s. Ref. No.: NIMA-D-20-00828R1

Title: On the properties of a negative-ion TPC prototype with GridPix readout Nuclear Inst. and Methods in Physics Research, A

Replies to the reviewer are written in blue

We thank the reviewer for their careful reading of the manuscript. We appreciate the constructive feedback, and have addressed all comments and questions. Please find our responses below.

Reviewer #1: Thank you for this revised version, and the extra information, which I read with interest.

I have a few more requests and inquiries. I also think one final, careful round of language polishing would be advantageous. (I have flagged a few language issues below, but definitely not all.)

In your reply, you explained how the efficiency was measured, but I would still like to understand the mechanism for why the single ion efficiency ends up being about 60%. This matters for designing future detectors that are closer to 100% efficiency, which is important, given the small minority carrier signals. Is the main inefficiency due to gain fluctuations, which can cause the single electron signal to go below threshold? Are two ions in coincidence needed to go above threshold with high probability? So then the 60% efficiency is charge density and drift velocity (and hence gas) dependent? Does the measurements from Isobutane/Argon then really apply to the negative ion drift gas? Does a single avalanche always hit a single pixel, or is there charge sharing that plays a role here? Anything else that contributes to the 60%?

Related question: Please add a comment about why you did you not simply operate at higher gain? It seems just a bit higher gain would have greatly increased the single ion efficiency.

ANSWER: In our previous reply we answered how we determined the single electron efficiency from the measured time over threshold. Raising the gain (so using a higher grid voltage) would certainly yield a higher efficiency (one would expect above 90%).
We didnot change the grid voltage and gain to study the efficiency in detail.
In the current laser setup, one can estimate roughly the single electron efficiency;
To perform a precise measurement one has to put the detector e.g. in a testbeam.

NOTE that in our device for a 1 cm track length one would expect a clear signal of about 100 single electrons (100%). At 60% or 90% efficiency one would still observe a clear track.

For the design of a larger detector more topics should be studied (e.g. at a testbeam) to reach an optimal working point with a high efficiency. This is beyond the scope of this paper.

Additional comments by line number:

L10 (abstract): The abstract has a lot of jargon: GridPix, quad module, Timepix3, negative ion TPC, the minority carriers. Much of it is in the first sentence. Please rephrase some of this, so that it is understandable to a general HEP instrumentation person. That will make the paper more interesting to a broader audience. For example, instead of "minority carriers" you could state that "multiple species of charge carrying ions with different drift velocity" are used, the word "quad module" is not needed since you state four chips are used in the same sentence, Timepix3 is "the Timepix3 pixelated readout ASIC" etc.

CHANGED TO: The performance of a GridPix detector to read out a negative ion TPC was studied using a module with four GridPix chips that are based on the Timepix3 pixelated readout ASIC.
CHANGED TO: The GridPix chips are sensitive to single drift ions, and allow for the determination of the drift distance using the velocities of the different ion species.

Also In the Conclusion we updated the same text.

L23 (abstract): if you want to state the quantitative drift distance precision, please state for which drift distance the result is.

CHANGED TO: For 429 detected ions, the precision on the absolute drift distance is expected to be 1.33 mm for a mean drift distance of 20 mm.

L33: "drift? by a field" sounds strange, rephrase

CHANGED TO: the electric field

L33: not clear which "resolution" is referred to. Add another word.

CHANGED TO: The track position resolution

L39-43: "If oxygen", "can be reconstructed" -> this sounds hypothetical, it's not fully clear that this is all referring to previous demonstrations by the DRIFT experiment. Rephrase slightly. ("With oxygen", "were reconstructed")

CHANGED TO It was demonstrated that when oxygen was present in the gas mixture, extra species of ions called minority carriers with a larger mobility were created

L51: signal strength -> not fully clear what is meant, I think "the amount of detected charge"? rephrase

CHANGED TO: the amount of detected charge.

L54: "in the context of a future" -> rephrase ("for a future")

CHANGED TO: for a future

Fig2: Is this a photograph or a high-quality rendering? It looks like a photo, but then "omitted" is not clear. I think you mean the guard was not installed or removed?

ANSWER: it is a photograph with text added
CHANGED TO: not yet installed to show the underlying wire bond PCB,

L90: verb missing after 2W

CHANGED TO: is used in the LV regulator.

92-94: "8 quad modules", "4 chips", usually small numbers like these are written as text
CHANGED TO: Eight quad modules ; four chips

L113-114: explain how you know the attachment distance is <200 microns for this concentration

ANSWER: A large attachment distance would show up in an increased resolution in e.g. the transverse plane. The data shown in Figure 9 allows for a resolution contribution from attachment of at most 86-126 microns (fitted resolution at z=0 and 5 mmm).

L115-116: briefly describe how oxygen and water vapor concentrations were measured, e.g. just state what type of instrument.

ANSWER: O2 is measured with a Mettler-Toledo trace oxygen meter, sensor InPro6950i. The humidity is measured with a Sensirion sensor type SHT85.

Fig 4 caption, last sentence should be: "The laser track direction is shown in purple".

DONE

L125-130: please also mention the noise level in electrons here, along with the sampling frequency or period at which it applies.

ANSWER In general the noise level is very low as you can see from the event display.
In the paper we don't want to quote any noise level, because e.g. our setup is sensitive to cosmics and particle backgrounds in the lab (that is not underground).
In our previous reply we added a display where one could see background (not chip noise).
Typically, we have 15 background hits/s for 262144 pixels.
It is likely that this can be brought down several orders of magnitude by going underground and adjusting the pixel thresholds. The fine granularity will also allow to reduce particle backgrounds.

L132: Add citation for MOPA.

ANSWER This is discussed in the reference [14]
TO MAKE THIS CLEAR IN THE TEXT CHANGED: "The laser " TO: This laser

L168, 169: "per run with" is a bit unclear. Break up long sentence and carefully/explicitly define "run".

ANSWER: Each run is taken at a different electric field strength. This is already described in lines 136-140.
CHANGED TO: In order to determine the drift properties, a `global' fit is made per run. Each run corresponds to a given electric field strength. A run has measurements taken at different drift distances.

Explain exactly what is done, instead of writing 'global' fit. My understanding is that Figure 5 is an example of one run? Are you really fitting this entire distribution (including the different drift lengths) in one go? That's how I read the current text in l168-169. But the text further below suggests that you are actually fitting each drift length within the run separately. I suspect you are actually doing a simultaneous fit to multiple datasets, which are not combined, but share fit parameters. Just give a bit more detail.

ANSWER: the new text should be clearer.

ANSWER: Indeed Fig 5 is one run. One run number corresponds to one E field setting. Inside the run, data for different z positions is fitted simultanuously. The fit function is given in Eq. 1. The fit parameters mu1 and r2 mu1 - that correspond to the mean drift times for majority and minority carriers - are shown in Fig 7.

L170 drift time -> drift time distribution.

DONE: The drift time t distribution is fitted

L179: I'm still unclear on whether the fraction of ions from minority carriers is really constant, as assumed in the analysis. In the extra plots you sent, you are showing the "leading peak height" and "subleading peak height" versus drift distance. Are these heights defined so that the ratios of those heights, is equal to the ratio of f2/f1? The plots you sent has a ratio that varies from 0.5 to 0.1, so holding this constant in the fit seems like a problem, as it differs from the assumption of fixed f2/f1. But I wonder if you forgot to include the width of the peak in the ratio plot you sent? The interesting quantity is the _integral_ of each peak versus drift length, and the ratio of those integrals.

ANSWER: Indeed leading peak height = f1 and subleading = f2. And f1 and f2 are the integrals given in Eq. 1 The ratio plot clearly shows that for drift distances above 15 mm f2/f1 goes to a plateau and constant. From this observation one can conclude that the fraction of ions from minority carriers is reasonably constant.
The region below 15 mm the fit is getting less and less sensitive to the fraction: the reason is clear: the peaks are merged and cannot be separated anymore.

If you force the ratio f2/f1 for the short-drift-length fits based on the other fits, aren't you then forcing the fitter to incorrectly detect a large minority peak, even if it may not actually be present?

ANSWER: We are not forcing a large minority peak; In the paper it is written that f2 is fixed to 4.4% (a small value). The region below 15 mm the fit is getting less and less sensitive to the fraction: the reason is clear the peaks are merged and cannot be separated anymore.

The larger question I am trying to get at is this: is the minority peak still reliably observable after large drift distances, for each event? If not, large drift distances cannot be distinguished from short drift distances.

ANSWER: from the plot one can conclude the higher the drift distance the better one can observe and separate the majority and minority peaks.

For example, in an experiment with single electron efficiency < 1, the minority carriers may end up below threshold unless there are multiple that arrive within a short time. You can see now why I also asked about the efficiency details. Typically, charge density also matters for efficiency.

ANSWER: The efficiency vs drift distance is in our opinion a different topic.
You wonder probably whether the different species of ions get absorbed if they drift longer distances. To study this effect we studied the data: the number of carriers was fitted as a function of drift distance. It remains constant within 8% for 35 mm of drift.
From this observation we conclude that no large absorption process takes place during the drift process.

My understanding is that you have on average of ~two minority carriers per event. Doesn't that mean that there's a probability of (0.4)^2 = 16% that neither of these minority carriers are detected? In that case, there should be some fraction of events where the fiducialization via minority carrier fails. Then, the diffusion might become more become important.

ANSWER: With the current intensity of the laser we create 43 ions and 4.4% so ~2 are minority carriers. If we increase the intensity of the laser we can also create ten times more ions.

ANSWER: It is possible that not enough minority carriers are created and detected to measure the z position. It is therefore important to have enough of them in an actual experimental setup.

You sent a nice error analysis, but it ignores that the minority carrier may not always be detected. Also minority carriers constrain the gas choice to NID gases. I think both the NID and the use of diffusion are very promising, and the combined use of both which you show here is particularly nice.

THANKS

ANSWER: As replied above: it is important to choose a gas in with sufficient minority carriers.

Some discussion, even minimal, along these lines, going into how widely this technique might work should be added. You could perhaps turn this around and say the technique demonstrated here depends on excellent single-electron sensitivity, which is one of the strengths of GridPix. GridPix also has good time resolution and spatial segmentation, enabling the longitudinal and transverse diffusion measurements in addition.

L223: this equation suggests that z increases with drift length. But on Fig 3 it is opposite. Explain the coordinate system somewhere, and make it consistent throughout paper.

ANSWER: Indeed we changed the Figure 3 and flipped the z direction.

L240-243: Is the beam symmetric in x and z? Then the beam width cannot be the leading contribution to sigma_z0? Can you then set a limit on the attachment distance?

ANSWER: The beam is approximately symmetric in x and z.
And you can set a limit on the attachment distance from these data.
Yes we can due to the high resolution set a limit; see our reply to lines 112-113.

Fig 7 caption: z-position is not drift distance with current coordinates -> just call it "drift distance" in caption

DONE

Fig 7,8: you mention larger systematic errors. I would call these systematic uncertainties instead.

DONE

The reference to gas composition in the captions sounds speculative. I would remove this unless you can back it up.

CHANGED TO: The statistical error is not shown, because it is negligible compared to the systematic uncertainties.

Is this discussed anywhere? In lines 255-257 you mention two sources of uncertainty. How do you know these statements are true?

WE COULD CHANGE TO: "In both cases, the most likely sources of uncertainty are the (local) temperature fluctuations and variations in the gas composition."

BUT WE PREFER TO: leave out this sentence.

L263 - 271. These comparisons between experiments should mention how far the drift was in each case. For DRIFT, I believe it was about 20 times the distance reported here.

ANSWER: Indeed that is relevant information: we added the mean drift distance.

L317: cite one of the reviews on directional detection here. I suggested some in my previous comments. Also a new one has just appeared on arxiv.

ANSWER: in our opinion references [18] [19] cover that.

L323: I think this idea was first proposed in: https://arxiv.org/abs/physics/0406114 Please cite them.

ANSWER: we added a reference to [15]; that is arxiv 0406114

L308: ion mobility -> state which ion. Primary charge carrier?

DONE: majority carrier ions

I don't see triggering explained anywhere. Is self-triggering used? How long does the DAQ run for each event/trigger? Please mention it briefly, as this would affect the noise rates,

CHANGED lines 135-136 TO: Data was taken using the data-driven mode of the Timepix3 chip in a series of nine automated experimental runs.
The time of the laser pulse was added to the pixel data stream.