Irradiation response of straw drift tubes

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Drift tubes filled with $Ar/CF_4/CO_2$ (74:20:6) were exposed to 26 MeV proton beams from the Munich Tandem accelerator to study the radiation effects and operation charateristics expected for the COMPASS experiment at CERN. Stable operation with no significant loss of gain and no significant Malter current was observed up to charge accumulations of 1.1 C/cm. For comparison, with Ar/CH_4 (90:10) the same detectors show a 23 % loss of gain and large Malter currents under the same irradiation condition. For $Ar/CF_4/CO_2$ a thin (< 0.1 μm) surface layer is observed by means of SEM on the anode wire in the irradiated detector section. As revealed by an ERDA study, the prominent components of this layer are C, O and Si.

1. Introduction

The COMPASS experiment at CERN is devoted to studies of the proton's spin structure and of hadron structure [1]. It uses μ, p or π beams with typical intensities of 100, 50 and 5 MHz, respectively. Typical energies are 100 GeV for μ and 40 GeV for hadrons. Straw detectors are used for large-area tracking. Because of the high rates, e.g. 5 x 10^4 Hz/cm^2, in the μ beam halo at the position of the inner straws, aging is a concern. At a gas gain of 10^5 (or 2 x 10^4) in 4 (or 20) years of the experiment, the charge accumulated in the inner straws is estimated to amount to 1 C/cm, which sets the goal for the present aging studies.

In the COMPASS experiment, straws of 3.2 to 3.7 m length and of 6 mm or 10 mm diameter are used. In the center of each straw layer, the beam passes through a physical hole. A 25 μm layer of carbon-loaded Kapton forms the inner layer of the straws. The anode wire of 30 μm diameter is made from W (+Re) and is plated with Au [2]. The chamber gas is a mixture of Ar, CF_4 and CO_2. Three double layers of straws were operated successfully in the commissioning run of COMPASS in the year 2001. The first-stage magnetic spectrometer will finally house 18 double layers with 13800 straws in total [3–5].

2. Method

Proton beams from the Munich Tandem accelerator were used to study the aging properties of straw drift tubes (Fig.1), operated with $Ar/CF_4/CO_2$ (74:20:6). The irradiated straw prototypes had a diameter of 8 mm. At the chosen energy of 26 MeV the proton energy loss amounts to an average of 16 keV per straw, corresponding to 700 electrons from primary ionization, which is about a factor of 7 larger than for 100 GeV muons.

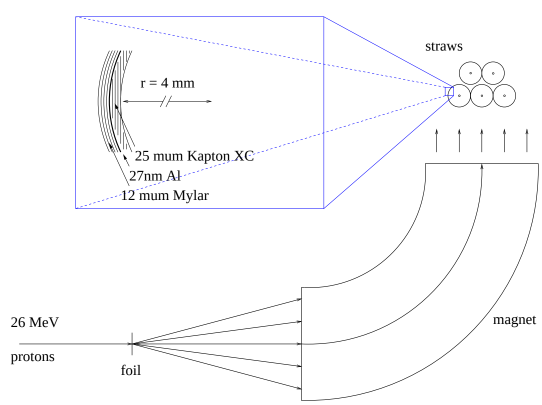

Figure 1. Set-up of the irradiation experiments.

A medical irradiation facility [6] with a vertical beam line, broad homogeneous beam profiles, and precise dosimetric control was available for these experiments. The irradiation flux was measured with a scintillation counter and an ionization chamber. The accumulated charge was measured with an electric current integrator.

Two irradiation experiments, each of 4 days duration, were carried out with consistent results for two samples of straw detectors, each of the above type [7]. At the chosen gains of (2-4) x 10^4, particle rates of (2-4) x 10^6 Hz/mm^2 were required to achieve total charge doses of about 1 C/cm. In order to accumulate this charge within a reasonable time scale at hadron accelerators, strongly enhanced rates, as compared to the real experiment, become inevitable. Therefore, close imitation is virtually impossible for hadrons. To overcome this problem, we have taken care to keep the gas gain at realistic values. This was achieved by increasing the anode voltage such that the monitored gas gain maintained the nominal value. In this way, space charge effects due to the high rates were compensated. The applied voltages were between 1950 V and about 2500 V.

Sections of 4 cm length of the tested straw detectors, with total length 80 cm and diameter 8 mm, were exposed to the homogeneous proton flux. The standard gas mixture was $Ar/CF_4/CO_2$ (74:20:6) at 1 atm and room temperature. In one case a gas mixture of Ar/CH_4 (90:10) was used to compare the performance with that of the above COMPASS gas mixture. The gas circuit consisted of Rilsan tubes with some connection pieces made from Cu.

3. Aging effects

3.1. Gas gain

No significant loss of gas gain G was found in two separate experiments with the standard gas mixture after accumulating total charges of 1.1 C/cm. Fig. 2 compares pulse height spectra measured with an ^{55}Fe source before and after irradiation. The peak from 5.9 keV X-rays is used as an indicator of the gas gain. It shows no shift after irradiation. From a Gauss fit we deduce a 2 σ value of the relative loss of gas gain:

$$\Delta G/G \leq 1\% \text{ per } 1.1 \text{ C/cm}. \quad (1)$$

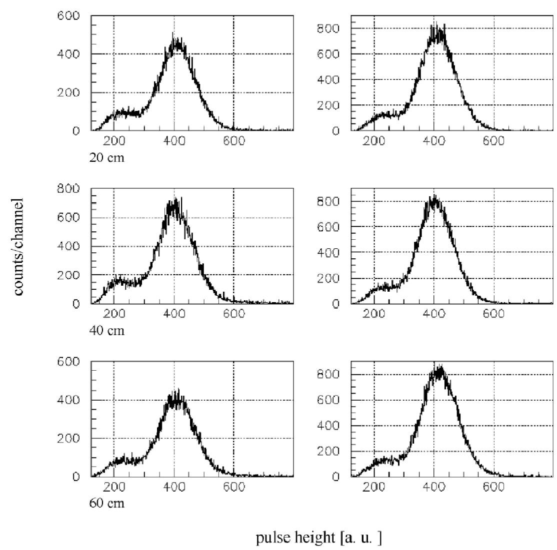

Figure 2. Pulse height spectra for an ^{55}Fe source, recorded with a straw detector at 1800 V filled with $Ar/CF_4/CO_2$ (74:20:6) before irradiation (left column) and after proton irradiation leading to an accumulation of Q/l = 1.1 C/cm (right column). The peak is due to 5.9 keV X-rays. The homogeneously irradiated straw section of 4 cm length was centered at 40 cm from one straw end (middle row). The upper and lower rows show spectra recorded in non-irradiated sections.

As demonstrated in Fig. 3, the aging performance of Ar/CH_4 (90:10) is drastically different, yielding

$$\Delta G/G = 23\% \text{ per } 1.1 \text{ C/cm}. \quad (2)$$

This value is in line with other test experiments [8]. For comparison, straws filled with the standard gas mixture show no loss of gain, also in this irradiation experiment (Fig. 3) reproducing

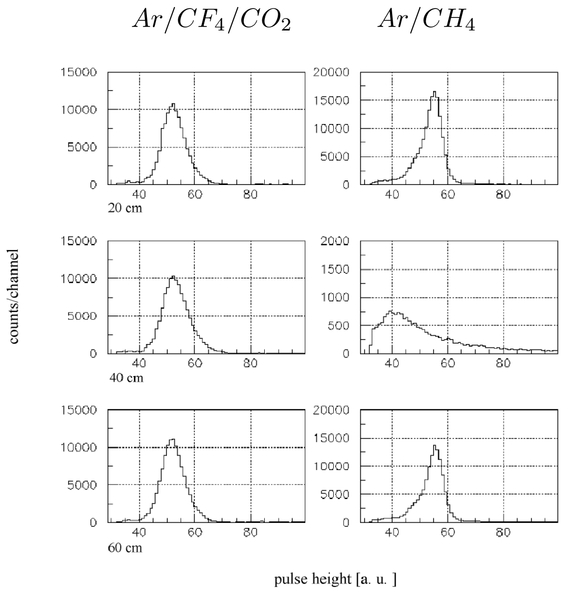

Figure 3. Comparison of pulse height spectra for an [55]Fe source recorded with irradiated straws (Q/l = 1.1 C/cm) filled with $Ar/CF_4/CO_2$ (74:20:6) and Ar/CH_4 (90:10) (left and right column, respectively). The measured positions of the 5.9 keV X-ray peak agree with those recorded before irradiation for $Ar/CF_4/CO_2$, but not for Ar/CH_4 in the irradiated section of 4 cm length at 40 cm (middle row), indicating the loss of gain discussed in the text.

the above value of $\Delta G/G \leq 1\%$.

The gas exchange rate in these experiments was about 1 detector volume per hour. However, one straw was operated as a dead end of the $Ar/CF_4/CO_2$ circuit, with an exchange rate much less than 0.1 detector volume per hour. No significant loss of gas gain was also observed in this particular case, with irradiation conditions as above.

In the course of the latter experiment, we have also measured the gas gain as a function of voltage (Fig. 4). These data serve as an empirical base for adjustment of the operation parameters for the COMPASS gas mixture, which contains a component (CF_4) with rather large electron attachment. In these particular measurements, the influence of space charge effects was eliminated by reducing the incoming flux until a plateau of the gas gain was reached, consistent with a constant value. The gas gain was determined directly from the measured integrated electrical current I and the incoming proton flux Φ according to

$$G = \int_0^{t_1} I \cdot dt \cdot \left[\int_0^{t_1} \Phi \cdot A \cdot Q_i \cdot dt \right]^{-1} \qquad (3)$$

where t_1 is the irradiation time, A = 40 mm x 8 mm is the irradiated area of one straw and Q_i is the primary ionization charge of about 700 e averaged over A.

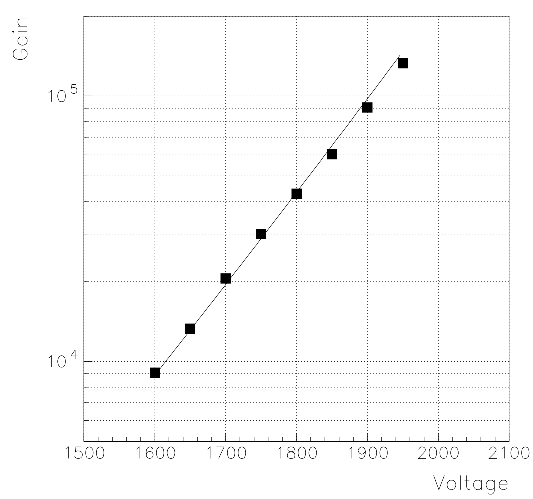

Figure 4. Gas gain for $Ar/CF_4/CO_2$ (74:20:6) at T = 293 K, P = 1 atm as a function of voltage, determined at a low proton rate as explained in the text.

3.2. Malter current

Irradiation-induced formation of cathode layers and resulting Malter currents have been known for a long time [8]. The currents are due to the accumulation of positive ions as a result of formation of high-resistivity films on the cathode surface. The ions induce field emission of electrons through the insulating layer. In our experiments with Ar/CH_4 (90:10), Malter current becomes evident by an increase of the anode current during irradiation with a constant proton flux (Fig. 5). The above interpretation is supported by the characteristic behaviour of self-sustained Malter current. After switching off the proton beam, an appreciable Malter current I_M was observed, and after switching the voltage off and on again, after a few minutes, the current increased gradually over a period of about 120 min from a value close to zero to I_M. Probably remnant activity in the counter played a role in the restoration of I_M.

In contrast to the Ar/CH_4 mixture, no significant Malter current occurred with $Ar/CF_4/CO_2$ (Fig. 5) during the full charge accumulation of 1.1 C/cm. Also, no significant increase of dark current was found, as compared to the non-irradiated detector.

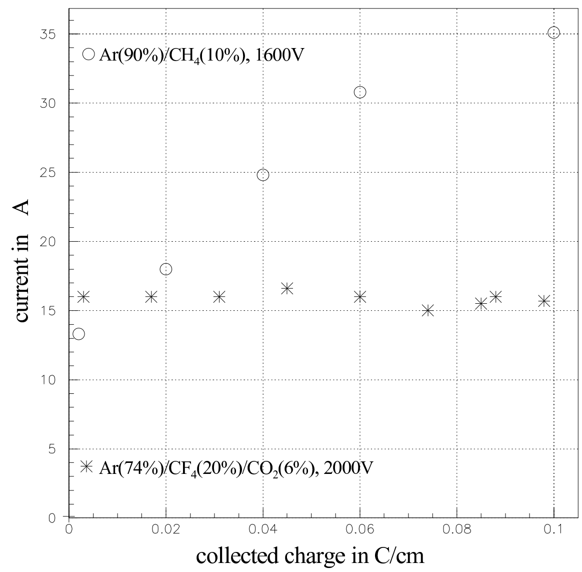

Figure 5. Current I during irradiation with protons of constant flux ($1.7 \times 10^7/(cm^2 \times s)$). The current is consistent with a constant value for $Ar/CF_4/CO_2$, U = 2000 V. The increase of I observed for Ar/CH_4, U = 1600 V is ascribed to Malter current.

3.3. Surface material modifications

Inspection of anode wire and cathode with a light microscope revealed inhomogeneous deposits and needles on both, and in addition droplets and rings on the anode, in the irradiated zone of the detector operated with Ar/CH_4 (90:10). Typical dimensions of the needles and droplets are 10-20 μm after collection of 1.1 C/cm [5].

For the $Ar/CF_4/CO_2$ mixture, no modification of the cathode surface, but a dark redish pigmentation of the anode wire was recognized with the light microscope. With a scanning electron microscope (SEM), a scaly deposit became visible on the anode. Inspection of the non-irradiated wire [2] revealed a variety of spots, where the Au layer was peeled off. Their diameters ranged up to 5 μm. These spots should be considered as potential nuclei of radiation damage.

The thickness of the deposits produced by irradiation is in a range that is not harmful for detector operation. From our SEM observations we can deduce an upper limit of $\Delta R < 0.1\ \mu m$ for Q/l = 1.1 C/cm. The corresponding upper limit for the change of field strength due to the anode wire deposits is in accordance with the upper limit for the change of gas gain given in eq. (1).

To find out which atomic elements contribute to the anode wire deposit, we peformed an elastic recoil detection analysis (ERDA) with 200 MeV Au ions from the Munich Tandem accelerator. The Au beam was directed on a piece of wire and the recoils from elastic scattering were detected at $\Theta_{lab} = 37^0$, corresponding to backward angles in the center-of-mass system, using a segmented ionization chamber that provided ΔE and E signals for particle identification[9]. In a plot of ΔE versus E, the relative abundances of light elements become visible (Fig. 6).

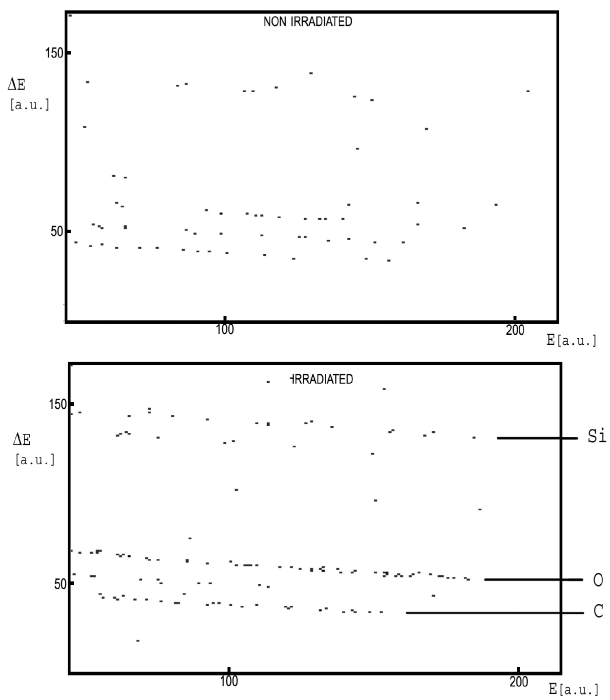

Figure 6. Elastically scattered recoils from the bombardment of wires from the non-irradiated and irradiated detector sections, respectively, of the aging experiments. The differential energy loss ΔE and the residual energy E of the ions are measured with different segments of an ionization chamber. The plotted range of E averages over roughly 0.5 μm penetration depth of the Au ions in the wire.

For a piece of wire that was not exposed to the proton beam (upper panel of Fig. 6), the branches recognized in the ΔE-E plot can be attributed to the elements C, N, O, and Al (from bottom to top). For a piece of wire that was irradiated with protons in the experiments described above, the relative abundances of C and O with respect to N, and of Si with respect to Al are apparent in the ΔE-E plot(lower panel of Fig. 6). As compared to the non-irradiated wire, it is found that C, O, and Si are the dominant components of the radiation-induced deposit.

4. Conclusion

Straw drift tubes made from Kapton XC, operated with $Ar/CF_4/CO_2$ (74:20:6), show no significant change in gas gain and dark current, and only a small, tolerable modification of the anode wire surface after collection of 1.1 C/cm in our proton irradiation experiments. In contrast, considerable losses of gas gain, Malter currents, and structured deposits were observed when the same detectors were operated with Ar/CH_4 (90:10) under the same irradiation conditions.

5. Acknowledgement

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