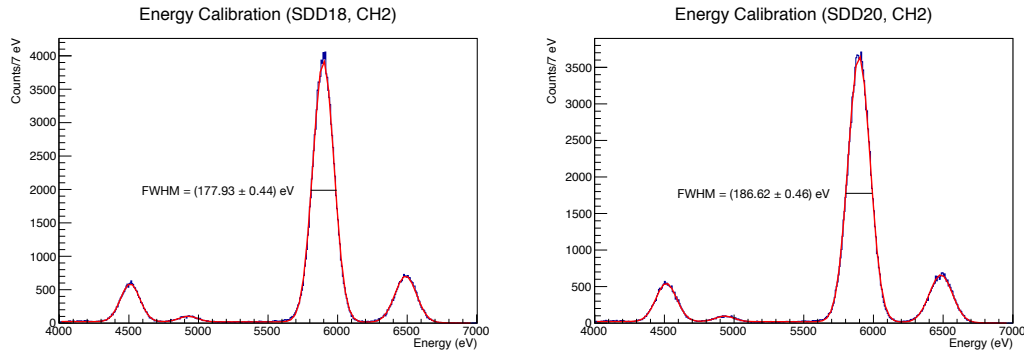
1. The first measurement was done with a bias voltage of $R_1 = -9.54$ V, $R_B = -55.6$ V and $R_N = -66.6$ V. The data taking period was ~ 31.5 hours. The FWHM of SDD no. 18 channel 2 is (175.04 ± 0.39) eV and of SDD no. 20 channel 2 is (187.65 ± 0.43) eV (see figure 28).



(a) Channel 2 of SDD no. 18 with a FWHM of the Mn K_α peak of 175.04 eV. (b) Channel 2 of SDD no. 20 with a FWHM of the Mn K_α peak of 187.65 eV.

Figure 28: Energy spectrum (Fe-55 + Ti) with a bias voltage configuration of $R_1 = -9.54$ V, $R_B = -55.6$ V and $R_N = -66.6$ V.

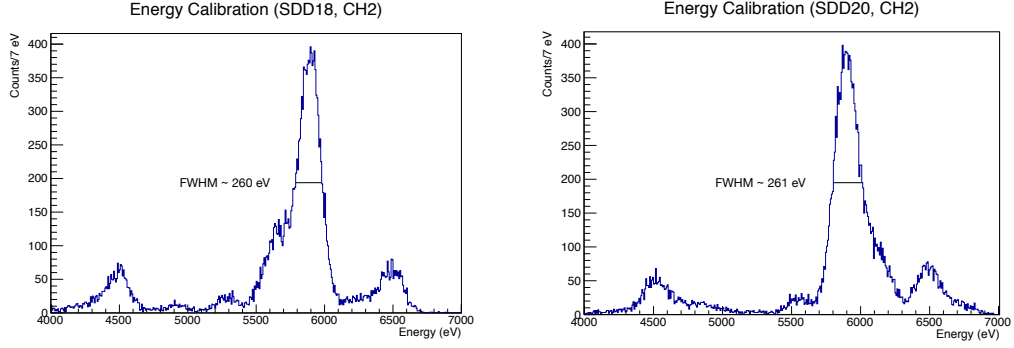
- For the second measurement a bias voltage of $R_1 = -14.7$ V, $R_B = -53.8$ V and $R_N = -78.2$ V was chosen, and data was taken for ~ 26 hours. The FWHM of SDD no. 18 channel 2 is (177.93 ± 0.44) eV and of SDD no. 20 channel 2 (186.62 ± 0.46) eV (see figure 29).



(a) Channel 2 of SDD no. 18 with a FWHM of the Mn K_α peak of 177.93 eV. (b) Channel 2 of SDD no. 20 with a FWHM of the Mn K_α peak of 186.62 eV.

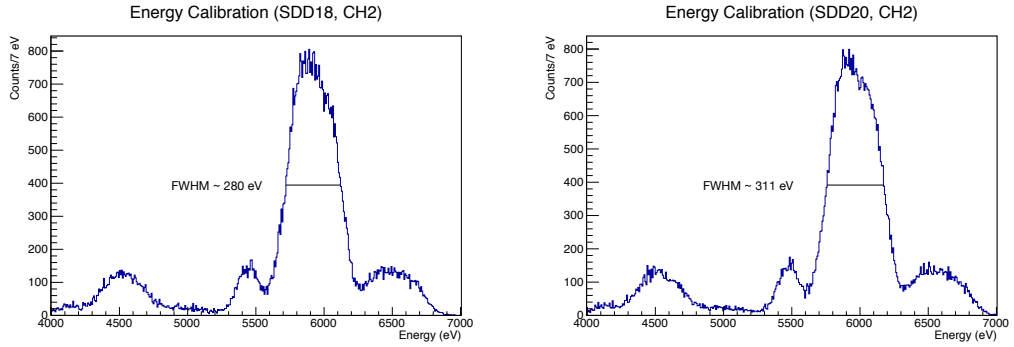
Figure 29: Energy spectrum (Fe-55 + Ti) with a bias voltage configuration of $R_1 = -14.7$ V, $R_B = -53.8$ V and $R_N = -78.2$ V.

- The third test measurement was performed with a bias voltage of $R_1 = -13.52$ V, $R_B = -60.2$ V and $R_N = -80.0$ V over ~ 6 hours. This bias voltage setting turned out to be causing a lot of unexplainable peaks in the spectrum, thus only the FWHM of the Mn K_α peaks was fitted by one gaussian function, ignoring the peak appearing in the spectrum on the left for SDD no. 18, and on the right for SDD no. 20. Therefore, the obtained results are rather a guideline than an actual fit. As the spectra could not be fitted correctly, the raw energy histogram is shown in figure 30. The FWHM for channel 2 of SDD no. 18 is ~ 260 eV and of SDD no. 20 channel 2 FWHM ~ 261 eV.
- The fourth measurement kept R_1 at -13.52 V and R_N at -80.0 V to see if the change of R_B to -55.4 V would end in a better energy resolution (the data taking duration was ~ 18 hours). Unfortunately, the energy resolution got worse, resulting in a FWHM ~ 280 eV for channel 2 of SDD no. 18 and FWHM ~ 311 eV for channel 2 of SDD no. 20. Again, as only the Mn K_α peak was fitted with one gaussian, the results of this measurement are not precise and are only meant as a benchmark. The energy histogram without the gaussian fit is shown in figure 31.
- For the final setting the bias voltage was turned to $R_1 = -15.5$ V, $R_B = -55.4$ V and $R_N = -80.0$ V to see if the change of R_1 would lead to a decrease of the FWHM of the channels. Data was taken for ~ 20.5 hours. As the spectra showed again unknown peaks and impurities in the peaks, only the Mn K_α peak



(a) Channel 2 of SDD no. 18 with a FWHM of the Mn K_α peak of ~ 260 eV. (b) Channel 2 of SDD no. 20 with a FWHM of the Mn K_α peak of ~ 261 eV.

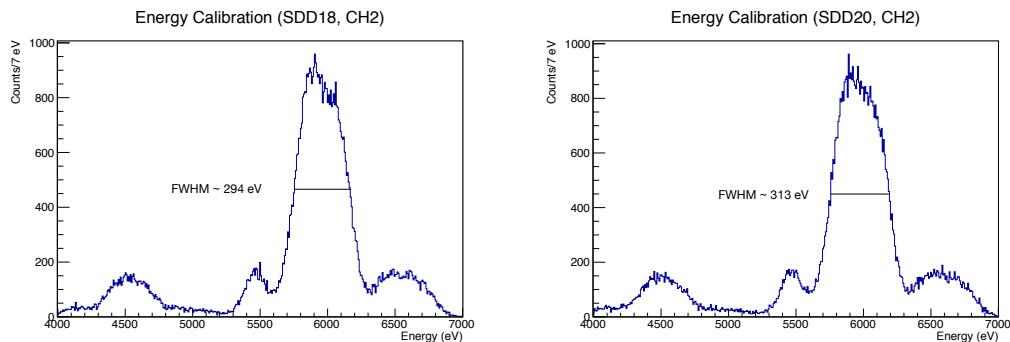
Figure 30: Energy spectrum ($\text{Fe-55} + \text{Ti}$) with a bias voltage configuration of $R_1 = -13.52$ V, $R_B = -60.2$ V and $R_N = -80.0$ V.



(a) Channel 2 of SDD no. 18 with a FWHM of the Mn K_α peak of ~ 280 eV. (b) Channel 2 of SDD no. 20 with a FWHM of the Mn K_α peak of ~ 311 eV.

Figure 31: Energy spectrum ($\text{Fe-55} + \text{Ti}$) with a bias voltage configuration of $R_1 = -13.52$ V, $R_B = -55.4$ V and $R_N = -80.0$ V.

was fitted with one gaussian function to be able to give an approximation of the FWHM. Unfortunately, this setting did not lead to the wished-for increase of the energy resolution, the FWHM for channel 2 of SDD no. 18 being ~ 294 eV and for channel 2 of SDD no. 20 ~ 313 eV (see figure 32).



(a) Channel 2 of SDD no. 18 with a FWHM of the Mn K_{α} peak of ~ 294 eV. (b) Channel 2 of SDD no. 20 with a FWHM of the Mn K_{α} peak of ~ 313 eV.

Figure 32: Energy spectrum (Fe-55 + Ti) with a bias voltage configuration of $R_1 = -15.5$ V, $R_B = -55.4$ V and $R_N = -80.0$ V.

The best energy resolution for SDD no. 18 and SDD no. 20 was achieved with the very first setting with a bias voltage of $R_1 = -9.54$ V, $R_B = -55.6$ V and $R_N = -66.6$ V. However, this setting achieved only an increase of the energy resolution of approximately 1 eV for all channels compared to the second voltage setting ($R_1 = -14.7$ V, $R_B = -53.8$ V and $R_N = -78.2$ V). Therefore, a stability study should be performed to see which of these settings enables the SDDs to operate for long durations of a few days. Unfortunately, this could not have been performed before finishing this master thesis.

Bias Voltage	CH1 (eV)	CH2 (eV)	CH3 (eV)	CH4 (eV)	CH5 (eV)	CH6 (eV)	CH7 (eV)	CH8 (eV)
$R_1 = -9.54 \text{ V}$	177.84 ± 0.41	175.04 ± 0.39	175.71 ± 0.39	174.53 ± 0.38	171.86 ± 0.38	172.54 ± 0.38	172.22 ± 0.38	x
$R_B = -55.6 \text{ V}$								
$R_N = -66.6 \text{ V}$								
$R_1 = -14.70 \text{ V}$	178.59 ± 0.44	177.93 ± 0.44	178.68 ± 0.43	178.75 ± 0.42	172.99 ± 0.41	174.11 ± 0.41	174.10 ± 0.43	x
$R_B = -53.8 \text{ V}$								
$R_N = -78.2 \text{ V}$								
$R_1 = -13.52 \text{ V}$	~ 258	~ 260	~ 275	~ 248	~ 245	~ 245	~ 238	x
$R_B = -60.2 \text{ V}$								
$R_N = -80.0 \text{ V}$								
$R_1 = -13.52 \text{ V}$	~ 318	~ 280	~ 326	~ 277	~ 286	~ 315	~ 293	x
$R_B = -55.4 \text{ V}$								
$R_N = -80.0 \text{ V}$								
$R_1 = -15.50 \text{ V}$	~ 313	~ 294	~ 332	~ 299	~ 292	~ 284	~ 279	x
$R_B = -55.4 \text{ V}$								
$R_N = -80.0 \text{ V}$								

Table 6: FWHM of the Mn K_α peak for all channels of SDD no. 18 with different bias voltage settings.

Bias Voltage	CH1 (eV)	CH2 (eV)	CH3 (eV)	CH4 (eV)	CH5 (eV)	CH6 (eV)	CH7 (eV)	CH8 (eV)
$R_1 = -9.54 \text{ V}$								
$R_B = -55.6 \text{ V}$	186.92 ± 0.43	187.65 ± 0.43	x	188.25 ± 0.42	185.08 ± 0.41	x	183.74 ± 0.41	185.23 ± 0.42
$R_N = -66.6 \text{ V}$								
$R_1 = -14.70 \text{ V}$								
$R_B = -53.8 \text{ V}$	188.64 ± 0.47	186.62 ± 0.46	x	189.89 ± 0.46	187.16 ± 0.45	x	184.92 ± 0.46	186.10 ± 0.46
$R_N = -78.2 \text{ V}$								
$R_1 = -13.52 \text{ V}$								
$R_B = -60.2 \text{ V}$	~ 262	~ 261	x	~ 200	~ 273	x	~ 256	~ 263
$R_N = -80.0 \text{ V}$								
$R_1 = -13.52 \text{ V}$								
$R_B = -55.4 \text{ V}$	~ 317	~ 311	x	~ 313	~ 298	x	~ 290	~ 334
$R_N = -80.0 \text{ V}$								
$R_1 = -15.50 \text{ V}$								
$R_B = -55.4 \text{ V}$	~ 308	~ 313	x	~ 320	~ 423	x	~ 328	~ 325
$R_N = -80.0 \text{ V}$								

Table 7: FWHM of the Mn K_α peak for all channels of SDD no. 20 with different bias voltage settings.

4.4 Drift Time Measurement

The results of this measurement can also be seen in [25].

The setup of the drift time measurement can be seen in chapter 3.3. The drift time was determined by comparing the incoming time signal of the scintillator with the time signal of the SDD-“OR” generated by the gate of all sixteen SDD cells (sixteen channels as two SDD arrays have been connected to the amplifier). As the electrons need a certain amount of time to drift to the anode and to create a signal, the time difference between the signal of the scintillator (which is detected straight after the hit) and the arrival of the information that a gate has been created inside the SDD array corresponds to the drift time of the SDD. SDD signals resulting from both electrons and Cu X-rays have been included in this analysis to obtain a high statistic data sample as the difference between the drift times of signals produced by electrons or by X-rays has been determined to be negligible by a dedicated MC study [26].

The drift time for channel 1 of SDD no. 11 at $T \sim 150$ K can be seen in figure 33 and was determined to be ~ 500 ns (FWHM), which will lead to a drift time of roughly 300 ns at 100 K [40]. Therefore, the drift time of ~ 500 ns (FWHM) meets the expectations.

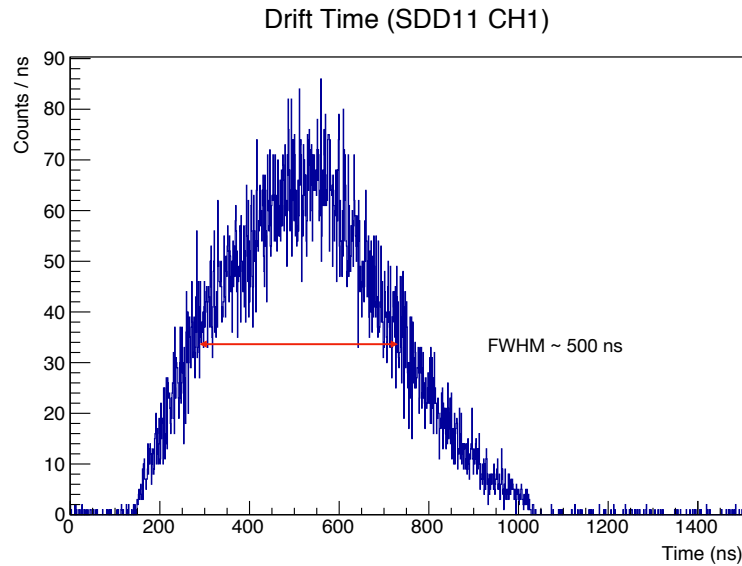


Figure 33: The drift time of channel 1 of SDD no. 11 is ~ 500 ns (FWHM) at $T \sim 150$ K [25].

4.5 SDD Cross Talk

The results presented here can also be seen in [25].

If a signal hits one SDD cell at the border to another unit, there is a small possibility of charge splitting even though the single units are divided by potential wells. A schematic picture of the layout of one SDD array is shown below in figure 34. The likelihood of charge separation is bigger at neighbouring channels than with channels which are not directly linked. Those should not show any crosstalk events. If a crosstalk between separated channels is seen, it is likely to come from electronic crosstalk rather than from charge splitting on the SDD array.

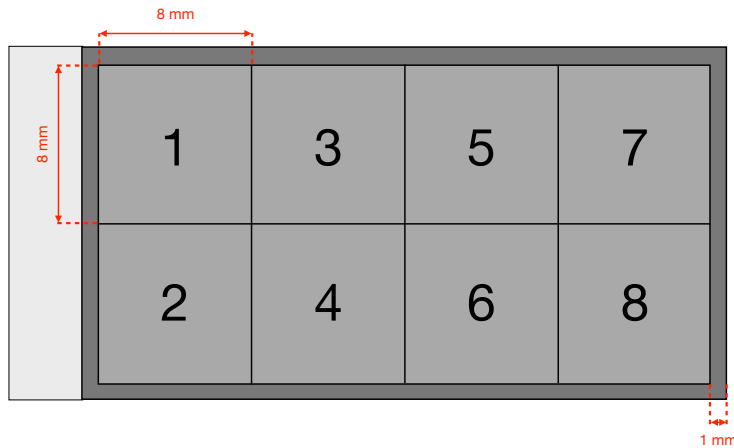


Figure 34: Schematic drawing of the channel numeration of one SDD array, the light grey area on the left side representing the connector plate.

To determine the crosstalk, a measurement with a Sr-90 source and an additional 21 μm thick Cu foil to produce characteristic X-rays has been carried out for SDD array no. 18. Representatively, a diagram of the crosstalk between the neighbouring SDD channels 5 and 7 is shown in figure 35. Only events higher than 500 ADC channel (~ 3 keV) have been considered as events below threshold are not used.

One can see, that the energy of the Cu K_α peak (the peak centre is normally positioned at ~ 1373 ADC channel) has been split up for ~ 60 events, which is indicated by the red circle. As the Cu K_α peaks of channel 5 and channel 7 hold approximately 12,000 events each, this corresponds to a charge splitting of $\sim 0.25\%$ at (8.0 ± 0.5) eV. However, the highest number of crosstalk events can be seen by overflow events (events higher than 4000 ADC channel) that initiate other overflow events in the neighbouring channel.

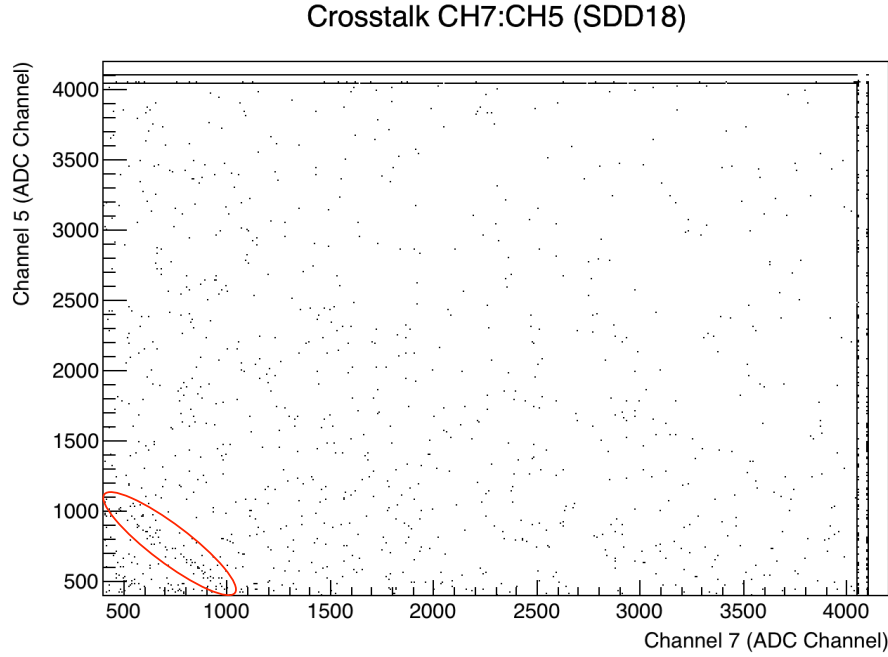


Figure 35: Crosstalk evaluation between channel 5 and 7 of SDD no. 18. The red circle indicates crosstalk in the energy region of the Cu K_{α} peak [25].

For the detailed analysis only overflow events (signals with energies > 4000 ADC channel, or > 24.8 keV) of one SDD cell were considered. This was then compared with signals seen by other SDD channels in the same time window. Representatively, the results of the evaluation done for channel 4 and channel 7 are shown in tables 8 and 9. The results of channel 7 can also be taken from [25].

The signals seen by other channels in coincidence with channel 4 (table 8) or channel 7 (table 9) detecting an overflow event are split into different energy regions:

1. In column 2 the probability of a signal with an energy between the low-level trigger (3.1 keV) and the beginning of the region of interest (ROI) (7.8 keV), where the Cu K_{α} is expected, is presented.
2. The probability of events with an energy in the ROI (7.8 - 9.3 keV) detected in coincidence with an overflow event are shown in column 3.
3. The probability of hits with an energy above the ROI (until close to the overflow peak, 9.3 - 24.7 keV) are given in column 4.
4. In column 5 the probability of simultaneous overflow events (> 24.7 keV) is given.

As expected, the crosstalk between channel 4 and the three neighbouring channels (channel 2, 3 and 6) is higher than with other channels. The crosstalk probability between channel 4 and non-neighbouring channels for events with an energy below $24.7 \text{ keV} < 0.1 \%$. For neighbouring channels this probability is slightly higher and amounts to $\sim 0.6 \%$. In the ROI the probability of crosstalk for non-neighbouring channels is below 0.005% , whereas for neighbouring it is below 0.05% . The most probable case of crosstalk is caused by simultaneous overflow events. The probability of a crosstalk event for events without contact to channel 4 are between 0.01% and 0.13% . For channels that share a border with channel 4 the probability for crosstalk events is higher amounting to $\sim 3 \%$. The only exception can be seen by channel 7, which shows a higher crosstalk probability than is expected from the SDD layout, the probability of simultaneous overflow events being approximately 2% . A possible explanation for this is that the crosstalk originates from electronic crosstalk rather than a bad potential well on the SDD array itself.

Channel	$500 < x < 1250$	$1250 < x < 1500$	$1500 < x < 4000$	$4000 < x$
1	0.021 %	0.005 %	0.029 %	0.128 %
2	0.172 %	0.042 %	0.290 %	2.982 %
3	0.200 %	0.048 %	0.333 %	3.233 %
5	0.017 %	0.004 %	0.024 %	0.129 %
6	0.185 %	0.043 %	0.295 %	3.051 %
7	0.000 %	0.000 %	0.001 %	1.686 %
8	0.001 %	0.000 %	0.001 %	0.011 %

Table 8: Crosstalk probability when channel 4 detects an overflow event (energy > 4000 ADC channel or $> 24.7 \text{ keV}$) compared to signals seen by all other channels for different ADC channel regions. The total number of overflow events seen by channel 4 amounts to 2.4×10^6 .

The crosstalk probabilities are slightly higher for channel 7. Even though the probability for events below the 24.7 keV is still $< 0.1 \%$ for non-neighbouring channels and around $\sim 0.6 \%$ for neighbouring channels, it can be seen that the probability of simultaneous overflow events is bigger, amounting to 0.7% up to approximately 2% for non-neighbours and $\sim 4 - 6 \%$ for neighbouring channels. Especially the high crosstalk probability between channel 7 and channel 1 is peculiar as those channels are separated the most on the silicon wafer. This underlines the argument of electronic crosstalk or a bad potential well of channel 7 and would also explain the higher crosstalk probability compared to the crosstalk evaluation of channel 4.

Channel	$500 < x < 1250$	$1250 < x < 1500$	$1500 < x < 4000$	$4000 < x$
1	0.024 %	0.015 %	0.039 %	1.841 %
2	0.025 %	0.012 %	0.037 %	0.737 %
3	0.023 %	0.014 %	0.040 %	1.449 %
4	0.024 %	0.014 %	0.039 %	1.356 %
5	0.164 %	0.045 %	0.271 %	3.870 %
6	0.039 %	0.016 %	0.054 %	2.058 %
8	0.174 %	0.050 %	0.319 %	6.331 %

Table 9: Crosstalk probability when channel 7 detects an overflow event (energy > 4000 ADC channel or > 24.7 keV) compared to signals seen by all other channels for different ADC channel regions. The total number of overflow events seen by channel 7 amounts to 2.9×10^6 [25].

A simple MC simulation with a Sr-90 source resulted in a crosstalk probability of approximately 2 % for neighbouring channels ([26]), which coincides with the experimental observation.

The first two columns (with an energy region between 3.1 keV and 9.3 keV) are covering the energy region of kaonic deuterium experiment as the kaonic deuterium peaks are expected to occur in an energy region of 5 - 9 keV. Therefore, if an overflow event occurs, the whole SDD array will be discarded for background reduction.

5 First SDD Measurement within the E62 Experiment at J-PARC

The E62 experiment at J-PARC wants to explore the kaonic helium $3d \rightarrow 2p$ transition of the two helium isotopes ^3He and ^4He . The measurement was performed in June 2018 by using superconducting transition-edge-sensors (TES) to determine the energy width with a (proposed) precision of 0.2 eV [41]. The SDDs have been installed in this experiment to test them in a real beam environment for the very first time. By the end of this master thesis, the data analysis has just been started and the first results will be expected in 2019.

5.1 Experimental Setup

For the E62 experiment, the K1.8BR beamline at J-PARC is used to send K^- particles with a momentum of 0.9 GeV/c into a liquid helium target and produce kaonic helium. Every five seconds a spill with a length of two seconds reaches the beam line. The target cell with a diameter of 6 cm and a length of 6 cm is cooled down to ~ 2.5 K and filled first with liquid ^3He , and afterwards with liquid ^4He . The TES detectors are placed at one end of the target cylinder and very closely to the target cell. To reach the TES working temperature of 50 mK an isolation foil is put between the target cell and the TES detectors. Opposite of the TES detectors, on the other side of the target cylinder, an X-ray generator with Cr, Co and Cu foils is placed for calibration purposes. Four SDD arrays are stationed above the target cell and are cooled to ~ 120 K. The whole setup can be seen in figure 36.

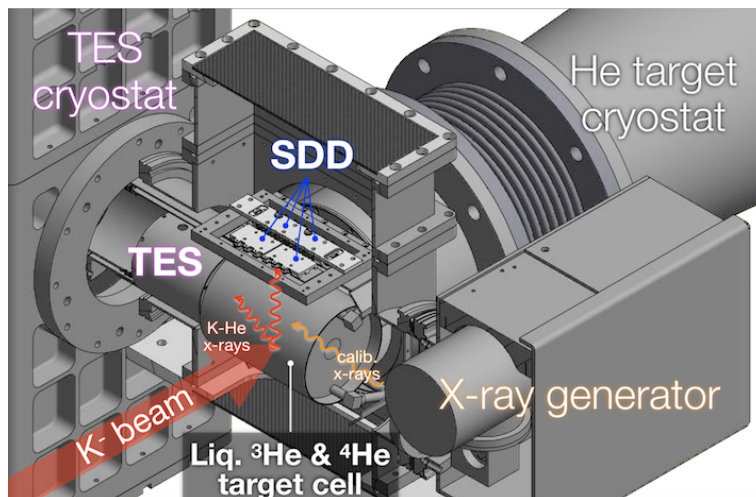
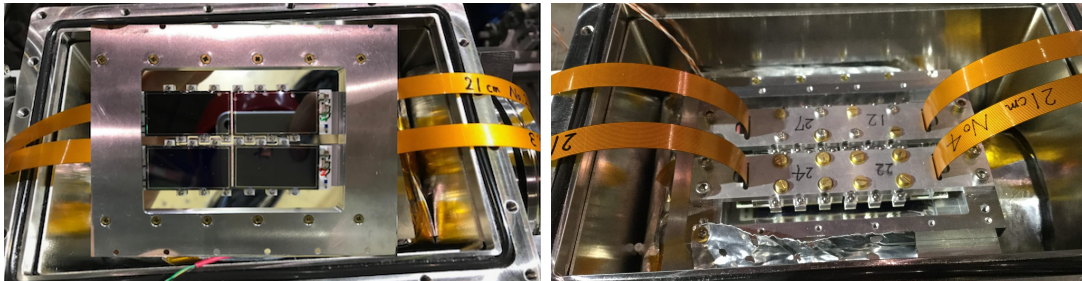


Figure 36: The E62 setup for the measurement of the $3d \rightarrow 2p$ transition of kaonic helium at J-PARC. *Picture courtesy of S. Okada.*

The SDD arrays used during the experiment were no. 27, 12 (both placed upstream of the interaction point), 22 and 24 (placed downstream of the interaction point). Figure 37 shows the placement of the SDDs inside the vacuum chamber.



(a) SDD arrays on the aluminium support structure with the entrance windows facing towards the reader. (b) SDD arrays placed inside the vacuum chamber with the entrance window facing the intersection point.

Figure 37: SDD setup of the four SDD arrays used in the E62 experiment at J-PARC. *Picture courtesy of E62 collaboration.*

Before the kaons hit the target cell, they pass through a 255 mm Cu degrader to reduce the energy of the kaon beam for optimising the kaonic helium production. Upstream of the degrader a cherenkov detector is placed for particle identification and background reduction. After the Cherenkov detector five scintillator bars (each with a dimension of $16 \times 3.2 \times 1 \text{ cm}^3$, see [34] for more details) are stationed to be used as the starting counter T0. Behind the degrader and the shielding another definition counter of one scintillator bar (with dimensions $12 \times 12 \times 1 \text{ cm}^3$, taken from [32]) is placed.

5.2 Test Measurements before the E62 Run

In the beginning of the E62 experiment, motherboards of V4 and amplifier cards V3.1 were connected to the SDD arrays no. 12, 22, 24 and 27. SDDs no. 22, 24 and 12 were working very well (see ramp values in Table 10), however SDD no. 27 was not working at all. Trying to adjust the bias voltage to different values had no effect, and also with the previously used amplifier boards no ramp could be seen. As this SDD array had worked fine at room temperature, it seems that the temperature of $T=115 \text{ K}$ was too low. Thus this SDD array was not taking any data. Therefore, only 3 SDD arrays could be used for this beam time. The bias voltage supply of the SDDs was at $R_1 = -15.0 \text{ V}$, $R_N = -65.0 \text{ V}$ and $R_B = -85.0 \text{ V}$.

As can be seen in Table 10, channel 1 of SDD no. 12 and channel 6 of SDD no. 22 were very short and thus these channels were turned off in the beginning.

Channel No.	SDD No. 22	SDD No. 24	SDD No. 27	SDD No. 12
CH1	7 s	14 s	x	3 μ s
CH2	6 s	7 s	x	3.7 s
CH3	7.6 s	15 s	x	5.8 s
CH4	4 s	6 s	x	2.8 s
CH5	1.6 s	14.4 s	x	9.2 s
CH6	180 ms	15 s	x	10.2 s
CH7	10 s	13.6 s	x	10.4 s
CH8	9.6 s	13 s	x	9.8 s

Table 10: Ramp check of four SDD arrays used in the E62 experiment.

5.2.1 SDD Performances During Beam Tuning

Beam tuning started on June 2nd 2018 and lasted for ~ 6.5 days. In the beginning, the three SDD arrays were working well, but on the 7th and 8th of June SDD no. 24 stopped working without obvious reasons. After changing the bias voltage of all SDDs, SDD no. 24 recovered.

Therefore, the bias voltage supply for the upstream SDDs and downstream SDDs was split up. The bias voltage as described in section 5.2, which was also used here, was probably close to the edge of an unstable working point for SDD no. 24. The bias voltage for the upstream SDDs was set to $R_1 = -17.0$ V, $R_N = -90.0$ V and $R_B = -65.0$ V; the SDDs located downstream of the intersection point were henceforth operated at $R_1 = -12.0$ V, $R_N = -90.0$ V and $R_B = -65.0$ V.

An additional change was performed by returning to the old amplifier boards (motherboard V1 and amplifier boards V2.0). After these changes, the SDDs were running stably and data taking commenced without any problems.

5.3 E62 experiment

The transition energy of kaonic ^3He should be different to the one of ^4He . For a rough estimation, one can calculate the Bohr energy levels from 2.2 for the second and third shell (with $c = 1$ and $\alpha = 1/137$), and subtract these values.

For kaonic ^3He the reduced mass is calculated from the kaon mass $m_K \approx 500$ MeV and the mass of the ^3He isotope $m_{He3} \approx 2800$ MeV: $\mu_{He3} \approx 424$ MeV.

Thus the binding energies equal to $B_{2,He3} \approx 11.3$ keV and $B_{3,He3} \approx 5.02$ keV, leading to a final electromagnetic energy value of the $3d \rightarrow 2p$ transition of

$$\Delta B_{3 \rightarrow 2, He3} \approx 6.3 \text{ keV}.$$

Repeating the same calculation for ^4He ($m_{He4} \approx 440$ MeV) yields a transition energy of

$$\Delta B_{3 \rightarrow 2, He4} \approx 6.5 \text{ keV}.$$

These energies are in the energy region where one expects the kaonic helium peaks to occur. A shift due to the strong interaction is expected in the order of a few eV, too small for a precise determination with SDDs.

5.3.1 Energy Calibration

An X-ray tube with Cr, Co and Cu foils was used for the energy calibration of the TES detectors. As the X-ray tube was pointed into the direction of the TES detectors, Compton scattering in the helium gas of the X-rays produced by the foils had to be taken into account. Hence this effect was corrected in the final energy calibration. A typical energy calibration spectrum can be seen in figure 38. The Ti and Zr peaks originate from additional foils in front of the SDDs.

Firstly, the Cr, Co and Cu peaks were fitted with one gaussian function for each SDD cell. Then differences of one SDD array in the ADC spectrum were compensated, and all individual SDD cells were summed up. Thus, an ADC spectrum for all channels is obtained. For the preliminary result (that can be seen in figure 46) 16 channels with the best energy resolution were used.

In the final step, the Ti and Zr peaks (as they were not affected by Compton scattering) were each fitted with one gaussian function, and a conversion factor could be determined.

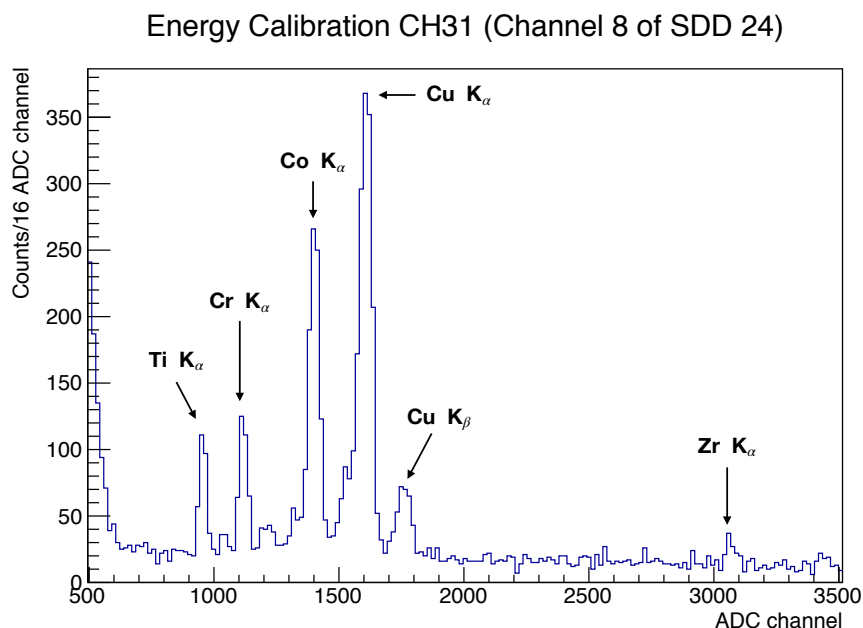


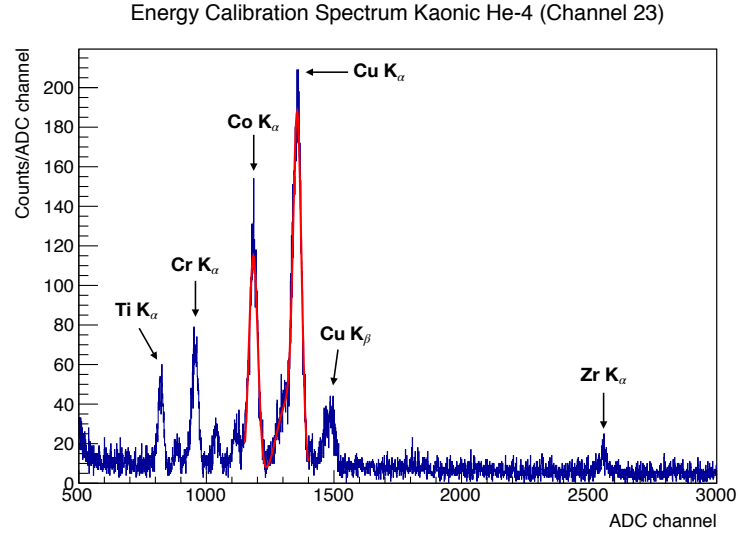
Figure 38: Energy spectrum of channel 31 (channel 8 of SDD 24) in ADC channel for run 431. The Ti and Zr peaks have been used for the energy calibration.

5.3.2 Peak Stability

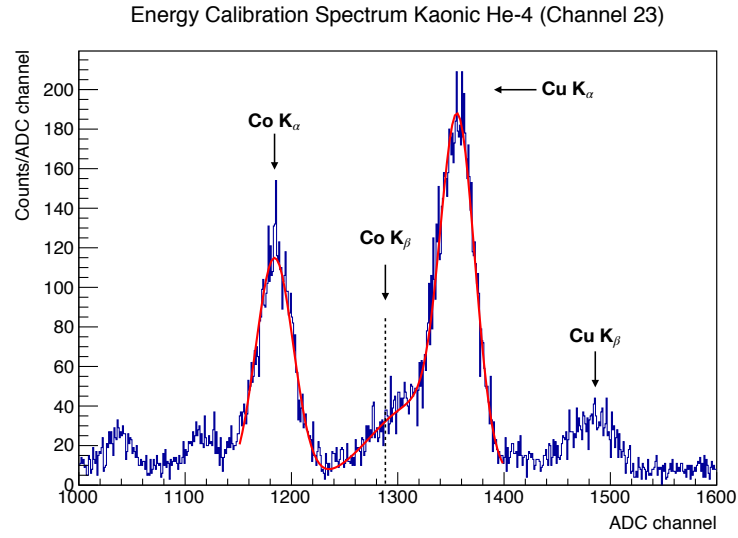
As already mentioned in chapter 3.1.1, the newly developed SDDs should show fluctuations of only a few eV to guarantee the summing of all channels. To check if this was the case during the E62 experiment, the peak position of the Co K_α and the Cu K_α of three channels, CH15 (CH8 of SDD no. 12), CH23 (CH8 of SDD no. 22) and CH31 (CH8 of SDD no. 24), have been analysed in the ADC channel spectrum. The Co K_β peak was not fixed to the Co K_α peak, but was allowed to vary peak position and width to include also the tail of the Cu K_α peak. The tail of the Cu K_α peak comes from the previously (in section 5.3.1) mentioned Compton scattering and from the fact, that electrons get captured by impurities on their way to the anode of the SDD. All three peaks have been fitted with one function consisting of three combined gaussians. An example of a fit of a data package for kaonic ^4He (run 414-418) can be seen in figure 39 for channel 23.

For kaonic ^3He , run 279 until run 373 (one run corresponds to ~ 2 hours of data taking) have been used and divided into packages of five runs (e.g. the data of run 279 until run 283 have been summed up and fitted together). The spectra for ^3He can be seen in figures 40, 41 and 42. The same has been done for kaonic ^4He using runs 379 until run 510; run 469 until run 475 have been ignored as runs 473-475 have been runs with a K^+ beam instead of a K^- beam, and four hours of data taking (runs 469-472) showed too little data to achieve an accurate peak position determination. The spectra are shown in figures 43, 44 and 45.

All of the analysed channels show fluctuations of under ± 1.2 ADC channel, which correspond to fluctuations of roughly ± 6 eV. The fluctuations of the peak stabilities for kaonic ^4He have only been analysed until run 458 as afterwards the peak positions strongly decreased. This was due to the fact that the temperature in the hadron hall at J-PARC increased as the outside temperature increased (by ~ 6 C°). Thus, a peak drift of 3 ADC channel was introduced. However, the results before the decrease and the results of the kaonic ^3He analysis show that the SDDs work well in a real beam environment, ensuring their stable operation of them during the E57 kaonic deuterium experiment.

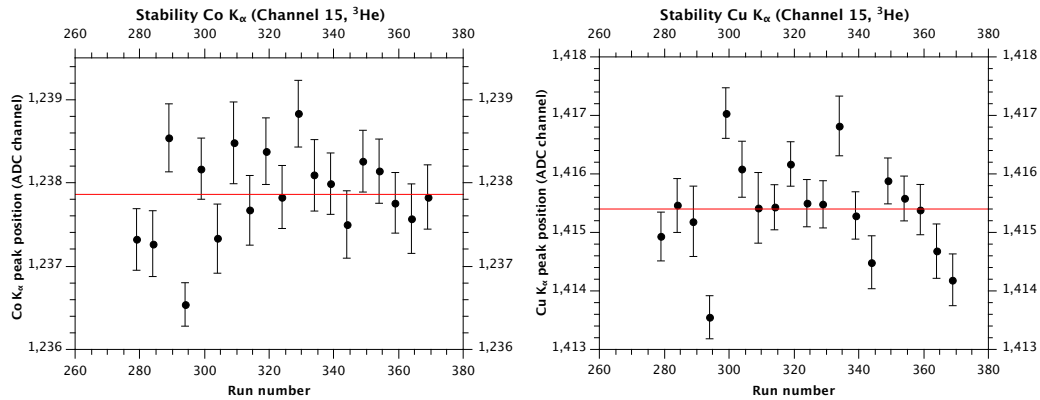


(a) Energy calibration spectrum of channel 23 including the fit.



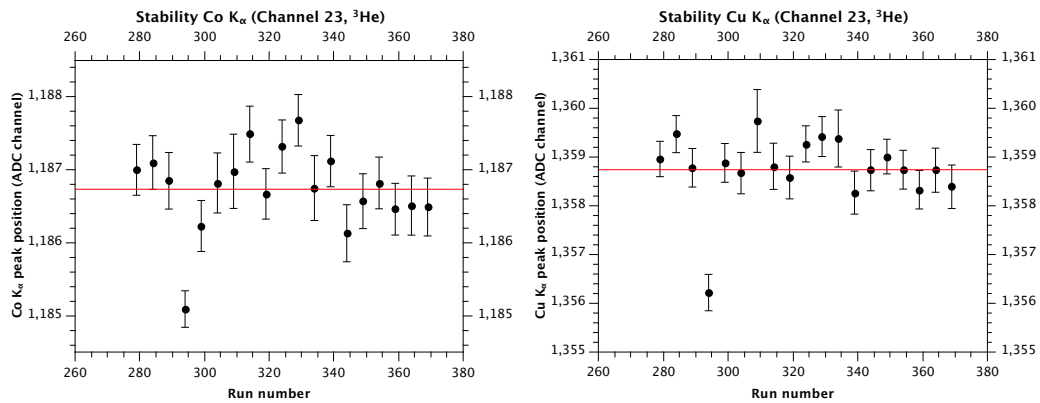
(b) Zoom of the energy calibration spectrum of channel 23 including the fit. The dashed line shows the approximate position of the Co K_β .

Figure 39: Fit of a typical energy calibration spectrum for kaonic ^4He of channel 23. The Co K_α , Co K_β (plus tail of Cu K_α) and Cu K_α have been fitted with a function of three combined gaussians.



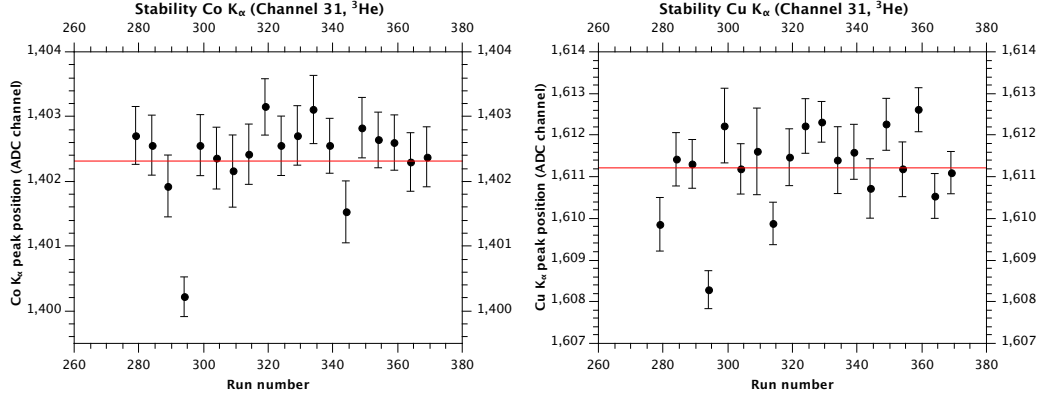
(a) Stability analysis of the Co K_α peak. (b) Stability analysis of the Cu K_α peak.

Figure 40: Peak stability analysis of CH15 (CH8 of SDD 12) for kaonic ^3He . The red line indicates the mean value of the data at (a) 1237.67 and (b) 1415.40 ADC channel. Both show fluctuations of ± 1 ADC channel, meaning fluctuations of approximately ± 6 eV.



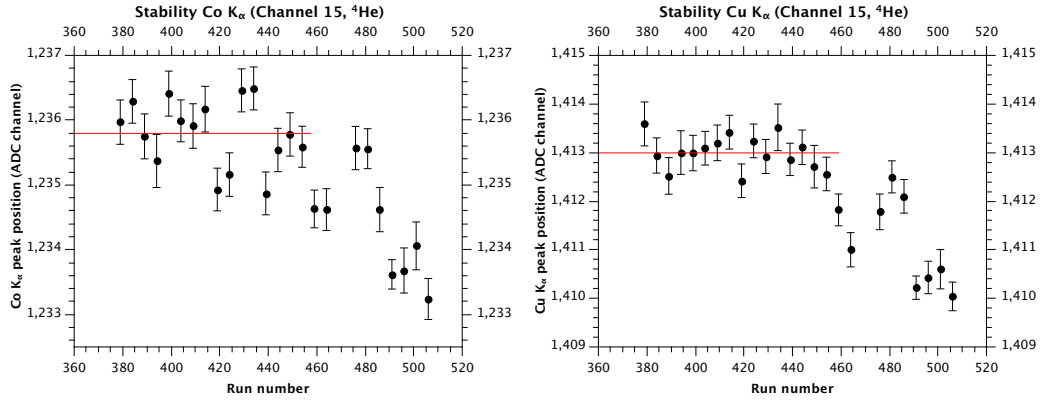
(a) Stability analysis of the Co K_α peak. (b) Stability analysis of the Cu K_α peak.

Figure 41: Peak stability analysis of CH23 (CH8 of SDD 22) for kaonic ^3He . The red line indicates the mean value of the data at (a) 1185.74 and (b) 1358.76 ADC channel. Both show fluctuations of under ± 1 ADC channel, meaning fluctuations of approximately ± 6 eV.



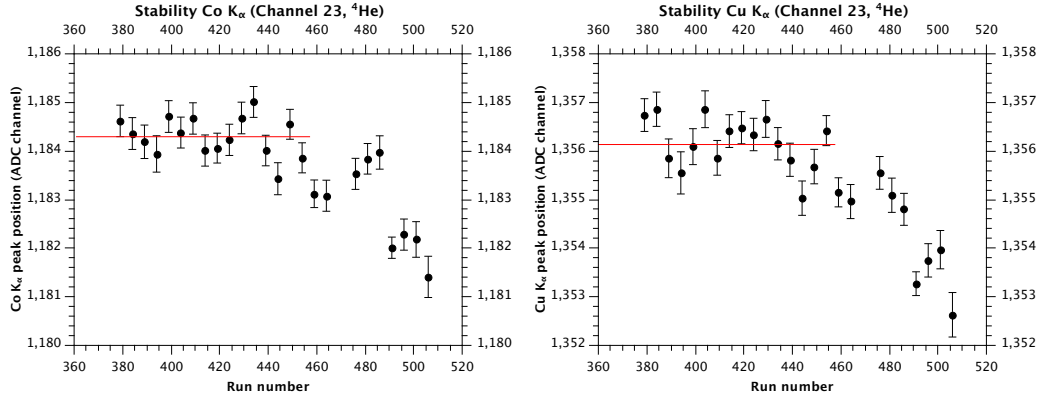
(a) Stability analysis of the Co K_α peak. (b) Stability analysis of the Cu K_α peak.

Figure 42: Peak stability analysis of CH31 (CH8 of SDD 24) for kaonic ^3He . The red line indicates the mean value of the data at (a) 1402.38 and (b) 1611.22 ADC channel. Both show fluctuations of ± 1 ADC channel, meaning fluctuations of approximately ± 5 eV.



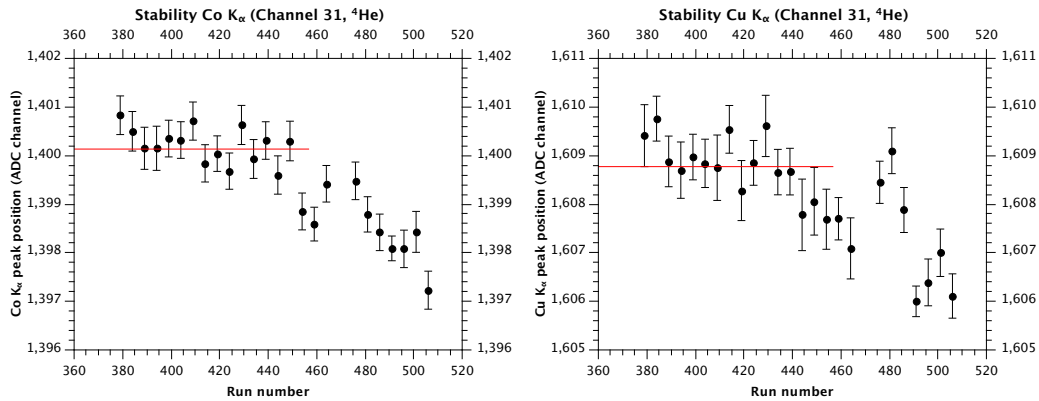
(a) Stability analysis of the Co K_α peak. (b) Stability analysis of the Cu K_α peak.

Figure 43: Peak stability analysis of CH15 (CH8 of SDD 12) for kaonic ^4He . The red line indicates the mean value of the data at (a) 1235.79 and (b) 1413.00 ADC channel until run 458. Until run 458 both peaks show fluctuations of ± 1 ADC channel, meaning a fluctuation of approximately ± 5 -6 eV.



(a) Stability analysis of the Co K_{α} peak. (b) Stability analysis of the Cu K_{α} peak.

Figure 44: Peak stability analysis of CH23 (CH8 of SDD 22) for kaonic ^4He . The red line indicates the mean value of the data at (a) 1184.29 and (b) 1356.18 ADC channel until run 458. Until run 458 both peaks show fluctuations of ± 1 ADC channel, meaning a fluctuation of approximately ± 6 eV.



(a) Stability analysis of the Co K_{α} peak. (b) Stability analysis of the Cu K_{α} peak.

Figure 45: Peak stability analysis of CH31 (CH8 of SDD 24) for kaonic ^4He . The red line indicates the mean value of the data at (a) 1400.14 and (b) 1608.78 ADC channel until run 458. Until run 458 both peaks show fluctuations of under ± 1.2 ADC channel, meaning a fluctuation of under ± 6 eV.

5.3.3 Energy Spectrum

In figure 46 the very first result of the energy spectrum of the SDD data can be seen. The energy spectrum is shown for kaonic ^3He , ^4He as well as for the few data collected with the K^+ beam. For kaonic ^3He the data duration for this analysis amounted to ~ 4 days, for kaonic ^4He to ~ 6 days, and for K^+ to ~ 5 hours. As can be seen in all three spectra, the Ti K_α and K_β , the Cu K_α peak as well as the kaonic carbon and kaonic oxygen peak are all situated at the same position. However, as is expected e.g. from the calculation in 5.3 for the L_α lines, the peaks are situated at 6.23 keV (^3He) and 6.45 keV (^4He), and both show a FWHM of under 200 eV.

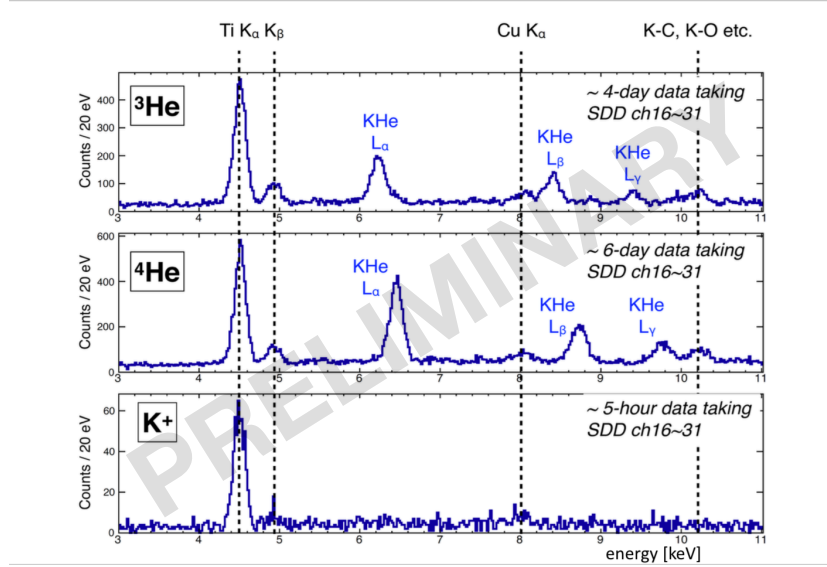


Figure 46: Energy spectrum of the kaonic helium experiment at J-PARC taken with SDDs. *Analysis performed by T. Hashimoto.*

5.3.4 Summary

Satisfactory results were achieved with the SDDs during the E62 beam time. The SDDs were running stably for ~ 1.5 weeks, and showed fluctuations in the peak position of only ± 6 ADC channel, which was expected from the test measurements performed at the SMI (refer to chapter 4.3 for the results of these test measurements). Furthermore, the energy resolution achieved during the E62 measurement with a FWHM of < 200 eV for both helium peaks ensures the determination of the kaonic deuterium transition with the proposed precision (peak shift: 60 eV and width: 140 eV [32]).

6 Summary and Outlook

6.1 Summary

In the experiments E57 at J-PARC and SIDDHARTA-2 at DAΦNE, the $2p \rightarrow 1s$ transition of kaonic deuterium is going to be determined. SDDs will detect the transition X-rays, and as the kaon will be close enough to the nucleus and feel the strong interaction, the shift and width of this transition can be determined with a precision of 60 eV and 140 eV, respectively.

To ensure the working of the SDDs, several test measurement have been performed at the SMI:

- An energy resolution of SDD no. 5 of below 160 eV (FWHM) at 6 keV has been achieved at a temperature of ~ 170 K.
- A drift time measurement resulted in a drift time of ~ 500 ns at a temperature of ~ 150 K. The measurement was performed with SDD no. 11.
- The stable operation of SDD no. 20 has been determined to be below ± 6 eV for the peak stability and ± 4 eV for the stability of the peak width during a test measurement with a Sr-90 source and an additional Cu foil. This stability result has also been confirmed during the E62 measurement at J-PARC, where fluctuations of the peak stability were in the order of ± 6 eV for SDDs no. 12, 22 and 24.
- The crosstalk probability between SDD cells of one SDD array are below 5 % for neighbouring channels, and below 0.05 % for non-neighbouring channels, if one of the channels detects an overflow event (a signal with an energy higher than 23.7 keV).

These experiments were performed with different amplifier boards, as changes were continually made to them. The latest versions used during this master thesis are the motherboard version 7 and amplifier boards version 3.0. Good energy resolutions have been performed with them.

The final test was the performance of the SDDs during the E62 run in June 2018, where an energy resolution (FWHM) of under 200 eV for the L_α lines of kaonic ^3He and ^4He at $T \sim 120$ K was achieved.

6.2 Outlook

As 48 SDD arrays are needed during the kaonic deuterium experiments, more tests on the energy resolution and stability need to be performed with different SDD arrays and with the latest amplifier versions.

Beam commissioning for the SIDDHARTA-2 experiment will start in the beginning

of 2019, whereas the E57 experiment will not take place before August 2019, as an additional test measurement of kaonic hydrogen has to be performed in spring 2019 beforehand. The data taking time of the E57 experiment will amount to ~ 2 weeks, thus the first results can be expected in 2020.

A Appendix: List of Tested SDD Arrays

SDD No.	LR	R_t (V)	R_{N^*} (V)	R_B (V)	T	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
2	10 k Ω	-20.6	-73.0	-93.0	~ 299 K	20 μ s	x	500 μ s	60 μ s	40 μ s	x	10 μ s	2.5 μ s
5	10 k Ω	-17.6	-70.0	-90.0	45.7 Ω	800 ms	x	90 μ s	400 ms	1.8 ms	x	x	400 ms
8	100 k Ω	-15.46	-60.4	-86.5	~ 299 K	x	x	x	600 μ s	5 μ s	25 μ s	1.6 ms	8 ms
10	10 k Ω	-17.9	-65	-95	~ 298 K	500 μ s	x	x	x	600 μ s	x	300 μ s	100 μ s
11	10 k Ω	-17.9	-65	-95	~ 298 K	600 μ s	200 μ s	600 μ s	500 μ s	300 μ s	?	600 μ s	x
18	100 k Ω	-15.46	-60.4	-86.5	153 K	35 s	13 s	30 s	25 s	28 s	27 s	25 s	23 s
20	100 k Ω	-15.46	-60.4	-86.5	153 K	200 ms	1 s	3 ms	3 s	6 s	no reset	7 s	7 s
22	10 k Ω	-17.7	-70.0	-90.0	39.0 Ω	3.4 s	2.5 s	1.6 s	2 s	1.6 s	150 ms	1.2 s	2.5 s
32	10 k Ω	-16.2	-61.0	-88.0	~ 298 K	150 μ s	1 ms	300 μ s	750 μ s	500 μ s	700 μ s	500 μ s	500 μ s
41	10 k Ω	-17.7	-70.0	-90.0	39.3 Ω	3.3 s	x	2.5 s	1.9 s	x	x	2.7 s	2.5 s

Figure 47: A list of all SDD arrays that were tested during this master thesis plus additional information about all the ramp length of each channel, as well as the line-driver termination resistor (LR) and the bias voltage used during the test measurements.

B Abbreviations

ADC Analog-to-Digital-Converter

BLR Base Line Resistor

CDC Cylindrical Drift Chamber

CDH Cylindrical Hodoscope

CDS Cylindrical Detector

CH Channel

CMOS Complementary Metal-Oxide-Semiconductor

DAFNE Double Annular Φ Factory for Nice Experiments

DAQ Data Aquisition

DEAR DA Φ NE Exotic Atom Research

FBK Fondazione Bruno Kessler

FWHM Full Width Half Maximum

JFET Junction gate Field-Effect Transistor

J-PARC Japan Proton Accelerator Research Complex

KEK High Energy Accelerator Research Organization

LDD Liquid Deuterium Density

LNF Laboratori Nazionali di Frascati

MC Monte-Carlo

QCD Quantum Chromodynamics

QED Quantum Electrodynamics

ROI Region Of Interest

SDC Silicon Drift Chamber

SDD Silicon Drift Detector

SIDDHARTA Silicon Drift Detector for Hadronic Atom Research by Timing Application

SiPM Silicon Photomultiplier

SMI Stefan Meyer Institute for Subatomic Physics

TDC Time-to-Digital-Converter

TES Transition-Edge-Sensors

VMEbus Versa Module Eurocard Bus

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