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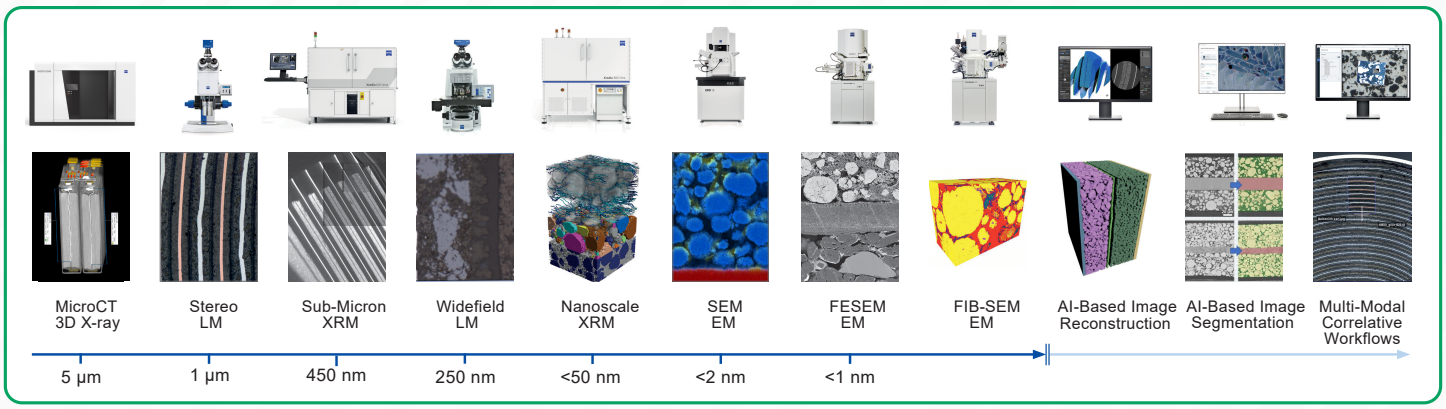
3D Nanoscale Imaging Transforms Battery Development from Guesswork to Precision Engineering

Battery Performance Through 3D Imaging

Introduction

The National Renewable Energy Laboratory (NREL) and ZEISS use advanced X-ray microscopy to reveal invisible battery features—grain orientations, cracks, and particle connections. This 50 nm resolution 3D imaging predicts failures, optimizes fast charging, and guides recycling without destroying samples, transforming battery development from guesswork to precision engineering.



Key Technologies

X-Ray Nano-Computed Tomography (CT): 50 nm Resolution, Non-Destructive

3D Segmentation: MATBOX Software for Crack Analysis

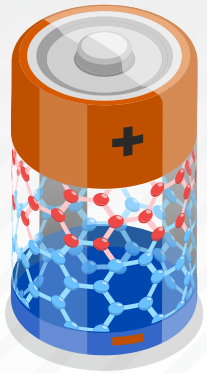
Multi-Scale Imaging: From Particles to Full Electrodes

Applications

Fast Charging Design
- Optimizes particle architectures
- Prevents lithium plating
- Guides laser ablation and dual-layer designs

Recycling Optimization
- Maps damage distribution
- Sorts materials
- Enables direct recycling

Manufacturing Guidance
- Validates synthesis targets
- Quality control
- Reduces trial and error



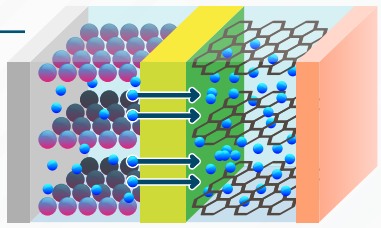
ZEISS Ultra: The Only Lab-Based System Capable of These Discoveries
Non-destructive 3D imaging at 50 nm resolution enabled NREL to track battery particles with cycling—impossible with any other laboratory technique.

Why Was This Microscope Essential?
- Visualize without destroying
- Phase + absorption contrast
- Detailed deep dives
- Correlative power

The Critical Advantage:
Only non-destructive imaging could reveal that edge particles crack 25% more than center particles after cycling.

Case Study 1: Single-Particle Architecture

Inside cathode particles, lithium travels along 2D planes within crystalline grains. NREL imaging reveals commercial batteries have random grain orientations, like scattered mosaic tiles, forcing lithium through maze-like paths. This cuts charging speed by 50% compared to radially aligned architectures.



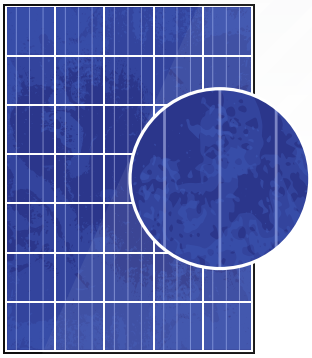
Mosaic Structure

Lithium Highway vs. Maze

50% Speed Penalty

Particle Architecture Insights:
Through 3D Electron Backscatter Diffraction imaging and modeling, researchers discovered that grain architecture determines whether a battery excels at longevity or rapid charging, but rarely both.

- Grain orientation mapping: quantifies radial vs. random alignment
- Large grains/small particles: approaching single crystals for maximum life
- Small grains/large particles: polycrystalline for fastest ion transport



Key Finding: The Application Sweet Spot:
Multi-physics modeling of real particle architectures revealed an unexpected insight: there's no universal "best" structure. The imaging tools now allow manufacturers to validate that they have achieved their target architecture.

- Single-crystal approach: 3x better longevity, slower charging
- Polycrystalline design: 2x faster charging, shorter lifespan
- Custom architectures: matches structure to application needs

Case Study 2: Recycling Damaged Cathodes

After 3,000 cycles, battery damage follows predictable patterns, edges crack 25% more than centers (9.5% vs. 8.5% crack volume). NREL's particle-by-particle analysis reveals edge regions suffer higher mechanical stress, cutting charging speeds by 65%. This location-based damage map unlocks targeted recycling strategies worth 70% more than the recovered value.

3,000 Cycle Journey

Edge vs. Center Stress

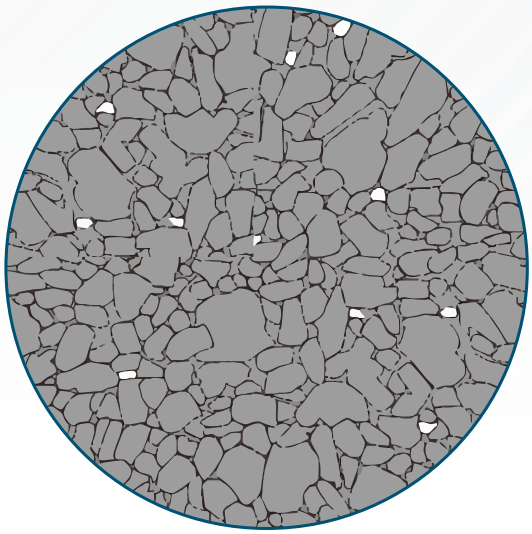
800 Particles Analyzed

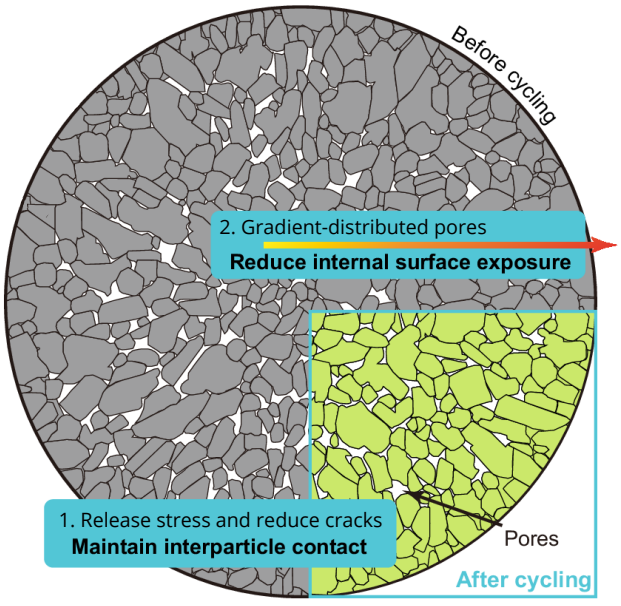
70% More Recovery Value

Damage Distribution Analysis:

Mapping crack volumes across 47 electrode layers revealed predictable damage patterns.

- Periphery regions: 9.5% crack volume (highest stress zones)
- Center regions: 8.5% crack volume (moderate degradation)
- Pristine baseline: 7.5% crack volume (manufacturing damage)





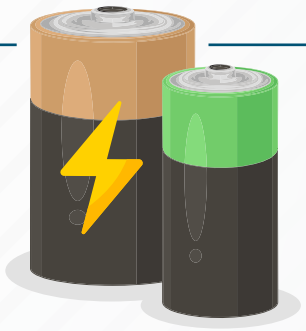
Smart Recycling Strategy:

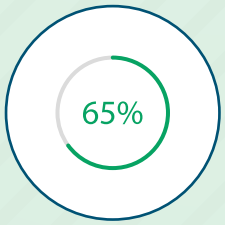
- Direct reuse for stationary storage: cells with <9% average cracking retain 90% capacity at low rates
- Targeted healing for high-value recovery: morphology restoration techniques for premium cathodes
- Location-based automated sorting: use damage maps to stream materials efficiently

Case Study 3: Fast Charging Electrode Design

Dual-layer electrodes and laser ablation create optimized pathways for lithium transport, enabling 65% charge capacity before lithium plating risk (vs. 50% for conventional designs).

Image-based modeling validated that these architectural modifications maintain their benefits throughout the battery's life, not just at the beginning.





65% vs. 50% Threshold

Lithium Plating Shield

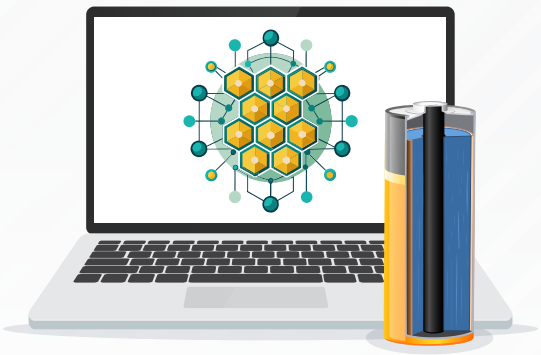
Lifetime Validation

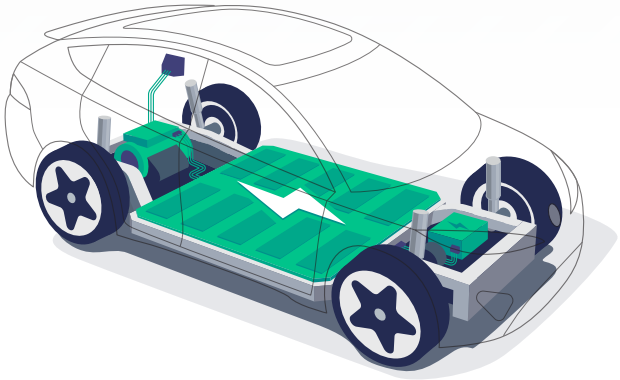
Direct Pathways

Design Innovations:

Strategic electrode modifications reduce the torturous paths lithium ions must travel, cutting charging time while preventing dangerous lithium metal formation.

- Laser ablation: straight channels reduce tortuosity by 40%
- Dual-layer coating: small particles (5 μm) over large (20 μm) for graduated current distribution
- Image-validated modeling: confirms channels remain open after 500 cycles





Performance Gains:

These structural improvements translate directly to user benefits; electric vehicles can add 100 miles of range in 10 minutes without compromising battery safety.

- 15% higher safe charging capacity before lithium plating occurs
- 30% reduction in charging time to 80% capacity
- Validated improvements persist through 1,000+ cycles

Quantitative 3D imaging transforms battery development from trial and error to data-driven design, accelerating the path to better electric vehicles and energy storage.

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Further Resources

Wiley Event: Register for free to watch the recording of:

ZEISS-Microstructural Properties and Battery Performance

For more information about Zeiss solutions, and to find the right system for your needs, please visit the Zeiss website.

ZEISS Global

Energy Materials Application