Long-term and efficient operation of the MWPC muon detector at LHCb

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Introduction

The Multi-Wire-Proportional-Chamber (MWPC) muon detector of LHCb is one of the largest instrument of this kind worldwide, and one of the most irradiated. All of the MWPCs are supplied with a 40% Ar + 55% CO_2 + 5% CF_4 gas mixture. For most of the LHC operation so far we took data at an instantaneous luminosity of 4×10^{32} cm^{-2} s^{-1}. The most irradiated MWPCs integrated over the past nine years ~0.6 C/cm of charge per unit length of wire.
In nine years of MWPCs operation in a high radiation environment, the chambers didn't show a gain reduction or any other apparent symptom of ageing. However, many gas gaps were affected by the sudden appearance of high currents. This effect, originating from localized areas in the individual gaps of the MWPCs, results in an increased noise rate and a trip of the high-voltage (HV) supply system due to a current exceeding the set threshold.
The observed phenomenon of currents triggered by high radiation, but self-sustained if beam goes off, suggests that most of the trips are due to Malter-like effects (ME). This phenomenon can be due to thin insulator deposits on the cathode coming from either the construction process, or from polymerization reactions taking place near the anode wires in the gas discharge plasma.
During operation of the LHC, about 100 gas gaps were affected every year by HV trips. Most of the problematic chambers could be recovered successfully in situ during data taking under nominal beam conditions by means of a long HV training performed on the affected MWPC gaps. This method has proven to be very effective, allowing recovery of normal operation conditions for most of the MWPC gaps affected by HV trips, so that the muon detection efficiency could be kept close 100%. This is a remarkable result, since the recovery of gas discharge detectors without disassembling is topical for many modern experiments.

Introduction

The muon detector of the LHCb experiment consists of five stations, M1-M5 placed along the beam axis. Station M1 is located in front of the calorimeters and is used to improve the p_T measurement of the muon trigger. Stations M2 - M5 are placed behind the hadronic calorimeter and are interleaved with iron absorbers to select penetrating muons. Each station is divided into four regions, R1-R4, with increasing distance from the beam axis, as shown in figure 1.

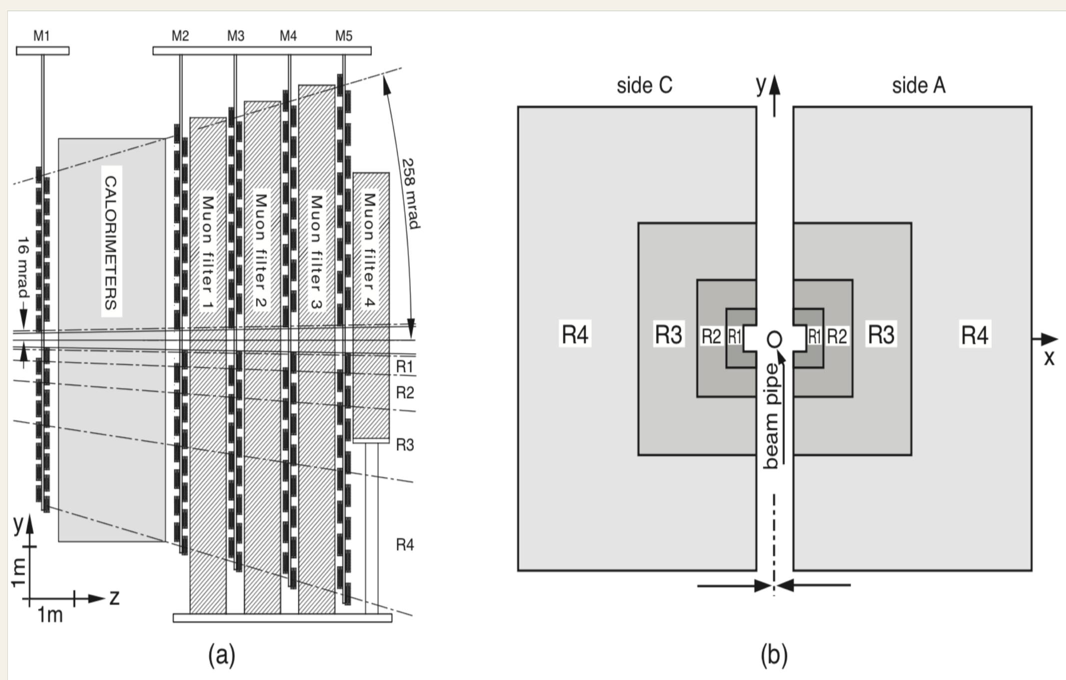

Figure 1. (a) Side view of the LHCb muon detector. (b) Station layout with the four regions R1–R4 indicated.

The area of the four regions increases quadratically while the irradiation per unit area decreases. In total, the muon detector is equipped with 20 types of muon chambers, varying mainly in size. MWPCs are used everywhere, with the exception of region R1 of station M1, where triple-GEMs were adopted due to the higher irradiation. The whole detector comprises 1380 chambers - 1368 MWPCs and 12 GEMs. Taking into account that out of the 1368 MWPCs, 1104 are made of four active gas gaps and 264 of two gaps, the total instrumented area amounts to about 1650 m^2. The number of chambers installed in each region of the detector, their relevant characteristics and the charge integrated so far are listed in table 1.

Station	Region	#Chamber	Active area [cm^2]	# Gaps per chamber	Readout type	Q_{int} [mC/cm]
M1	R2	24	48×20	2	cathode	95 ÷ 630
M1	R3	48	96×20	2	cathode	20 ÷ 220
M1	R4	192	96×20	2	wire	4 ÷ 80
M2	R1	12	30×25	4	mixed	56 ÷ 150
M2	R2	24	60×25	4	mixed	18 ÷ 80
M2	R3	48	120×25	4	cathode	1.3 ÷ 14
M2	R4	192	120×25	4	wire	0.15 ÷1.6
M3	R1	12	32×27	4	mixed	13 ÷ 50
M3	R2	24	65×27	4	mixed	3 ÷ 22
M3	R3	48	130×27	4	cathode	0.13 ÷ 2.2
M3	R4	192	130×27	4	wire	0.03÷0.3
M4	R1	12	35×29	4	cathode	9 ÷ 40
M4	R2	24	70×29	4	cathode	1 ÷ 10
M4	R3	48	139×29	4	cathode	0.1 ÷ 1.6
M4	R4	192	139×29	4	wire	0.02 ÷ 0.2
M5	R1	12	37×31	4	cathode	12 ÷ 34
M5	R2	24	74×31	4	cathode	1.3 ÷ 9
M5	R3	48	149×31	4	cathode	0.3 ÷ 5
M5	R4	192	149×31	4	wire	0.1 ÷ 1.5

Table 1. Relevant parameters for all of the 19 types of MWPCs in the LHCb muon detector; in the last column the charge integrated during the full data taking is reported, with reference to the least and most irradiated chamber of each region.

Despite of different dimensions, each chamber has the same internal geometry, as shown in figure 2. Anode planes are centered inside 5 mm gas gaps and are formed by 30 µm diameter gold-plated tungsten wires, with 2 mm spacing. The cathodes are made of FR4 fiberglass plates with two-sided 35µm thick copper coating. In regions R1-R3, the cathodes have an additional gold coating of about 100nm. Adjacent gaps are separated by honeycomb panels or rigid polyurethane foam, which provide precise gap alignment over the whole chamber area. The MWPCs in stations M2-M5 have four gaps, while station M1 is equipped with two-gap MWPCs. The total number of MWPC gaps in the system is 4944. The gas mixture is supplied into the gaps sequentially, as shown in figure 2. Depending on the HV settings, which varies from 2.53 – 2.63 kV, the gas gain ranges between 4.4×10^4 and 8.6×10^4, as shown in figure 3. An independent HV channel supplies each MWPC gap.

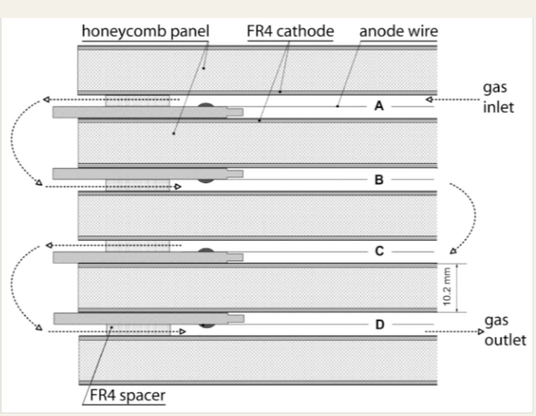

Figure 2. Cross section of a MUON MWPC, with four gaps.

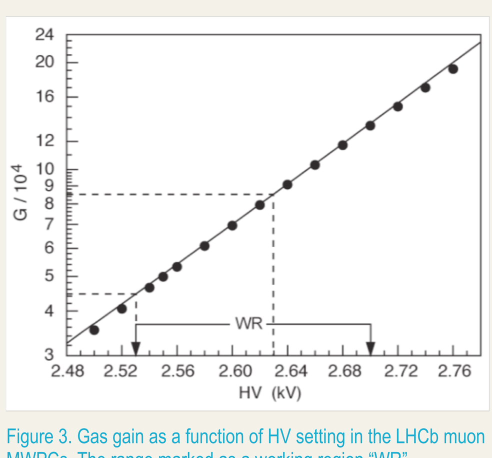

Figure 3. Gas gain as a function of HV setting in the LHCb muon MWPCs. The range marked as a working region "WR" corresponds to the "efficiency plateau". The actual working HV applied in the muon detector chambers is between the dashed lines.

Operation in presence of high detector currents

While no typical ageing effects have been observed on the system, about 100 MWPC gaps suffered every year from the appearance of high currents and the concomitant HV trips. Most of the problematic chambers were successfully recovered in situ, under the nominal beam conditions, by means of HV training with the working gas mixture, as discussed in the following. A typical example of the appearance of a self-sustained current in one of the MWPC gaps in region M5R3 is shown in figure 4 (left). For this particular chamber type, operating at a nominal voltage of 2.6 kV, the maximum current value in the presence of colliding beams is ~0.6 µA. As shown in figure 4, at some point the HV channel powering this MWPC gap tripped due to the ignition of a high current. Following the trip, an especially developed algorithm reduces the HV settings until the measured current is again below the nominal threshold. The operator is alerted as well, who then chooses the optimal training parameters, which can be further tuned. During the training, the HV settings are varied normally automatically, keeping a relatively high current of 30 $\pm$ 4 µA, which is below the safe limit of ~40 µA. Having a relatively high current is the best strategy for recovery in presence of ME. The CF_4 component in the gas mixture allows to increase the local concentration of fluorine radicals, which in turn react with deposits like silicone and polymers by means of surface etching. The high value of the current is maintained independently of the presence of colliding beams.

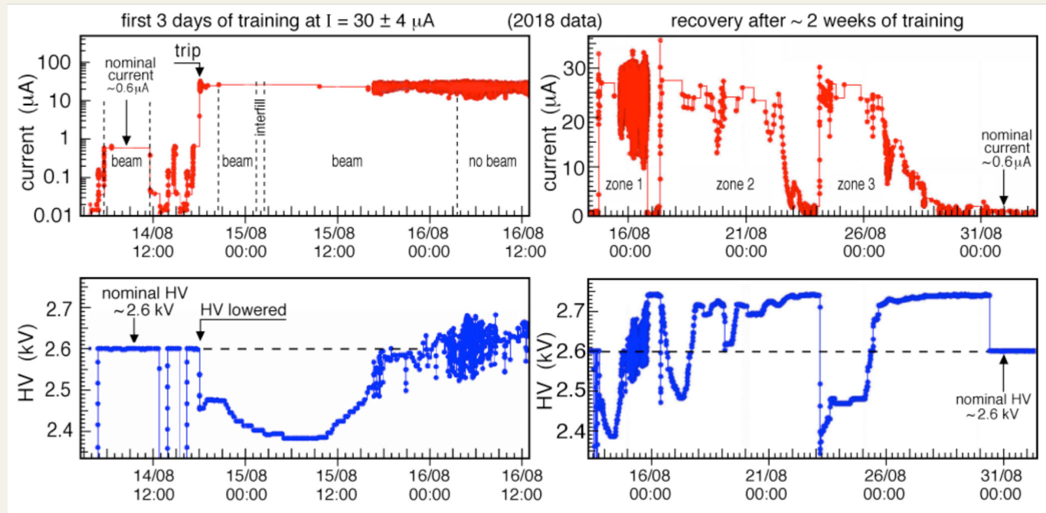

Figure 4. A typical example of the appearing of a self-sustained current and the recovery procedure from ME during normal LHCb operation with beams, applied to one of the MWPC gaps in region M5R3. The plots on the left show the current (top) and HV setting (bottom) during a period of about 3 days around the first appearance of the HV trip and the subsequent start of HV training. The plots on the right show the current (top) and HV setting (bottom) during the full recovery procedure, which lasted about two weeks. The nominal HV setting for this gap is 2600 V; the average current in presence of colliding beams is about 0.6 µA.

The training period can last between one week and several months. The full recovery cycle for the gap above is shown in figure 4 (right). The MWPC is considered as recovered when the current at the maximum HV accepted for the training, 2.75 kV, reaches the nominal value in presence of colliding beams, for this particular case 0.6 µA, and drops to zero in the absence of beams. If the same stable condition is kept for a couple of days of operation with beams, the trained gap is put back in normal operation at the nominal voltage.
It should be noticed that the MWPC gap taken as an example in figure 4 was recovered in a relatively short time. The average duration of the training procedure is rather about two months. During this long training period, most of the affected gap remains efficient, since the high current originates from a localized area and a sufficiently high voltage is kept for most of the training time.
In addition, when access to the detector is possible, mainly during the year-end-technical-stops, all chambers affected by high currents are passed through a conditioning procedure at negative and positive HV polarity. This conditioning aims at reaching the same "goodness" criteria that were established before the chamber installation: stable operation during several hours at a positive HV of 2.85 kV with dark current below 10 nA per gap, and at a negative HV of -2.3 kV with dark current below 150 nA. The same training is applied preventively to the regions where the largest number of trips were observed, with the result that approximately 50% of the gaps have been treated this way during nine years of operation.

Statistics of HV trips and training results

Since the start of the LHC in 2010, a total of 375 MWPC gaps were affected by trips due to ME and treated in situ with the method described above. Only 27 gaps could not be restored to the normal operation. Table 2 reports the total number of gaps affected by HV trips observed every year of data taking since 2010, together with the integrated luminosity and the run length. The latter is defined as the number of effective days with colliding beams. The number of affected gaps is split into gaps tripping for the first time ("new trips") and gaps that had already tripped in the previous years ("recurrent trips").

Year	2010	2011	2012	2015	2016	2017	2018	Total
Effective run days	29	56	76	39	86	80	72	438
Integrated lumin. (pb^{-1})	40	1220	2210	370	1910	1990	2460	10200
New trips	90	84	69	11	76	18	27	375
Recurrent trips	0	31	67	15	74	32	32	251

Table 2. Days of LHC beam and integrated luminosity per year since 2010, number of gaps tripping for the first time ("new trips") and gaps which had already tripped in the previous years ("recurrent trips").

Regarding the distribution over time, we suffered a higher trip frequency when LHC was in the luminosity ramp-up phase, although the integrated luminosity was rather low in those periods. In figure 5 the cumulative number of MWPC gaps affected at least once by HV trips, normalized to the total number of gaps (4944), is shown as a function of the total number of effective run days. The percentage of gaps affected after nine years of operation is still below 8% which reflects the high quality standards maintained during the chamber construction. The 375 gaps affected are distributed over 259 out of the 1368 MWPCs, demonstrating that most of the time only one gap in a chamber is affected by ME and suggesting that possible problems occur mostly in the construction phase, thus pointing more to single gaps than to the full multi-gap chamber. The curve is flattening out over the years of operation.

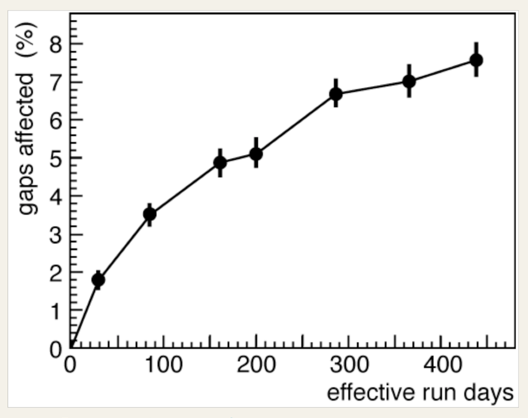

Figure 5. Fractional number of new trips observed in the detector, with statistical error, as a function of the effective run time (days), between 2010 and 2018, normalized to the total number of gaps (4944). The values are evaluated after each year of data taking.

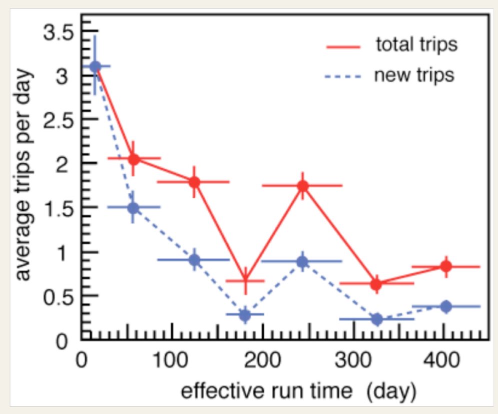

Figure 6. Average number of trips per day observed during each year of data taking, as a function of the effective run time (days); the total number of trips is shown in red (full line), the number of new trips in blue (dotted line).

The average number of affected gaps per day is reported in figure 6 for all gaps and for the ones affected for the first time. The number of gaps with recurrent trips is much higher than what expected by a random effect, given the very small percentage of gaps concerned. This fact, together with the decreasing trend of new trips, is a confirmation that high current problems are rather correlated with initial chamber imperfections than ageing or other possible problems occurring during the run. An exception to the decreasing trend is observed around 250 effective run days (during the 2016 run), when we suffered from a sharp increase in the trip frequency, which is due to a significant increase of the chamber gas gain. The cause could not be fully explained, but seems to be linked to an unwanted change of the gas mixture.

The number of gaps with recurrent trips remains at a very reasonable level, given the fact that the number of concerned gaps is steadily increasing with time. In figure 7 the number of recurrent trips per day is normalized to the total number of gaps tripping in the previous year. The recurrences observed during the last two years is around 0.1% per day, equivalent to less than 10% probability during the full run. This demonstrates that the adopted training procedure solves the problems in most of the cases.

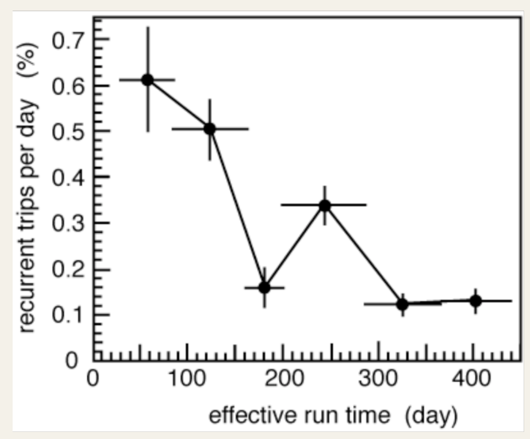

Figure 7. Average number of recurrent trips per day observed during each year of data taking normalized to the total number of gaps tripped in the previous years.

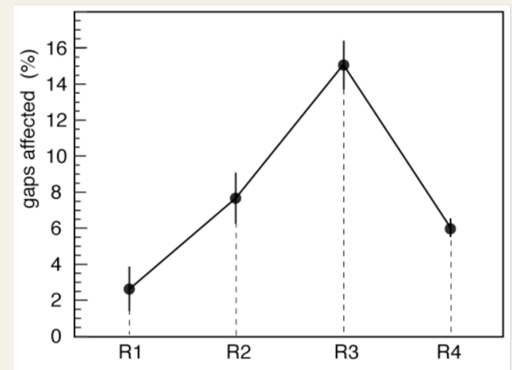

Figure 8. Fractional number of gaps affected by HV trips in each region of the detector, normalized to the total number of gaps present in the same region, with statistical error.

Some of the key features which are expected to contribute to the increase of probability for a gap to manifest high current problems are the particle flux and the active area of the MWPC gaps. While the particle flux dose per unit area strongly decreases from region R1 to region R4, the area of the gaps scales for R1, R2, R3, R4 with the ratio 1:2:4:4 in the five stations of the detector. For this reason, it is interesting to compare the different regions. The percentage of gaps affected by HV trips in all the stations for each region is shown in figure 8. The observed values of affected gaps for regions R1, R2 and R3 turn out to be roughly consistent with proportionality to the area, and surprisingly independent of the irradiation dose per unit area. Different from this, the drop of region R4 as compared to region R3 seems following the expected behavior, given by the same gap active area and the reduced irradiation. The behavior of the inner regions R1 and R2 is presumably related to the fact that the chambers passed in this case through an additional step of the training procedure under strong irradiation at the GIF, which reduced a lot the trip probability during the subsequent running period at LHC.

Accelerated recovery of MWPCs with addition of oxygen in the gas mixture

Despite the success of the described method, the long duration of the training procedure introduces some complications for its application. This is mostly related to possible interruptions of the recovery procedure due to power cuts or planned stops in the operation of the LHC and the detector, which is of course very probable on a time scale of weeks. To optimize the duration of the recovery procedure and to make it more efficient, a new approach was investigated, consisting in the addition of a small amount of oxygen to the gas mixture during the training procedure .
To investigate the above procedure, four MWPCs were tested during LS1 in 2013-2014. In the laboratory, the localization of the cathode regions affected by ME on the damaged MWPC gaps was performed with a collimated ^{90}Sr β-source. Currents hundred times larger than the ionization current were triggered by the ^{90}Sr source. As a result of a scan performed on each of the four MWPC gaps of each chamber, seven zones affected by ME were identified, as listed in table 3.

Chamber Type	Number of detected ME zones	ME ignition voltage, (kV)	Time for recovery (h)
M2R4	2 (gap A)	2.75	3
		2.8	1
M4R4	1 (gap D)	2.7	5
M5R4	1 (gap A)	2.6	4
	1 (gap B)	2.7	3
M5R4	1 (gap A)	2.7	4
	1 (gap D)	2.8	2

Table 3. The chamber gap recovery test with oxygen: chamber type, number of damaged zones, ignition voltage, and time needed for successful recovery. The 4 gaps of a MWPC are named A, B, C, D, see figure 2 for details.

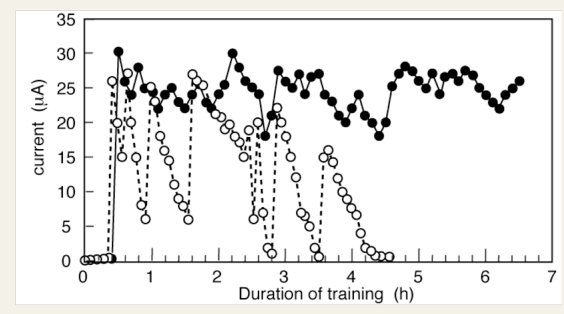

Figure 9. Current in the MWPC during the ME recovery training: nominal mixture (full circles) is compared with a mixture containing 2% of oxygen (open circles).

For each of the above zones, a recovery training was first tried for few hours with the standard gas mixture. Then a new training was performed with a new gas mixture, adding ~2% of oxygen to the nominal one. In all cases the concerned area was kept under irradiation by the ^{90}Sr β-source. Figure 9 shows the results obtained for one of the gaps. With the standard gas mixture no current decrease is observed after more than 6 hours, coherent with what was obtained in the training with colliding beams. In presence of oxygen, however, the initial current of 25 µA (ignited at the voltage of 2.6–2.7 kV) drops sharply until it raises again by a corresponding increase of the high voltage in 50V steps. After a few iterations the current finally drops to zero. The total time required to recover the ME zone in this case was around four hours. Similar results were obtained for all zones affected by ME, as listed in table 3. After the training with oxygen, all of the MWPCs above have been installed back on the apparatus and work properly, with no recurrent trip during the full Run 2 of LHC.
The above tests confirm the hypothesis of an accelerated recovery procedure in presence of oxygen, based on plasma chemical etching of silicon and organic compounds by electronegative active radicals and ozone produced in the gas discharge. Volatile compounds created during the etching are then removed by the gas flux.

Conclusion

A method for a non-invasive recovery in-situ has been developed and applied individually to all problematic gaps, consisting of a HV training in the presence of colliding beams and with MWPCs working with the standard gas mixture. The training procedure must normally be continued for a long time (two months on average), before the gaps are recovered and can be restored back to normal operation. Nevertheless, the whole LHCb muon detector could be kept close to 100% efficiency for almost a decade, as it was designed for. The redundancy build into the muon detector, using multi-gap MWPC, has been crucial to obtain this result. The recovery procedure developed and tuned over the years resulted to be very effective. Less than 1% of the chambers had to be replaced because of HV trips in 9 years of operation. The percentage of gaps treated with this method in the past and showing again high current problems decreased with time and was measured to be about 10% during the last two years of LHC operation.
With the purpose of making the training procedure faster and more efficient, a method for accelerated recovery has been investigated and successfully tested, using a small (~2%) amount of oxygen in the nominal gas mixture. This can be an important ingredient for the efficient operation of the Muon system at increased luminosity.
In general, the non-invasive character of the recovery technique discussed in this paper makes it appealing for many experiments, where the detectors operate with gas mixtures containing CF_4.