PROCEEDINGS OF SCIENCE

Reconstruction of Complex Particle Trajectories in the SuperNEMO Detector

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The SuperNEMO experiment is designed to search for neutrinoless double beta decay, a rare process whose discovery would confirm the Majorana nature of neutrinos and provide insight into their absolute mass scale. Unlike most detectors focused only on calorimetry, SuperNEMO uniquely combines energy measurement with a tracking system composed of 2034 Geiger-mode drift cells, enabling detailed topological reconstruction of charged particle trajectories. This dual approach enhances background rejection and allows for the study of decay kinematics, such as angular distributions and single-electron energy spectra. This work presents a novel algorithm for particle track reconstruction tailored to SuperNEMO's tracking detector. Building on a previously developed method based on the Legendre transform, we introduce an improved reconstruction approach based on a maximum likelihood method that incorporates a tunable model of the detector's response to identify the most probable particle trajectories. This method evaluates how well candidate tracks explain the observed data, allowing for precise 3D reconstruction even with limited information. What sets this approach apart is the unique nature of the tracking data in SuperNEMO's low-activity environment, where events typically contain only one or two tracks. Each Geiger cell provides a ring-shaped constraint on the particle's position, rather than a precise point, making trajectory reconstruction a non-trivial task. With only a few such measurements per track, the algorithm must combine this limited information as effectively as possible to accurately recover the full 3D path. To handle complex trajectories affected by scattering, the algorithm employs a polyline trajectory model, reconstructing paths as sequences of linear segments. These are identified using recursive clustering, ordered and refined through geometrical criteria, and assembled into complete trajectories. The result is a robust and accurate reconstruction method, capable of resolving both simple and complex topologies. These improvements represent a step toward achieving the experiment's ultra-low background goals and will contribute to the sensitivity of the current and upcoming physics run.

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1. SuperNEMO Demonstrator

The SuperNEMO Demonstrator is designed to investigate neutrinoless double beta ($0\nu\beta\beta$) decay using a source of 6.11 kg of ^{82}Se. Its design integrates a tracking detector and a segmented calorimeter to provide not only individual particle energy measurements, but also detailed event topology. Apart from enhanced background rejection, it also provides otherwise unreachable observables like individual particle energy spectra or angular spectra.

The source material is shaped into a thin foil placed at the centre of the tracking detector [1]. Surrounding the foil on both sides, the tracker comprises 2034 drift cells operating in Geiger mode. A comprehensive description of the tracker geometry and construction can be found in [2]. Encasing the tracker, the calorimeter system, composed of 712 independently triggered optical modules, measures the energy of the emitted electrons.

2. Tracker cell

Each SuperNEMO tracker cell contains a vertical central anode wire held at high voltage (approximately 1600 V), surrounded by grounded field-shaping wires and capped by cathodes at the top and bottom. When a charged particle crosses the volume of the cell, it ionizes the gas. The released electrons drift to the anode, initiating an electron avalanche, which is accompanied by emission of ionizing UV photons. These photons induce further avalanches along the wire, resulting in plasma propagation travelling to the cathode caps.

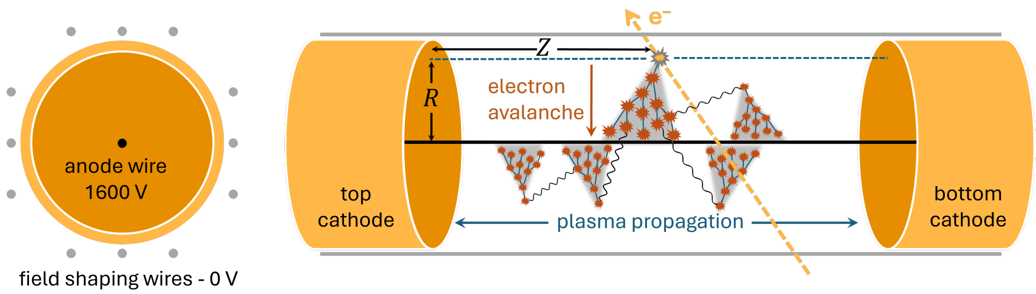
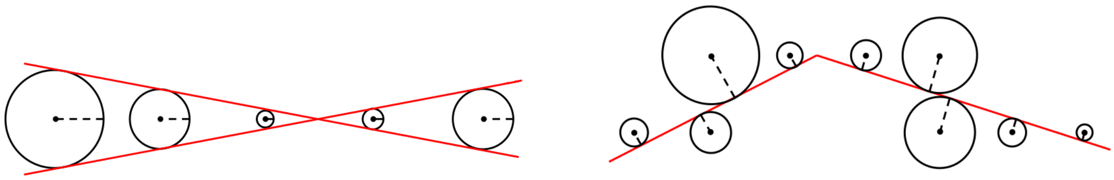


Figure 1: Scheme of a SuperNEMO tracker cell and its detection mechanism. For convenience, the cell is shown horizontally and proportions are not to scale.

The detector measures the initial electron avalanche at the anode and the plasma propagation as it reaches the cathodes. From these times we extract the drift radius R_i (the horizontal distance to the anode) and the vertical position Z_i (see Figure 1). Each hit can thus be represented as a circle of radius R_i centred on the anode wire (x_i, y_i) with a vertical coordinate Z_i.

3. Track Reconstruction in the SuperNEMO Detector

The goal of track reconstruction in SuperNEMO is to determine charged particle trajectories from tracker hits. Each hit is represented as a circle around an anode wire, with the radius given by the measured drift distance and the vertical coordinate obtained from plasma propagation. The task is therefore to identify trajectories tangent to sets of such circles. The problem is further complicated by measurement uncertainties, overlapping tracks, electron scattering, and ambiguities arising from the symmetries of the tracker geometry.



(a) Ambiguity

(b) Kinked trajectory

Figure 2: Illustration of problematic topologies in SuperNEMO track reconstruction. (a) Ambiguity caused by tracker hits aligned on a line. (b) Example of a kinked trajectory produced by electron scattering in the tracking gas or in the thin wires.

An ambiguity arises when triggered anode wires lie on a line. In such a case the group of tracker hits is symmetric under reflection, leading to two equally valid trajectory candidates (see Figure 2a). To avoid misinterpreting such events, it is necessary to identify both of these solutions. Another complication is the presence of kinked tracks, produced by scattering in the tracking gas or off the wires of the tracker (see Figure 2b). The algorithm distinguishes between two separate tracks and a single kinked trajectory by using a polyline trajectory model. To properly resolve these problems, the reconstruction algorithm can be divided into three main phases:

1. **Clustering phase:** First, a clustering step separates hits into subsets corresponding to the individual linear parts of trajectories and creates partial estimates of these lines. The clustering algorithm is based on the Legendre transform reconstruction method introduced in [3]. The Legendre transform maps circles (tracker hits) into lines in dual space (described by angle and distance to the origin), where common tangent lines appear as intersections. Although originally intended as a stand-alone reconstruction tool, it is repurposed in this algorithm as an estimator to guide clustering and fitting. The algorithm is enhanced with spatial clustering. The algorithm alternates between two complementary approaches, exploiting local information in detector space and global information from dual space.

2. **Fitting phase:** In the fitting phase, each cluster is fitted with a line using maximum likelihood estimation [4]. The statistical model allows incorporation of measurement uncertainties and additional uncertainty caused by scattering in the tracker gas. The semi-analytical fitting efficiently uses the partial estimates from clustering phase and provides full 3D line fits. Finally, this phase detects mirror symmetries and, if necessary, analytically reflects the identified line fits (Figure 2a).

3. **Connection phase:** In the final step, the connection phase links linear segments into polyline trajectories to account for sharp kinks (Figure 2b). Candidate connections are evaluated based on geometric criteria, such as kink angle, positions of the nearby associated tracker hits or distances between the two segments. Additional refinements adjust clustering and fitting decisions to ensure consistency of the final solution. An example of a fully reconstructed trajectory for a simulated event is shown in Figure 3.

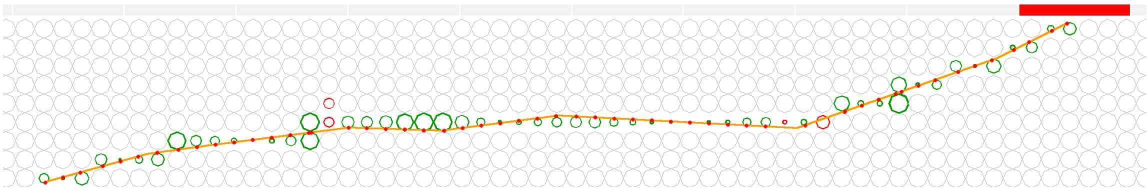


Figure 3: Simulated event reconstructed with the Cimrman Reconstruction Module [5]. Red circles correspond to unused hits, green circles indicate associated hits, with red dots marking the precise association points. This event illustrates the algorithm's ability to resolve highly challenging multi-kinked topologies.

4. Conclusion

The algorithm has been implemented as the so-called Cimrman Reconstruction Module [5] in the official SuperNEMO software framework, Falaise [6]. Preliminary studies suggest an increased speed compared with previously available algorithms, while allowing for more complex polyline reconstructions. A more detailed article describing the methodology and performance studies is currently in preparation.

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