Overview of the data analysis and new micro-pattern gas detector development for the Active Target Time Projection Chamber (AT-TPC) project.

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Abstract. The Active Target Time Projection Chamber (AT-TPC) project at the NSCL (National Superconducting Cyclotron Laboratory, Michigan State University) is a novel active target detector tailored for low-energy nuclear reactions in inverse kinematics with radioactive ion beams. The AT-TPC allows for a full three dimensional reconstruction of the reaction and provides high luminosity without degradation of resolution by the thickness of the target. Since all the particles (and also the reaction vertex) are tracked inside the detector, the AT-TPC has full 4\(\pi\) efficiency. The AT-TPC can operate under a magnetic field (2 T) that improves the identification of the particles and the energy resolution through the measurement of the magnetic rigidity. Another important characteristic of the AT-TPC is the high-gain operation achieved by the hybrid thick Gas Electron Multipliers (THGEM)-Micromegas pad plane, that allow operation also in pure elemental gas. These two features make the AT-TPC a unique high resolution spectrometer with full acceptance for nuclear physics reactions. This work presents an overview of the project, focused on the data analysis and the development of new micro-pattern gas detectors.

1. Introduction

Time projection chambers operated in active target mode have recently gained popularity with the advent of new facilities dedicated to produce very exotic radioactive beams [1, 2]. In active targets the filling gas is simultaneously the tracking medium and the target. The latter is commonly a light gas such as hydrogen, deuterium, helium or argon. Inside the detection medium, particles leave an ionization trace that can be discretized by measuring two projected coordinates in a highly segmented pad plane and by the drift time of the ionized electrons. The characteristic energy loss pattern and range of the particles is also recorded. The addition of a solenoidal magnetic field adds another variable in the reconstruction of the kinematics of the reaction by measuring the magnetic rigidity of the particle. Under such conditions active targets become a powerful solenoidal spectrometer with full acceptance, large dynamic range and detection efficiency. In addition, the typical excitation energy degradation caused by the reaction target thickness is dramatically reduced. Target thickness can be increased by an order of magnitude with respect to the most common setups with solid targets.

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The AT-TPC, developed at the NSCL [3, 4], is currently one of the thickest reaction targets operating under a magnetic field of 2 T. With a luminosity of around 100 times larger than conventional setups and full geometrical acceptance (depending on the reaction of interest) the AT-TPC allows experiments with beam intensities down to 100-1000 Hz. The read-out of the detector, composed of a hybrid micromegas [5] and thick GEMs [6, 7, 8], enables high-gain operation in pure elemental gas without addition of a quencher that introduces background reactions. The AT-TPC allows the reconstruction of the reaction in three dimensions with high resolution on an event-by-event basis. The complexity underlies on how the track coordinates are transformed into variables of kinematic interest (i.e. angle, energy and time), that usually are inferred directly. Such a complex system demands a sophisticated data analysis framework with the capability to classify the events of interest and reconstruct the kinematics of the particles with high resolution. The most challenging aspects are the large energy loss dynamic range of the particles and the fact that particles that are stopped in the gas will describe highly non-linear trajectories (helices) characterized by a strong change on the radius of curvature as it slows down. We have developed a novel algorithm that classifies the tracks of the particles and permits the inference of the kinematic variables used for further post-processing. In this work, we present the general aspects of the algorithm as well as a brief discussion on new thick GEM technologies developed for the AT-TPC. The detailed description of the AT-TPC detector as well as its performance can be found in Ref. [3].

2. Classification of spiral particle tracks

We conducted a commissioning experiment with a re-accelerated radioactive beam of $^{46}$Ar in ReA3 separator of the NSCL. The AT-TPC was filled with isobutane gas ($C_4H_{10}$) at 18 torr to perform the resonant elastic scattering of $^{46}$Ar on protons at 4.6 MeV/u. In the left panel of Fig. 2 we show the three dimensional hit pattern of a proton track in the gas medium within a magnetic field of 2 T. Each point of this hit pattern has been reconstructed by projecting the electron drift signals in the pad plane (composed of 10240 triangular pads), obtaining three cartesian coordinates and the peak amplitude that represents the energy loss per unit volume. As shown in Fig. 2, the tracks are characterized by a helical trajectory with a radius of curvature decreasing due to the energy loss of the particle of the medium. This particular track geometry cannot be described by any analytical parameterization that represents helical trajectories in the space. Thus, a multi-step reconstruction algorithm based on random sampling was implemented in several steps. The whole procedure involves the classification of the tracks and noise reduction, and the fit of each spiral track using a Monte Carlo algorithm. The latter is further explained in a forthcoming publication [3].

For the classification of the spiral tracks we used a global pattern recognition algorithm based on the Hough transformation [9]. The idea of this algorithm is to detect shapes in images by transforming the image data set given in the coordinate space into a parameter space (Hough space) described by the parameters of the shape we want to find. We chose the parameterization of a circle based on a straight line between two neighboring points of the hit pattern and a perpendicular line to it. Such a line intersects the center of the circle if the pair of points belongs to it. This reduces the dimensionality of the problem with only two parameters to consider: the distance of the circle center with respect to the origin of the coordinate system XY and its angle with the positive x-axis. Although the projection of the spiral track into the pad plane does not have the shape of a unique circle, one can see that the total shape is composed by several superimposed circles of different radius of curvature.

By using this parameterization each one of the points of the hit pattern is transformed into a
Figure 1. Three-dimensional image of a scattered proton. The coordinates of each point are inferred from the position of the particle in the pad plane and the drift time converted into length. The size of each point of the hit pattern is proportional to the energy loss.

Figure 2. (Left panel) Projection of the track in the XY pad plane. The local energy loss per time is recorded in each activated pad. (Right panel) Distance-angle parameter space. The parameters of the trajectory are determined from the bin with maximum number of counts.

binned two-dimensional function in the distance-angle parameter space (see right panel of Fig. 2). The bin with maximum number of counts gives the parameters of the circle we want to find. Misidentified tracks can be rejected by evaluating the maximum/minimum bin ratio. Once the parameters are determined, we can transform back the point of interest into the coordinate space to infer the radius of curvature and the magnetic rigidity, the polar (scattering) and azimuthal angles, and the vertex of the reaction. These starting parameters allow us to perform a Monte
Figure 3. Reconstructed proton track. Red boxes represent the hit pattern while the green dots refer to the reconstructed track. The inset shows the projection in the XY pad plane.

Carlo fit to determine the energy and the scattering angle of the particles with higher precision. The fitting procedure is described elsewhere [3]. The fit algorithm generates a large number of possible tracks with a simulation of the signals induced in the pads. The simulated tracks are compared to the energy loss and hit patterns of the real track. The $\chi^2$ between the simulated and experimental tracks is calculated and minimized. The energy loss of the particles was computed using SRIM code [10]. The reconstructed track is shown in Fig. 3 as green dots. Together with the pattern recognition task, we apply a noise reduction filter based on the statistical analysis of each point. We used the Statistical Outlier Removal filter from the Point Cloud Library [11] prior to the Hough space calculation. The AT-TPC collaboration is developing a modular data analysis framework that includes several tools to unpack, sort and analyze the data taken with the detector [12].

3. Development of new thick Gas Electron Multiplier (GEM) based on ceramic substrates.
As mentioned in the previous sections, one of the important features of the AT-TPC is the use of advanced GEM-like multiplier devices that allow us to operate the detector with pure noble gases. A novel charge-avalanche concept was recently introduced, multi-layer THGEM (M-THGEM) [7]. The M-THGEM is composed of a stack of two or three conventional THGEM, one on top of the other. The diameter and pitch of the holes are 0.5 mm and 1 mm, respectively. These detectors showed an excellent performance when operated in low-pressure pure noble gas, achieving comparable gains than the ones obtained with mixtures such as He+CO$_2$. The main reason is the strong confinement of the avalanche inside the M-THGEM hole, which leads to an effective reduction of the photo-mediated secondary effects.
Figure 4. (Left panel) Ceramic thick GEM mounted on the test chamber. (Right panel) Pulse height as a function of the time.

One of the most common problems present in GEM-like multipliers, and in gaseous detectors in general, are long-term variations caused by charge collected on the dielectric surface during the avalanche process (charging up effects). These effects are a complex phenomenon, which involve several factors, including certain impurities in the substrates that affect the surface resistivity of the insulator or very different substrate materials combined together. The FR-4/G10 material used for conventional THGEMs is made of glass fiber and epoxy plus many other chemical compounds and impurities (including water) that increase charging up effects. On the other hand, other materials such as ceramic have less impurities and absorb lower amounts of water. In addition, the surface of the FR-4/G10 is quite irregular. Ceramic substrates (especially with laser production and suitable cleaning procedure for removing impurities and humidity) lead to a lower amount of water and a more regular surface, resulting in a lower (not fully suppressed) charge building up effects. Therefore, we developed thick GEMs based on ceramic substrates. A three-layer 10×10 cm$^2$ thick GEM prototype was mounted together with a single readout pad plane, to pick-up the signal of the avalanche, inside a vacuum chamber. Our preliminary measurements using a mixture of He+CO$_2$ gas at 300 torr, show a stable operation during a period of 17 h when irradiated with a $^{241}$Am source (see Fig. 4) at relative low rate (a few hundred Hz). In addition, we measured an energy resolution from the collected charge of around 5% (FWHM). These results will be published in a separated paper.

4. Conclusions
We have developed a novel data analysis framework for the Active Target Time Projection Chamber (AT-TPC) project at the NSCL that includes pattern recognition algorithms coupled to a Monte Carlo fit. The pattern recognition algorithm, based on the Hough transformation, is used to classify the tracks and extract the kinematical parameters from them. Using these parameters as initial starting point, we perform a fit using a Monte Carlo optimization algorithm. We also present a new multi-layer thick GEM device based on ceramic substrate that shows a better stability against charging up effects and high-gain operation in low-pressure pure elemental gas.

References
[1] S. Beceiro-Nov et al., “Active targets for the study of nuclei far from stability,” Progress in Particle and Nuclear Physics, vol. 84, pp. 124 – 165, 2015.
[2] W. Mittig et al., “Active target detectors for studies with exotic beams: Present and next future,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 784, pp. 494 – 498, 2015. Symposium on Radiation Measurements and Applications 2014 (SORMA XV).

[3] J. Bradt et al., “The active-target time projection chamber,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2017. submitted.

[4] D. Suzuki et al., “Prototype at-tpc: Toward a new generation active target time projection chamber for radioactive beam experiments,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 691, pp. 39 – 54, 2012.

[5] Y. Giomataris et al., “Micromegas: a high-granularity position-sensitive gaseous detector for high particle-flux environments,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 376, no. 1, pp. 29 – 35, 1996.

[6] M. Cortesi et al., “Studies of thgem-based detector at low-pressure hydrogen/deuterium, for at-tpc applications,” *Journal of Instrumentation*, vol. 10, no. 09, p. P09020, 2015.

[7] M. Cortesi et al., “Multi-layer thick gas electron multiplier (m-thgem): A new mpgd structure for high-gain operation at low-pressure,” *Review of Scientific Instruments*, vol. 88, no. 1, p. 013303, 2017.

[8] A. Breskin et al., “A concise review on \{THGEM\} detectors,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 598, no. 1, pp. 107 – 111, 2009.

[9] J. Illingworth and J. Kittler, “The adaptive hough transformation,” *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 9, pp. 690 – 698, 1987.

[10] J. F. Ziegler et al., “\{SRIM\} - the stopping and range of ions in matter (2010),” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 268, no. 11 - 12, pp. 1818 – 1823, 2010. 19th International Conference on Ion Beam Analysis.

[11] “Point cloud library.” https://github.com/PointCloudLibrary pcl/releases/tag/pcl-1.8.0.

[12] Y. Ayyad et al., “In preparation.” https://github.com/ATTPC/ATTPCROOTv2.