



SOF recovery under real-world driving conditions

ALBA Plus Webinar 1

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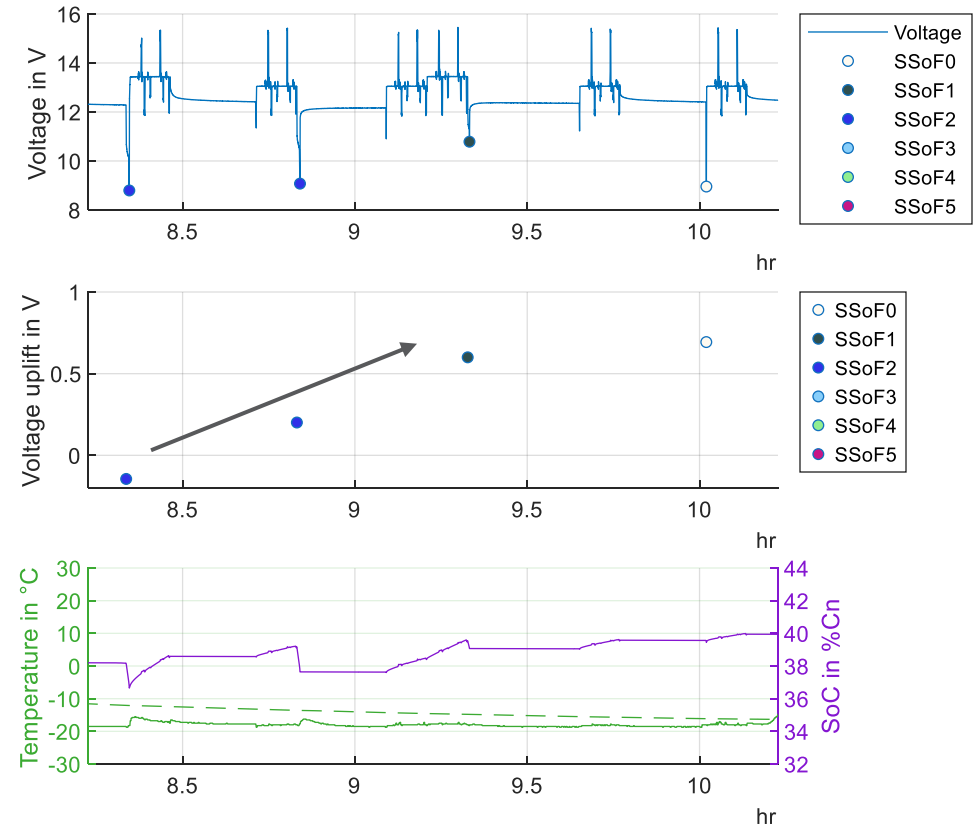
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ALBA Plus – Project motivation

- Industry relevance
 - Fast recovery of State-of-Function (SoF) is key for customer satisfaction
 - Extensive drive-cycle data available from the CBI SSoF working group
- Customer benefit
 - Provide evidence of robust SoF recovery of lead batteries in real-world usage
 - Enable OEMs to restore full vehicle functionality early during the trip
 - Demonstrate the advantage of lead batteries for functional safety in winter
- Project funding
 - CBI 2026

X23072809 | BEV3

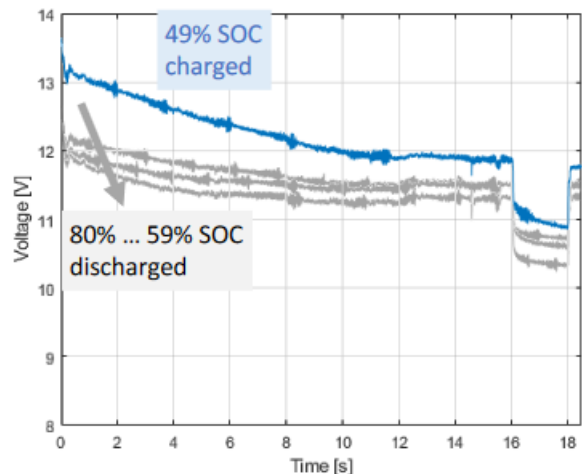
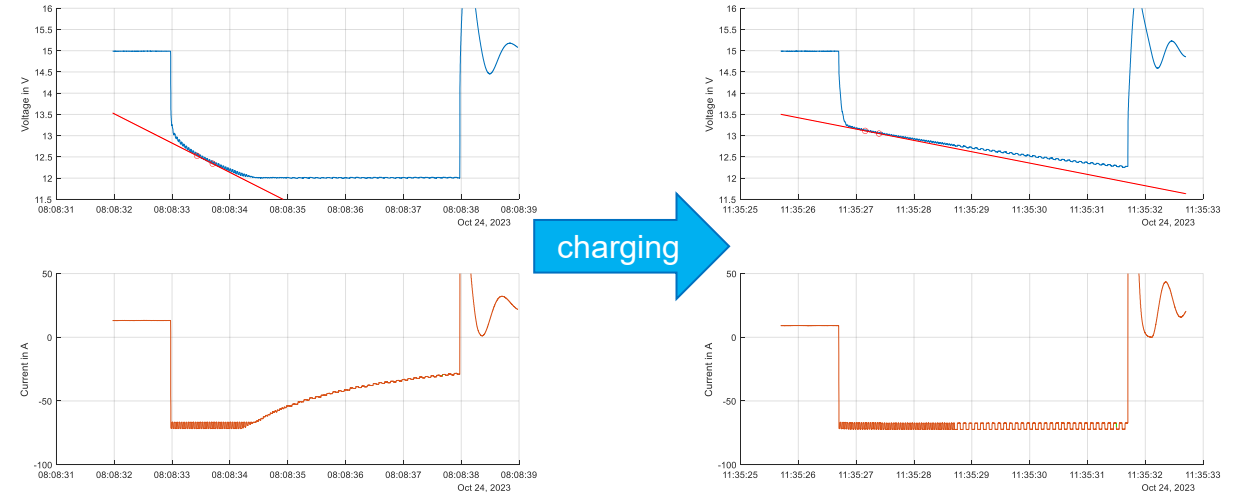


SSoF recovery out of charging condition

Batteries are sized to guarantee safety-critical pulse power even at low SoC and cold temperature. If we only account for the **static SoC effect** when charging, we lose availability in these challenging conditions.

Two effects accelerate transient recovery of SSoF beyond the SoC-recovery effect alone:

1. **Pseudo-capacitance** of the positive electrode building up during charging (cf. *Eberhard Meissner, ALBA 2024*)
→ Stabilizes voltage for short pulses (< 1 s)



Source: Eckhard Karden, ALBA 2024

2. **Voltage plateau uplift** compared to battery at equilibrium or freshly discharged (cf. *Grzegorz Pilatowicz, Dissertation 2017*)
→ Improves even large SSoF events on top of the SoC effect

→ During charging, SSoF recovers very fast – already within a few percent of SoC change

Outline

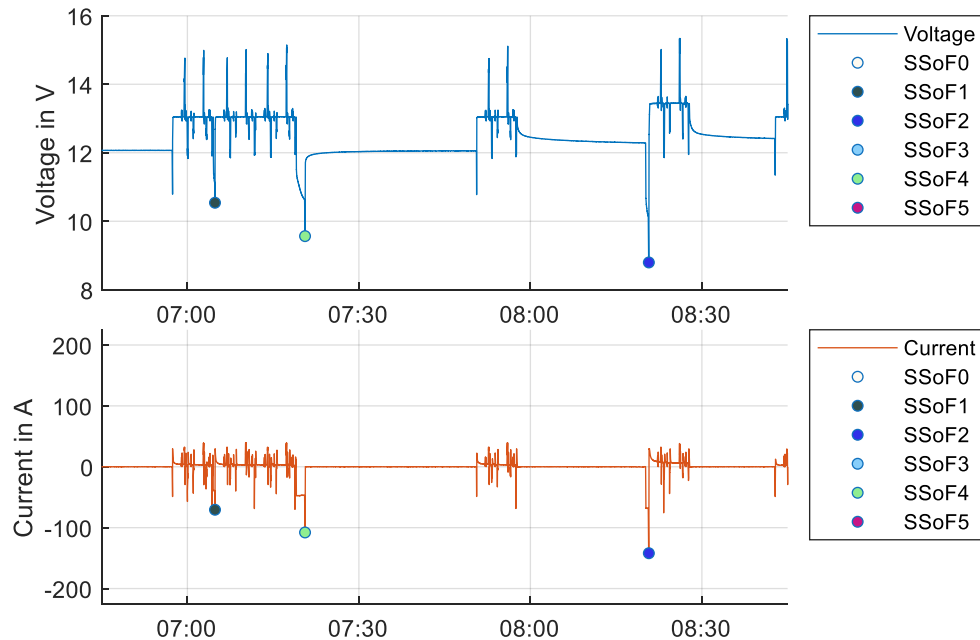
1. General approach
 - Data sets, workflow and cycles
2. Pseudo capacitance
 - Methodology
 - AGM results
 - EFB results
3. Voltage plateau uplift
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 - AGM results
 - EFB results
4. Conclusion & Outlook

Approach for this study

- Analysis of two data sets from CBI SSoF Cloud
 - Bench simulation of complex real-world driving profiles (1 kHz data recording)
 - Broad range of new & aged batteries, usage scenarios, vehicle controls, temperatures, ...
 - Stored data: 320 test days with > 3,000 SSoF events, > 50,000 large- and > 80.000 small-signal stimuli
 - This study: 2 × 13 days selected
- Fit pseudo capacitance for discharge stimuli & SSoF
- Determine voltage plateau uplift for SSoF vs. ALBA battery sizing tool

Driving cycle sequences

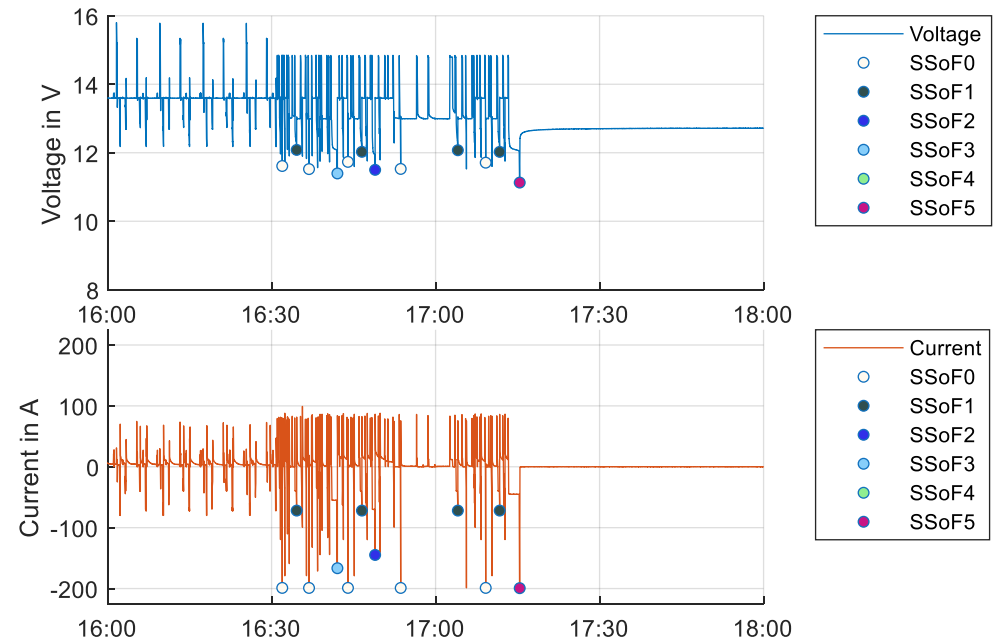
X23072809 | BEV3



- BEV sequence

- Mainly charging in trips of varying duration
- Stimuli while charging: voltage-setpoint changes (dch/cha), ripples
- SSoF events across trips, startup and afterrun events
- Usage patterns covered: sales agent, kindergarten/work commuter, eldercare, craftsperson, ...

BVe800_C1 | uHEV1

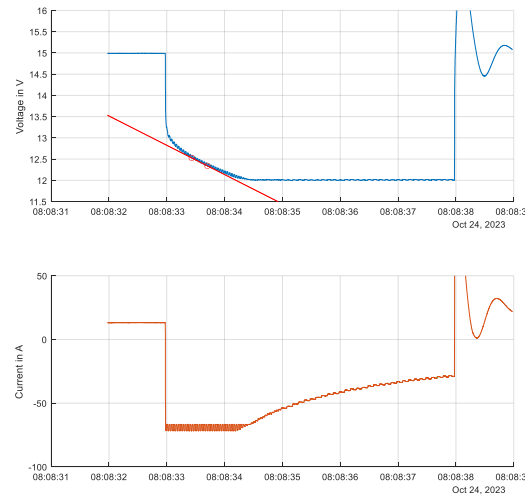


- μ HEV sequence

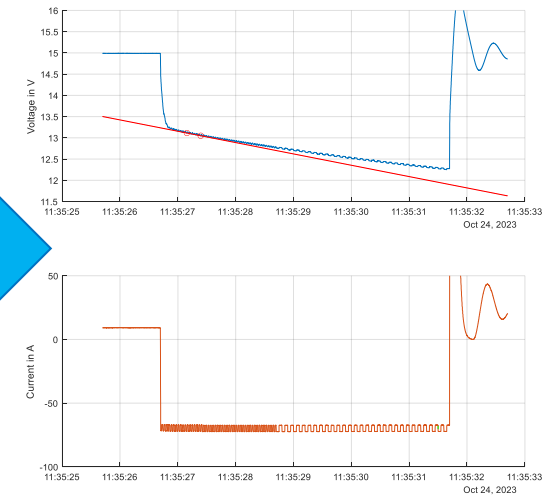
- Stop/start operation in urban parts
- Continuous charging with stimuli in extra-urban parts (as in BEV)
- SSoF events across trips, partly replacing startup/afterrun
- Similar usage patterns covered as in BEV sequence

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charging

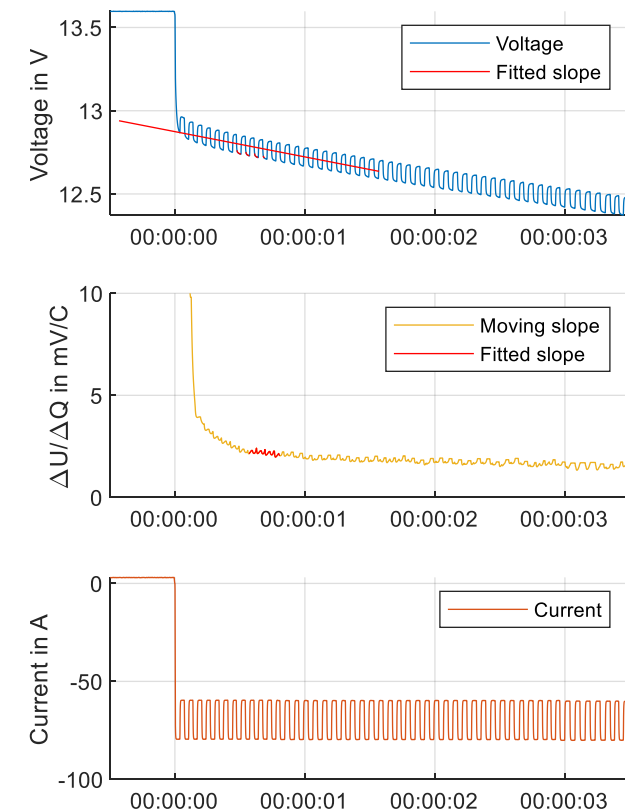


Methodology for pseudo capacitance fitting

- Fit of voltage slope over a moving window (0.24 As/Ah normalized to C_n)
 - Events with ripples, high current parts are used (low current parts yield same results)
 - Fast transients at beginning of discharge are ignored (0.45 As/Ah normalized to C_n)
- Mean value of first “valid” window is taken to calculate equivalent C_{pseudo} (~ to $1/(\Delta U/\Delta Q)$)
 - ⚠ With falling voltage, main reaction takes over lowering the voltage slope, eventually leading to erroneously high C_{pseudo} values → higher risk at low SoC and after discharge

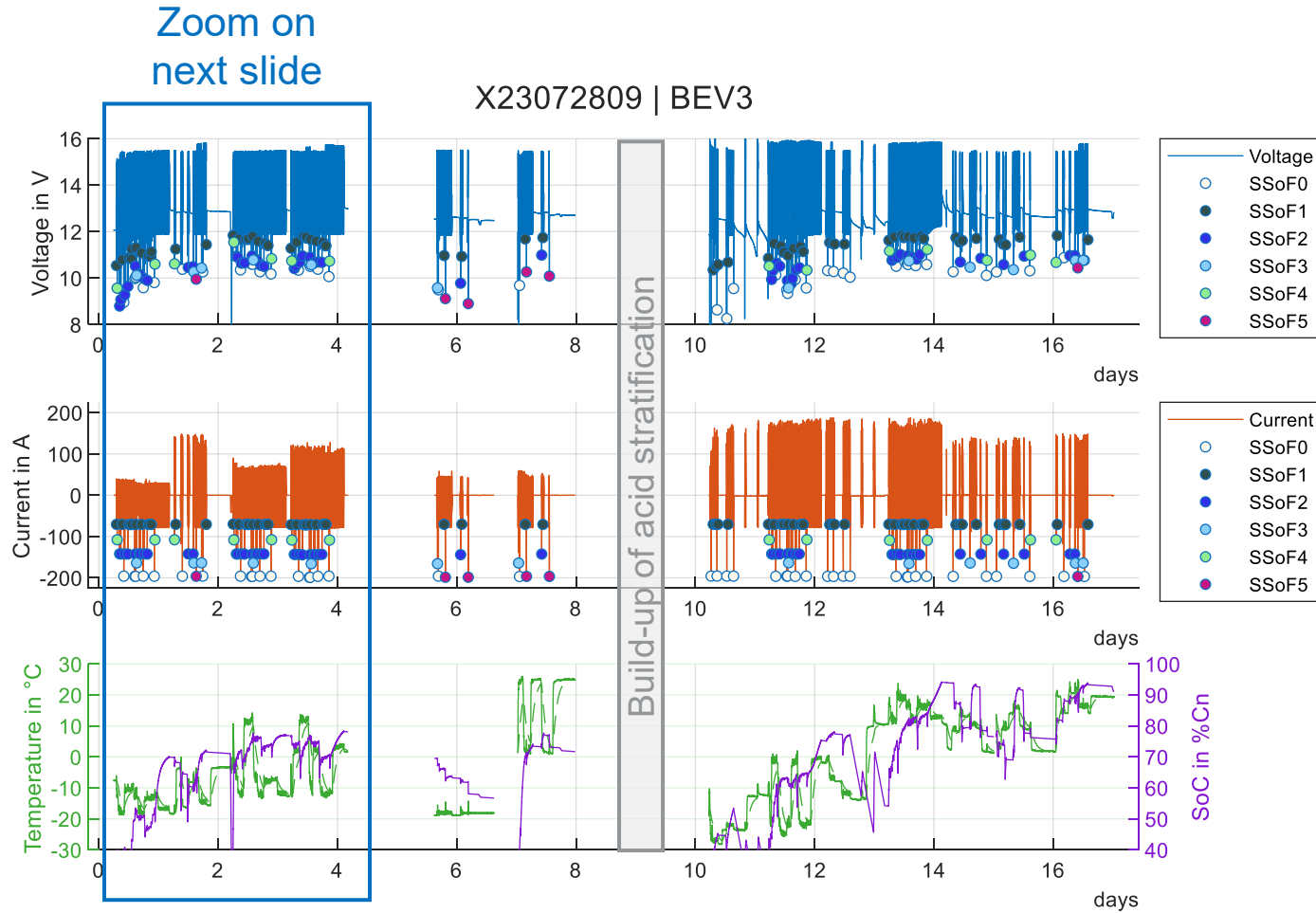
Event name	Step 1	Step 2
dch_step1	~70 A/12.0 V for 5+ s	---
dch_step3	~30 A/12.7 V for 5+ s	---
SSoF0	200 A for 1 s	---
SSoF1	40 A for 18 s	72 A for 1 s
SSoF2	70 A for 30 s	145 A for 3 s
SSoF3	55 A for 55 s	167 A for 5 s
SSoF4	48 A for 90 s	110 A for 3 s
SSoF5	45 A for 118 s	200 A for 5 s

Example dch_step1 C_{pseudo} fitting



BEV3 sequence on AGM battery

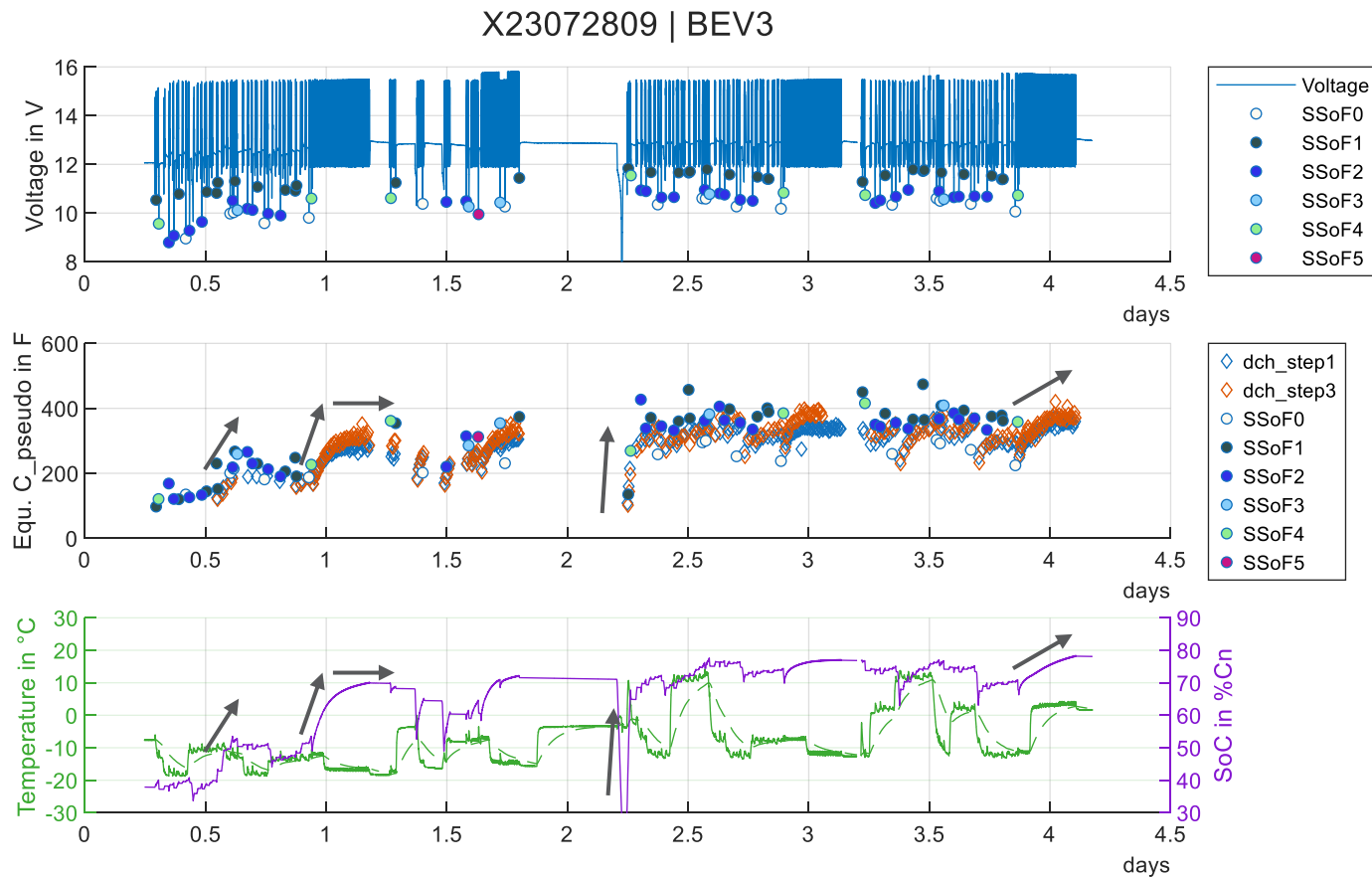
Overview



- Driving cycle sequence on an aged AGM B24 45 Ah battery
- Battery suspected to have internal soft shorts
- Temperature range: -25 to 25 °C
- SoC range: 25% to 95%
- Stratification procedure not expected to strongly effect an AGM battery

BEV3 sequence on AGM battery

Pseudo capacitance for first days

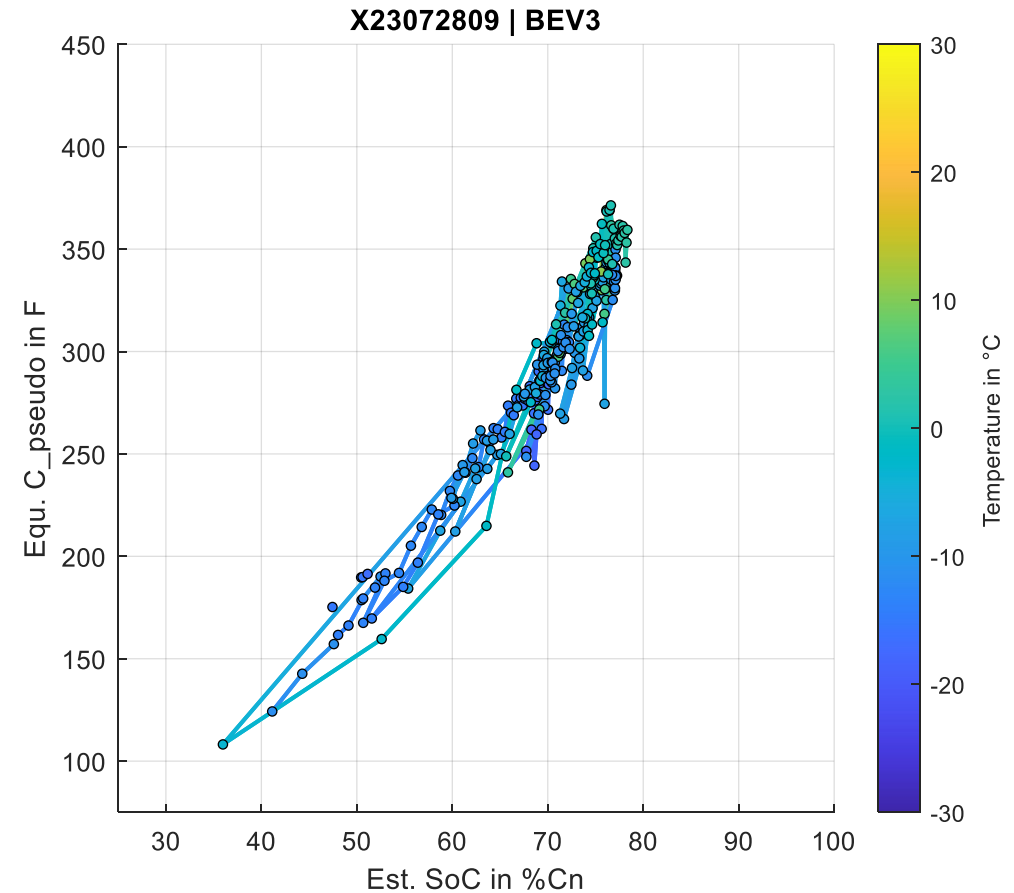


- Pseudo capacitance starts at relatively low value of 100 F and raises with SoC increase
- Its shape closely follows the SoC
- Different events (dch steps, SSoF) give very similar values

BEV3 sequence on AGM battery

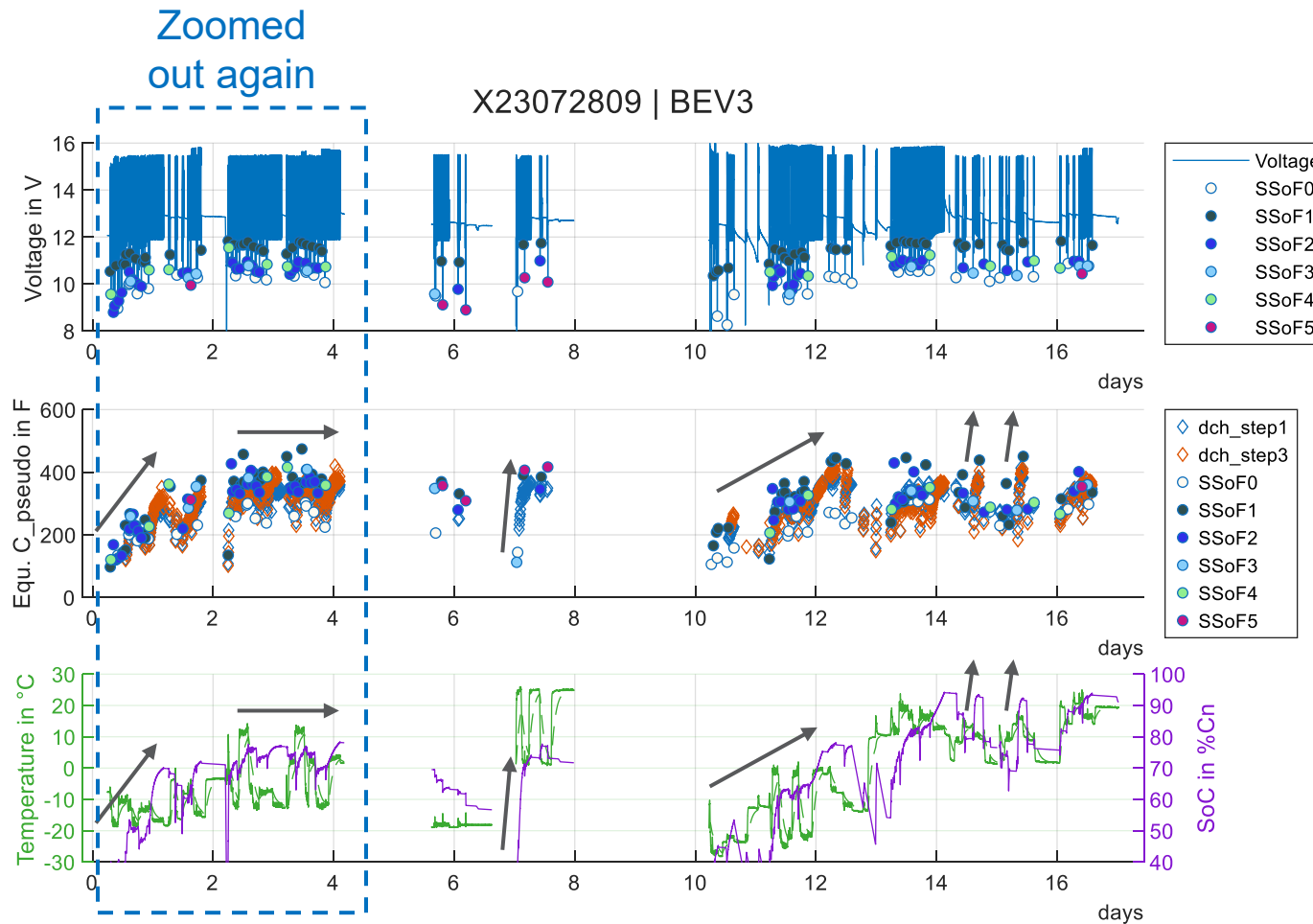
Pseudo capacitance over SoC – first days

- Plot shows pseudo capacitance for dch_step1 only
- Strong correlation between pseudo capacitance and SoC in time-series plot is also visible in correlation plot



BEV3 sequence on AGM battery

Pseudo capacitance for whole sequence

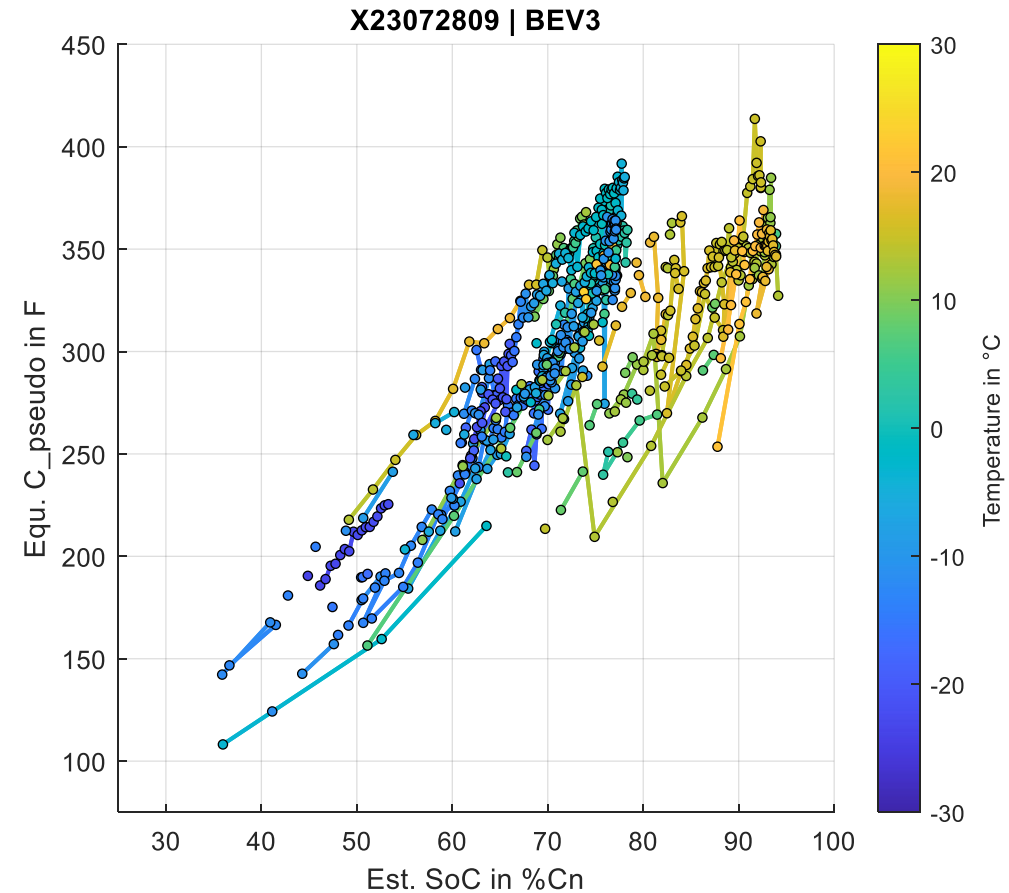


- On larger scale, strong correlation holds over the whole sequence
- In last days SoC keeps rising while pseudo capacitance remains stable

BEV3 sequence on AGM battery

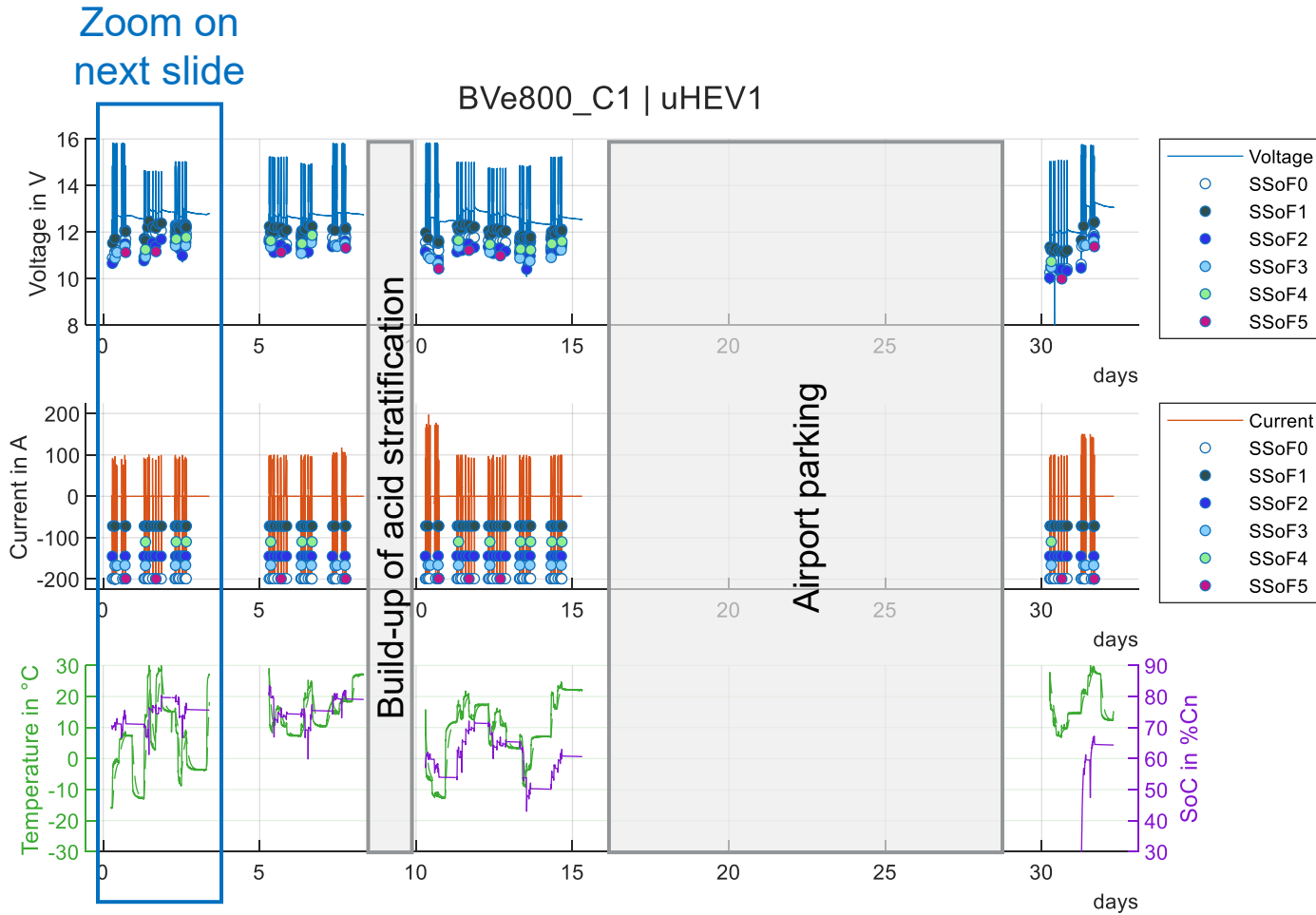
Pseudo capacitance over SoC – whole sequence

- Strong correlation between pseudo capacitance and SoC remains visible over the whole sequence
- Temperature does not seem to have a strong influence on steepness of the curve but probably on chargeability
- Last days are visible as a shift to higher SoC but not higher pseudo capacitance, indicating that charging history might be more influencing than the absolute SoC



μHEV1 sequence on EFB battery

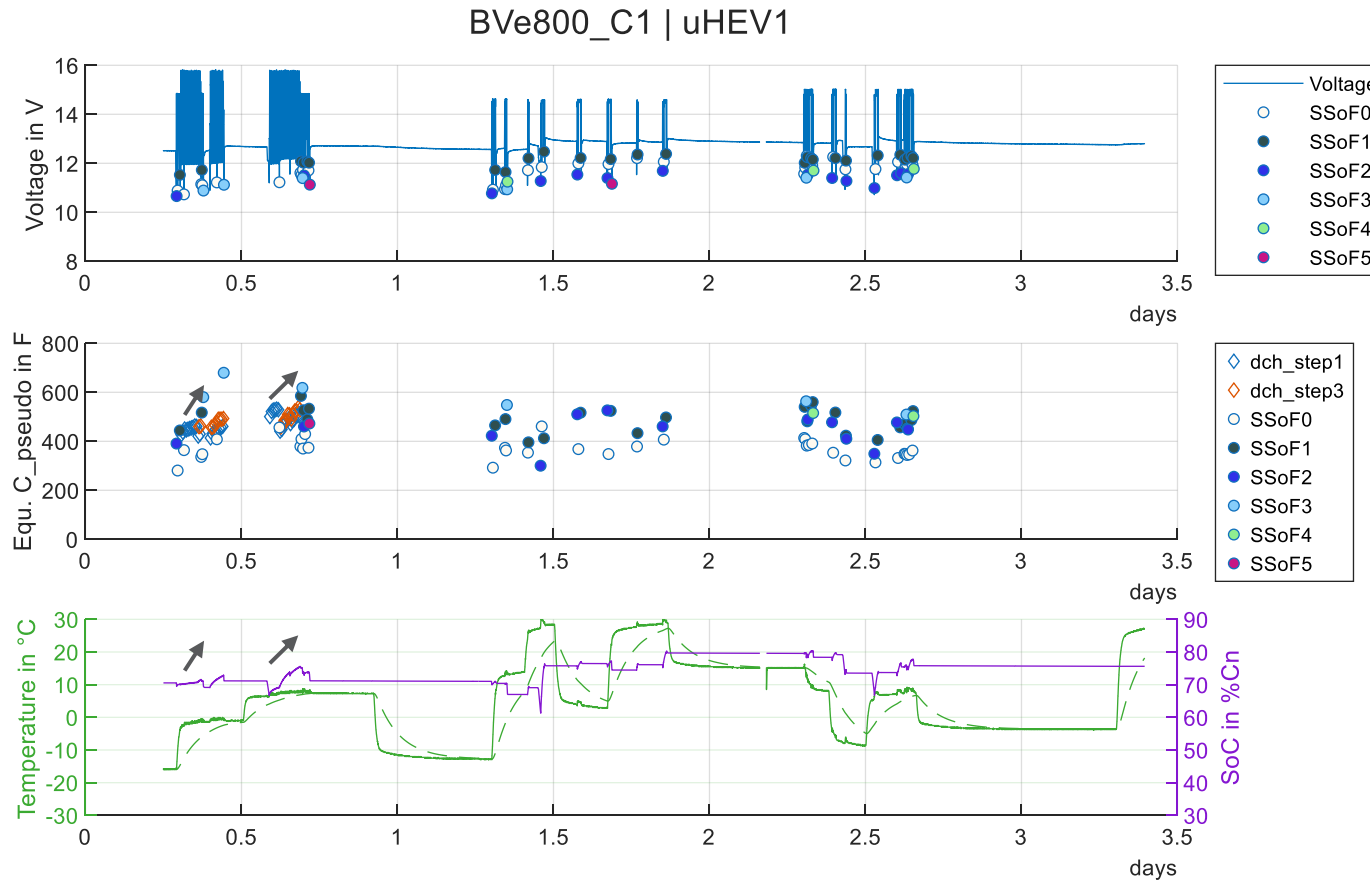
Overview



- Driving cycle sequence on new EFB LN3 70 Ah battery
- Temperature range: -15 to 30 °C
- SoC range: 5% to 80% SoC
 - Intended airport parking discharge ~25%
 - Possible higher load due to connected measurement equipment

μHEV1 sequence on EFB battery

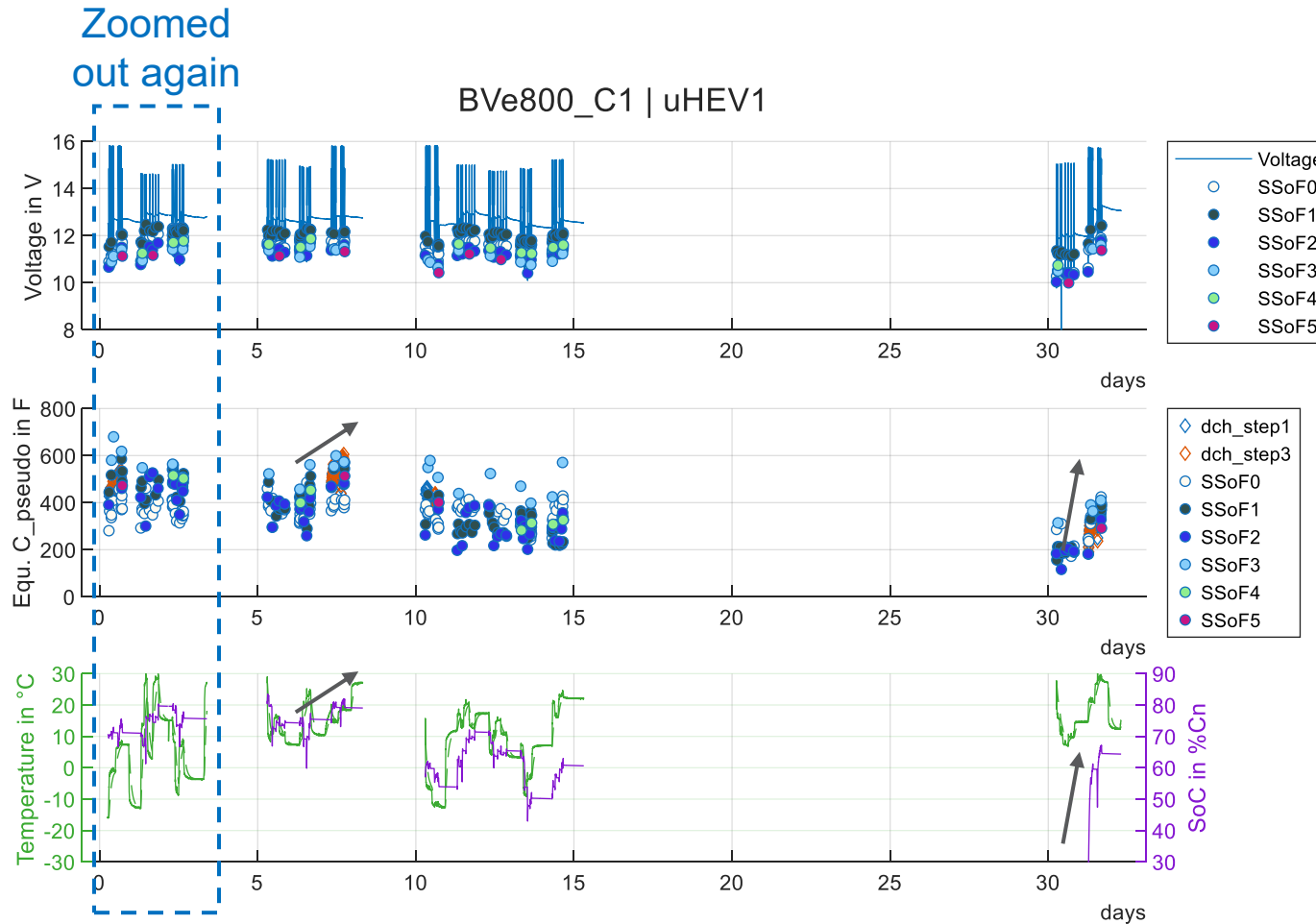
Pseudo capacitance for first days



- Pseudo capacitance starts higher than AGM in BEV3 cycle
- It follows small SoC changes in extra-urban (charging) parts
- Pseudo capacitances calculated for SSoF show higher variation in urban parts due to varying history
 - Stop/start events few seconds before
 - Part of stop/start as cranking
 - Used as part of vehicle startup or afterrun
- SSoF events might be filtered by conditions just before the pulse

μHEV1 sequence on EFB battery

Pseudo capacitance for whole sequence

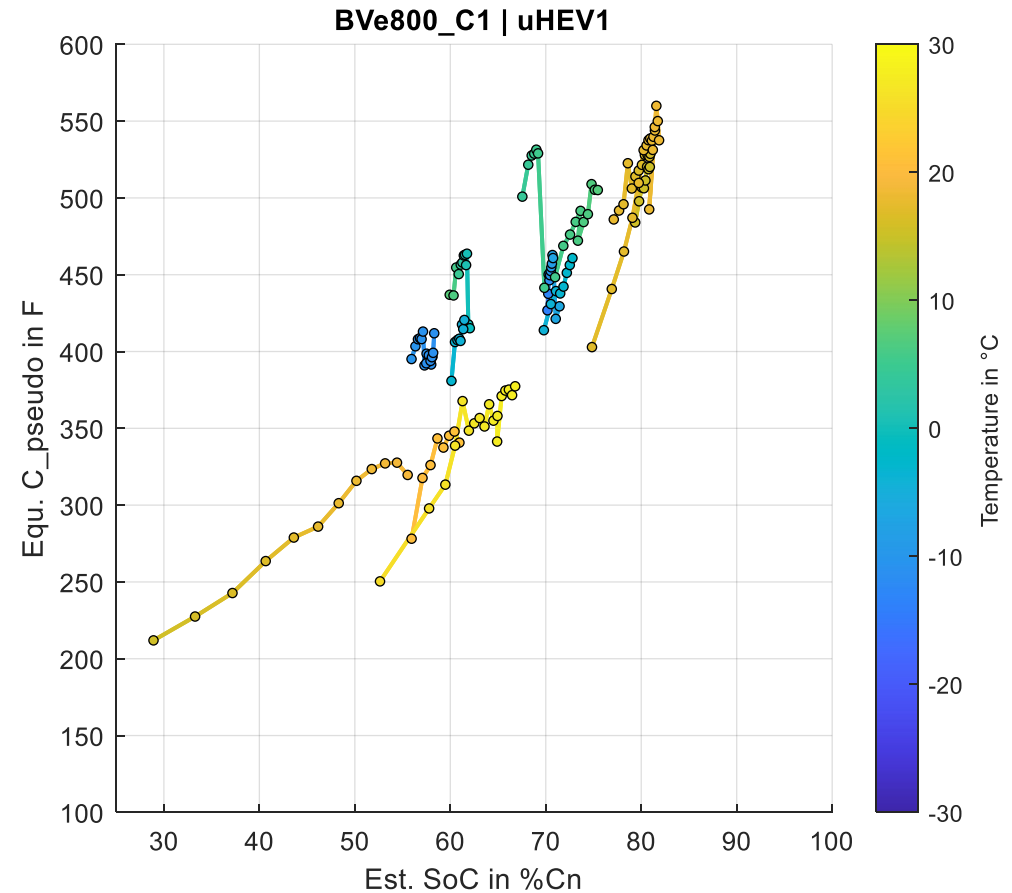


- On larger scale, pseudo capacitance still follows SoC curve in several parts with extended charging
- However, larger variances still dominating in urban parts
- Careful filtering might allow for a more sensible analysis

μHEV1 sequence on EFB battery

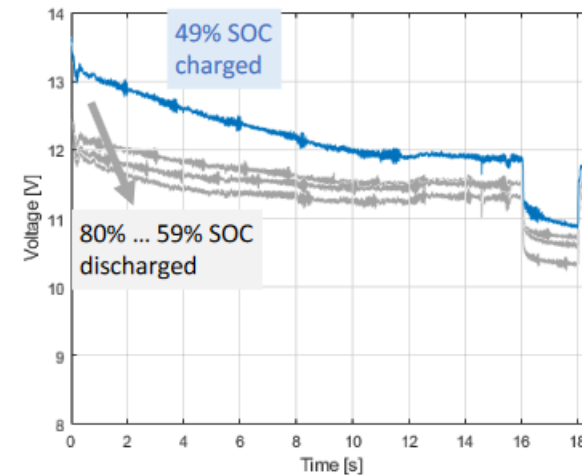
Pseudo capacitance over SoC – whole sequence

- Plot shows pseudo capacitance for dch_step1 only (in extra-urban parts)
- Strong correlation between pseudo capacitance and SoC clearly present for EFB battery, like for AGM battery in BEV3 cycle



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Source: Eckhard Karden, ALBA 2024

Methodology for voltage plateau uplift determination

- Compare measured vs. predicted SSoF end voltages
 - ALBA battery sizing tool, based on IEC 60095-8 Pulse Power Characterization (PPC) procedure and requirements
 - Inputs: SoC, temperature and I_{cc} rating, load profile
 - Tool assumes equilibrium after discharge → difference reflects uplift beyond the SoC effect
- SoC & temperature estimation
 - Charge balance ($\eta = 0.97$), start SoC from OCV, recalibration after long rests
 - 0 to 100% SoC : 11.5 to 13.0 V for AGM battery, 11.6 to 12.9 V for EFB battery
 - Manual adjustments for stratification where present
 - Temperature model with 1.5 h time constant
 - No self-heating from current throughput considered
- I_{cc} adjusted to actual performance at begin of sequence
 - Aged AGM 45 Ah: 330 A
 - New EFB 70Ah: 700 A

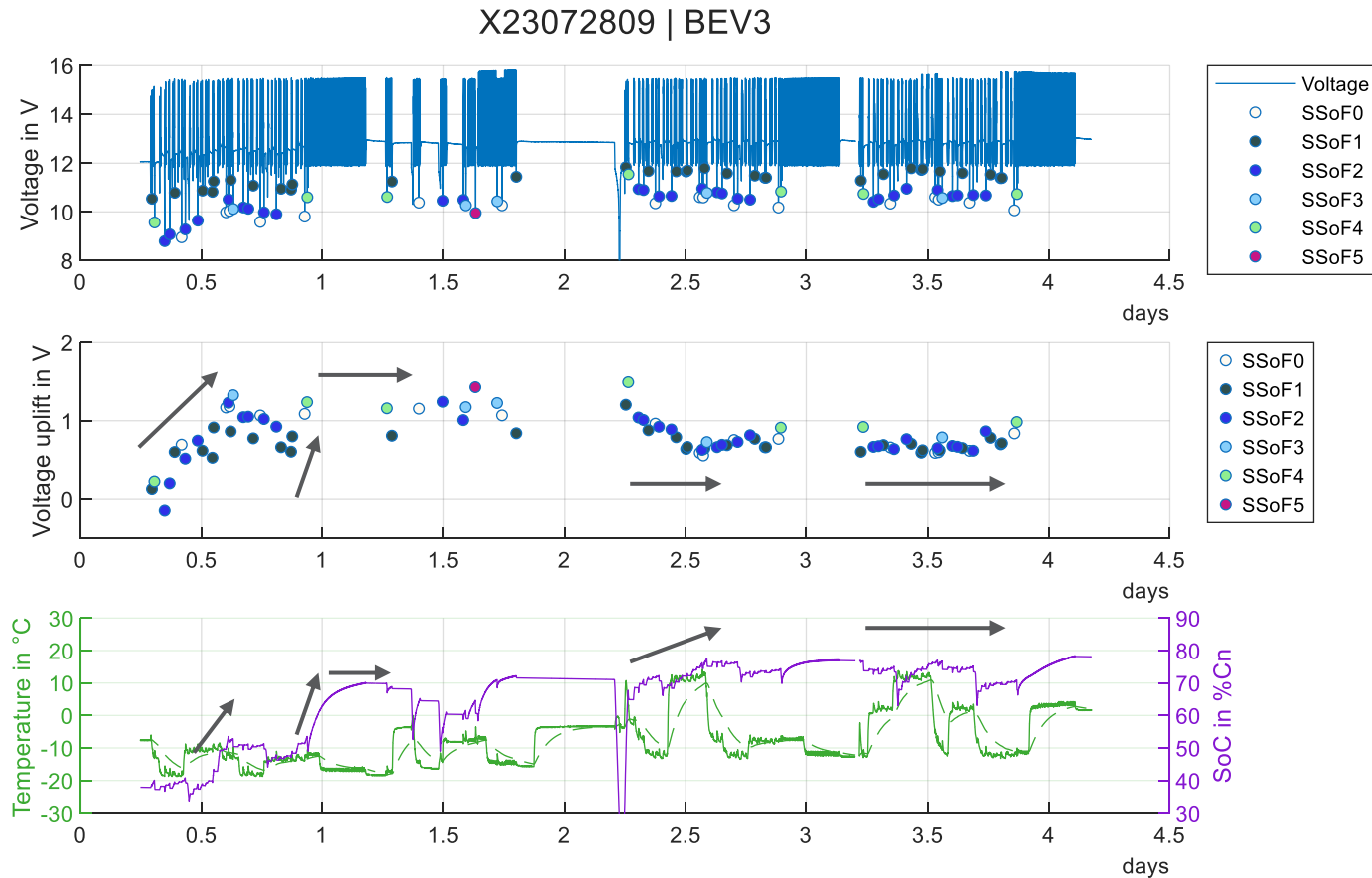
Pulse	SoC	Temp	U _{end,ppc}	U _{end,meas}	U _{uplift}
1	38%	-12 °C	8.94 V	8.80 V	-0.14 V
2	39%	-13 °C	8.87 V	9.07 V	+0.20 V
3	41%	-15 °C	8.77 V	9.28 V	+0.51 V
4	39%	-13 °C	8.90 V	9.64 V	+0.74 V
...	...	...	...	...	...

Example: SSoF2 on AGM in BEV3 sequence

⚠ Predicted values carry uncertainty in SoC, temperature, I_{cc} and tool accuracy. Focus is on qualitative trends, not exact values

BEV3 sequence on AGM battery

Voltage plateau uplift for first days

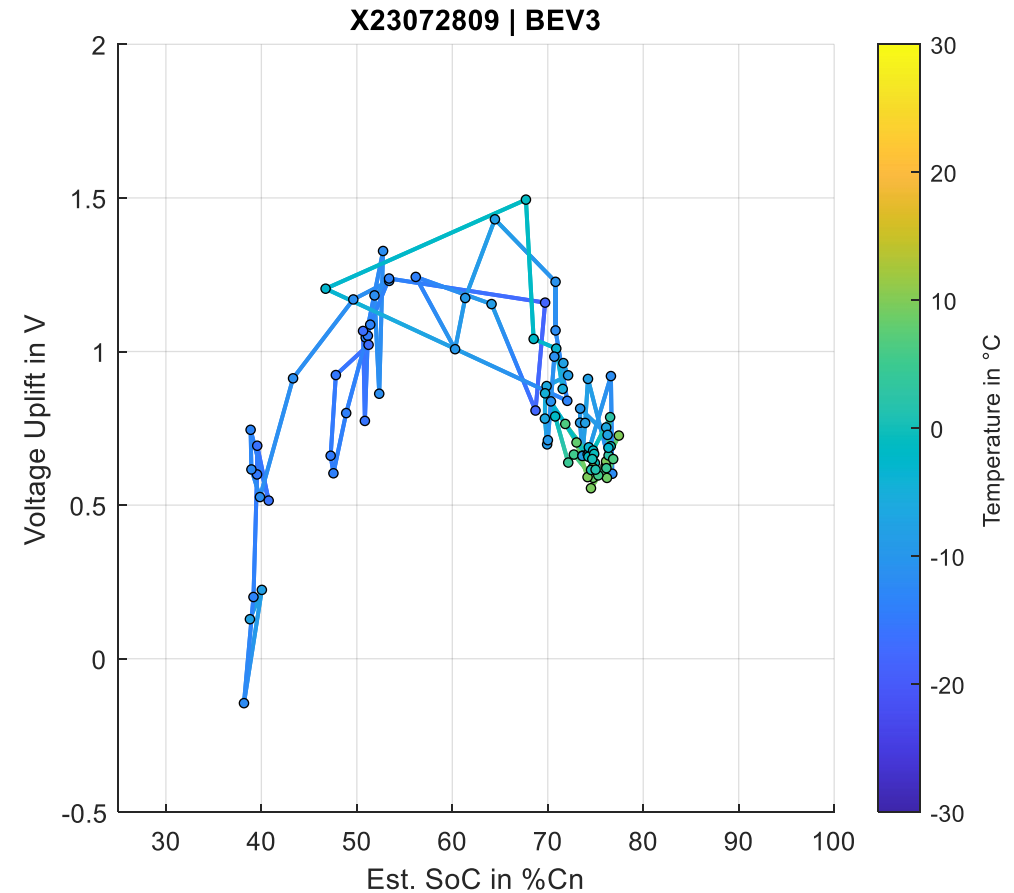


- Uplift not present at begin and raises quickly to ~ 1 V
- Then stabilizes and only partly follows further SoC increases (possible saturation)
- Different SSoF events give very similar uplift values

BEV3 sequence on AGM battery

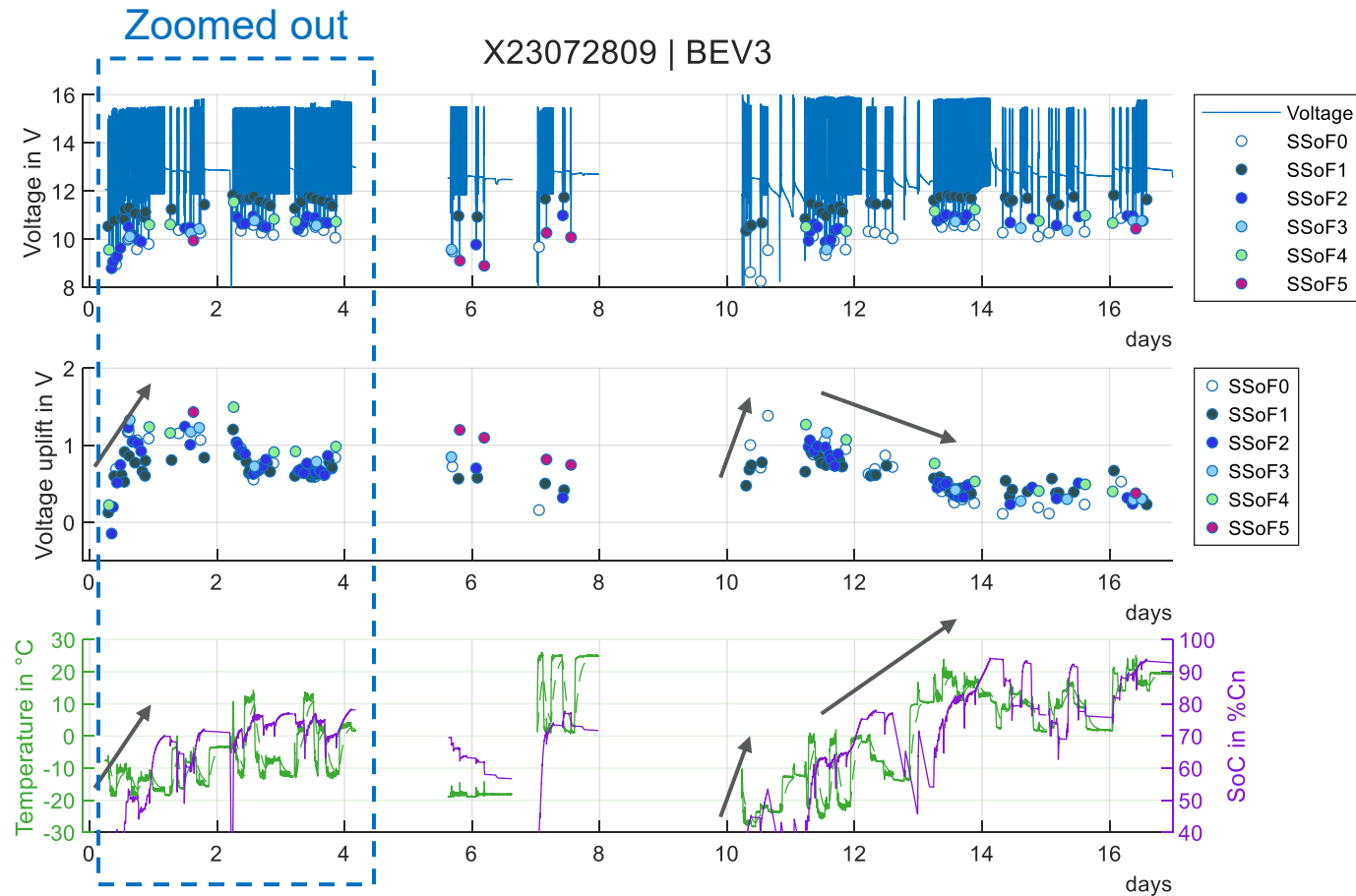
Voltage plateau uplift over SoC – first days

- Plot shows all SSoF event types
- Quick voltage plateau uplift over minimal SoC change visible in the left part before stabilizing at higher SoC
 - Due to SSoF and discharge stimuli loads while driving, total charging amount is higher than indicated by SoC change alone



BEV3 sequence on AGM battery

Voltage plateau uplift for whole sequence

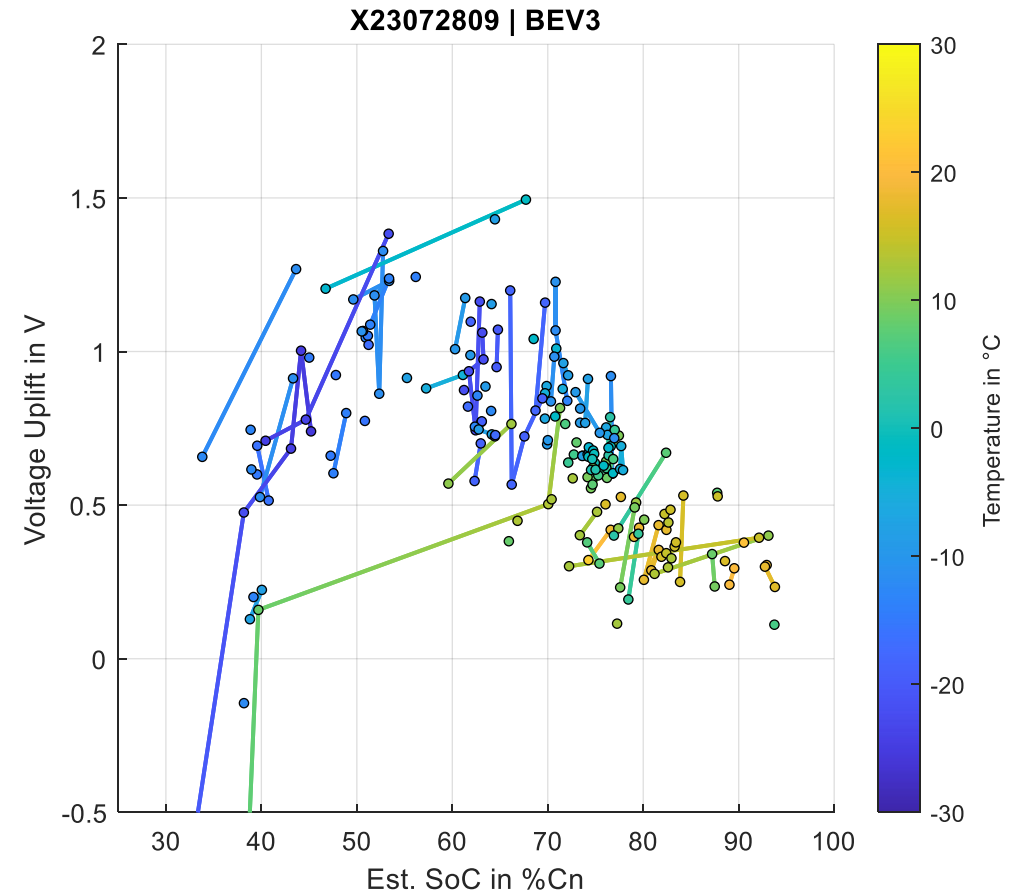


- On larger scale, voltage plateau uplift mostly raises at the onset of driving from low SoC before stabilizing/saturating
- Over several days uplift slowly fades, microcycling by SSoF and discharge stimuli contributing to this
- Absolute voltages remain at a performant level

BEV3 sequence on AGM battery

Voltage plateau uplift over SoC – whole sequence

- The quick voltage plateau uplift over minor SoC change visible in the left part remains before stabilizing at higher SoC
- For continuous charging and cycling at elevated SoC, the voltage plateau uplift seems to fade out as seen on the time-series plot
- The temperature does not seem to have a strong influence on the resulting voltage uplift values

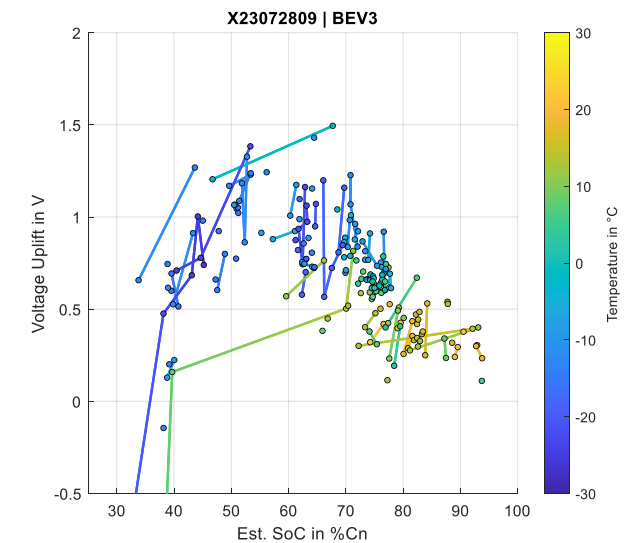
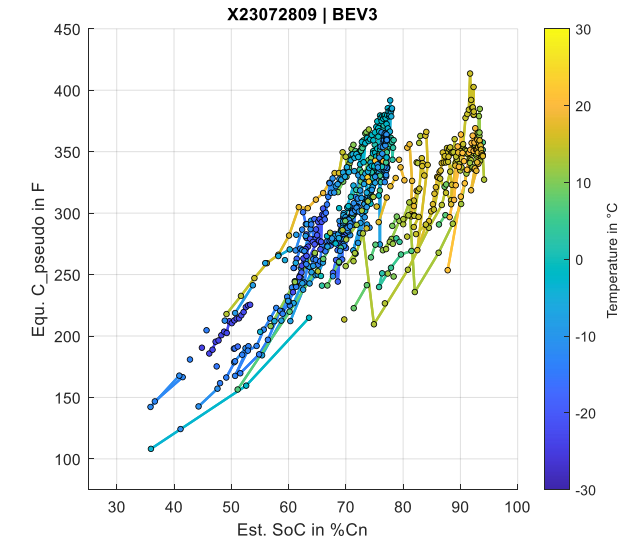


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Conclusion & Outlook

- Evaluation framework for large data sets
 - Covers variations of vehicle and battery types, ageing conditions and usage scenarios
 - ALBA battery sizing tool as end-voltage reference
- Pseudo capacitance strongly correlated with charging history and SoC
 - Consistent across battery types and temperatures
 - Significant for short-term voltage stabilization (< 1 s)
- Quick build-up then saturation for voltage plateau uplift
 - A significant performance gain on top of SoC, even for large events
 - Continuous operation and microcycling probably slowly fades it
- Next steps useful to substantiate findings
 - Further CBI SSoF Cloud data evaluation for robustness
 - Focused parameter variation in additional tests to quantify influences
 - Challenge models to improve understanding





Thank you

Acknowledgements

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