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A large, 64-pixel PIN-diode detector for low-energy beta-electrons

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Abstract

The Karlsruhe Tritium Neutrino Experiment (KATRIN) neutrino mass experiment is based on a precise energy measurement ($\Delta E/E = 5 \times 10^{-5}$) of electrons emerging from tritium beta decay ($E_{\max} = 18.6\,\mathrm{keV}$). This is done by a large electrostatic retarding spectrometer, which is followed by an electron detector. Key requirements for this detector are a large sensitive area ($\sim 80\,\mathrm{cm}^2$), a certain energy resolution ($\Delta E = 600\,\mathrm{eV}$ at 18.6 keV) but also a certain spatial resolution ($\sim 3\,\mathrm{mm}$) which leads to a multi-pixel design. We present as a tentative design a detector system with a reduced size ($16\,\mathrm{cm}^2$) and a reduced pixel number (64), making use of a monolithic segmented silicon PIN diode. Apart from a description of the electronic design, very first results are presented showing the capability of this detector technology to detect electrons from Tritium β-decay on a large entry window.

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1. Introduction

The Karlsruhe Tritium Neutrino Experiment (KATRIN) [1,2] is designed to measure the mass of the electron neutrino in a direct and model-independent way with a sensitivity of $m_\nu < 0.2\,\mathrm{eV}/c^2$ (90% confidence level). It is a next generation tritium β-decay experiment scaling up the size and precision of previous experiments [3–5] by an order of magnitude. The energies of β-electrons from Tritium β-decay are analyzed near the endpoint ($E_{\max} = 18.6\,\mathrm{keV}$) by a retarding spectrometer with magnetic adiabatic collimation [6] achieving an energy resolution of $\Delta E = 0.9\,\mathrm{eV}$. The spectrometer is then followed by the so-called Focal Plane Detector (FPD) to detect the β-electrons, which have passed the spectrometer.

The key requirements for this detector system, which are described in detail in Ref. [2], are a sensitive area of the order of $\sim 80\,\mathrm{cm}^2$, a spatial resolution of a few millimeters and an intrinsic background level of $B < 3.5 \times 10^{-6}\,\mathrm{Hz}/(\mathrm{keV\,cm}^2)$, as well as a high detection efficiency ($\varepsilon > 0.9$ at 18 keV). The required sensitive area of $\sim 80\,\mathrm{cm}^2$ is given by the size of the tritium source and the electromagnetic design of the spectrometer. The spatial resolution of the point of incidence of an electron on the detector yields its crossing point through the spectrometer analyzing plane. Knowing this crossing point allows offline corrections for inhomogeneities of the retarding potential in the analyzing plane. The desired energy resolution of $\Delta E = 600\,\mathrm{eV}$ (FWHM, at 18.6 keV) contributes to an improved background suppression against events arising from natural radioactive impurities in the proximity of the detector.

Owing to the relatively large differential energy losses $\mathrm{d}E/\mathrm{d}x$ of electrons in this energy range, the detector should exhibit dead layers below 50 nm.

In the design of the detector system, very special attention has to be paid to the mounting and connection technique, as the detector will be operated in an extreme high vacuum environment ($p < 10^{-10}\,\mathrm{mbar}$) and in strong magnetic fields up to $B = 6\,\mathrm{T}$. Furthermore, proven by

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simulations, the choice of materials in the proximity of the detector is crucial with regard to the required background rate.

For evaluation purposes and for actual measurements in a smaller electrostatic spectrometer (the KATRIN *pre-spectrometer* experiment), a 64-pixel implementation was built.

We present this detector system with an emphasis on the design of the readout electronics (Section 2) including the mounting and assembly technology and we describe the test facility (Section 3) for characterizing the detector performance. First results on the detector performance for detecting electrons with energies above 10 keV are presented (Section 4).

2. Design of the detector system

2.1. Concept

The primary decision to be made in designing the electron detector is the choice of detection technique. A multi-pixel (segmented) silicon PIN diode was chosen since this is a relatively mature technology.

A modular assembly concept was developed that allows the adaptation of the detector system to different mounting conditions and facilitates replacement, repair and possible design changes to individual components. In this concept, the readout electronics is arranged in three groups:

- JFET front end stages mounted close to the detector chip on a cooled ceramics carrier.
- Main circuit board, located outside the vacuum, performing signal and power distribution and carrying a test pulser.
- Preamplifier sub-boards also containing low-noise power conditioning and cable drivers.

In the presented 64-pixel implementation of the detector concept, the detector chip is a large monolithic silicon PIN diode ($44 \times 44\,\mathrm{mm}^2$ including guard zone), which is segmented into 8×8 individual pixels. Each detector element has a junction capacitance of 16 pF when fully depleted (at a 20 V bias). The chip, which is manufactured by *Canberra* at Olen, Belgium, exhibits a dead layer of 100 nm. Fig. 1 shows a longitudinal section of the detector system.

The segmented PIN diode chip is softly clamped onto a liquid-nitrogen-(LN_2-)cooled ceramics carrier board by a stainless steel bezel which avoids mechanical stresses during thermal cycling. Cooling is done via a cold finger that is coupled to the ceramics through a solid copper ring. The ceramics board also accommodates a JFET source-follower stage for each detector element. This arrangement minimizes the size of the charge-sensitive nodes in order to reduce EMI noise, crosstalk, and microphonics—an important feature given the very small signal amplitudes—an 18 keV electron produces a charge of only about $5000\,e^-$ in the silicon p–n-junction. The source-follower configuration avoids the need of an additional charge-feedback signal line for each channel, thus reducing the required number of vacuum feedthrough pins. The low output impedance of these stages (approximately $60\,\Omega$) suppresses effectively EMI and crosstalk onto the detector signals on their way through the vacuum feedthroughs. This design is relatively insensitive to major changes to the mechanical arrangement which may increase the distance between detector chip and preamplifiers. Moreover, a high signal bandwidth is maintained ensuring acceptable timing accuracy.

A disadvantage of the source-follower front end stage is its voltage gain of <1. This leads to an overall amplifier noise which is dominated by the second stage (here: low-noise bipolar operational amplifier, $2\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$) instead of the front end stage. However, in the given setup, an assumed white voltage noise of $3\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ for the overall amplifier corresponds to an equivalent noise charge (ENC) of about $160\,e^-_{\mathrm{rms}}$, using a $\mathrm{CR(RC)}^4$-shaper with a shaping time of $\tau = 6\,\mu\mathrm{s}$. This yields an energy resolution of about 1.4 keV (FWHM) for electrons. Though not yet in accordance with the desired resolution, this was considered satisfactory for a first design. Moreover, first measurements show that in the current design microphonics are more critical to energy resolution than amplifier noise (see Section 4.2).

A second drawback of the source follower is the dependency of the charge-to-voltage conversion factor on the detector junction capacitance and, in case of resistive loads, the JFET transconductance. These restrictions however are alleviated by periodic recalibration, which will be done on the whole KATRIN spectrometer anyway.

Biasing of the JFET gates is done by $660\,\mathrm{M}\Omega$-resistors, which take up the leakage and signal currents of the detector elements. The front end stages are DC-coupled to maintain the option of monitoring the leakage currents and—at high irradiation levels—the signal currents. The ceramics carrier also accommodates PT-1000 temperature sensors and heating resistors to adjust the optimum operating temperature which lies between -100 and $-60\,^{\circ}\mathrm{C}$.

The buffered signals are connected to the vacuum feedthrough pins by an array of spring-loaded needles and appropriate connector bushings. The needle contacts allow an easy assembling/disassembling, avoid soldering, and exhibit a low thermal conductance.

On the ambient pressure side, custom-designed low-noise preamplifiers amplify the signals and drive $50\,\Omega$ cables. The amplifiers are located on individual sub-boards with two channels each, which are arranged in a radial pattern. This results in a high-density assembly which is well adapted to the 100 mm tube, into which the 64-pixel detector electronics is to be mounted. A circular-shaped main circuit board plugged onto the vacuum feedthrough pins distributes the signals and power to the preamplifiers and serves as a base for the sub-boards.