Numerical studies of alpha particle tracking in a small TPC

RD51 Collaboration Meeting

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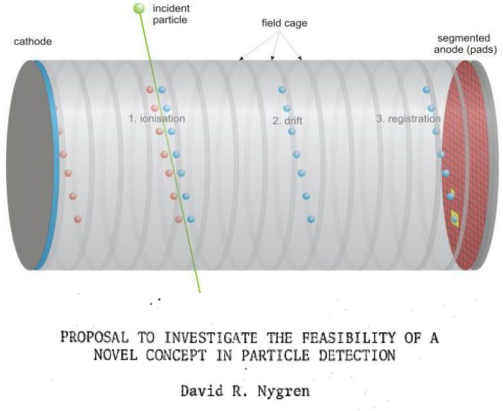
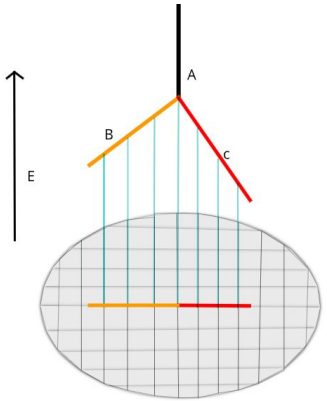
Outline

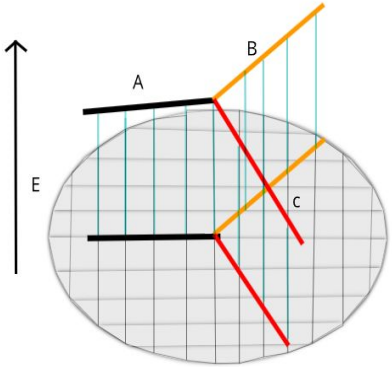
- Motivation
- Time Projection Chamber
- Simulation of Primary Ionisation in TPC
  - Garfield++
  - Geant4
  - COMSOL
- Simulation of electronic signal in anode plane of TPC
- Track reconstruction
- Conclusion
- Future Plan

Time Projection Chamber (TPC)

- TPC has an active gas volume with a good position-sensitive electron collection system inside an electric field and a charged particle will produce primary ionization along its track



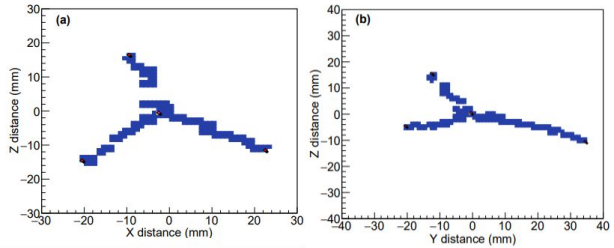




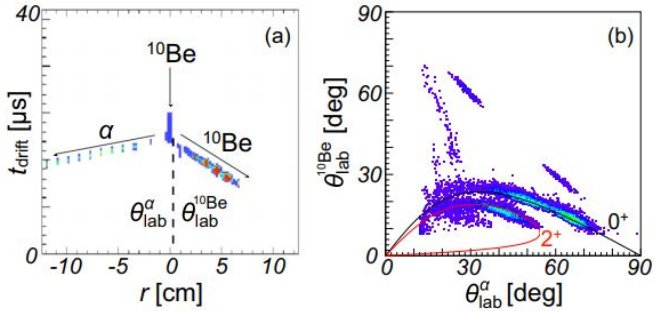
- The primary electrons drift under the action of the uniform electric field towards the end equipped with an electron multiplier for collecting signal producing a 2d image of the track
- 3rd dimension from the drift time of electrons
- Information
  - Angles, Energy (from range or charge), particle identification

Nuclear physics experiments in active target TPC

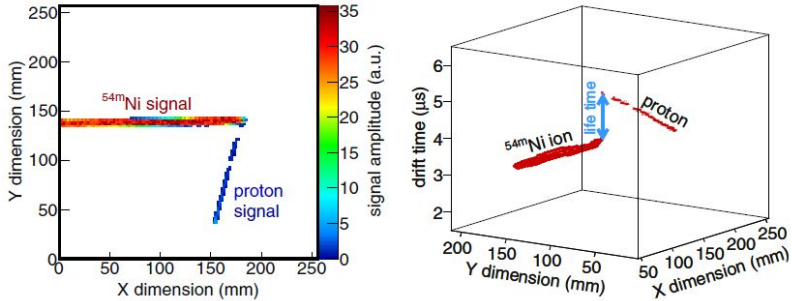
- In the field of low-energy nuclear physics, Active-Target Time Projection Chambers (AT-TPCs), the detector gas of the TPC is at the same time the target in which nuclear reactions take place
- Reconstruction of tracks created by charged particles leads to identify and measure their directionality which provides complete information about the reaction vertex kinematics in low-energy nuclear and high energy physics
- AT-TPC is advantageous for 4π detection efficiency and event by event 3D track reconstruction
- ATTPC, TexAT, ACTAR, Maiko are examples of active target TPC used in low energy nuclear physics



Direct and sequential Hoyle state decay in TexAT TPC
2012.08437.pdf (arxiv.org)



α resonant scattering at ATTPC
D. Suzuki et al., Phys. Rev. C 87, 054301 (2013)



proton-emission branches from an isomeric state in 54mNi
https://doi.org/10.1038/s41467-021-24920-0 (Actar TPC)

Motivation for alpha tracking in TPC

3 body alpha decay kinematics in

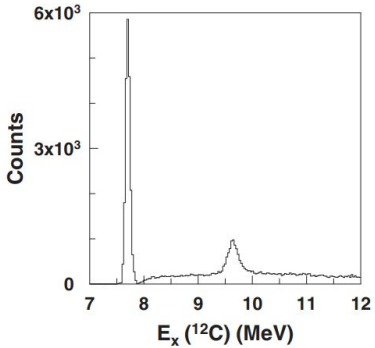
CM frame

$\alpha + {}^{12}C \longrightarrow {}^{12}C^* \longrightarrow \alpha_1 + {}^{8}Be \longrightarrow \alpha_1 + \alpha_2 + \alpha_3$

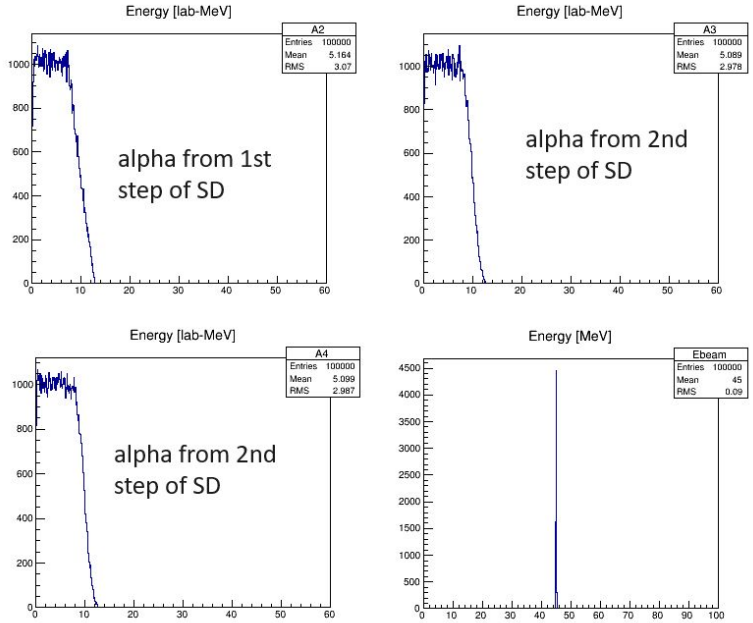
$$P_{\alpha 1} = P_{8_{Be}}$$

$$E_{\alpha 1} = \frac{P_{\alpha 1}^2}{2m_\alpha} = \frac{2}{3}Q_1$$

$$E_{\alpha 2} + E_{\alpha 3} = \frac{1}{3}Q_1 + Q_2 = \frac{P_{\alpha 1}^2}{4m_\alpha} + Q_2$$



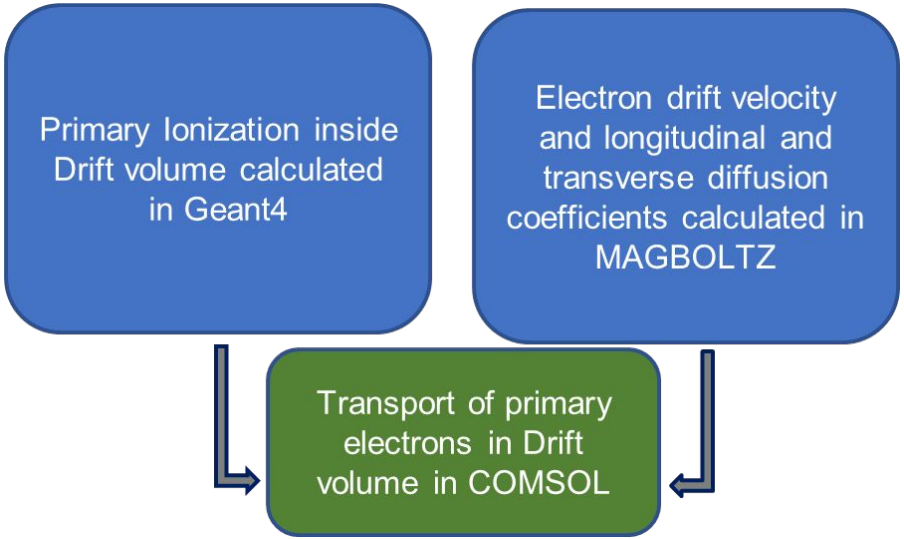
Lab frame



4He beam energy (30-60 MeV) @
K130 cyclotron at Variable Energy Cyclotron Centre, Kolkata

Introduction to simulation framework

- Our goal is to find the amount of primary ionization by alpha particle in a sensitive volume of TPC and its transport parameters respectively.
- The particle generation and tracking were governed by low energy ElectroMagnetic physics list Livermore, Penelope and PAI.
- Transport parameters of primary electrons and ions has been obtained from MAGBOLTZ in Garfield++ package
- A Finite Element Method (FEM) package, COMSOL used for time evolution of primary electrons in drift volume

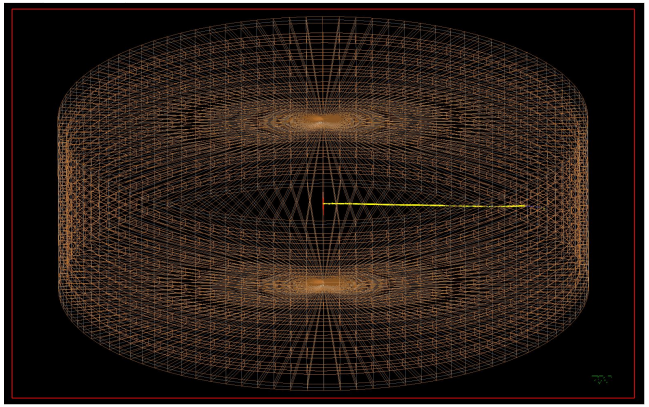


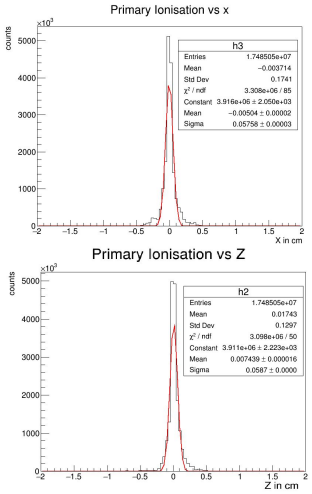
Simulation Framework for primary ionisation by alpha particle

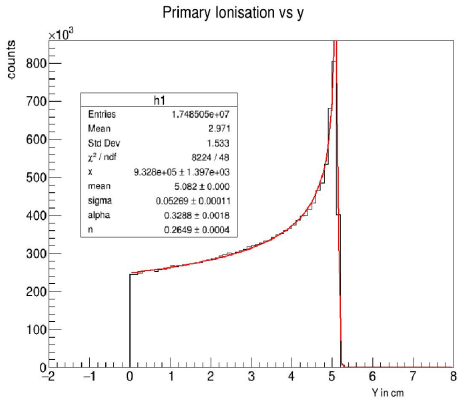
- Energy deposition increases with square of the charge of incoming projectile
- Number of gaseous particle decreases with decreasing pressure

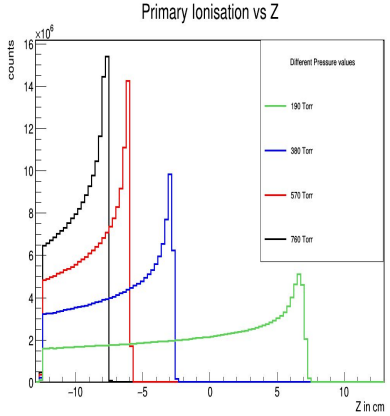
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 c^2 \rho \frac{Z}{A} \frac{q^2}{\beta^2} \left[ln\left(\frac{2m_e \gamma^2 \nu^2 W_m ax}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad \rho = \frac{mP}{K_B T}$$

$$PV = nRT = NK_B T$$









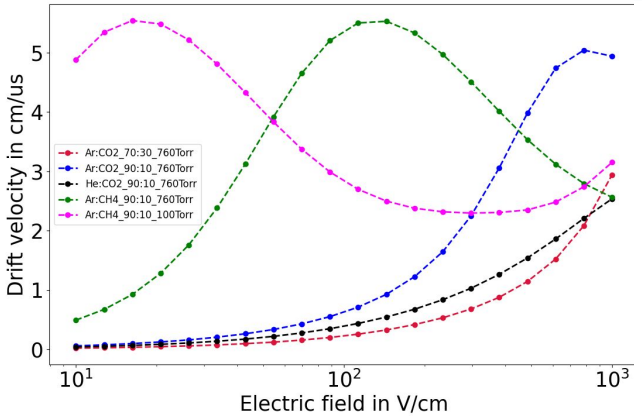
- Low pressure is suitable for nuclear reaction in gaseous detector

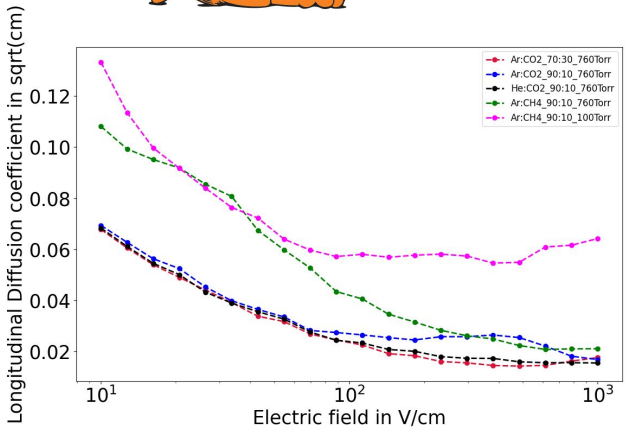
Transport properties of different gas mixtures

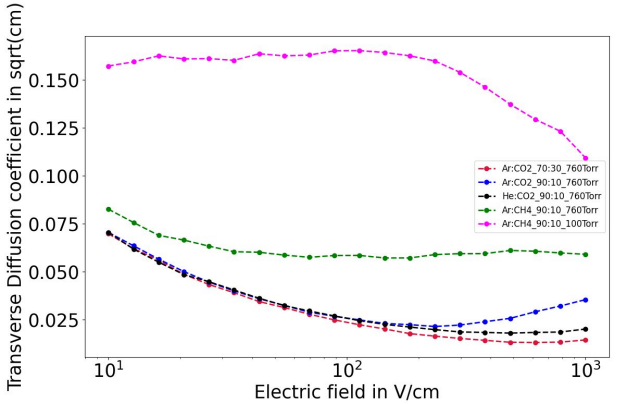
- This simulation utilizes the transport parameters from Garfield++ to perform the simulation.
- Diffusion and drift velocity for different drift field have been calculated for different pressure.
- The positive ions and negative electrons are considered to be charged fluid in the gas volume.
- The hydrodynamics is governed by convection and migration mechanism which is governed by drift-diffusion reaction.

$$\frac{\partial c_i}{\partial t} + \vec{\nabla}\left(-D_i\vec{\nabla}c_i + \vec{u_i}c_i\right) = S_i$$

$$\vec{E} = -\vec{\nabla}V \qquad \vec{\nabla}\cdot\vec{D} = -\rho$$

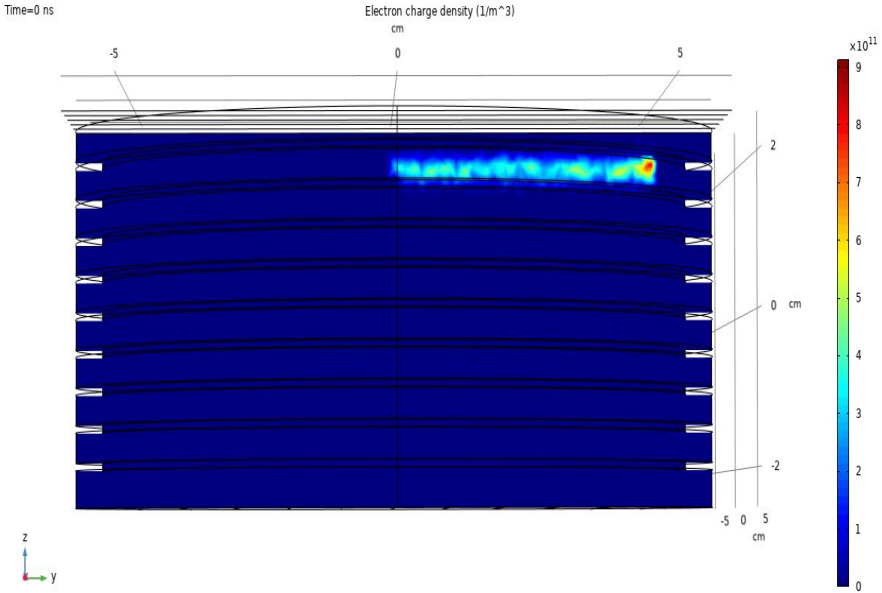


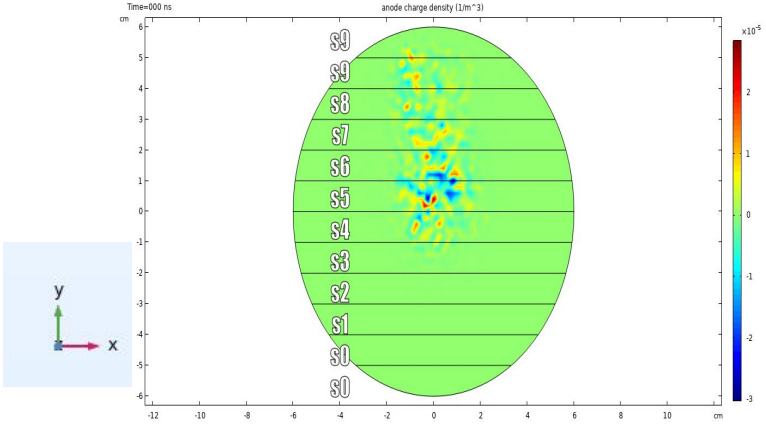


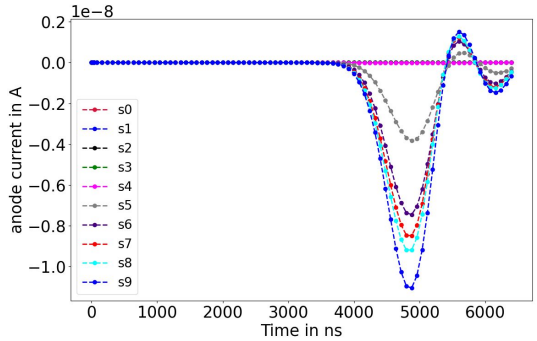


Transport of primary electron in drift region of TPC

- The Detector plane is segmented into 10 1d strips with 1 cm width
- The simulation is performed with 150 V/cm drift field and in atmospheric pressure

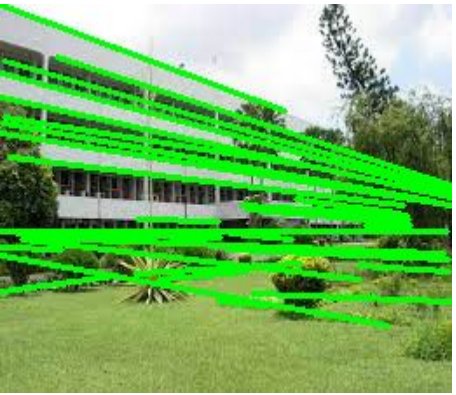


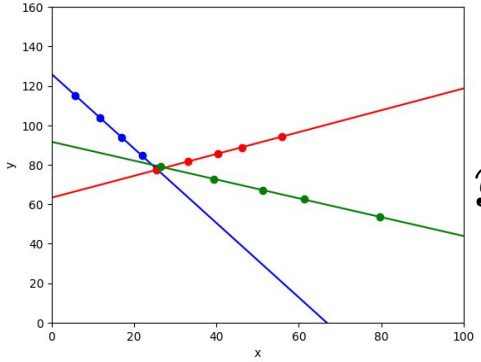




Track Reconstruction

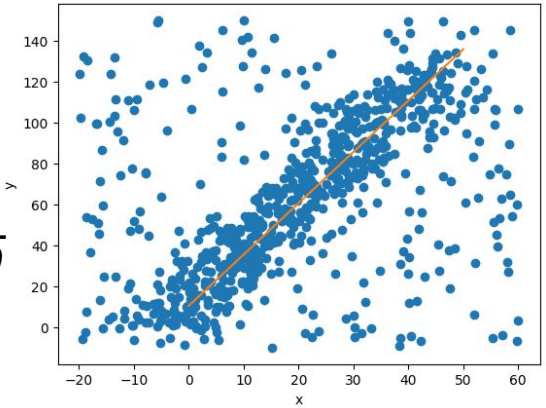
Hough transform is a feature classification technique use in image analysis and computer vision by transforming the track parameter (x,y) to (r,θ)

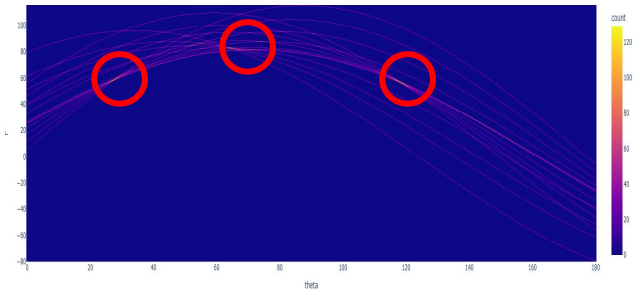


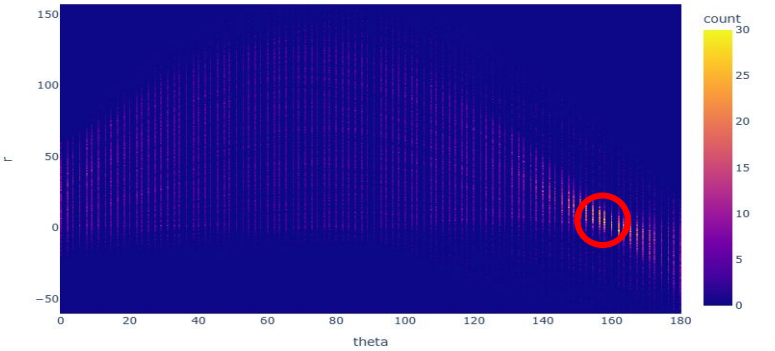


$$r = x_i cos\theta + y_i sin\theta$$

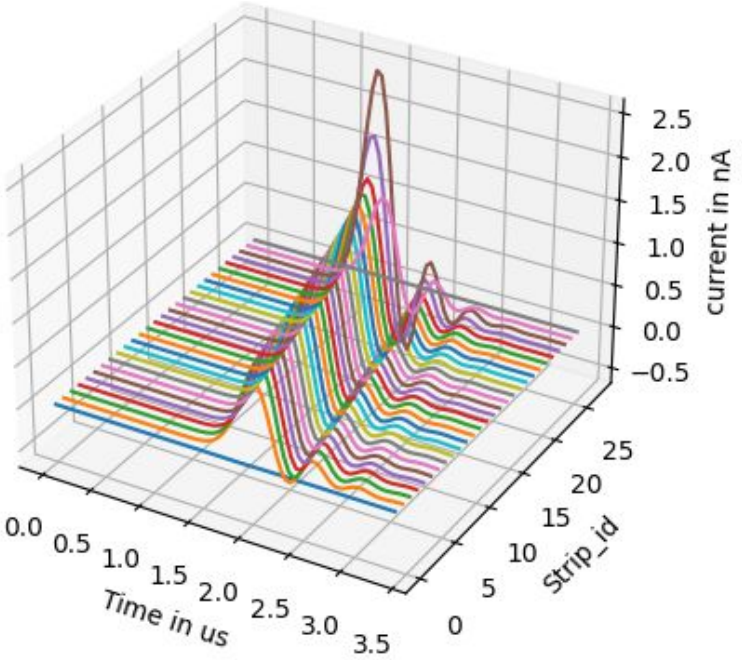
$$y = -\frac{x}{tan\theta} + \frac{r}{sin\theta}$$

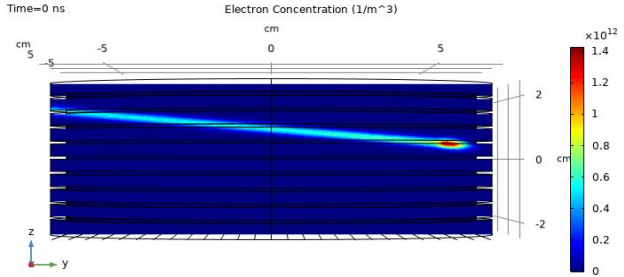


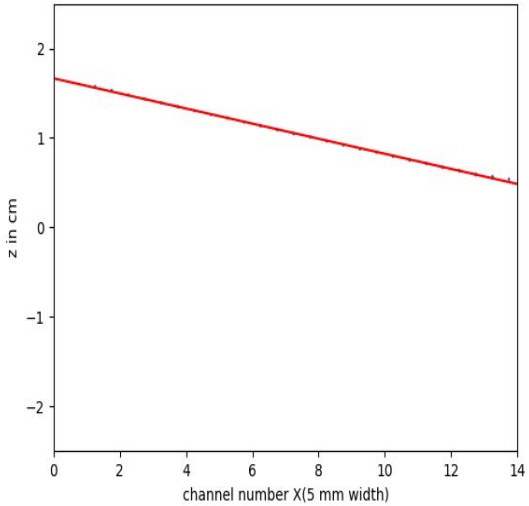


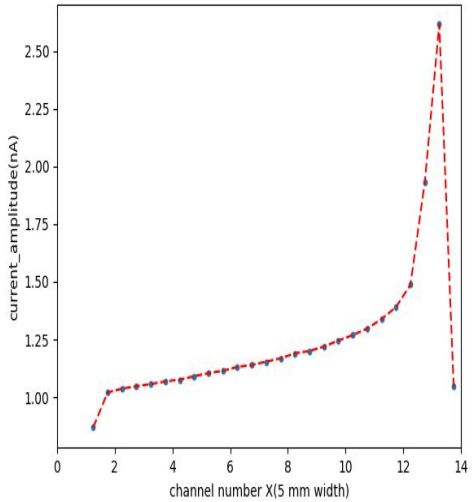


Simulation of alpha particle track reconstruction of in drift region of TPC ($He:CO_2$ 90:10)



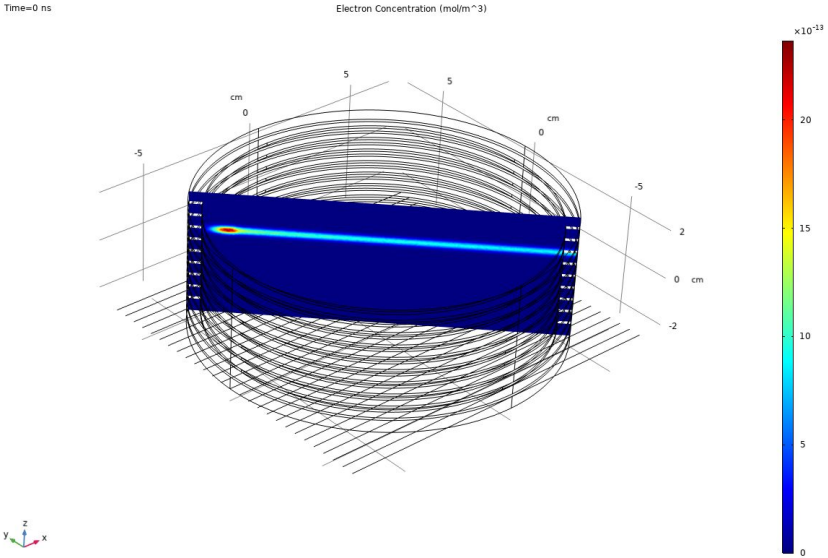


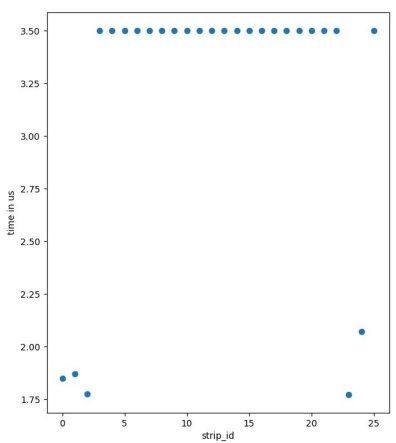


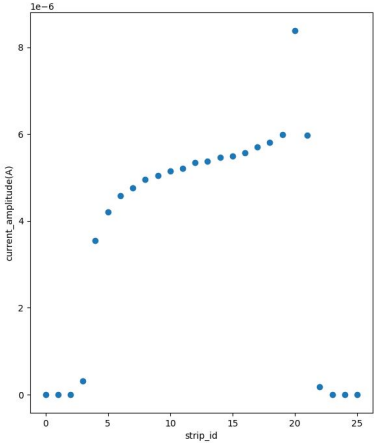


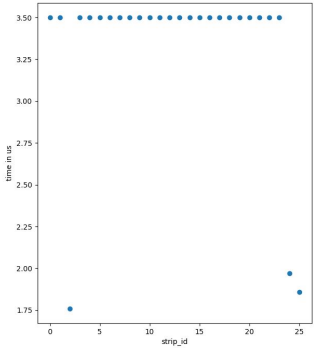
- The Detector plane is segmented into 26 1d strip with 0.5 cm width
- The simulation is performed with 800 V/cm drift field and in atmospheric pressure

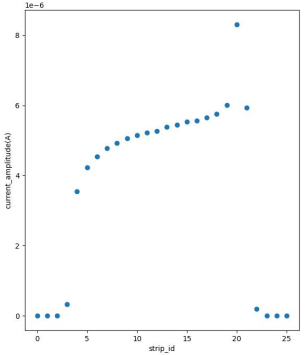
Simulation of alpha particle track reconstruction of in drift region of TPC ($He:CO_2$ 90:10)



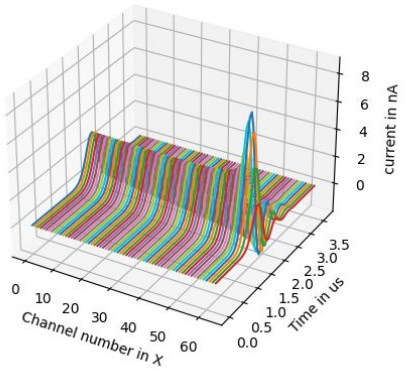


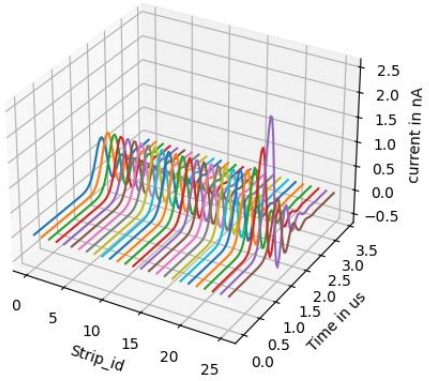


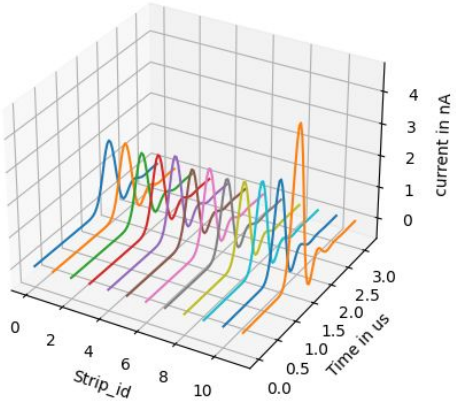




Optimising Readout geometry



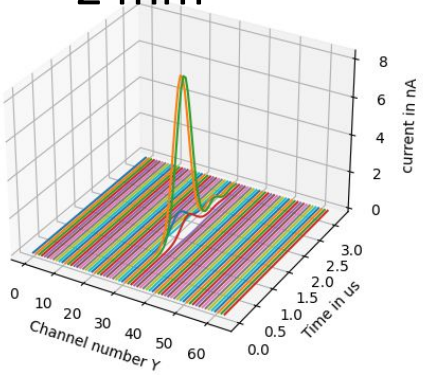


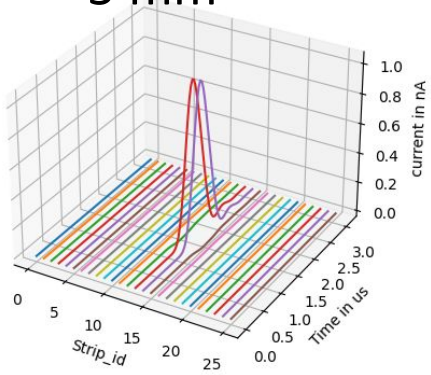


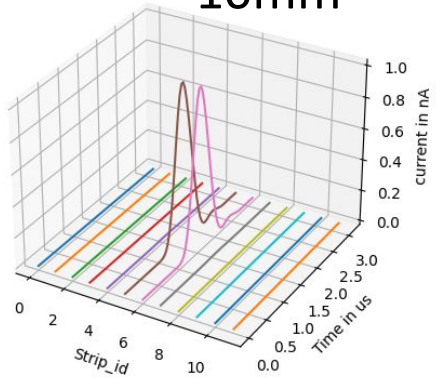
2 mm

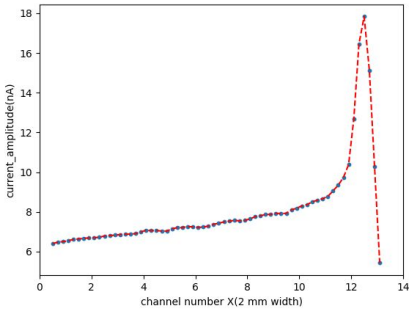
5 mm

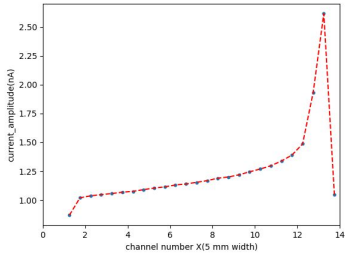
10mm

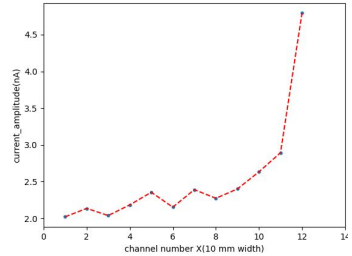




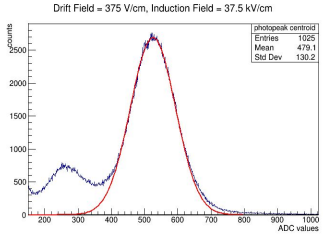


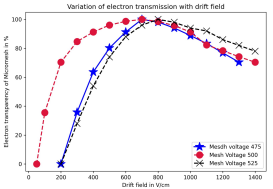


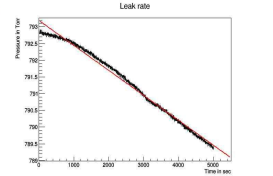


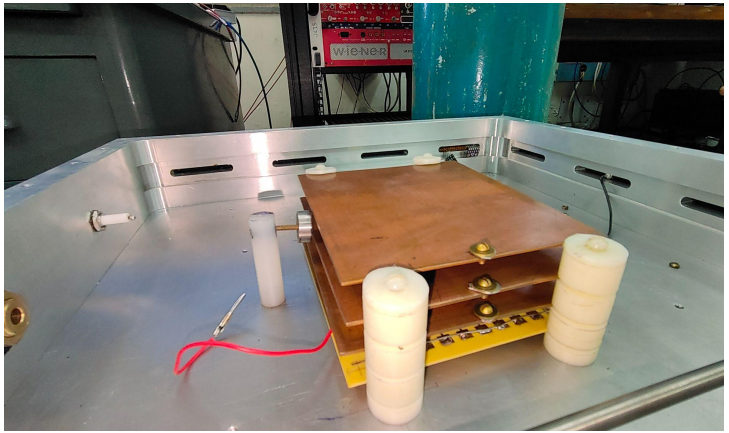


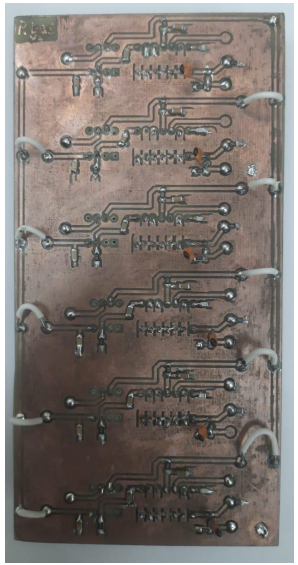
Development of prototype small TPC

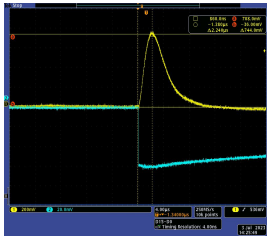


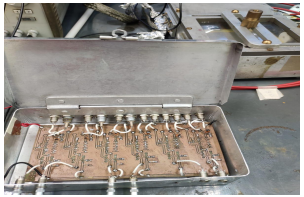












- we are developing a small TPC for tracking with ^{241}Am 5.5 MeV alpha source
- Pressure information in the chamber is measured using BMP180 sensor and arduino nano
- Change in pressure in the chamber 2.685 torr per hour

Conclusion

- We have studied the primary ionization using Geant4 and electron transport using Hydrodynamic simulation (Garfield++ and Comsol) in TPC.

- Drift time information which is required for measuring z coordinate of the track determined from the time evolution of charge collection at the anode of TPC.
- Reconstruction of tracks using Hough Transformation

Future Work:

- Time and position information from the segmented TPC readout
- Development of prototype time projection chamber
- Track reconstruction of alpha cluster decay and (p,α) reactions

Thank you for your kind attentions
Questions,Comments