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

Pralay Kumar Das
Saha Institute of Nuclear Physics, Kolkata
Homi Bhabha National Institute, Mumbai

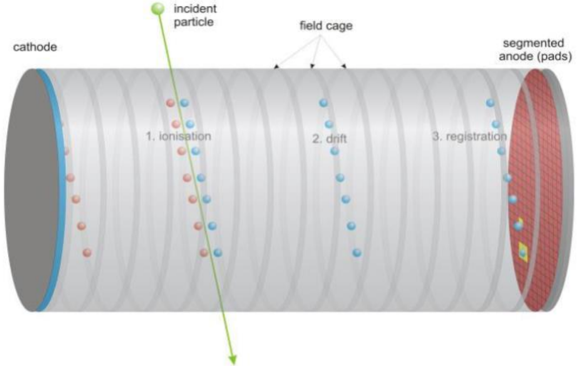
22 October, 2024
27th Conference on Computing in High Energy and Nuclear Physics

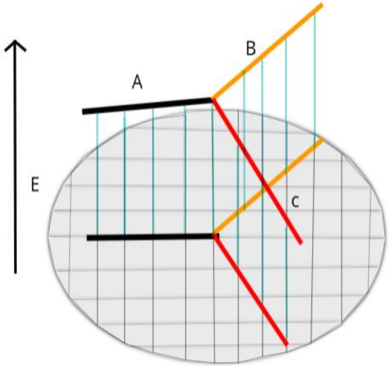
Outline

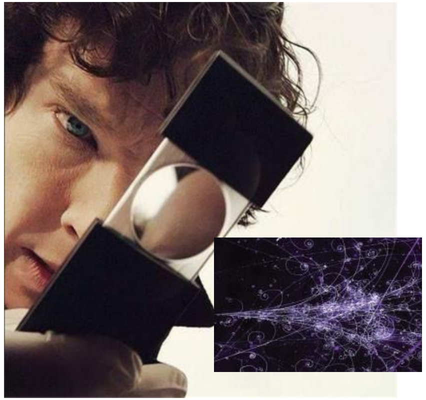
- ❖ **Motivation**
- ❖ **Active Target Time Projection Chamber**
- ❖ **Simulation of prototype TPC for alpha particle tracking**
- ❖ **Development of prototype TPC for alpha particle tracking**
- ❖ **Beam induced space charge effects in low energy nuclear physics experiments**
- ❖ **Anode segmentation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



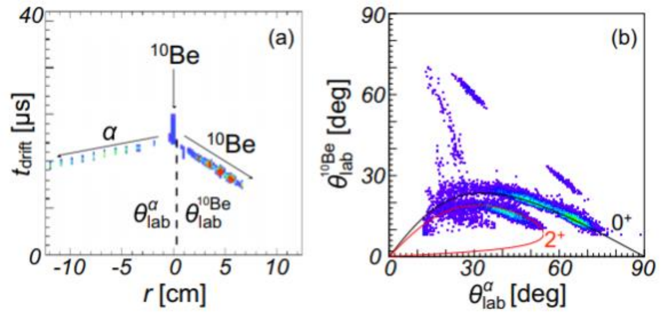




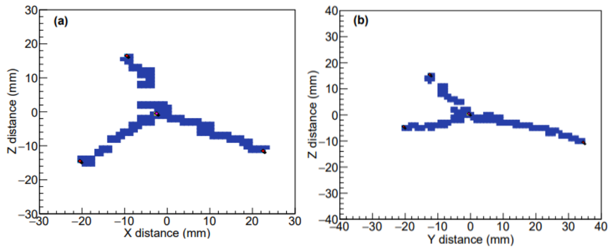
- ❖ The primary electrons drift under the action of the uniform electric field towards the end equipped with an electron multiplier for collecting signal producing a 2d image of the track
- ❖ 3rd dimension from the drift time of electrons
- ❖ Information
  - ➢ Angles, energy loss (from range or charge),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

Configuration particle tracking in TPC

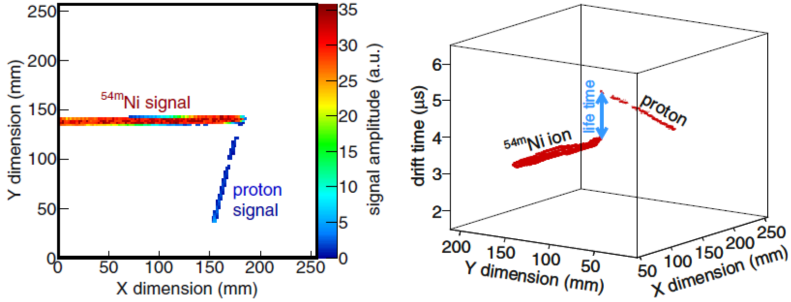
- In the field of low-energy nuclear physics, Active-Target Time Projection Chambers (AT-TPCs), the detector gas of the TPC is at the same time the target in which nuclear reactions take place
- AT-TPC is advantageous for 4π detection efficiency and event by event 3D track reconstruction
- ATTPC, TexAT, ACTAR, Maiko are examples of active target TPC used in low energy nuclear physics



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

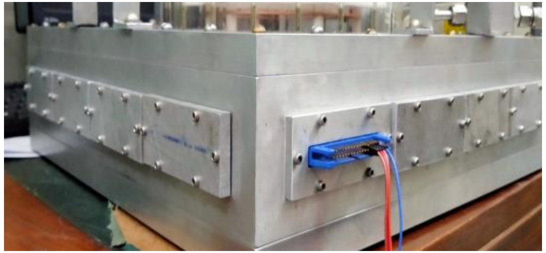


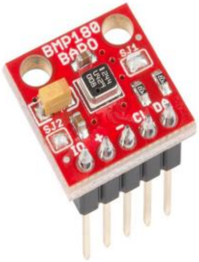
Direct and sequential Hoyle state decay in TexAT TPC
2012.08437.pdf (arxiv.org)

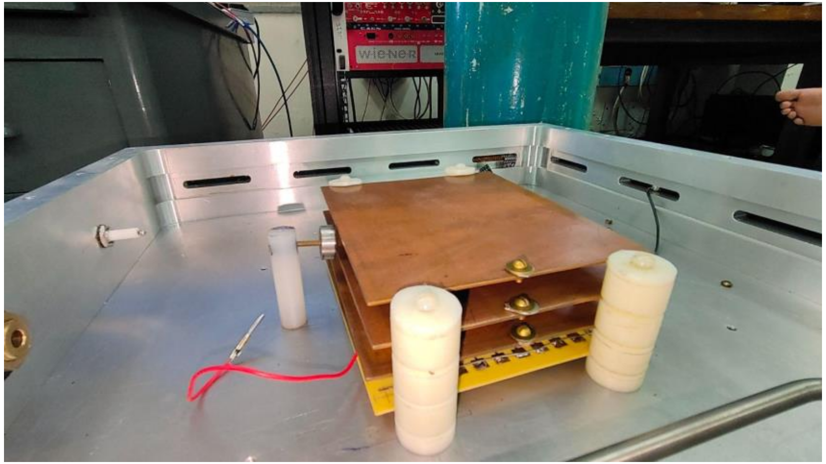


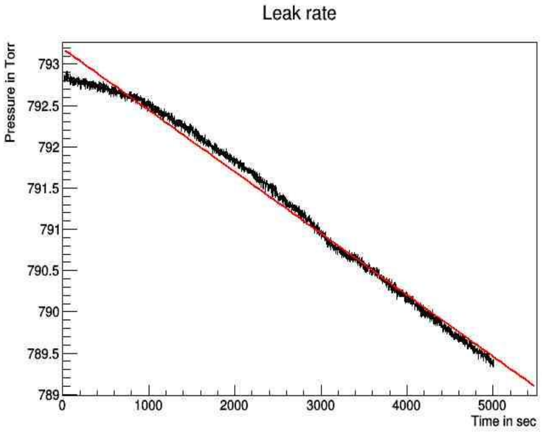
proton-emission branches from an isomeric state in 54mNi
https://doi.org/10.1038/s41467-021-24920-0 (Actar TPC)

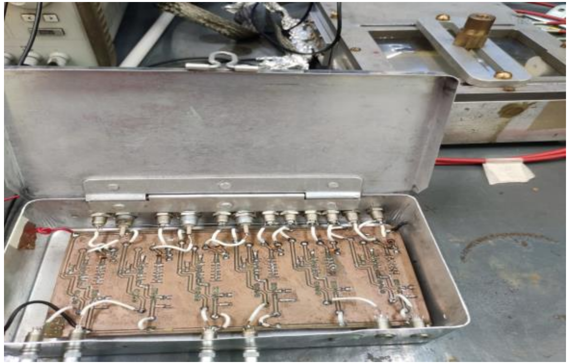
Development of prototype small TPC

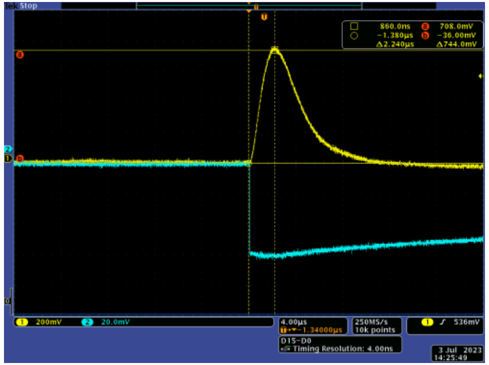








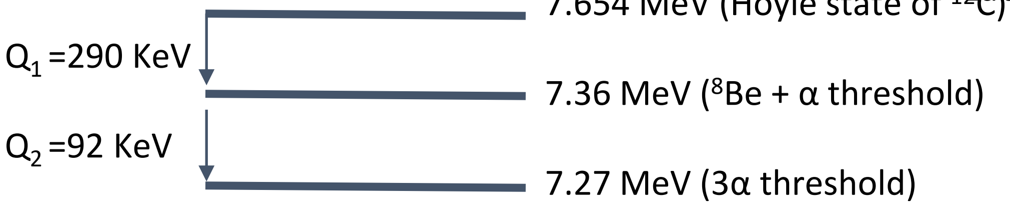




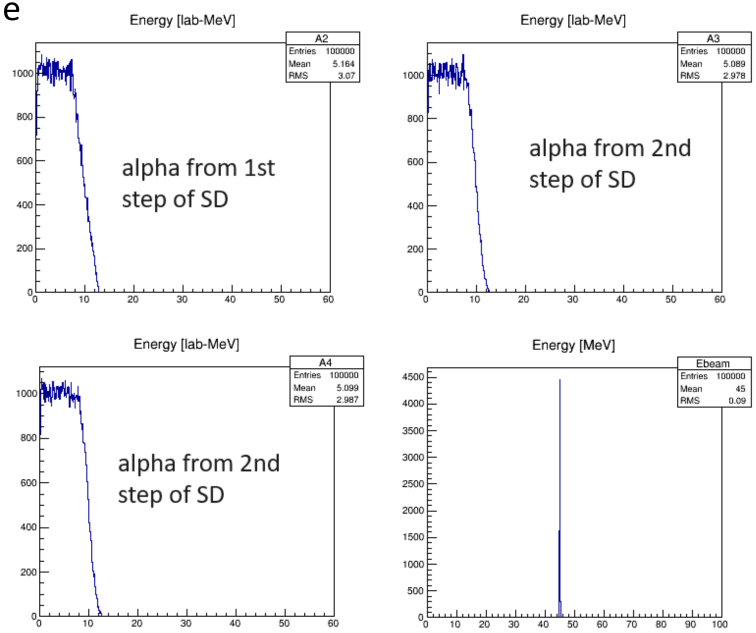
Motivation for alpha tracking in TPC : Hoyle state decay

3 body kinematics in

CM frame



Lab frame



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

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

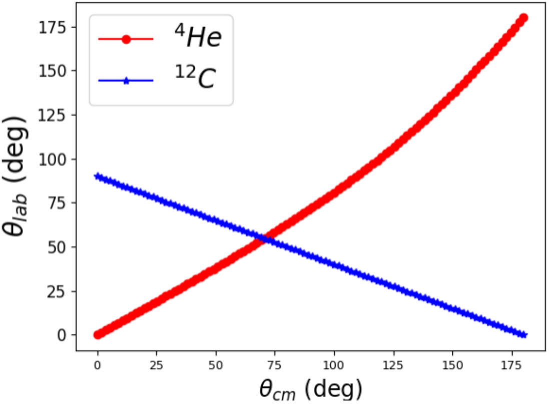
$$P_{\alpha 1} = P_{^8Be}$$

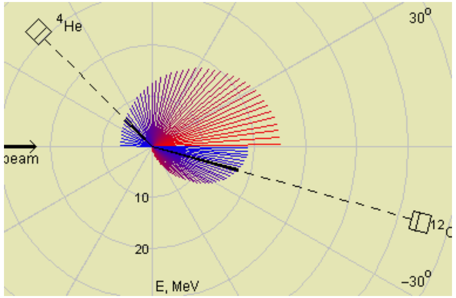
$$E_{\alpha 1} = \frac{P_{\alpha 1}^2}{2m_\alpha} = \frac{2}{3}Q_1$$

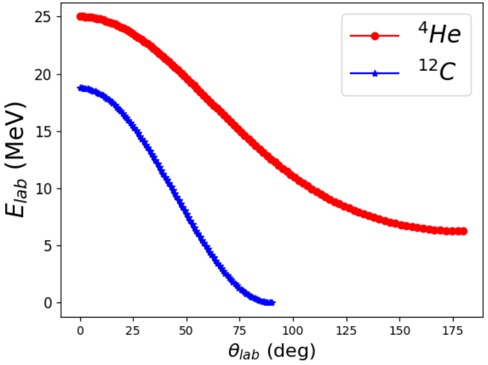
$$E_{\alpha 2} + E_{\alpha 3} = \frac{1}{3}Q_1 + Q_2 = \frac{P_{\alpha 1}^2}{4m_\alpha} + Q_2$$

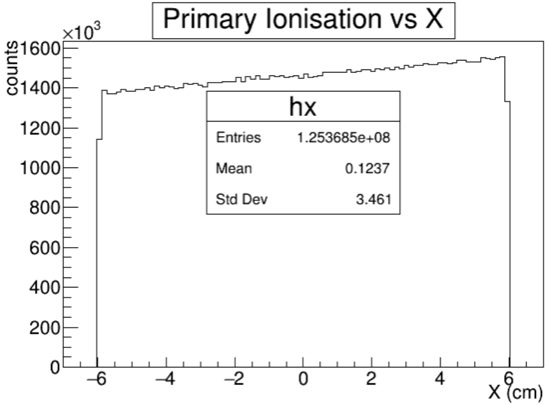
4He beam energy (30-60 MeV) @
K130 cyclotron at Variable Energy Cyclotron Centre, Kolkata

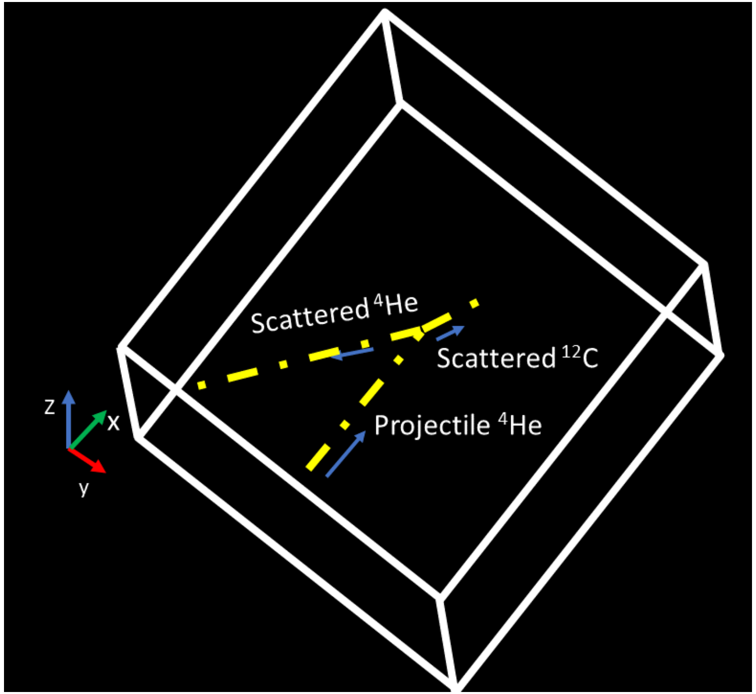
Case study of elastic scattering events of ^{4}He + ^{12}C





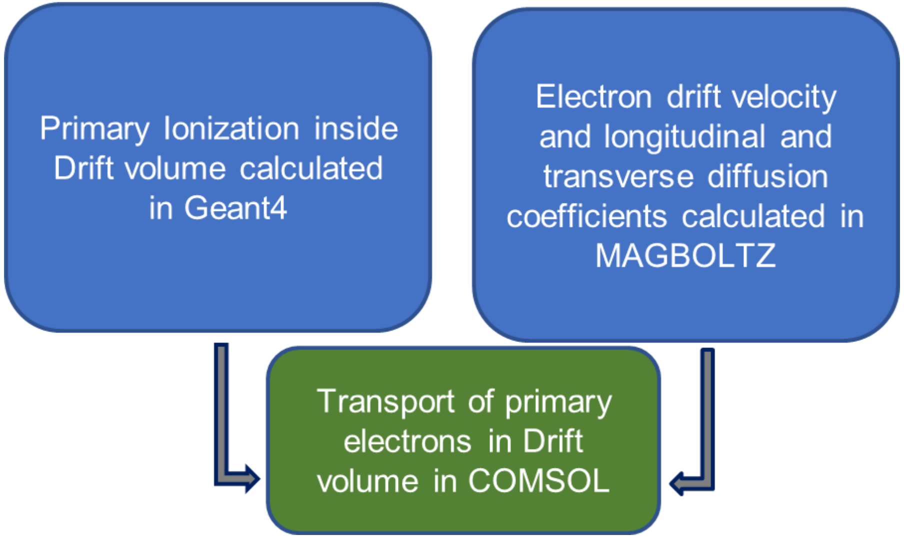






Introduction to simulation framework

- 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

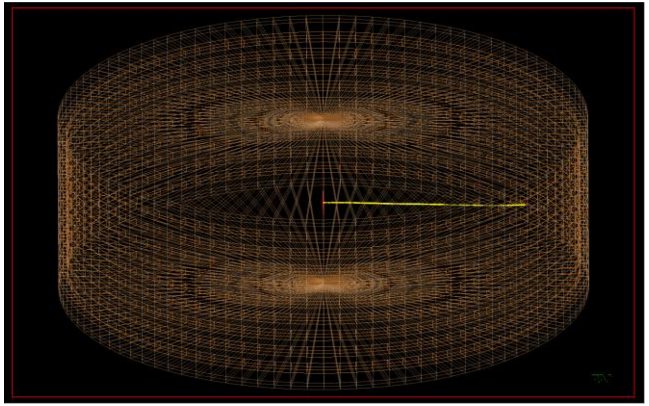


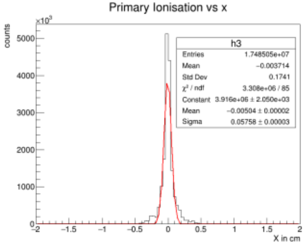
Simulation Framework for primary ionisation by alpha particle

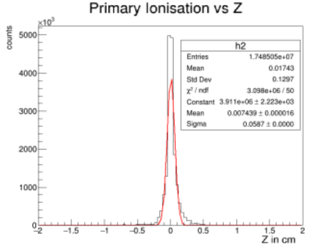
- ❖ Energy deposition increases with square of the charge of incoming projectile
- ❖ Number of gaseous particle decreases with decreasing pressure

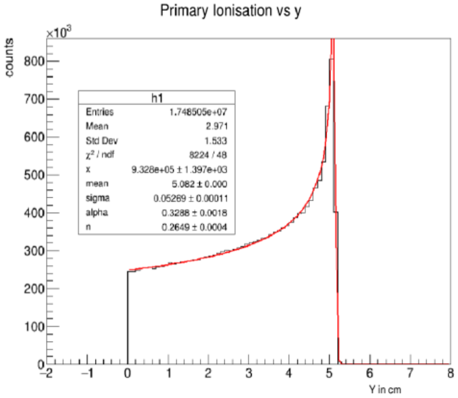
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 c^2 \rho \frac{Z}{A}\frac{q^2}{\beta^2}\left[ln\left(\frac{2m_e\gamma^2\nu^2 W_max}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right] \quad \rho = \frac{mP}{K_B T}$$

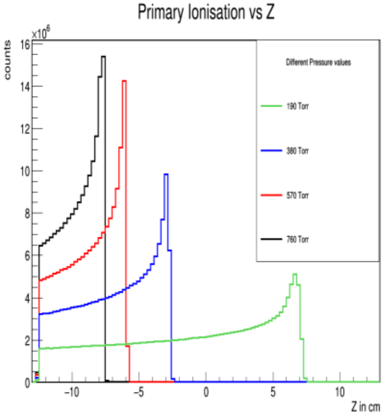
$$PV = nRT = NK_BT$$











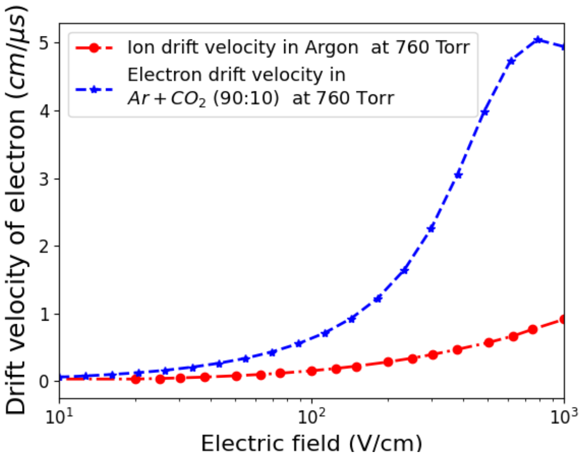
- ❖ Low pressure is suitable for low energy particle tracks in gaseous detector

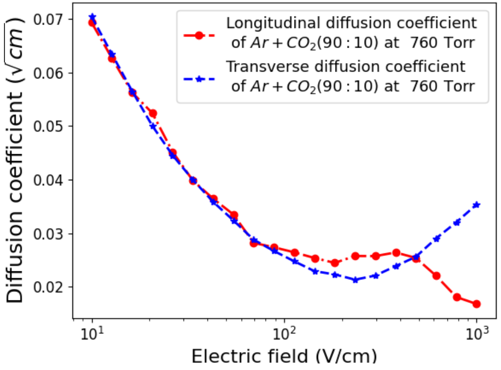
Transport properties of different gas mixtures

- 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.

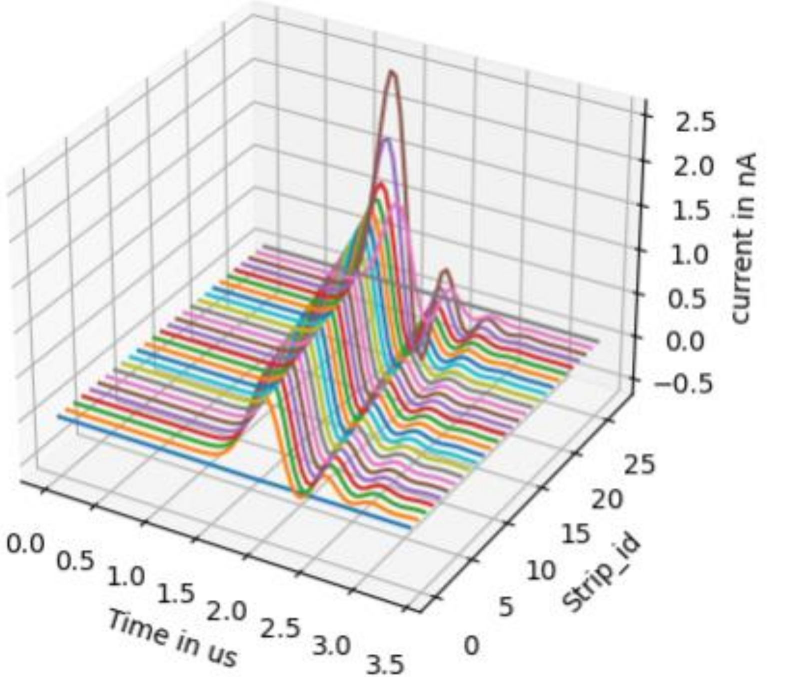
$$\frac{\partial c_i}{\partial t} + \vec{\nabla}\left(-D_i \vec{\nabla} c_i + \vec{u_i} c_i\right) = S_i$$

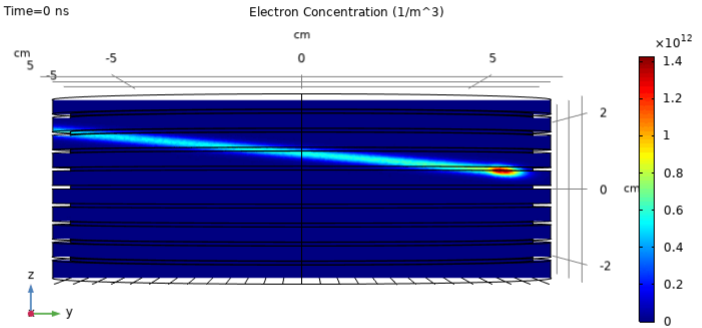
$$\vec{E} = -\vec{\nabla} V \qquad \vec{\nabla} \cdot \vec{D} = -\rho$$

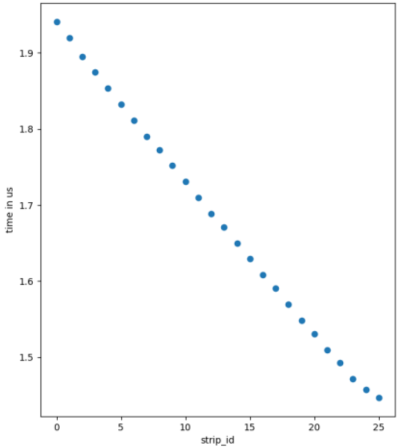


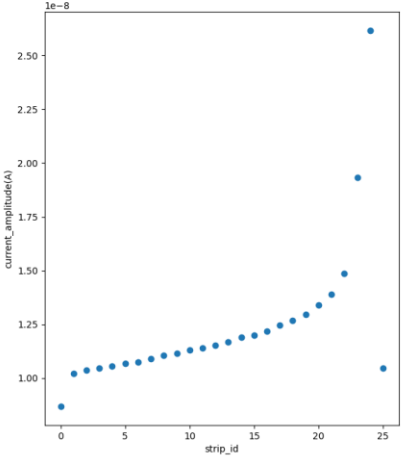


Transport of primary electron in drift region of TPC (He:CO_2 90:10)





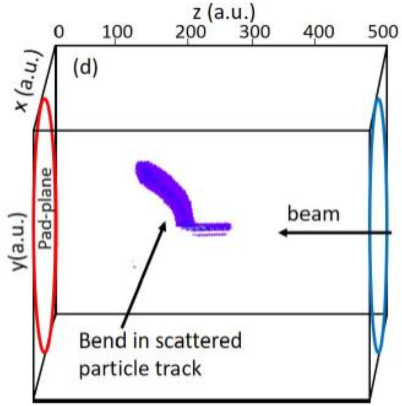




- ❖ The Detector plane is segmented into 26 1d strips with 0.5 cm width
- ❖ The simulation is performed with 800 V/cm drift field and in atmospheric pressure

Space charge effects in low energy nuclear physics experiments

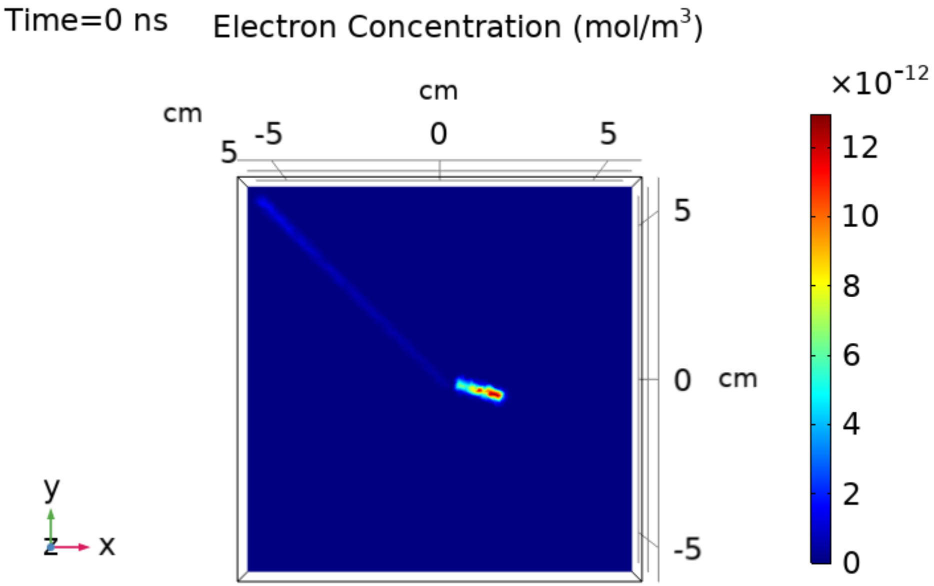
- ❖ Tracking capabilities of TPC depends on
  - ➢ Homogeneity of drift field
  - ➢ Ion BackFlow (IBF) due to secondary ionizatio
- ❖ Space-charge effects
  - ➢ Distortion in electric field
  - ➢ On Ion mobility and impact on track distortion
  - ➢ Low-energy nuclear physics experiments are mainly expected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

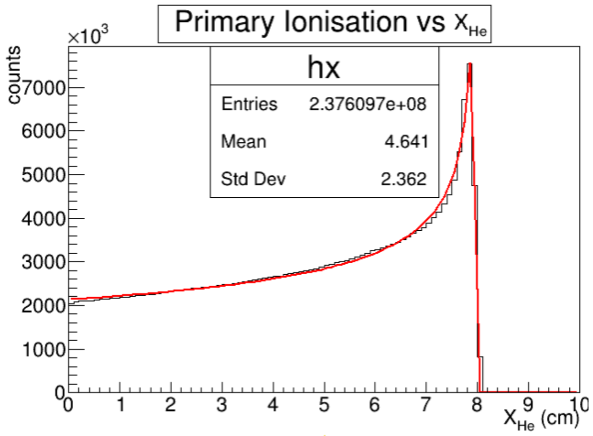


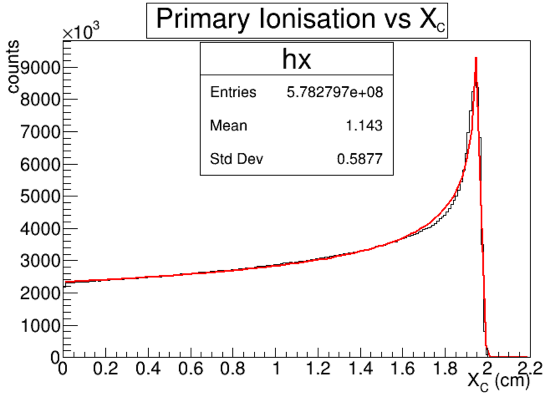
Jaspreet S. Randhawa et. al, NIM-A, 2019
"Beam induced space-charge effects in Time Projection Chambers in low-energy nuclear physics experiments"

Seed cluster tracks

$\theta^{lab}_{^4He}(deg)$	$E^{lab}_{^4He}(MeV)$	$\theta^{lab}_{^{12}C}(deg)$	$E^{lab}_{^{12}C}(MeV)$
135	7.6	15.68	17.4







Characteristic of 25 MeV ^{4}He Beam

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

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

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

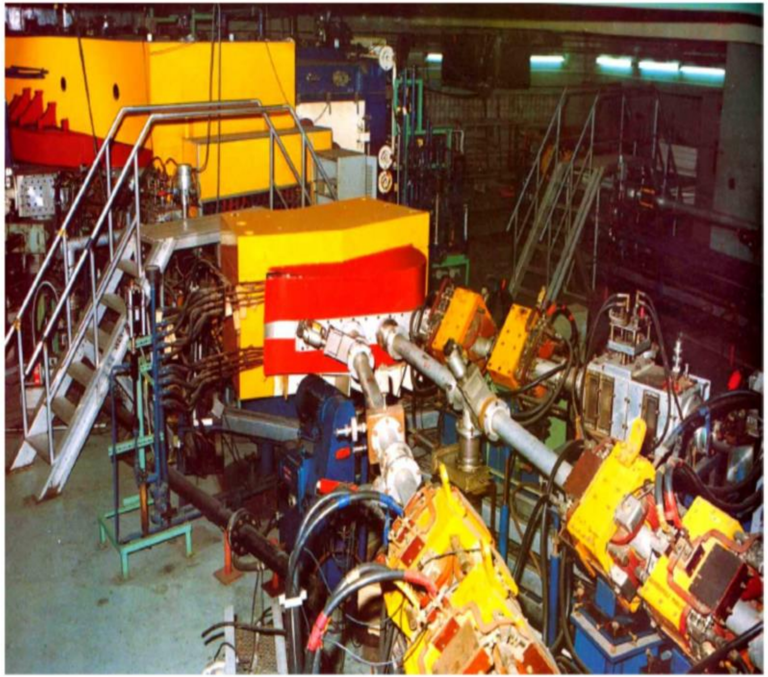
$$\Delta z = \Delta t * v_d = 798nm$$

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

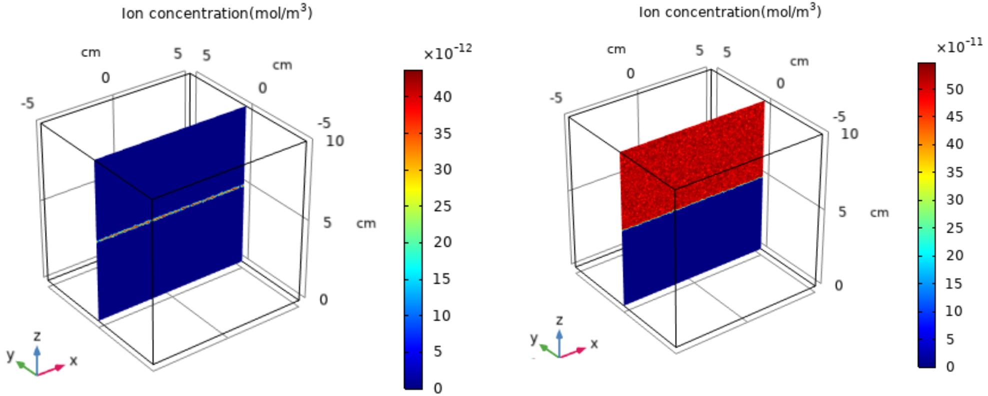
$$Nb = 140ns * 7.18 * 10^{6} = 1$$

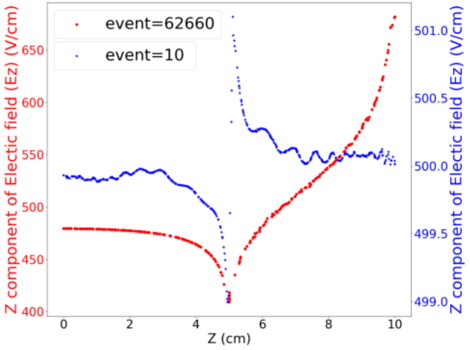
$$no.ofevents$$

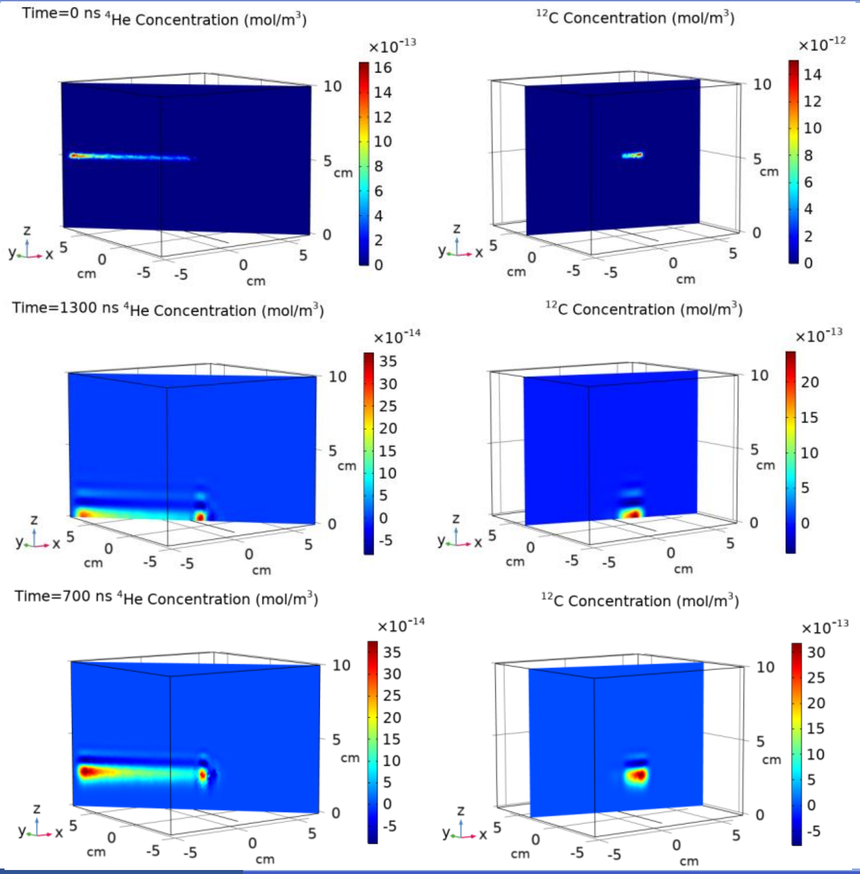
$$= \frac{t_{\frac{z}{2}}}{\Delta t} = 1 * \frac{0.008772}{140*10^{-9}} = 6.266 * 10^{4}$$



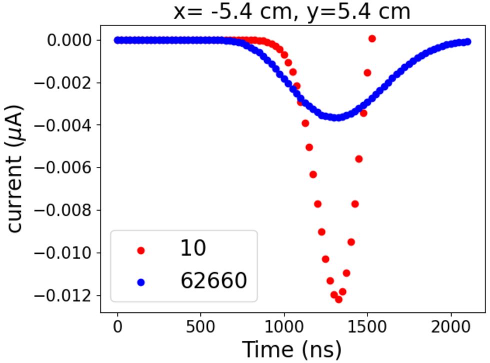
Transport of primary electrons in presence of space charge

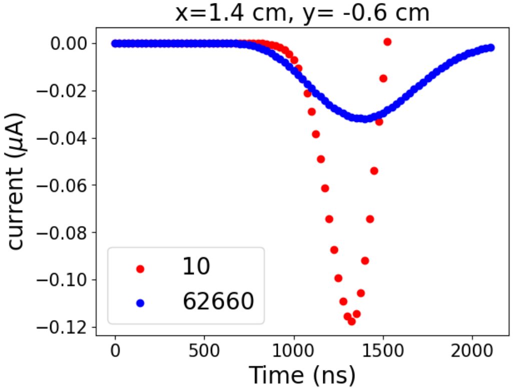


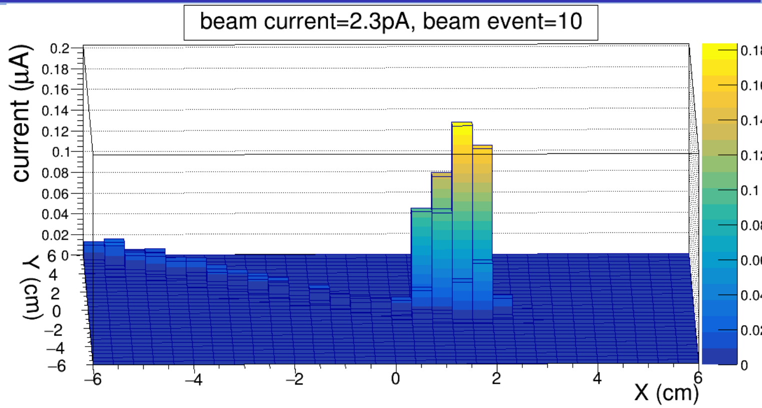


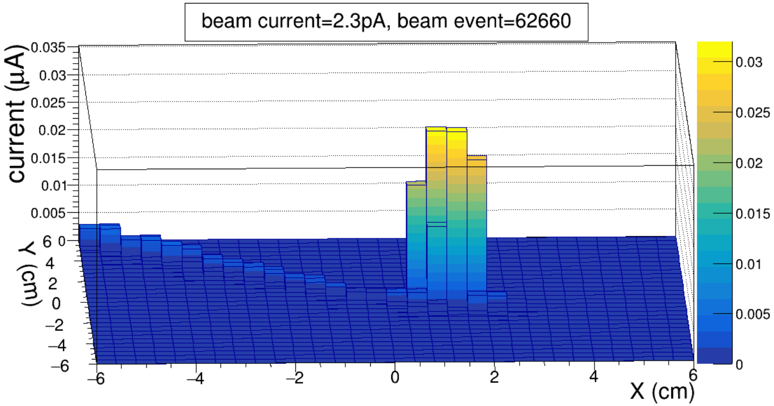


Current on anode readout pads

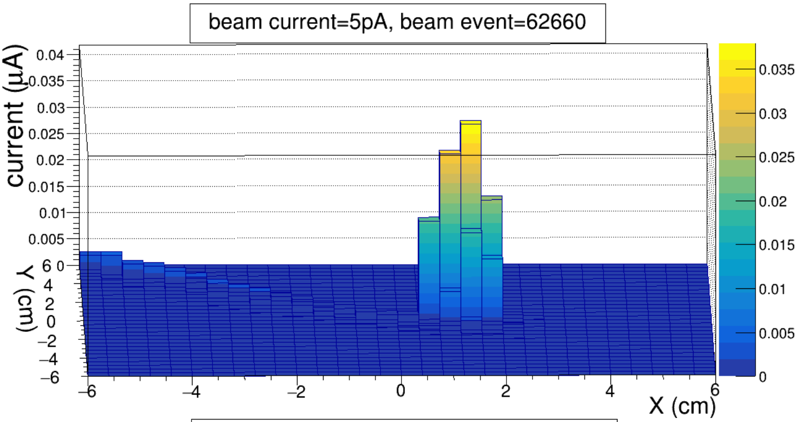


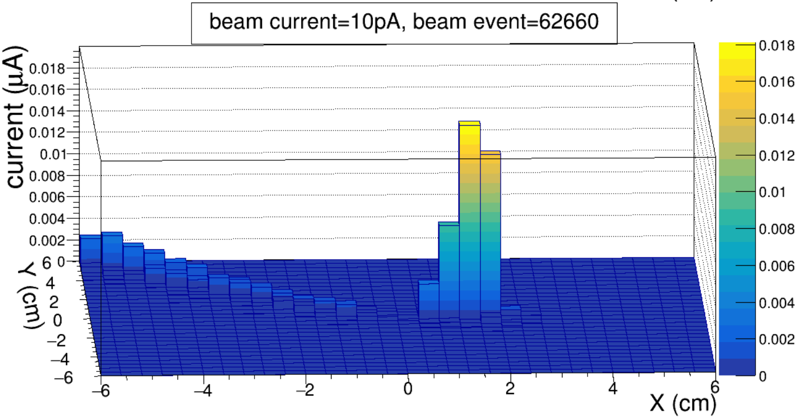


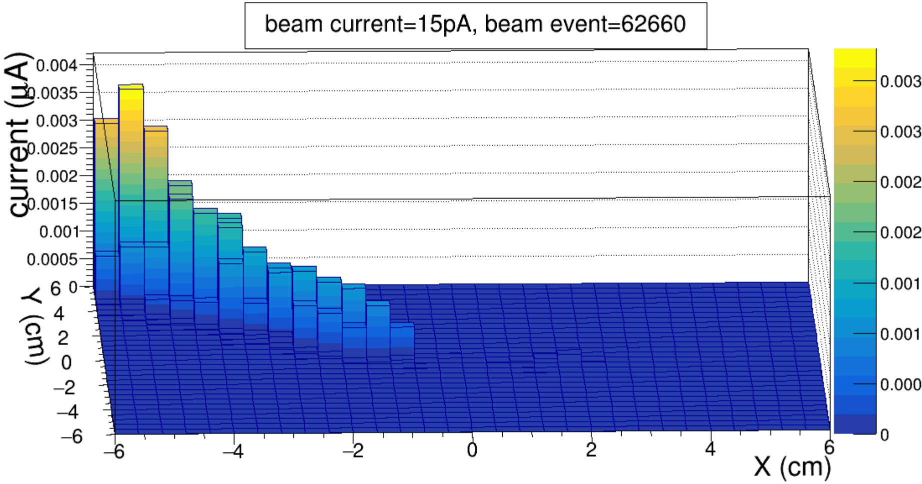




Effect of beam current on collected signal at readout

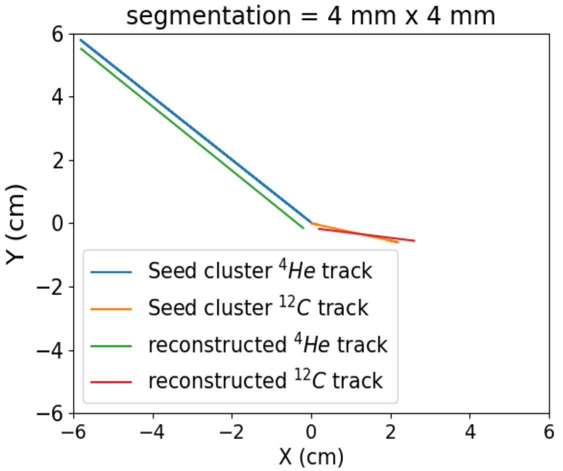


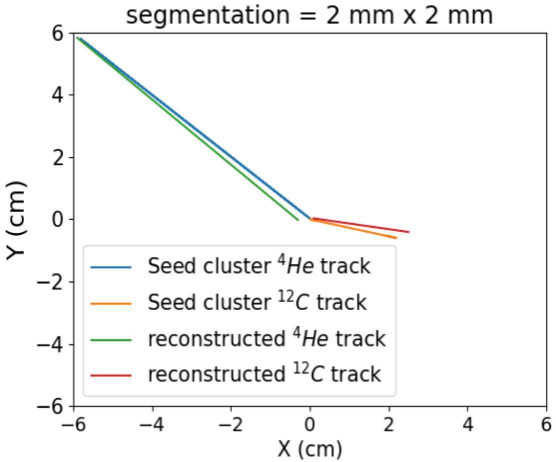


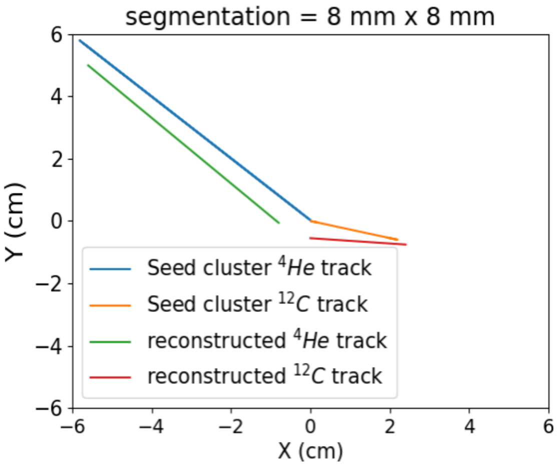


Seed cluster and Reconstructed tracks

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







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}He of energy 25 MeV with active gaseous target ^{12}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 $mm \times 4$ mm for satisfactory tracking performance along with cost effective production of the SAT-TPC prototype.

ACKNOWLEDGEMENTS

Acknowledgements

- I like to thank the organizers for giving me the opportunity to present my work.
- I would like to thank my Collaborators Dr. Jaydeep Datta, Dr. Subhendu Das, Prof. Tilak Ghosh and Prof. Nayana Majumdar and Prof. Supratik Mukhopadhyay
- 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