VOLTAIQ

Enhanced COTS Cell Qualification with Electrochemical Pulsing Protocols

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Voltaiq software is **production-proven** at leading companies spanning the battery value chain:

Founded in 2012, Voltaiq pioneered the battery intelligence category, and remains the leader in battery quality analytics software today. Our robust solution and world-class team of battery experts is ready to help accelerate our customers to success.

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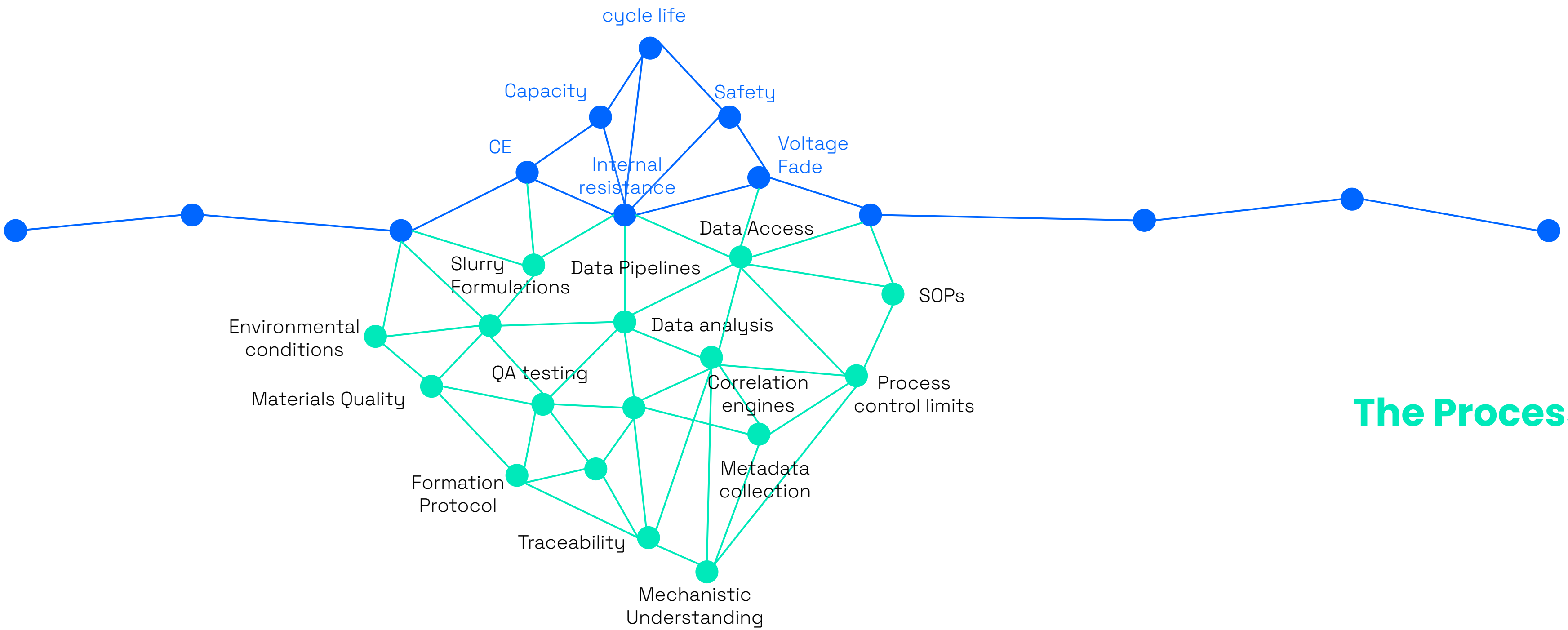
Logos reflect a selection of Voltaiq customers and partners

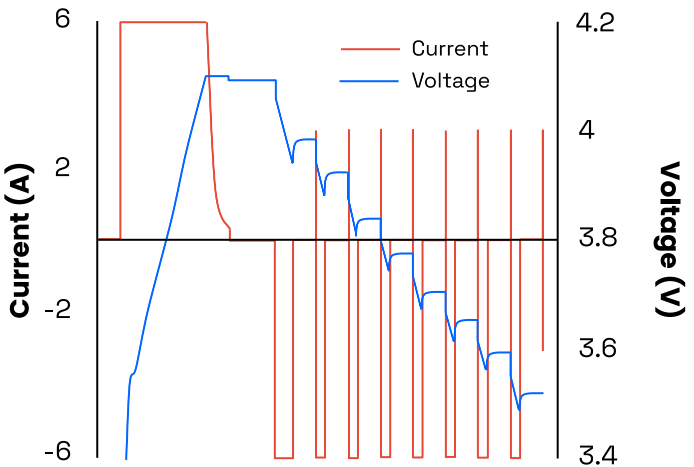
The Battery Iceberg: Performance or Process

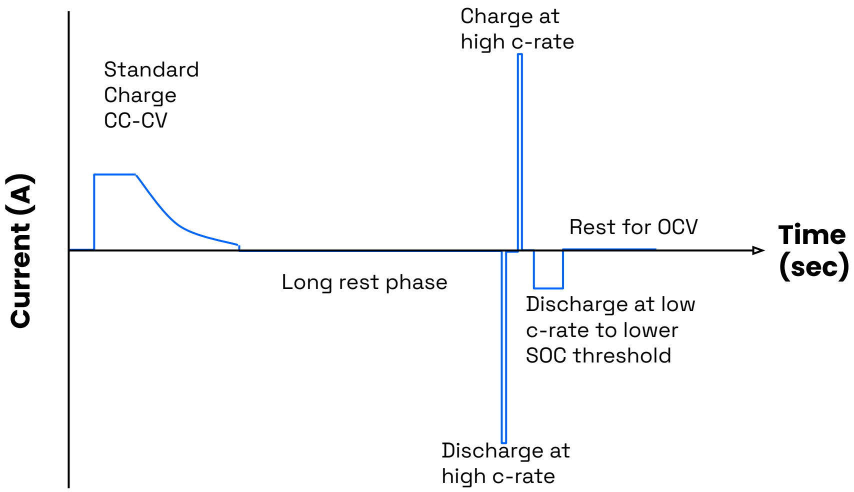
The Performance



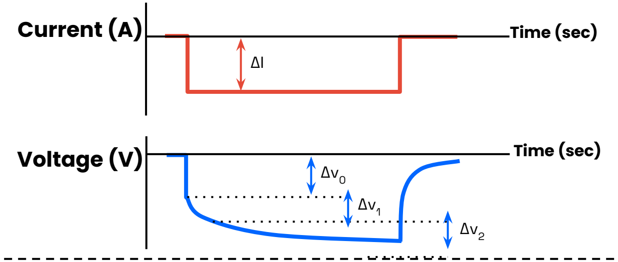
The Process

HPPC lacks connection to fundamental phenomena

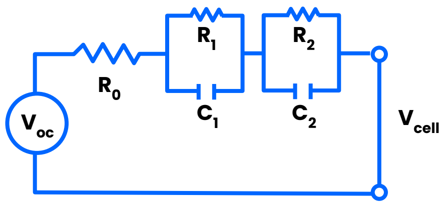




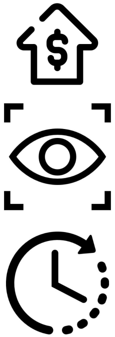
Analyzing HPPC data via Equivalent circuit



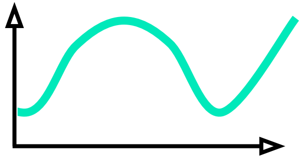
$R_x = \Delta v_x / \Delta I$



EIS complements DC pulsing, but is expensive and hard to scale

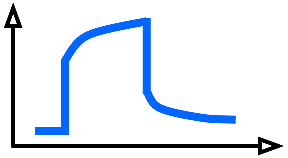


Electrochemical Impedance Spectroscopy

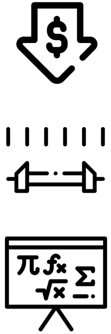


- **Uses alternating current** and frequency response analyzer
- Empirical analysis established
- Clearly **separates out time dependent phenomena**
- Testing at different voltages difficult
- Must be used **only at small currents**

Pulse Testing

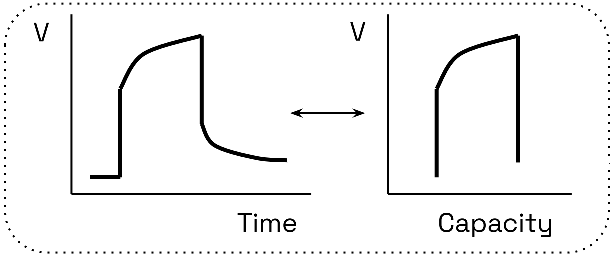


- Uses direct current and no special equipment
- Empirical analysis not obvious
- Does not clearly separate out time dependant phenomena
- Can test a range of currents
- Testing at different voltages is straightforward



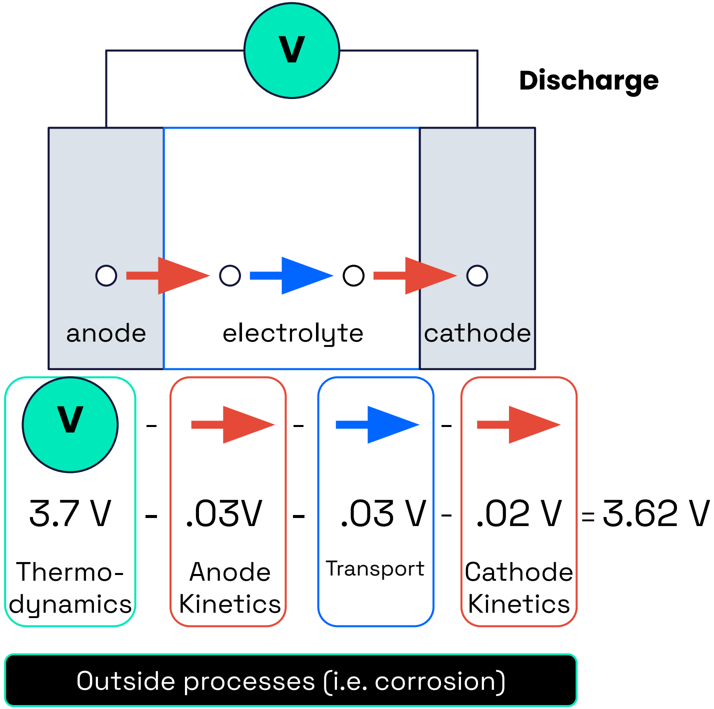
Voltage changes inform us of fundamental phenomena

Thermodynamics, kinetics, and transport



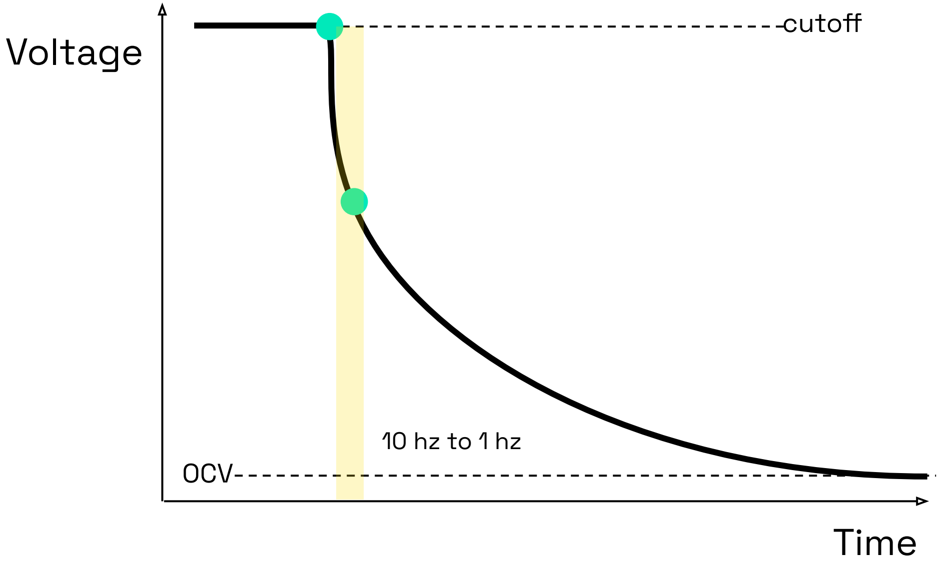
Voltage can change due to:

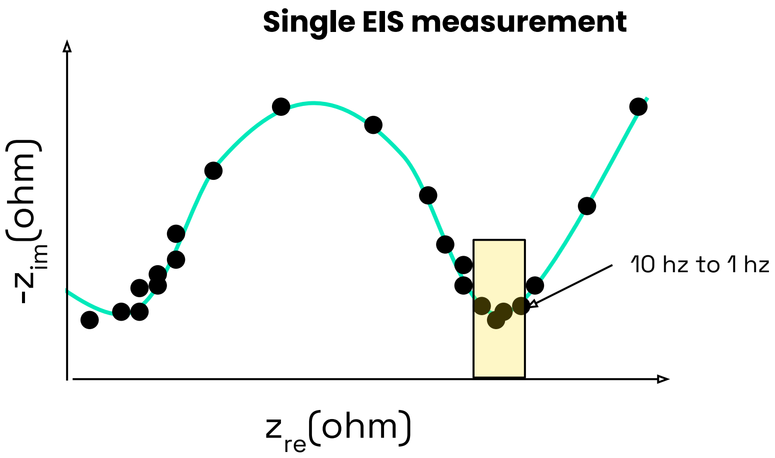
1. Changes in standard electrode potential
2. Anode kinetics
3. Transport phenomena
4. Cathode kinetics
5. Outside processes



Wood, K.N. *Battery Science and Technology*, In process

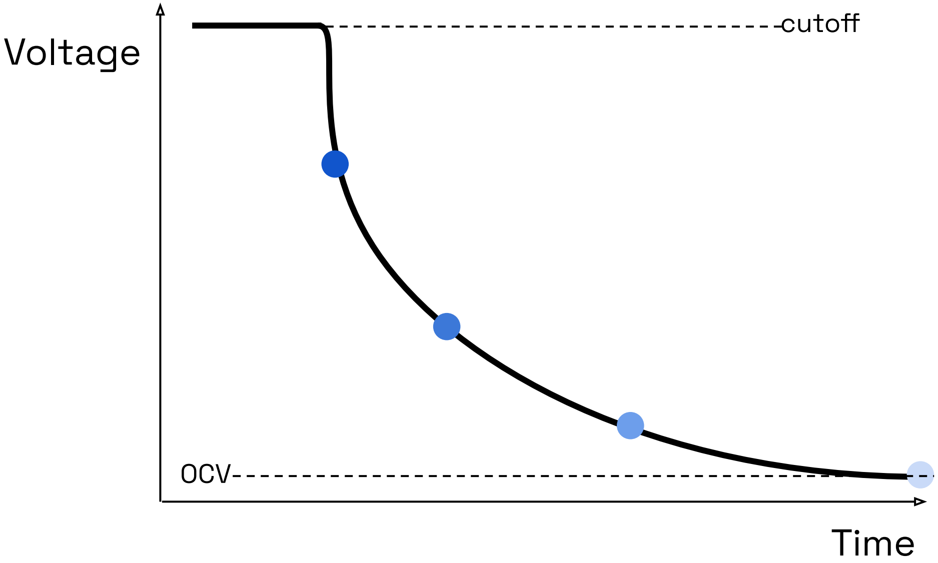
Kinetics account for initial change after current interruption

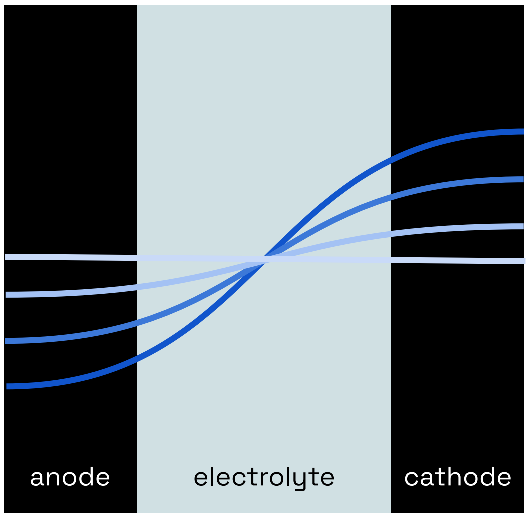




- Some potential must be sacrificed at each electrode to move an ion from electrolyte to electrode
- This potential change is removed after the current is removed

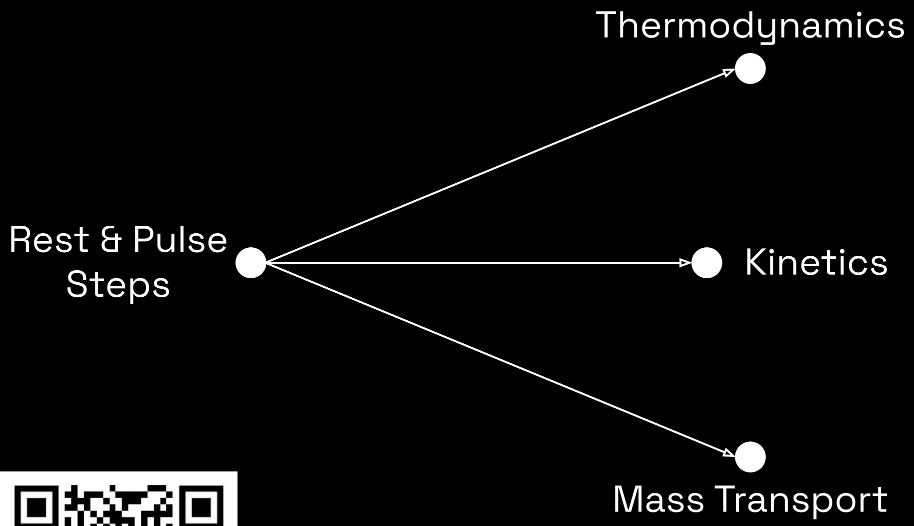
Transport accounts for change after initial drop

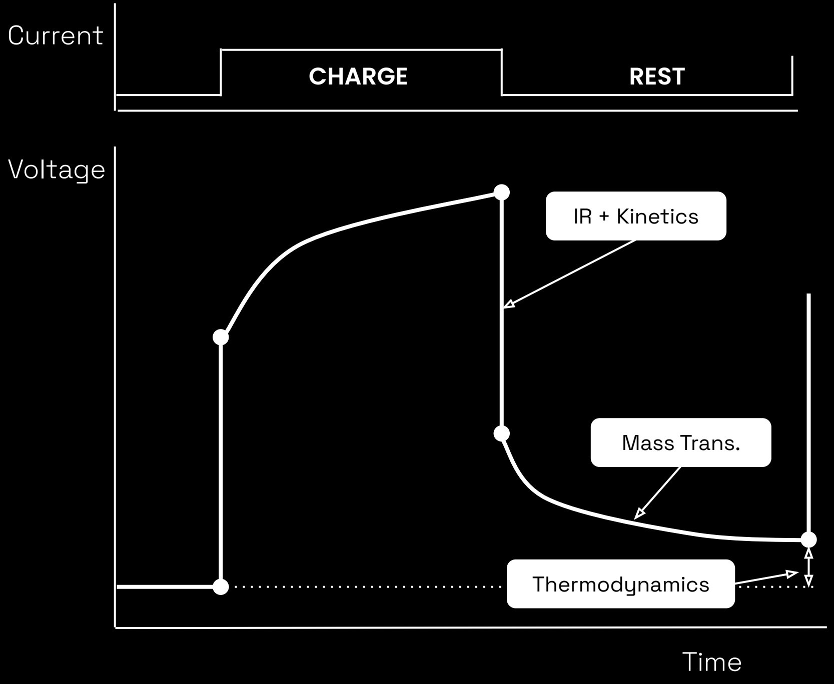




- After current perturbations are removed Li-ions can move back to equilibrium
- The change in concentration affects cell voltage

A better way towards mechanistic understanding





<u>The pulse</u> is not new but the *ANALYSIS and STRUCTURE is...*

K. N. Wood, W. B. Hawley, G. Less, J. Gallegos, J. Electrochem. Soc. 171 (2024) 080501.

APP enables efficient gathering of maximal information

Capacity-Controlled Pulses

Allows for constant dQ step in s-DQDV

Multiple Currents

Allows for fitting to Butler-Volmer kinetics, understanding how resistance shifts with current

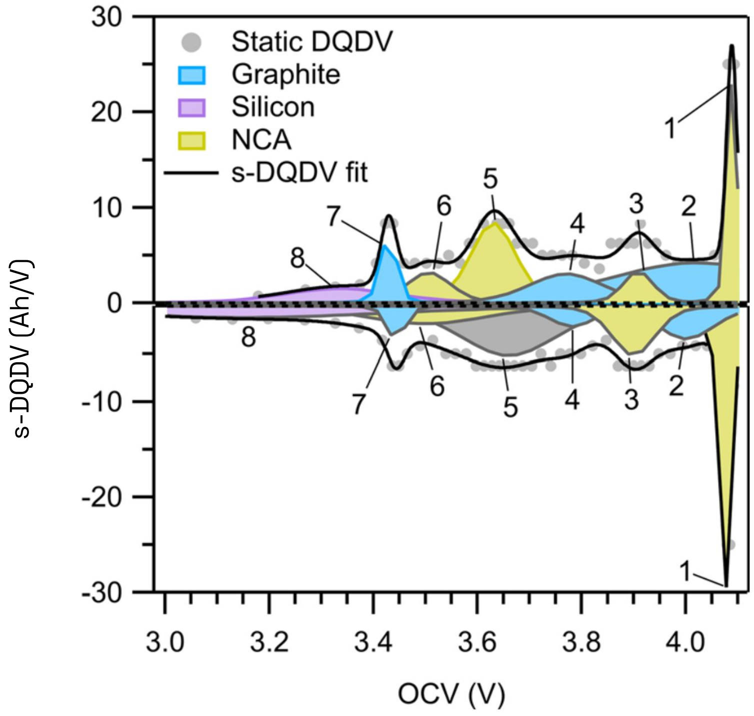
Optimized Sampling

High-frequency sampling during pulse and immediately after interruption, low-frequency elsewhere

dV/dt End Condition for Rest

Avoids unnecessarily long rest times when cell has already reached equilibrium

s-DQDV with Gaussian fit, dQ/dV half cell data for full mapping



Feature	Peak 1	Peak 2	Peak 4	Peak 5	Peak 8
Voltage Position Charge (V)	4.09	4.02	3.77	3.63	3.34
Voltage Position Discharge (V)	4.08	4.01	3.78	3.66	3.15
ΔG_{rxn} (kJ/mol)	-394.5	-387.9	-363.7	-350.3	-321.8
Dominant Cathode Rxn	H2 <> H3	H2	M	H1 <> M	H1
Dominant Anode Rxn	Stage II <> Stage I	Stage II <> Stage I	Stage IIL <> Stage II	Stage IIL <> Stage II	Si

$$\Delta G_{rxn} = -nFV_{peak}$$

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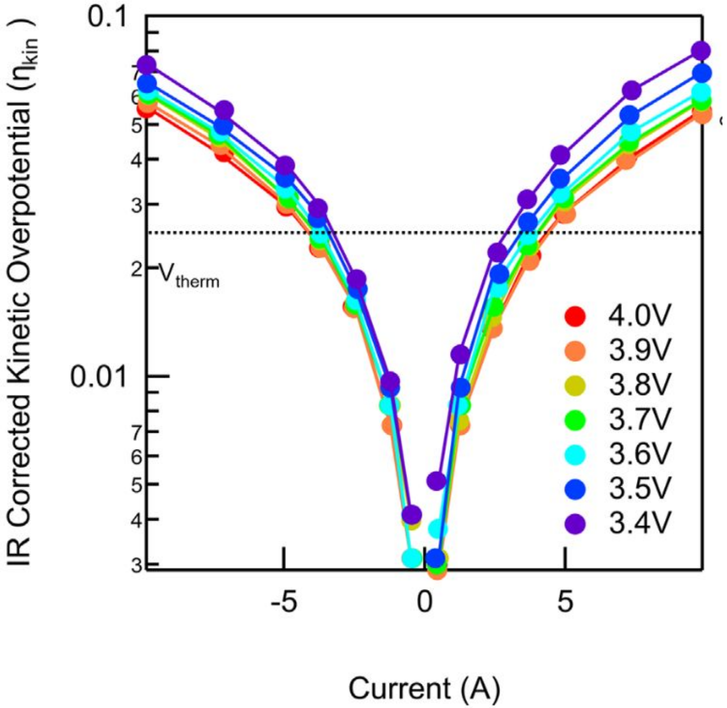
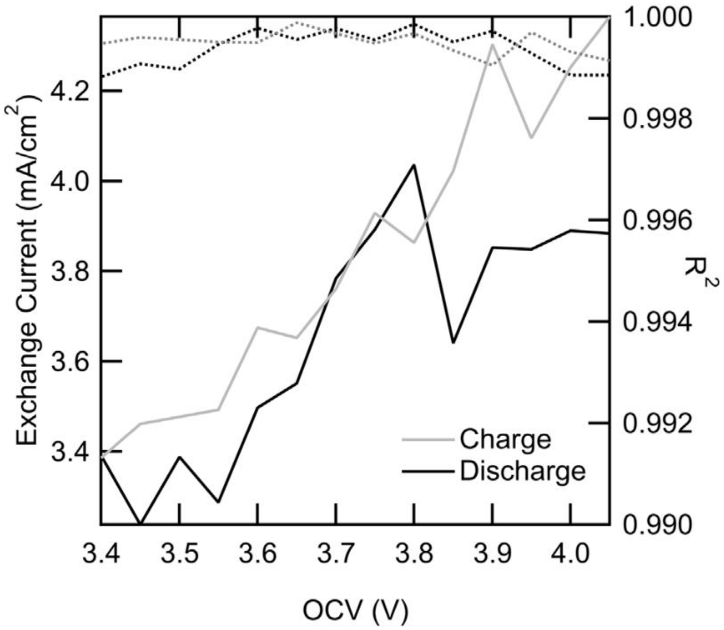
Pulsing unlocks non-linear Butler-Volmer kinetics





$$j = j_0\left[Ae^{\frac{(1-\alpha)nF\eta_{kin}}{RT}} - Be^{\frac{\alpha nF\eta_{kin}}{RT}}\right]$$

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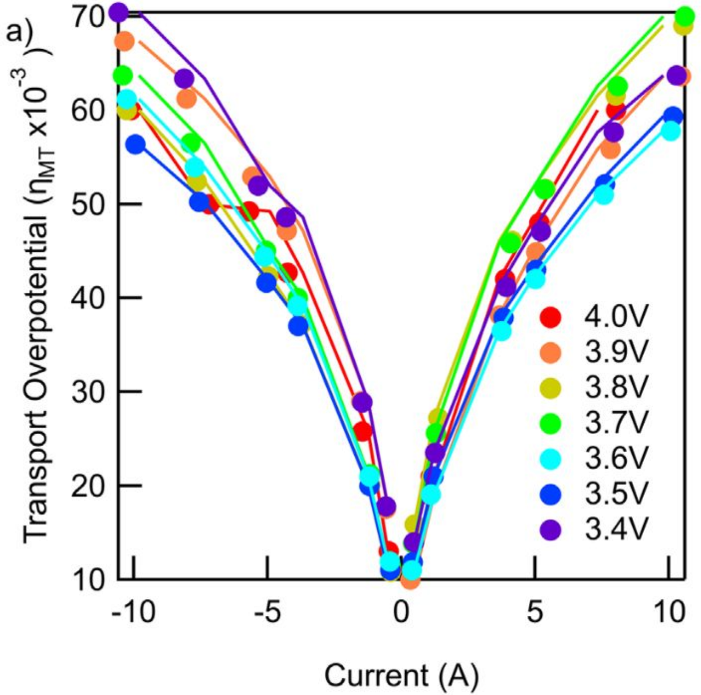
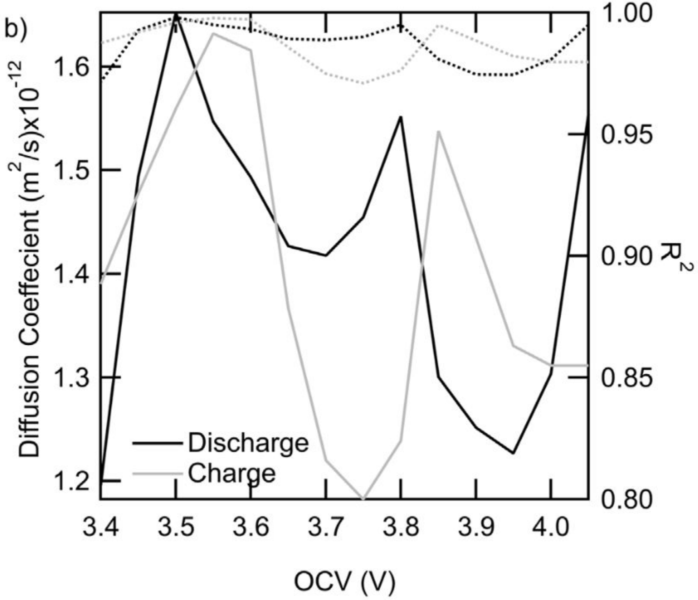
Crossover in diffusion coefficient correlate with phase changes





$$j = \frac{Cz^2F^2}{2RT}\sqrt{\frac{nD}{t}}\eta_{mt}$$

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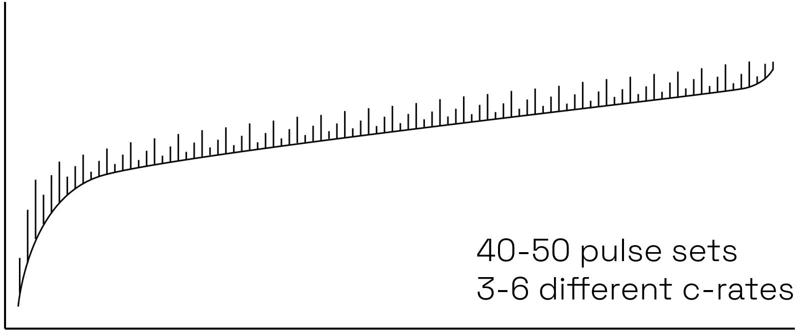
APPs for Cell Qualification or Rapid Benchmarking

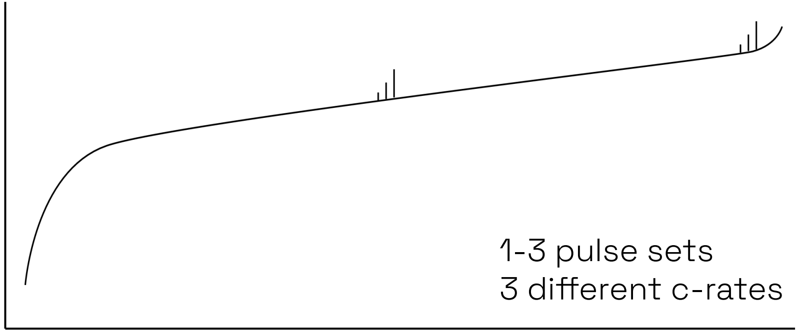
Analytical Pulsing Profiles (APPs) can be adapted to time and data constraints to provide full mechanistic insight

Cell Qualification



- Graphical Analysis
- Cell level mechanistic information
- Understanding of chemistry and process

Rapid Benchmarking



- Device level information
- Identify outliers mechanistically
- Understand process deviations

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Thank you!

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