LHCb-MUON 2004-029
22 April 2004

Extensive aging test of two prototypes of four-gap MWPC for the LHCb Muon System

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Abstract

We present the results of an aging test on two prototypes of four-gap MWPC designed for the LHCb Muon System. The test was carried out with a ^{60}Co source, the Calliope gamma facility at ENEA-Casaccia Research Center, near Rome. We monitored the currents in the two chambers under test and in a similar chamber used as a reference.

Over a period of thirty days, we integrated a charge up to 440 mC/cm of wire in the chamber in gas open mode, equivalent to 4.6 LHC years (in region M1R2), without any appreciable deterioration of the detector gas gain.

1 Introduction

In this note we report the results of an aging test of two prototypes of Multiwire Proportional Chamber (MWPC), designed for the LHCb Muon System and built at the INFN Laboratories in Frascati. The goal of the test was to prove that the performances of these detectors are not deteriorated by the large radiation dose expected in the experiment in several years of operation.

The test was carried out with the ^{60}Co source of the Calliope γ facility at the ENEA-Casaccia Research Center, near Rome. We monitored the currents in three four-gap MWPC's: two test chambers and a reference one. These detectors are described in detail elsewhere [1, 2]. The tested chambers were operated at a voltage corresponding to a gas gain $\sim 8{\cdot}10^4$, about twice the value which will be adopted during the experiment [3], integrating up to 440 mC/cm of wire in thirty days.

In Section 2 we shortly describe the Calliope γ facility. In Section 3 we describe the detectors and the experimental setup. Then, in Section 4 we report the test results. In last Section we draw the conclusions of the test.

2 The Calliope gamma facility

The Calliope plant is a pool-type irradiation facility equipped with a ^{60}Co radioisotope source placed in a shielded cell of volume 7x6x3.9 m^3 [4].

The source is characterised by a cylindrical geometry with the ^{60}Co pencils placed in a circular rack. The emitted radiation consists of two photons with energy of 1.17 MeV and 1.33 MeV. The maximum licensed activity was 3.7 10^{15} Bq and the present activity at the time of the test was 7.98 10^{14} Bq (June, 15th, 2003).

This plant offers the possibility to choose the dose rate for sample irradiation and the maximum dose rate (along the rack longitudinal axis) is 7270 Gy/h (June, 15th, 2003). The storage water pool dimensions are 2x4.5x8 m^3 and two separate source emergency storage wells are positioned on the bottom of the pool. The irradiation protection shield is realized in baritic concrete (180 cm thickness).

To determine the irradiation dose rate, at the Calliope plant three different dosimetric methods are available [5]: the Fricke absolute dosimetry (20-400 Gy), the alanine dosimetry (from few Gy up to 500 kGy) and the Red Perspex dosimetry (5-50 kGy).

Table 1: Summary of numbers caracterising the tested prototypes. REF(A,B) and REF(C,D) indicate the two double-gaps of the reference chamber. In the first four days of test, gaps A and B were connected in gas closed loop, while C and D were in open mode. Then, we switched the connection: (A,B) in open mode, (C,D) in closed loop.

	REF (A,B)	REF (C,D)	TEST1	TEST2
Area (cm^2)	500	500	500	1200
Volume (l)	0.5	0.5	1	2.4
Wire pitch (mm)	1.5	1.5	1.5	2
Gas mode	open	closed	closed	open
I (μA/gap)	$\sim$ 20	$\sim$ 10-20	$\sim$ 100-200	$\sim$ 1000-1500
HV range (kV)	$3.05 - 3.15$	$3.0 - 3.15$	$3.15 - 3.2$	2.75
Dose rate (Gy/h)	not measured	not measured	0.072	0.31

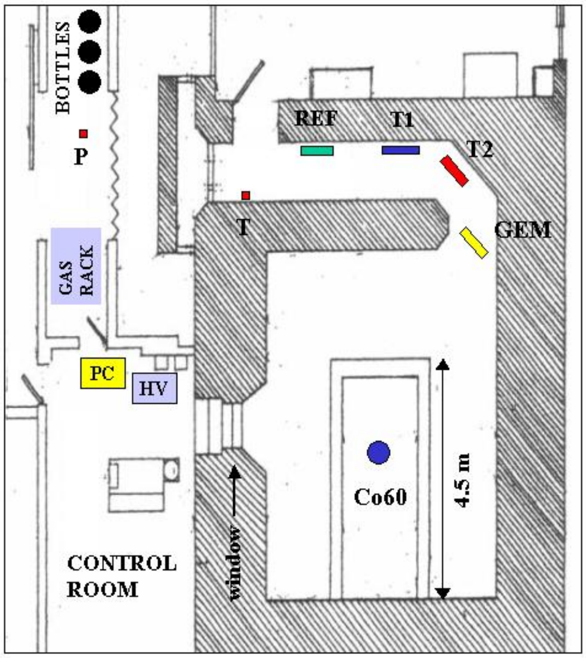

Figure 1: Map of the irradiation cell and of the control room. *REF*: MWPC reference chamber. *T1*: test chamber TEST1. *T2*: chamber TEST2. *GEM*: GEM chambers. *T*: temperature sensor. *P*: pressure sensor. *BOTTLES*: gas bottles for MWPC's and GEM's.

3 Setup for the aging test

3.1 Description of chamber prototypes

A detailed description of the MWPC's for the region 3 of the LHCb Muon System can be found in [1, 2]. The main parameters of the three prototypes are summarized in Table 1. Each prototype is composed of four gaps of 5 mm, each with an anode wire plane at the center of the gap. The positive high voltage is applied to the wires, while the cathode planes are grounded.

The two cathode planes on each gap have a different structure: one is a continuous gold-plated copper plane, the other is divided in pads (because in the chambers of region 3 the signal is read out from pads). However, since these cathode planes are always grounded, their structure is not relevant for the parameter we measure: the total current per gap.

There are some differences between the three prototypes, however the chambers TEST1 and REF are identical: each gap has 134 tungsten wires $\sim$ 25 cm long with 30 μm diameter, and a sensitive area of $\sim 200 \times 251$ mm^2, representing $\sim$ 1/6 of one final MWPC for region M3R3. Chamber TEST2 is somewhat different, mainly in the wire pitch (2 mm as in final design instead of the 1.5 mm of TEST1 and REF).

We placed the two chambers TEST1 and TEST2 in different positions with respect to the source: TEST1 is the chamber at lower exposure. The reference chamber REF was far from the source, protected by a concrete wall. This chamber was already exposed to radiation in a previous short aging test [6], integrating only $\sim$ 50 mC/cm of wire.

Using a weather station we monitored the atmospheric pressure and the temperature in the irradiation cell. A LabView program allows to read the currents of all twelve gaps and the information of the weather station and to record the data. During the test, also two more MWPC's built by the CERN LHCb-Muon group and several GEM chambers [7] built in LNF were irradiated. A map of the irradiation cell is shown in Fig. 1.

3.2 Gas system

Among the goals of this test was a validation of the LHCb gas system. Therefore we connected two gaps of chamber REF and all gaps of TEST1 to the gas closed loop. The closed loop included a gas purifier with two components: the first one is based on molecular sieve spheres, for the absorption of water; the second one, based on Cu, is for the absorbtion of oxygen.

The other two gaps of REF, together with all gaps of TEST2, were in open mode: gas went directly from the mixer to the chambers and then to the exhaust line.

The connections are illustrated in Fig. 2, including the position of the CERN chambers (CERN1 and CERN2). The gas mixture was $Ar/CO_2/CF_4$ with percentages 40/40/20. We used a different bottle for each gas, connected to a mass flowmeter regulated through an MKS system. Then, the three gases entered an aluminum box acting as a mixer.

The total gas flow was $\sim$ 6 l/h to the mixing box. Typical flows were:

- Open Mode: $\sim$ 4.8 l/h ($\sim$ 2 volumes/h of chamber TEST2);
- Closed loop: fresh gas $\sim$ 1.35 l/h; circulating gas $\sim$ 5.2 l/h.

The flow of fresh gas should be 10% of the circulating gas, but below the 25% the system was unstable. The GEM chambers were connected to the same gas bottles through separate flowmeters and mixer. We checked that the currents did not change at higher gas fluxes.

We summarize the gas system setup during the test:

Table 2: Summary of the gas system setup during the test. In the first column we give the time elapsed from the beginning of the data acquisition (in days).

Day of ACQ	Date	Gas system status
-	June,11	Start system with two open loops.
-	June,13	Closed loop starts.
0	June,14	Start data acquisition.
2	June,16	Purifier included in the loop.
3	June,17	Closed loop reached steady state.
14-15	June,28-29	Mixture out of control (low CO_2 content).
16	June,30	$Ar/CO_2/CF_4$ = 40/18/20 cc/min at 8:30 AM while set values are 40/40/20 cc/min.
17-19	July,1-3	Still mixture problems.
19	July,3	Control unit of CO_2 mass flowmeter replaced. Gas purifier changed.
21-22	July,5-6	Again low CO_2 content in gas mixture.
23	July,7	MWPC mixture 40/10/20 cc/min; low CO_2 content also in GEM mixture; CO_2 bottle and mass flowmeter are changed; Gas system is oversaturated with CO_2.
24	July,8	Closed loop is off. Two parallel open loops.
30	July,14	Test is finished.

The first purifier was used from June 16 to July 3. Then, a second purifier was used until the end of the test. The content of O_2 was measured and did not change during the test, but water

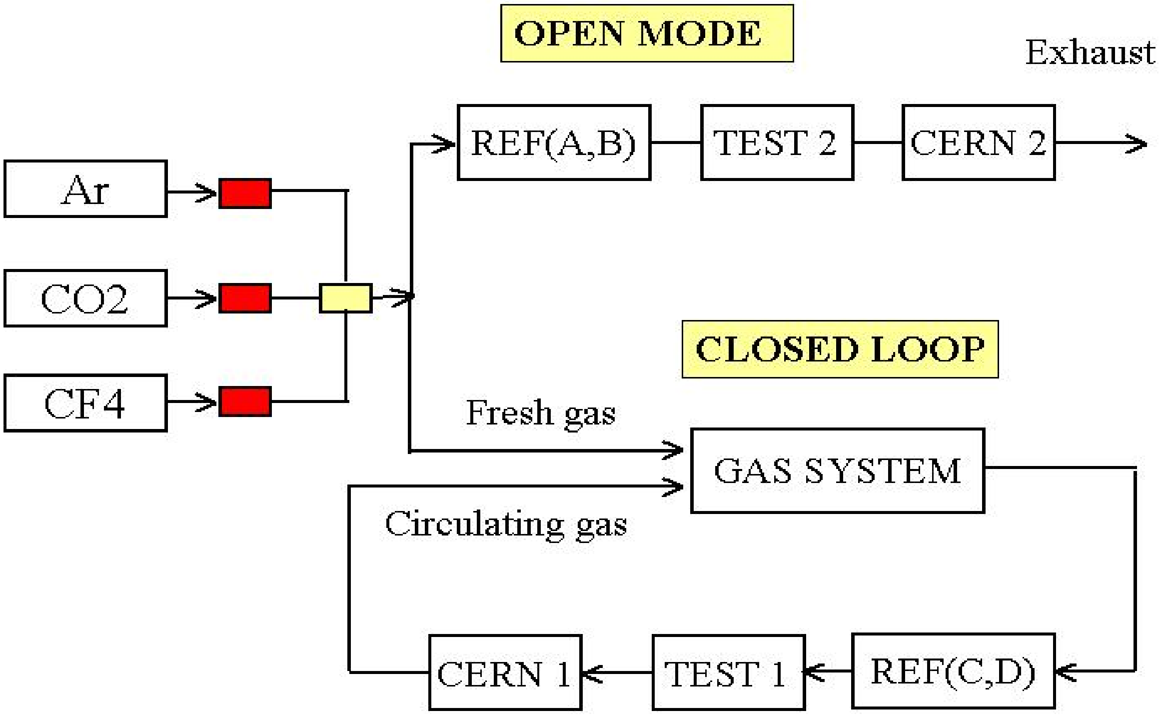

Figure 2: Layout of the gas connections. In the first four days of test, gaps A and B of chamber REF were connected in gas closed loop, while C and D were in open mode. Then, we switched the connection: (A,B) in open mode, (C,D) in closed loop.

content was not monitored. We noticed that the purifier response time was long (about one day). Therefore when the mixture was unstable or the purifier was changed, the closed loop system required a long time to reach a steady state.

During the test the CO_2 content in the gas suddenly decreased. The problem was not observed in the GEM chambers, therefore the common CO_2 bottle could not be the cause of the increase. We changed the MKS channel connected to the CO_2 and got again a correct displayed mixture. The problem arose again after about two days and was observed also in GEM gas mixture. This time we changed the bottle and decided to operate the closed loop in open mode, to reach a stable situation in a short time. However, at the end of the test, the observed currents were systematically lower (of $\sim$ 25%) respect to currents at begin. This suggests that the CO_2 content before the change of the bottle was probably lower than expected.

3.3 Monitoring of temperature and pressure

Within a good approximation, the gas gain and therefore the current I, are related to high voltage (V) and gas temperature (T_g) and pressure (P_g), by the formula:

$$I = k \cdot e^{\alpha\ V\ T_g/P_g} \qquad (1)$$

where k and α are constants. During the test, we recorded the temperature T in the irradiation cell and the atmospheric pressure P. We did not have sensors to measure directly the temperature and pressure of the gas mixture. The measured values of T and P cannot be considered precise estimates of the gas temperature and pressure inside the two chambers. Therefore, even if the overall variations of T and P are small, (1.3% for T and 1.2% for P) we have normalized the currents in the gaps under test to the currents in the reference gaps, in order to remove the T and P dependence.

4 Results

4.1 Chamber in open mode

The chamber in gas open mode (TEST2) was exposed at a high dose rate 0.31 Gy/h. Gaps A,B,C were permanently switched on at a voltage HV=2.75 kV, corresponding to a gas gain $\sim 8{\cdot}10^4$ [3]. Gap D was permanently at 2.05 kV and was moved to 2.75 kV once about every three days for about five hours (until current was stable) to be used as a monitor. At 2.75 kV, the current in each gap was of the order of $\sim$ 1000-1500 μA.

During the experiment the chambers will be operated at a lower HV value (2.6-2.65) kV, at least in regions M2-M5 where an efficiency $>$95% for each double-gap is sufficient. The value HV=2.75 kV chosen for the test was the result of a compromise between the need of accelerating the aging test and the need of operating the chamber in safe conditions.

In Fig. 3 (Left) we show the currents in the four gaps. It is evident that during about thirteen days (day$\sim$ 12-15) the CO_2 content in the mixture was anomalously low and led to very large values of the currents.

The spikes in the figure correspond to three events in which the chamber tripped (the current in at least one gap exceeded the 2 mA set limit). This large current was probably the cause of the broken wire in gap C at day$\sim$ 21.7 (see the discussion in Section 4.5).

Also, as already mentioned above, after the change of the CO_2 bottle (day $>$25), currents stabilized at a lower value. This suggests that the CO_2 content in the mixture was probably lower than expected since the beginning of the test.

To remove the dependence on temperature, pressure and precise mixture content, we calculated the ratio of the currents in A,B,C respect to the current in monitor gap D. These ratios are calculated about once every three days, when the gap D is switched on and its current reaches a stable value. Results are shown in Fig. 3 (Right). The ratios are constant within $\sim$ 4%.

Also the gaps of chamber REF (exposed at a negligible dose rate) were used as a monitor. In the first four days of test, gaps A and B were connected in closed loop, while C and D were in open mode. Then, we decided to switch the connection: (A,B) in open mode, (C,D) in closed loop, because the gap D was not very stable and we considered more important the test of the chamber in open mode (exposed to a higher dose rate).

In Fig. 4 (Left) we show the currents in gaps (A,B) of reference chamber REF. In Fig. 4 (Right) the ratios between the currents in gaps A,B,C of chamber TEST2 and the average current in gaps A and B of REF are reported. At day $\sim$ 25, a wire in gap B of REF broke, probably due to the high current drawn during the decrease of CO_2 content in the gas mixture. Therefore, for day $>$ 25 the current ratios refer to gap A alone, not to the average current in (A,B). Even though the currents in REF (A,B) are very irregular, due to heavy fluctuations of CO_2 pecentage, the current ratios appear very stable. These results prove that gas gain in chamber TEST2 did not change.

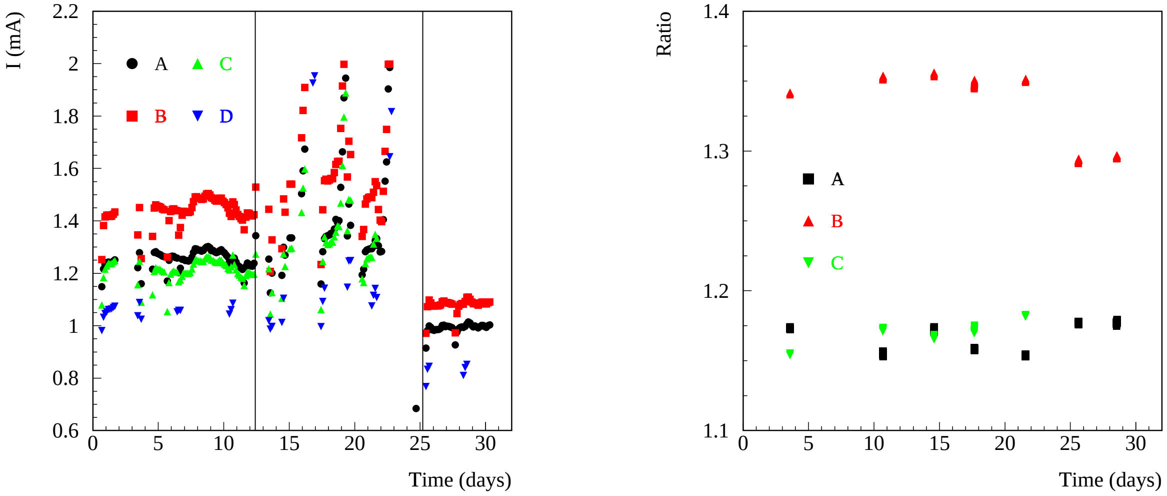

Figure 3: Left: currents (averaged over three hours) in gaps A,B,C,D of chamber TEST2 when HV=2.75 kV. During the period included between the vertical lines the gas mixture was unstable. Right: ratios (averaged over about half an hour) between the currents in gaps A,B,C and the current in monitor gap D.

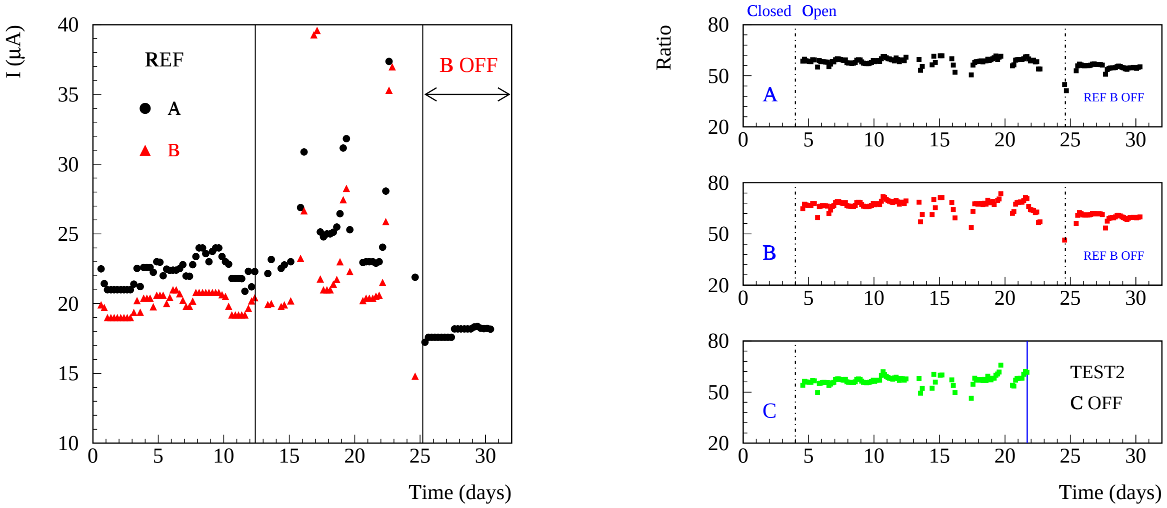

Figure 4: Left: currents (averaged over six hours) in gaps A,B (in open mode for day > 4) of reference chamber REF, when HV=3.15 kV. During the period included between the vertical lines the gas mixture was unstable. At day ~ 25 the gap B was switched off. Right: ratios (averaged over three hours) between the currents in gaps A,B,C of chamber TEST2 and the average current in gaps A and B of REF. For day > 25, the current ratios refer to gap A of REF alone.

4.2 Chamber in closed loop

The chamber in closed loop (TEST1) was exposed to a dose rate 0.072 Gy/h, about four times less than for TEST2. The gaps B,C,D were permanently switched on at HV=3.15-3.2 kV. Gap A, used as a monitor, was permanently at 2.65 kV and moved to 3.2 kV once about every three days for about five hours (until current was stable). Since TEST1 had a smaller wire pitch (1.5 mm) with respect to TEST2 (2 mm), the same gas gain as in TEST2 gaps was obtained for a voltage $\sim$ 400 V higher in TEST1, so at 3.15 kV in TEST1 the gain is $\sim 8{\cdot}10^4$ [3]. Currents in gaps B,C,D were of the order of $\sim$ 100-200 μA.

During the test, the high voltages of gaps B and C were changed: from 3.2 to 3.15 kV in B (at day $\sim$ 13.6); from 3.15 to 3.2 kV in C (at day $\sim$ 10.5). At day $\sim$ 13.6 we have also removed limiting resistors of 470 kΩ from gaps A,B,D (in C there was no resistor). These resistors provoked a voltage drop of the order of $\sim$ 80 V. Currents in all gaps were corrected using scaling factors in order to account for this voltage drop and for changes in the set HV values during the test (see the Appendix for details on the calculation of the correction factors).

In Fig. 5 (Left) we show the corrected currents in the four gaps. During about thirteen days (day$\sim$ 12-15), the currents are higher as a consequence of the low CO_2 content in the mixture.

Just before the end of the test (day $\sim$ 27.5), the currents in gaps C and D sharply decreased, of 26% in gap C and of 33% in gap D. A similar effect was not observed neither in gaps A and B, nor in the gaps of the CERN chambers. We do not know the cause of this decrease. We can only state that a sharp and simultaneous decrease of the currents in two different gaps cannot be attributed to an aging process.

As already observed for the TEST2 chamber, here also all the currents at the end of the test were systematically lower respect to the currents at begin.

We computed the ratio of the currents in B,C,D with respect to the current in gap A, used as a monitor. Results are shown in Fig. 5 (Right). The current ratios are stable, within $\sim$ 13%, all over the test except for the last measurement. We do not have any explanation for this last measurement.

The gaps C,D of the chamber REF were used as a reference. In the first four days, (C,D) were connected in open mode. Then, we switched the connection: (A,B) in open mode, (C,D) in closed loop. At the same time, since current in gap D was about four times larger than in other gaps, we lowered its high voltage from 3.15 to 3.0 kV. Also the high voltage in gap C was changed (from 3.15 to 3.05 kV) at day $\sim$ 13.6. The currents were rescaled using the scaling factors reported in the Appendix.

In Fig. 6 (Left) we show the currents in gaps C,D of REF. Figure 6 (Right) shows the ratios between the currents in gaps B,C,D of TEST1 and the reference gap C of REF. We calculated the ratio respect to gap C alone, because the behaviour of gap D was anomalous: larger current than in other gaps and presence of residual current when we switched the radioactive source off ($\sim$ 1200 nA at 3.15 kV). Except for the period with big current variations ($12.4<\text{day}<25.2$) due to CO_2 content out of control, the current ratio for gap B is stable within $\sim$ 15%, while for C and D we find a sharp decrease at the end of the test, as already observed in Fig. 5 (Left).

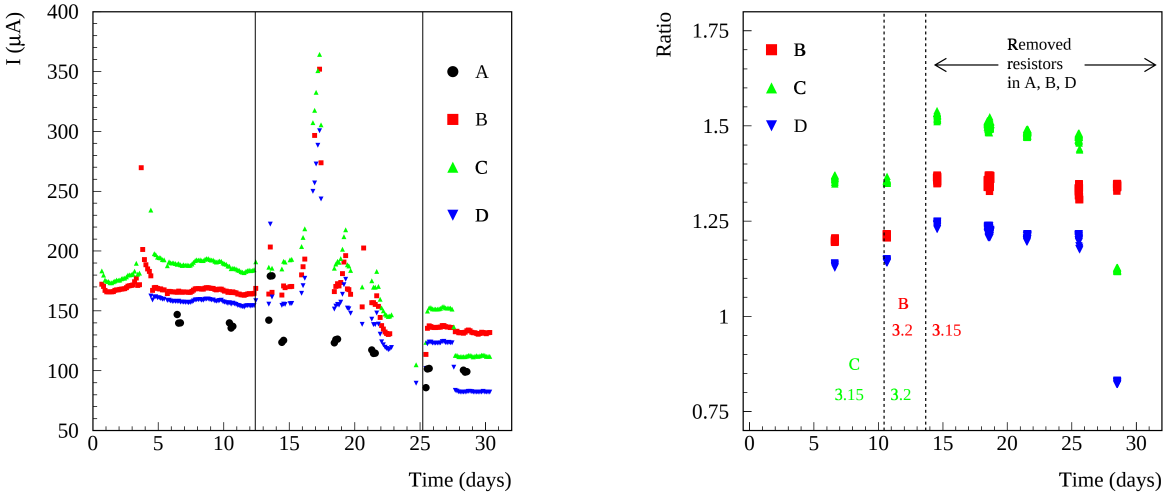

Figure 5: Left: currents (averaged over three hours) in gaps A,B,C,D of TEST1. During the period included between the vertical lines the gas mixture was unstable. Right: ratios (averaged over about one hour) between the currents in gaps B,C,D and the current in gap A. During the test, the high voltages of gaps B and C were changed, as shown by vertical dashed lines. The currents are corrected as shown in the Appendix.

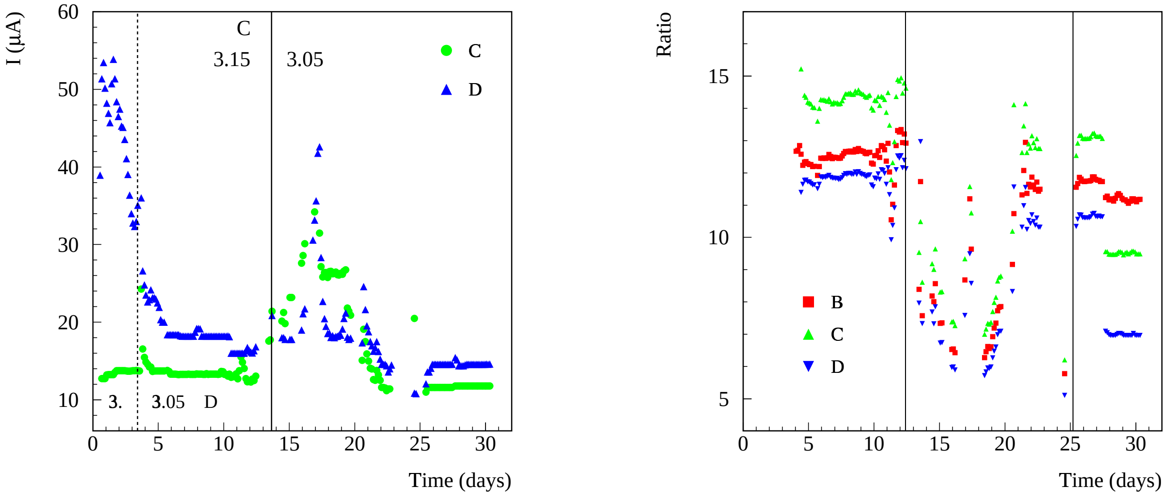

Figure 6: Left: currents (averaged over six hours) in gaps C,D of chamber REF. The lines show when the HV was changed (dashed line for D, continuous for C). Right: ratios (averaged over one hour) between the currents in chamber TEST1 (B,C,D) and the current in gap C of REF. The period in which the gas mixture was unstable is included between the vertical lines. The currents are corrected as shown in the Appendix.

4.3 Dark currents

We have measured the currents in the chambers with the radioactive source off. The power supply used for the test (CAEN SY2527) had a sensitivity of 0.1 μA and a different offset for each channel, between 0 and 1 μA. Therefore, the SY2527 is unable to read currents smaller than 1 μA. For this reason, after reading the SY2527 currents, we switched off each gap and powered it with a NIM N471A, with sensitivity 1 nA.

In Table 3 the currents after about fourteen days of test are shown. Only gap D of reference chamber draws a permanent current, but this effect cannot be related to aging, because the dose rate on this chamber was negligible. Further measurements were performed in the lab, after the end of the test. We did not find any self-sustaining rest current in the chambers.

Table 3: Currents in chambers measured with radioactive source off after about fourteen days of test. We indicate with (*) the currents with an evident decreasing trend. Unless otherwise indicated, high voltage applied is 3.15 kV for chambers REF and TEST1 and 2.75 kV for TEST2. The current offset in each SY2527 channel is in the range 0-1 μA.

Gap	REF SY2527 (μA)	REF N471A (nA)	TEST1 SY2527 (μA)	TEST1 N471A (nA)	TEST2 SY2527 (μA)	TEST2 N471A (nA)
A	0.8	0	28.8	5 at 3.2 kV	0.6	70 (*)
B	0.2	0	0.4	9 (*)	0.4	70 (*)
C	13.2	0 at 3.3 kV	0.2	9 (*)	0.2	38 (*)
D	5.6	1200	0.2	7 (*)	0.4	28 (*)

4.4 Integrated charges

In Fig. 7 we show the integrated charges as function of time and the total value at the end of the test. From Montecarlo calculations of the maximum particle rates in each detector region [8], with the following assumptions:

- ten LHC years correspond to 10^8 seconds of machine operation (LHC duty cycle=0.32);
- luminosity is $2{\cdot}10^{32}$ cm^{-2} s^{-1};
- safety factors are 2 in M1 and 5 in M2;
- gas gain is 10^5;
- the charge is corrected by a factor 0.5 in M1 and M2/R1-R2 (assuming the use of double cathode readout);

the integrated charge in ten years is: 950 mC/cm of wire in M1R2 and 550 mC/cm in M2R1. With these assumptions, the largest integrated value (440 mC/cm in gap B of TEST2) corresponds to $\sim$ 4.6 years equivalent for region M1R2 and $\sim$ 8 years for region M2R1.

Defining $T_{\mathtt{eq}}$ the time equivalent in M1R2 (=55.2 months), c the LHC duty cycle (=0.32), and $T_{\mathtt{test}}$ the test duration (=1 month), the corresponding test acceleration factor F is:

$$F = T_{\mathtt{eq}} \cdot c/T_{\mathtt{test}} \sim 17.6$$

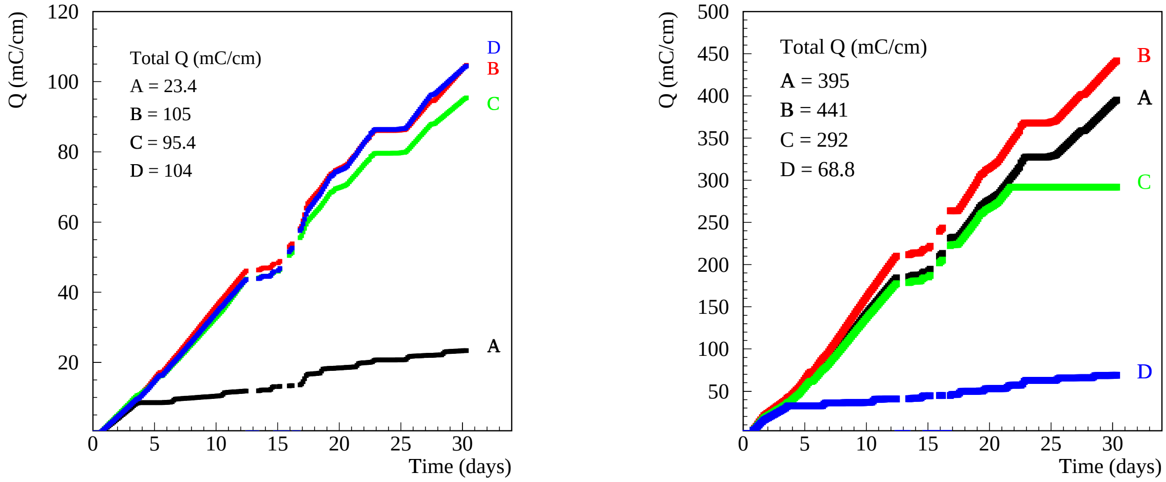

Figure 7: Integrated charges in test chambers as function of time. Left: chamber TEST1. Right: chamber TEST2.

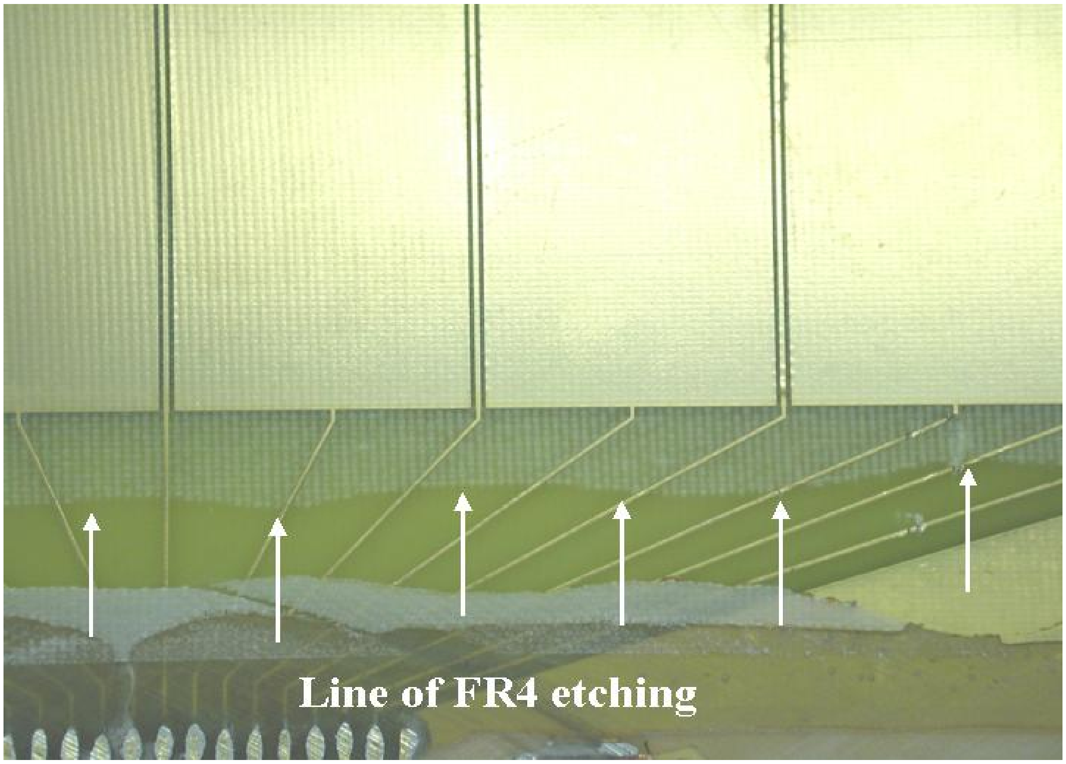

Figure 8: Etching of the FR4 glass epoxy layer in chamber TEST2.

4.5 Visual inspection of the chamber in gas open mode

After the aging test, we opened the chamber TEST2 (which received the largest dose) to perform a visual inspection and in an attempt to find the cause of the broken wire in gap C.

In general, on all gaps we found that:

- the epoxy layer on FR4 glass epoxy was etched (see Fig. 8);
- there are no traces of discharges under the wires (see Fig. 9);
- wires are clean.

In more detail:

- Gap A : at the gas input, we observe some discharge area ($\sim$ 3 cm^2) under the wires, visible on both cathode surfaces (pad-structured and continuous) (see Fig. 10). Traces of etching activity are visible on the pads (“bumps” under ground guard traces, see Fig. 11). The ground layer is in perfect conditions.
  It ought to notice that these damages in guard traces on the pads show a peculiar pattern. They appear in strips separated by $\sim$ 5-6 cm and approximately diagonal with respect to the chamber (see Fig. 12).
- Gap B : there are traces of small etching activity on the pads. The ground layer is in perfect conditions.
- Gap C : we observe large etching activity on one of the cathode pads, small on the others. In a very small area there are traces of discharges near the gas inlet. A wire was broken and the two terminals of the wire for few millimeters are carbonized (see Fig. 13).
  We should consider that in this chamber the wires had no HV limiting resistor, in order to perform the accelerated aging test. In this way a single wire could have drawn a very large current (order of mA). We believe that the broken wire is due to such an effect and not to the effect of aging.
- Gap D (monitor gap): we find no etching on pads, only on FR4 elements. From this we can infer that etching of pads is due to the current drawn by the chamber, while the etching of the FR4 frame comes from the sole gas flow.

Considering that gaps are connected in series and that gas enters the chamber in gap A and flows out from gap D, the etching effect seems not be correlated with the gas flow direction.

5 Conclusions

We have presented the results of an aging test performed on two prototypes of MWPC for the LHCb Muon System.

The interpretation of data for the chamber in closed gas loop is quite difficult. The currents in the gaps are quite stable, except for the period in which the CO_2 percentage in the gas mixture was out of control and for the very end of the test, in which two gaps exhibit a sharp unexplained decrease in the current. It is evident that this effect (sharp and simultaneous on both gaps) cannot be explained in terms of aging.

As far as the chamber in gas open mode is concerned, the results are very satisfactory: the currents, normalized to monitor gaps, are quite stable over one month of test, even though the gas mixture was not well defined for a relevant time fraction of the test. The largest integrated value (440 mC/cm of wire in gap B of TEST2) corresponds to $\sim$ 4.6 years equivalent for region M1R2 and $\sim$ 8 years for region M2R1.

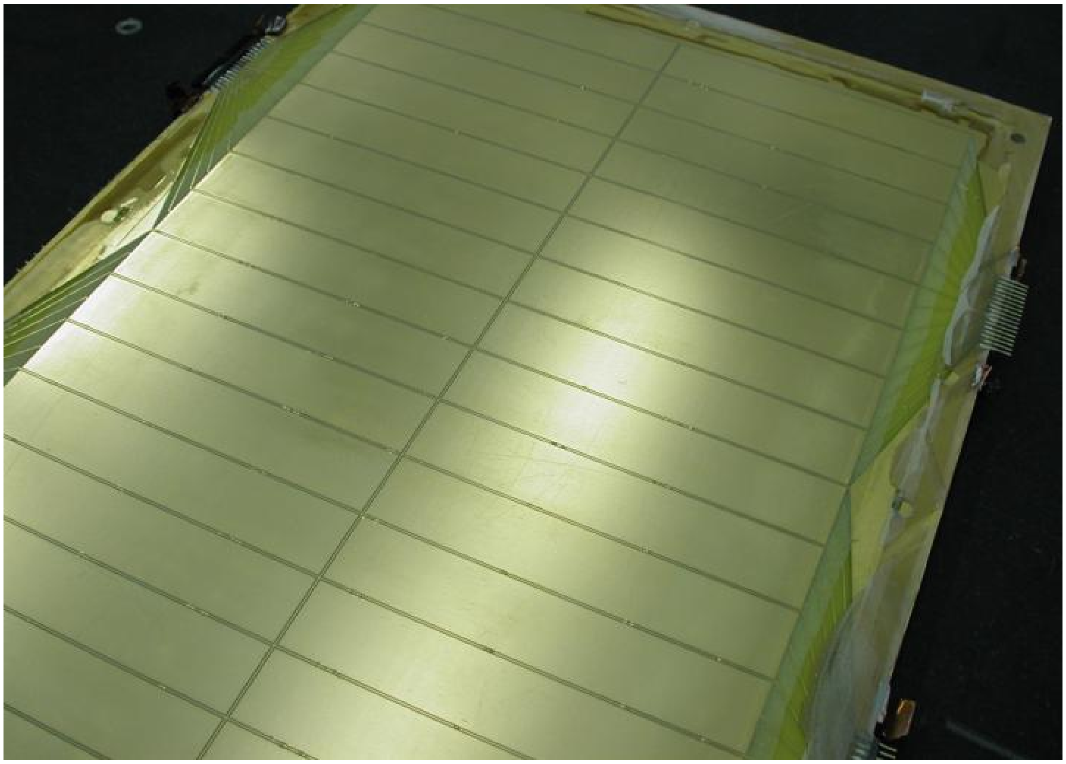

Figure 9: No traces of discharges or deposits under the wires of chamber TEST2.

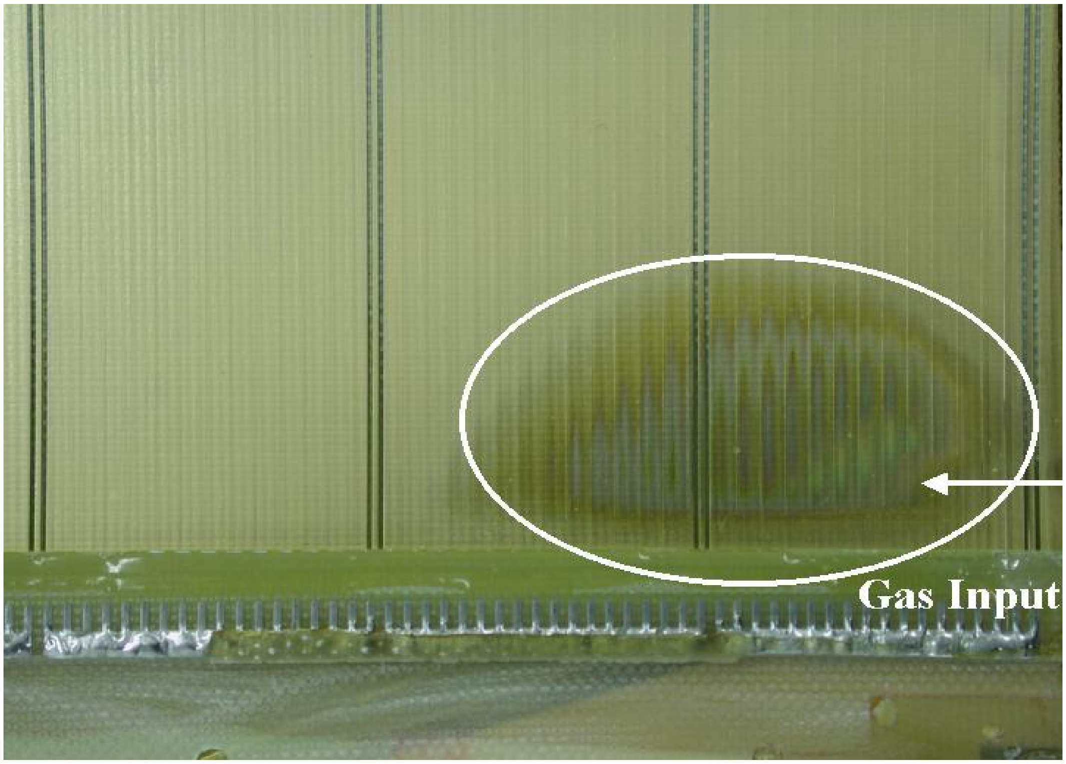

Figure 10: Effect of the discharge activity near the gas input.

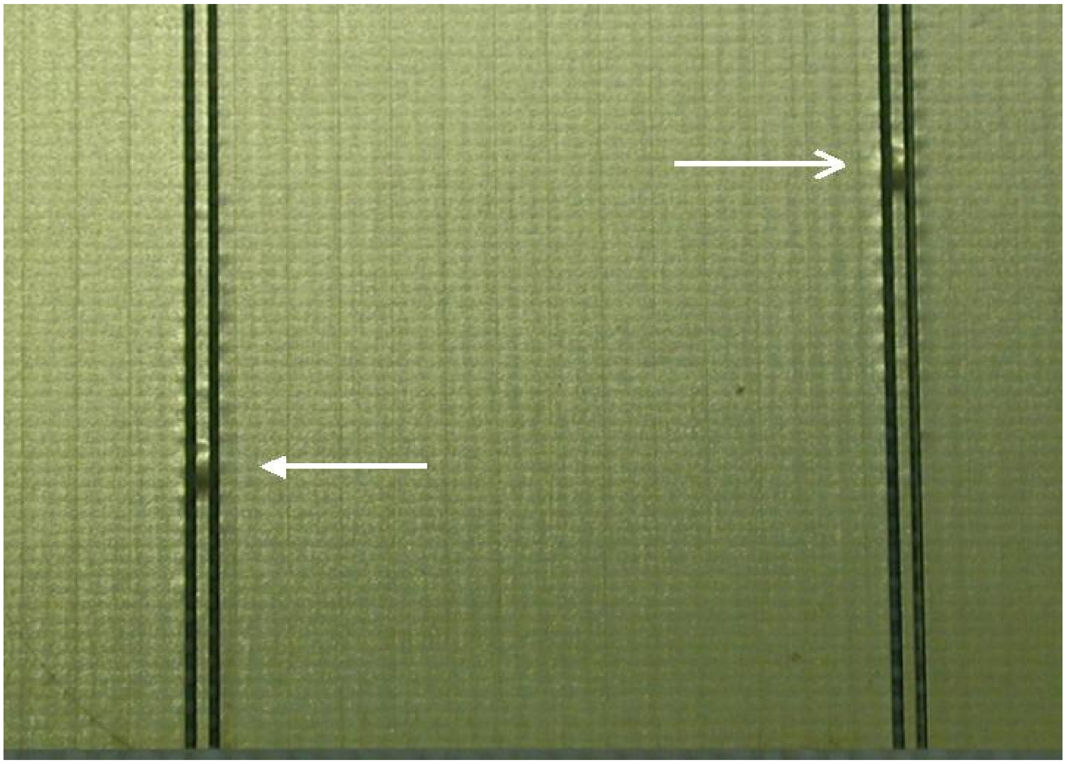

Figure 11: “Bumps” on the guard strips of the pads.

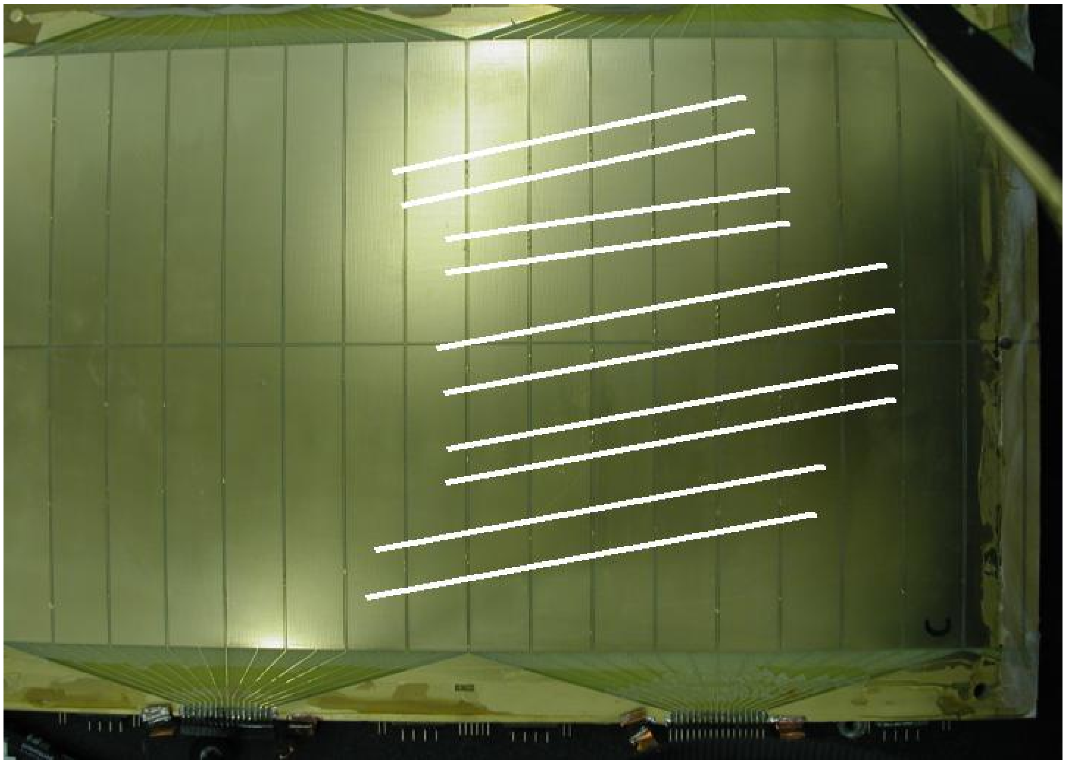

Figure 12: “Preferred” directions of pad etching. Most of the “bumps” under ground guard traces are included between the pairs of parallel lines in the picture.

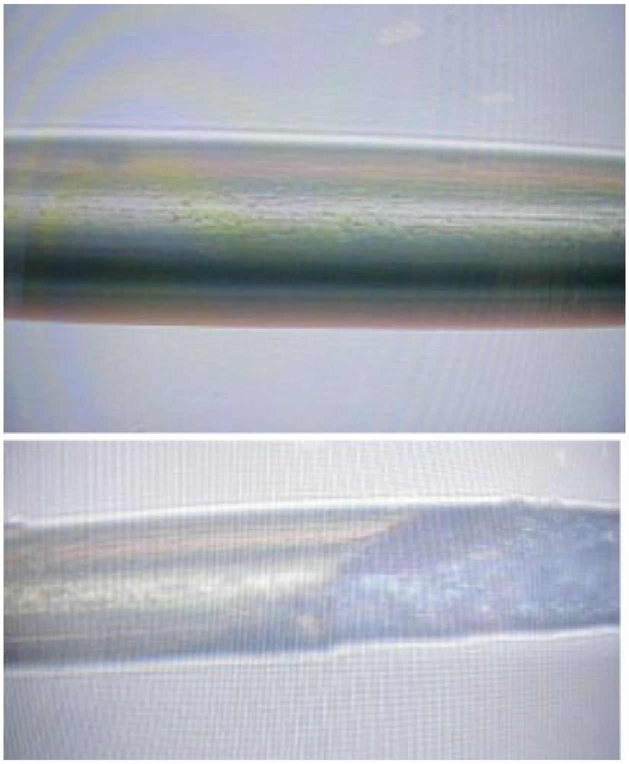

Figure 13: A wire of the chamber (above) and the broken one (below).

The visual inspection revealed that the broken wire in one gap is probably due to an overcurrent and not to aging. Also, both the etching on cathode pads (related to the current drawn because not present in the monitor gap) and the etching of the FR4 frame (present also in monitor gap) could be partially due to the big acceleration factor of the test ($\sim$ 18 for region M1R2). In particular, this acceleration causes a big gas pollution, since only two volumes/hour are exchanged. In any case, the current stability proves that the overall detector gain is not affected by these effects.

Appendix

In previous sections we reported the measurements of the chamber currents and of their ratios respect to monitor gaps. Some measurements were corrected using scaling factors because in some cases we changed the operating conditions during the test.

For what concern chamber TEST2, no correction factor was applied. All currents of Fig.3 and 4 (Right) refer to high voltage 2.75 kV in all four gaps.

The gaps A and B of chamber REF were used as reference gaps in open mode. Here also, no correction factor was applied on the currents shown in Fig.4 (Left), because these gaps were always operating at 3.15 kV.

For the chamber TEST1 some scaling factors were needed, because during the test:

- we changed the high voltage of gaps B and C;
- we removed the 470 kΩ limiting resistors from gaps A,B,D (in C there was no resistor).

To calculate the correction factors, for each gap we fitted the current I as a function of the high voltage V with a power-law function:

$$I\ [\mu A] = \alpha\cdot (V/1\ kV)^{\beta} \qquad (2)$$

The parameters α and β are reported in Table 4.

For example, consider the case of gap A. The current before removing the R=470 kΩ limiting resistor was I=179.3 μA, corresponding to a voltage drop:

$$\Delta V = R \cdot I = 0.083\ kV \qquad (3)$$

Then, the scaling factor is:

$$I_{\texttt{corr}}/I_{\texttt{raw}} = [(3.2 - \Delta V)/3.2]^{\beta} = [(3.2 - 0.083)/3.2]^{15.681} = 0.662 \qquad (4)$$

For what concern gap B, when we removed the limiting resistor we also changed the HV from 3.2 to 3.15 kV to reduce the current. In that case, the voltage drop of 78 Volts is reduced by 50 Volts and leads to a correction factor close to one (=0.87).

The gaps C and D of chamber REF were used as reference gaps in closed loop. Since their HV was changed during the test, a correction factor was applied here also to the currents. The parameters are shown in Table 5.

Table 4: For gaps A,B,C,D of chamber TEST1, the tables report: the parameters α (in μ A) and β of the fit of the current as function of the high voltage (Eq.2); the voltage drop ΔV due to the presence of the limiting resistors (Eq.3); the scaling factor applied to the current in different test periods, according to the value of the high voltage and to the presence of the limiting resistors.

Gap A	$\alpha\cdot 10^6$	β	ΔV (Volt)	**Gap B**	$\alpha\cdot 10^6$	β	ΔV (Volt)
	2.094	15.681	83		2.333	15.846	78

Period	HV (kV)	Limiting R	Factor	Period	HV (kV)	Limiting R	Factor
				day<4.5	3.15	yes	1.28
day<13.6	3.2	yes	1.	4.5<day<13.6	3.2	yes	1.
day>13.6	3.2	no	0.662	day>13.6	3.15	no	0.870

Gap C	$\alpha\cdot 10^6$	β	ΔV (Volt)	**Gap D**	$\alpha\cdot 10^6$	β	ΔV (Volt)
	1.465	16.064	-		0.918	16.719	73

Period	HV (kV)	Limiting R	Factor	Period	HV (kV)	Limiting R	Factor
day<10.4	3.15	no	1.29	day<13.6	3.2	yes	1.
day>10.4	3.2	no	1.	day>13.6	3.2	no	0.680

Table 5: For gaps C,D of chamber REF, the tables report: the parameters α (in μ A) and β of the fit of the current as function of the high voltage (Eq.2); the scaling factor applied to the current in different test periods, according to the value of the high voltage.

Gap C	$\alpha \cdot 10^9$	β	**Gap D**	$\alpha \cdot 10^9$	β
	1.086	20.842		1.309	20.615

Period	HV (kV)	Factor	Period	HV (kV)	Factor
day<13.6	3.15	0.51	day<3.7	3.0	1.406
day>13.6	3.05	1.	3.7<day<10.5	3.05	1.
			10.5<day<12.5	3.1	0.715
			day>12.5	3.05	1.

Acknowledgements

We thank the staff of the Calliope facility (A. Pasquali, F. Zarbo) for the great help in preparing and realizing the test.

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