

Comment list

- ☑ L79: Please mention the GWP of the third gas used to operate the RPCs at CERN as well.
- ☑ L82: Experts → users or physicists (its unbecoming to call oneself as experts if though they are)
- ☑ L85: Its understood that an eco friendly replacement is required for all the GHGs so why the paper is focussed only on finding the replacement for C₂H₂F₄ only? Even though the percentage wise the SF₆ contribution is only 1% but looking at the total volume of gases used to operate RPCs at CERN experiments this would still be significant.
- ☑ L91: Moderate flammability → Please quantify or elaborate because even a moderate flammability is still not good.
- ☑ L95: Please provide a reference in support of this statement or quantify the increase in working voltage
- ☑ L101: two sided → two pronged or bi-directional
- ☑ L104-105: Not a clear statement. What do you mean by simulated by performing aging test? It's a simply prolong operation of RPC with eco-friendly gas mixture or something more is being communicated here?
- ☑ L106: simulating → Mimicking
- ☑ L140: sends → sending it to detectors. Gas flow,
- ☑ L151-152: Provide a reference in support of this statement.
- ☑ L155: few ten of V → a few tens of volt
- ☑ L166: highlighted → highlighting
- ☑ L167: 3 and 6 m → 3 m and 6 m or 3 and 6 meters
- ☑ L168: (blue rectangles, the internal ones and red rectangle, the external ones)
- ☑ L180: specific front end electrons → Please provide a bit more detail on these front end boards or provide a reference for the sake of clarity
- ☑ Table 2: In the eco friendly gas mixture, which gas is acting as a primary ionising gas under different compositions? Why SF₆ concentration increased from 0.3% in STD to 1% in all other gas mixtures? Shouldn't this increased concentration should also be taken into account while comparing the performances with the STD mixture?

R: To reply to your first part of the question, we report here some numbers on the HFO/R134a and CO₂ to explain.

- In the standard gas mixture, the primary ionizing gas is the **R134a**, which has a first ionization energy (I) of 95 eV and it produces a number of primary electron/ion pairs (N_p) of 80 pairs/cm. Of course, this gas is also electronegative so it also contributes to capture some free electrons (less than SF₆ though)
- The same numbers for the HFO are: I = 92 eV and N_p = 89.5 pairs/cm (the figures for these gases are taken from this [reference](#)) and for CO₂ one has: I = 13.8 eV and N_p = 36 pairs/cm (this values are taken from Sauli's book "GASEOUS RADIATION DETECTORS", as reported in table 2.1 at page 27).

In principle the HFO is much more dense than the CO₂ so it is the main contributor to the primary ionization in the eco-friendly candidates (this is the reason why if you increase the HFO fraction in the mixture you get a higher maximum efficiency, although it's not clearly seen in the plots we put in the paper you can check this [thesis](#), especially Fig. 6.8 where you see that increasing greatly the HFO fraction the maximum efficiency clearly increases). Of course the CO₂ is also participating slightly in the primary ionization but the main contributor is the HFO (this also explains why the maximum efficiency reached under irradiation decreases less if you add more HFO to the mixture).

There is another point to consider, which is the fact that, as stated in this [paper](#), the effective Townsend coefficient of HFO is much lower than R134a and this explains why you have to increase the operating voltage with respect to the standard mixture to get a similar charge multiplication and this explains why the efficiency curves of mixtures with a higher HFO concentration are shifted to higher voltages (this can be explained by considering the higher electron attachment coefficient of HFO, as shown [here](#)). This higher electron attachment coefficient could also explain why the large signal probability decreases when more HFO is added to the mixture.

Lastly, the increased fraction of SF₆ simply has the effect to shift the working point to higher values, the reason why we had to increase it is because otherwise it was observed that the mixture would not be quenched enough and the large signal probability would be too large because the electronegativity/attachment of the HFO does not suffice in reducing the contamination of large signals.

- ~~L213-215: The different digitizer time window for different RPCs would make the comparison of their performances difficult unless it has been accounted in while carrying out the analysis, for eg. While looking at the charge distribution or signal strength? I suggest re-writing this paragraph by adding more information and explanation.~~
R: Explained in a later section how this was kept into account (added reference to this section in the paragraph)
- ~~Fig. 3: Follow consistent labelling and legends.~~
- ~~Fig. 3: The fit of STD plateau in right panel seems to be quite bad. The efficiency seems continue to rise while fit becomes flat. Since the error bars on these numbers are not visible so I assume that they are quite small.~~
R: The error bars are small because of the high statistics (i.e. in the beam test we have decided to use 5000 trigger for each HV value to reduce the errors as much as possible). We don't reach efficiency saturation because the use of a single thin gap of 1 mm
- ~~Fig. 3, left panel: The current density plot seems to be problematic. It has non-zero value before 9000 V and then goes to zero and then suddenly rises to more than 1 nA/cm² around 9700 V. What is the cause of such behaviour? Doesn't seem like a random fluctuations. The right panel current density seems stable.~~
R: Some values of current were not saved during the scan and were put to 0 by the author of the plot, we removed the missing values now

- L228: Is it 30/65 or 35/60 as mentioned in the Table 2?
- L233-234: How is asymptotic efficiency extracted, for eg. In Fig. 3 (right panel) for STD gas mixture?
R: We get the maximum efficiency from the fit (it is on of the three free parameters of the logistic function reported in Eq. 2). Even in the case of the STD gas mixture for BARI-1p0 where the fit doesn't match very well the data because of no efficiency saturation, as explained earlier
- L242: Is CO₂ acting as primary ionising gas here?
- R:** See previous reply on the question related to Table 2
- L246: Is CO₂ decreasing from 69% to 65 or 60%?
R: From 69 to 60% (as reported in table 2)
- L246: plateau efficiency increases from EGO3 to EGO2. How? Which figure? This is clearly not the case in Fig. 3. The efficiencies seems pretty much the same for the 2 mixtures.
R: We removed this phrase since the 1% increase in efficiency observed cannot be easily attributed to the slightly increased concentration of HFO
- L285-286: Shouldn't the charge collected be more with the lower threshold value?
R: Having a lower threshold leads to "tag" signals with a lower charge as efficient and the signal charge for those is smaller, hence there is a higher number of signals with small charge, leading to a smaller average value in the charge distribution histogram
- L300: Of course → But,
- L301: Is HFO acting as a quenching gas or an ionising gas? If this is a quenching then CO₂ is ionising? This seems confusing because in L245-246 an opposite effect is observed where by decreasing the ionising gas (presumably CO₂) the efficiency is claimed to increase though its not seen in Fig. 3. Please see above comments.
R: see reply to comment related to table 2 for the quenching/ionizing gas for the increase in efficiency we have applied the previous comment but, as stated earlier (in the comment on table 2, you can check this thesis to see the effect of adding more HFO to the maximum efficiency, visible because the author of the thesis added much more HFO to the mixture)
- Again in L320-321, it is being claimed that by increasing the HFO fraction above 50% is advisable in order to reach high efficiency plateau. This claim is opposite to the effect described in L301. So basically section 3.1.3 is not consistent with the earlier paras.
R: see reply to question on Table 2
- L324-325: The statement about increase of working point also increases with the HFO concentration increase is true if HFO is acting as quenching gas.
R: see reply to question on Table 2
- Fig. 6: Please use label large signal probability or Streamer probability in both the panel to be consistent. Since in the text you clarified that its large signal probability so use that instead.
R: We have also changed the order of the entires in the legend, in order to mimic other previous plots, we also changed the colors and legend of Fig.5 right panel for consistency with other figures in the paper
- Fig. 6, left panel: The probability for EGO3 and MIX4 seems to be same but then there is a drop for EGO2. What is the explanation for this? MIX4 is in between EGO3

and ECO2 so this is so clear. Please explain. Also, what is the order of errors on these numbers? In the right panel, why is there a few percent probability for ECO3 below threshold voltage around 11k? Also, the STD and ECO3 data is not plotted beyond 500V?

R:

- See reply to question on table 2 for the reply to the first part of the question
- Order of error is much less than 1% and the error bars are shown in the left panel of the figure (we changed the markers to make the error bar more visible)
- The few % points for ECO3 at -1 kV are there due to very low statistics at such low high voltage values and it happened that all the few events have a high large signal probability
- STD and ECO3 don't go beyond due to the chosen high voltage values (note that the points scanned for each mixture are different) and it was not needed to go further since we already well in the efficiency plateau region (this can be checked by looking at the definition of working point)

L337-339: Again, if CO2 is primary ionising gas then shouldn't efficiency increase with increase in its concentration?

R: see reply to question on Table 2

L347: ad → as

Fig. 7: Adding HFO decreases the efficiency in higher background but adding further more HFO increases the efficiency (middle panel). This is surprising. What could be the reason behind it. No explanation is provided.

L359-360: The statement is not true according to data in Fig. 8. In fact, ALICE and EP-DT detectors shows very different rates, almost a factor of 2 different. Am I missing something here?

R: The reason is that the EPDT detector is much closer to the source (3m) while ALICE is at 6 m from the source, so the same ABS corresponds to different rates

L360-362: How is the variation with the distance? $1/r^2$ or $1/r$? Please clarify.

R: The absolute photon rate varies as $1/r^2$ (with r distance from the source) but one needs to consider other factors such as: 1) absorption of photons from other setups 2) intrinsic gamma detection efficiency of the RPCs (for example the electrodes of the EPDT and ALICE RPCs are made by different companies) → One cannot expect to find the $1/r^2$ dependence only looking at the measured gamma rates

L364-365: Again, the results are not comparable. The right panel of Fig. 8 shows a large variation in rates for different gas mixtures. The rates vary by more than a factor of 2. Since these two detectors are at the same distance so dependence on distance is not a factor here but still they are very different.

R: This can be explained by considering the previous comment (i.e. different distances from the source and so on)

Fig. 8, right panel: There is also a big variation in the rates for various gas mixtures which doesn't show any particular pattern. For eg. ECO2 rates at around 20 ABS is about 100 whereas ECO3 is almost around 180 with STD in between. This is again very surprising. The similar variation is not present in the Fig. 8 left panel. In Fig. 9, the ECO3 and ECO2 rates are very similar for the ABS of 20 but again different for

~~ABS of 10. So all these three figures doesn't seem to be in agreement with each other and appears to convey different messages.~~

R: we discussed with the responsible for this specific detector and the answer we got is that this detector showed quite a high current (even without gamma background) which could be related to a varying dark counting rates which could, in principle, affect also the rate measured with a higher gamma background

- ~~While the gaps for BARI and EP-DT are different but its same for ALICE and EP-DT so again this doesn't explain the variations amongst different detectors and different mixtures.~~

R: Same observation as before related to different distance of the two RPCs and so on

- L381: Only the last data point for ECO3 drops significantly otherwise the variation in efficiencies seems consistent. What could be the cause for this?

- ~~Fig. 10: Why the efficiencies are different for the same gamma cluster size between ALICE and EP-DT even though they are having similar detector parameters?~~

R: The EPDT detector, at the time of this data taking, was showing a very high absorbed current, leading to an Ohmic voltage drop across the bakelite, effectively reducing the voltage applied to the gas. For this reason the efficiency is lower for the same gamma rate

- ~~L391-393: So, what is the conclusion? Is 1mm gap better for the RPC performance?~~

R: We added a closing sentence to this paragraph explaining that, on the one hand, it is true that the working point shift for increasing gamma irradiation is lower for a 1 mm gap RPC with respect to a 2 mm RPC but, on the other hand, it is also true that the maximum efficiency reached in this case decreases so it is not necessarily better for performance. The smaller shift of working point can be explained by considering that, for increasing irradiation, the current absorbed by the detector increases and this leads to a voltage drop across the resistive electrodes which, as explained briefly in the paper, leads to a reduction of the high voltage effectively applied to the gas. In the case of the 1 mm RPC, the electrodes are thinner and the resistance is lower (proportional to the thickness) so for the same gamma rate the voltage drop across the bakelite is smaller with respect to thicker RPCs. The maximum efficiency is lower due to the reduced electric field and the thinner gap, which reduces the probability of primary ionization sufficiently further from the electrodes, allowing for charge multiplication to reach values above threshold

- ~~L396: is a significance feature -> is of significance~~

- ~~Fig. 14: The data right panel is having large error bars for ECO2 and ECO3 but more data should have been collected with these mixtures instead. Also, since the ALICE and BARI detectors are different so what is being compared here?~~

R: The error bars are due to the fact that the cluster size is normally calculated in number of strips (and not cm) and in order to normalize here, we decided to convert to cm and for this specific detector, the pitch of the strips is 0.5 cm and this translates into the big errors that we see in the plot. For the second part of the question, we are not really comparing the two detectors here, rather we are showing a series of plots of the same quantities for all the detectors to highlight that, even though the RPCs are different, those quantities have similar behaviors for the different mixtures

- ~~What is the cause for the large current in the BARI detector? Was it investigated?~~

R: The cause was not deeply investigated yet, mainly due to time reason. Our idea now is that it might have something to do with some studies that have been performed in a beam test not described in the paper, where the RPC was tested at high irradiation levels with mixtures of almost pure CO₂, leading to very high absorbed current and big charge release inside the gas (although we don't have a clear way to test this idea)

~~L446: Indeed->Moreover,~~

~~Fig. 16: Please explain this figure in more detail as it contains too much information which has not been explained in the text. For eg. What are dotted lines?~~

~~L477-481: There are just too many free parameters and variations allowed in the study so it would be difficult to conclude things succinctly from this.~~

R: We removed and reshaped this sentence to make them more clear and explained further what is shown in fig. 16

~~L506-508: While Fig. 17 shows an increasing trend of Ohmic dark current in the beginning but it doesn't shows a stable behavior for higher values. A distribution of the order of 30-40% can be seen all over at higher values for the left panel of the Fig. so I really do not see a stable behavior. The right panel figure does shows a more stable behavior for the 9.8kV range. An explanation for this randomness would be needed or else the authors need to quantify what they mean by stable behavior.~~

R: Indeed for the right portion of the figure the Ohmic part of the dark current is much more stable with respect to the left one. Although the variation you report in the comment (30-40%) is of course there, this could be attributed to different reasons. For example:

- The dark current at working point is estimated by a fit to the I(HV) curve, as reported in the left panel of fig. 15, and although the fit is always executed in the same HV range, the error on the current measured in each point is not the same every week
- We noticed that if you take a dark current scan as soon as the irradiation is stopped, you get higher values than if you wait some time after the irradiation is stopped and this time is not always there when the source is off
- Slight temperature variations could also influence the value of Ohmic dark current if the latter is flowing through the bakelite as well as changes in the relative humidity of the gas mixture could influence the ohmic dark current

The bottom line is that there are no clear explanations for the moment and, as explained towards the end of section 4.2 (after Fig. 18) we are planning to monitor the relative humidity of the mixture going in each detector (for now we have only a measurement of the gas mixture dew point before the gas is split among the different detectors so maybe it changes when entering in the RPCs (plastic pipes are permeable to the water present in air) and also we are comparing the performance of the RPCs after irradiation to see if this increase of the dark current has brought up with it a worsening in the performance of the detectors. In general, what we mean with "stable behavior" is that the dark current is not increasing dramatically over time (this kind of oscillation around a stable values are deemed stable)

~~What is the reason for a factor of 2 difference in the integrated charge density between SHiP and EPDT even though their efficiencies do not differ by a factor of 2?~~

R: The EPDT RPC has a higher value of dark current (total in this case, since the Ohmic part is subtracted in the calculation of integrated charge) which leads to a

higher integrated charge, moreover the SHiP RPC was initially kept at much lower efficiency than the other RPCs and this also explains this phenomenon

- ☑ ~~Section 4.2 ends without any analysis and conclusion so what the readers are supposed to learn from it? Its understood that these are very preliminary results for aging studies and hence authors may not be willing to draw any conclusion but the authors at least must explain what they learned from their observations and what other studies are needed in order to draw some concrete conclusions.~~

R: We swapped the last two paragraphs in this section to have a conclusive sentence of the paragraph

- ☑ ~~L532-535: It seems that the efficiency is always a bit lower with irradiation while it is claimed otherwise in these lines.~~

R: Indeed, we specified in this sentence that this is the case only in the source off condition. For what concerns the situation under irradiation we describe it later on in the section

- ☑ ~~L540-542: Again what is claimed here is not supported by Figs. 3 and 6. These figures clearly shows that the operating region increased for eco friendly alternatives. Or are these conclusions based on some other figures? If so then please state?~~

R: This is observed by looking at figures 6 alone, in the sense that one can see that the streamer probability for the STD gas mixture is almost 0 at WP and it stays below 10% up to 500 V above the working point. The same cannot be said for the eco-friendly alternatives which, as shown in fig 6, have a low large signal probability at WP but it increases much faster wrt STD, leading to the mentioned smaller operation region. Hope this clarifies this comment

- ☑ ~~L553 & 554: Dangling division sign?~~

- ☑ ~~L555: visible → pronounced~~

- ☑ ~~L558: ECO → ECO2 (35/50 or 35/60)?~~

- ☑ ~~L561-562: Again Figs. 16 & 17 does not show stable current under irradiation over time? Should we be looking at some other figure to draw this conclusion?~~

R:

- Fig. 16 shows the trend of the total current absorbed by the detector no matter the source status (i.e. with and without irradiation) vs the charge integrated by the RPC. For the left panel, from 0 to 20 mC/cm² the current is higher because the high voltage applied is higher (as it can be seen from the red line) and then the trend is quite stable over time. There is another discrete step just after the 40 mC/cm² mark and that could be due to the fact that other detectors in front of ours have been removed, leading to a higher irradiation rate and a higher current. For what concerns the right panel, the high voltage was increased in steps so it is expected that the current increases accordingly, though in each “high voltage step” the current is stable. Only toward the end of the irradiation period we saw an increase and the cause is still being investigated and we don’t have an answer at the moment
- Fig. 17 shows the trend of the dark current only (both ohmic and total) extrapolated at working point. In the left panel one can see that, after an initial increase, the ohmic dark current (in red) is stable over time (with a small spread of course) while the total dark current (in blue) keeps increasing and then fluctuates a lot (note that the reason for this behavior is still being investigated and we don’t have a clear answer for the moment). The right

panel of Fig. 17 shows the trend for another RPC and the discrete steps that are visible are due to the fact that in the different sections of the figure we take the dark current at different values of high voltage (so one expects it to be higher) but in each period of the figure the current is stable.

L563: ~~will~~ → would be

L568: ~~lead~~ → led

L571: ~~eco friendly alternatives~~ → eco friendly alternatives studies in this manuscript.