# Physics-Constrained Parameter Identification for Electrochemical Impedance Spectroscopy Modeling

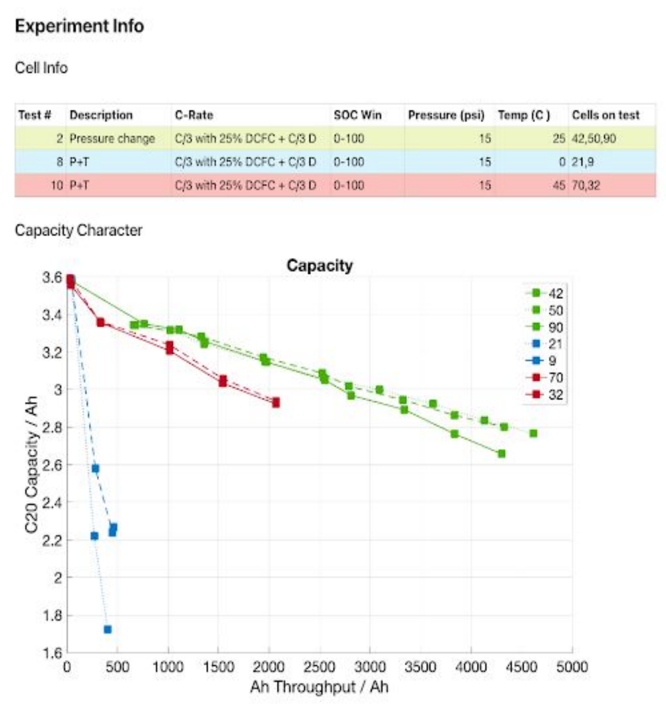
MICHIGAN ENGINEERING
ELECTRIC VEHICLE CENTER
UNIVERSITY OF MICHIGAN

Thirulok Sundar Mohan Rasu[1], Jiawei Zhang[1], Min Jae Jung[1], Jason B. Siegel[2], Ziyou Song[1]

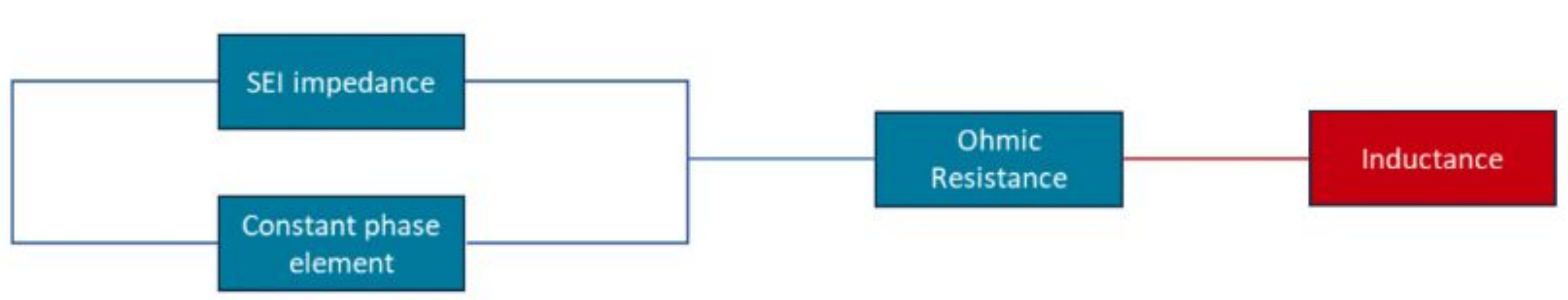
[1]Department of Electrical Engineering and Computer Science, [2]Department of Mechanical Engineering

## Overview

- **Problem:** Conventional equivalent circuit models (ECMs) for EIS fitting lack physical interpretability. Full physics models contain 20+ parameters and are too complex to solve for on-board BMS applications
- **Idea:** Hybrid model combining a physics-based transmission-line SEI impedance with compact ECM elements ($R_0$, $L_S$), fitted via physics-constrained differential evolution




## Physics-based Model Architecture




Input: frequency (roughly from 10 Hz to 10 kHz) [1]
Output: Impedance

- $Z_{SEI,I} = \frac{L_{SEI}}{a_n l_n A_n \sigma_{SEI}} + \frac{1}{a_n l_n A_n \sigma_{SEI}\sqrt{\frac{s}{D_{SEI}}}} \frac{(1-\cosh(\sqrt{\frac{s}{D_{SEI}}}L_{SEI}))}{\sinh(\sqrt{\frac{s}{D_{SEI}}}L_{SEI})}$
- $Z_{SEI} = \frac{Z_{SEI,I}}{1+sZ_{SEI,I}Z_{SEI,CPE}}$;
- $Z_{SEI,CPE} = \frac{1}{s^{n_{SEI}} Q_{SEI}}$
- $s = jw$
- Known design parameters – $a$: specific surface area, $l$: electrode thickness, $A$: electrode area
  - ✓ Unknown parameters – $L$: thickness of the SEI/CEI film; $\sigma$: conductivity of the SEI film, $D$: Diffusivity in film,
    $Q\&n$: capacitance and the factor of Constant Phase Element (CPE),
    $R_0$: ohmic resistance in series
    $L\_i$: inductance in series

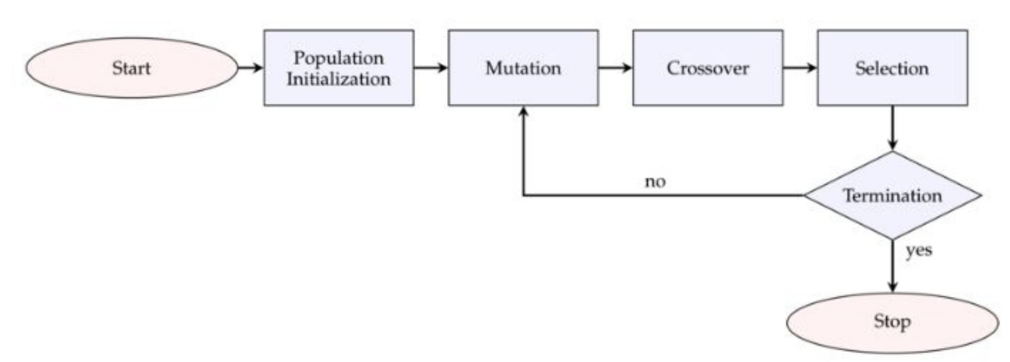
- **ECM section:** Fixed series inductance $L_S$ = 107.78 nH + ohmic resistance $R_0$
- **Physics-based section:** Transmission-line SEI impedance $Z_{SEI}$ governed by 5 physical parameters

## Methodology

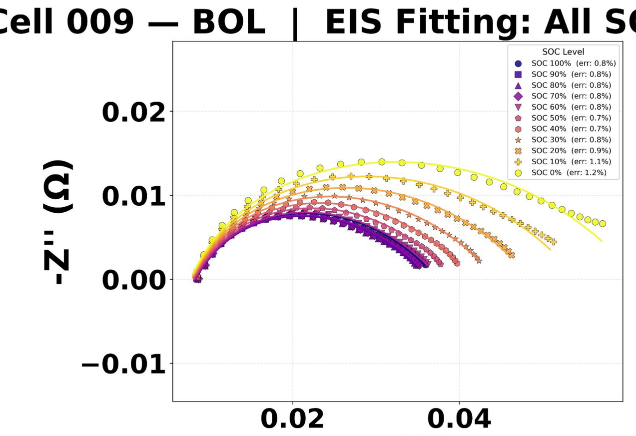
- **Cost Function Selection**
  - 5 candidates evaluated; hybrid step weighting selected
  - Highest-frequency points weighted 10×; 2× weight on imaginary component

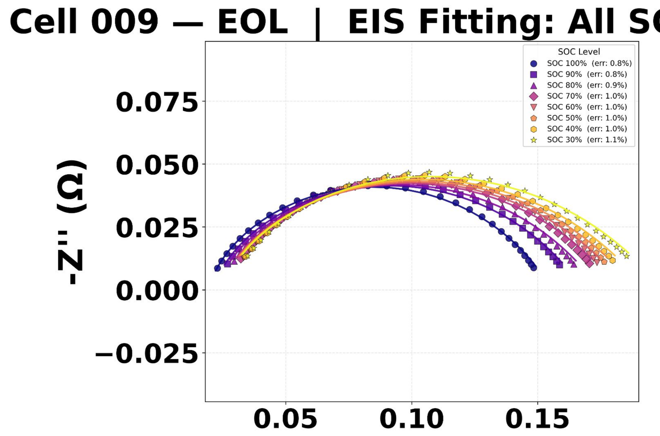
$$\mathcal{L}(\theta) = \sum_k w_k \left(Z'_{\text{exp}}(f_k) - Z'_{\text{sim}}(f_k)\right)^2 + 2\sum_k w_k \left(Z''_{\text{exp}}(f_k) - Z''_{\text{sim}}(f_k)\right)^2$$

- **Differential Evolution Optimiser**
  - Global, gradient-free optimiser: robust for the non-convex, multi-decade parameter landscape
  - Parameters spanning orders of magnitude (L, D, σ) optimised in $\log_{10}$-space
  - Local L-BFGS-B polish applied to final solution for precise convergence



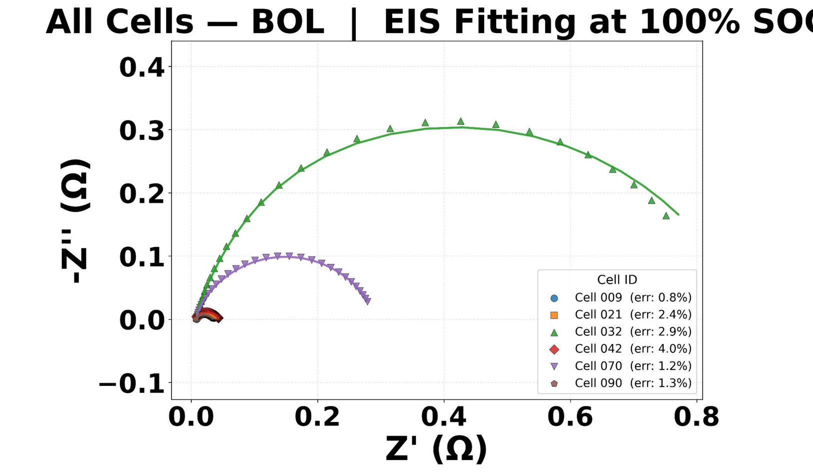

- **Multi-SOC Constraint Strategy (6 → 3 free parameters)**
  - Fit highest SOC with all 6 parameters free
  - Fix L_SEI, D_SEI, $R_0$ across remaining SOCs (material/structural i.e., SOC-invariant)
  - Allow σ, C, n to vary (transport/capacitive i.e., weakly SOC-dependent)
- **Degradation Constraints**
  - L_SEI(EOL) ≥ L_SEI(BOL): SEI grows with cycling
  - $R_0$(EOL) ≥ $R_0$(BOL): ohmic resistance increases with aging

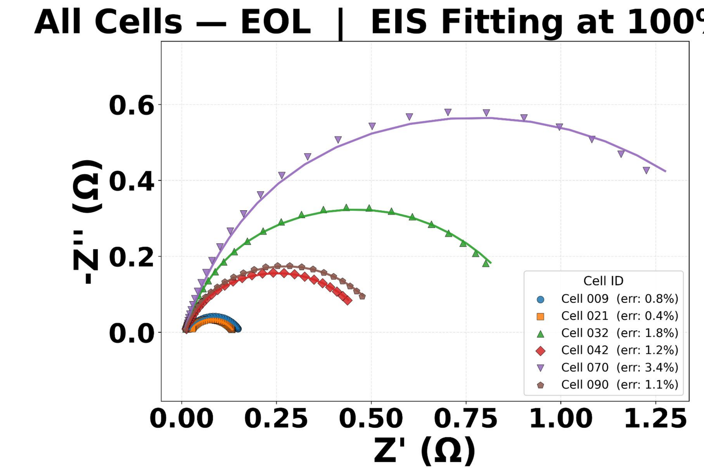


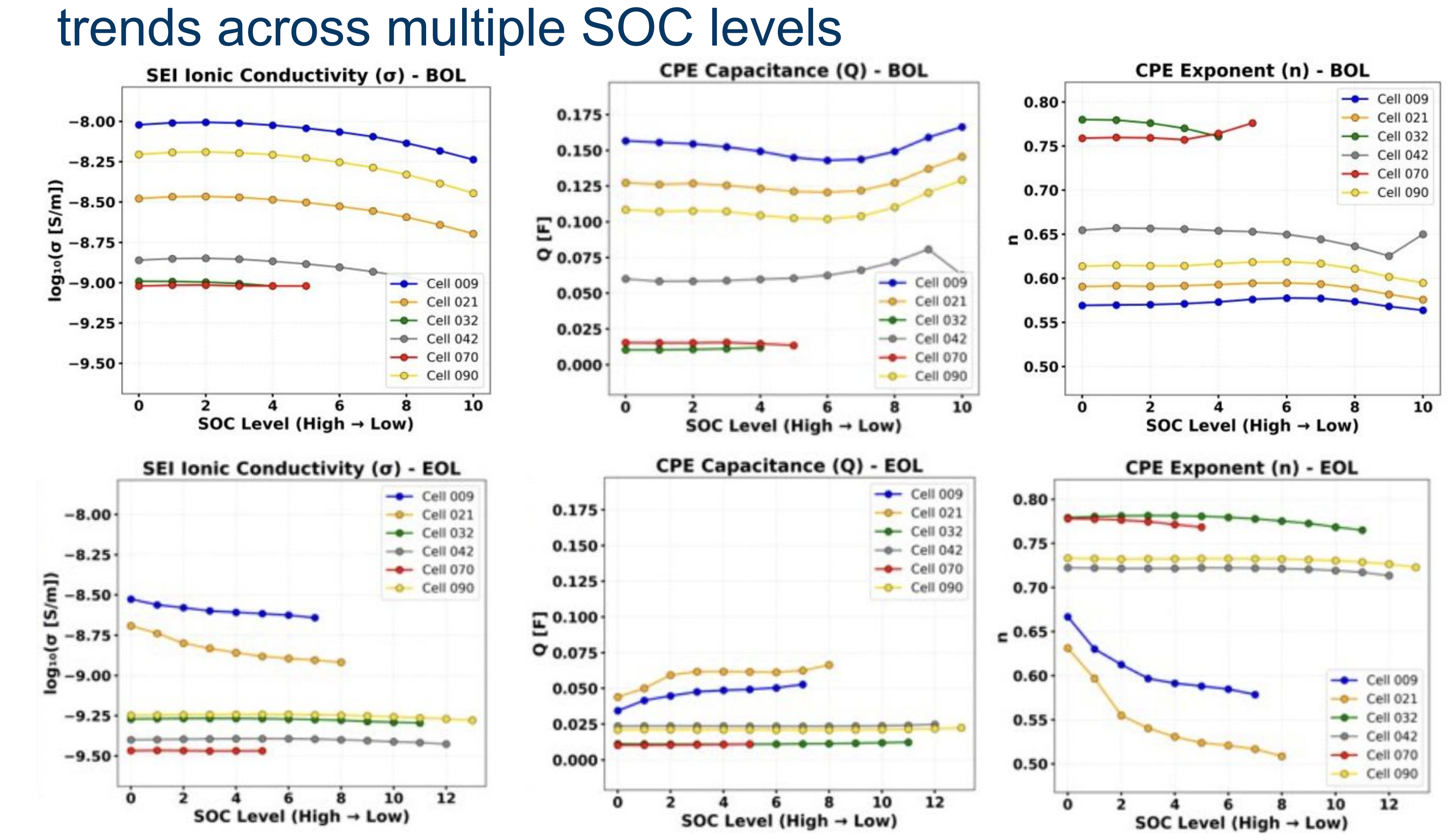

## Experimental Results

- 1.7% average MAPE over 119 EIS tests - simulations match experimental data
- 11 SOC levels fitted in 37.5 s




- Studied temperature dependence - higher temp. results in higher SEI impedance
- Studied SEI parameter sensitivity; separate parameter trends across multiple SOC levels




## Conclusions

- Hybrid physics+ECM model reproduces EIS across 6 cells × 2 SOHs × 10 SOCs with **mean 1.77% error**
- Degradation constraints (L↑, $R_0$↑) ensure **physically consistent** BOL→EOL trends in all 6 cells
- Multi-SOC constraint strategy reduces free parameters from **6 → 3**, improving efficiency and consistency
- **Future work:** extending to additional electrochemical process and combining with degradation modeling

[1] Qi Zhang, et. al, An electrochemical impedance model of lithium-ion battery for electric vehicle application, Journal of Energy Storage, Volume 50, 2022, 104182