

Simulation and Reconstruction of e^+ and e^- Trajectories in a Time Projection Chamber with Orthogonal Fields

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IPNP CUNI & IEAP CTU PRAGUE

Preprint: [arXiv:2606.18821](https://arxiv.org/abs/2606.18821) [1]



DRD1
Gaseous Detector Technologies

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Outline

- 1 Motivation
- 2 Track Simulation
- 3 Track Reconstruction
- 4 Energy Reconstruction
- 5 Summary



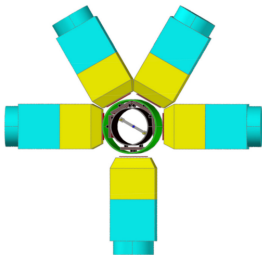
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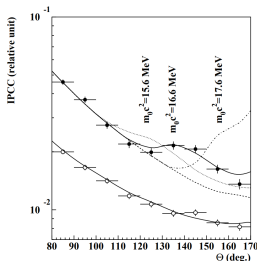
Motivation: ATOMKI Measurements

- Measurement of anomalies in the angular correlation of an e^+e^- pair internally produced in excited ^8Be [2, 3], ^4He [4, 5] and ^{12}C [6]
- Angular resolution $\sim 7^\circ$, energy resolution 4.5% at 17.6 MeV
- Other experiments [7–10], but no independent measurement confirms or disproves it yet, possible explanation — new boson X17 [11]

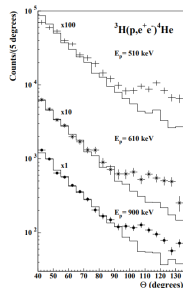


ATOMKI spectrom. [12]

Beam pipe (black), MWPC, ΔE det.
(red), E scintillators (yellow), light guides
(blue)

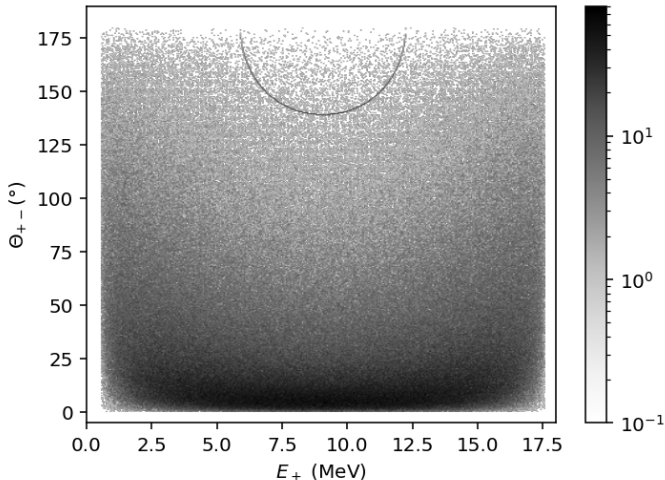


^8Be , e^+e^- pair angular
correlation. [2]



^4He , e^+e^- pair angular
correlation. [4]

X17 Decay Signature in IPC

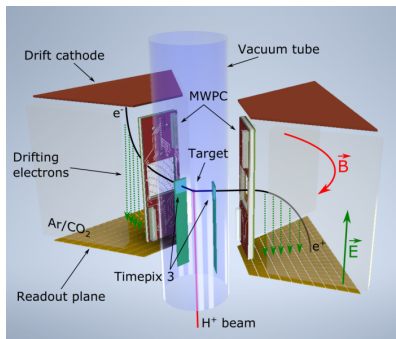


Geant 4 simulation (ideal case): Histogram of e^+e^- pair angle and positron energy produced by standard IPC and by the decay of a hypothetical boson X17 (branching ratio $3 \cdot 10^{-3}$).

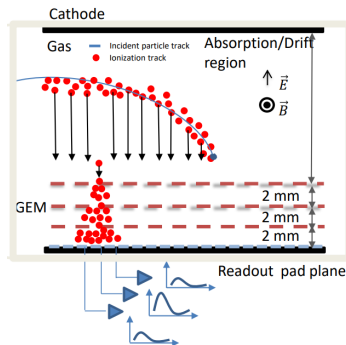


OFTPC: Detector Configuration

- Time Projection Chamber with Orthogonal Fields (OFTPC) – electric and magnetic field perpendicular (gas mixture Ar/CO₂ – 70/30, 90/10)
- Reasons for OF: no solenoid, space constraints (SAMPA/SRS, number of channels)

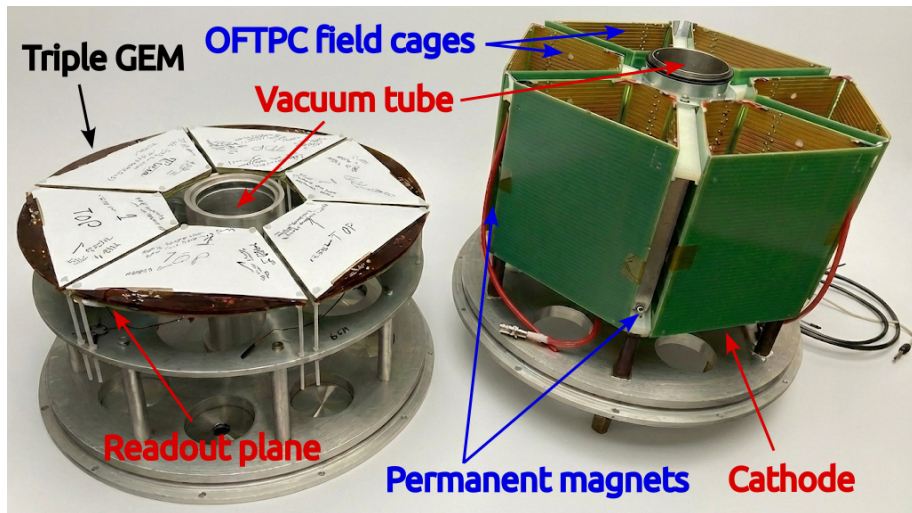


Two out of the six OFTPC chambers. [13]

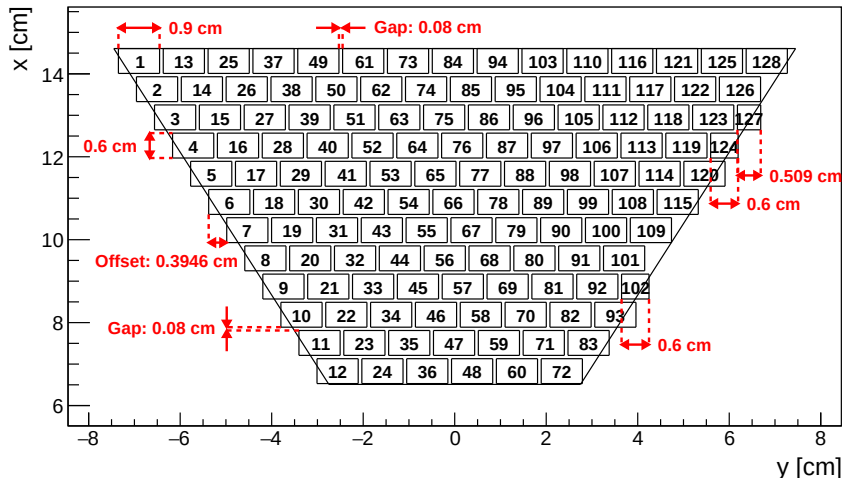


OFTPC with a triple gas electron multiplier (GEM) readout. [13]

OFTPC: Detector Configuration

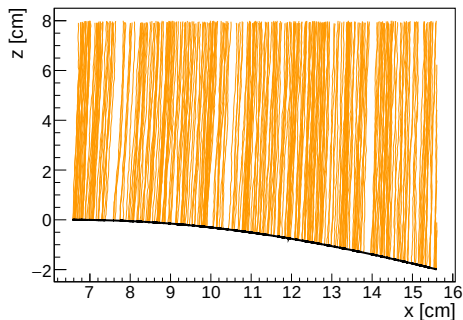
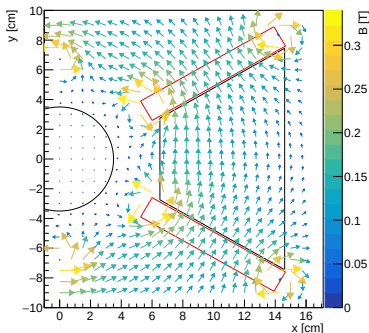


OFTPC: GEM Readout — Pads



OFTPC: Complications

Inhomogeneous magnetic field (simulated using Maxwell [14])



- The field interferes with the direction of the drift of ionization electrons (position dependent Lorentz angle)
- Curvature of the track is not constant in this field (deviation from a circle)



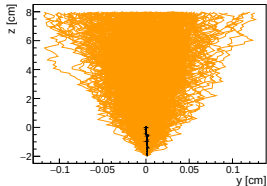
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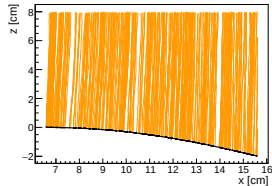


Track Simulation: Initial Approach

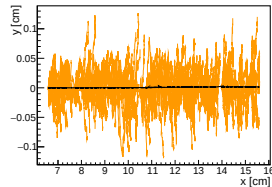
- At first simplified Garfield++ simulation (HEED, AvalancheMicroscopic)
- Five batches of 9702 tracks with different initial parameters simulated on a grid (MetaCentrum [15])
 - Electrons and positrons
 - 11 different energies from 3 MeV to 13 MeV (covers range for ^8Be)
 - 21 different angles φ and 21 different angles θ
- Example e^- track with kinetic energy 8 MeV, $\theta = 0^\circ$ and $\varphi = 0^\circ$
- Diffusion less than 1.5 mm in both directions



Diffusion front view



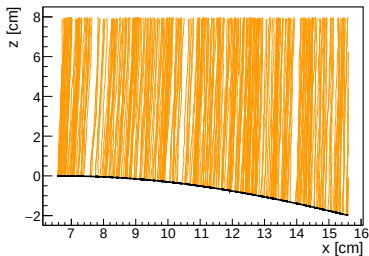
Electron drift



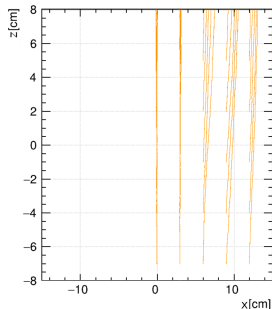
Diffusion top view

Ionization Electron Map Simulation

- We want an unambiguous map of the drift of ion. e^- for the reconstr.
- We can use a simulation of evenly spaced electrons
 - Current spacing 5 mm, 100 electrons simulated in each location with 0.1 eV energy in a random direction
- Result = mapping from initial coor. (x, y, z) to readout (x', y', t)
- Inverse map used for reconstruction of track voxels



Electron drift

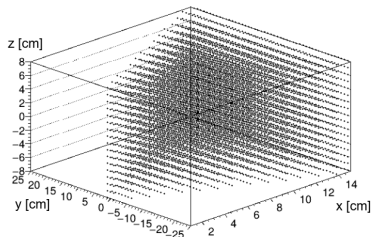


Partial simulation of the map



Ionization Electron Map Simulation: Visualization

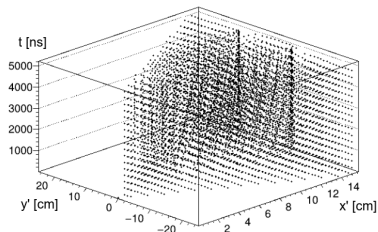
Detector space $\mathcal{D}$



$\overline{\mathcal{M}}$

$\overline{\mathcal{M}}^{-1}$

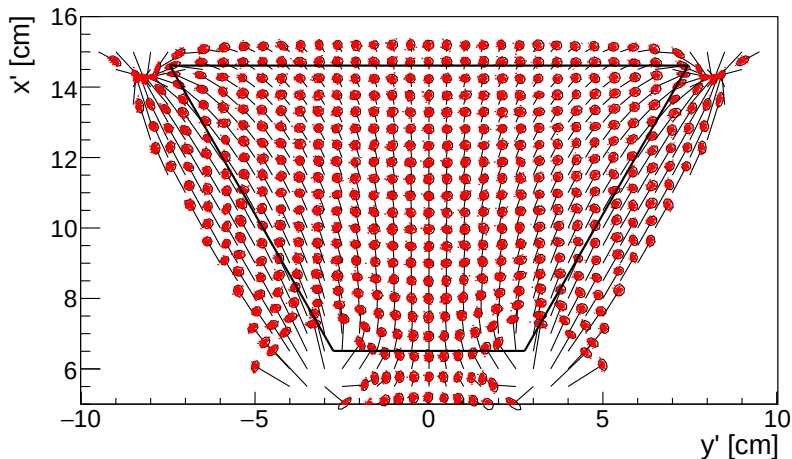
Readout space $\mathcal{R}$



3D visualization of the simulated mapping $\overline{\mathcal{M}}$ and the inverse mapping $\overline{\mathcal{M}}^{-1}$.



Ionization Electron Map Simulation: Diffusion

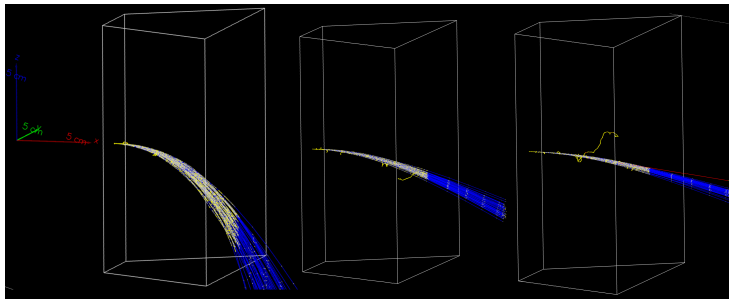


Worst case x and y coordinate distortion for maximal initial distance from readout. Ellipses with 95 % confidence are shown for each starting position.



Track Simulation: Multiple Scattering

- HEED does not account for multiple scattering of relativistic primaries in the gas mixture.
- At relatively low e^+/e^- energies of 3–13 MeV, it can significantly distort the trajectory.
- Therefore, we are implementing a Geant4-Garfield++ interface (inspired by Pfeiffer et al. [16]). Preliminary tests were done.



Visualization three sets of 50 electron tracks with zero initial angles θ, φ and energies 3, 8, and 13 MeV.



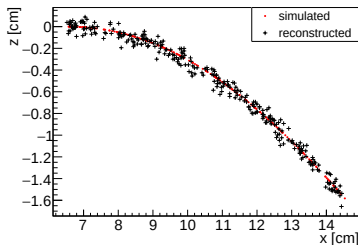
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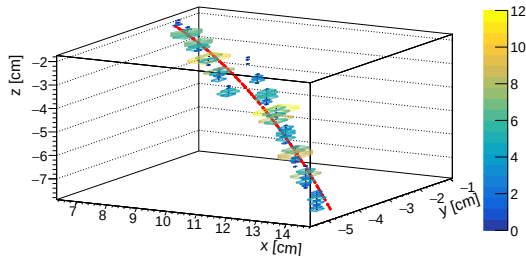


Track Reconstruction

- At first using only the inverse map (not accounting for readout pads)
- Later simple reconstruction with pads and time bins, counting the number of electrons in each bin



Original and reconstructed interaction points on the simulated track



Reconstruction with pads



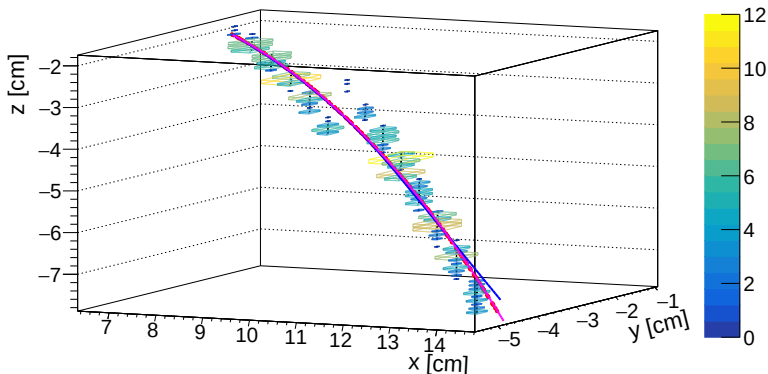
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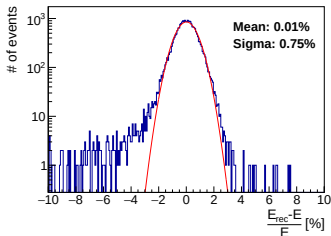
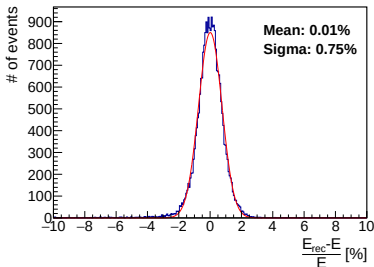
Energy Reconstruction

- Prefit with circle with smoothly attached lines (blue)
- Kinetic energy fit using 4th order Runge-Kutta (magenta)
- Known initial position and direction of the particle assumed
- Apply systematic error correction (obtained from simulation using a 3D linear fit)
- Currently around 0.3 CPU seconds per track

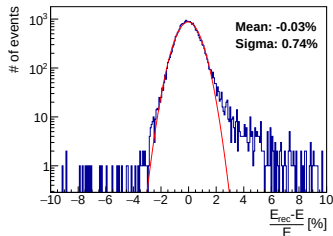
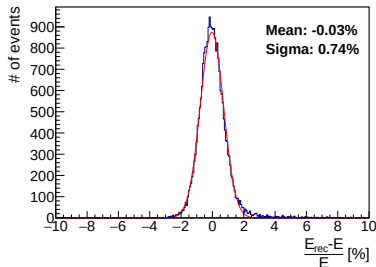


Energy Reconstruction Precision (overall)

Electrons



Positrons

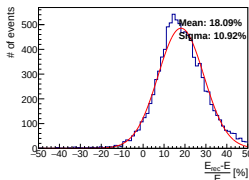


Relative reconstruction deviation of the kinetic energy of electron and positron tracks
(ca. 24 000 of each simulated).

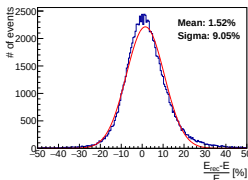
Effect of multiple scattering (preliminary)

- Preliminary tests show significant impact of multiple scattering on the resolution.
 - Reconstruction of electron tracks with zero θ, φ and total energy 3, 8 and 13 MeV.
 - Simulation of the full parameter grid is being prepared.
- Delta electrons not taken into account for better comparison with previous simulations.
- Initial position and orientation still fixed in the fit (might increase the error).

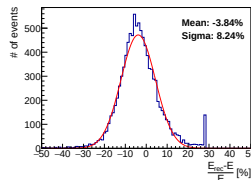
3 MeV



8 MeV



13 MeV



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Summary

- Several batches of tracks have been simulated for testing purposes.
 - $\theta \in [-17.1^\circ, 17.1^\circ]$, $\varphi \in [-16.3^\circ, 16.3^\circ]$, $E_k \in [3, 13]$ MeV
- The map of ionization electron readout positions and drift times has been generated.
- The map has been tested by the track reconstruction.
- Some of the systematic errors were corrected.
- The results suggest that:
 - Current energy resolution (fitted sigma) is 0.75 % for electrons and positrons under idealized conditions.
 - Multiple scattering is expected to reduce it significantly (up to ~11 % for low energies), further investigation is needed.
 - OFTPC works well on a simulation level.



Thank you for your attention.



- [1] Martin Vít Vavřík et al. *Track and energy reconstruction algorithms for a time projection chamber with orthogonal fields*. 2026. arXiv: 2606.18821 [physics.ins-det]. URL: <https://arxiv.org/abs/2606.18821>.
- [2] A. J. Krasznahorkay et al. "Observation of Anomalous Internal Pair Creation in Be8: A Possible Indication of a Light, Neutral Boson". In: *Phys. Rev. Lett.* 116.4 (Jan. 2016). ISSN: 1079-7114. DOI: 10.1103/physrevlett.116.042501. URL: <http://dx.doi.org/10.1103/PhysRevLett.116.042501>.
- [3] N. J. Sas et al. *Observation of the X17 anomaly in the ${}^7\text{Li}(p, e^+ e^-){}^8\text{Be}$ direct proton-capture reaction*. 2022. arXiv: 2205.07744 [nucl-ex]. URL: <https://arxiv.org/abs/2205.07744>.



- [4] A. J. Krasznahorkay et al. *New evidence supporting the existence of the hypothetical X17 particle*. 2019. arXiv: 1910.10459 [nucl-ex]. URL: <https://arxiv.org/abs/1910.10459>.
- [5] A. J. Krasznahorkay et al. “New anomaly observed in He4 supports the existence of the hypothetical X17 particle”. In: *Phys. Rev. C* 104.4 (Oct. 2021). ISSN: 2469-9993. DOI: 10.1103/physrevc.104.044003. URL: <http://dx.doi.org/10.1103/PhysRevC.104.044003>.
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- [10] F. Bossi et al. “Search for a new 17 MeV resonance via e^+e^- annihilation with the PADME experiment”. In: *J. High Energy Phys.* 2025.11 (Nov. 2025). ISSN: 1029-8479. DOI: [10.1007/jhep11\(2025\)007](https://doi.org/10.1007/jhep11(2025)007). URL: [http://dx.doi.org/10.1007/JHEP11\(2025\)007](http://dx.doi.org/10.1007/JHEP11(2025)007).
- [11] Jonathan L. Feng et al. “Protophobic Fifth-Force Interpretation of the Observed Anomaly in Be^8 Nuclear Transitions”. In: *Phys. Rev. Lett.* 117 (7 Aug. 2016), p. 071803. DOI: [10.1103/PhysRevLett.117.071803](https://doi.org/10.1103/PhysRevLett.117.071803). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.117.071803>.



- [12] J. Gulyás et al. “A pair spectrometer for measuring multipolarities of energetic nuclear transitions”. In: *Nucl. Instr. Meth. A* 808 (2016), pp. 21–28. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2015.11.009>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900215013716>.
- [13] Institute of Experimental and Applied Physics, Czech Technical University in Prague. *The search for the X17*. <https://aladdin.utef.cvut.cz/projekty/vdg/x17/>. Project page of the Van de Graaff accelerator laboratory (VdG) at ÚTEF ČVUT — experiment X17. 2025.
- [14] ANSYS Inc. *ANSYS Maxwell, Electromagnetic Field Simulation Software*. <https://www.ansys.com/products/electronics/ansys-maxwell>. ANSYS Inc. Canonsburg, PA, USA, 2025.



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<https://metavo.metacentrum.cz/en/about/index.html>.
Accessed: 2024-11-27. 2023.
- [16] Dorothea Pfeiffer et al. “Interfacing Geant4, Garfield++ and Degrad for the simulation of gaseous detectors”. In: *Nucl. Instrum. Methods Phys. Res. Sect. A: Accel. Spectrom. Detect. Assoc. Equip.* 935 (Aug. 2019). Example source code: <https://github.com/lennertdekeukeleere/Geant4GarfieldDegradInterface>, pp. 121–134. ISSN: 0168-9002. DOI: 10.1016/j.nima.2019.04.110. URL: <http://dx.doi.org/10.1016/j.nima.2019.04.110>.
- [17] Matěj Gajdoš et al. “Denoising 3D Time Projection Chamber data using convolutional neural networks”. In: *J. Instrum.* 20.05 (May 2025), p. C05014. DOI: 10.1088/1748-0221/20/05/C05014. URL: <https://dx.doi.org/10.1088/1748-0221/20/05/C05014>.



Backup



Track Simulation: Parameters

Spherical angles (θ, φ) with respect to z
 θ taken from the equatorial plane xy

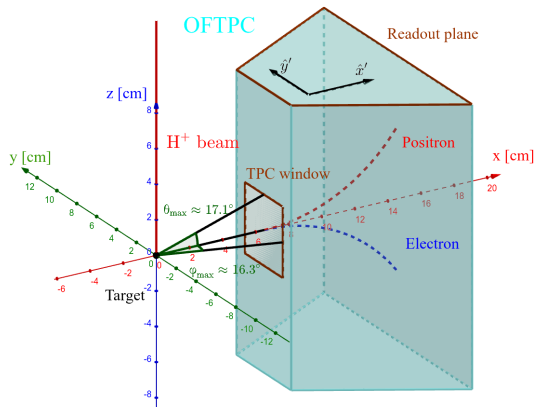


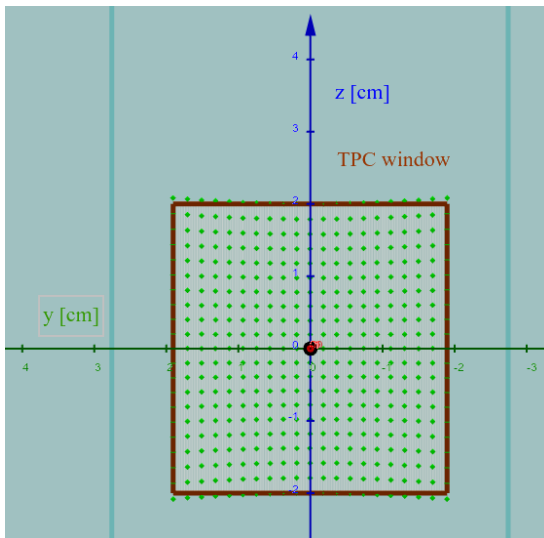
Diagram of the batch simulation parameters:

$$\theta \in [-17.1^\circ, 17.1^\circ], \varphi \in [-16.3^\circ, 16.3^\circ], E_{\text{kin.}} \in [3, 13] \text{ MeV.}$$

Made with GeoGebra®.



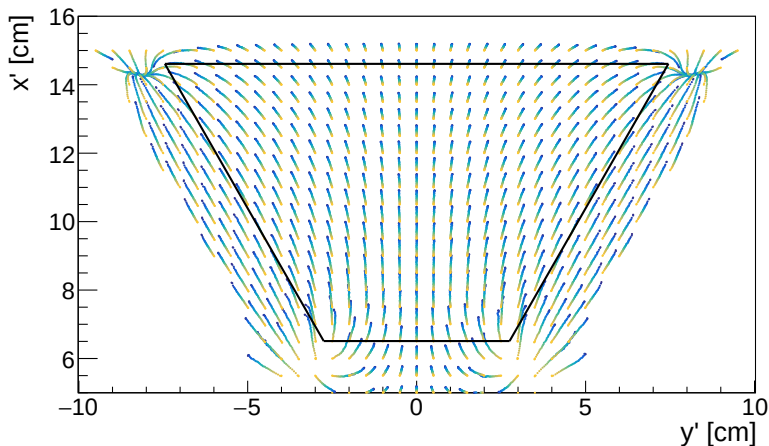
Track Simulation – TPC Window



Initial points of tracks. Made with GeoGebra®.



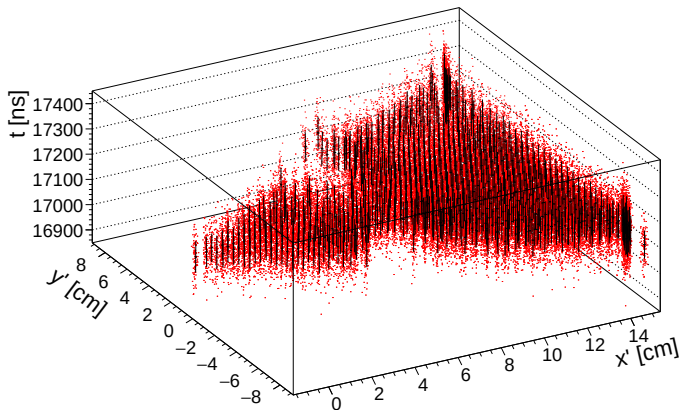
Ionization Electron Map Simulation: Coordinate Distortion



x and y coordinate distortion at different z values (denoted by colors).



Ionization Electron Map Simulation

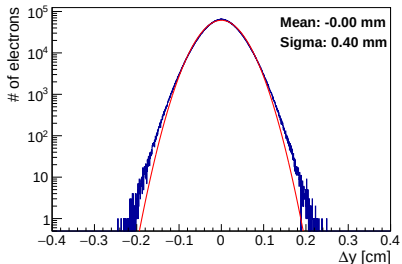
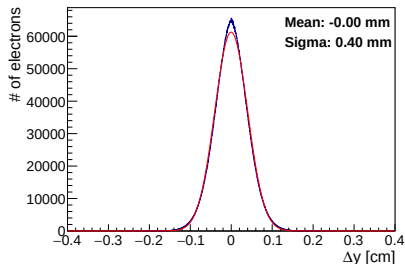
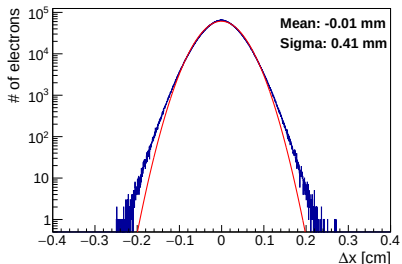
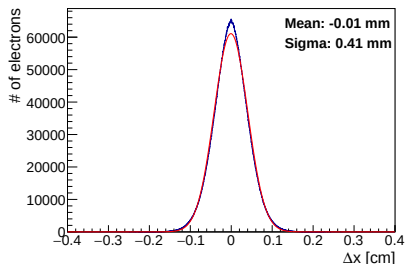


Mapping of the layer furthest from the OFTPC readout.



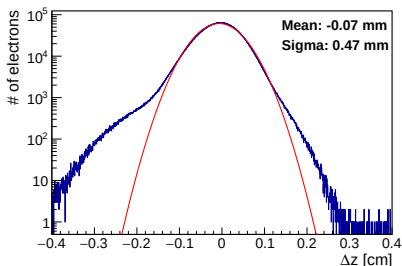
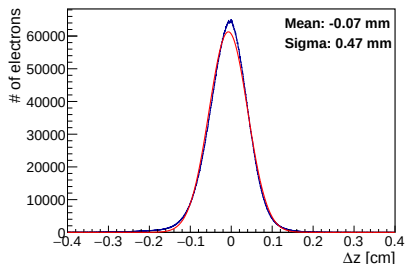
Ionization Electron Map Reconstruction Residuals (x, y)

Residuals of init. positions of 14.3 M simul. track ion. e^- reconstructed using the map



Ionization Electron Map Reconstruction Residuals (z)

Residuals of initial positions of 14.3 million simulated track ionization e^- reconstructed using the map

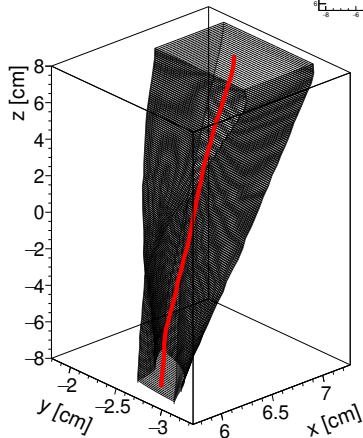


Deviations likely caused by non-zero initial velocity of electrons

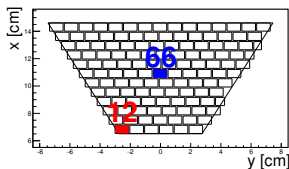


Inverse Mapping of Pads

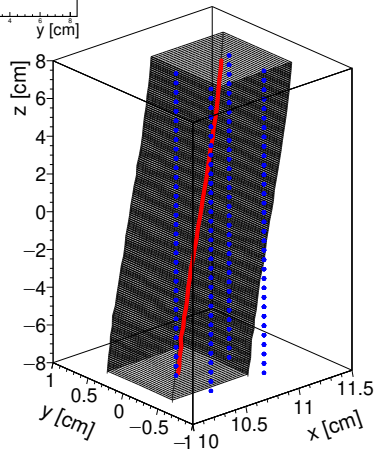
Pad 12
(near magnet pole)



Inversion by gradient descent

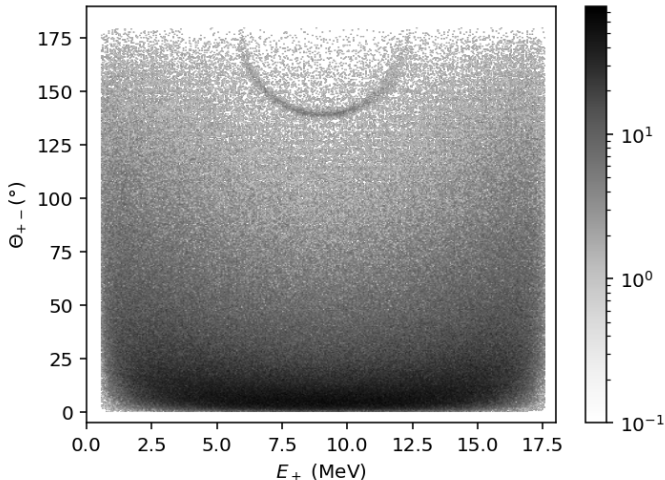


Pad 66
(near center)



Inversion by interpolation

X17 Decay Signature in IPC (with preliminary errors)



Geant 4 simulation + errors: Histogram of e^+e^- pair angle and positron energy produced by standard IPC and by the decay of a hypothetical boson X17 (branching ratio $3 \cdot 10^{-3}$).

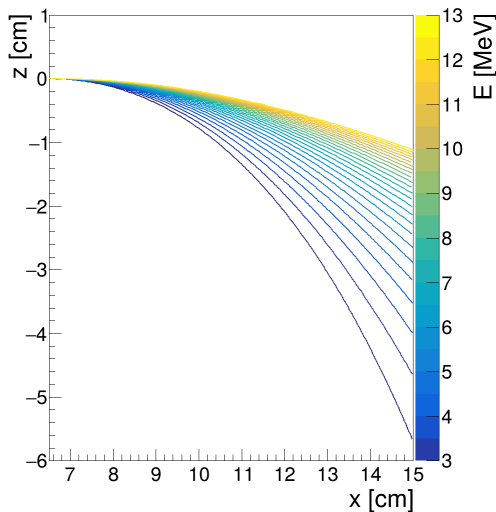


Reconstruction Testing Summary

- 1 Ionization electron map simulation of ionization electrons in the entire volume of the OFTPC
- 2 Track(s) simulated using HEED and microscopic tracking
- 3 Counting the number of ionization e^- in each pad and time bin of the readout
- 4 Using the map to reconstruct the position of centers of pads for given centers of time bins
- 5 Fitting of the reconstructed points with circle and lines fit using least squares weighted by the number of ionization e^- in each point
- 6 Using the magnetic field in the middle of the track to get first energy estimate
- 7 Using the 4th order Runge-Kutta fit with least squares to refine the energy estimate
- 8 Correct systematic errors using a 3 parameter linear function

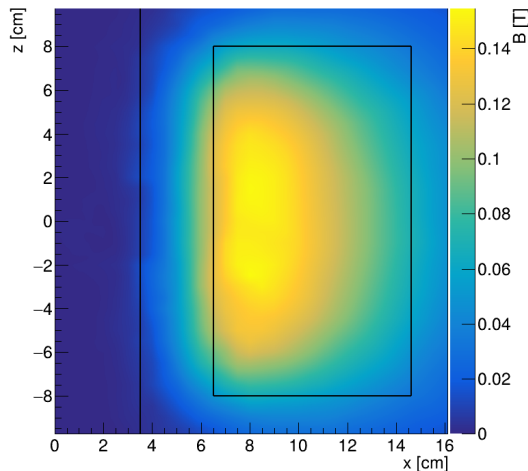


Runge-Kutta energy comparison



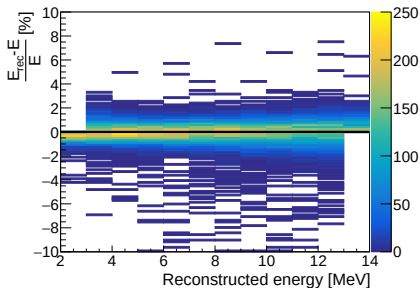
Comparison of 25 tracks with same initial position and orientation and different energies in the range 3–13 MeV.

Magnetic field in the XZ plane

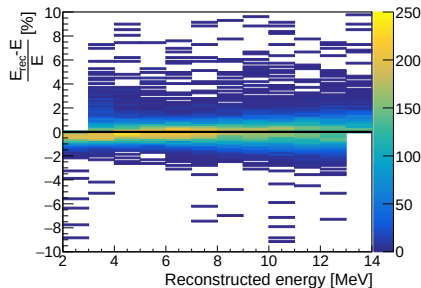


Energy Reconstruction Precision (energy dependence)

Electrons



Positrons

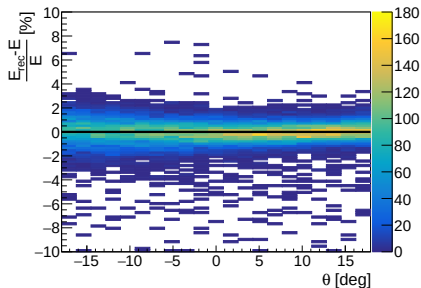


Relative reconstruction deviation of the kinetic energy of electron and positron tracks
(ca. 24 000 of each simulated).

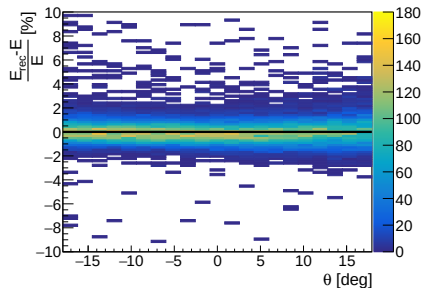


Energy Reconstruction Precision (theta dependence)

Electrons



Positrons

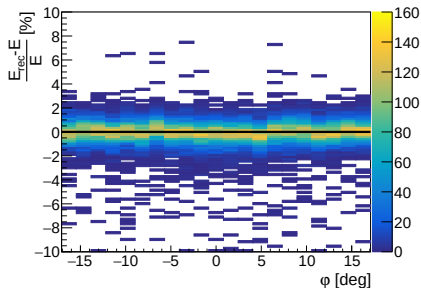


Relative reconstruction deviation of the kinetic energy of electron and positron tracks (ca. 24 000 of each simulated).

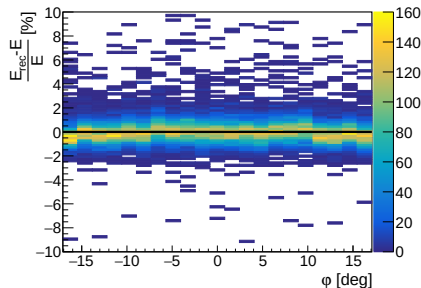


Energy Reconstruction Precision (phi dependence)

Electrons



Positrons



Relative reconstruction deviation of the kinetic energy of electron and positron tracks (ca. 24 000 of each simulated).



Future Steps

- Complete the Geant4 simulation with multiple scattering for the full parameter grid
- Account for parasitic tracks caused by high energy secondary electrons
- Account for GEM in the simulation, charge distribution between pads
- Account for noise (denoising using a convolutional neural network — M. Gajdoš [17])
- Optimize Runge-Kutta integration fit with likelihood approach (instead of least squares) if needed
- Test different geometries
- Make a better simulation of magnetic and electric fields, compare with measurements

