

The Last Micrometer: Silicon Nanotips for Low-Threshold Neutrino Detection in Liquid Argon

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Abstract

Few-electron ionisation signals in liquid argon remain challenging for conventional charge readout, motivating detector concepts that can amplify charge before it reaches the front-end electronics. LArCADE investigates a geometric approach to this problem, using arrays of electrically biased, nanofabricated silicon tips to generate intense local electric fields at the charge-collection surface. Here we develop a fabrication-informed electrostatic description of KOH-etched (100) silicon tips, with the aim of identifying which features of the fabricated geometry govern the field available for charge amplification. The calculations show that crystallography itself becomes an electrostatic design parameter: the near-edge field follows the Meixner scaling imposed by the $\{111\}$ facets, while restoring the full square-cap geometry reveals distinct edge and strongly localised corner fields. At the scale of the array, finite-pitch calculations show that neighbouring tips progressively screen this enhancement, with the leading dependence organised by the relative tip height h/p . Together, these results separate the geometric parameters that create the local enhancement from those that determine how much of it survives in a manufacturable array, and are informing prototype structures now under fabrication. In parallel, COMSOL field maps have been coupled to TRANSLATE, a microscopic Monte Carlo framework for electron transport in argon. The three-dimensional structure exposed here motivates the next development of that framework: interfacing TRANSLATE with full 3D COMSOL fields, ultimately carrying realistic fabricated geometries through to microscopic predictions of electron focusing, ionisation, and charge amplification.

Keywords: liquid argon, charge amplification, field enhancement, silicon nanotips, CE ν NS, electrostatics, microscopic electron transport

1. Introduction

Particle physics increasingly operates near the limits of detector sensitivity. In many neutrino and rare-event measurements, the potential physics reach is determined not only by interaction rate or target mass, but by how efficiently the smallest energy deposits can be converted into measurable signals. Detector concepts that exploit strongly localised electric fields offer a promising route toward lower detection thresholds, provided that the resulting field geometry and charge transport can be understood with sufficient fidelity.

Coherent elastic neutrino-nucleus scattering (CE ν NS) provides a particularly compelling example. At sufficiently low momentum transfer, the weak neutral-current scattering amplitudes associated with the nucleons add coherently, enhancing the cross section. CE ν NS measurements can consequently provide sensitivity to precision electroweak observables, including the weak mixing angle, while also probing neutrino electromagnetic properties and non-standard neutrino interactions with quarks [1]. The experimental challenge is that this physics is encoded in low-energy nuclear recoils. Measurements of nuclear-recoil ionisation in liquid argon show charge yields of only a few electrons per keV at low recoil energies, with a significant dependence on recoil energy and applied field; for example, yields of $3.6 - 6.3 e^-/\text{keV}$ have been measured for 6.7 keV argon recoils [2]. At stopped-pion neutrino sources, the resulting CE ν NS signals can correspond to primary ionisation deposits ranging from a few tens to approximately 10^3 electrons.

Liquid-argon time-projection chambers (LArTPCs) provide an

established charge-imaging technology for neutrino and rare-event experiments, but this charge scale presents a particular challenge for conventional readout. Even cryogenic low-noise front-end electronics developed for large LArTPCs exhibit equivalent noise charges of around several hundred electrons per channel. In MicroBooNE, for example, the residual equivalent noise charge after signal processing remained below approximately $400 e^-$ for the longest wires [3]. A practical charge-detection threshold must lie above the electronic noise, leaving a substantial fraction of the low-energy CE ν NS ionisation spectrum inaccessible to conventional charge readout without adding additional gain before the front-end electronics. Fig. 1 illustrates the CE ν NS interaction and the microscopic scale of the ionisation deposited by the resulting argon nuclear recoil.

The Liquid Argon Charge Amplification Devices (LArCADE) project addresses this threshold gap geometrically. Rather than increasing the electric field throughout the detector volume, nanofabricated, electrically biased doped-silicon tips (or needles) reshape and enhance the field locally at the point of charge collection. Drifting electrons are focused into a micron-scale high-field region near the tip surface; if the local field is sufficient to produce secondary ionisation, charge multiplication can occur before the signal reaches the downstream electronic readout. LArCADE therefore aims to raise otherwise sub-threshold primary ionisation deposits above the electronics-limited readout threshold, while retaining spatial information through a patterned array of collection sites. As the amplification acts on transported charge rather than on a particular interaction channel, the same low-threshold, spa-

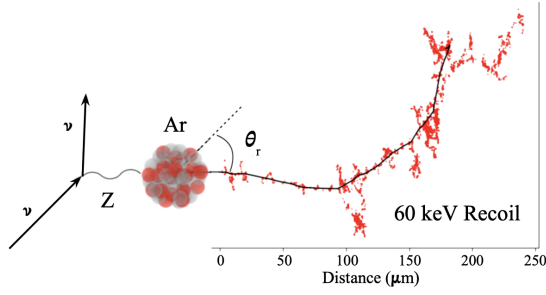


Figure 1: Schematic of coherent elastic neutrino-nucleus scattering in argon and the subsequent nuclear-recoil trajectory. The representative 60 keV recoil illustrates the microscopic spatial scale over which recoil energy is transferred through secondary interactions, motivating spatially resolved, low-threshold charge detection in liquid argon.

tially resolved readout concept may also be relevant to other rare-event measurements in liquid argon, including searches for low-mass dark matter.

Realising this concept requires connecting electric-field structure across very different spatial scales to the microscopic transport of electrons in liquid argon. The field must guide charge over tens to hundreds of micrometres while developing strong local enhancement around micron-scale tip features. Whether that enhancement produces charge multiplication, however, depends not simply on the maximum field but on the field sampled along an electron trajectory and the corresponding electron-argon interactions.

To address these coupled scales, COMSOL Multiphysics® is used to construct a fabrication-informed electrostatic description of the LArCADE silicon tips. A finite-curvature axisymmetric model enables systematic studies of tip geometry and array pitch, while a full three-dimensional unit cell captures the square cap and crystallographic $\{111\}$ facets of the etched structure. Representative COMSOL field maps are then interfaced with TRANSLATE, a microscopic Monte Carlo framework for electron transport in argon, linking the device-scale electrostatics to the microscopic transport relevant for charge amplification.

2. Theory and Experimental Setup

2.1. LArCADE Detector Concept

The LArCADE concept uses arrays of electrically biased doped-silicon tips to combine local field enhancement with spatially segmented charge collection. Ionisation electrons are transported through the bulk liquid by the applied drift field before entering the strongly non-uniform near-tip region, where they are focused toward the collection surface. If the local field is sufficient for secondary ionisation, charge multiplication occurs before the signal reaches the downstream electronics, while the patterned array retains transverse information through the collection site. The drift, focusing, and local amplification sequence is illustrated schematically in Fig. 2.

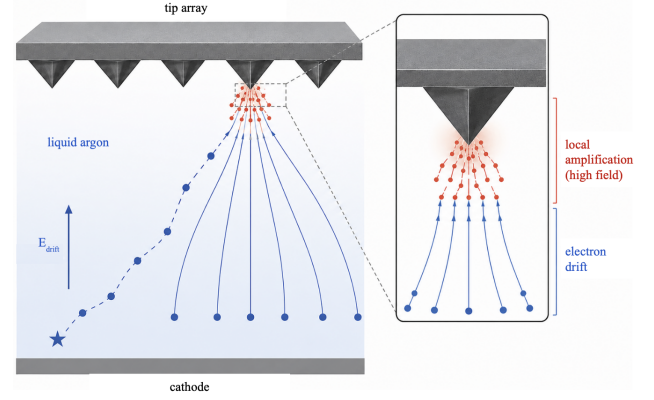


Figure 2: Schematic of the LArCADE operating principle. Ionisation electrons drift through liquid argon under the applied field and are focused towards the silicon-tip array, where the enhanced near-tip field can produce secondary ionisation and local charge amplification.

2.2. Fabrication-Informed Silicon Tip Geometry

The LArCADE geometry is set by the crystallography of the silicon substrate and the anisotropic wet-etch process used to fabricate it. Prototype structures are formed from heavily boron-doped, (100)-oriented silicon using potassium hydroxide (KOH). Because the $\{111\}$ planes etch much more slowly than the $\{100\}$ and $\{110\}$ orientations, lithographically defined structures evolve toward facets inclined by 54.74° relative to the (100) wafer surface. The fabricated geometry therefore links the tip height and lateral dimensions through the crystal structure, while finite edge and corner curvature supplies the physical length scale that regularises the near-field enhancement. The as-designed model includes:

- a $\{111\}$ -faceted pyramidal tip body, with a conical axisymmetric idealisation used for reduced-dimensional studies;
- a lithographically defined square cap;
- finite edge and corner curvature;
- the array pitch between neighbouring tips; and
- the surrounding liquid-argon volume and relevant electrode boundaries.

2.3. Prototype Device and Experimental Programme

The present LArCADE programme couples numerical optimisation to the fabrication and cryogenic testing of prototype devices. Earlier, non-crystallographically-constrained amplification structures exhibited appreciable tip-to-tip variation, motivating the move toward crystallographically defined KOH-etched silicon as a route to more uniform and reproducible electrodes. The simulations presented here are being used to inform the dimensions of the current test structures under fabrication.

Measurements are performed using a modified purity-monitor platform at Fermilab, shown in Fig. 3. A photocathode illuminated via optical fibres provides a controlled source of photoelectrons that drift through the active argon volume toward the anode

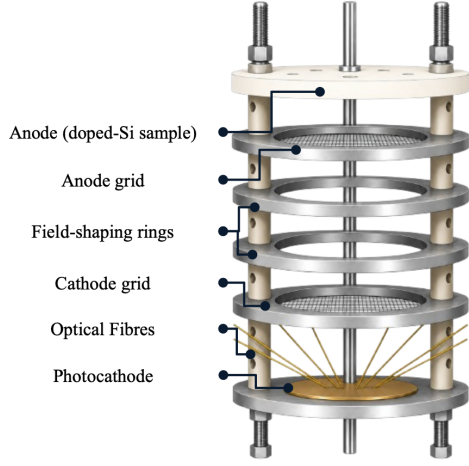


Figure 3: Schematic of the modified purity-monitor setup used for LArCADE measurements at Fermilab.

grid and doped-silicon collection structure, providing a configurable testbed for charge transport and amplification across different electrode geometries and operating conditions.

3. Numerical Model

The electric field surrounding the silicon tips was modelled in COMSOL Multiphysics® using coupled electrostatic and conductive domains. Liquid argon was treated with the *Electrostatics* interface, while the boron-doped silicon was represented using the *Electric Currents* interface. This retains the common conductive substrate explicitly while allowing the surrounding field to emerge self-consistently from the device geometry and applied bias.

3.1. Electrostatic Formulation and Boundary Conditions

In the liquid-argon domain, $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$ and $\mathbf{E} = -\nabla V$. With no free volume charge and a spatially uniform relative permittivity, $\epsilon_r = 1.5$, the potential satisfies

$$\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = 0 \quad \Rightarrow \quad \nabla^2 V = 0. \quad (1)$$

At the surface of an equipotential conductor the tangential electric field vanishes, while the normal displacement in the liquid is supported by the induced surface charge, $\mathbf{n} \cdot \mathbf{D}_{\text{LAr}} = \sigma_s$. The strongest fields therefore occur where charge is concentrated by the local geometry. A mathematically sharp conducting edge produces a singular near-field solution; introducing finite curvature provides the physical length scale required for a mesh-independent peak field.

Classical smooth-emitter electrostatics provides a useful limiting comparison. For an emitter of height h and characteristic apex radius R_a ,

$$E_{\text{apex}} = \gamma_a E_{\text{bulk}}, \quad \gamma_a \simeq \frac{2h/R_a}{\ln(4h/R_a) - \alpha}, \quad (2)$$

where α depends on the emitter geometry [4]. The LArCADE structures terminate instead in a finite cap bounded by crystallographic facets and rounded edges, so Eq. 2 is used only as a qualitative smooth-apex benchmark for the axisymmetric results of Sec. 4.1.

The doped-silicon domain obeys stationary current conservation, $\nabla \cdot \mathbf{J} = 0$, with $\mathbf{J} = \sigma_{\text{Si}} \mathbf{E} = -\sigma_{\text{Si}} \nabla V_{\text{Si}}$. The potential V_{tip} is applied to the back surface of the common silicon substrate and the remaining exterior silicon boundaries satisfy $\mathbf{n} \cdot \mathbf{J} = 0$. In the zero-current configuration considered here, the connected silicon domain is necessarily equipotential. Defining $u = V_{\text{Si}} - V_{\text{tip}}$,

$$\int_{\Omega_{\text{Si}}} \sigma_{\text{Si}} |\nabla u|^2 d\Omega = 0 \quad \Rightarrow \quad \nabla u = 0, \quad (3)$$

and hence $V_{\text{Si}} = V_{\text{tip}}$ throughout the structure. The silicon resistivity therefore does not affect the present electrostatic solution; it becomes relevant only when a non-zero collection current is drawn. The *Electric Currents* domain is retained to verify this coupling numerically.

At the Si-LAr interface, continuity of potential is imposed, $V_{\text{LAr}} = V_{\text{Si}}$. A nominally uniform drift field is established through the upper liquid boundary, $V(z = h_{\text{LAr}}) = V_{\text{tip}} - E_{\text{bulk}} h_{\text{LAr}}$, with $E_{\text{bulk}} = 500 \text{ V cm}^{-1}$; this imposed value is used as the reference for all quoted enhancement factors. In the large-domain axisymmetric model, symmetry is imposed at $r = 0$ and the outer radial boundary satisfies $\mathbf{n} \cdot \mathbf{D} = 0$. Finite-pitch axisymmetric calculations place the same symmetry boundary at the equal-area unit-cell radius $r_{\text{cell}} = p/\sqrt{\pi}$. In three dimensions, the tip is centred in a square cell of side p ; the lateral liquid boundaries satisfy zero normal displacement and the corresponding silicon boundaries are electrically insulating. For the centred geometry and uniform vertical excitation used here, these mid-plane conditions mirror the solution into neighbouring cells and represent an interior tip in a regular array. An explicit periodic-boundary check at $p = 1 \text{ mm}$ reproduced the same field solution. Physical perimeter effects of a finite array are not included.

3.2. Model Geometry and Mesh

The computational geometries are summarised in Fig. 4 and follow from the fabrication-informed parameters introduced in Sec. 2.2. A sharp-edge axisymmetric truncated cone is retained as a numerical diagnostic of the edge singularity. The corresponding finite-curvature axisymmetric geometry provides the reduced model used for the geometry and pitch scans, while the full three-dimensional square unit cell restores the fabricated cap and crystallographic $\{111\}$ facets. Wherever possible, nominal dimensions are held fixed so that differences between solutions trace the geometry rather than a change in device scale.

The mesh is concentrated around the cap, edges, and corners, where the field varies most rapidly, before being progressively coarsened into the bulk liquid. For the sharp-edge geometry, E_{max} continues to increase under local refinement because the underlying electrostatic solution is singular; this geometry is therefore used only as a numerical diagnostic. Once a finite curvature scale is introduced, the near-tip maximum can instead be tested for convergence against that physical length scale.

The principal field-enhancement metric used throughout Sec. 4 is

$$\beta = \frac{E_{\text{max}}}{E_{\text{bulk}}}, \quad (4)$$

where E_{max} is the maximum electric-field magnitude in the liquid-argon domain and E_{bulk} is the nominal imposed field defined above. Spatially resolved field maps are additionally ex-

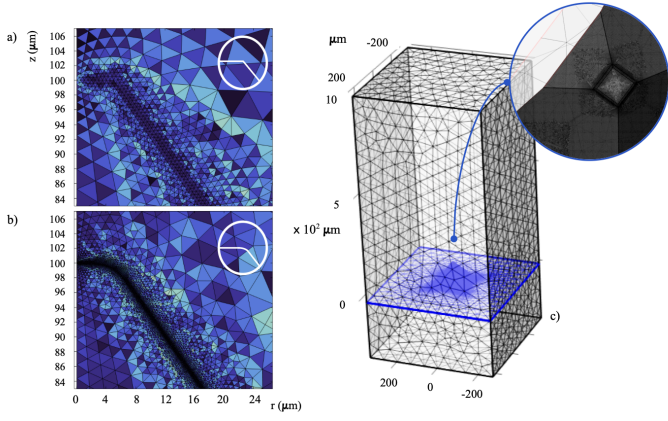


Figure 4: Finite-element geometries and mesh refinement used in the electrostatic model. (a) Sharp-edge axisymmetric truncated cone. (b) Corresponding finite-curvature model with local refinement near the tip. (c) Full three-dimensional fabrication-informed geometry with square cap and crystallographic $\{111\}$ facets; the inset shows the refined near-tip mesh. The mesh is progressively coarsened into the bulk liquid argon.

ported from COMSOL for the microscopic electron-transport calculations of Sec. 5.

4. Simulation Results and Discussion

4.1. Field Enhancement in the Axisymmetric Model

Before the reduced model is used for geometric parameter studies and microscopic transport, its near-tip enhancement must be separated from the numerical singularity introduced by an ideal sharp edge. We therefore establish mesh convergence first, and then use the finite-curvature geometry to identify the fabrication parameters that control the attainable field.

Figure 5(a) shows the mesh-refinement behaviour of the sharp-edge model and of otherwise identical tips with finite edge radii of 1 and 5 μm . Once a physical curvature scale is introduced, the solution settles rapidly: reducing the maximum local element size from 0.10 to 0.05 μm changes E_{max} by only 0.07% for $r_{\text{edge}} = 1 \mu\text{m}$, and by less than 0.01% for $r_{\text{edge}} = 5 \mu\text{m}$. The sharp geometry shows the opposite behaviour, with E_{max} rising from 9.90 to 16.19 kV cm^{-1} over the full refinement sequence without approaching a plateau. The contrast is therefore physical as well as numerical: finite curvature supplies the length scale that regularises the edge singularity and gives the peak field a well-defined meaning. With that scale established, Fig. 5(b) maps the enhancement obtained by varying the tip height from 100 to 400 μm and the edge radius from 0.5 to 5 μm , at fixed $w_{\text{cap}} = 10 \mu\text{m}$. Taking the imposed bulk field, $E_{\text{bulk}} = 500 \text{ V cm}^{-1}$, as the reference field, this slice of the broader geometry scan spans $10.75 \leq \beta \leq 41.61$: taller structures provide greater geometric leverage, while tighter edge curvature concentrates the field more strongly at the cap rim. The direction of these trends is familiar from conventional field-emitter electrostatics; their functional form is not. In particular, the dependence on curvature is markedly weaker than the smooth-apex behaviour represented by Eq. 2, suggesting that the relevant local geometry is the rounded edge of the finite cap rather than an effective point-like apex.

Figure 5(c) tests this interpretation directly. The local behaviour of electromagnetic fields at conducting edges is described by the classical Meixner edge condition [5, 6]. For the $54.74^\circ \{111\}$ facet produced by the KOH etch, the liquid occupies a reflex angle of 234.74° , from which the local solution of Laplace's equation gives

$$|\mathbf{E}| \propto r^{-m}, \quad m = 1 - \frac{\pi}{\Omega} \simeq 0.233. \quad (5)$$

Finite edge rounding truncates this singular behaviour at $r \sim r_{\text{edge}}$, so the curvature dependence of the enhancement should inherit the same exponent. Crucially, m is fixed here by the crystallographic angle and is not obtained from the COMSOL data.

The comparison in Fig. 5(c) bears this out. Holding the exponent at $m = 0.233$ and fitting only the normalisation of each height family reproduces the four-point $r_{\text{edge}} = 0.5\text{--}5 \mu\text{m}$ scans with $R^2 \simeq 0.9973$ for all three heights and maximum deviations below 1.8%. If the exponent is instead allowed to float, the three families independently return

$$m = 0.2230, \quad 0.2232, \quad 0.2233 \quad (6)$$

for $h = 100, 200$, and $400 \mu\text{m}$, respectively, with $R^2 > 0.9995$. The fitted exponent is therefore essentially independent of tip height and remains close to the $m = 0.233$ value specified a priori by the crystallographic edge geometry. The conventional smooth-apex fits shown alongside fail to reproduce the same curvature dependence, even when their shape parameter is allowed to vary.

This agreement provides the central validation of the near-edge physics captured by the reduced model. The simulations recover more than the generic expectation that sharper structures produce stronger fields: they recover a local scaling law whose exponent is specified independently by the geometry of the etch. The field near the cap rim therefore carries a quantitative imprint of the crystal structure from which the tip was made.

The separation between the height families also shows that the local edge geometry does not determine the enhancement alone. To quantify the remaining geometric dependence, a matched $3 \times 3 \times 3$ scan was performed over $h = \{100, 200, 400\} \mu\text{m}$, $w_{\text{cap}} = \{5, 10, 20\} \mu\text{m}$, and $r_{\text{edge}} = \{0.5, 1, 2\} \mu\text{m}$. With the curvature exponent fixed to the independently predicted Meixner value, all 27 solutions are described by the semi-empirical relation

$$\beta \simeq 2.22 \left(\frac{h}{r_{\text{edge}}} \right)^{0.233} \left(\frac{h}{w_{\text{cap}}} \right)^{0.373}, \quad R^2 = 0.9995. \quad (7)$$

The maximum fractional deviation across the scan is approximately 2.2%. Over the complete scan, the strongest axisymmetric enhancement is $\beta = 54.14$, obtained for $h = 400 \mu\text{m}$, $w_{\text{cap}} = 5 \mu\text{m}$, and $r_{\text{edge}} = 0.5 \mu\text{m}$. Allowing both exponents to vary instead gives $m = 0.229$ and a cap exponent of 0.376, with $R^2 = 0.9996$ and a maximum deviation below 1.9%. The cap exponent is empirical rather than universal, but the collapse of the full three-parameter scan identifies cap truncation as a second geometric control on the attainable enhancement, distinct from the local edge singularity.

The reduced model therefore provides a direct fabrication guide: the crystallographic facet angle fixes the local edge class, edge rounding controls the near-field concentration, and tip height and cap width set the larger-scale geometric leverage. The three-dimensional calculation can then isolate what this rotational reduction necessarily omits - the redistribution of that field around the square cap and its corners.

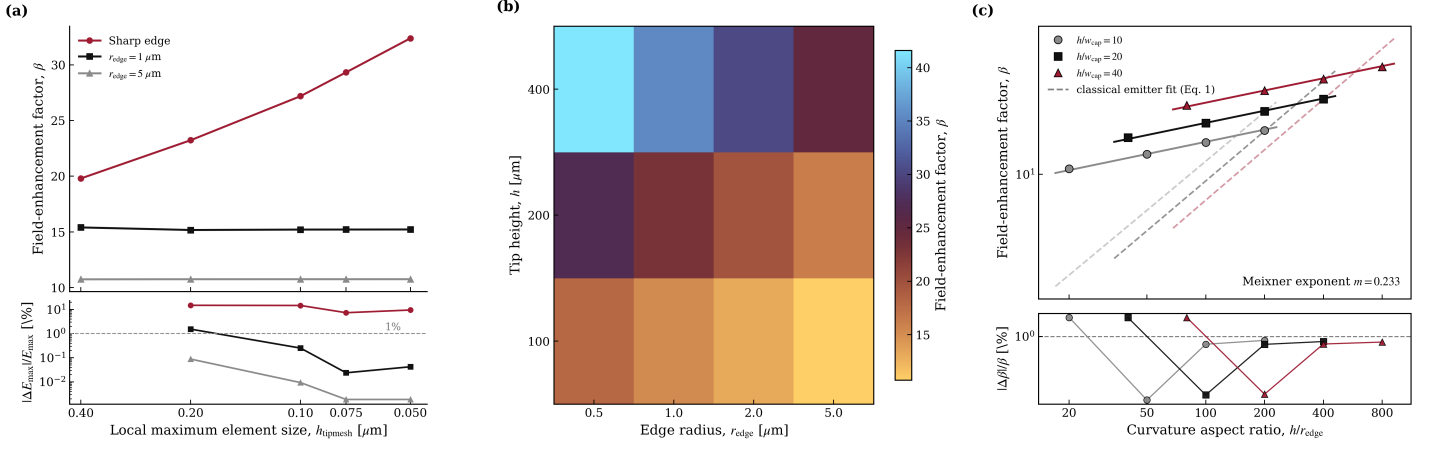


Figure 5: Axisymmetric field-enhancement study. (a) Mesh convergence for sharp and finite-curvature tips. (b) Dependence of β on tip height and edge radius for the $w_{\text{cap}} = 10 \mu\text{m}$ slice of the geometry scan, with $h = \{100, 200, 400\} \mu\text{m}$ and $r_{\text{edge}} = \{0.5, 1, 2, 5\} \mu\text{m}$. (c) Scaling of the same $w_{\text{cap}} = 10 \mu\text{m}$ data with h/r_{edge} , comparing the Meixner edge prediction ($m = 0.233$) with the conventional smooth-apex expectation.

4.2. Three-Dimensional Field Structure and the Axisymmetric Approximation

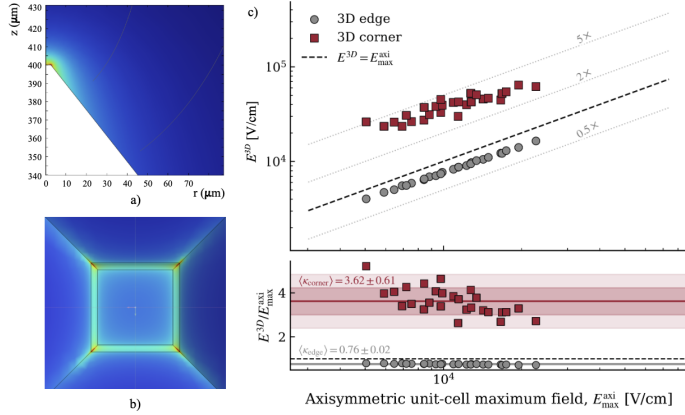


Figure 6: Three-dimensional modification of the near-tip field in a $p = 600 \mu\text{m}$ unit cell. (a,b) Axisymmetric equal-area and full three-dimensional field solutions for the representative geometry $h = 400 \mu\text{m}$, $w_{\text{cap}} = 5 \mu\text{m}$, and $r_{\text{edge}} = 0.5 \mu\text{m}$. Restoring the square cap localises the strongest field at the corners rather than continuously around the rim. (c) Three-dimensional fields at the non-corner cap edge and rounded corner as a function of the corresponding axisymmetric unit-cell maximum for 27 matched geometries at a common local mesh resolution. Dashed and dotted lines indicate equal-field and fixed-ratio references. The lower panel shows $E^{3D}/E_{\text{max}}^{\text{axi}}$; solid lines denote the mean ratios and shaded bands their one- and two-standard-deviation spreads across the geometry scan. The pointwise corner maximum is more mesh-sensitive than the rim or non-corner edge field and is used here to characterise field localisation rather than as a converged absolute field scale.

The large-domain axisymmetric calculations of Sec. 4.1 establish the local geometry dependence where sensitivity to the outer radial boundary is small. The fabricated device, however, consists of tips at finite pitch. To compare the reduced and three-

dimensional descriptions at a representative fabrication spacing, a $p = 600 \mu\text{m}$ square unit cell was matched to an equal-area circular axisymmetric cell,

$$\pi r_{\text{cell}}^2 = p^2, \quad r_{\text{cell}} = \frac{p}{\sqrt{\pi}}. \quad (8)$$

Restoring the square cap breaks the continuous rotational symmetry of the reduced model and redistributes the field around its perimeter. Matched calculations were performed over the same $3 \times 3 \times 3$ design space considered in Sec. 4.1, evaluating the three-dimensional field separately along the non-corner cap edge and at the rounded corners. For the representative geometry shown in Fig. 6(a,b), the axisymmetric unit-cell maximum is 22.7 kV cm^{-1} and the ordinary three-dimensional cap edge gives 16.5 kV cm^{-1} ; the square geometry additionally concentrates the field into much stronger, spatially localised corner hotspots.

Figure 6(c) shows that the axisymmetric maximum does not correspond to a single three-dimensional field scale. Defining

$$\kappa_{\text{edge}} = \frac{E_{\text{edge}}^{3D}}{E_{\text{max}}^{\text{axi}}}, \quad \kappa_{\text{corner}} = \frac{E_{\text{corner}}^{3D}}{E_{\text{max}}^{\text{axi}}}, \quad (9)$$

the common-resolution 27-geometry comparison gives $\langle \kappa_{\text{edge}} \rangle = 0.76 \pm 0.02$ and $\langle \kappa_{\text{corner}} \rangle = 3.62 \pm 0.61$, with ranges of 0.73 - 0.80 and 2.63 - 5.22, respectively. The quoted spreads are standard deviations across the geometry scan, not numerical uncertainties. A separate refinement check shows that the pointwise three-dimensional corner maximum is more mesh-sensitive than the axisymmetric rim or non-corner edge field; the corner ratios are therefore interpreted as a fixed-resolution measure of localisation, not as converged absolute field-enhancement factors.

The reduced model consequently retains the characteristic field scale and broader focusing structure while smoothing away the azimuthal structure introduced by the square cap. Its rim slightly overestimates the ordinary three-dimensional cap-edge field, but cannot reproduce the four discrete corner hotspots. Corner rounding and local morphology must therefore be treated as fabrication and metrology parameters alongside tip height, cap width, and edge radius. The axisymmetric field remains a computationally

tractable input to the transport study of Sec. 5, while the full three-dimensional model identifies the local structure that this reduction necessarily omits.

4.3. Finite-Pitch Scaling and the Large-Pitch Limit

The $p = 600 \mu\text{m}$ calculations of Sec. 4.2 describe a relatively dense array. For fabrication, however, the relevant question is not only how strongly an individual tip enhances the field, but how much of that enhancement survives in the presence of its neighbours. The absolute three-dimensional maximum is set locally by the square-cap corners, whereas inter-tip screening acts over the larger unit-cell scale. The axisymmetric model is therefore used here to isolate the fractional dependence on pitch.

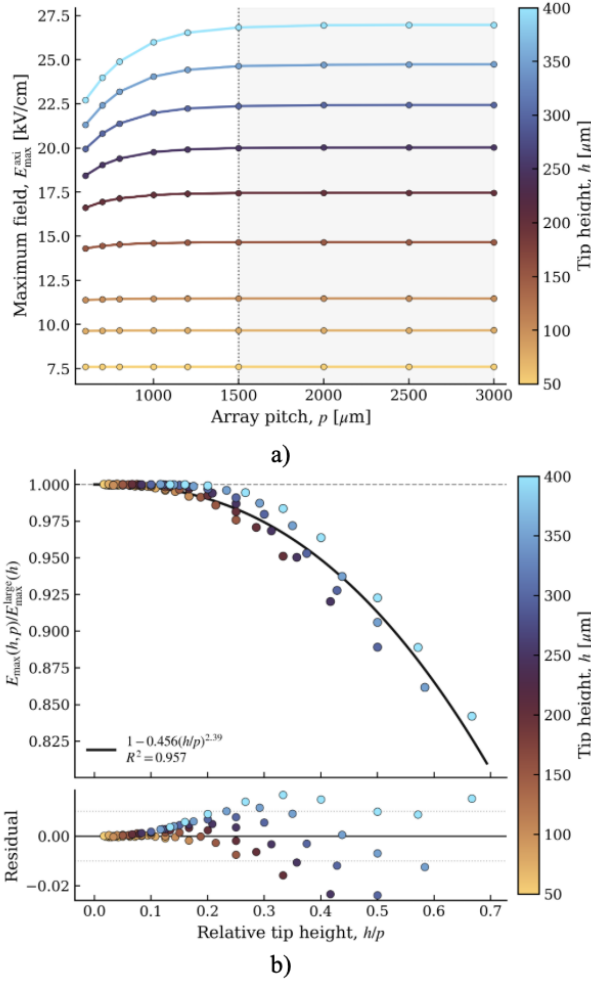


Figure 7: Finite-pitch dependence of the axisymmetric unit-cell model. (a) Maximum field versus pitch for $h = 50 - 400 \mu\text{m}$ at $w_{\text{cap}} = 5 \mu\text{m}$ and $r_{\text{edge}} = 0.5 \mu\text{m}$; the shaded region marks pitches for which all heights lie within 1% of their large-pitch values. (b) Normalised field versus h/p for the 81-point scan. The solid curve shows the empirical fit, while the lower panel shows the corresponding residuals.

At fixed $w_{\text{cap}} = 5 \mu\text{m}$ and $r_{\text{edge}} = 0.5 \mu\text{m}$, an 81-point scan was performed over $h = 50 - 400 \mu\text{m}$ and $p = 600 - 3000 \mu\text{m}$, using the equal-area radius $r_{\text{cell}} = p/\sqrt{\pi}$. A height-dependent large-pitch reference, $E_{\text{max}}^{\text{large}}(h)$, was defined from the mean of

the $p = 2.5$ and 3.0 mm solutions; these differ by less than 0.1% at every height. Screening strengthens rapidly as the tip height approaches the array spacing. At $p = 600 \mu\text{m}$, the maximum field is reduced from its large-pitch value by only 0.8% for $h = 100 \mu\text{m}$, but by 4.9% and 15.8% for $h = 200$ and $400 \mu\text{m}$, respectively [Fig. 7(a)]. Across the full scan, all geometries lie within 5% of the large-pitch limit by $p = 1.0 \text{ mm}$ and within 1% by $p = 1.5 \text{ mm}$. The $r_{\text{dom}} = 1 \text{ mm}$ domain used in Sec. 4.1 corresponds to $p_{\text{eq}} \simeq 1.77 \text{ mm}$ and differs from the large-pitch limit by only 0.36% even for the most pitch-sensitive geometry.

Normalising the field as $S = E_{\text{max}}(h, p)/E_{\text{max}}^{\text{large}}(h)$ shows that the leading dependence is organised by h/p (Fig. 7(b)). The empirical description shown in the figure gives $R^2 = 0.957$ with a maximum residual of approximately 2.4 percentage points: h/p therefore captures the dominant screening scale, but not an exact similarity relation.

This separation between local enhancement and array-scale screening maps directly onto the fabrication parameters. Varying $w_{\text{cap}} = \{5, 20\} \mu\text{m}$ and $r_{\text{edge}} = \{0.5, 2\} \mu\text{m}$ changes the absolute peak field by more than a factor of two, while leaving the fractional pitch dependence comparatively stable. At $p = 600 \mu\text{m}$, the suppression spans only 4.9 - 5.5% for $h = 200 \mu\text{m}$ and 15.7 - 16.4% for $h = 400 \mu\text{m}$. Cap width and edge curvature therefore set the local field scale available for charge amplification, while tip height and pitch determine how much of that enhancement is retained in an array.

A sparse three-dimensional pitch scan, performed with a fixed local tip-mesh scale of $0.025 \mu\text{m}$, provides an independent check of this picture. Because the pointwise corner maximum is more sensitive to local mesh resolution in absolute magnitude, only its fractional pitch response at fixed resolution is used here. For $h = 400 \mu\text{m}$, where screening is largest, the corner field increases monotonically from $p = 600 \mu\text{m}$ to 2 mm . The field at $p = 600 \mu\text{m}$ is 17.5% below that at 2 mm , compared with a 15.7% reduction in the axisymmetric model over the same interval. The agreement in fractional response supports the reduced model for finite-pitch screening, while the full three-dimensional geometry remains necessary to resolve the local corner field itself.

5. Electron Focusing and Microscopic Transport with TRANSLATE

The electrostatic calculations of Sec. 4 establish the geometric parameters controlling both the attainable near-tip field and its modification within an array. These trends are being used directly to inform the dimensions of test structures currently under fabrication at the UCSB Nanofabrication Facility. Predicting charge amplification, however, requires the resulting field distributions to be coupled to the microscopic transport of electrons through liquid argon.

Axisymmetric COMSOL field maps have therefore been interfaced with TRANSLATE, a time-domain Monte Carlo framework for electron transport in argon [7]. TRANSLATE propagates individual electrons using energy-dependent electron - argon cross sections, including scattering, excitation, and ionisation, while reproducing macroscopic transport behavior such as drift and diffusion. Figure 8 shows a representative calculation for $h = 400 \mu\text{m}$, $w_{\text{cap}} = 5 \mu\text{m}$, and $r_{\text{edge}} = 0.5 \mu\text{m}$, in which electrons undergo stochastic transport in the bulk liquid before being progres-

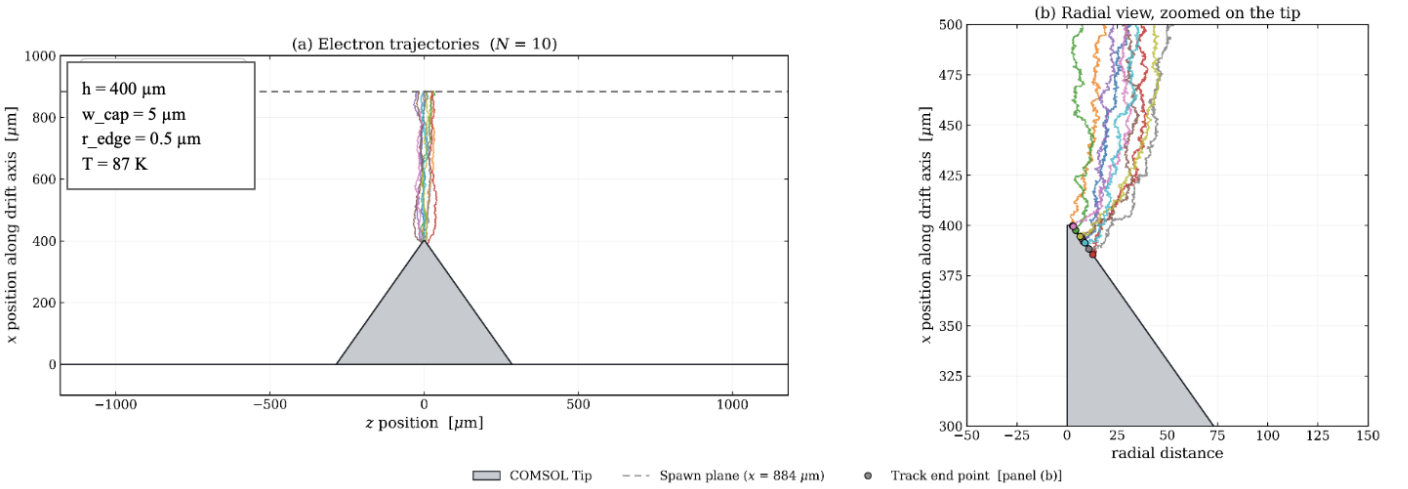


Figure 8: Electron transport through an axisymmetric COMSOL field map for $h = 400 \mu\text{m}$, $w_{\text{cap}} = 5 \mu\text{m}$, and $r_{\text{edge}} = 0.5 \mu\text{m}$ in liquid argon at a nominal bulk field of 500 V/cm . (a) Ten stochastic electron trajectories from the release plane towards the tip. (b) Enlarged near-tip view showing diffusion and field-driven focusing. The calculation demonstrates the present COMSOL - TRANSLATE interface and is not used here to infer a quantitative charge gain.

sively focused by the COMSOL field near the tip. The trajectories demonstrate the present field-map interface rather than a quantitative prediction of gain.

At present, this coupling is restricted to the reduced axisymmetric field description. The three-dimensional calculations of Sec. 4.2 show that the fabricated square-cap geometry introduces distinct edge and corner field scales that are absent from that approximation. These results therefore motivate an extension of TRANSLATE to accept full three-dimensional COMSOL field maps, allowing the fabrication trends identified here to be propagated through electron focusing, scattering, excitation, and ionisation towards a microscopic prediction of charge amplification.

6. Outlook and Conclusions

A coherent electrostatic picture emerges from these studies: the geometry written into silicon by KOH etching is carried directly into the field available for charge amplification. The $54.74^\circ \{111\}$ facets set the local edge scaling, while edge curvature, cap width, and tip height determine the attainable enhancement; restoring the full three-dimensional structure further reveals strong corner localisation absent from the axisymmetric model. At the scale of the array, the pitch introduces a distinct constraint, with inter-tip screening governed primarily by h/p . The calculations therefore separate the parameters that create the local field from those that determine how much of that enhancement survives in a fabricated array: findings that have already informed the design of prototype structures now under fabrication. The next stage will be to carry the same fabrication realism into the transport problem by extending the present COMSOL-TRANSLATE coupling to full three-dimensional fields, ultimately enabling direct comparison between microscopic amplification predictions and cryogenic measurements of the fabricated devices.

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