# Long-term Operation of the LHCb Multi-Wire-Proportional-Chambers

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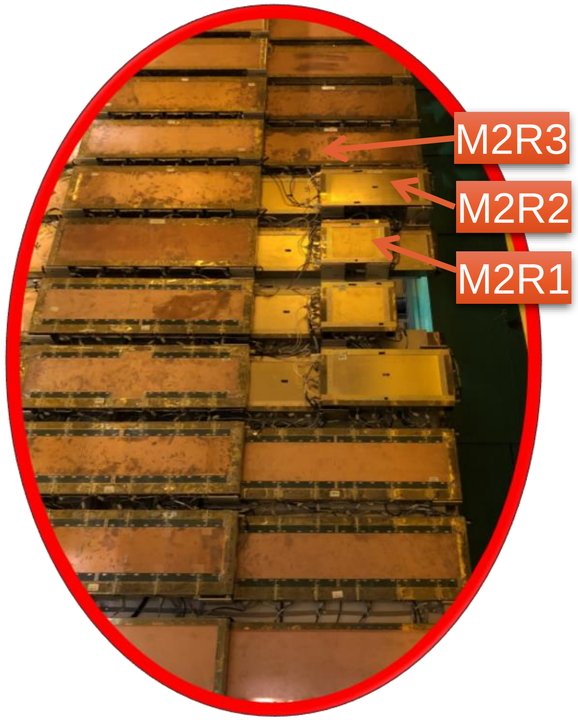
# Outlines

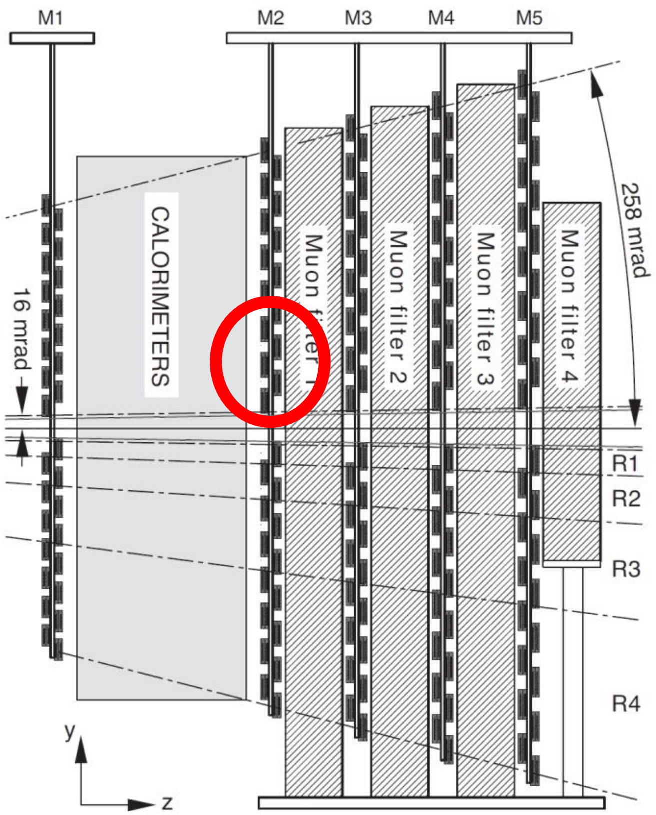
- LHCb Muon subsystem;
- Design of MWPCs;
- Gas system and operation conditions;
- The malfunctioning chambers during the Runs;
- The process of chamber recovering;
- The process of chamber recovering with oxygen;
- Results;

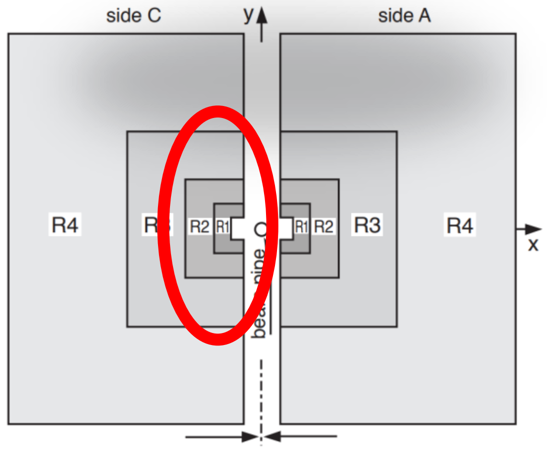
# LHCb Muon System

## LHCb Muon System:

- 5 stations M1-M5 (Run 1) reduced to 4 M2-M5 (Run 2 and Run 3);
- 4 regions R1-R4;
- 20 chamber types;
- 1368 MWPCs cover 435 $m^2$.



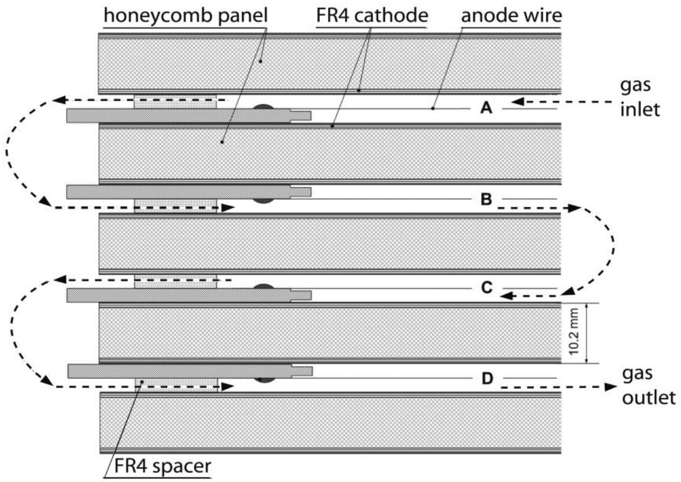




## Operational information:

- $L_{instantaneus} = 4 * 10^{32}\ cm^{-2} * s^{-1}$
- Operational efficiency > 99 %;
- More than 13 years of sustained work.

# Design of MWPC (M2-M5)

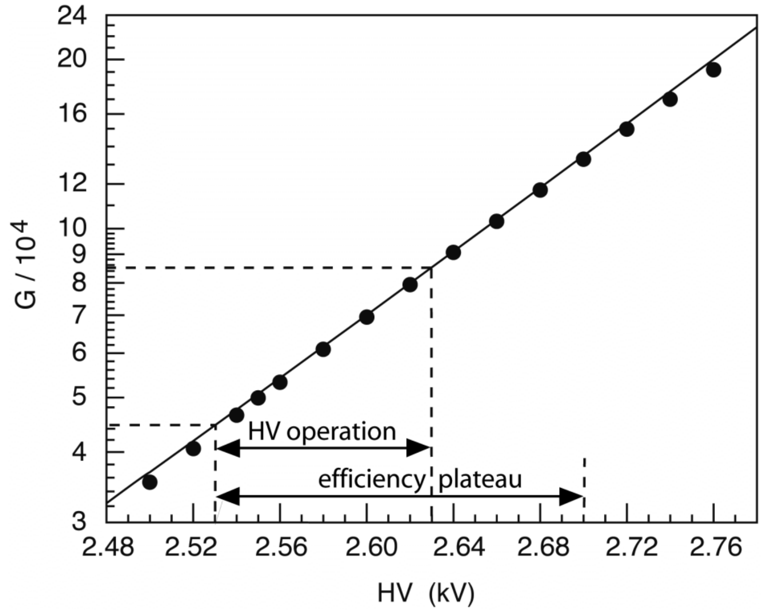
- 4 High Voltage independent gaps (A,B,C,D) per chamber;
- **Anode:** 30 µm gold coated tungsten wires;
- **Cathode**: fiber-glass plates (FR4) + 35 µm copper coating;
- Gap-structures divided by **Polyurethane Foam** planes;
- **OR**-ed readout;
- 40% $\boldsymbol{Ar}$ + 55% $\boldsymbol{CO_2}$ + 5% $\boldsymbol{CF_4}$ gas mixture;




Internal structure of MWPC

# LHCb Muon Gas System

- 40% ***Ar*** + 55% $\boldsymbol{CO_2}$ + 5% $\boldsymbol{CF_4}$ gas mixture[1];
- $\boldsymbol{CF_4}$:
  - prevents the formation of Si-deposits during MWPC operation;
  - provides to suppress an effect of Malter-like currents;
- Operations on Efficiency plateau: **2.53-2.63 kV**;
- Gas Gain coefficient on Efficiency plateau: $\mathbf{4.4*10^4}$ **-** $\mathbf{8.6*10^4}$**;**




**Gas gain as a function of Voltage in the LHCb Muon MWPCs[2]**


1. **Werner Riegler,** Detector physics and performance: simulations of the MWPCs for the LHCb muon system, LHCb-2000-060.
2. **E. Dané, G. Penso, Davide Pinci, A. Sarti**, Detailed study of the gain of the MWPCs for the LHCb muon system, NIM A, Volume 572, Issue 2, 11 March 2007, Pages 682-688.

# MWPC Initial conditions

- **General training procedure** – the process of the voltage increasing to the nominal value step by step and controlling the values of currents on gaps are in the tiny current window;
- $V_{pos}(max) = 2.85$ kV, $I_{max} < 0.010$ uA[1];
- $V_{neg}(max) = 2.30$ kV, $I_{max} < 0.150$ uA[1];

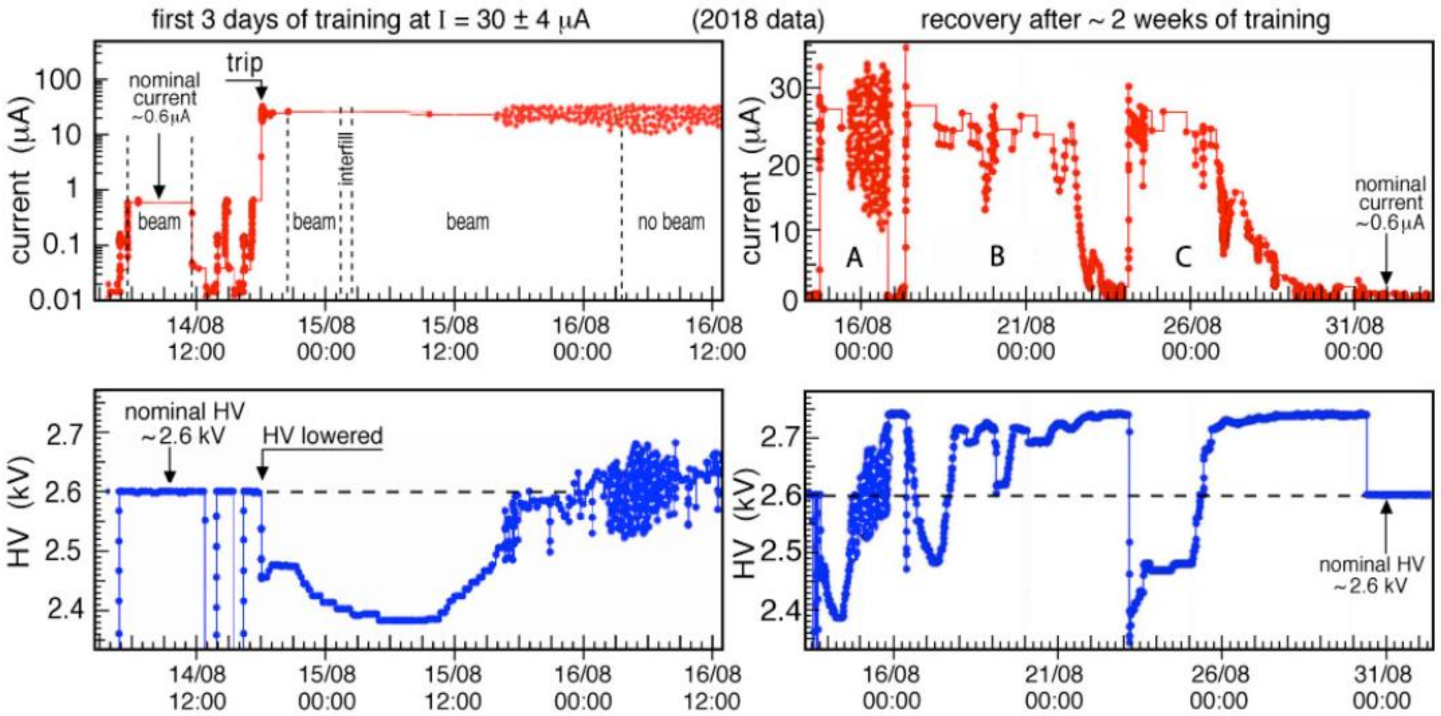
- **Additional training procedure** for R1/R2 chambers on Gamma Irradiation Facility[2];
- $V_{pos}(max) = 2.75$ kV
- $t_{irr.} = 48$ hours;
- $q_{deposited} = 1$ mC/cm.


1. **V. Souvorov et al.**, First results of an aging test of a full scale MWPC prototype for the LHCb muon system, Nucl. Instrum. Meth. A 515 (2003) 220.
2. **S. Agosteo et al**., A facility for the test of large-area muon chambers at high-rates, Nucl. Instrum. Meth. A 452 (2000) 94.

# Effectiveness of training procedure

## Status of malfunctioning MWPCs:

- Reduction of gas gain have not been observed;
- The effect of high **self-substained currents** has been detected in ~100 MWPCs gaps per each year;
- **A higher current increases the concentration of fluorine radicals, produced by CF4, which react with deposits (silicone, polymers), leading to surface etching by means of the creation of volatile products in the plasma;**
- The procedure of training provides to restore the functionality of MWPC gap affected by Malter-like currents[1].




1. **J.-S. Graulich et al.**, Conditioning of MWPCs for the LHCb Muon System, NSS/MIC IEEE 2005 Conference Record.

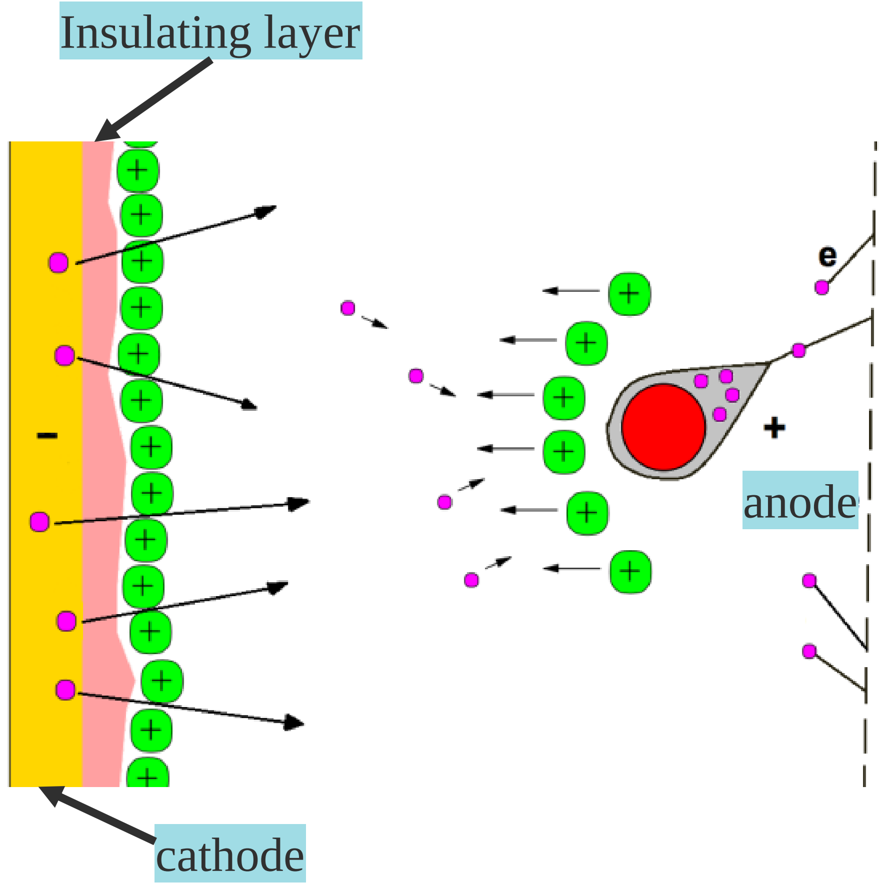
# Malter Effect

**Malter Current Effect** is secondary electron emission which appears when:

1. an insulating layer exists on the cathode;
2. the rate of ion build-up is higher than its removal from the insulating layer;
3. some ignition mechanism take place .

**Manifestation of Malter Current Effect:**

1. self-sustained discharge ignited by high intensity irradiation and micro sparks;
2. sustained uA current independent from external irradiation.



# Curing Malter-like effects in MWPC in presence of CF4

- Polyurethane foam is injected between two mold planes forming the cathode surface at the stage of MWPC production;
- A mold release agent (ACMOIL36-4600) contains 5-10% silicone;
- This product is suspected to create patches of insulating film on the cathode surface[1,2];
- Dissociation process of $CF_4$ provides to cure the Malter-like effect. Free radicals of $CF_4$ dissociation are produced around anode wires at the electric field 20 –200 kV/cm;
- The radicals $CF_3$, $\bullet CF_2$ , $F\bullet$ react with different silicon formations.
- Formed molecules of $CO_2$, $O_2$ and $SiF_4$ are removed from the detector volume by the gas flow;
- **The formation process is ongoing around anode wires. The concentration of free radicals is low around the cathode!**

$$e^- + CF_4 \rightarrow CF_3^+ + F\bullet + 2e^-$$
$$e^- + CF_4 \rightarrow \bullet CF_3 + F\bullet + e^-$$
$$e^- + CF_4 \rightarrow \bullet CF_2 + 2F\bullet + e^-$$

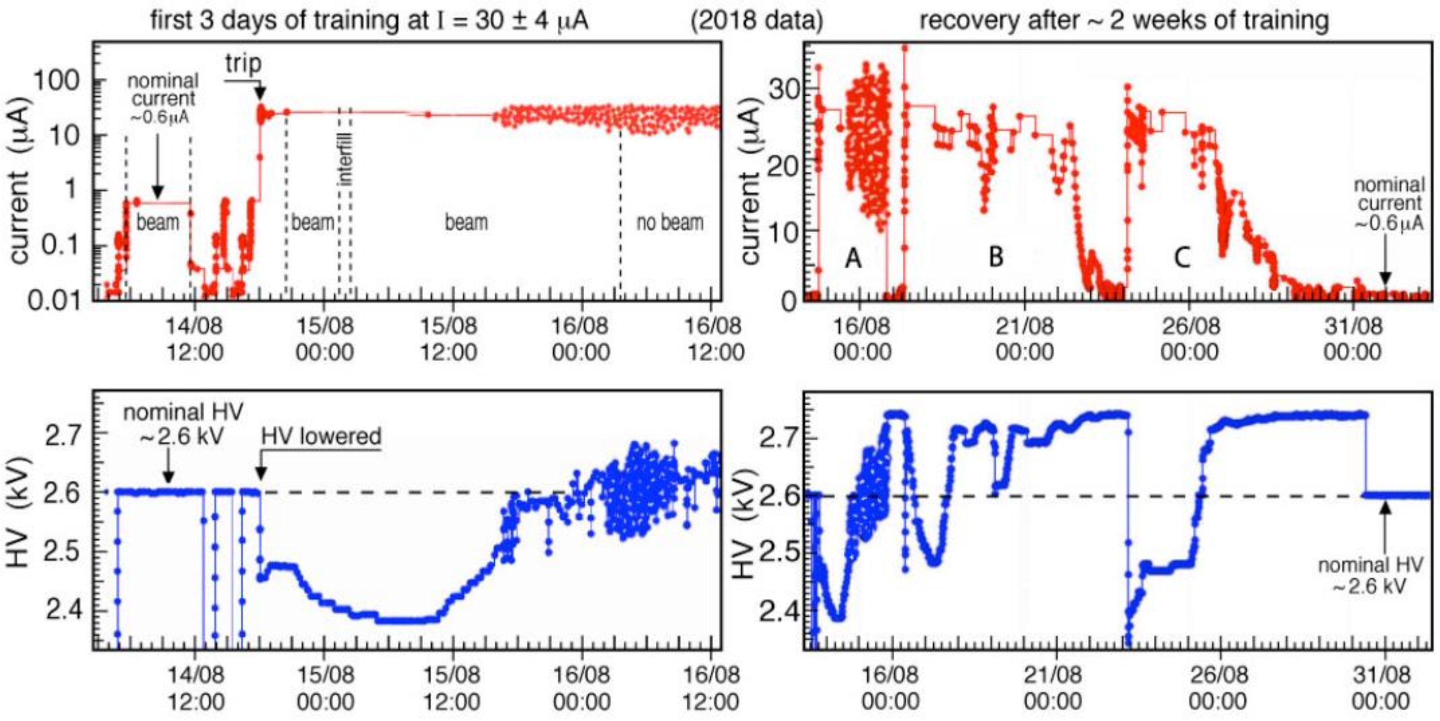
$$4F\bullet + Si \rightarrow SiF_4\uparrow$$
$$4F\bullet + SiO_2 \rightarrow SiF_4\uparrow + O_2\uparrow$$
$$Si + \bullet CF_3 + F\bullet + 2O \rightarrow SiF_4\uparrow + CO_2\uparrow$$

**The training process requires a lot of time**


1. **M. Capeans**, Aging and materials: lessons for detectors and gas systems, Nucl. Instrum. Meth. A 515 (2003) 73.
2. **S. Belostotski et al.**, Extension of the operational lifetime of the proportional chambers in the HERMES spectrometer, Nucl. Instrum. Meth. A 591 (2008) 353.

# Training procedure

- **MWPC Type:** LHCb M5R3
- **Operation conditions:**
  - Beam: V = 2.6 kV, I ≤ 0.6 uA;
  - No beam: I ~ 0 uA;
- **Affected conditions:** V = 2.6 kV, I > 30 uA;
- **Training procedure:**
  - Decreasing the voltage to safe limit: $I_{lim}$=30 uA with ΔI = 4 uA;
  - **Ramping voltage up/down step by step to hold the current around limit $I_{lim}$;**
  - Training process required ~2 weeks;
  - Restored the current values close to the nominal ones.
  - Nominal values turned back to operational conditions




**Phases of training:**

A. ~3 days. Slightly decreasing of Malter-like current, appearing of the current at the end of period;

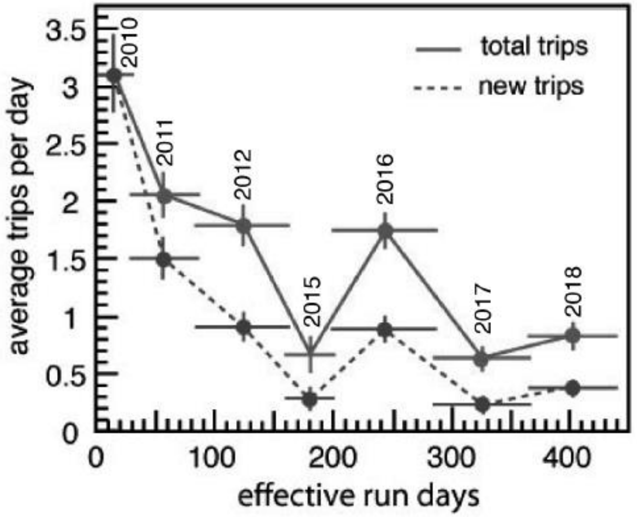
B. ~7 days. Decreasing of current value during two weeks and it appearing at the end of period;

C. ~7 days. Fully recovered after one (last) week of training.

# Training procedure: statistics

- ❑ Average duration of training is around two months (in some cases the procedure required four months);
- ❑ ~25-30 gaps go through the training procedure at the same time (efficiency loss is less than 1%);
- ❑ 375/ 4944 gaps were affected by Malter-effect and have been treated;
- ❑ 27/375 haven't been restored;
- ❑ Most of self-substained currents appeared during the luminosity ramping-up phase;
- ❑ No correlation with particle flux and integrated luminosity.

| Year | 2010 | 2011 | 2012 | 2015 | 2016 | 2017 | 2018 | Total |
|---|---|---|---|---|---|---|---|---|
| Effective run days | 29 | 56 | 76 | 39 | 86 | 80 | 72 | 438 |
| $L_{int}$ ($pb^{-1}$) | 40 | 1220 | 2210 | 370 | 1910 | 1990 | 2460 | 10200 |
| $L_{peak}$ ($10^{32}$ $cm^{-2}$ $s^{-1}$) | 1.7 | 3.8 | 4.0 | 3.5 | 3.7 | 3.5 | 4.4 | – |
| New trips | 90 | 84 | 69 | 11 | 76 | 18 | 27 | 375 |
| Recurrent trips | 0 | 31 | 67 | 15 | 74 | 32 | 32 | 251 |



# Oxygen recovering: Gas composition for accelerated recovery from Malter effect

- Etching rate in a $CF_4/O_2$ mixture is significantly higher in comparison to the one in a pure $CF_4$ plasma;
- Oxygen radicals provide to produce the $\bullet COF_x$
- $\bullet COF_x$ quickly dissociates with electrons and atoms and indirectly increases the number of fluorine radicals in the gas discharge plasma;
- Both oxygen molecules O• • and $*O_2$ are chemically aggressive and may be used for the etching processes;
- **$O_2$ content in MWPC working gas mixture must be optimized** due to reducing of the electron density in discharge plasma;
- The optimization of $O_2$ content in LHCb Muon MWPCs was based on a GARFIELD simulation in range of $O_2$ percentage 0-20%;
- At 1- 4 % $O_2$ content the electron attachment coefficient increases only in the drift region (around the cathode surface). While the oxygen content is more than 10%, the electron attachment occurs at the all drift and avalanche regions;
- The optimized value ~2 %.

$$O\bullet + \bullet CF_3 \rightarrow \bullet COF_2 + F\bullet$$

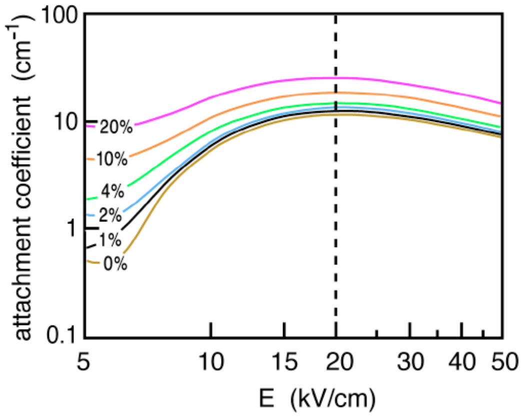
$$O\bullet + \bullet CF_2 \rightarrow \bullet COF + F\bullet$$

$$e^- + COF_2 \rightarrow \bullet COF + F\bullet + e^-$$

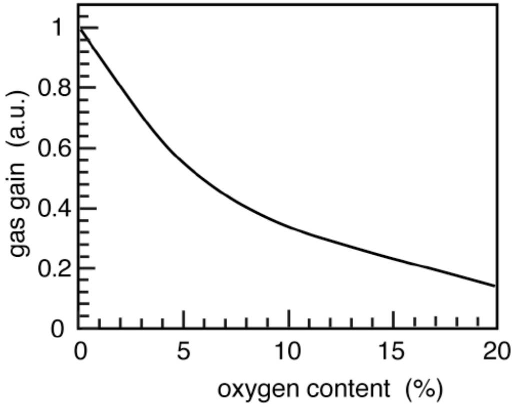
$$O\bullet + \bullet COF \rightarrow CO_2\uparrow + F\bullet$$

$$e^- + O_2 \rightarrow O^- + O^{\bullet\bullet}$$

$$e^- + O_2 \rightarrow {}^*O_2 + e^-$$




Electron attachment coefficient as a function of an electric field



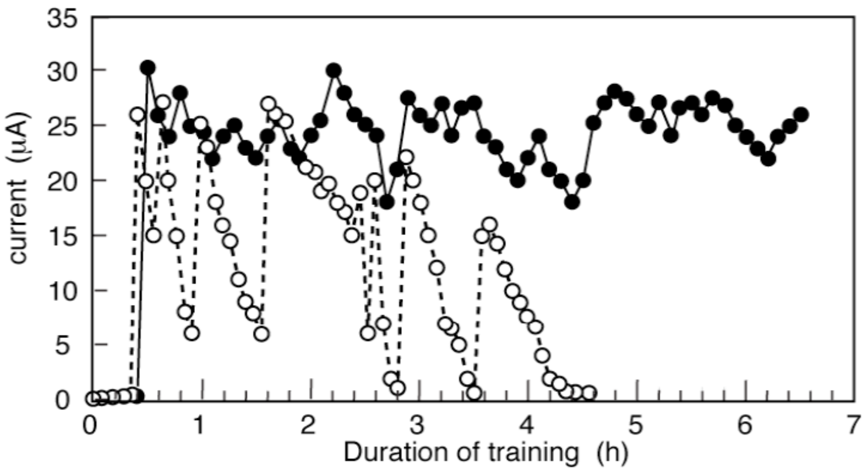

Relative gas gain coefficient as a function of Oxygen content


1. **Yu.N. Grigoryev, A.G. Gorobchuk,** Numerical Simulation of plasma-chemical reactors, Comput. Technol. 2003. Vol. 8. Special Issue. Pt. 2. P. 53–73.
2. **J. Mogab, A. C. Adams, and D. L. Flamm**, Plasma etching of Si and SiO2 - The effect of oxygen additions to CF4 plasmas, J. Appl. Phys. 49 (1978) 3796.

# Oxygen recovering: Accelerated recovery of MWPCs

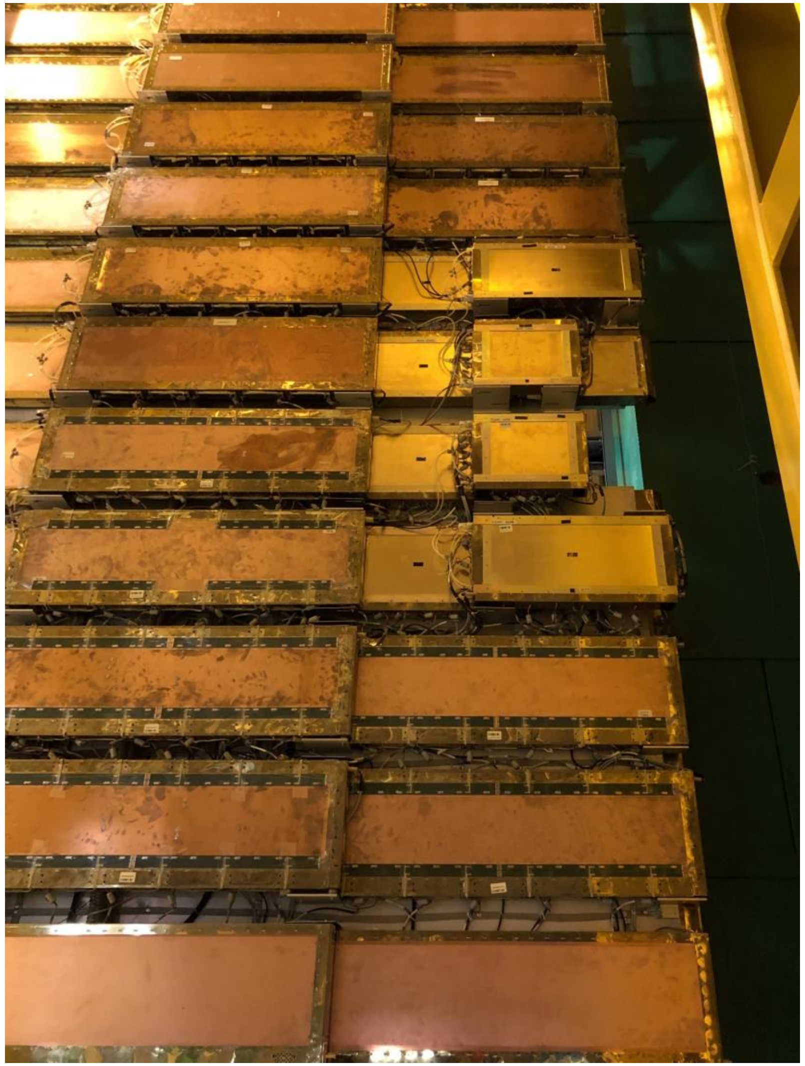
- Test the Oxygen recovering on LHCb Muon MWPCs removed from the Detector due to the high currents during LHC Long Shutdown 1;
- HV+ and HV- trainings did not provide a successfully recovering;
- Several ***“problematic” zones*** have been found during MWPCs irradiation by $Sr^{90}$ source;
- ~7 hours of training procedure use ***nominal gas mixture*** + ***$Sr^{90}$ irradiation***
- ~5 hours of training procedure use ***oxygen + nominal mixture + $Sr^{90}$ irradiation***;
- All MWPCs gaps have been recovered and mounted back to detector;
- **Successfully LHCb Muon operations with recovered chambers during Run 2.**

| 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 |
| | 1 (gap D) | 2.8 | 2 |



# Conclusion

- ✓ LHCb muon detectors **did not show a gain reduction** or any other apparent deterioration in performance;
- ✓ **19%** out of **1368** chambers were affected by self-substained currents;
- ✓ **Less than 1%** MWPCs have been replaced in 9 years of operation;
- ✓ Non-invasive method has been applied to **restore the detector efficiency**;
- ✓ Tested additional technique of **fast restoring by adding an oxygen into gas mixture**;
- ✓ **The high efficiency of both techniques have been demonstrated.**



# Many thanks for your attention!