

Numerical studies of space charge effect on particle tracking in a small TPC

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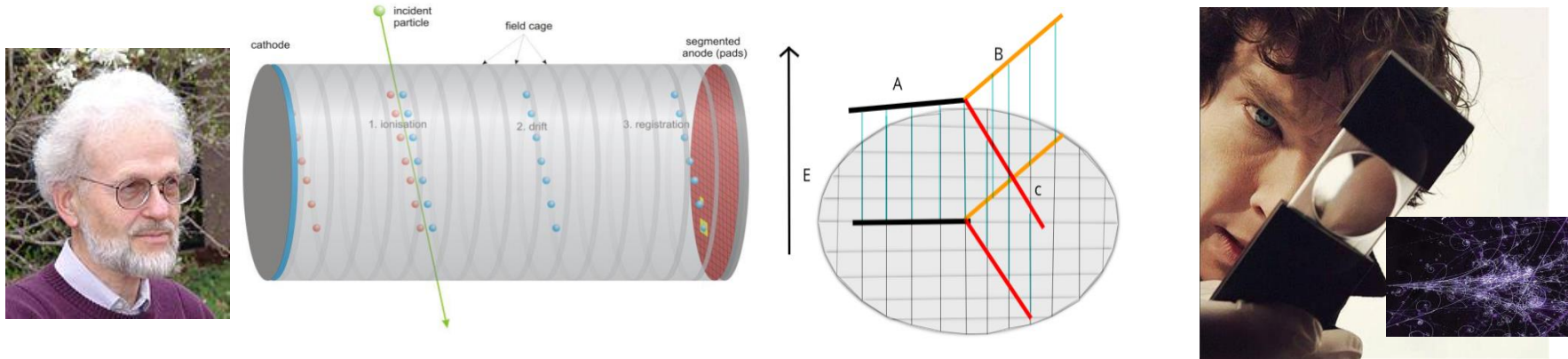
27th Conference on Computing in High Energy and Nuclear Physics

Outline

- ❖ **Motivation**
- ❖ **Active Target Time Projection Chamber**
- ❖ **Simulation of prototype TPC for alpha particle tracking**
- ❖ **Development of prototype TPC for alpha particle tracking**
- ❖ **Beam induced space charge effects in low energy nuclear physics experiments**
- ❖ **Anode segmentation optimization for track reconstruction**
- ❖ **Summary and future plan**

Time Projection Chamber in a nutshell

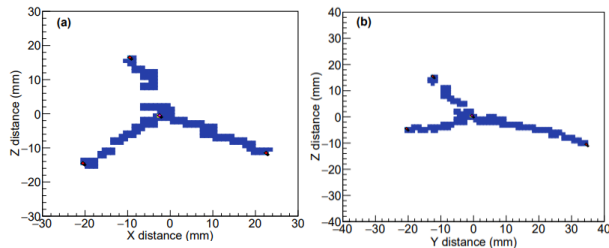
- ❖ TPC has an active gas volume with a good position-sensitive electron collection system inside an electric field and a charged particle will produce primary ionization along its track



- ❖ 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 loss (from range or charge), particle identification

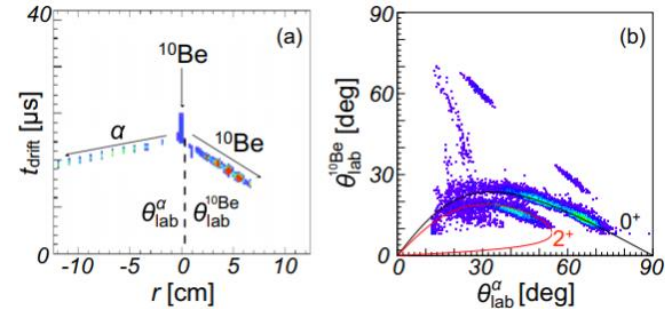
Configuration particle tracking in TPC

- ❖ 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
- ❖ 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

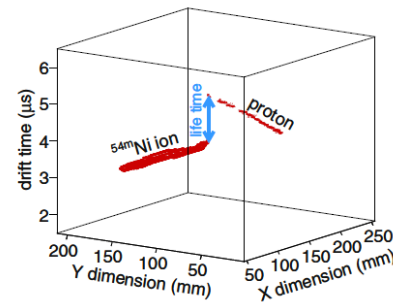
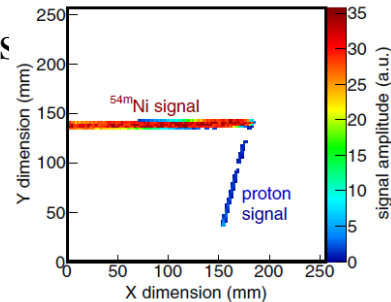


Direct and sequential Hoyle state decay in TexAT TPC

2012.08437.pdf (arxiv.org)
 Prajaya Kumar Das (SINP)



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

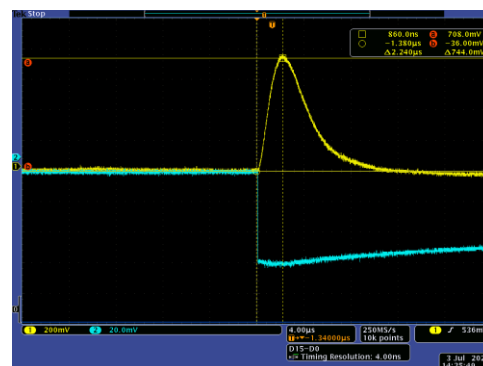
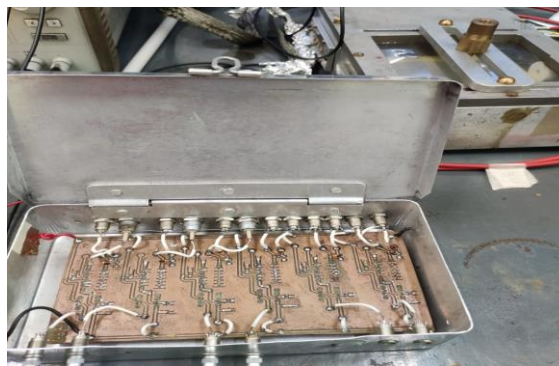
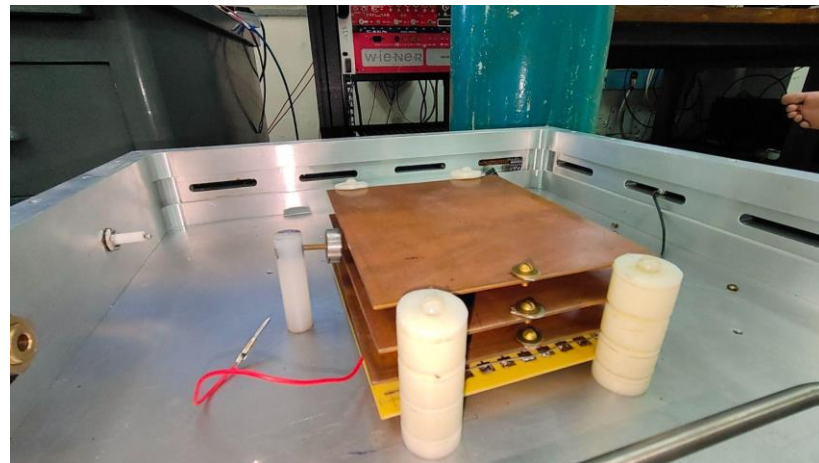
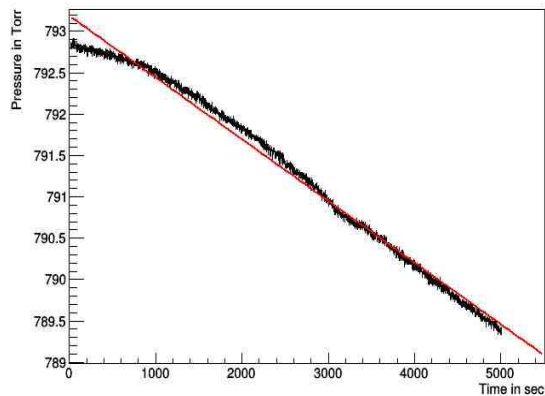


proton-emission branches from an isomeric state in ^{54m}Ni
<https://doi.org/10.1038/s41467-021-24920-0> (Actar TPC)

Development of prototype small TPC



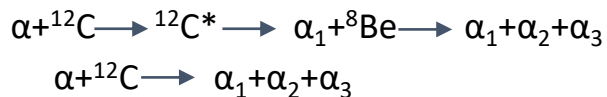
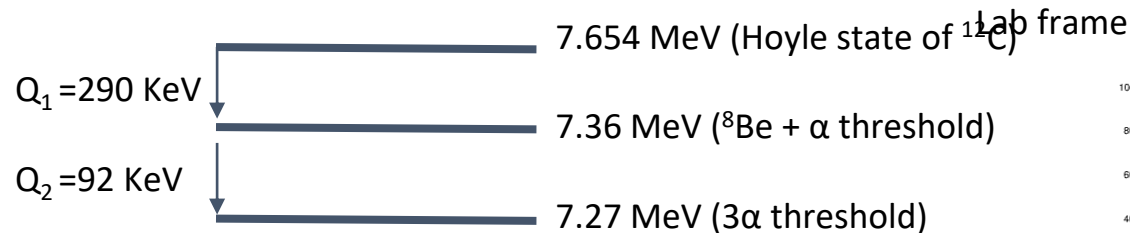
Leak rate



Motivation for alpha tracking in TPC : Hoyle state decay

3 body kinematics in

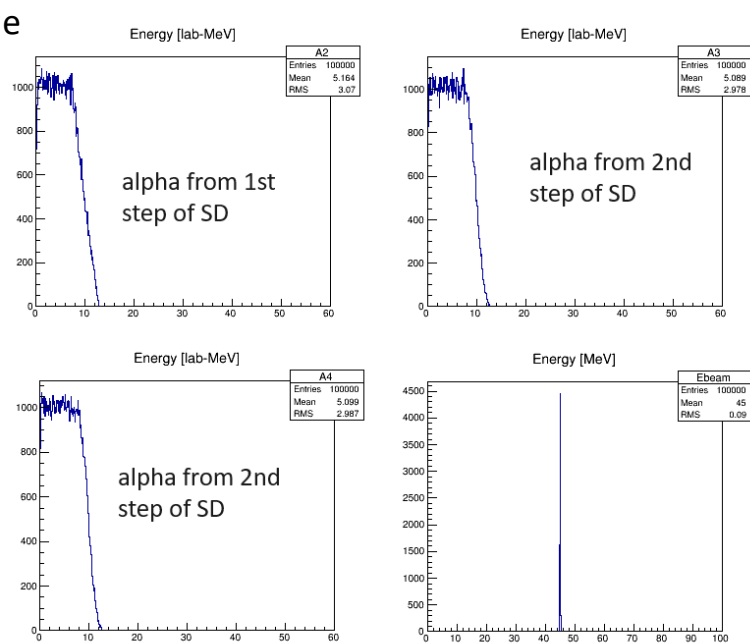
CM frame



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

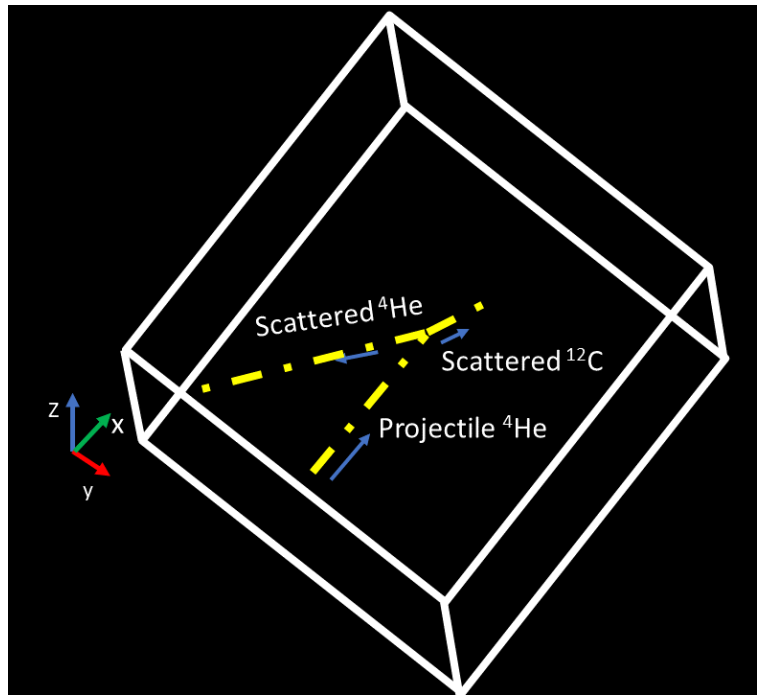
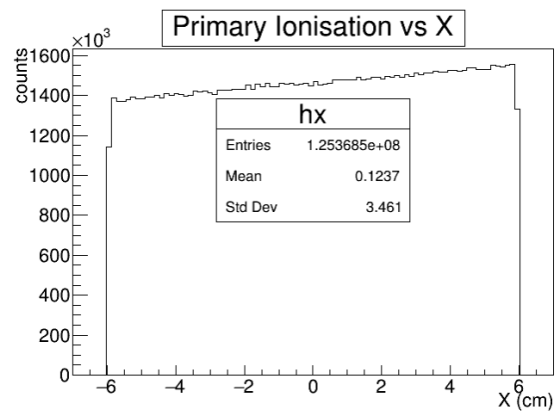
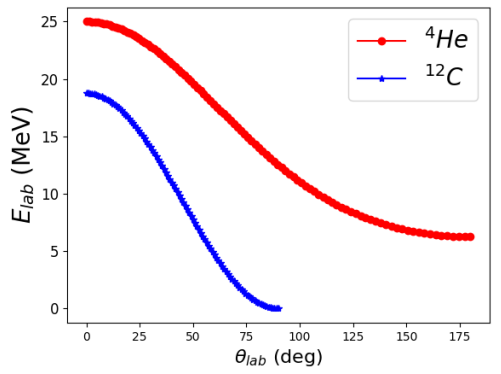
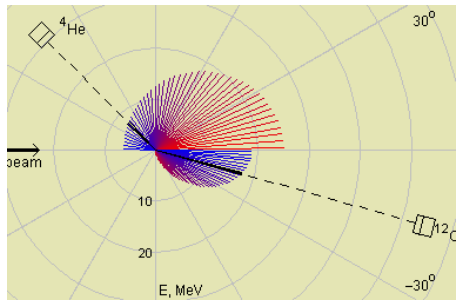
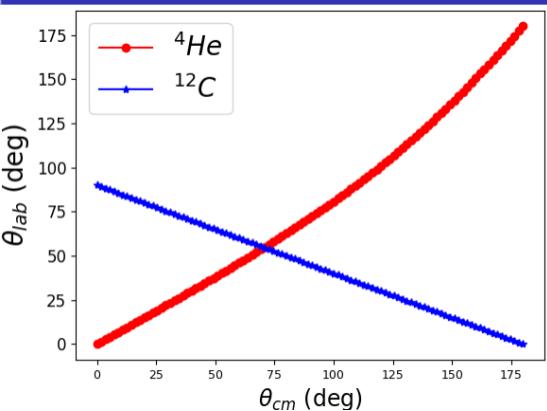
$$E_{\alpha 1} = \frac{P_{\alpha 1}^2}{2m_{\alpha}} = \frac{2}{3}Q_1$$

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



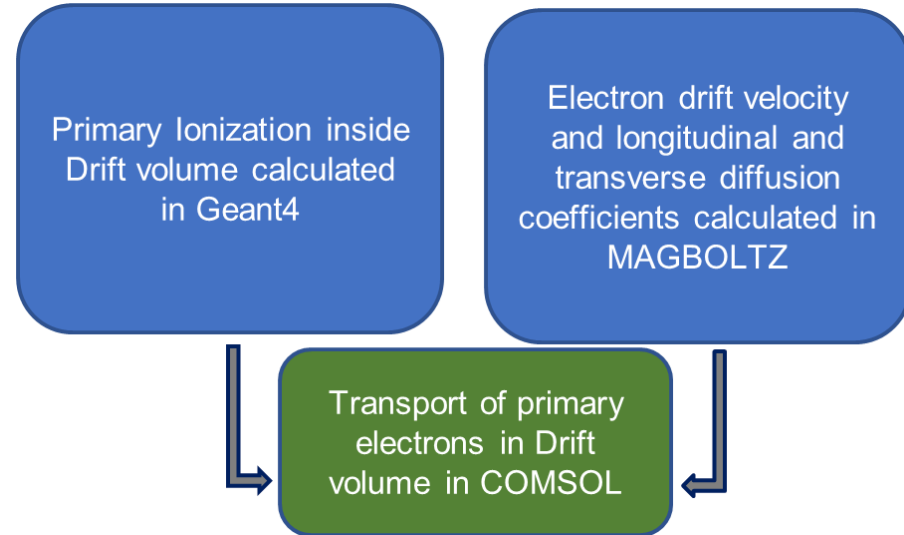
4He beam energy (30-60 MeV) @
 K130 cyclotron at Variable Energy Cyclotron Centre, Kolkata

Case study of elastic scattering events of ${}^4\text{He} + {}^{12}\text{C}$



Introduction to simulation framework

- ❖ Our goal is to find the amount of primary ionization by a charge 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

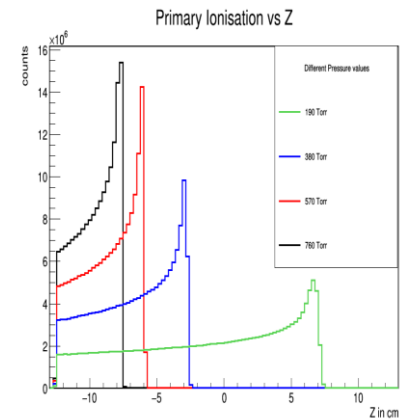
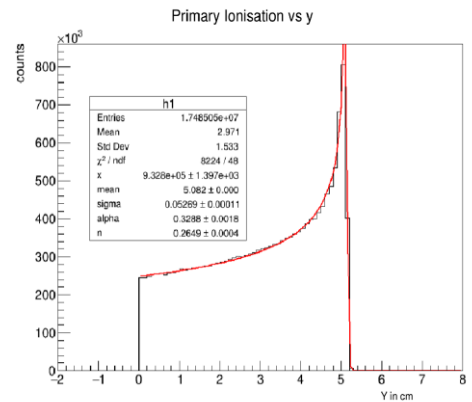
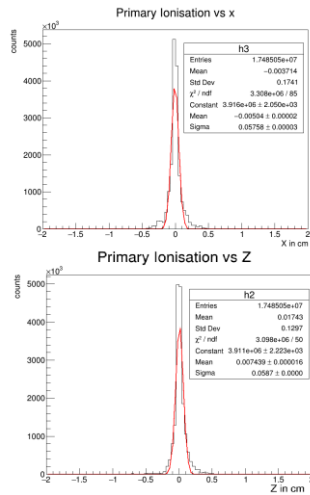
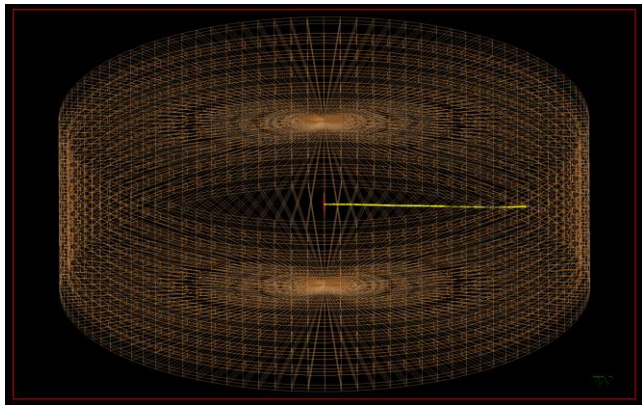


Simulation Framework for primary ionisation by alpha particle

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

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

$$PV = nRT = NK_B T$$

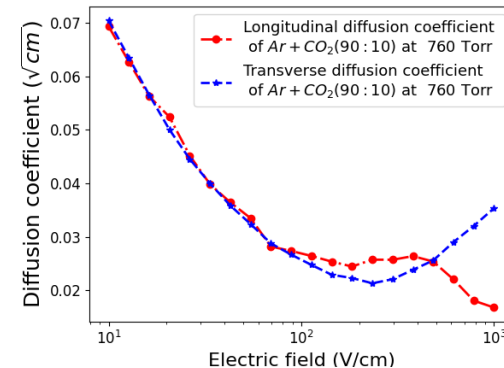
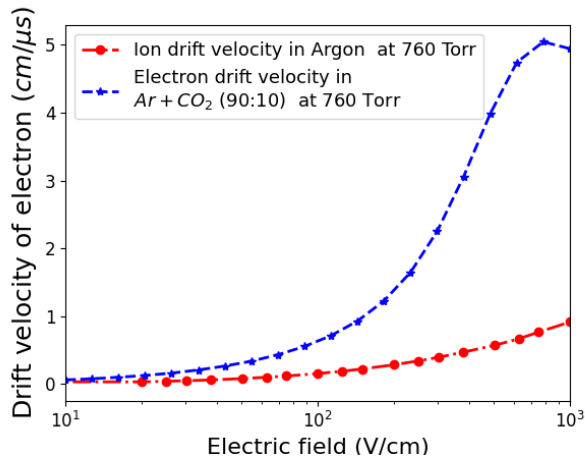


- ❖ Low pressure is suitable for low energy particle tracks in gaseous detector

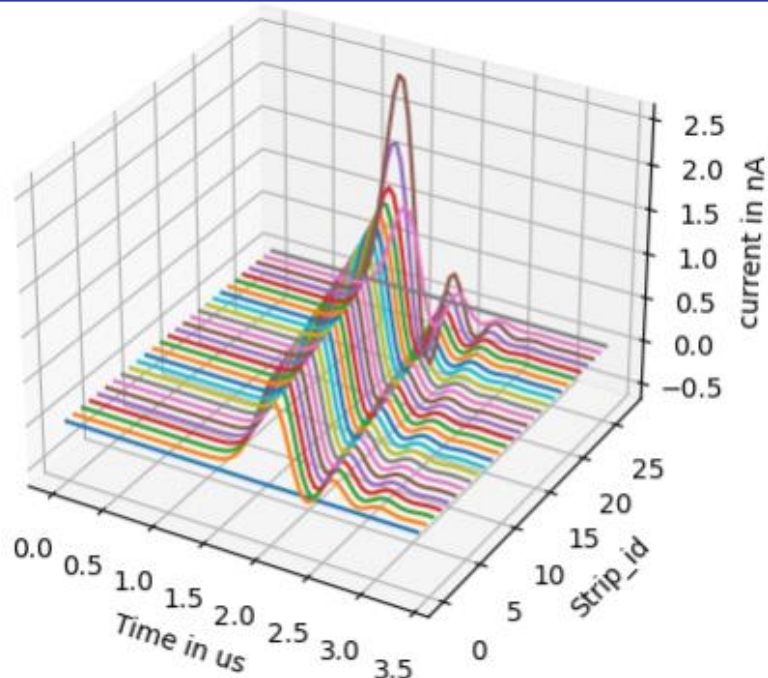
Transport properties of different gas mixtures

- ❖ 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 solute in the solvent gas volume.
- ❖ The hydrodynamics is governed by convection and migration mechanism which is governed by drift-diffusion reaction.

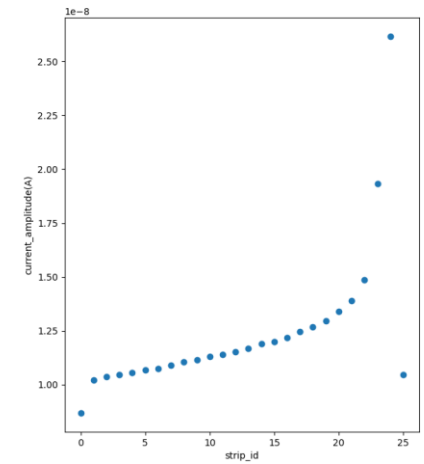
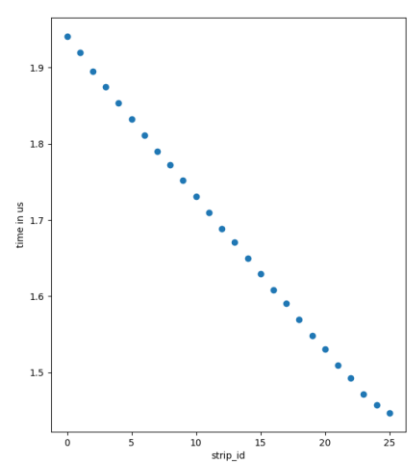
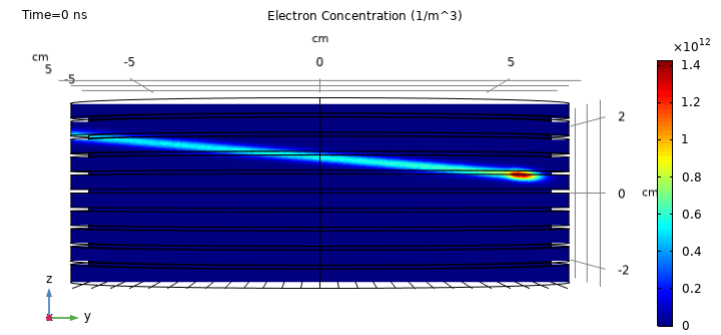
$$\frac{\partial c_i}{\partial t} + \vec{\nabla} \cdot (-D_i \vec{\nabla} c_i + \vec{u}_i c_i) = S_i$$
$$\vec{E} = -\vec{\nabla} V \quad \vec{\nabla} \cdot \vec{D} = -\rho$$



Transport of primary electron in drift region of TPC (He:CO₂ 90:10)

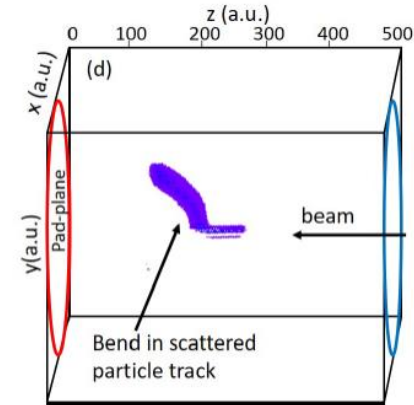


- ❖ The Detector plane is segmented into 26 1d strips with 0.5 cm width
- ❖ The simulation is performed with 800 V/cm drift field and in atmospheric pressure



Space charge effects in low energy nuclear physics experiments

- ❖ Tracking capabilities of TPC depends on
 - **Homogeneity** of drift field
 - **Ion BackFlow** (IBF) due to secondary ionization
- ❖ Space-charge effects
 - **Distortion** in electric field
 - On Ion **mobility** and impact on track distortion
 - Low-energy nuclear physics experiments are mainly expected to be induced by the high ionizing beam particles

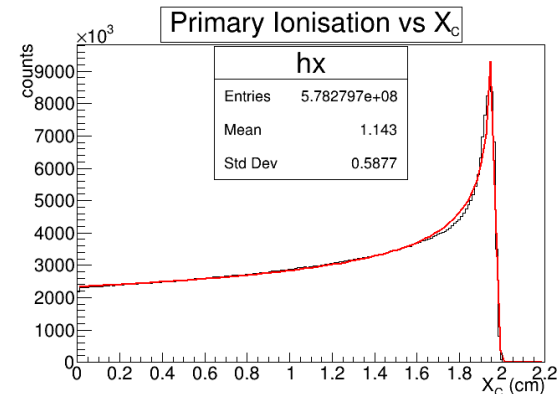
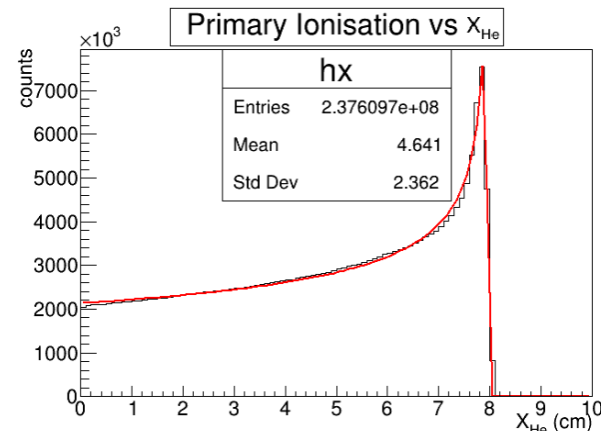
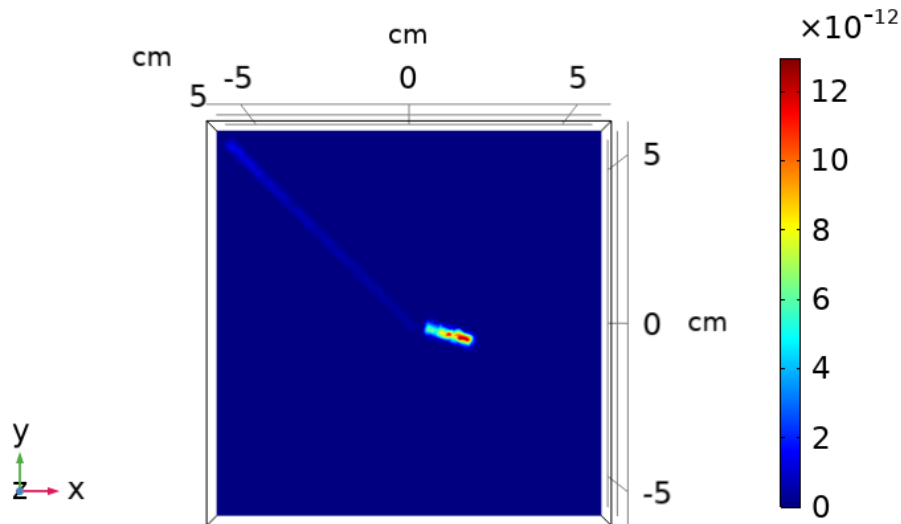


Jaspreet S. Randhawa et. al, NIM-A, 2019
“Beam induced space-charge effects in Time Projection Chambers in low-energy nuclear physics experiments”

Seed cluster tracks

$\theta_{^4\text{He}}^{\text{lab}} \text{ (deg)}$	$E_{^4\text{He}}^{\text{lab}} \text{ (MeV)}$	$\theta_{^{12}\text{C}}^{\text{lab}} \text{ (deg)}$	$E_{^{12}\text{C}}^{\text{lab}} \text{ (MeV)}$
135	7.6	15.68	17.4

Time=0 ns Electron Concentration (mol/m³)



Characteristic of 25 MeV ^4He Beam

$$pA = Z * pps * e * 10^{12} \quad , pps = \frac{nA}{Z * e * 10^9}$$

$$pps(2.3pAHe) = \frac{2.3}{2 * 1.6 * 10^{-19} * 10^{12}} = 7.18 * 10^6$$

$$\Delta t(1naHe) = 140ns, v_d = 570cm/s$$

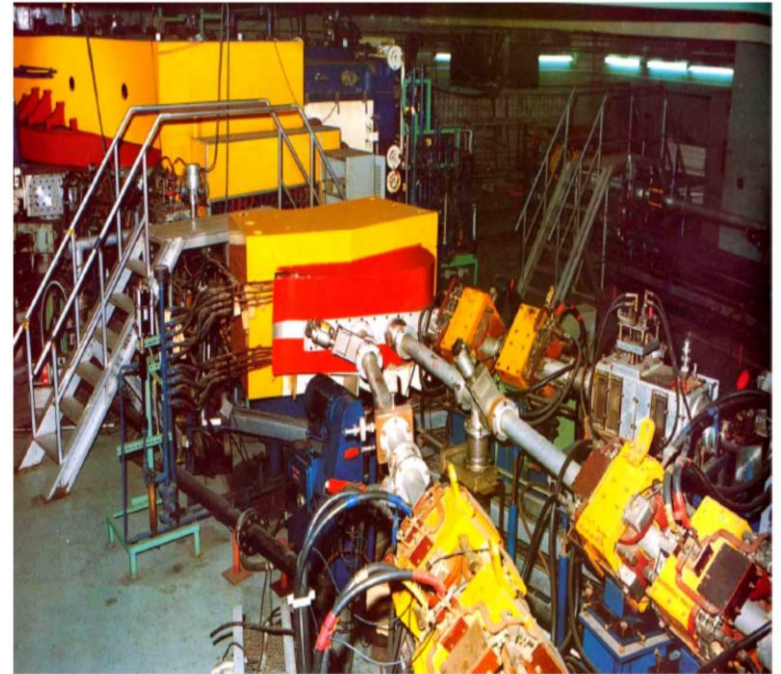
$$\Delta z = \Delta t * v_d = 798nm$$

$$t_{\frac{z}{2}} = \frac{z_{\frac{1}{2}}}{v_d} = \frac{5[cm]}{570[cm/s]} = 0.008772[s]$$

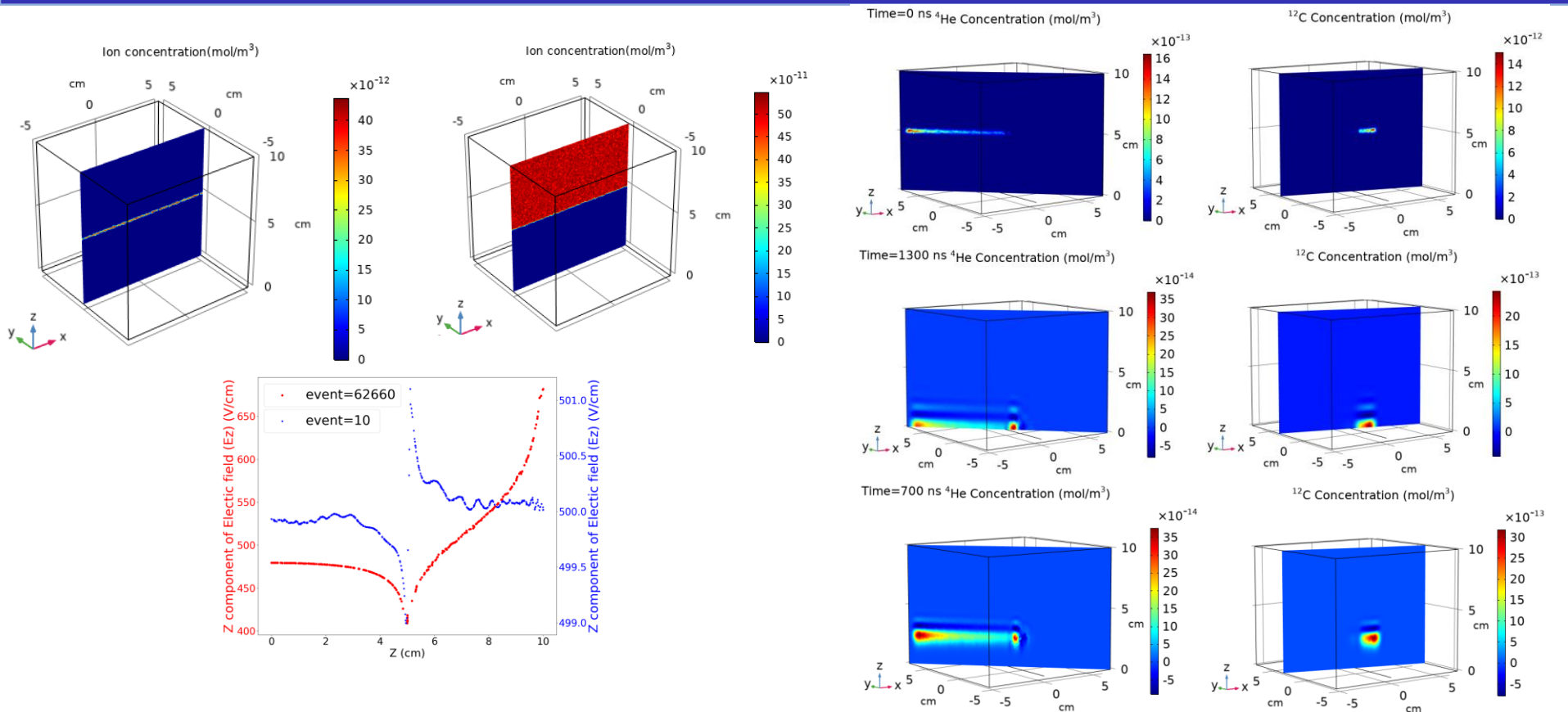
$$Nb = 140ns * 7.18 * 10^6 = 1$$

no. of events

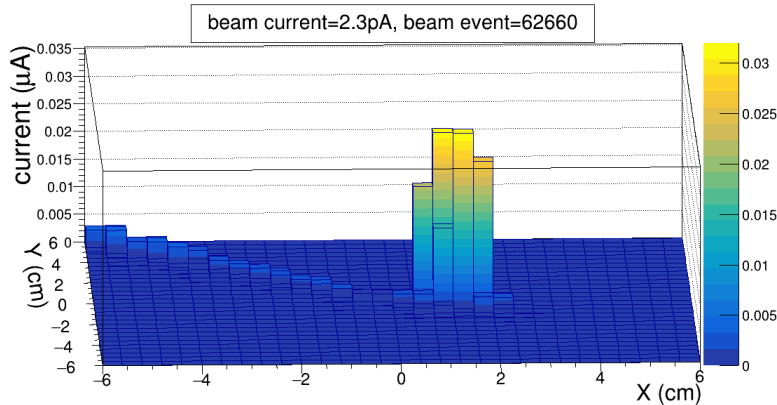
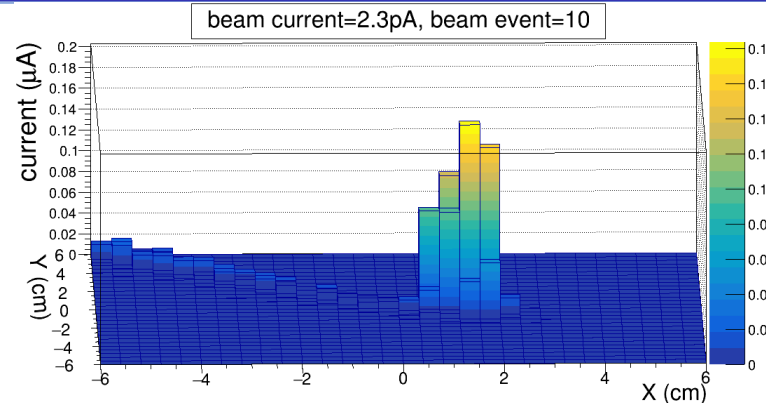
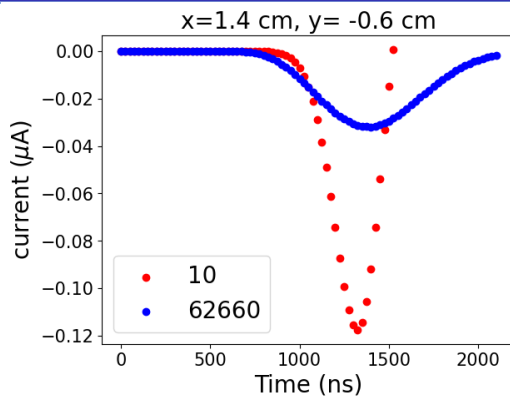
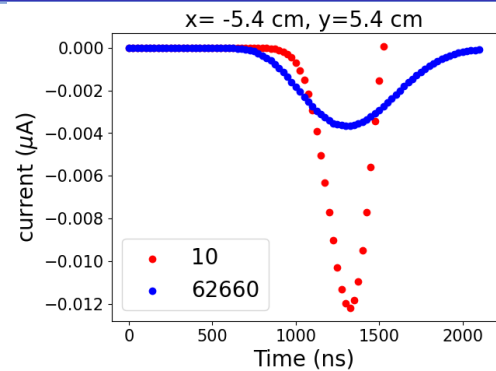
$$= \frac{t_{\frac{z}{2}}}{\Delta t} = 1 * \frac{0.008772}{140 * 10^{-9}} = 6.266 * 10^4$$



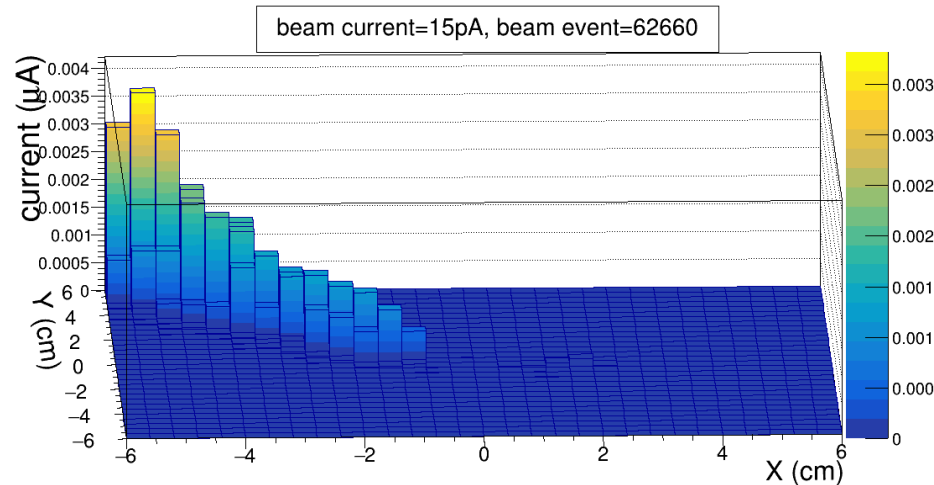
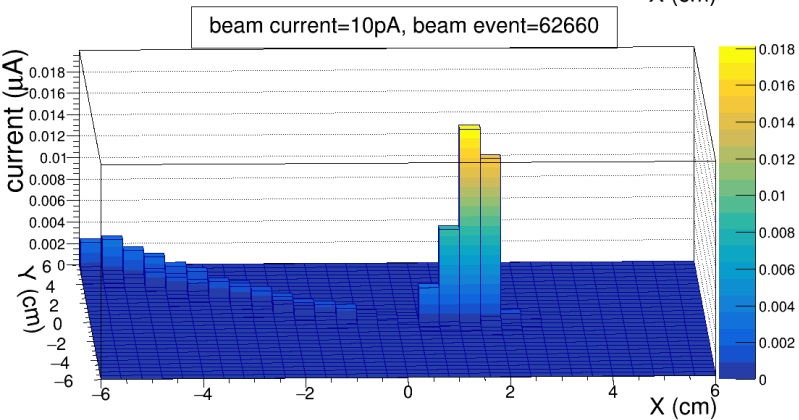
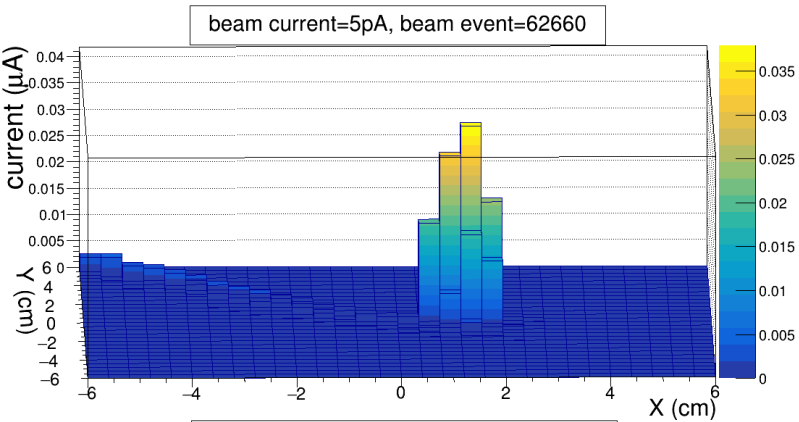
Transport of primary electrons in presence of space charge



Current on anode readout pads

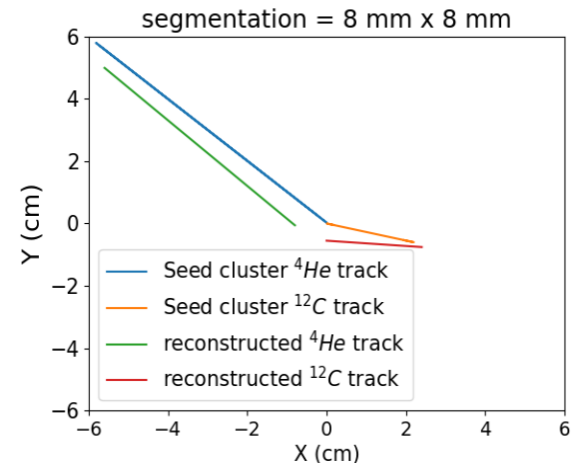
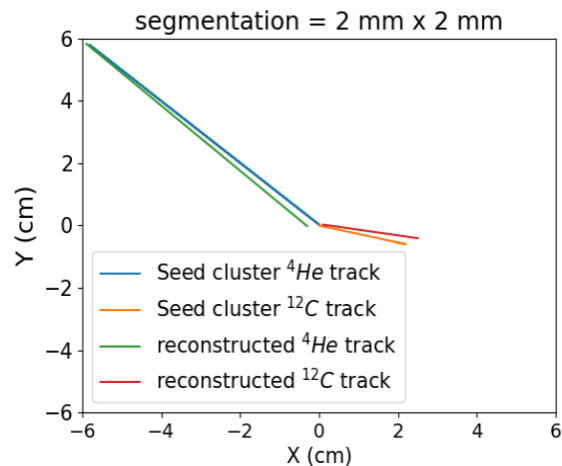
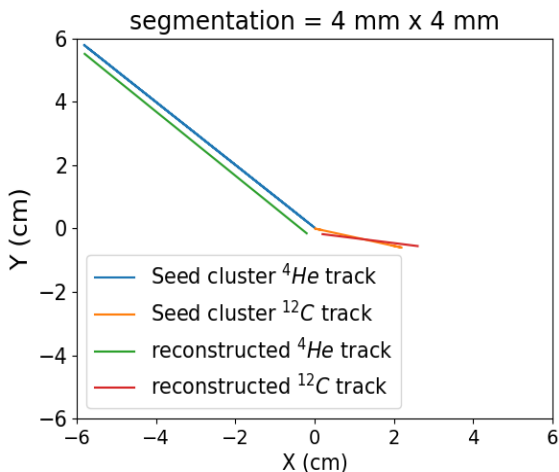


Effect of beam current on collected signal at readout



Seed cluster and Reconstructed tracks

	2 mm × 2 mm	4 mm × 4 mm	8 mm × 8 mm	seed cluster
${}^4\text{He}$ track angle	$133.75^\circ \pm$ 0.36	$134.13^\circ \pm$ 1.54	$133.56^\circ \pm$ 1.41	$135.33^\circ \pm$ 0.3
${}^{12}\text{C}$ track angle	$10.3^\circ \pm$ 1.34	$6.56^\circ \pm$ 0.98	$4.85^\circ \pm 1$	$15.27^\circ \pm$ 1.81



Summary and Conclusion

- ❖ The hydrodynamic model, which is computationally less expensive in comparison to particle model, has been found to perform satisfactorily in emulating the device dynamics of an AT-TPC.
- ❖ The hydrodynamic model has been utilized for optimization of operational limit of beam current and anode segmentation of the proposed SAT-TPC prototype to study non-relativistic elastic scattering of ${}^4\text{He}$ of energy 25 MeV with active gaseous target ${}^{12}\text{C}$.
- ❖ the beam current should be restricted to below 10 pA , where the signal amplitude for the scattered particle tracks has been found to reduce by $25 - 30\%$.
- ❖ The numerical investigation on the anode segmentation to optimize its dimension has led to a choice of $4\text{ mm} \times 4\text{ mm}$ for satisfactory tracking performance along with cost effective production of the SAT-TPC prototype.

ACKNOWLEDGEMENTS

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- ❖ I like to express my gratitude towards SINP for providing me necessary funding and equipment throughout the work.

Thank you for your attention
Questions, Comments