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High resolution gas ionization chamber in proportional mode for low energy applications

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ABSTRACT

The operation of the ETH gas ionization detector as a proportional chamber, where a secondary ionization avalanche is initiated between the Frisch grid and anode, was investigated for ions covering the mass range from H to ^{127}I. By amplifying the detector electron signal through secondary ionization, the limitations due to the sensitivity of the detector electronics are minimized. It could be demonstrated that in the energy range of a few hundreds of keV and below a proportional chamber clearly outperforms a conventionally used gas ionization detector. Protons below 10 keV were measured with a resolution better than 1.4 keV and a good linearity of the particle energy and detector signal was found in the energy range between 50 and 1000 keV. At higher energies almost no difference in resolution for the two operation modes could be found.

1. Introduction

The identification of energetic ions and precise determination of the kinetic energy are essential in accelerator mass spectrometry (AMS) and many ion beam analysis (IBA) experiments. In this context gas ionization chambers (GIC) represent very powerful instruments, which clearly outperform solid state detectors concerning radiation hardness and energy resolution for heavy masses [1–3]. The aim of this paper is to investigate the characteristics of proportional chambers for ions below 1 MeV and compare the performance with conventionally operated GICs.

1.1. Gas ionization chamber in ionization detection mode

In IBA and AMS experiments GICs are typically operated in the ionization detection mode, where electron ion pairs produced by the stopping of energetic ions are collected on electrodes by applying an electric field. A charge sensitive preamplifier integrates the current induced on the electrodes during the charge charrier drift (Shockley-Ramo theorem [4,5]) and the resulting signal amplitude corresponds to a measure for the energy loss of the particle.

Significant improvements in the detector performance have been achieved recently in the energy region of a few MeV and below [1–3,6–12]. Optimizing the performance of such a detector means that the ratio of the energy resolution and the detector pulse height (relative resolution $\delta E/E$) has to be minimized. Significant processes and contributions affecting this ratio are the energy loss and straggling in the entrance window, the electronic noise of the preamplifier, the fluctuation and yield of the ionization process, the charge collection efficiency and geometrical effects due to the spatial distribution of produced charge carriers in the chamber. Here only a very brief overview of these contributions and their importance will be given. A more detailed discussion can be found in [1,6].

1.1.1. Detector geometry and charge collection

In a simple detector design, where just two electrodes are placed in the gas volume to collect electron-ion pairs, the detector pulse height becomes sensitive to the position of the charge carrier production [13]. For this reason, a so-called Frisch grid is mounted in order to shield the anode from the ionization region [14]. In this way the electron signal pulse height becomes independent from the position of charge carrier, since the anode is shielded from positive ions and electrons ideally induce a signal on the anode just after passing the grid. The inefficiency of the shielding is thereby determined by the geometrical configuration of the electrodes and the grid (wire diameter and pitch), while the electron transport efficiency, which is limited by the optical transmission of the grid, has to be optimized by an appropriate choice of the field strength ratio above and below the grid [15].

1.1.2. Entrance window

The detector entrance window corresponds to a so-called dead layer, since the deposited energy does not contribute to the

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detector signal resulting in lower pulse heights. Heavy ions deposit thereby more energy in the detector window due to the Z^2 dependence of the stopping power, which contributes to the so-called 'pulse height defect' for heavy particles [1,6,16]. Due to the statistical nature of the energy loss process the resolution is affected by energy loss straggling. For heavy ions the relative contribution of the straggling to the total energy resolution increases. The window thickness also corresponds to a theoretical limit of the lowest detectable ion energy, which depends on the particle type and the window characteristics (material, thickness and homogeneity). Nowadays mostly silicon nitride membranes are used as detector entrance window, since they provide excellent homogeneity and high tear resistance even at thicknesses of a few tens of nm. For many GIC applications the energy loss and straggling in the silicon nitride entrance window contributes only marginally to the detector performance. A quantitative estimation of the energy straggling in silicon nitride can be performed using the Yang model [17,18].

1.1.3. Ionization of the gas

Energy loss in matter is a statistical process related to the interaction of energetic ions with the electronic (electronic stopping) and the nuclear or atomic (nuclear stopping) system of the target material [19]. Ionization of the target atoms corresponds thereby to one channel of energy loss among various others (electronic or vibrational excitation, etc.). The average energy needed to produce an electron ion pair w_i is therefore significantly higher than the minimal ionization energy of the gas particles. Isobutane for example, which is a frequently used detector gas, has an ionization energy of 10.6 eV, while w_i for protons amounts to 23 eV [13,14,20]. This number increases with the atomic number of the projectile leading to lower pulse heights for heavy ions, which is another aspect of the pulse height defect for heavy masses [1,16]. The variation of the charge carrier production is proportional to the square root of the energy, while the proportionality factor increases with the ion mass. For high projectile masses and light particles at high energies the detector resolution is essentially determined by the variation of the ionization process. Large angle scattering processes with gas particles lead to additional tailing in the energy spectrum. Therefore, a gas composition with low atomic numbers (as isobutane) is preferable.

1.1.4. Electronics

At low particles energies (<1 MeV) the number of produced charge carriers in a gas is only of the order of 10^3–10^4. As a consequence, the electronic noise of a charge sensitive preamplifier becomes a limiting factor for the energy resolution especially for light ions. Two sources for electronic noise can be identified, first leakage currents at the input FET (intrinsic noise) and second noise caused by the capacitance of the GIC (capacitive noise). By cooling the input FET with Peltier elements it was possible to obtain an intrinsic preamplifier noise level of less than 80 electron RMS [21]. Additionally, the detector designs were optimized with regard to capacitance resulting in significant improvements of the detector resolution for light ions below 1 MeV [1,6].

In terms of these effects and contributions the relative energy resolution can be expressed as

$$\frac{\delta E^2}{E^2} = \frac{\sigma_{gas}^2 + \sigma_{foil}^2 + \sigma_{el.}^2}{n_{pg.}^2} \tag{1}$$

where σ_{gas} is the variation of produced charge carriers during the ionization process, σ_{foil} the variation due to the energy straggling in the entrance window, $\sigma_{el.}$ the electronic noise, and $n_{pg.}$ the number of electrons passing the Frisch grid.

1.2. Proportional mode

Proportional chambers are used since many decades in nuclear and particle physics experiments for example as multi-wire detectors to track particle trajectories [22]. Charge carriers produced in the detector gas are drifting towards the collecting electrode forced by an electric field. During the drift electrons collide with gas particles. In a GIC operated in the ionization detection mode the energy loss and gain between two collisions approaches an equilibrium, which in a homogeneous electric field yields a constant mean drift velocity. If the energy of the drifting electrons reaches the ionization potential of the gas particles secondary ionization occurs leading to an ionization avalanche.

The mean amplification factor of the number of charge carriers increases thereby exponentially with the mean energy gained between two collisions and can be expressed as a function of the electric field strength normalized by the detector pressure, i.e. the reduced electric field E/p. Initially the detector signal remains proportional to the particle energy (proportional region) until the so-called Geiger-Müller region is reached, where the response of the detector becomes almost energy independent [13]. The mean electron amplification factor M in a proportional chamber can be determined by the first Townsend coefficient α [23,24], which expresses the strength of the electron multiplication depending on the gas type and the reduced electric field strength

$$M\left(\frac{E}{p}\right) = e^{\int_a^b \alpha\left(x, \frac{E}{p}\right) dx} \tag{2}$$

where a and b correspond to the starting and end point respectively of the electron drift path.

The variation of the multiplication process is determined by statistical fluctuations of the charge carrier avalanche [25–29] and the detector design, since the amplification factor strongly depends on the electrical field configuration. In cylindrical detectors for example a deviation of the electron avalanche from the exponential form is observed due to the inhomogeneity of the electric field towards the collecting anode wire [29–33].

In terms of the relative energy resolution for a GIC operated in the proportional mode Eq. (1) can be rewritten as

$$\frac{\delta E^2}{E^2} = \frac{\sigma_{gas}^2 + \sigma_{foil}^2}{n_{pg.}^2} + \frac{\sigma_{el.}^2 + \sigma_{mult.}^2}{M^2 \cdot n_{pg.}^2} \tag{3}$$

where $\sigma_{mult.}$ represents the fluctuations of the electron multiplication process and M the mean amplification factor of the electron multiplication process. The relative contribution of the ionization process and the energy straggling in the foil is not affected by the proportional operation mode, since both the detector pulse height as well as the variation of these two effects are amplified by the same factor. But, the significance of the electronic noise for the energy resolution declines for increasing M since the absolute level of electronic noise is constant and the electron signal is amplified before the electronic processing. So, the effect of the electronic noise to the detector performance can be virtually neglected at higher amplification factors. On the other hand, the variation of the avalanche process has to be considered, which is in a homogeneous field configuration dominated by statistical fluctuations. An improvement in the energy resolution compared with a conventional GIC is achieved if the following condition is fulfilled

$$\frac{\sigma_{mult.}^2}{M^2 - 1} < \sigma_{el.}^2 \tag{4}$$

Previous experiments operating GICs as proportional chambers for the detection of carbon ions were very promising [7,34]. Motivated by these results it is the aim of this paper to investigate the operation of the ETH GIC [6] as a proportional chamber, where the