Measurement of the electron drift velocity for directional Dark Matter detectors

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Drift velocity: introduction

3D Track reconstruction requires a precise knowledge of the electron drift velocity

\[ \Delta Z = \Delta T \times V_d \]

→ Magboltz simulations give good result for pure CF$_4$
→ Differences with real life gas mixture (impurities?)?
→ Measure the electron drift velocity with our directional prototype
Drift velocity: Experimental setup

- Use of an 5.47 alpha source ($^{241}$Am)
- Alpha particles go through the entire drift chamber
- A starting and an ending point
- Measurement of the 3D tracks and charge profile

2D projections of 500 $\alpha$ tracks
A pencil point-like source (5° opening angle)

3D reconstruction of one $\alpha$ track crossing the whole drift space

J. Billard et al., arXiv:1305.2360

F. Mayet - Cygnus 2013, Toyama, Japan
Drift velocity: **Straightforward analysis**

\[ \Delta t_e \text{ Time difference between } \alpha \text{ arrival time and last primary electrons} \]

- depends on readout time constants
  → underestimation of the drift velocity

\[ \Delta t_c \text{ Time difference between first and last spatial coincidence} \]

- depends on amplification electric field (gain)

(Probability to have a spatial coincidence depends on the number of electrons)
Measurement of the transfer function $F(t)$ of the charge preamp.

- Charge injection on the grid
- Voltage step injected through a capacitor $C$

\[ I_{\text{ind}}(t) = C \frac{dU(t)}{dt} \]

- When $I(t) \rightarrow \delta(t)$ then $V(t) = F(t)$ (pulse response)

Possibility to measure the charge collection profile
Drift velocity: **Electronic signal modelisation (2)**

Modeling the signal output $V(t)$:

$$V_{th}(t) \propto \int \int \int \frac{dE}{dt}(t - \xi) \times Q_{ion}(\xi - \tau) \times g_{\text{diff}}(\tau - T) \times F(T) \, dT \, d\tau \, d\xi$$

- **Induced current on the grid:**
  - $-dE/dZ \Rightarrow dE/dt$
  - Signal from ions
  - Electrons diffusion

- **Calculation of $V(t)$**
  - Convolution product with $F(t)$

- **Time derivative of $V(t)$**
  $\Rightarrow dV/dt(t)$

An important delay is induced!

$$V = h/\Delta t \rightarrow \text{biased}$$

**Likelihood approach**

J. Billard *et al.*, arXiv:1305.2360

F. Mayet - Cygnus 2013, Toyama, Japan
Drift velocity: How to fit the data?

For each configuration, we measure ~ 500 alpha particles

$V(t)$ Profile

Strong correlations between $V(t_i)$

Mean profile $V'(t)$ is being adjusted by the signal model $V_{th}'(t; v_d, v_{ion}, D_t)$

$V'(t)$ Profile

Negligible correlations between $V'(t_i)$

Correlation matrix is not diagonal
Drift velocity: The likelihood function

- We fit the time derivative of the charge collection $V'(t)$:

\[
\mathcal{L}(v_d, v_{ion}, D_l, \delta t, A) = \exp\left(-\frac{1}{2} \sum_{i=1}^{N_t} \left[ \frac{A \times V'_{th}(t_i - \delta t; v_d, v_{ion}, D_l) - \bar{V}'(t_i)}{\sigma V'(t_i)} \right]^2 \right)
\]

Free parameters:
- Electron drift velocity $v_d$
- Ion drift velocity $v_{ion}$
- Longitudinal diffusion coefficient $D_l$
- 2 additional parameters: $A$ (amplitude) and $\delta t$ (delay)
Drift velocity: Illustration

Consider the following case:

Pure CF$_4$ @ 50 mbar, $E_d = 138$ V/cm and $E_a = 14.5$ kV/cm

Maximisation of the likelihood function:

- Good agreement between the data and the model!
- Robust estimation of $V_d$
- Small deviations on $V'(t)$ -> estimation of the falling time of $F(t)$
Drift velocity: Error bars and constraints

Estimation of the error bars using a profile likelihood

We used the profile likelihood ratio test statistic:

\[
\lambda(v_d) = \frac{\mathcal{L}(v_d, \hat{v}_{d_{\text{ion}}}, \hat{D}_t, \delta t, \hat{A})}{\mathcal{L}(\hat{v}_d, \hat{v}_{d_{\text{ion}}}, \hat{D}_t, \delta t, \hat{A})}
\]

@ 68% C.L., we solve:

\[-2 \ln[\lambda(v_d \pm \sigma_{v_d}^\pm)] = 1\]  
(follows a $\chi^2$ distribution with 1 d.o.f)

Precise measurement of $V_d$

(0.1% error)

\[v_d = 122.7 \pm 0.14 \, \mu m/ns \quad (68\% \, \text{C.L.})\]
Drift velocity: result for pure CF$_4$

- Fair agreement (up to 10%) with the Magboltz simulation

  - Validation of the charge collection all along the drift chamber

- Discrepancy highlights the need to measure the electron drift velocity with our own detector.

  - to account for impurities in the gas mixture, electric field inhomogeneities…

  - Effective velocity

J. Billard et al., arXiv:1305.2360
Drift velocity: result for $\text{CF}_4 + \text{CHF}_3$

The addition of $\text{CHF}_3$ lowers the electron drift velocity while keeping a large Fluorine content.

Good agreement with Magboltz

J. Billard et al., arXiv:1305.2360
Conclusion

• A new measurement method of the electron drift velocity
  - $\alpha$ source
  - profile Likelihood analysis
  - full modeling of the signal on the grid
  -> avoid bias due to electron diffusion, ion collection time and elec. readout
• In situ measurement of the effective electron drift velocity, accounting for
  - Large drift distances
  - Field inhomogeneities
  - Impurities
• A golden gas mixture for MIMAC
  
  $70\%\text{CF}_4 + 28\%\text{CHF}_3 + 2\%\text{C}_4\text{H}_{10} @ 50 \text{ mbar}$

  -> low electron drift velocity & large Fluorine fraction