Performance and aging studies for the ALICE muon RPCs

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Outline

1. The ALICE detector
2. Performance of ALICE MTR during LHC RUN 2
3. Aging studies with an argon plasma
4. Conclusions

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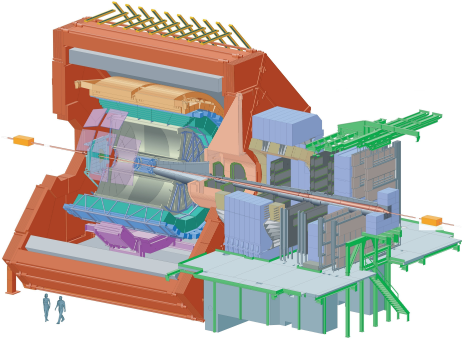
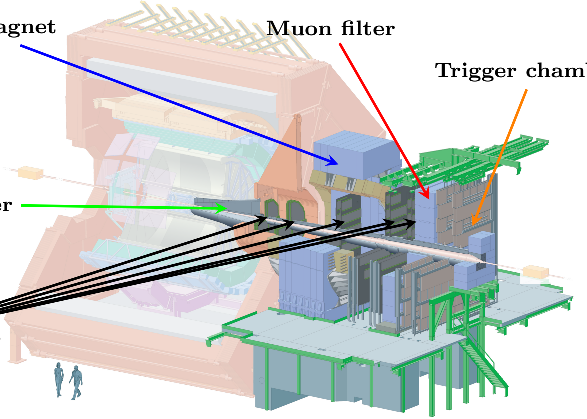
The ALICE detector

- ALICE (A Large Ion Collider Experiment) is one of the four large experiments at the LHC
- It is specialized to study signatures of the Quark Gluon Plasma (QGP) in ultra-relativistic heavy-ion collisions
- The central barrel region covers the pseudo-rapidity interval $|\eta| < 0.9$ while the forward muon spectrometer coverage is $-4 < \eta < -2.5$

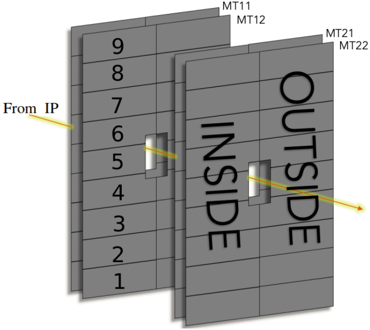


The ALICE muon spectrometer in RUN 1-2



- Set of two absorbers to reduce the flux of hadrons in the muon spectrometer
- Tracking chambers to reconstruct muon tracks
- Dipole magnet to bend the muon tracks
- Trigger system (**MTR**): composed of 4 planes of **single-gap RPC detectors**, used for online event selection and offline muon identification

- 72 single-gap RPCs organized in two stations with two planes each
- Three different shapes to accommodate the beam pipe:
  1. Long: 1 to 3 and 7 to 9
  2. Tapered (or cut): 4 and 6
  3. Short: 5
- 2 mm gas gap and 2 mm thick bakelite electrodes with low resistivity ($10^9 \div 10^{10}$ Ωcm) with a double linseed oil coating
- Total active area per detection plane $\sim 5.5 \times 6.5$ m^2
- Operated in maxi-avalanche mode (FEE w/o amplification and low threshold value) with a gas mixture of 89.7% $C_2H_2F_4$, 10% i-C_4H_{10} and 0.3% SF_6 with $\sim$ 37% Relative Humidity (RH)
- RPCs are read out on both sides by $\sim$ 21k electronics channels



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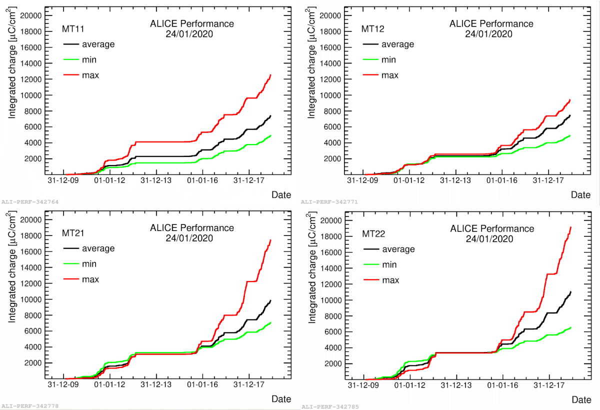
Running conditions in ALICE during RUN 2

1. 2015
   - pp @ $\sqrt{s}$ = 13 TeV and pp @ $\sqrt{s}$ = 5.02 TeV
   - Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV
2. 2016
   - pp @ $\sqrt{s}$ = 13 TeV
   - p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s_{NN}}$ = 8.16 TeV
3. 2017
   - pp @ $\sqrt{s}$ = 13 TeV
   - Xe-Xe @ $\sqrt{s}$ = 5.44 TeV
4. 2018
   - pp @ $\sqrt{s}$ = 13 TeV and pp @ $\sqrt{s}$ = 5 TeV
   - Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV
5. **Maximum counting rate** across all RPCs and all colliding systems $\sim$ 30 Hz/cm^2
6. Total recorded luminosity in run 2
   - pp @ $\sqrt{s}$ = 13 TeV. $\boldsymbol{\mathcal{L}_{INT} \sim 36\ pb^{-1}}$ and @ $\sqrt{s}$ = 5.02 TeV. $\boldsymbol{\mathcal{L}_{INT} = 1.3\ pb^{-1}}$
   - Xe-Xe @ $\sqrt{s}$ = 5.44 TeV. $\boldsymbol{\mathcal{L}_{INT} = 0.3\ \mu b^{-1}}$
   - p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV and $\sqrt{s_{NN}}$ = 8.16 TeV. $\boldsymbol{\mathcal{L}_{INT} = 3\ nb^{-1}}$ and $\boldsymbol{25\ nb^{-1}}$
   - Pb-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV. $\boldsymbol{\mathcal{L}_{INT} = 800\ \mu b^{-1}}$

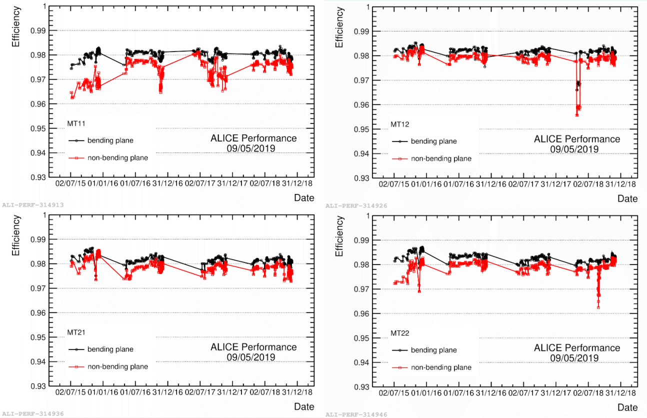
Maximum instantaneous luminosity in RUN 2 (Hz/cm^2)	
pp 5.02 TeV	10^{31}
pp 13 TeV	$5 \cdot 10^{30}$
p-Pb 5.02, 8.16 TeV	$1.5 \cdot 10^{29}$
Pb-Pb 5.02 TeV	10^{27}

- Integrated charge after dark current subtraction
- Three curves for each plane:
  1. **Black**: trend of the average integrated charge
  2. **Red**: RPC that had collected the maximum integrated charge at the end of run 2
  3. **Green**: RPC that had collected the minimum integrated charge at the end of run 2
- Aging tests up to 50 $\frac{mC}{cm^2}$ during R&D
- Most exposed gaps for each plane:
  1. MT11 $\sim 12\ \frac{mC}{cm^2}$
  2. MT12 $\sim 9\ \frac{mC}{cm^2}$
  3. MT21 $\sim 18\ \frac{mC}{cm^2}$
  4. MT22 $\sim 19\ \frac{mC}{cm^2}$



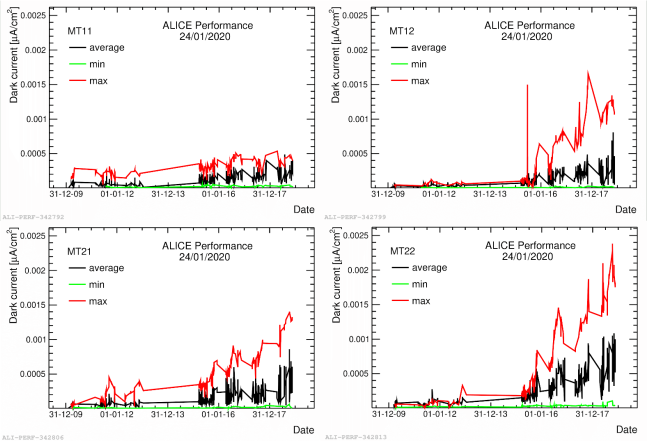
Efficiency

- Efficiency showed satisfactory results (> 96%) and stability over time for all the chambers during run 2
- Fluctuations are mainly due to local issues (noise in FEE etc.)
- Detector availability 95% throughout run 2 (the ∼ 5% inefficiency includes runs when RPCs were kept OFF due to unavailability of tracking chambers)



Dark current

- Dark current = the current absorbed by the detector when not irradiated
- Same color code as integrated charge
- Increase in the absorbed dark current over time
- Not accompanied by a loss of efficiency → causes are under investigation



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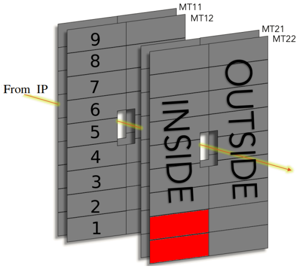
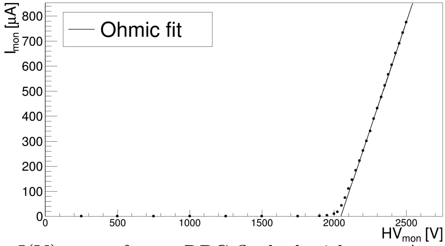
Motivation for the argon-plasma test

- An increase in the dark current absorbed by the ALICE muon RPC was observed during run 2
- No decrease in detection efficiency
  $\rightarrow$ no obvious aging effect is observed. Interesting to better understand the causes of the dark current increase
- Possible explanation: deposition of fluorinated compounds (e.g. HF) on the inner surfaces of the detectors
- Attempt to study this effect by creating an Ar plasma inside the detectors
  - Study of compounds produced by the interaction of the plasma with the inner surfaces of the detector using a Gas Chromatograph/Mass Spectrometer (GC/MS) and Ion Selective Electrode (ISE) by analyzing the exhaust gas
  - Effect on currents (?)

- Two chambers were selected for the Ar plasma treatment: MT 22 IN 1 and MT 22 IN 2
- The plasma was created and maintained at different currents
- GC/MS analyses performed to study the presence (and concentration) of new compounds, ISE to measure the F^- ion production
- Periodic resistivity measurements

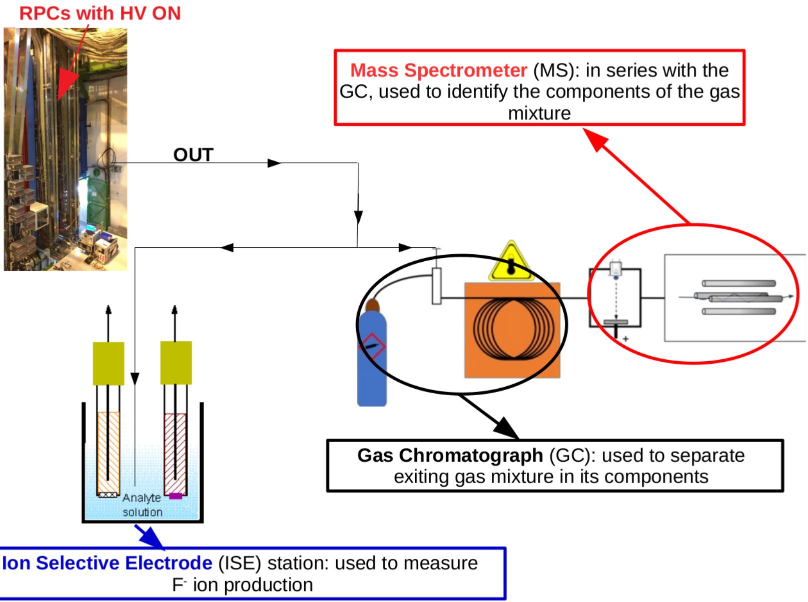


- ☐ At $\sim$ 2000 V Ar ionization begins
- ☐ When it is fully ionized
  → plasma is created
  → I(V) curve follows Ohm's law



I(V) curve for an RPC flushed with pure Ar

Experimental setup



Scheme of the experimental apparatus employed during the Ar plasma tests

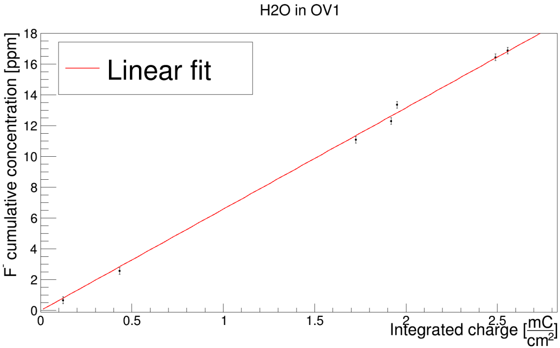
F^- ion production

- Free charges and photons formed by ion-electron recombinations in the plasma might be sufficiently energetic to detach the fluorinated compounds that have deposited during operation
- An ISE is used to identify the presence of F^- ions in the exiting gas mixture
- It provides a voltage value (mV) converted to concentration (ppm) via a calibration curve
- Integrated measurements were performed
  $\rightarrow$ gas is bubbled through 33 ml of distilled water and the pH of the solution is buffered with the $TISAB$[1] II solution
  $\rightarrow$ the concentration of accumulated F^- ions is measured after a few hours of integration

[1] TISAB = Total Ionic Strength Adjustment Buffer, used to improve the F^- ions concentration measurements

Correlation between cumulative F^- ion production and integrated charge

- Visible correlation between accumulated F^- ions and integrated charge



- F^- ions might be produced by the "cleaning" action of the Ar plasma
- Accumulation rate does not seem to slow down up to $\sim 2.5\ \frac{mC}{cm^2}$ of integrated charge $\rightarrow$ presence of residual fluorinated impurities inside the chambers (?)

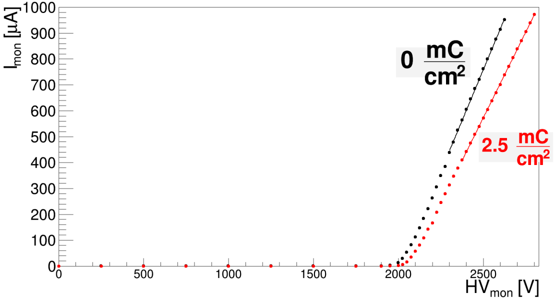
Bulk resistivity

- Ar plasma represents a short circuit between the bakelite electrodes → considered as two series resistors
- Linear fit to the Ohmic part of the I(V) curve provides $\frac{1}{R}$
- Estimate of the bulk resistivity as:

$$\overline{\rho} = \frac{RS}{2l} \tag{1}$$

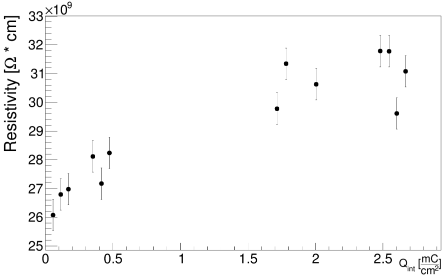
where $\overline{\rho}$ is the mean resistivity, S is the RPC surface (270x70 cm^2) and l is the electrode thickness (2 mm)

- The values of resistivity are corrected for temperature effects

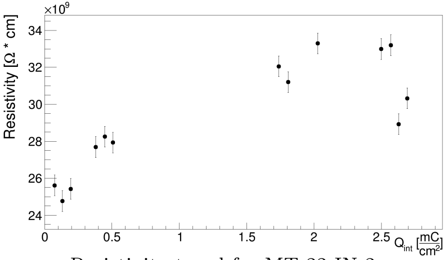


Different I(V) curves in Ar for different values of integrated charge

Bulk resistivity trend



Resistivity trend for MT 22 IN 1

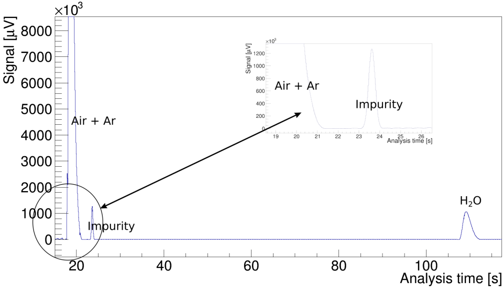


Resistivity trend for MT 22 IN 2

- Bulk resistivity increases as the integrated charge increases
- Probably due to a drying effect of the plasma on the bakelite

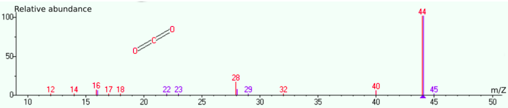
CO_2 production

- GC/MS analyses showed the presence of an impurity when the plasma is created (HV ON)



Chromatogram taken during Ar plasma tests

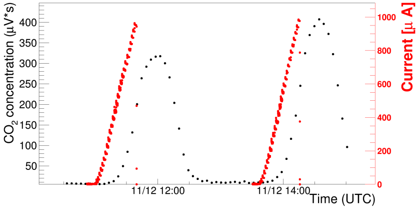
- Impurity identified as CO_2 thanks to the mass spectrometer (MS)



Identification of impurity as CO_2

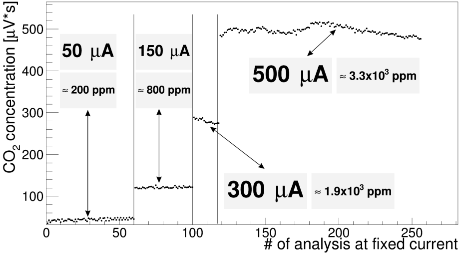
Correlation between applied current and CO_2

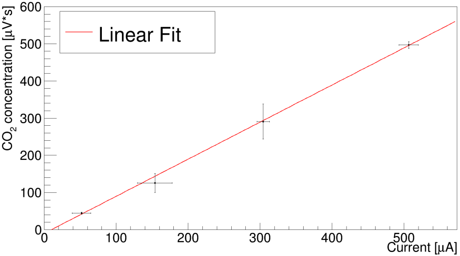
- If the current is increased → the CO_2 concentration increases
- Time lag between current increase and CO_2 observation ∼ 30 min



Time lag observed during two resistivity scans

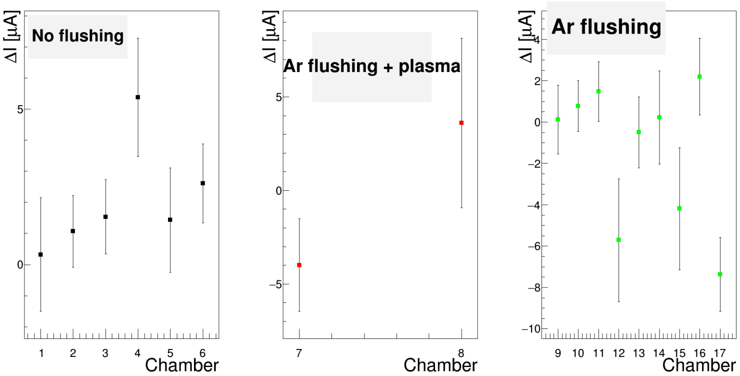
- A strong correlation between the applied current and the CO_2 concentration (given by the area under the peak in the chromatogram, measured in μV*s) is observed





Dark current comparison

- Some RPCs were flushed with Ar but the HV was kept OFF (no plasma was created) and some were kept as a reference (not flushed with argon at all)
- Plot of the quantity ΔI = current after the test - current before the test, with the ALICE standard gas mixture for all the chambers flushed with Ar



- No significant effect on the absorbed current is observed, either in the chambers treated with Ar plasma or the ones left untouched

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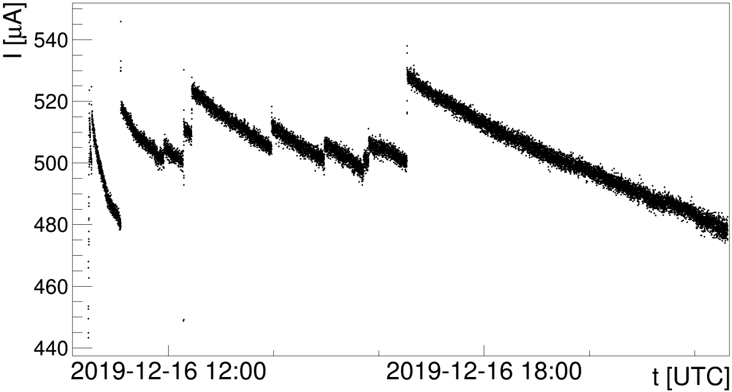
Conclusions

- The ALICE muon RPCs have shown satisfactory results during run 2:
- Efficiency was stable over time and was typically $> 96\%$
- Some of the chambers have collected a significant amount of charge wrt to the certified lifetime and may have to be replaced[2] before run 3
- An increase in the absorbed dark current was observed
- An Ar plasma test was carried out on the ALICE muon RPCs in order to gain more insights into such an increase:
  1. The production of F^- ions was observed in the exiting gas mixture
  2. An increase in the bulk resistivity was observed during these tests
  3. The production of CO_2 correlated with the circulating current was observed
  4. No significant effect on the dark current at the working point is observed
- Investigation ongoing to find possible explanations for the observed effects

[2] See Livia Terlizzi's talk today @ 14:20

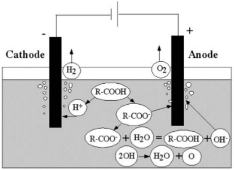
- Another observation that can point to a resistivity increase is the following:



- Keeping the HV constant, the current steadily decreases over time
- The current steps correspond to a manual raise in the HV

Possible explanation for the CO_2 production (1)

- Va'vra proposed a conduction model in linseed oil[3] based on ionic current



Conduction in linseed oil

- Linseed oil is a very complicated substance, composed of various fatty acids
- When polymerized, the fatty acids can be described as R-COOH where R is a complicated carbon-based chain and "-COOH" is a carboxyl group

- The mechanism works as follows: R-COOH molecules break into R-COO$^-$ and H$^+$:

$$\text{R-COOH} \;+\; \Delta V \longrightarrow \text{R-COO}^- \;+\; \text{H}^+$$

- The R-COO$^-$ might react with water to recreate R-COOH and OH$^-$:

$$\text{R-COO}^- \;+\; H_2O \longrightarrow \text{R-COOH} \;+\; OH^-$$

- R-COOH returns the fatty acid and OH$^-$ delivers the charge to the anode and H$^+$ delivers the charge to the cathode, forming H_2 and escaping near the cathode

$$2OH \longrightarrow H_2O \;+\; 2O$$

- Lastly, $2O \rightarrow O_2$ and it delivers oxygen near the anode

[3] J. Va'vra, "Physics and chemistry of aging–early developments" in Nuclear Instruments and Methods in Physics Research A 515 (2003) 1–14

Possible explanation for the CO_2 production (2)

- The key element in the previous reaction is water
- The conduction of current "consumes" the water in the linseed oil
  → This could explain the observed resistivity increase
- Note that, due to the high circulating current, many R-COO$^-$ molecules are formed. In this situation, the Kolbe electrolysis[4] could also be taking place:

$$2RCOO^- \xrightarrow[-2CO_2]{-2e^-} R\text{-}R$$

- Va'vra observed the presence of gas bubbles in his tests
  → Might be oxygen and hydrogen
- If this model was correct, it could explain both the resistivity increase and the CO_2 production

[4] https://www.organic-chemistry.org/namedreactions/kolbe-electrolysis.shtm