

Article

Characterization of Alpha Particle Track Lengths in LR-115 Detectors

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Abstract

We investigate the dependence of the maximum etched track length ($L_{\max}$) on alpha-particle energy and incidence angle in LR-115 type II nuclear track detectors by combining Geant4 Monte Carlo simulations with controlled chemical etching experiments. The bulk (V_B) and track (V_T) etch rates were determined under standardized conditions, yielding $V_B = (3.1 \pm 0.1) \mu\text{m/h}$ and $V_T = (5.98 \pm 0.06) \mu\text{m/h}$, which correspond to a critical detection angle of about $(58.8 \pm 1.2)^\circ$. Simulations covering initial energies spanning 1 MeV to 5 MeV and incidence angles up to 70° confirmed that the maximum etched track length varies quadratically with particle energy E and depends systematically on incidence angle θ . Empirical parameterizations of $L_{\max}(E, \theta)$ were obtained, and energy thresholds for complete track registration within the 12 μm sensitive layer were established. The angular acceptance predicted by the V_T/V_B ratio was validated, and the results demonstrate that $L_{\max}$ provides a monotonic and more reliable observable for energy calibration compared to track diameter. These findings improve the quantitative calibration of LR-115 detectors and strengthen their use in environmental radon monitoring, radiation dosimetry, and alpha spectrometry. In addition, they highlight the utility of Geant4-based modeling for refining solid state nuclear track detector response functions and guiding the development of optimized detector protocols for nuclear and environmental physics applications.

Keywords: LR-115; chemical etching; maximum track length; track detection critical angle

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1. Introduction

Solid-state nuclear track detectors (SSNTDs) are extensively used for the detection and measurement of ionizing radiation, including electrons, protons, neutrons, alpha particles, fission fragments, and cosmic rays, through the formation of latent tracks in the detector material [1–3]. This technique is recognized as one of the simplest, most versatile, and cost-effective methods for charged-particle registration, with applications spanning a wide range of disciplines, from nuclear and particle physics to geology, environmental monitoring, space research, and archeology [4–6].

When a charged particle interacts with a polymeric material, it loses energy mainly through inelastic collisions with electrons in the medium (electronic stopping), which induce physical and chemical modifications of the molecular structure [1,7]. At sufficiently high energies, an additional contribution arises from radiative energy losses due to

bremsstrahlung emission, although this effect is negligible for low-energy heavy charged particles, such as alphas.

The damaged trail left by the particle is referred to as a latent track. This track can be revealed by chemical etching, which preferentially dissolves the damaged zones at a higher rate than the undamaged bulk material, thus enlarging the track until it becomes optically visible under a standard microscope [8]. Track development is governed by two key parameters: the bulk etch rate V_B and the track etch rate V_T . When $V_T > V_B$, track enlargement occurs, enabling visualization [3]. Therefore, studying etching efficiency is essential for understanding the detection sensitivity of SSNTDs.

Track parameters such as length, depth, and diameter are critical for characterizing detector response. While previous studies have explored aspects of alpha-particle interactions in detectors such as CR-39 and LR-115, they often focused on either limited energy ranges or normal incidence conditions, and did not provide a comprehensive view of how these parameters evolve with both energy and incident angle [2,3]. Here, LR-115 (Kodak Pathé, Paris, France) refers to a cellulose nitrate-based SSNTD, and CR-39 (Pershore Moldings Ltd., London, UK) refers to a polyallyl diglycol carbonate (PADC) SSNTD. For clarity, we use their commonly known commercial names (LR-115 and CR-39) throughout this manuscript.

Recent work underscores a renewed interest in LR-115 SSNTDs for radon diagnostics and detector physics. For example, non-destructive characterization via XRD/UV-Vis (X-rays diffraction/ultra-violet-visual) methods has been employed to study LR-115 sensitivity limits and dose-dependent structural/optical changes; large-scale field campaigns continue to deploy LR-115 in diffusion chambers and bare mode; and novel sensing configurations (e.g., activated-carbon-assisted LR-115) have demonstrated improved sensitivity and fine spatial mapping [9–12]. These advances contextualize and motivate our focus on alpha-track length characterization in LR-115 and help clarify the manuscript's contribution relative to the current state of the art.

The present paper presents a comprehensive investigation of the geometric and etching characteristics of alpha-particle tracks in LR-115 detectors, focusing on the maximum etched track length as a function of initial alpha energy (1–5 MeV) and incident angle (0–70°). While previous studies typically examined either the energy–range relationship (e.g., [2]) or the angular dependence of track detection (e.g., [3]) in isolation, this study uniquely combines both variables within a unified simulation framework. By simultaneously exploring the influence of energy and incident angle, we determine the critical detection angle and establish quantitative etching thresholds. These findings are crucial for improving detector calibration and enhancing applications in radiation dosimetry and environmental monitoring.

Furthermore, we employ Geant4 Monte Carlo simulations, a robust and highly validated toolkit for modeling particle–matter interactions [13,14]. In contrast to prior analytical or semi-empirical models, such as those employing the Durrani–Green function to describe etching ratios [15] or empirical equations for track-length evolution in CR-39 [16], our approach enables a high-resolution simulation of track geometry formation by accounting for energy loss, angular scattering, and material interactions in LR-115. Through this method, we derive empirical relationships, such as quadratic fits, between the maximum etched track length and the particle's energy and angle, thereby offering a new predictive framework for SSNTD response under varied experimental conditions.

2. Analytical Procedure

To investigate the track formation and evolution of alpha particles in LR-115 detectors, we adopted a two-pronged approach, combining Monte Carlo simulations with controlled laboratory experiments. The simulation component was used to model particle interac-

tions and energy deposition profiles inside the detector material, enabling a systematic study of the maximum track lengths as a function of the incident angle and initial energy. Complementarily, experimental measurements were carried out to determine key etching parameters, such as the bulk and track etch rates, which govern the development of etched tracks. Together, these methods provide a comprehensive framework for analyzing the range-dependent behavior of alpha tracks and evaluating the critical conditions that define their maximum observable length.

2.1. Experimental Approach

The bulk etch rate of the LR-115 nuclear track detector was obtained experimentally by analyzing the increase in track diameter with etching time under normal incidence, i.e., with alpha particles impinging perpendicularly on the detector surface ($\theta = 0^\circ$), following the standard procedure described in Refs. [3,17]. The detector employed in this study is the LR-115 type II non-strippable film. Each sample consisted of a 12 μm thick sensitive layer of red cellulose nitrate deposited on a 100 μm thick non-etchable clear polyester base. The foils were cut into $1 \times 1 \text{ cm}^2$ pieces and irradiated for one minute with alpha particles from a ^{226}Ra point source of nominal activity 3.3 kBq ($8.9 \times 10^{-8} \text{ Ci}$). The source was positioned approximately 1 mm from the detector surface and centrally aligned with the sensitive area to ensure uniform irradiation and adequate track density, with such a short distance guaranteeing negligible energy loss of the emitted alpha particles in air.

After irradiation, the detectors were chemically etched in a 2.5 N NaOH solution at $60.0 \pm 0.5^\circ\text{C}$ using a thermostatically controlled water bath [18]. Etching times ranged from 20 to 140 min in 20 min increments. Tracks became visible under the optical microscope only after about 80 min of etching, while at 140 min, the sensitive LR-115 layer was completely removed from the polyester base. Consequently, the evolution of track parameters was systematically analyzed for etching times between 70 and 130 min, in 10 min steps. The observed dependence of the base diameter on etching time provided the experimental determination of V_B under these conditions [19].

Track analysis was carried out in a semi-automatic mode using an optical microscopy system consisting of a Leica optical microscope operating at $100\times$ magnification, coupled with a digital camera and a computer interface. This setup enabled the etched tracks to be observed and analyzed directly on the screen. The acquired images were processed and analyzed using the Image Pro Plus 4.5 software [20] which allowed for the precise determination of track diameters and densities. For each etching condition, multiple detector samples were examined, and at least 50 tracks per sample were measured to ensure statistical reliability. The resulting track distributions were homogeneous across the detector surface, and this methodology provided a reproducible and high-resolution characterization of the etched alpha tracks.

Regarding the track etch rate, it was determined using the general expression [21]:

$$V_T = V_B \left(\frac{1 + Y^2}{1 - Y^2} \right), \quad (1)$$

where $Y = D/(2x)$, D denotes the measured track diameters, and $x = V_B t$ is the thickness of the detector bulk material removed during the etching time t . This formulation remains valid for finite $p = V_T/V_B$, unlike the simplified $V_B = D/2t$ relation.

During etching, V_T exceeds V_B and the track length increases with time. Once the etchant reaches the particle endpoint, V_T approaches V_B ; the conical geometry collapses, and the etched track enters an over-etched stage. At this point, the etched track length reaches its maximum value, L_{max} , defined as the longest measurable track before over-etching occurs [22]:

$$L_{\max} = R - V_B t_c \quad (\text{for normal incidence}) \quad (2)$$

or

$$L_{\max} = R - \frac{V_B t_c}{\cos \theta} \quad (\text{for an incident angle } \theta), \quad (3)$$

where R is the particle range obtained from the Monte Carlo simulation, and $t_c = R/V_T$ is the time for the etchant to reach the end of the latent track.

The experimentally determined values of V_B and V_T were then used as input parameters in the Monte Carlo simulations, as described in Section 2.2 just below.

2.2. Monte Carlo Simulation Strategy

The interaction of alpha particles with the LR-115 nuclear track detector was simulated using Geant4 (Geometry and Tracking—version 11.3.2), a Monte Carlo-based toolkit for modeling particle transport and interactions with matter [13]. We employed the `emstandard_opt4` physics list with a detailed treatment of multiple scattering, ionization, and energy-loss processes. The LR-115 active layer was represented as a 12 μm cellulose nitrate film (density = 1.4 g/cm³) supported by a polyester substrate. Production cuts and step limits were set to ensure submicron accuracy in track-length determination.

A collimated monoenergetic alpha-particle beam was simulated with energies sampled uniformly between 1 and 5 MeV. The incidence zenith angle θ was varied from 0° (normal to the detector plane) to 70° in steps of 10°. To refine the determination of the critical angle for track registration, additional simulations were performed in 1° steps between 51° and 59°. For each angle, 1×10^5 primary events were generated using independent random seeds.

$L_{\max}$ was obtained from the particle ranges simulated with Geant4. For non-normal incidence, the simulated ranges were corrected by projecting the trajectory onto the detector surface using the factor $\cos \theta$. These geometry-corrected ranges were then combined with the experimentally measured etching parameters, V_B and V_T , to compute the complete etching time t_c . The final observable track length was then calculated as

$$L_{\max} = R - V_B t_c \quad (\theta = 0^\circ) \quad \text{or} \quad L_{\max} = \frac{R - V_B t_c}{\cos \theta} \quad (\theta > 0).$$

We define $L_{\max}$ as the longest etched track that can be observed before the etchant reaches the end of the latent track, beyond which the track transitions into an over-etched stage and no further elongation occurs [2,3,22]. This combined procedure enabled the evaluation of the angular cutoff and the mapping of $L_{\max}(E, \theta)$ in LR-115 under the adopted standard etching conditions. In addition, to obtain the ionization rate distributions presented in Section 3.2, the simulations also recorded the energy E deposited per unit track length in comparably small spatial steps, allowing the calculation of the stopping power ($-dE/dx$) as a function of penetration depth in the sensitive layer.

3. Results and Discussion

3.1. Etched Track Analysis of Alpha Particles in LR-115 Detector

Figure 1 shows the track density distribution as a function of etching time. Since most alpha particles strike the detector surface nearly perpendicularly, the analysis of track diameters focused on those exhibiting circular openings. Figure 2 illustrates the geometry of a conical (non-overetched) track. As the etching process progresses beyond the point where the etchant reaches the end of the latent track, the structure enters the overetched regime. At this stage, the initially conical form gradually evolves into a hybrid geometry, partly conical and partly spherical, due to isotropic etching at the track tip. This

morphological evolution alters the track's optical contrast and may reduce its visibility under a microscope, particularly for tracks near the critical incidence angle or produced by relatively low-energy alpha particles. This schematic provides the conceptual basis for interpreting the experimental measurements of track diameters.

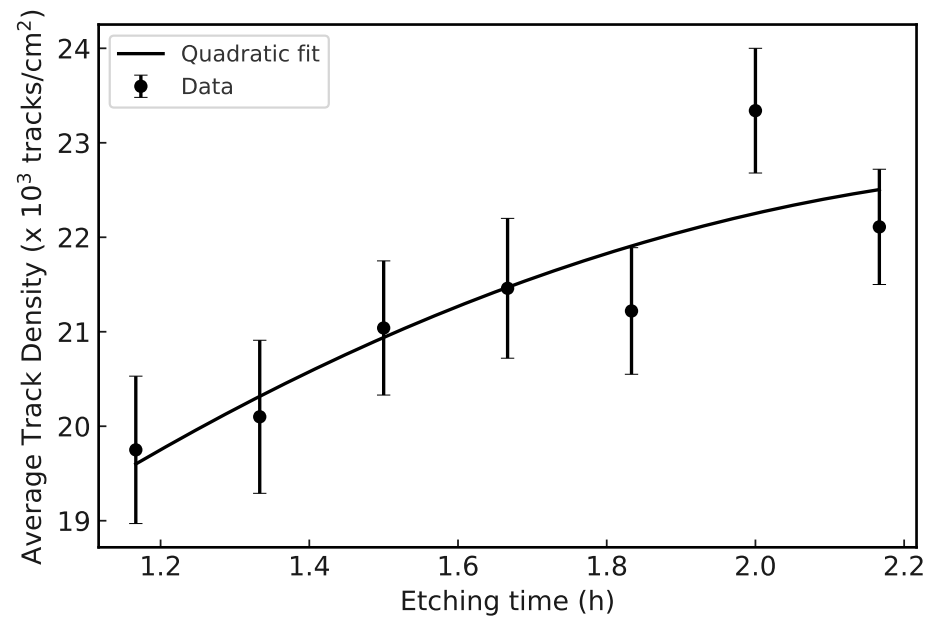


Figure 1. Average track density as a function of the etching time of the cellulose nitrate type II (LR-115) detector.

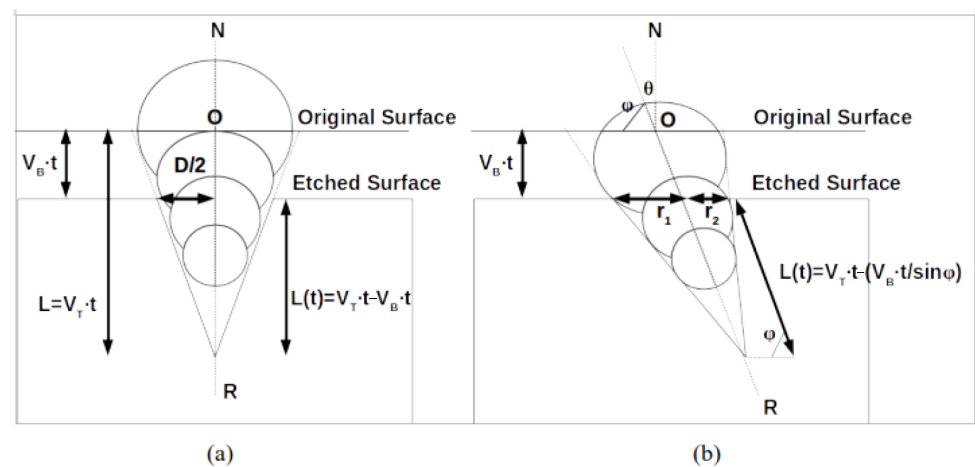


Figure 2. Geometry of a charged particle track for (a) perpendicular incidence and (b) incidence at an angle θ relative to the surface normal N . The main parameters shown include the base cone diameter, the major and minor axes, the height of the etched cone $L(t)$, and the etching rates—bulk (V_B) and track (V_T). Taken from Ref. [23] (copyright permission by Elsevier).

Figure 3 then depicts the distribution of the mean track diameter as a function of etching time. Since tracks are not optically resolvable before a finite visibility threshold time ($t_{\text{vis}} \approx 80$ min), we analyze the diameter–time relation using the shifted variable $t' = t - t_{\text{vis}}$. In the finite- p regime for alpha tracks, the base diameter grows linearly with time after visibility onset, so we fit $D(t')$ with a zero-intercept model. This approach avoids the artifact of a non-zero intercept at $t = 0$, which may otherwise be misinterpreted as a latent track diameter, and ensures consistency with the physical onset of track visibility.

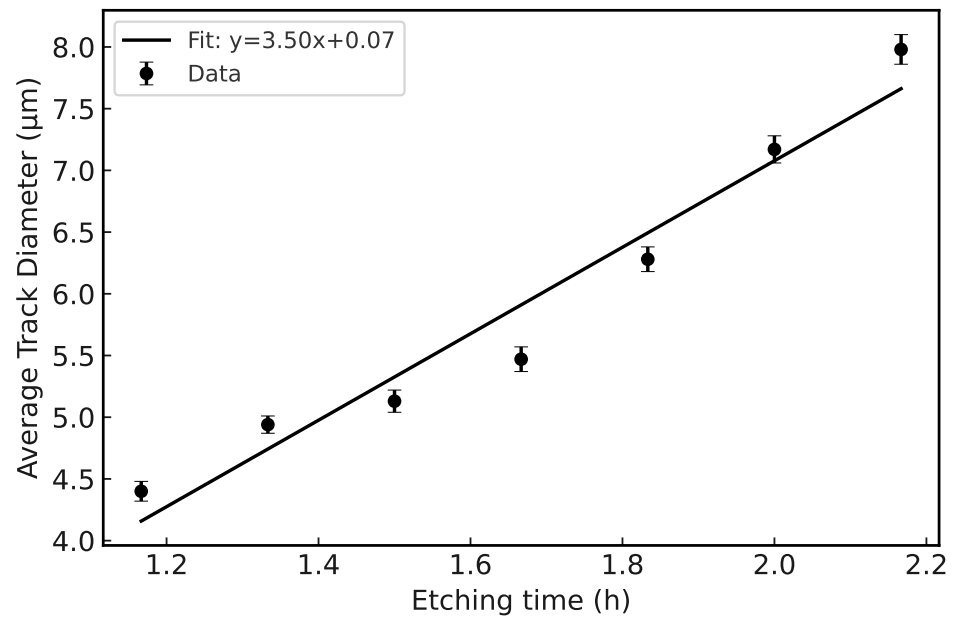


Figure 3. Average track diameter of alpha-particle tracks in LR-115 detectors as a function of chemical etching time under normal incidence.

The least-squares fit of the mean track diameter as a function of the shifted etching time $t' = t - t_{\text{vis}}$ (with $t_{\text{vis}} \approx 80$ min) for LR-115 yielded a slope of (3.50 ± 0.35) $\mu\text{m}/\text{h}$, with a correlation coefficient of 0.95, described by

$$D(t') = (3.50 \pm 0.35) t', \quad (4)$$

where t' is the effective etching time after the onset of track visibility. The fit was constrained to pass through the origin, thereby avoiding the non-physical implication of a finite track diameter at zero etching time. According to the general finite- p relation [3], the slope corresponds to

$$s = 2V_B \sqrt{\frac{p-1}{p+1}}$$

rather than directly to V_B . Using this relation together with the observed geometry, we obtained a bulk etch rate of (3.1 ± 0.1) $\mu\text{m}/\text{h}$, in consistency with the earlier obtained values: (3.4 ± 0.1) $\mu\text{m}/\text{h}$ found in Ref. [18] and $V_B \approx 3.3$ $\mu\text{m}/\text{h}$ determined from mass difference measurements in Ref. [24]. The corresponding track etch rate, calculated from the general expression (1) shows just quite a weak dependence on etching time and may be approximated by a constant average value of $V_T = (5.98 \pm 0.06)$ $\mu\text{m}/\text{h}$ under the etching conditions applied here; see Figure 4. Some minimum one observes around 1.7 h of etching time in Figure 4 is believed to correspond to the transition from the initial surface activation stage to steady-state etching, during which the etchant gradually penetrates the damaged zones of the detector material before reaching a stable track etch rate. A linear fit described by $V_T = (0.004 \pm 0.005)t + (5.97 \pm 0.01)$, with the coefficient of determination of the fit, $R^2 = 0.93$, confirms that the slope is statistically compatible with zero.

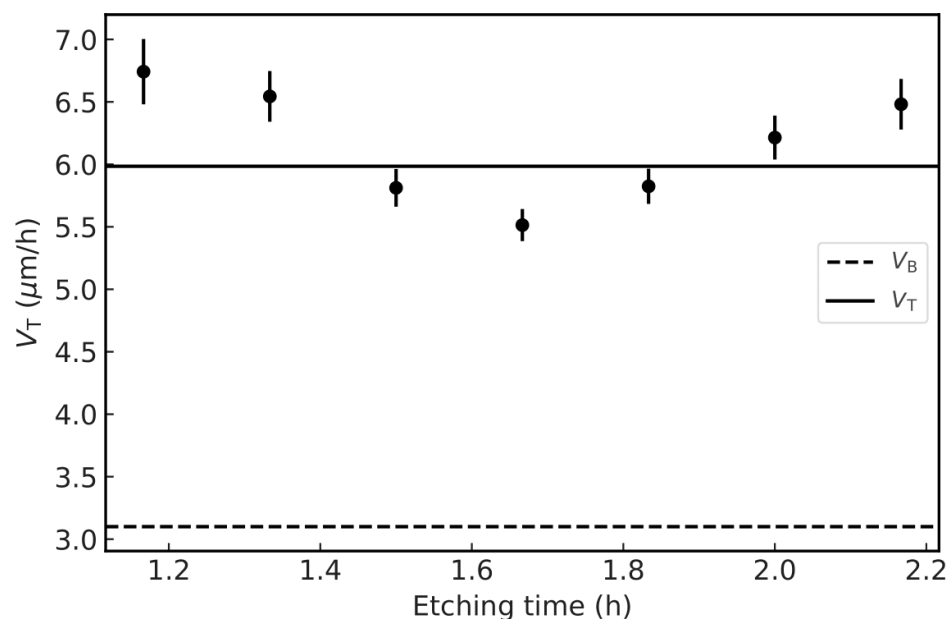


Figure 4. Track etch rate (V_T) of alpha-particle tracks in LR-115 detectors as a function of chemical etching time, derived from the evolution of the mean track diameter. The solid line shows V_T calculated from the general expression (1), and the dashed line shows V_B obtained from the linear fit to the experimental data. The corresponding track etch rate exhibits only a weak dependence on etching time and may be approximated by a constant average value of $V_T = (5.98 \pm 0.06) \mu\text{m/h}$ under the etching conditions applied here.

3.2. Numerical Modeling of LR-115 Detector Response to Alpha Particles

Having established the experimental etch rates and track diameter behavior in LR-115, let us now turn to numerical modeling to further interpret these results. Monte Carlo simulations performed with Geant4 allow us to calculate the local ionization rate of alpha particles as they traverse the detector and relate this to the observed etching dynamics. This complementary approach provides a microscopic picture of the energy deposition processes underlying the experimentally measured track growth.

Figure 5 presents the ionization rate ($-dE/dx$) of alpha particles with initial energies between 1 and 5 MeV as a function of their penetration depth in the LR-115 detector, obtained from Geant4 Monte Carlo simulations. In these simulations, the detector was modeled as a $12 \mu\text{m}$ cellulose nitrate sensitive layer, and the energy deposited per unit path length was recorded for each particle along its trajectory. The resulting distributions describe how the stopping power varies with depth for different initial energies.

The track etch rate $V_T(E, x)$ is proportional to the local ionization rate $I(E, x)$, i.e.,

$$V_T(E, x) \propto I(E, x). \quad (5)$$

As can be seen in Figure 5, the ionization rate of alpha particles does vary with penetration depth, even within the $12 \mu\text{m}$ sensitive layer of LR-115. For example, a 5 MeV alpha particle shows an increase from about 0.14 to 0.18 MeV/ μm across this depth. However, compared to the sharp Bragg peaks occurring near the end of the particle range, the relative variation within the LR-115 layer is moderate. For practical purposes, and to allow quantitative parameterization of etched track growth, we approximate the track etch rate V_T by an effective average value under our etching conditions. This effective V_T is consistent with the mean experimental value of $(7.2 \pm 0.1) \mu\text{m/h}$ reported in Ref. [18].

For illustration, the ionization rate of a 4 MeV alpha particle was estimated at 0.19 MeV/ μm , being consistent with the 0.18 MeV/ μm obtained from TRIM (Transport of Ions in Matter) simulations [25] as cited in Ref. [18]. The pronounced peaks observed for 1–3 MeV particles correspond to the Bragg peak, which occurs near the end of the trajectory when the kinetic energy is low enough, and the interaction cross-section increases sharply. By contrast, higher-energy alphas (close to 5 MeV) traverse the sensitive layer more rapidly, depositing less energy per unit length and only developing their Bragg peak near the end of their longer ranges outside the LR-115 active layer.

It is worthy emphasizing that the experimental and simulated results are consistent within uncertainties. For instance, the bulk etch rate obtained from the diameter–time relation, $V_B = (3.1 \pm 0.1) \mu\text{m}/\text{h}$, agrees well with the value inferred from the Monte Carlo parameterization of $D(t')$. Similarly, the critical angle derived from simulation, $\theta_c \approx 56.5^\circ$, is in close agreement with the analytical estimate $\theta_c = (58.8 \pm 1.2)^\circ$ calculated using the experimental V_T/V_B ratio. This quantitative agreement validates the Monte Carlo framework and supports its use in extending the detector response analysis beyond the conditions directly accessible in the experiment.

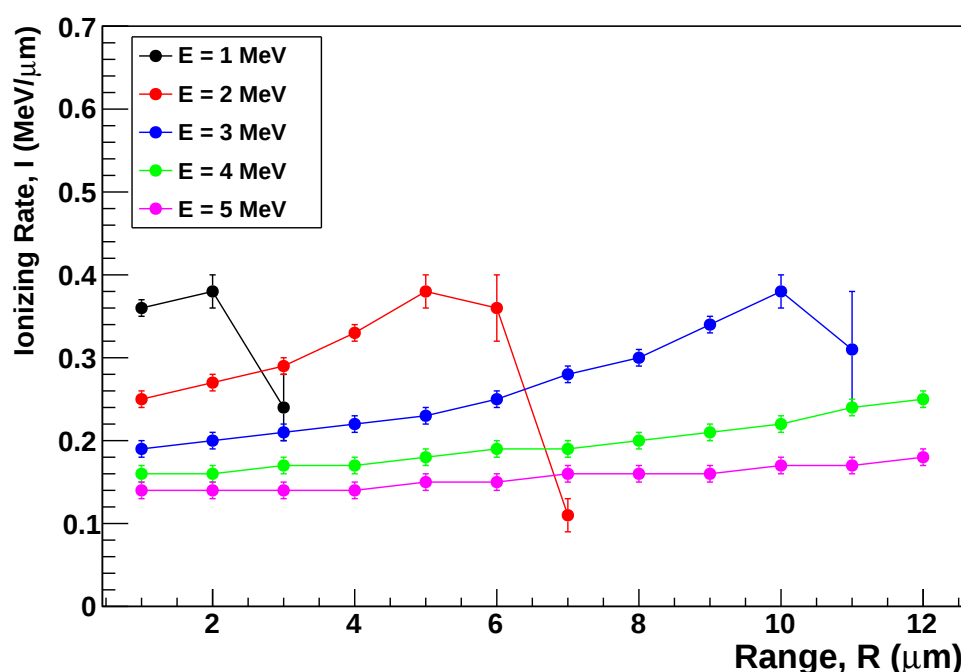


Figure 5. Ionization rate ($-dE/dx$) of alpha particles with initial energies from 1 to 5 MeV as a function of their particle range in the LR-115 detector. Results were obtained from Geant4 Monte Carlo simulations.

Figure 6a shows the average energy deposited by alpha particles per unit path length in the LR-115 detector, i.e., the linear stopping power ($-dE/dx$), as obtained from Geant4 simulations. Since the rate of energy loss is inversely proportional to the particle's kinetic energy [1], lower-energy alpha particles deposit more energy per unit length, producing stronger damage tracks in the detector material. Figure 6b presents the simulated particle range as a function of the initial energy E .

Figure 7a shows the parameterization of L_{max} as a function of particle energy for different incident angles. The solid lines represent quadratic regressions of the form

$$L_{\text{max}} = a_0 + a_1 E + a_2 E^2, \quad (6)$$

with the fitting parameters as listed in Table 1. Figure 7b presents the complete etching time, t_c , as a function of energy. At large incident angles close to the critical angle, the regression curves can yield negative values of $L_{\max}$. These negative values do not represent physical etched tracks but indicate that, under such conditions, the particle trajectory is completely removed by bulk etching before a visible track can form. In other words, those values signal about the loss of detector sensitivity at these angles. Overall, the results show that the LR-115 detector ceases to register tracks at incident angles greater than 60° .

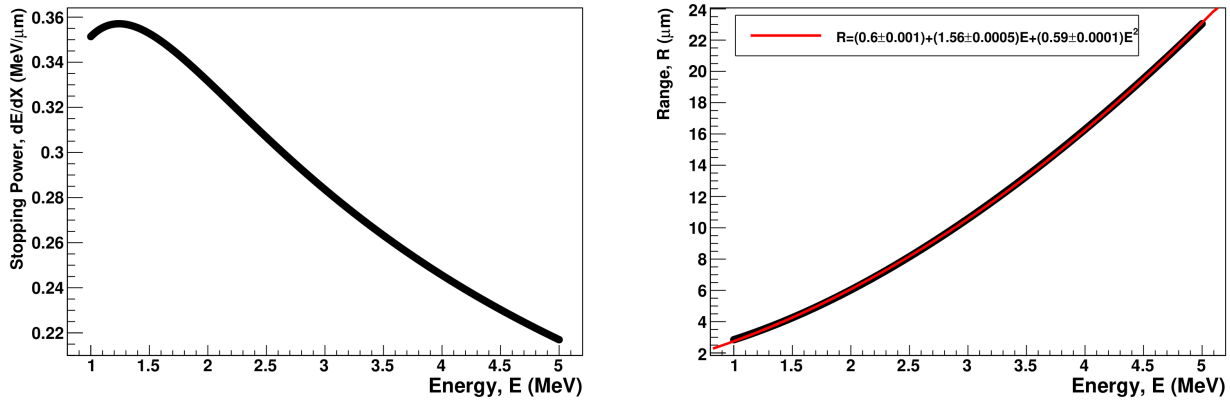


Figure 6. (a) Stopping power ($-dE/dx$) and (b) range (R) of alpha particles in the LR-115 detector.

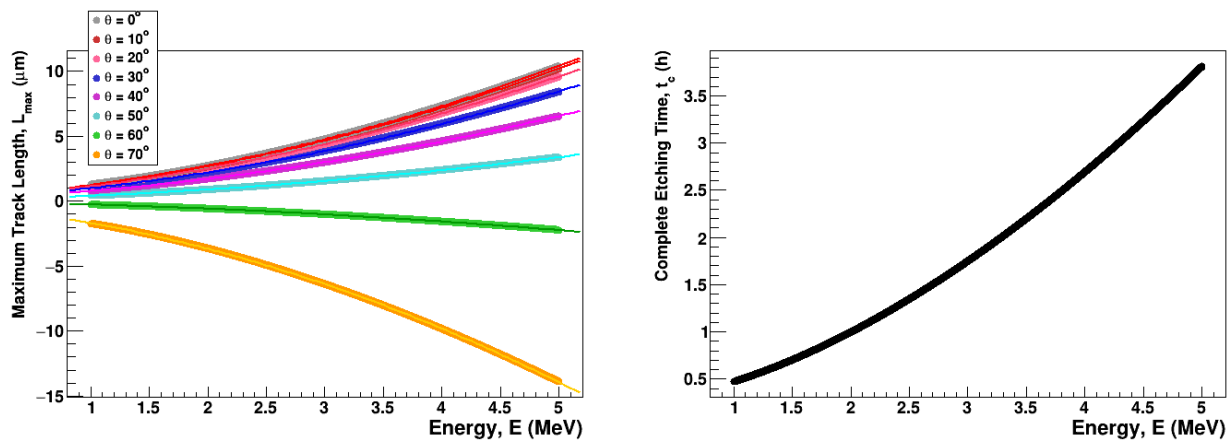


Figure 7. Monte Carlo parameterization of the maximum etched track length. (a) Maximum track length $L_{\max}$ as a function of alpha-particle energy for different incident angles, with quadratic fit (6) to the simulated data. (b) Complete etching time t_c as a function of energy. These parameterizations provide calibration relations for $L_{\max}(E, \theta)$ in LR-115 detectors.

Table 1. Fitted parameters of the quadratic regression model (6) used to describe $L_{\max}$ as a function of energy (in MeV) for different incident angles. Here, a_0 , a_1 , and a_2 are the regression coefficients, and R^2 denotes the coefficient of determination of the fit.

Incident Angle	a_0	a_1	a_2	R^2
0°	0.270 ± 0.003	0.7000 ± 0.0002	0.27 ± 0.00004	0.9997
10°	0.270 ± 0.003	0.6900 ± 0.0002	0.26 ± 0.00004	0.9997
20°	0.250 ± 0.003	0.6500 ± 0.0002	0.25 ± 0.00004	0.9997
30°	0.220 ± 0.003	0.5700 ± 0.0002	0.22 ± 0.00004	0.9997
40°	0.1700 ± 0.0002	0.4400 ± 0.0001	0.17 ± 0.00002	0.9997
50°	0.0900 ± 0.0001	0.2300 ± 0.0001	0.09 ± 0.00001	0.9997
60°	-0.0600 ± 0.0001	-0.1500 ± 0.00005	-0.06 ± 0.00001	0.9997
70°	-0.3600 ± 0.0004	-0.9400 ± 0.0003	-0.36 ± 0.00005	0.9997

To refine the determination of the critical angle, additional simulations were carried out for incidence between 50° and 60° . As shown in Figure 8, the simulations reveal a sharp cutoff at $\theta \approx 56.5^\circ$, above which the etched track ($V_T \cdot t$) lies entirely within the bulk-etched layer ($V_B \cdot t$), and no surface opening is formed. This cutoff value agrees remarkably well with the analytical estimate

$$\theta_c = \cos^{-1}\left(\frac{V_B}{V_T}\right) \approx (58.8 \pm 1.2)^\circ, \quad (7)$$

thus validating both the Monte Carlo framework and the analytical approach. Importantly, let us emphasize that θ_c depends only on the etch rate ratio (V_B/V_T) and is therefore independent of the alpha-particle energy.

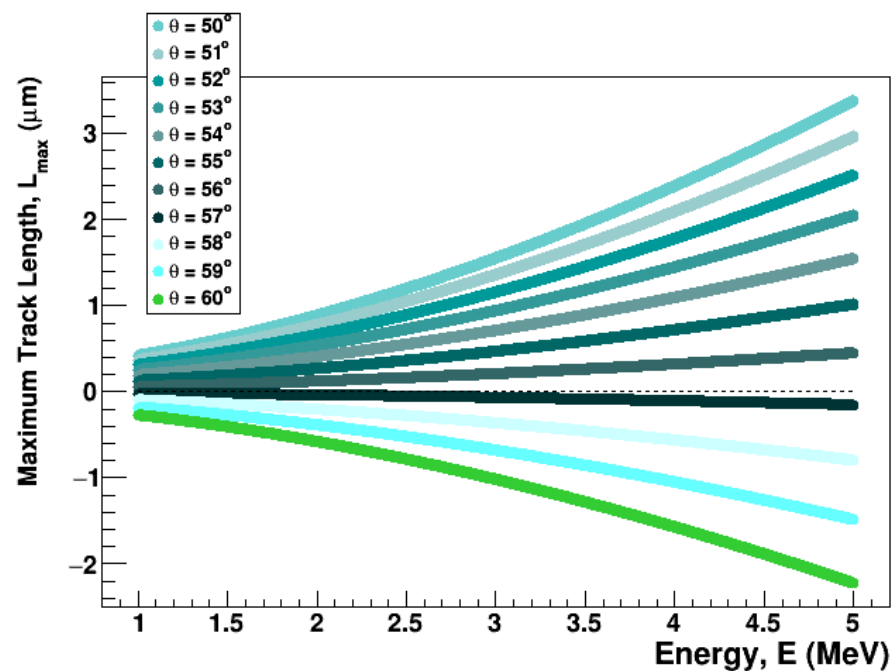


Figure 8. Monte Carlo determination of the critical angle. Maximum track length as a function of alpha-particle energy for incidence between 50° and 60° . A distinct cutoff appears at $\theta \approx 56.5^\circ$, in exceptional agreement with the analytical estimate $\theta_c = (58.8 \pm 1.2)^\circ$.

Importantly, the parameterization of $L_{\max}$ provides a practical advantage over traditional track diameter analyses. While the track diameter often exhibits a non-monotonic dependence on energy (leading to degeneracies where different energies correspond to similar diameters), $L_{\max}$ increases monotonically with energy. This unique correspondence reduces ambiguity in energy estimation and improves the reliability of detector calibration.

Finally, the simulations clarify how the particle endpoint shifts toward the detector surface with increasing incident angle (Figure 9). For normal and near-normal incidence, the alpha-particle range remains fully contained within the $12\ \mu\text{m}$ sensitive layer up to a well-defined energy threshold (Table 2). At larger incident angles, however, only a fraction of the track is contained within the active film, and the effective maximum energy for full containment decreases accordingly. It is important to emphasize that these thresholds are distinct from the critical angle θ_c : while θ_c is determined by the etch-rate ratio (V_B/V_T), the tabulated thresholds result from the finite detector thickness and define the highest initial energy for which full containment occurs at a given angle. For $\theta > 56.5^\circ$, alpha particles traverse the sensitive layer without leaving observable etched tracks under the experimental conditions used here. This explicit distinction between etch-rate-driven limits

and geometry-driven thresholds further strengthens the case for using $L_{\max}$ as a robust observable for unambiguous energy calibration in LR-115 detectors.

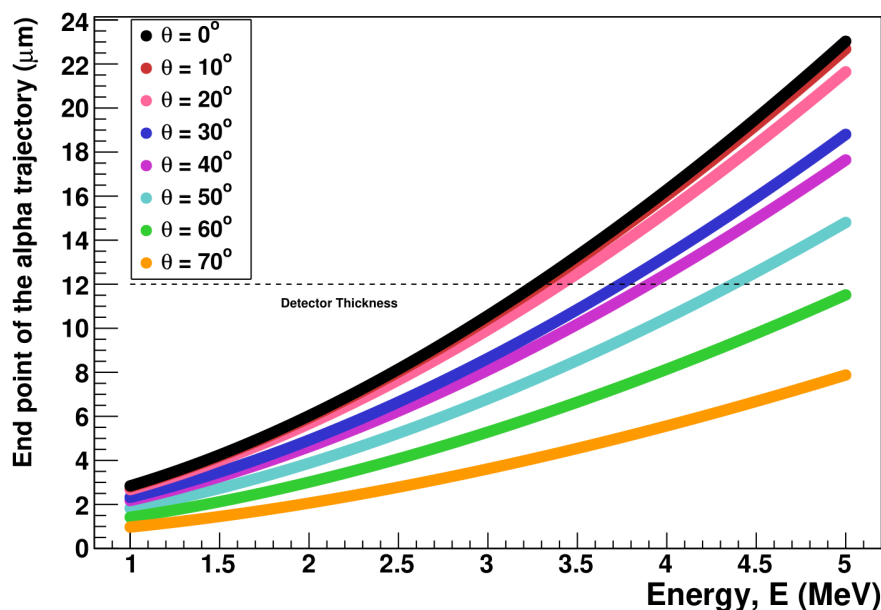


Figure 9. Monte Carlo simulation of the track endpoint depth. End point of the alpha-particle range in LR-115 as a function of the initial energy for different incident angles. The dashed line marks the 12 μm thickness of the sensitive film, above which tracks are no longer fully contained.

Table 2. Maximum alpha-particle energy for which tracks are fully contained within the 12 μm sensitive layer of the LR-115 detector.

Incident Angle	Energy Threshold (MeV)
0°	3.260 ± 0.005
10°	3.290 ± 0.005
20°	3.400 ± 0.006
30°	3.730 ± 0.006
40°	3.900 ± 0.006
50°	4.360 ± 0.007
60°	—
70°	—

Altogether, these results demonstrate that the Monte Carlo model does not just confirm the existence of a critical angle, but also provides a quantitative framework that links two complementary limits of detector response: the etch-rate-driven cutoff at θ_c and the geometry-driven energy thresholds for full track containment. By mapping $L_{\max}(E, \theta)$ across energies and angles, the simulations establish calibration-ready relations that strengthen energy reconstruction and improve the practical use of LR-115 detectors in radiation dosimetry and environmental monitoring.

4. Conclusions

In this study, we characterized the etched track properties of LR-115 type II nuclear track detectors exposed to alpha particles and chemically processed under standard conditions. The bulk and track etch rates (V_B and V_T) were determined experimentally as $V_B = (3.10 \pm 0.10) \mu\text{m/h}$ and $V_T = (5.98 \pm 0.06) \mu\text{m/h}$, and validated against analytical models, yielding values consistent with the literature. The transition from the conical to the over-etched phase was quantified through the definition of the maximum etched track length, $L_{\max}$, which represents the physical upper limit to track elongation.

Monte Carlo simulations were then employed to explore the dependence of $L_{\max}$ on particle energy and incident angle. Unlike track diameter, which may display non-monotonic or degenerate behavior with respect to energy, $L_{\max}$ was shown to increase monotonically with alpha-particle energy, providing a unique correspondence between track length and initial energy. This monotonic behavior establishes $L_{\max}$ as a more robust and practical observable for detector calibration. The simulations also reproduced the well-established critical angle for track registration, yielding $\theta_c \approx 56.5^\circ$ in exceptional agreement with the analytical prediction of $\theta_c = \cos^{-1}(V_B/V_T) = (58.8 \pm 1.2)^\circ$. In addition, maximum energy thresholds for complete track containment within the 12 μm active layer were determined as a function of the incident angle.

Altogether, these results extend the calibration framework of LR-115 detectors in ways that are of direct help in applied research and monitoring. The parameterizations of $L_{\max}(E, \theta)$ enable improved and less ambiguous energy reconstruction compared to conventional track-diameter methods. The angular cutoff analysis provides quantitative limits on the detector's sensitivity range, guiding its correct use in practical measurements. Finally, the determination of energy thresholds for full containment within the sensitive layer establishes the operational energy window of LR-115 detectors. Overall, this study confirms the reliability of LR-115 detectors for alpha-particle measurements while introducing calibration-ready relations based on the maximum etched track length, $L_{\max}$. These relations provide a physically consistent framework that complements traditional diameter-based approaches and have the potential to reduce ambiguities in energy reconstruction. As such, the results enhance the applicability of LR-115 detectors in fields such as radiation dosimetry, radon monitoring, and environmental surveillance.

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