Implications of long drift

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Module of Opportunity for DUNE - BNL - 12th November 2019

Overview

- LAr purity

- Space charge

- HV, drift and diffusion

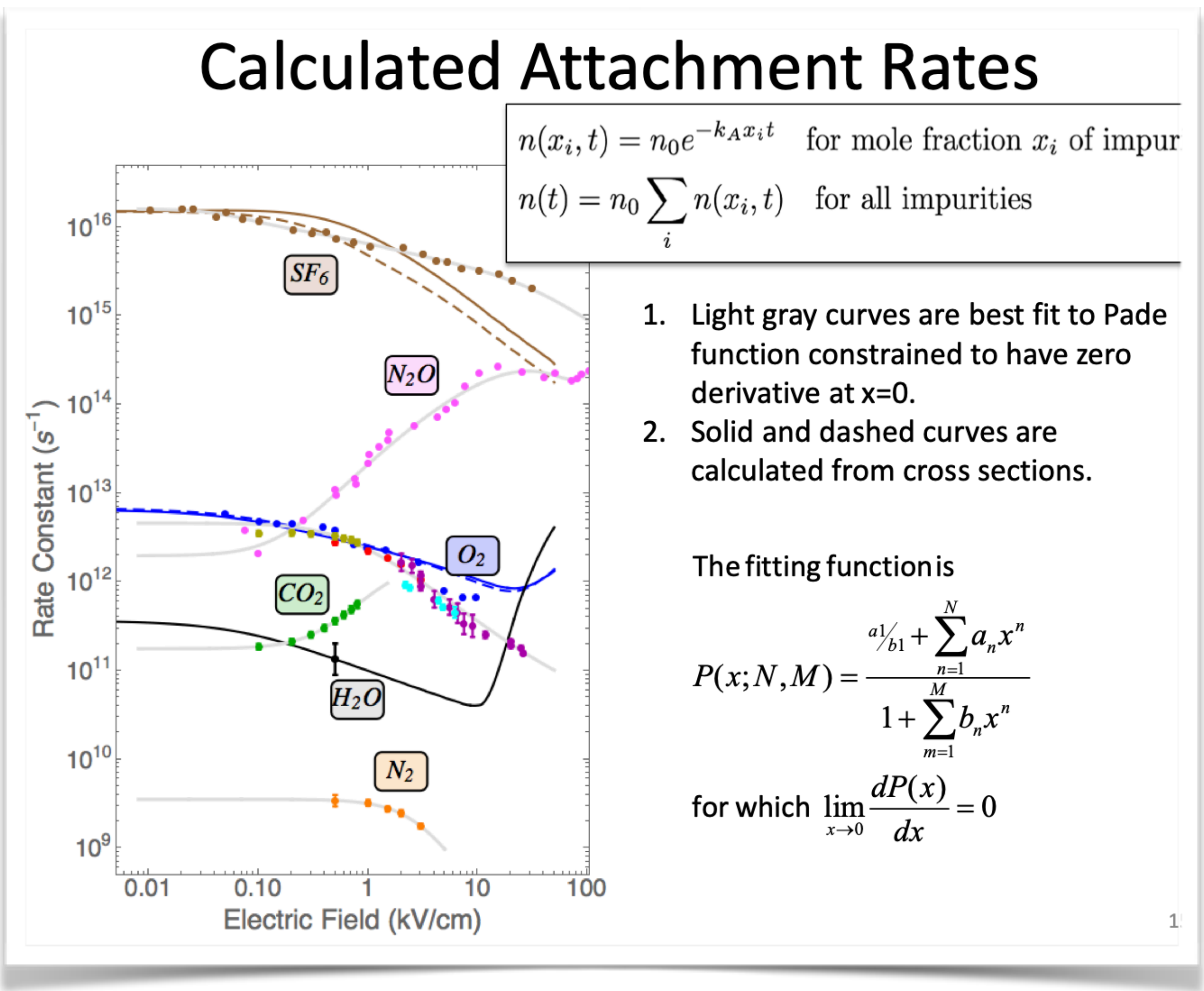
- Photon detection

- Overview of vertical drift

Liquid argon purity

Electronegative impurities diluted in liquid argon form with the drifting electrons negative ions.
Due to their much slower drift velocities, they induced negligible signals.
As a result, the electron signal attenuates along the drift.
Contamination required such that electrons drift for meters is sub-ppb level O_2^{eq}.
LAr purity is achieved continuously filtering the argon (gas and liquid) through dedicated filters.
Dilution of contamination and convection of cleaned argon depends on the LAr movement.

https://indico.cern.ch/event/782904/contributions/3258331/attachments/1774692/2885047/Electron_Attachment_in_LAr.pdf



O_2 and N_2 from air pockets or leaks to atmosphere
CO_2 and N_2 from leaks to the insulation
H_2O from outgassing materials

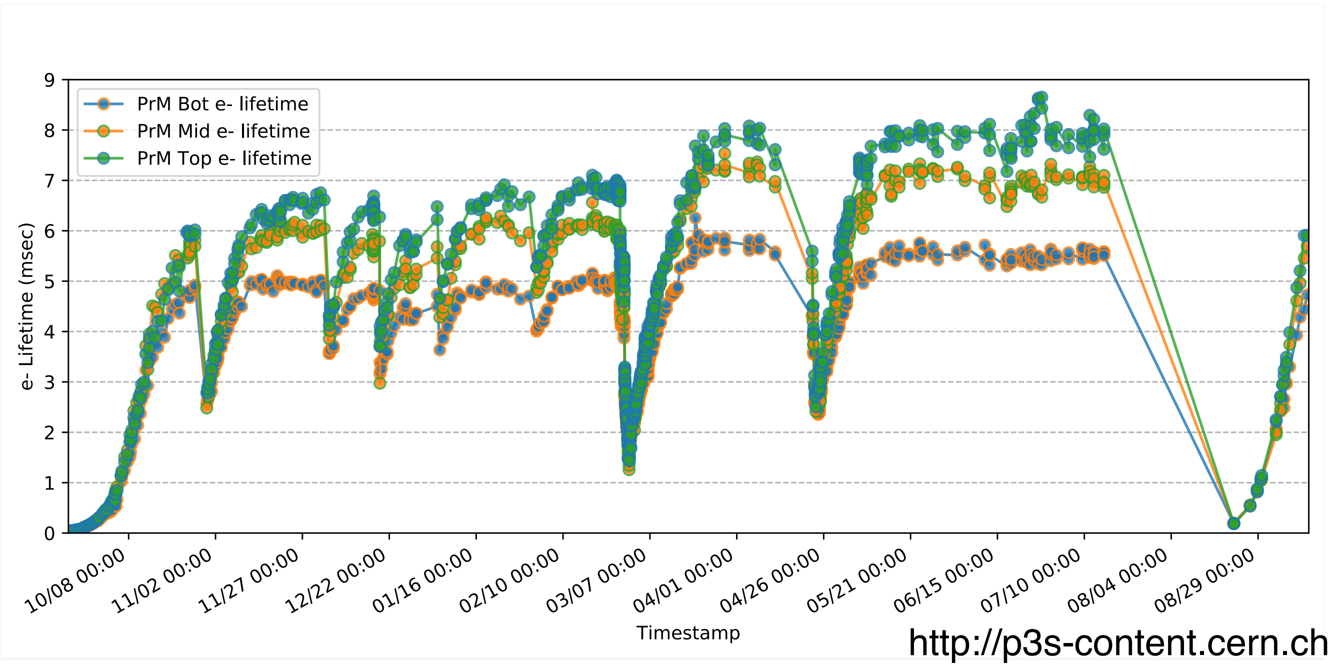
Simple model assuming perfect mixing of clean and dirty argon in the volume

$$\frac{\partial \rho_{O_2}}{\partial t} = S - \epsilon \frac{\rho_{O_2}}{\tau_{cir}}$$

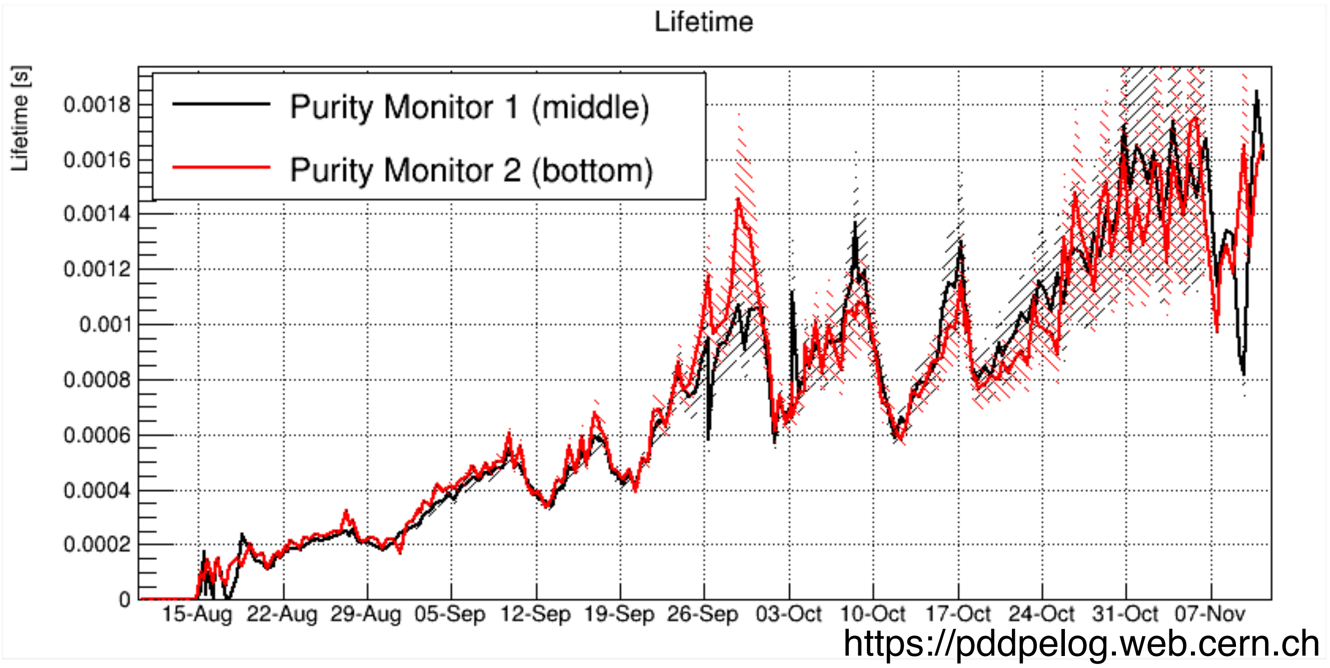
For NP04 S of the order of 5 ppt/day

ProtoDUNEs experience

NP04



NP02



No notable differences in NP02/NP04 cryo systems

Detector operated since about 15 months
Less material budget in the vapour
Less penetrations
Volume divided in two by the cathode
Open questions:
- Is the stratification accurately measured?
- Does it reflect what happens in the TPC too?

Detector operated since about three months
More material budget in the vapour
More penetrations
One single large volume
Open questions:
- Are the fluctuations real?
- Is the purity actually limited below 2 ms?

ProtoDUNEs experience

Tests on the purity in ProtoDUNE-SP are compatible with the assumption that most of the impunities comes from the vapour:
When stopping the liquid purification, contamination increase slower if the non-purified boil-off is released instead of being re-condensed.

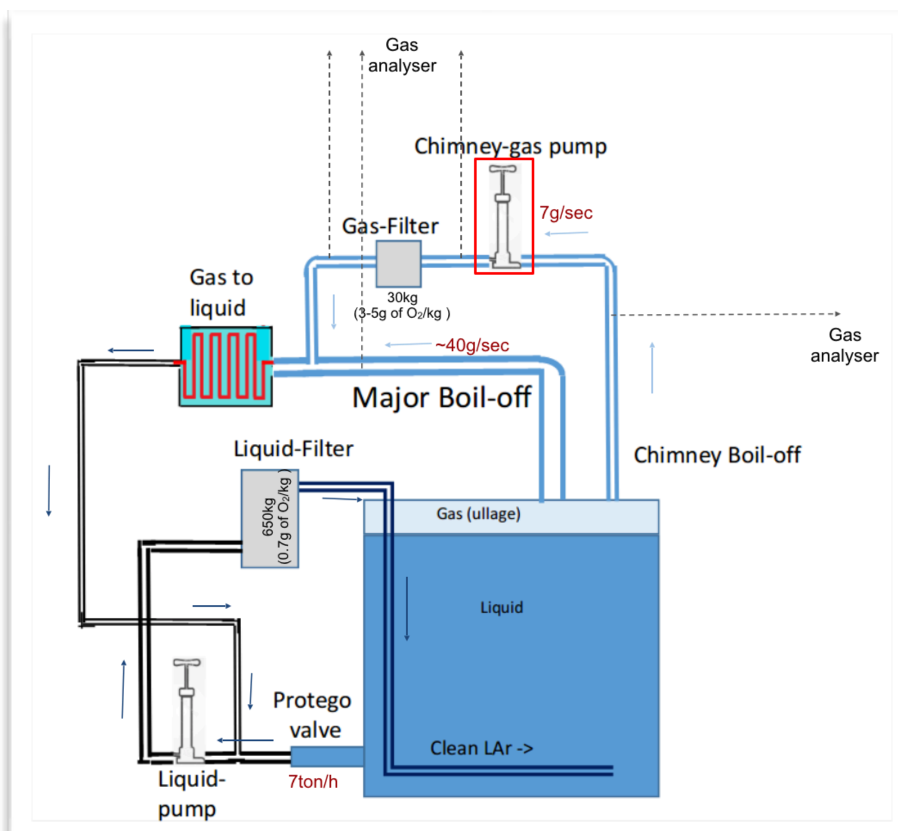
Reducing the liquid argon flow sent to the purification cartridges, the liquid argon bulk purity is not affected in the short time scale of few days, i.e. the recirculation speed is important to reach ultra high purity quickly, and less important to maintain it.

Valuable input from ProtoDUNEs operation for design considerations of DUNE modules.
Further tests on NP02 and NP04 to deeper study the behaviour of these large systems on longer time scale before the beginning of ProtoDUNE phase II.

In the next few slides *hiccoughs* related to liquid argon contamination and purification experienced during the operation of ProtoDUNEs.

NP04 purity issue (I)

The pump that pushes the warm gas argon from the chimneys through the purification cartridge developed a leak to the atmosphere on Sunday 21st of July 2019.
The problem was found with the Purity Monitors on Monday and it was confirmed by the TPC events recorded during the night.
The pump was sucking air: oxygen was filtered by warm and cold filters up to saturation, nitrogen was directly diluted in the liquid argon.
The problem was identified because the temperature of the filter increases due to the exothermal reaction of oxygen absorption.
From the size of the filters and the results on liquid argon scintillation, the contaminations after the incident are estimated to be O_2 ~ 300 ppb and N_2 ~ 5 ppm.



NP04 purity issue (II)

After the regeneration of the cold filters, the liquid purification was restarted. Given the large amount of O_2 content, the regeneration was scheduled twice.
In 5 weeks the drifting electrons lifetime was restored above the nominal 3 ms.
The N_2 contamination, which is not filtered with the available purification cartridges, reduces the light detected to about 60%.

In order to understand a complex system like NP04 it is fundamental to operate it for a long period of time.
The system is now more robust and a number of lesson were learned.
This incident was taken as an opportunity for further developments and differentiate the ways to monitor the NP04 operation.

Mitigations put in place:
- optimise the pressure in the cryostat and in the gas circuit in order to guarantee sufficient argon flow from the chimneys even without the pump,
- in the process of implementing O_2 monitor (ppm level) after the pump and after the filters,
- set up alarms on the increase of the warm filter temperatures,
- online processing of the data to monitor the number of hit per event.

NP02 filter clogging

Since the beginning of the liquid bulk purification in the middle of August 2019, the pressure across the liquid argon filters increases with time.

The pressure increase is mostly across the input mechanical filter. In order for the liquid argon pump to work properly, the pressure across the filters must be kept below 1 bar.
As a temporarily remedy, a fraction of the liquid flow can be diverted, bypassing the filters.

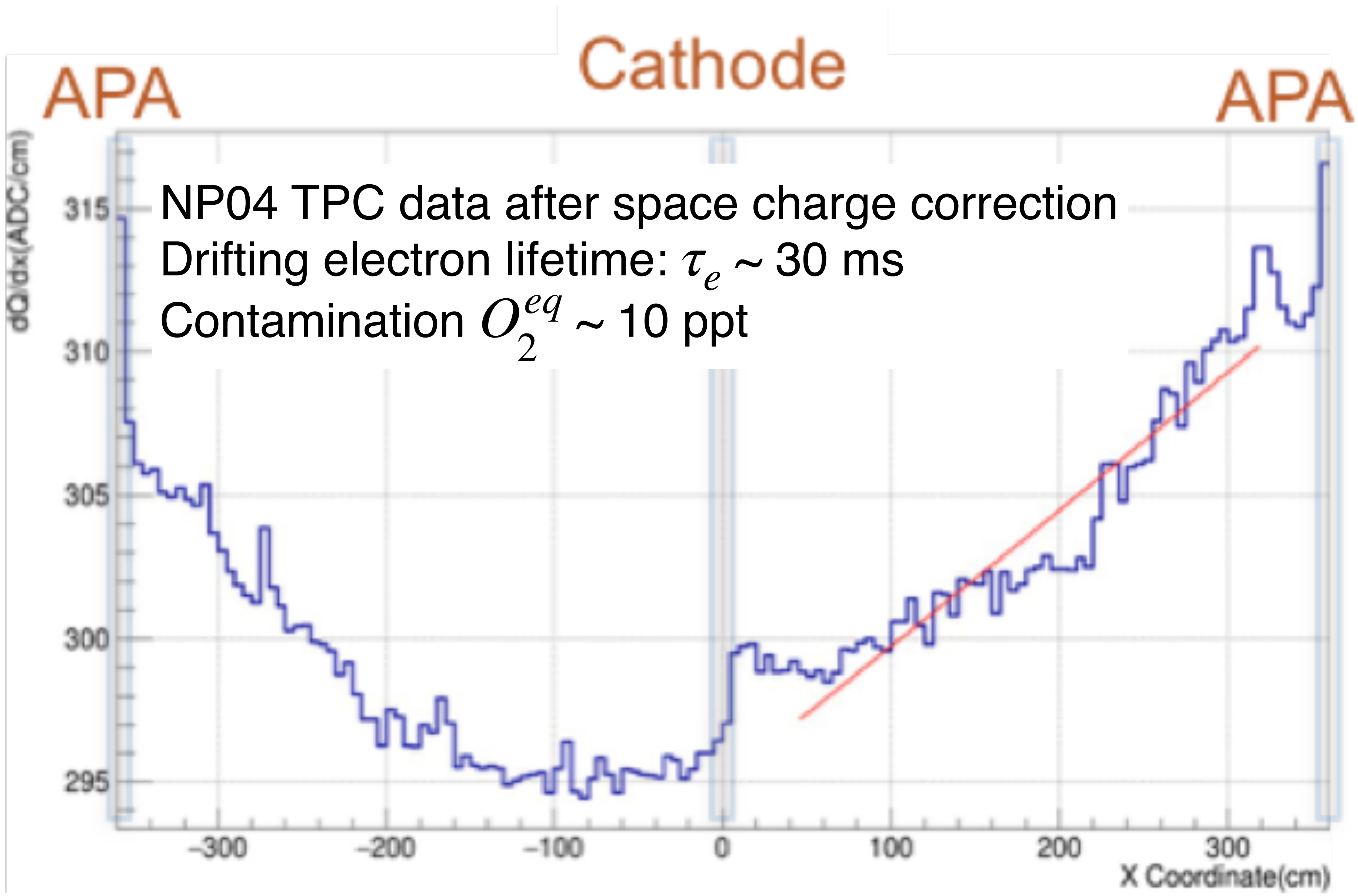
In September the input mechanical filter was warmed up and inspected with an endoscope camera. Dust-like material was extracted.

This operation was done six times.
The amount of dust extracted from the filters is now negligible.
The pressure across the filters still increases but at a smaller rate of 2-3 mbar/h.

The source of the dust is not yet identified.

Purity evaluation with the TPC

Electric field distortion due to space charge make this measurement challenging.
On surface the significant ionisation from cosmic ray results in an increase of the electric field at the cathode and a decrease at the anode, with the consequent modification of the electron ion recombination. This effect tends to overestimate the liquid argon purity.



https://indico.fnal.gov/event/21445/session/19/contribution/92/material/slides/0.pdf

How to translate to DUNE case

The contamination is at most proportional to a *surface* and it is diluted in a *volume*, therefore this figure *should* improve at larger scales.
Nonetheless, it is more difficult to purify at ppt level larger amount of liquid argon.

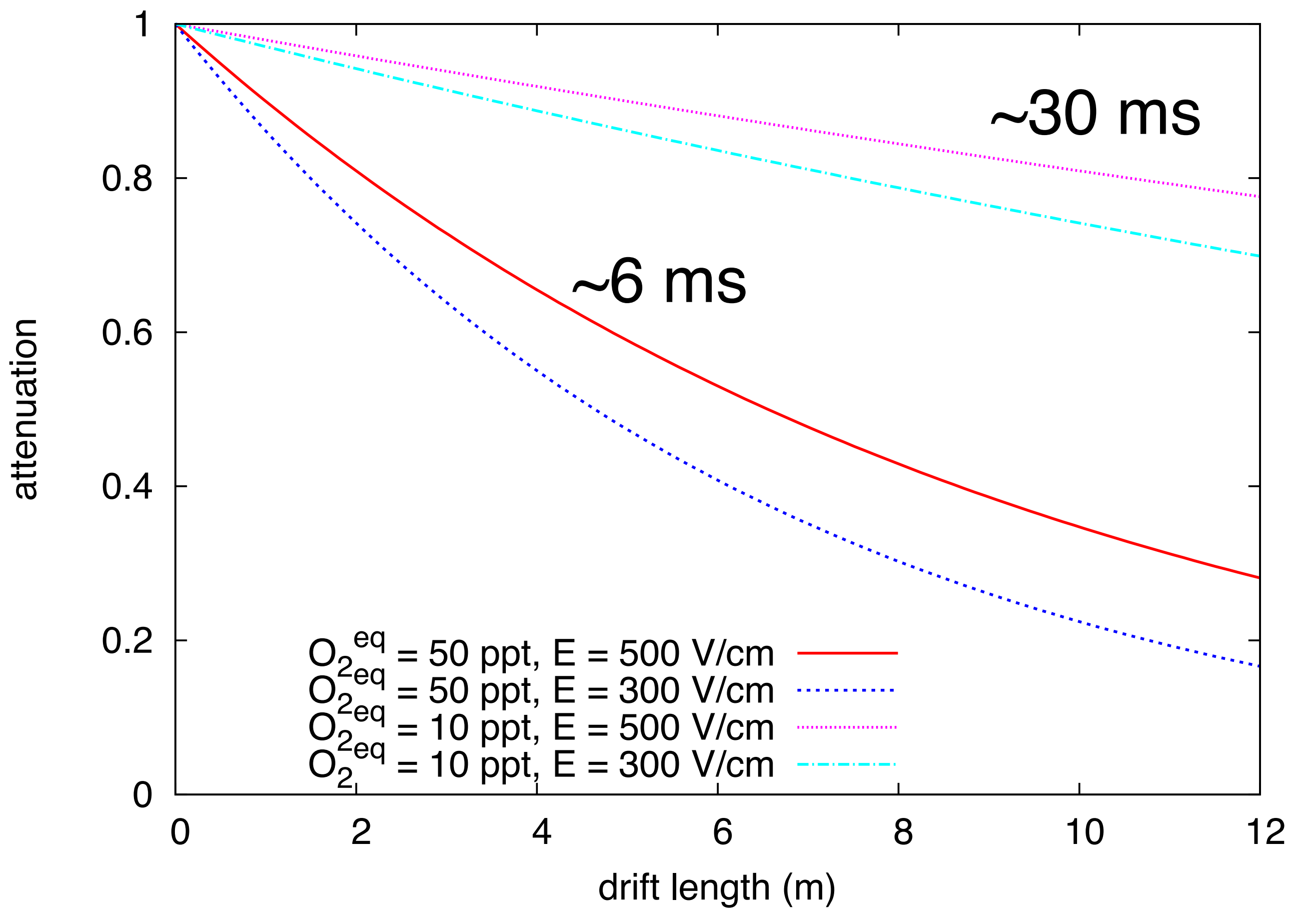
In order to extrapolate the LAr purity of the far detector from the protoDUNEs, a solid CFD simulation of both ProtoDUNE and DUNE is needed.
From the simulations and with some assumptions (like no leaks from the primary membrane, minor leaks towards the atmosphere, impurities coming mostly from the material in the warm gas, ...) one could compare the ProtoDUNE and the DUNE systems.

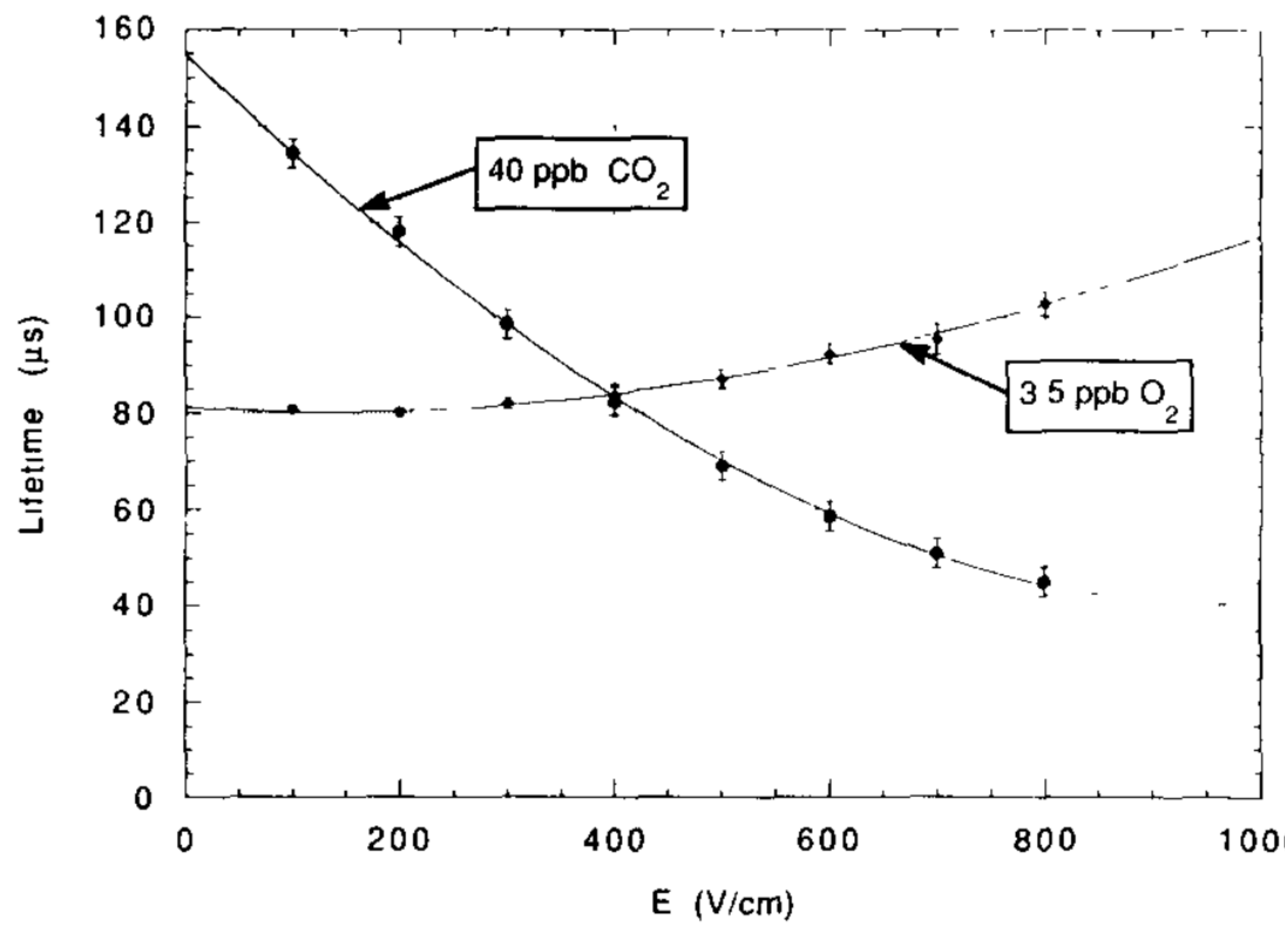
To gain confidence, the simulation should be validate with measurements in ProtoDUNEs, like the liquid argon temperature distribution, the contamination distribution, and the effect that the fluid flow has on the space charge.

For any quantitative claim on the purity levels in DUNE (for any configuration) a detail study corroborated by empirical comparisons is fundamental.

How to translate to DUNE case

Problems related to signal attenuation due to electronegative contaminants:
- The signal to noise decreases with drift time.
- Need time tag each charge track with interaction time in order to correct for attenuation.
- The worse is the purity, the larger is the dynamic range with which that the electronics and the digitisation must cope.
- Contamination not necessary uniform in the active volume: significant corrections may dependent not only on the drift time, but on the 3D position and on the liquid argon flow.





A. Bettini *et al.*, "A study of the factors the electron lifetime in ultra-pure liquid argon" NIM A305 (1991) 177-186

Scaling from the SP-TDR values at 500 V/cm:
3 ms for 3.5 m, 5.2 ms for 6 ms, and 10.3 ms for 12 m.

Space charge

Positive ions are created at the same rate of electrons, but due to their slower speed are evacuated in a much longer time, resulting in a net positive charge in the liquid argon bulk. Electronegative impurities trap electrons generating slow negative ions as well.

Positive charge piles up at the cathode, negative charge piles up at the anode. Typically the electric field is increased at the cathode and decreased at the anode.

The drift velocity of ions at typical drift field around 1 cm/s. Natural and forced convections move the liquid argon bulk at similar, if not larger, speeds.

ProtoDUNE-SP observe distortions that are ~50% more than what was expected.

A model for the space charge

$$\vec{\nabla} \cdot \epsilon \vec{\nabla} V = -q_e(\rho_i - \rho_n - \rho_e)$$

$$\frac{\partial \rho_e}{\partial t} = R_{rec} I - \rho_e/\tau_e - \vec{\nabla} \cdot \vec{W}_e \rho_e$$

$$\frac{\partial \rho_i}{\partial t} = R_{rec} I - \vec{\nabla} \cdot \vec{W}_i \rho_i$$

$$\frac{\partial \rho_n}{\partial t} = \rho_e/\tau_e - \vec{\nabla} \cdot \vec{W}_n \rho_n$$

- permittivity: ϵ
- voltage: V
- electron, positive and negative ion densities: ρ_i, ρ_n, ρ_e
- electron charge: q_e
- charge recombination factor: R_{rec}
- ionisation *rate*: I
- drift velocities: $\vec{W}_e$, $\vec{W}_i$, $\vec{W}_n$
- drifting electron lifetime: τ_e

Several assumption, including uniform distribution of impurities and still LAr bulk which we know are both not accurate approximation for NP04

Space charge sources

On surface the source of space charge is certainly cosmic rays:
~200 Hz/m^2 of muons releasing 6.25 x 10^6 Ar$^+$/m @ 500 V/cm.

Underground the dominant source is ^{39}Ar:
1 Bq/kg of beta decays with endpoint at 565 keV.
On average ~8x10^3 Ar$^+$/decay at 500 V/cm.

^{39}Ar is the dominant contribution but not the only important one.

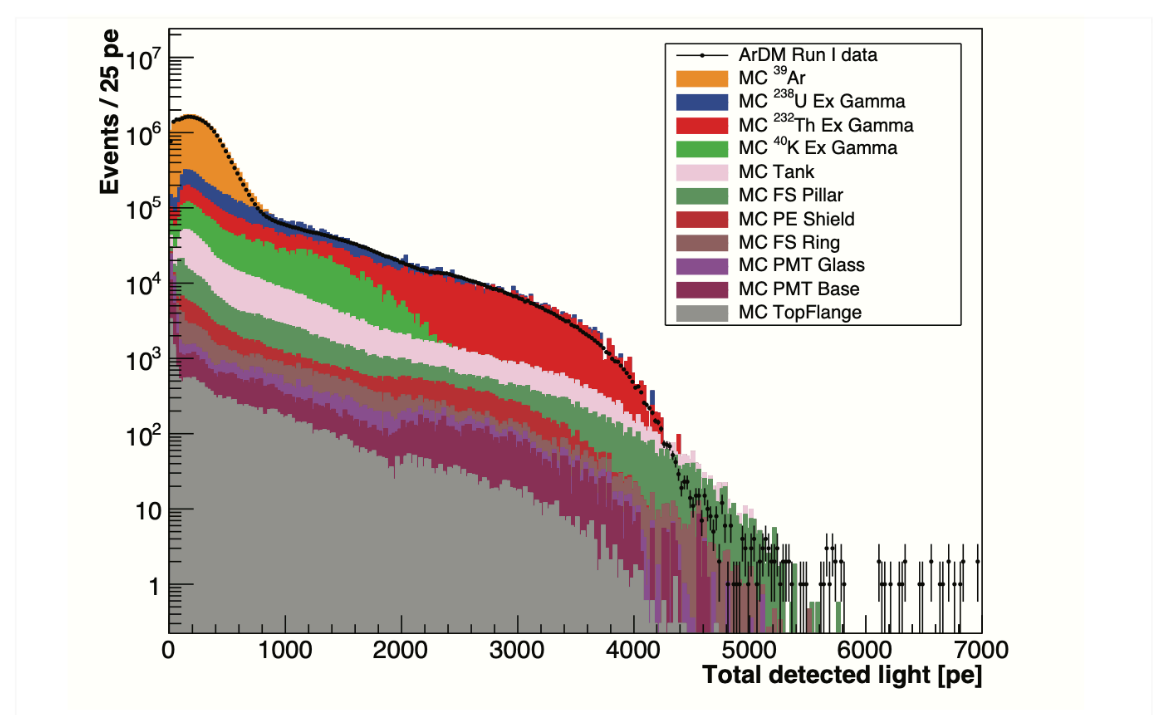
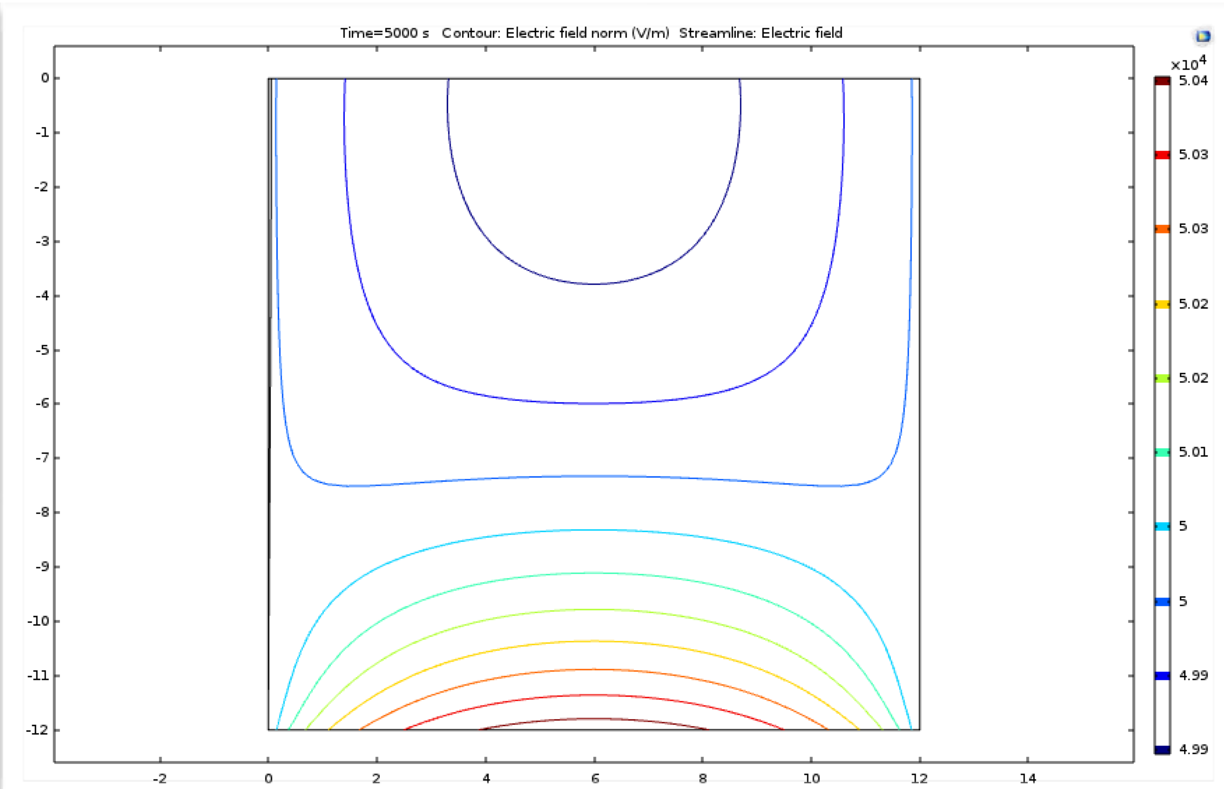


Figure 4. Comparison of the experimentally obtained ER light spectrum to various backgrounds derived from the MC simulations. The events are selected using $0.4 < TTR < 0.6$ and $0 < f90 < 0.6$.

ArDM Collaboration, "Backgrounds and pulse shape discrimination in the ArDM liquid argon TPC," arXiv:1712.01932

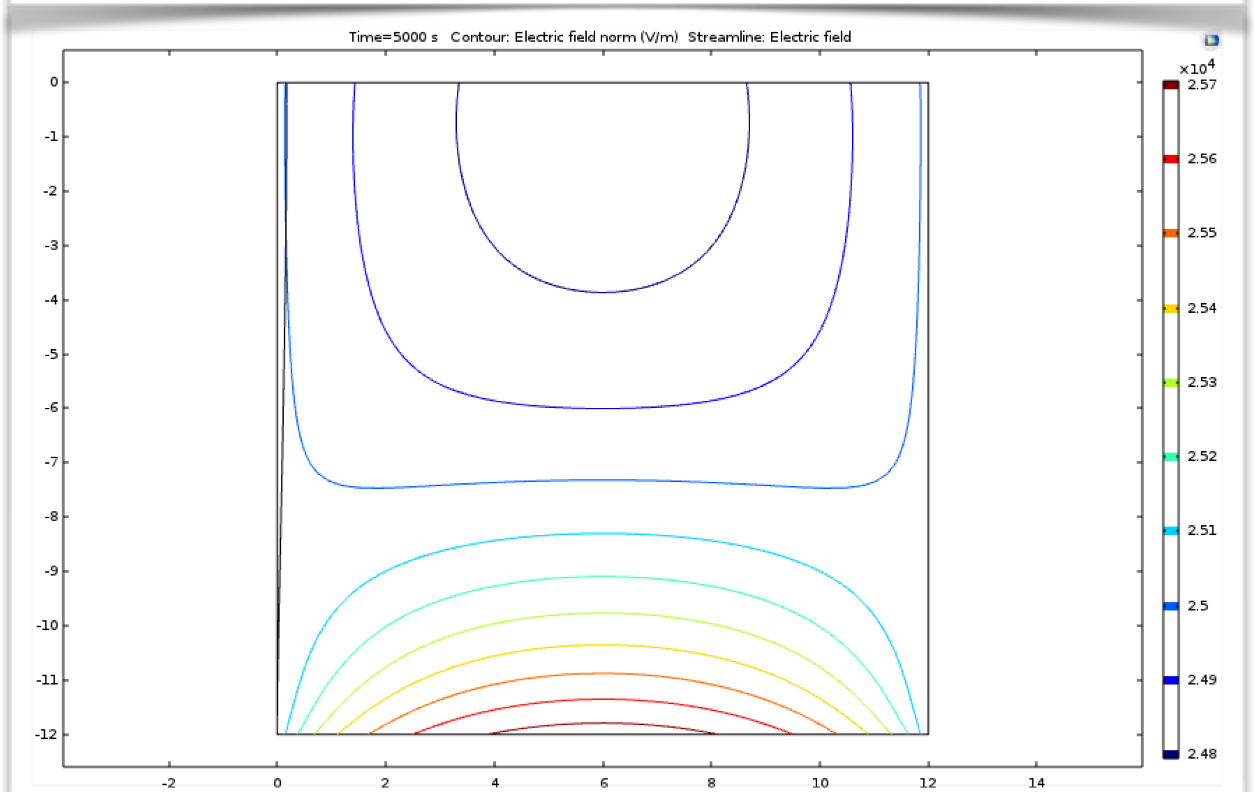
Some cases

Considering only ^{39}Ar as source



Geometry:
- Infinitely long volume
- 12 m wide

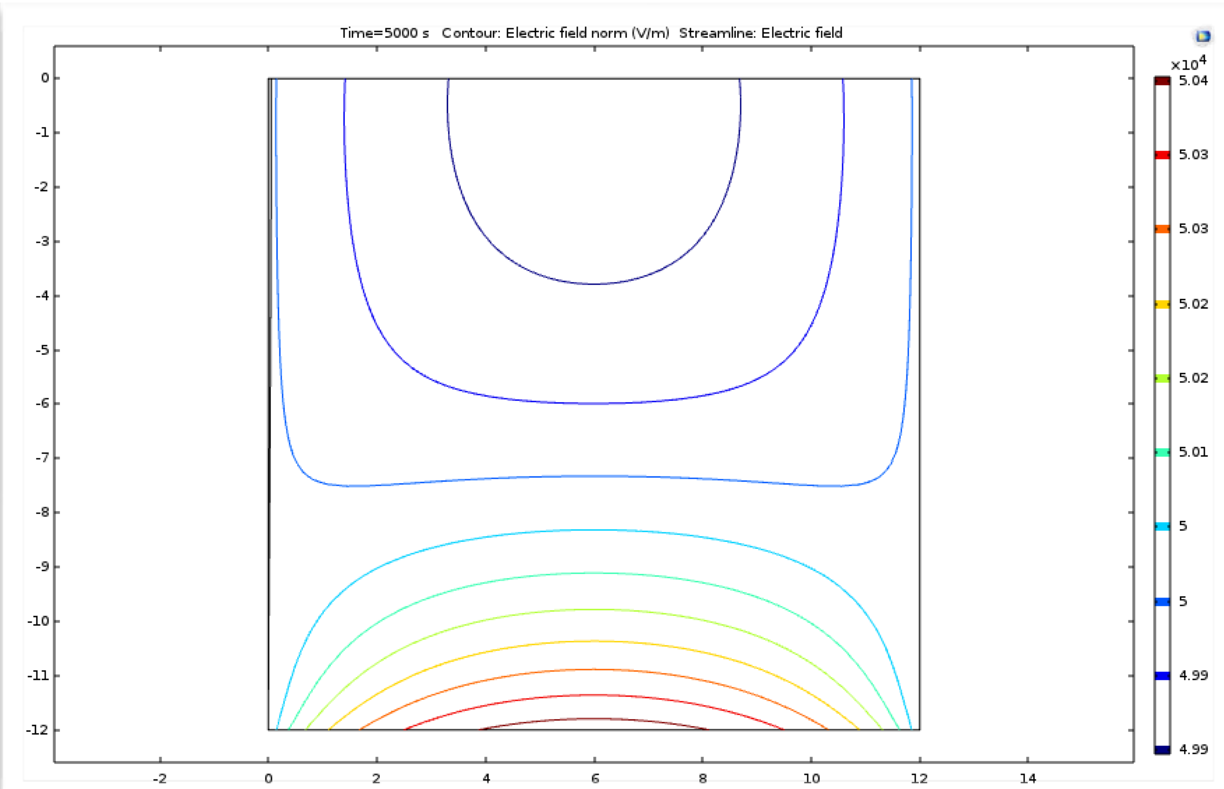
Drift length 12 m
Nominal field E_d = 500 V/cm
Field distortion: -0.2% +0.8%
Position distortion: ~5 cm

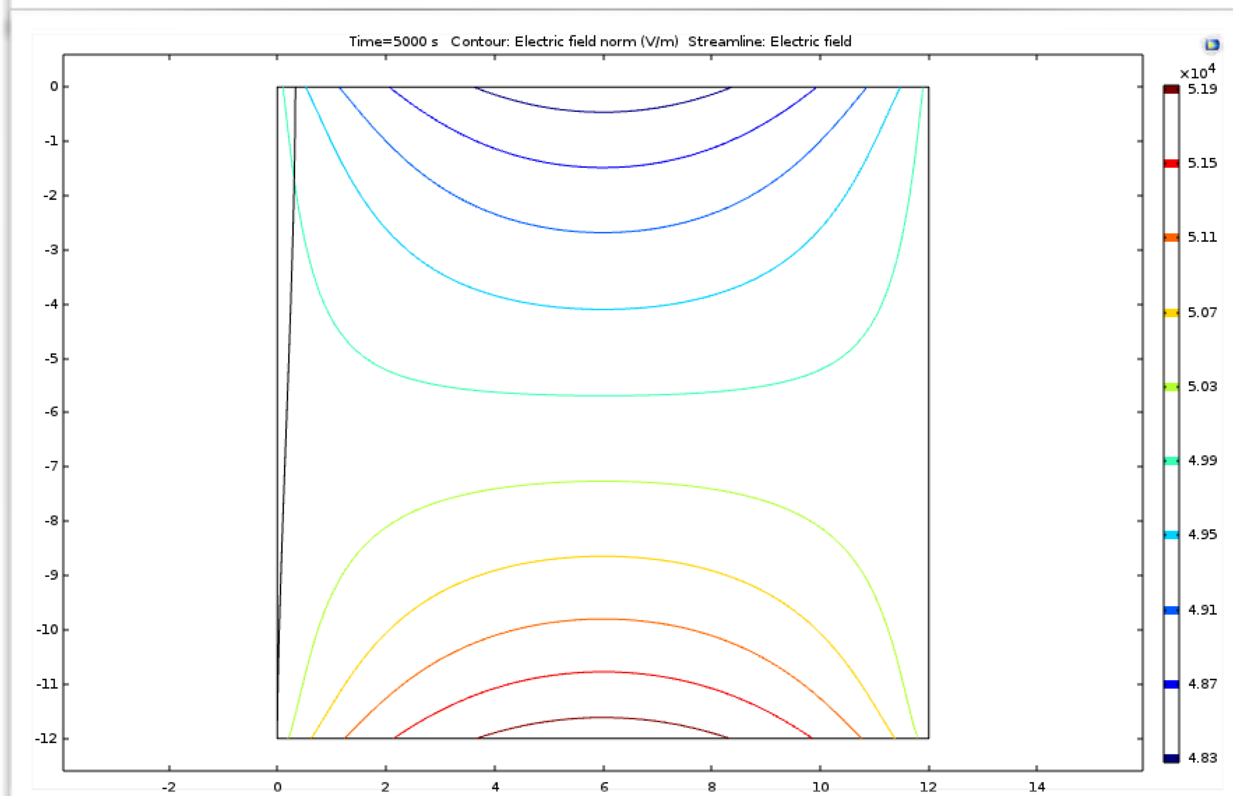


Drift length 12 m
Nominal field E_d = 250 V/cm
Field distortion: -1% +3%
Position distortion: ~17 cm

Some cases

Considering only ^{39}Ar as source





Geometry:

- Infinitely long volume
- 12 m wide

Drift length 12 m

Nominal field E_d = 500 V/cm

Field distortion: -0.2% +0.8%

Position distortion: ~5 cm

Drift length 12 m

Nominal field E_d = 500 V/cm

Included IBF* of 3 Ar^+ every e^-

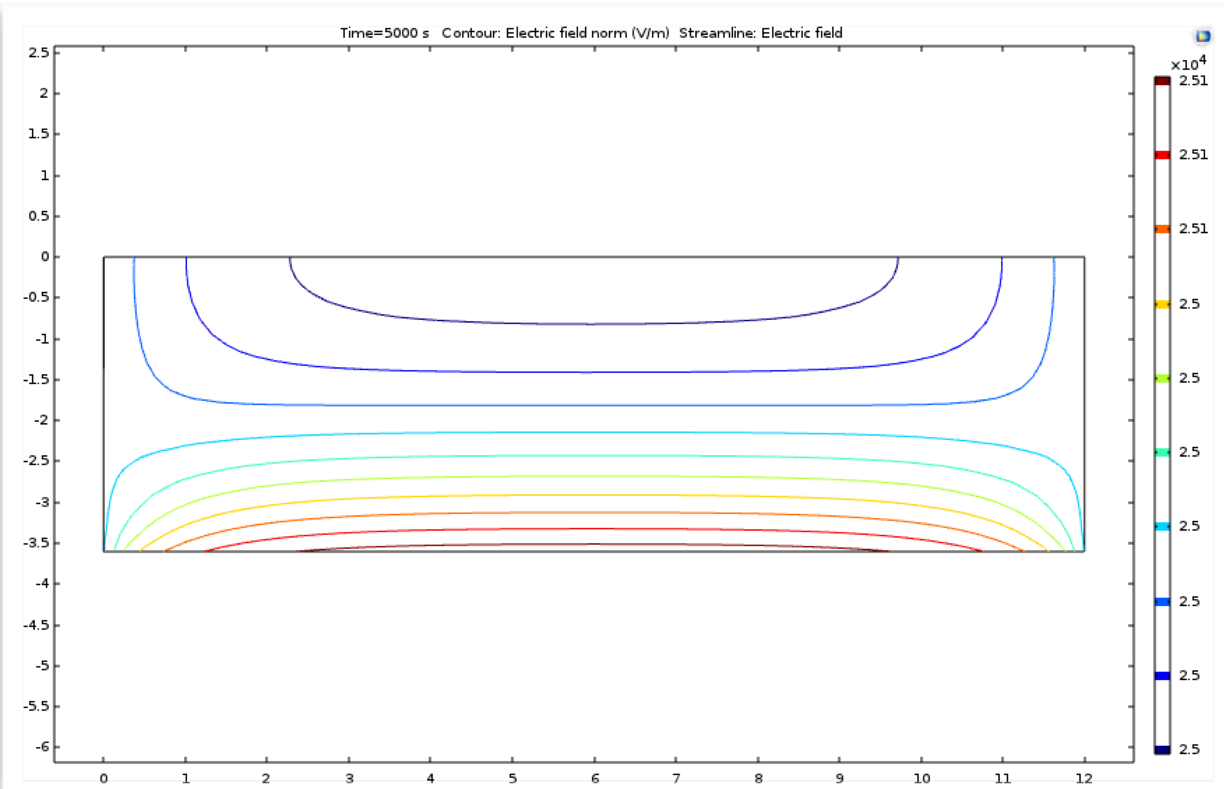
Field distortion: -1.5% +4%

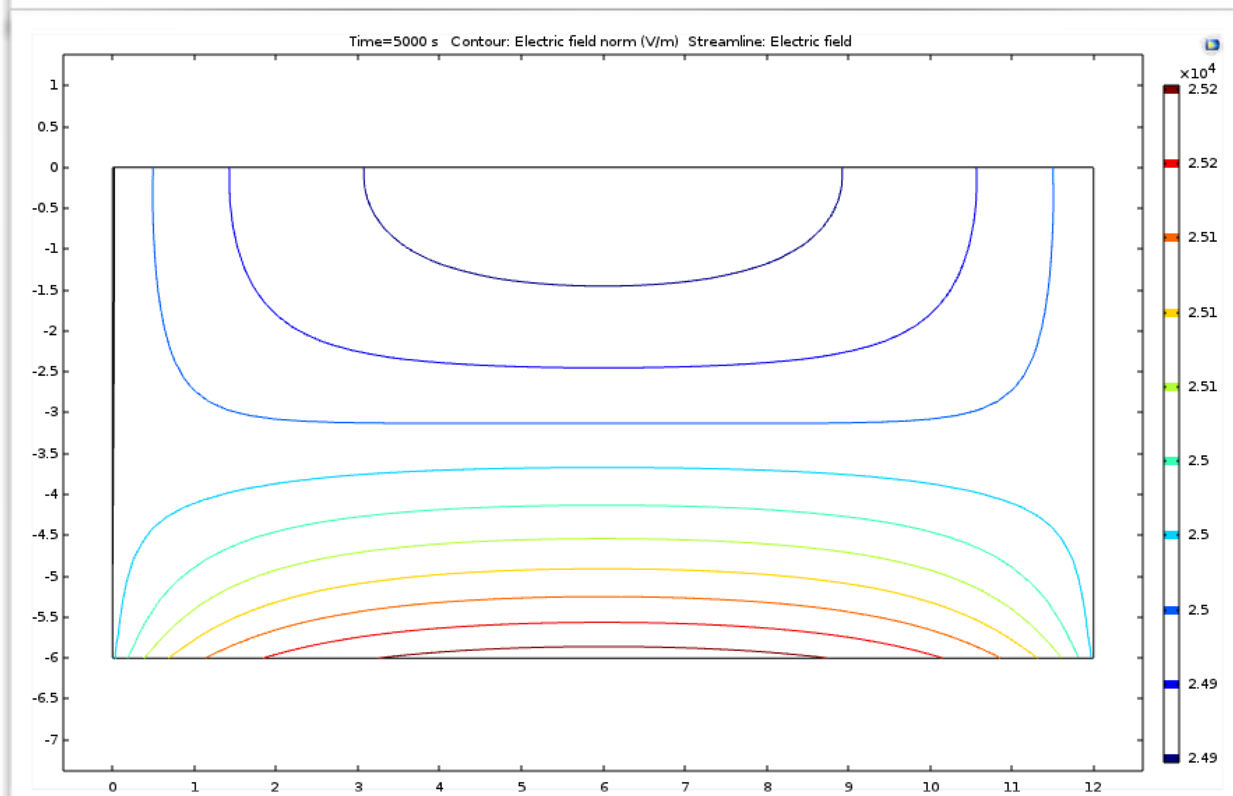
Position distortion: ~33 cm

*Assuming that to produce an effective gain of 10 15 Ar+/e- pair are generated in the LEMs and 20% of the ions (due to drift/extraction fields ration) pass the extraction grid entering the active volume.

Some cases

Considering only ^{39}Ar as source





Geometry:
- Infinitely long volume
- 12 m wide

Drift length 3.5 m
Nominal field E_d = 250 V/cm
Field distortion: -0.% +0.3%
Position distortion: ~0 cm

Drift length 6 m
Nominal field E_d = 250 V/cm
Field distortion: -0.4% +1%
Position distortion: ~2 cm

Slide presented by F. Cavanna
at the Double-Drift Detector Configuration Workshop
https://indico.fnal.gov/event/20996/

PHOTON DETECTOR

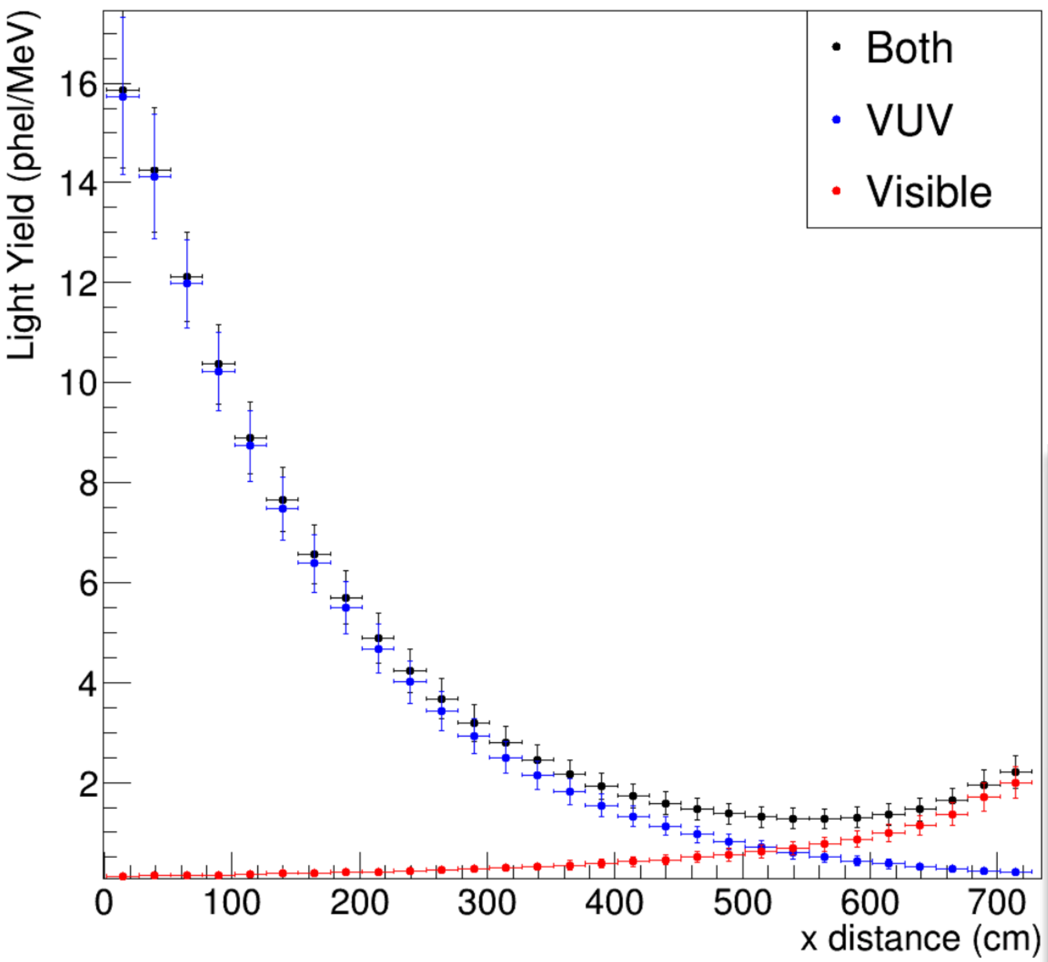
- The photon collection system in the 3.6 m drift configuration features an extremely high level of non-uniformity along drift coordinate (a factor ~20 from APA to CPA)
- WLS-reflector foils on the Cathode with collection of reflected visible light alleviate the issue, with a reduced non-uniformity limited to a factor ~2.

DOUBLE DRIFT:

- With a 7 m drift the non-uniformity will be much higher. Simulations indicate a factor ~75 from APA to CPA (~$1/d^2$ dependence) if no foils cathode coverage, and a factor ~8 with foils.
- Rayleigh Scattering in LAr (λ_R=60-90 cm) plays a significant role in the large DUNE volume
- Xe Doping (wls to longer wl → longer Rayleigh Sc. length) ⊕ WLS-reflector foils reduce non-uniformity to a factor ~3

Slide presented by F. Cavanna
at the Double-Drift Detector Configuration Workshop
https://indico.fnal.gov/event/20996/

QE=3.5%, mesh transmission = 70%, 50% arapuca windows TPB covered



DOUBLE DRIFT

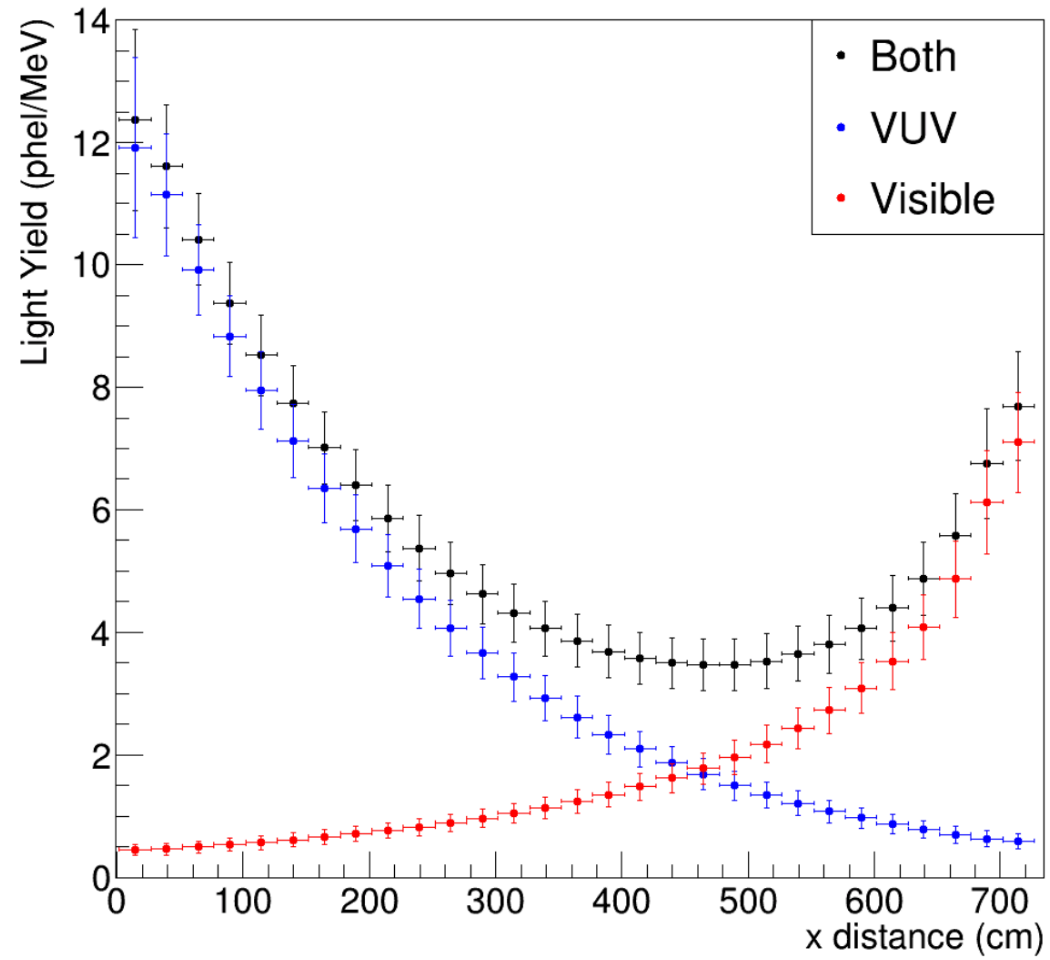
w/ WLS-reflector foils

the majority of low energy events would not yield detectable light signals

A. Szelc group @ Manchester

5 June 20, 2019 Flavio Cavanna | Double-drift Detector Configuration Workshop
Implications on Photon Detectors

RS=180cm, QE=3.5%, mesh transmission = 70%, 50% arapuca windows TPB covered



DOUBLE DRIFT

w/ WLS-reflector foils

⊕

Xe Doping

(λ_R= 180 cm)

A. Szelc group @ Manchester

7 June 20, 2019 Flavio Cavanna | Double-drift Detector Configuration Workshop
Implications on Photon Detectors

Fermilab DUNE

Summary

Longer drift lengths are interesting because smaller instrumented surface is required, yielding to cheaper detector and cheaper/faster installation.

Constraints on the HV system scales linearly with the drift length:
- 180 kV proven successfully in NP04 and further improvement are foreseen.
- 300 kV must still be proven in NP02.
- To go beyond, strong development effort is required e.g. low noise DC power supplies providing more than 500 kV are not commercially available (nor the compatible cable is).

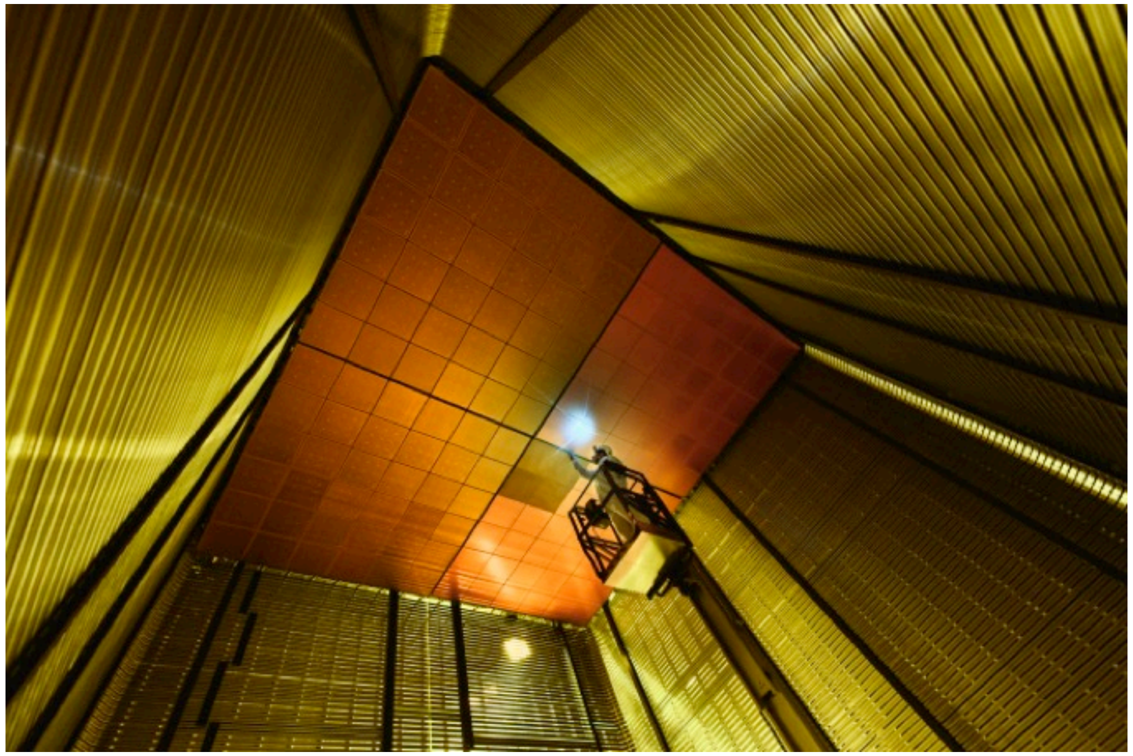
Measurement of diffusion coefficient range from 4.9 cm^2/s to 15 cm^2/s that result in longitudinal spread of the signals over 12 m drift at 500 V/cm order of 3-5 mm, which may affect the quality of the induction signals.
http://www.hep.princeton.edu/~mcdonald/microBooNE/KTM/diffusion_constant.pdf

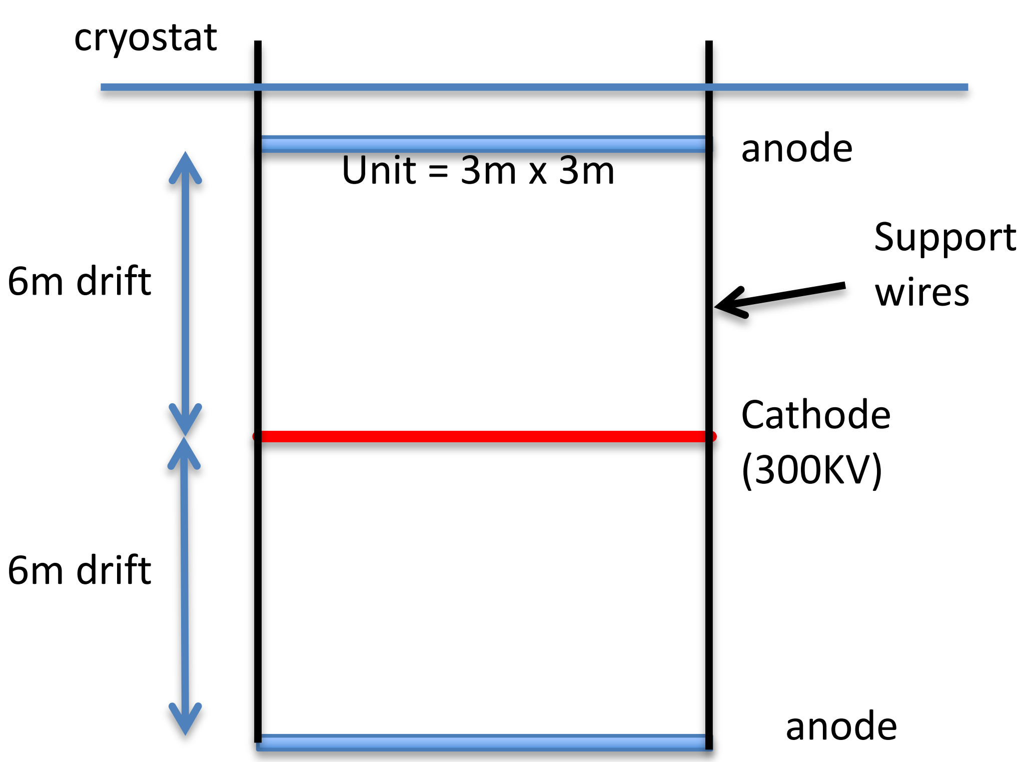
Requirement on the liquid argon purity become more and more stringent the longer is the drift.
S/N ratio is not the only figure affected by finite argon purity.
The absolute position (T_0) of each track along the drift is required for offline corrections.
Light detection suffers strong non-uniformities that become more severe the longer the drift is.

Space charge effects strongly depend on the electric field and the drift length.
Several are the difficulties to predict its effects (liquid argon motion being one).
Space charge effect in ProtoDUNE-SP was largely underestimated.

Vertical Drift SP TPC

- *First introduced at the CERN mini workshop in June 2019*
- Based on the easier assembly concept of the DP field cage
- 6m drift, 300KV technology almost acquired. Could be tested in the NP02 layout
- Less requirements on purity as for the case of a DP 12m drift
- Easy to install, because very modular

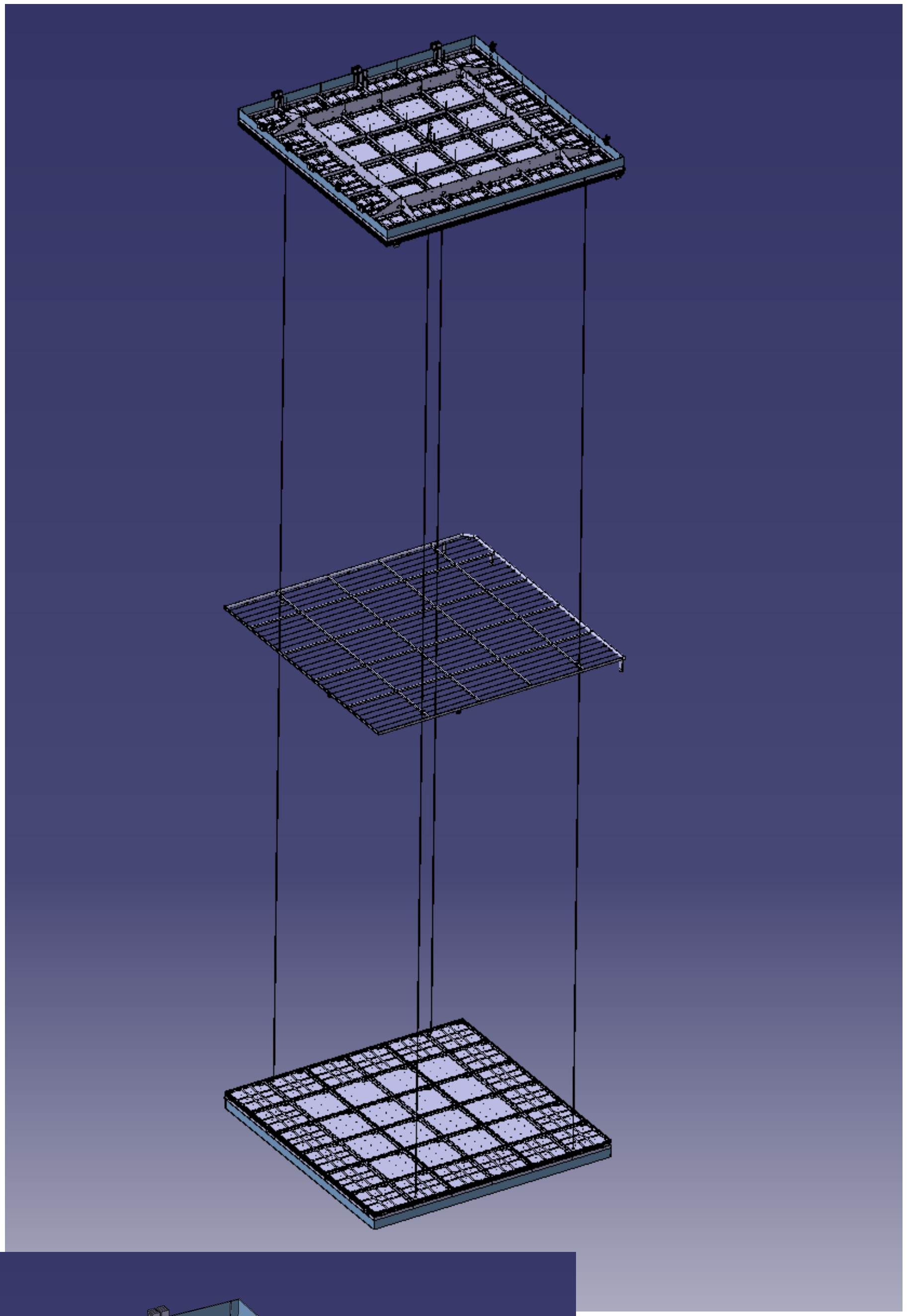


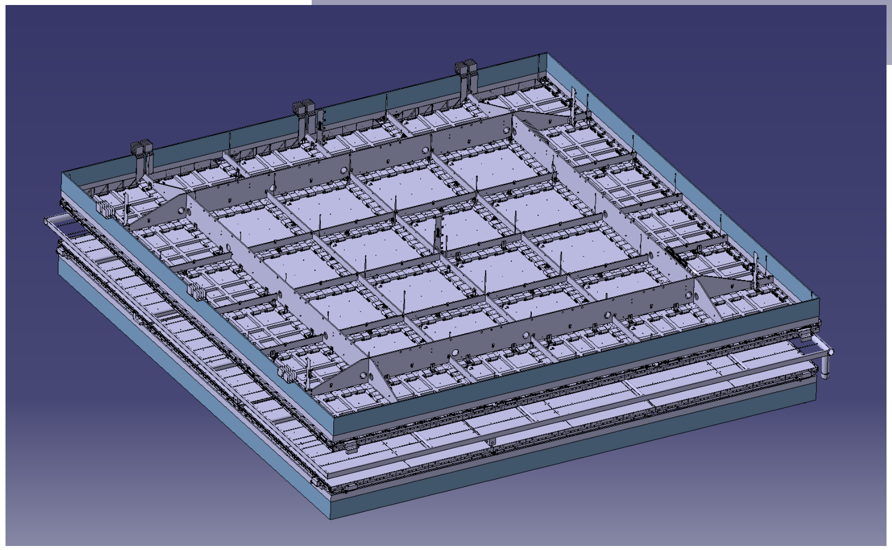


- Cathode, similar to the DP one, transparent, made of small tubes
- Anode structure can be supported in the same way as done for DP, but must be more rigid then a standard APA
- SP cold electronics similar to the one already planned (top anode cables short, bottom anode cables long, not very different then SP baseline)
- Embedded in the same FC concept as the DP

Basic Module

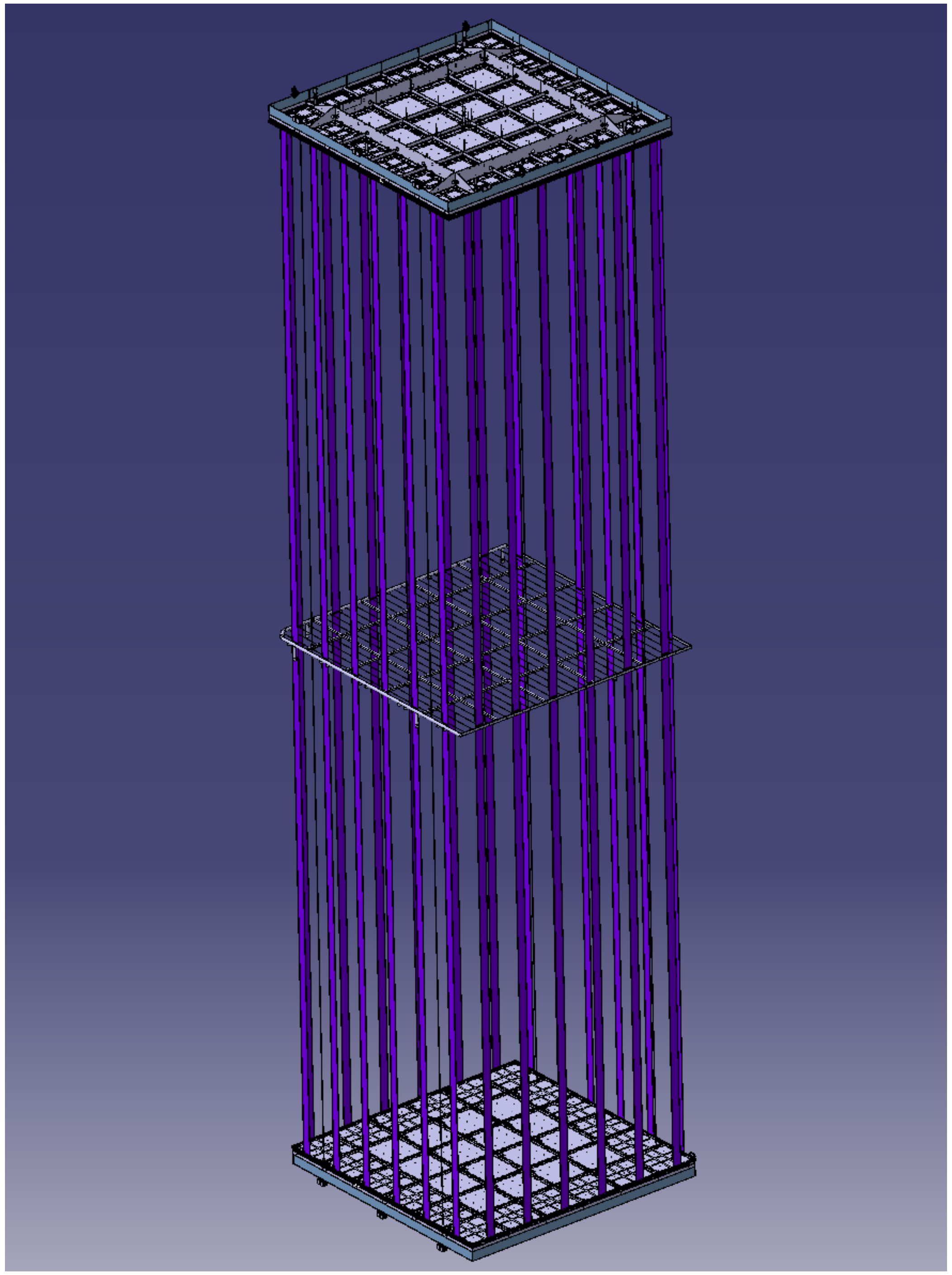
- *Anode Plans*
  - *Based on the Thick-GEM with strips electrodes for induction/collection signals (see dedicated talk) and onboard FE*
  - *Encouraging early feasibility test*
  - *Highly modular; can exploit the supporting structure developed for the DP detector (3x3 m3)*
- Cathode Plane
  - *Similar concept as in DP: resistive bars supported in metallic frame*
  - *Same modularity as Anode planes*
  - *Frame similar to the one developed for the Ground Grid*
- Supporting system
  - *Insulating wires Supports*
  - *Top AP, center CP and bottom AP*
  - *Full structure hanging as in the DP detector*



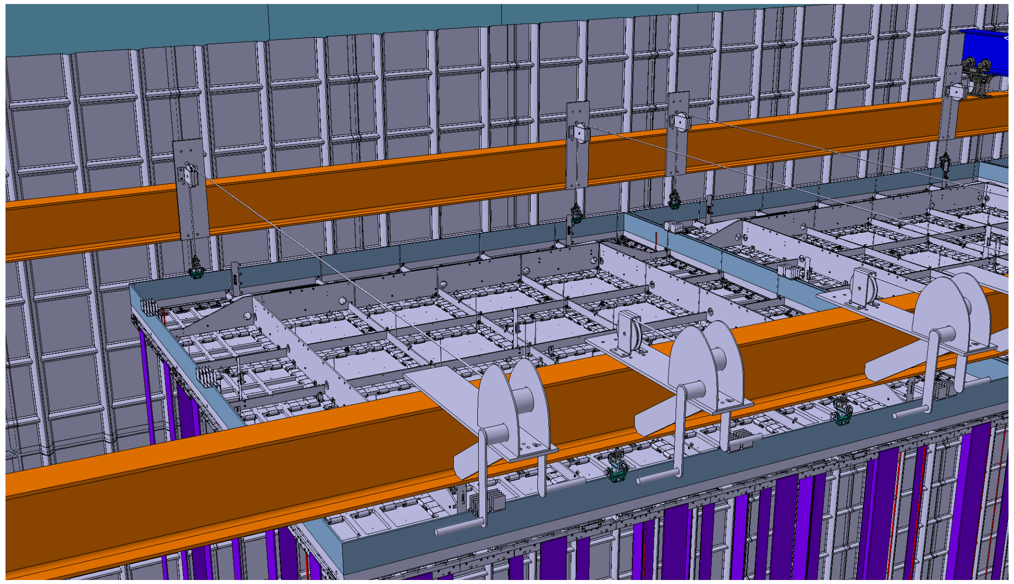


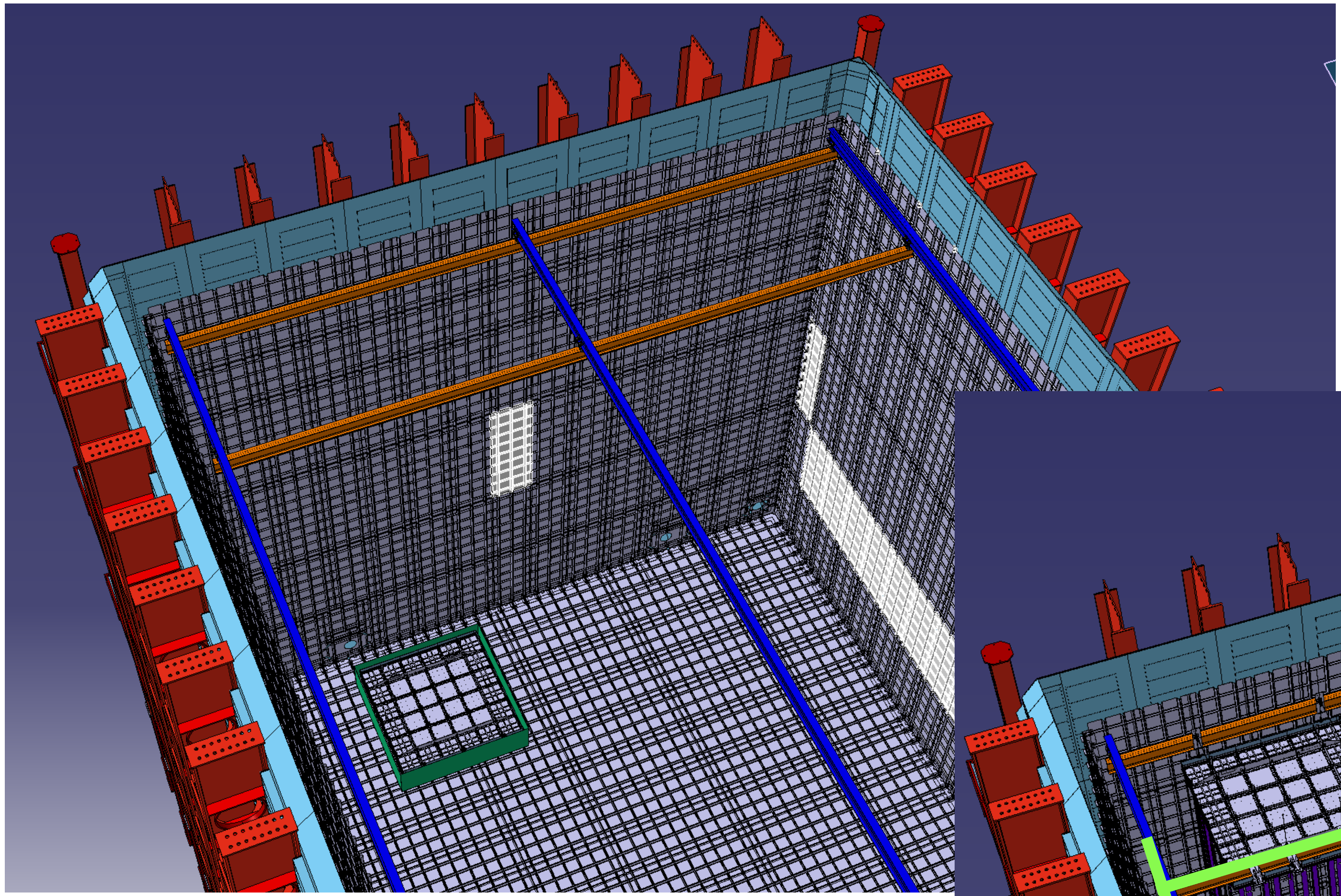
Photon detector idea

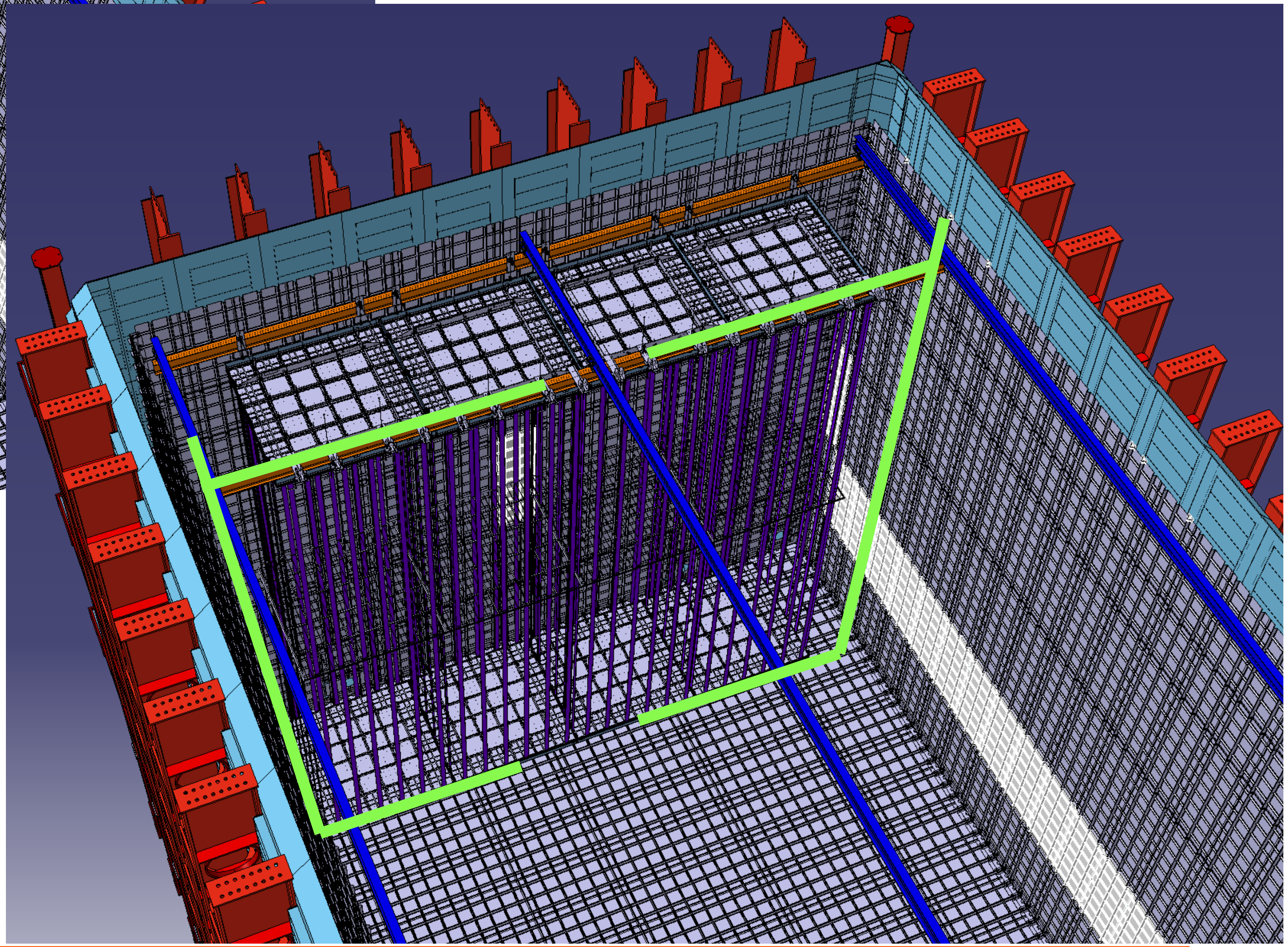
- *With "solid" readout planes and cathode in the middle, difficult to embed standard photon det.*
- Alternative solutions:
  - PD's along the Field Cage → detection limitation due to Rayleigh scattering
  - Inside the drift volume: need fully insulating thin material to minimize distortions of E-field and blind regions.
- One possible design under investigation:
  - Thin wave-shifting panels (PEN?) with embedded green shifting fibers
  - Fibers allow photon transportation over several meters
  - PEN panels could be extruded in similar length
  - Could be placed vertically inside the drift volume at the boundary of the 3x3 m module and readout with PD's behind the Anode planes
- Test on feasibility and collection efficiency ongoing at CERN



Installation sequence







The transportation box in
position for lifting
Few penetrations for the DSS
Signal penetrations possibly only
along the long side of the cryostat