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Gas Gain Study for CO_2/Isobutane Mixtures

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Abstract

We have studied gas amplification properties of a proportional tube filled with CO_2/Isobutane gas mixtures. The gas gain was measured for X-rays and β-rays as a function of the anode-wire surface field and was used to estimate gain variation along 4.6 m-long stereo anode wires of our proposed central drift chamber for JLC. During the gas gain study, we observed a strong saturation effect for point ionizations.

1 Introduction

In the course of generic R&D's for detectors at the future linear e^+e^- collider (JLC), feasibility of a large cylindrical drift chamber with mini-jet cells is under serious studies [1, 2, 3, 4] for its central tracker. In the present design, the central drift chamber (CDC) is required to have inner and outer radii of $R_{in} = 45$ cm and $R_{out} = 230$ cm, and a length of $L = 460$ cm with an r-ϕ resolution better than 100 μm over the maximum drift length of 50 mm. In order to achieve such a high resolution over such a large sense volume, we chose a CO_2(90%)/Isobutane(10%) gas mixture, taking into account its small diffusion coefficient and small Lorentz angle under a magnetic field as strong as 2 T.

Up to now, this gas mixture has been primarily used in relatively small but high-precision drift chambers to measure decay vertices of short-lived particles [5]. Our concern here is any possible problem induced by the size of the chamber, in its operation with this gas mixture. Stable chamber operation becomes difficult, if there is any significant gas gain variation along sense wires. There is an unavoidable source of such gain variation in our present design of the CDC, which is the existence of stereo super-layers for z coordinate measurements [3].

Any stereo cell belonging to a stereo super-layer has a cross-sectional size which varies along its sense wires, and this cell deformation is determined, once its stereo angle is given. We can see this by imagining that the introduction of any stereo angle deforms an otherwise cylindrical mantle of a stereo wire layer into a hyperboloidal surface. The cell size is thus minimum at the center of the cylinder length. This geometrical deformation of the cell changes the surface fields of the sense wires, thus induces some variation of the gas amplification factor along the wires. It is, therefore, vitally important to know the magnitude of the gain variation along the stereo sense wires for stable operation of the chamber.

We have proposed a general procedure to decide the stereo angles of individual super-layers and to design the super-layer layout in reference [3]. The main purpose of this paper is thus to supplement this reference by providing experimental background. In addition to the gas gain stability issue, also important is the proportionality in the gas amplification process for this gas mixture, in particular when one wants to use dE/dx information for particle identification: any output signal is desired to be proportional to its corresponding primary ionization. In the CO_2/Isobutane gas mixture, however, some strong gain saturation effect is expected due to its small diffusion coefficient. In order to evaluate to what extent we can use the signal charge information for the dE/dx measurement, detailed knowledge on the saturation properties is essential.

In this paper we study the gas amplification properties of CO_2/Isobutane gas mixtures as a function of the sense wire surface field for inonizations due to X-rays and β-rays. The paper is organized as follows: in section 2 we begin with a brief explanation of our experimental apparatuses including a single-wire proportional tube. Since the gas amplification is a local process near a sense wire where the electric field is symmetric, the gas amplification properties are expected to be the same for both the single-wire tube and the mini-jet cell type drift chamber[1], provided that their high voltages are adjusted to produce the same surface field. In section 3 we thus describe our measurements with the single wire tube, for which various analytical formulas are available and data analyses are easier. The validity of the measurements is also demonstrated in this section by comparing our results for a reference gas mixture of Ar(90%)/CH_4(10%) with existing data. Implications of these results to the chamber design and operation are discussed in section 4.

2 Experimental Apparatus

2.a Single-wire proportional tube

A single-wire proportional tube was prepared for general gas gain measurements under various conditions. As shown in Fig.1, the tube consists of a 110 mm-long aluminum cathode cylinder with an inner diameter of 10 mm and a 30 μm-thick anode sense wire made of gold-plated tungsten.

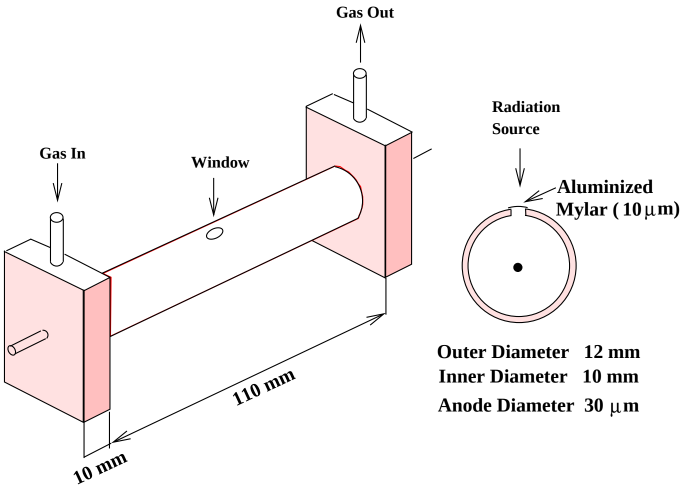

Figure 1: Single-wire proportional tube.

The cross-section of the tube was chosen so as to simulate the electric field around a sense wire of the proposed mini-jet cell type drift chamber at approximately the same anode high voltage. The aluminum cathode has a 10 μm thick aluminized Mylar window with a diameter of 5 mm to inject ionizing particles.

The electronics system used for the gas gain measurement is shown in Fig.2. We used an EGG & ORTEC charge-sensitive preamplifier, Model 142H, and a spectroscopy amplifier, Model 672. The shaping time constant is 1.0 μs, during which more than $\sim$ 50 % of the total signal charge is expected to be collected at the electrodes. The output pulse amplitude from the spectroscopy amplifier is analyzed by a LeCroy qVt, Model 3001. We calibrated the electronics system with a charge impulse injected through an 8 pF capacitor. The qVt channel number is plotted as a function of the input charge in Fig.2.

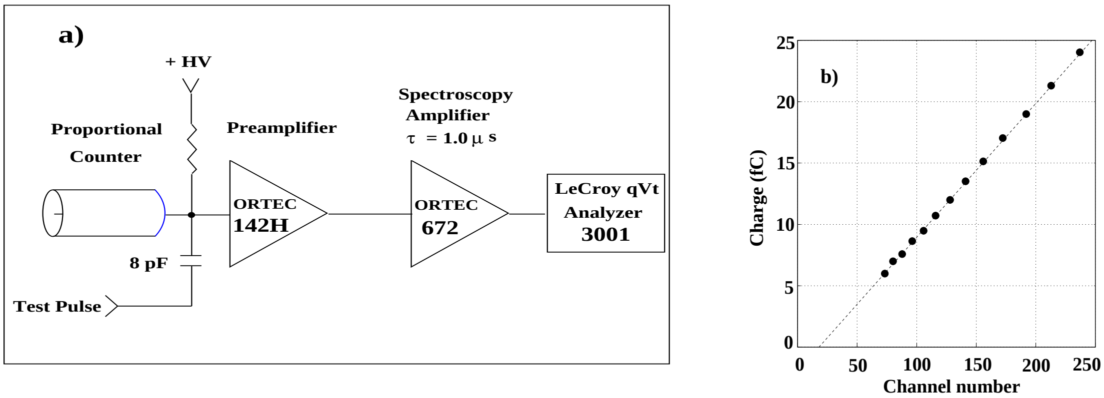

Figure 2: Block diagram (a), and calibration data (b) for the gas gain measurement electronics system. The calibration data is for the amplifier gain of 500.

2.b Gas system

In this experiment, gas gain was measured for two kinds of gas mixtures: P10 gas, namely a pre-mixed mixture of Ar(90%)/CH_4(10%) and mixtures of CO_2 and Isobutane. These gas mixtures were flushed through the tube at flow rates of 50 to 200 cc/min. As for the CO_2/Isobutane gas mixtures, high purity CO_2 and Isobutane gases were mixed at a desired ratio by adjusting their flow rates with mass controllers (STEC, Model SEC-400MK2). The resultant relative accuracy of the Isobutane concentration was 1%.

2.c Radiation sources

The basic gas gain characteristics is measured with ^{55}Fe X-rays (5.89 keV). In order to study the gas properties for charged particles, we have used ^{90}Sr β-rays (2.283 MeV max). The β-rays are collimated by an aluminum plate with a 5 mm-diameter hole so as to limit the β-ray injection angle. Therefore the track length in the gas volume is close to the tube diameter.

3 Measurements and Results

3.a Calibration with Ar(90%)/CH_4(10%) gas mixture

First, we have measured the gas gain for the P10 gas mixture Ar(90%)/CH_4(10%) as an overall calibration of our gas gain measurement system. Typical pulse-height spectra for ^{55}Fe X-rays at anode high voltage of 1.5 kV are shown in Fig.3.

We can clearly see two peaks, corresponding to the total-absorption peak (5.89 keV) and the escape peak (2.93 keV). There exists a third peak at about 25 % of the main peak

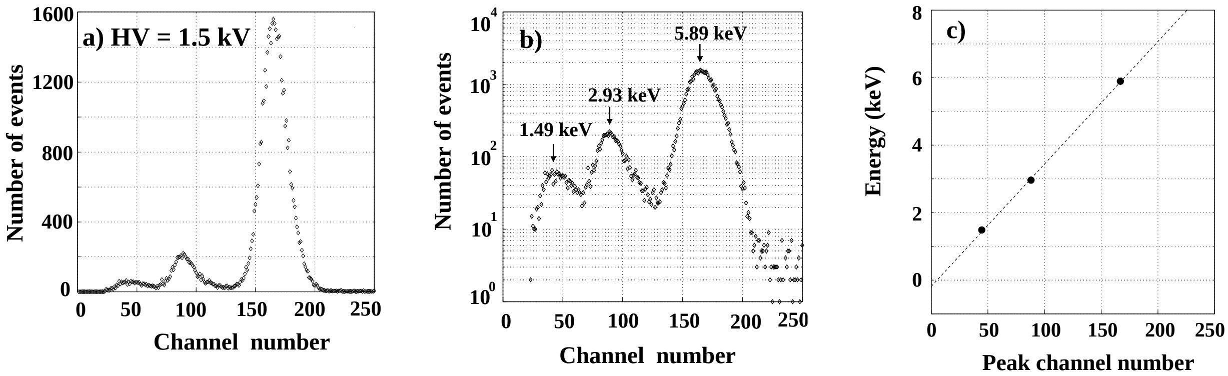

Figure 3: Pulse-height spectra for ^{55}Fe X-rays with the Ar(90%)/CH_4(10%) mixture at HV=1.5 kV: (a) in a linear scale, (b) in a logarithmic scale, and (c) energy deposit as a function of the peak channel number.

as shown using a logarithmic scale in Fig.3. The relative intensity of the third peak is about 1 % of the main peak. We speculate that this peak corresponds to a characteristic X-ray of Al (1.49 keV) originating from the aluminized Mylar window that absorbed a 5.89 keV X-ray photon.

Solid circles in Figs.4-(a) and (b) are the relative width of the main peak and the ratio of the escape peak to the main peak, respectively, as a function of the high voltage. On the other hand, the open circles in Fig.4-(b) are the ratio of the third peak to the main one. In the proportional region, these ratios should stay constant. Any upward deviation

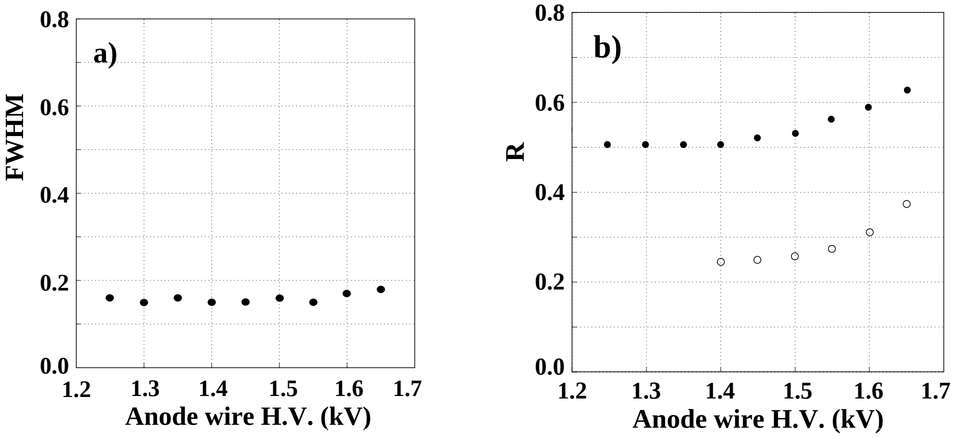

Figure 4: (a) resolution of the main peak and (b) pulse-height ratios (R) of the escape peak (•) and the third peak (○) to the main peak, as a function of the anode wire high voltage.

from this value signals onset of gas gain saturation, and is accompanied by degradation of the energy resolution. The figure indicates that the proportional region extends up to a high voltage value of around 1.5 kV. The energy resolution in the proportional region is about 15%(FWHM), as is typical for this type of tubes.

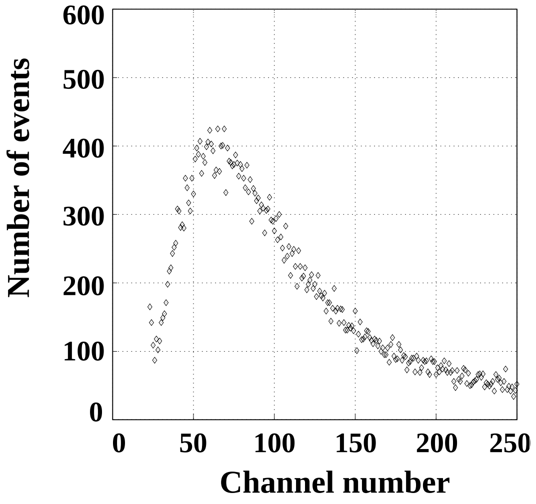

Figure 5: Pulse-height spectra for β-rays with the Ar(90%)/CH_4(10%) mixture at the HV of 1.5 kV.

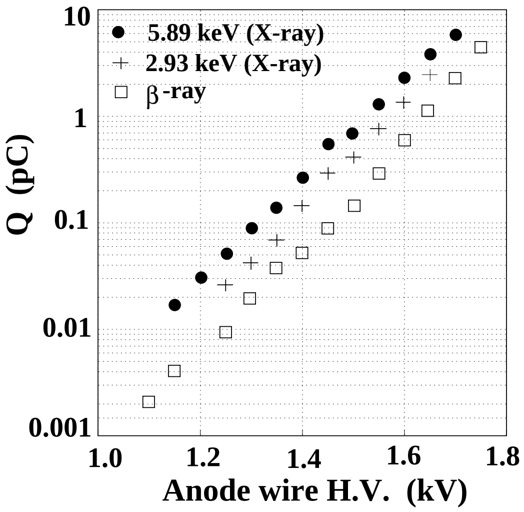

Figure 6: HV dependence of the charges collected in 1.0 μs with the Ar(90%)/CH_4(10%) mixture.

The pulse-height spectra for β-rays are shown in Fig.5. In the proportional region, the pulse-height spectrum has a typical Landau distribution. Its peak value is 2.5 keV, which is consistent with the expected energy loss.

The high voltage dependence of the collected charges within 1 μs is plotted in Fig.6 for X-rays and β-rays. The slopes are different for different ionizations, which might be attributed to the difference in ionization densities. A 5.89 keV X-ray photon is absorbed by an Ar atom via photoelectric effect, emitting a 2.93 keV electron. The range of this electron in the Ar gas at 1 atm is about 100μm. The ionization density is thus estimated to be 294 keV/cm. On the otherhand, a minimum ionizing particle loses its energy in the Ar gas by 2.44 keV/cm, which is a factor of 100 less. Consequently, the gas gain saturation is expected to start at higher high voltages than in the case of X-rays.

3.b CO_2/Isobutane gas mixtures

We made the same measurements as described in the previous section for the CO_2 / Isobutane gas mixtures. Typical pulse height spectra for X-rays are shown in Fig.7. In these gas mixtures, X-rays are absorbed by a C or O atom through photoelectric effect. The absorption cross section is rather small compared to the Ar case because of their lower atomic numbers. By the same token, the energies of characteristic X-rays from the C or O are rather small: 0.28 keV and 0.52 keV, respectively. The pulse height spectra are thus dominated by a single peak corresponding to the total energy and there is no escape peak unlike the P10 case.

There is, however, an additional peak in the low-energy region. This peak corresponds to characteristic X-rays from Al as with the third peak we saw in the case of the P10 gas. The observed spectra for the CO_2/Isobutane gas mixtures at higher voltages

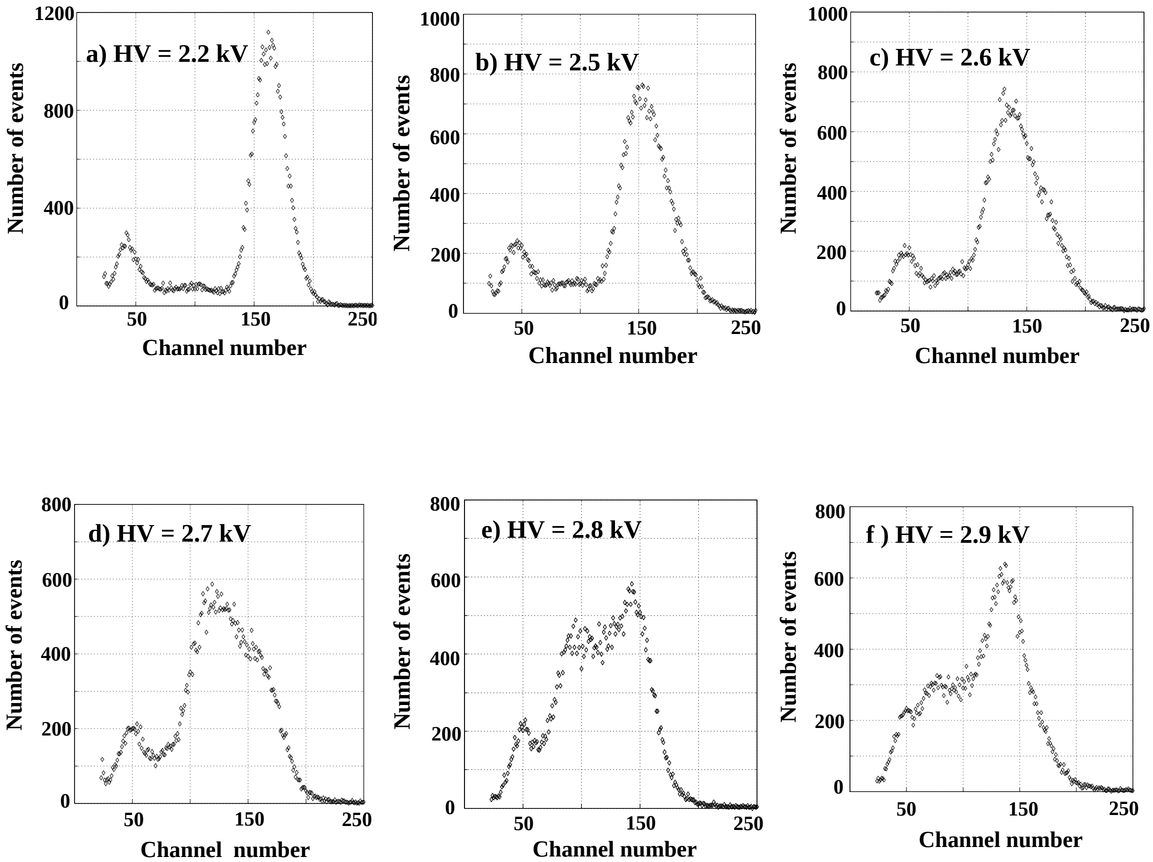

Figure 7: Pulse-height spectra for ^{55}Fe X-rays with the CO_2(90%)-Isobutane (10%) mixture. Six spectra are obtained at HV's of (a) 2.2 kV, (b) 2.5 kV, (c) 2.6 kV, (d) 2.7 kV, (e) 2.8 kV, and (f) 2.9 kV. The gain of the electronic system is adjusted for each measurement so as to keep the whole spectrum within the ADC dynamic range.

are quite different from those of the P10 gas and the difference becomes more and more prominent as the applied high voltage increases. In the proportional region, the width of the main peak is comparable to the P10 case. As the voltage approaches 2.6 kV, a hint of yet another peak appears, which becomes dominant at 2.9 kV. These facts show that the gas amplification mechanism will change at a certain voltage. This transition, in some cases (depending on gas mixtures, anode radius, etc.), results in sudden avalanche size change as large as a factor of 10 and is known as onset of the limited streamer mode[6]. But, in this case, the step is only a factor of 2.

Fig.8-(a) plots the FWHM of the main peak, while Fig.8-(b) shows the pulse-height ratio between the second peak (1.49 keV) and the main peak (5.89 keV), as a function of the anode wire high voltage for the CO_2(90%)-Isobutane (10%) mixture. The ratio stays constant up to about 2.5 kV, indicating that we are in a proportional mode there. It should also be emphasized that the ratio is quite consistent with those for the P10 gas

(open circles below 1.5 kV in Fig.4-(b)).

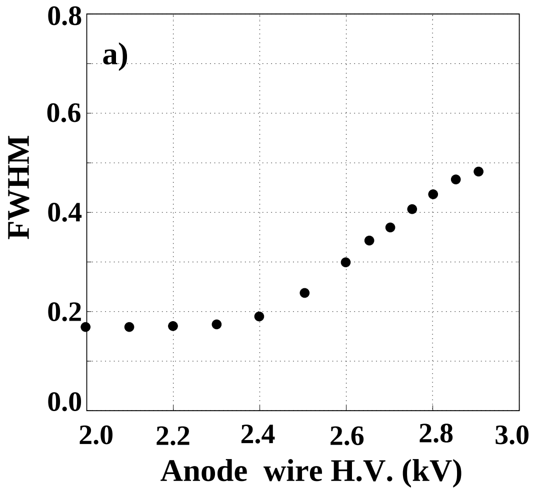

Figure 8: (a) resolution of the main peak and pulse-height ratio (R) between the second (1.49 keV) peak and the main (5.89 keV) peak as a function of the anode wire HV for the CO_2(90%)-Isobutane (10%) mixture.

Although the spectrum shows very broad and irregular distribution, we took the mean value for the collected charge. The spectra for β-rays are not so different compared to the P10 case and are shown in Fig.9. The collected charge is plotted in Fig.10 as a function of the applied high voltage for X-rays and β-rays.

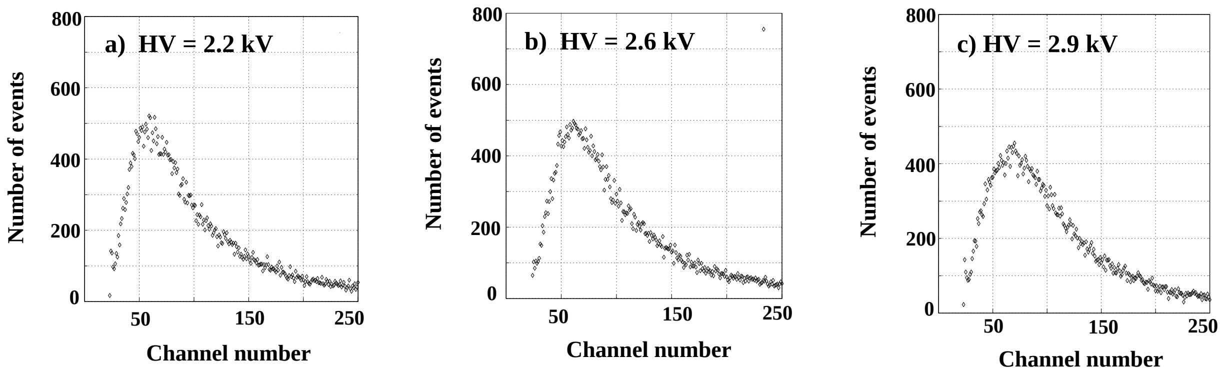

Figure 9: Pulse-height spectra for β-rays with the CO_2(90%)-Isobutane (10%) mixture at the HV's of (a) 2.2 kV, (b) 2.6 kV, and (c) 2.9 kV.

Gas gain measurements for different Isobutane concentrations (5%, 10%, and 15%) have been made. The results for X-rays are shown in Fig.11. There is no big difference observed in the pulse-height spectrum. The gas gain increases as the Isobutane concentration becomes bigger.

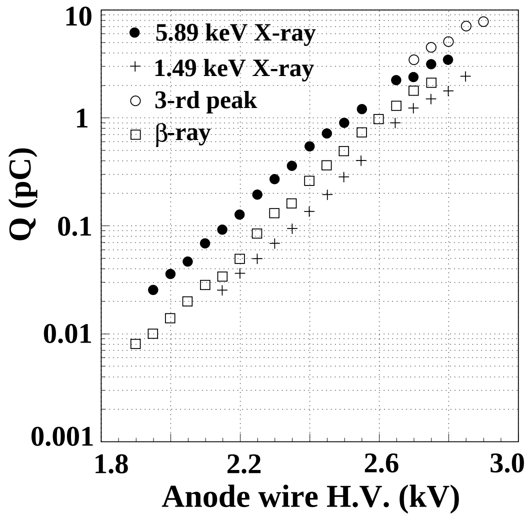

Figure 10: Anode wire high voltage dependence of the charges collected in 1.0 μs for X-rays and β-rays with the CO_2(90%)-Isobutane (10%) mixture.

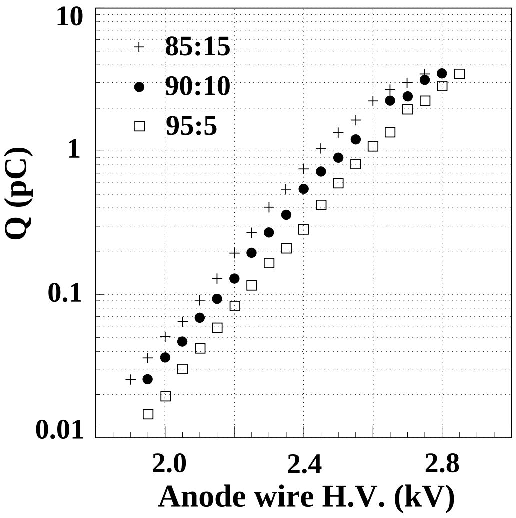

Figure 11: HV dependence of the charges collected in 1.0 μs for X-rays with three different concentrations of the CO_2/Isobutane mixture.

3.c Gas gain as a function of the sense-wire surface field

In order to calculate the gas gain as a function of the applied high voltage, we used the X-ray data as a reference. The number of primary ion-pairs can be calculated from the energy deposit and the mean ionization energy of 26 eV for the P10 gas and 32 eV for CO_2/Isobutane. The number of primary electrons for the 5.89 keV X-ray is calculated to be 227 in P10 and 184 in CO_2/Isobutane and the corresponding charge is 3.6×10^{-2} fC and 3.0×10^{-2} fC, respectively. The gas gain is defined here as the ratio between the collected charge within 1 μs and the primary ionization charge. The gas gain results are shown as a function of the high voltage in Fig.12.

For comparison with different chamber geometries, the horizontal axis is also shown in terms of the surface field E of the anode wire in addition to the applied high voltage. The surface field E is calculated as $E = k \cdot V$, where $k = 1/a \cdot \ln(b/a)$=114.9 [cm^{-1}] and V is the applied high voltage of the anode wire.

In order to compare the present results with the previous measurement, we fitted the gas gain data based on the Diethorn formula, Eq.3.1:

$$\ln G = \frac{\ln 2 \cdot V}{\ln(b/a) \cdot \Delta V} \cdot \ln \frac{V}{\ln(b/a) \cdot a \cdot E_{min}(\rho_0) \cdot (\rho/\rho_0)}, \tag{3.1}$$

where V is the applied voltage, a and b are the anode and cathode radii, ρ_0 is the normal gas density. ΔV is the average potential required to produce one more electron in the gas and E_{min} is the minimal field needed for electron to be multiplied. The parameters ΔV and E_{min} depend only on the gas mixture. The previous results for the P10 gas

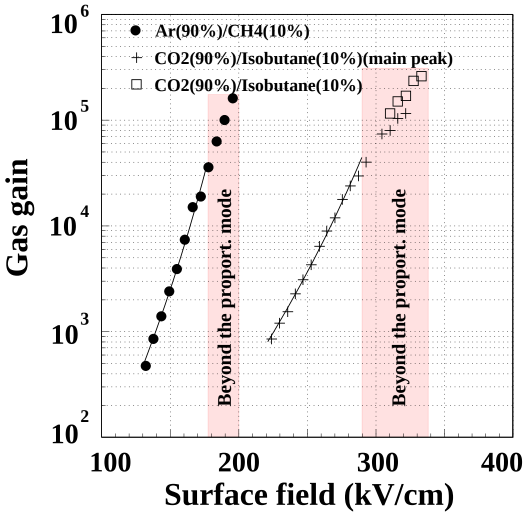

Figure 12: Gas gain as a function of the surface field for the Single Wire Tube with the CO_2(90%)-Isobutane (10%) gas mixture.

measured by Wolff [7] are shown by the curve fitted with parameters ΔV= 23.6 V and E_{min} = 48 kV/cm. The agreement between the present results and the their results is reasonably well. When we fit our data with the above formula, we obtained ΔV= 27.8 V and E_{min} = 37 kV/cm for the P10 gas and ΔV= 38.3 V and E_{min} = 74 kV/cm for the CO_2/Isobutane mixture.

4 Discussions

4.a Stereo-angle determination

In the course of designing the stereo-wire geometry for a long cylindrical drift chamber, we found some unavoidable geometrical deformation of drift cells, depending on the stereo angle[3]: the size of any stereo cell shrinks as we move away from endplates and attains its minimum at the middle of the wires. Accordingly the anode surface field varies and becomes maximum there. If we set the acceptable gain variation along the anode wires at a certain level, we can determine an upper limit on the stereo angle. Needless to say, the best spatial resolution in the z-direction can be obtained with the maximum allowable stereo angle.

The measured data on the gain variation as a function of the surface field are fitted in Fig.12 to the following empirical formula:

$$\ln Q = a + bE_0, \tag{4.2}$$

where a and b are the parameters to be determined. From these data, we can obtain the following relation:

$$\frac{\Delta Q}{Q} = (15 \sim 20)\left(\frac{dE_0}{E_0}\right) \tag{4.3}$$

around $E_0 \simeq 300$ kV/cm, where the gas gain is about $10^4 \sim 10^5$. If we set the gas gain variation along the wire to be less than 15%, the maximum alowable surface field variation is 0.8 %. This can be achieved with a reasonable stereo angle of 60 - 120 mrad depending on the radial wire position.

4.b Saturation effect

We observed a strong saturation effect for the CO_2/Isobutane gas mixtures. However, this signal charge saturation is accompanied by onset of a new gas amplification mechanism that compensates it. Therefore, the net effect turned out to be rather smooth as a function of the applied voltage.

In the real JLC CDC operation, we want to measure dE/dx for charged particles. Because of their smaller primary ionization densities and longer drift distances, the saturation effect may be less serious than in the case of X-ray ionizations. Nevertheless, to what extent we can use the pulse height information for particle identification is still an open question and requires further studies. The saturation effect might also play a complex role in the signal formation process, which should be carefully studied if one wants to use the pulse shape information as recorded with flash ADC's as is expected for future JLC experiments.

In order to test the particle identification capability with this gas mixture through dE/dx measurements, we are planning to make a beam test using momentum-analyzed e, π, and p beams at the 12 GeV proton synchrotron at KEK.

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