



**Creating a Cleaner World™**

## **ALBA 2026** **CR 26**

Optimizing voltage distribution in Charge Recovery  
by GEM negative electrodes

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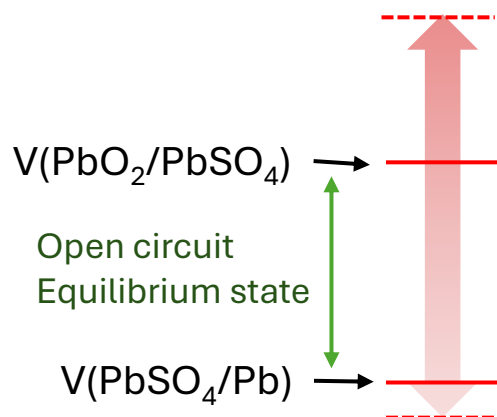
ALBA2025  
CRM6 Wertz



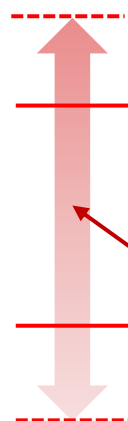
## Positive polarizations strongly affects the SoF behavior

- Positive electrodes “holds” the polarization from charging step
- Contributing to the pseudo-capacitor slope

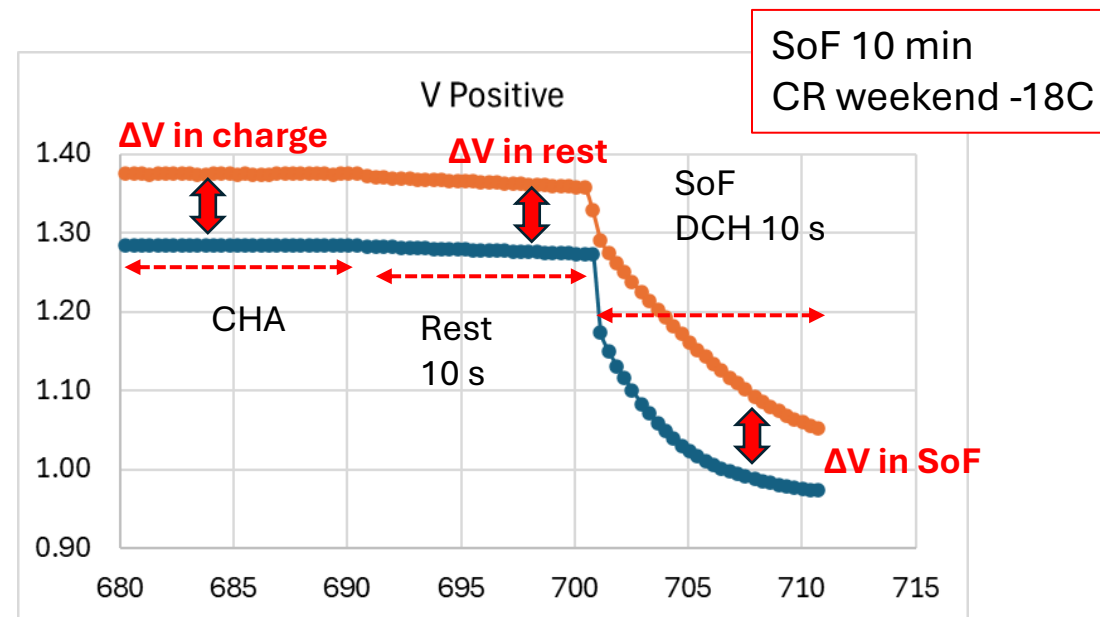
High Positive  
polarization



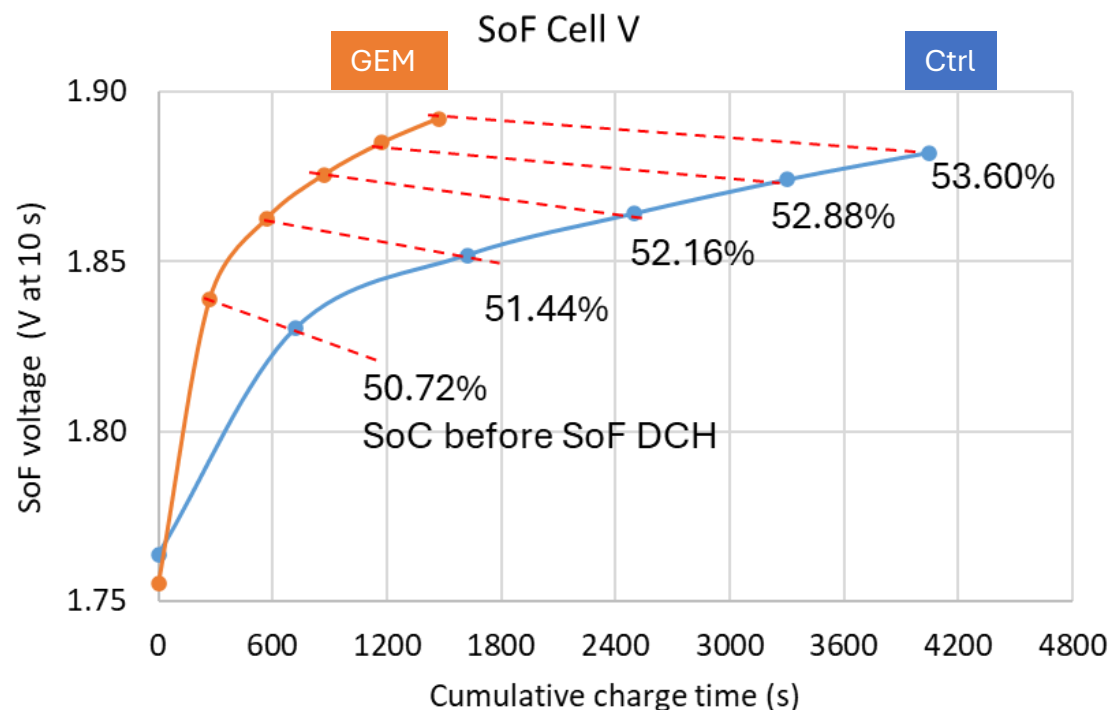
Normal Positive  
polarization



$$\text{CHA } V = V_P - V_N$$



“SoF-time-SoC” curve



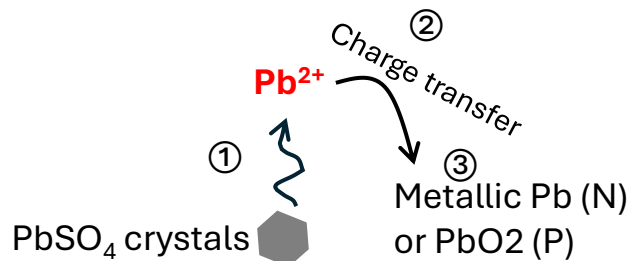
## Pushing more overpotentials to P electrodes

- Higher “charged voltage” of pseudo-capacitance: “energetic fresh PAM” (cf. CR11)
- Faster and stronger SoF recovery even at same SoC

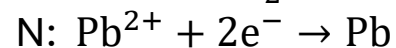
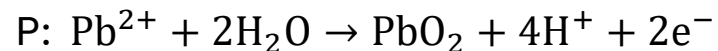
- **How to achieve this goal?**    ARCACTIVE  
Optimize electrode reaction kinetics to release more overpotentials towards positive electrodes

- Electrode reactions and rate-determining step
- Experimentally recorded individual electrode voltage
- Charge recovery with **time-ctrl recharge (test #1)** and **Ah-ctrl recharge (test #2)**
- Summary and Ongoing work

Recharge reactions on plate surface



Electrolyte species concentrations >> Pb<sup>2+</sup>

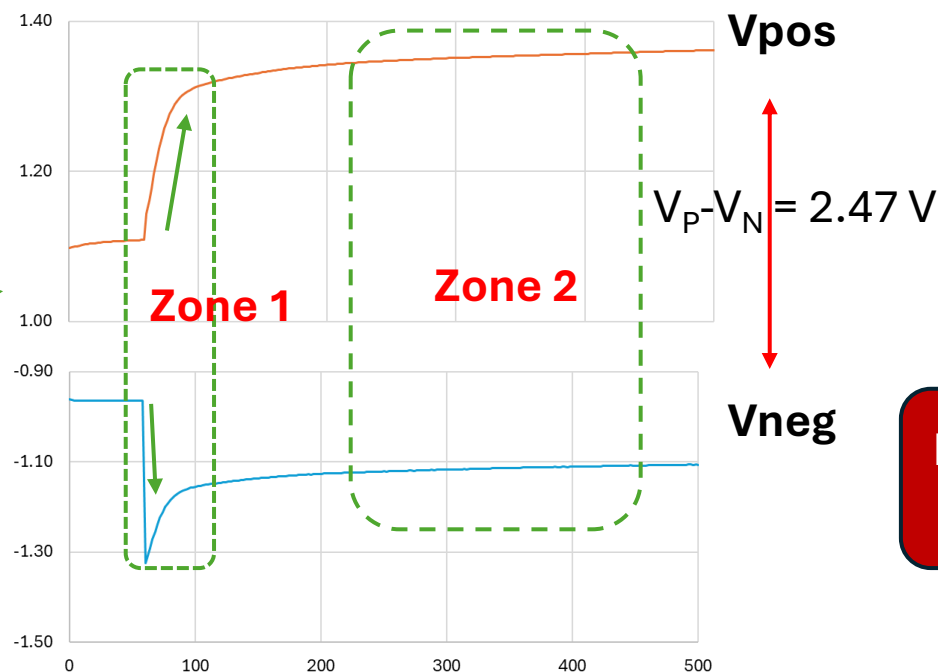
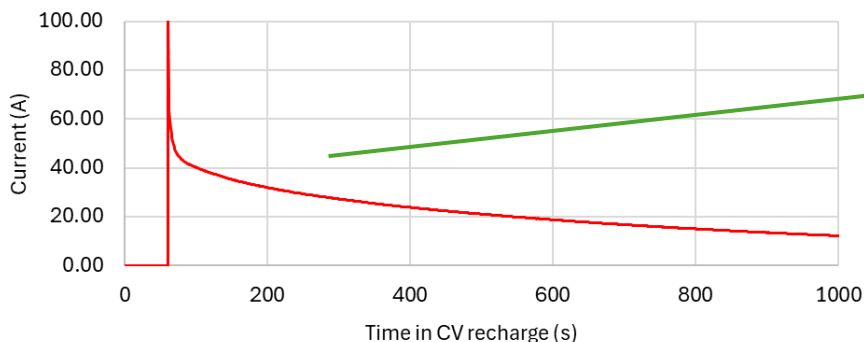


**Limiting: (1) overpotential (2) reagents concentration**

3P4N 30 Ah 2V AGM

CV recharge from 70% SoC, RT

Cell current



- Zone 1 (short) saw the drastic increase in POS voltage
- Zone 2 (long) is reaching Pb<sup>2+</sup> mass transport limitation

N electrodes limit current and overpotentials on P electrode

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High Positive  
polarization

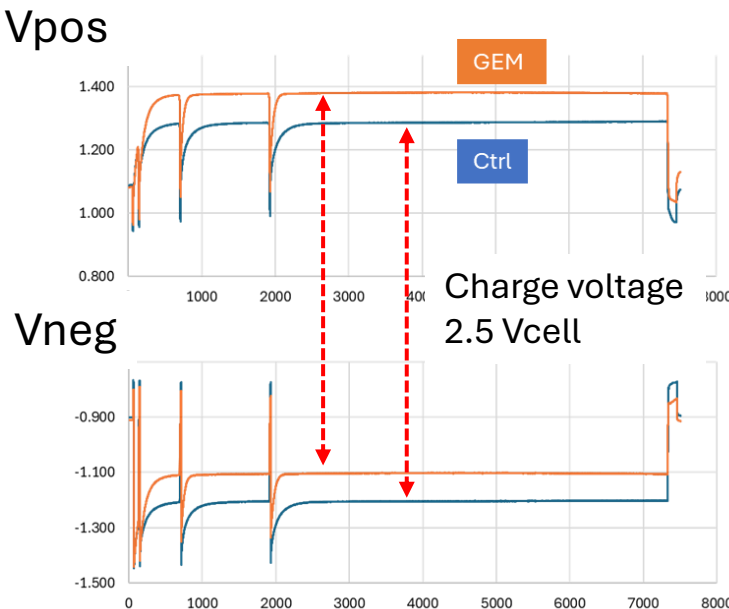
Normal Positive  
polarization

$V(\text{PbO}_2/\text{PbSO}_4)$

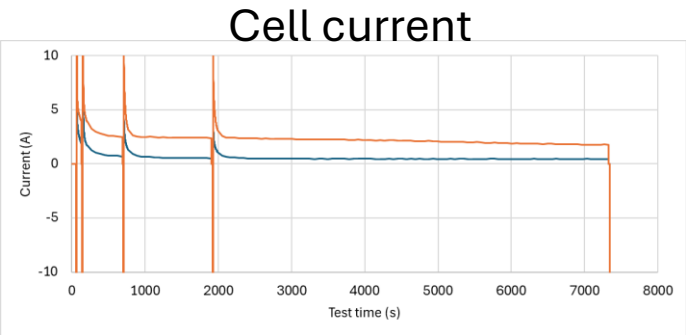
Open circuit  
Equilibrium state

$V(\text{PbSO}_4/\text{Pb})$

$\text{CHA } V = V_P - V_N$



30 Ah 2V AGM cell  
CR weekend, -18 C  
**Time-ctrl charge (test #1)**



- Negative electrode optimization to alleviate mass transport limitation.
- Balance higher electrode reaction rate and promotes higher positive electrode polarization



Hollingsworth & Vose®

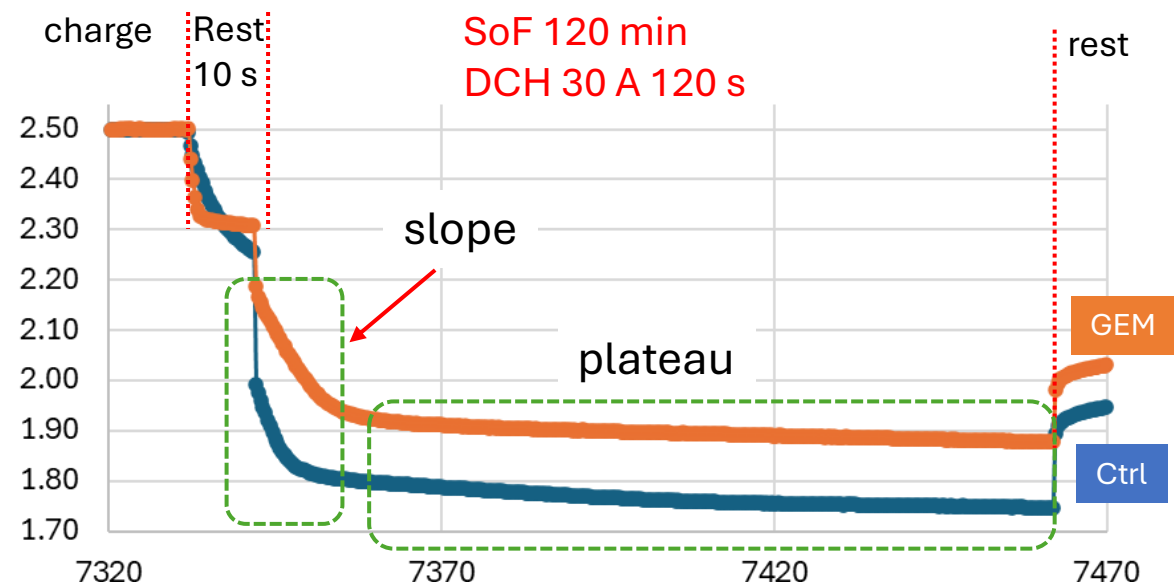


ARCACTIVE

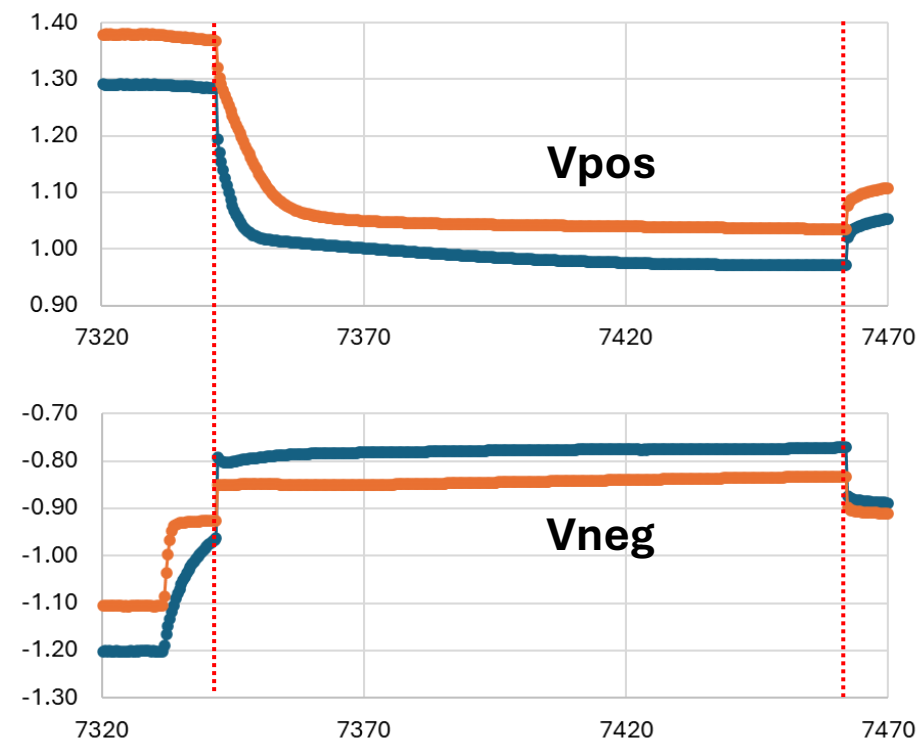
30 Ah 2V AGM cell  
CR weekend, -18 C

## Time-ctrl charge (test #1)

### Cell voltage in CR



### Electrode voltage in CR



Positive polarizations strongly affects the SoF behavior:

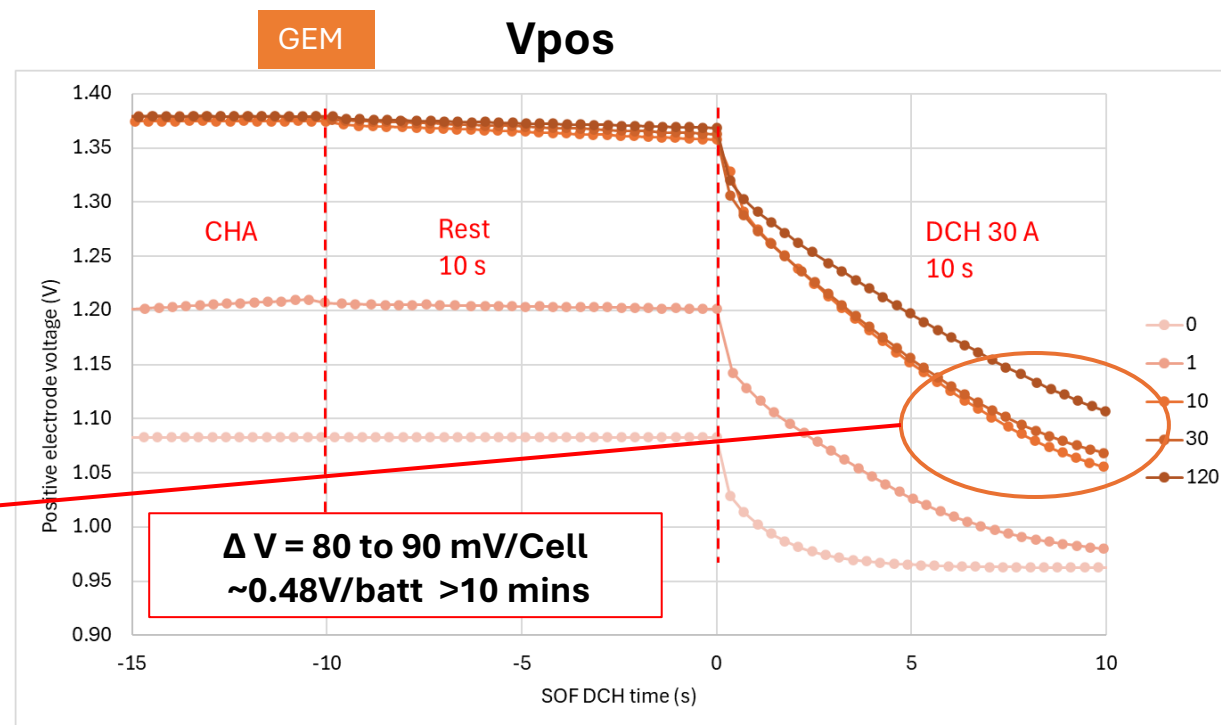
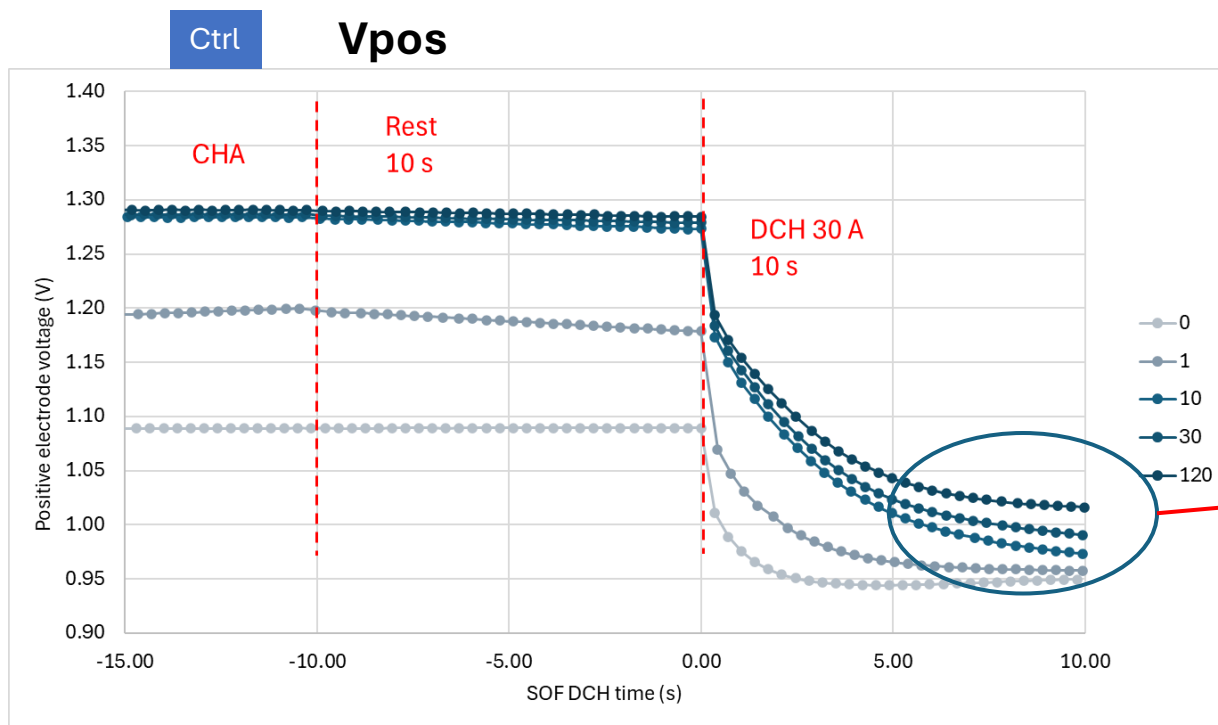
1. **Capacitor-like slope** developed after charge
2. Extra energy ( $V > V_{ocv}$ ) stored in PAM
3. A more energetic PAM for a certain capacity

30 Ah 2V AGM cell  
CR weekend, -18 C

**Time-ctrl charge (test#1)**

Higher positive polarizations  
benefit CR-based applications

GEM higher SoF V after 10 min than Ctrl after 30 min



## Test #2

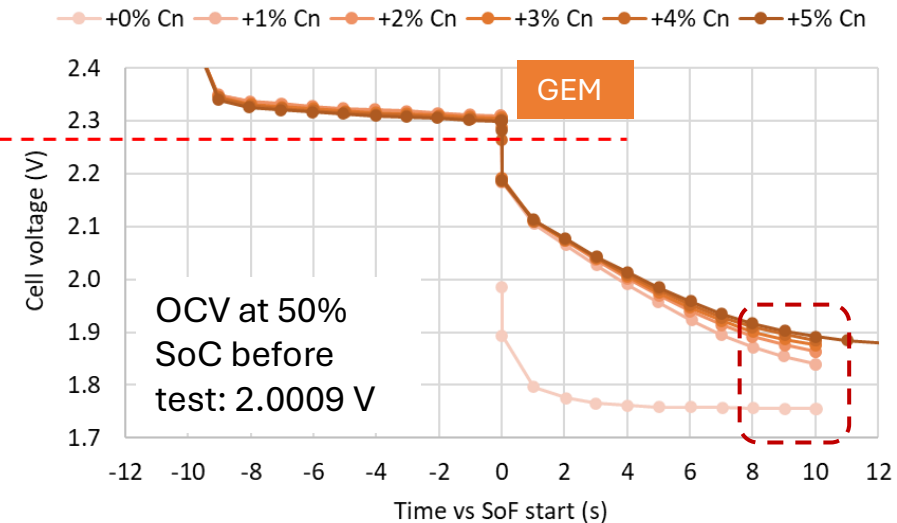
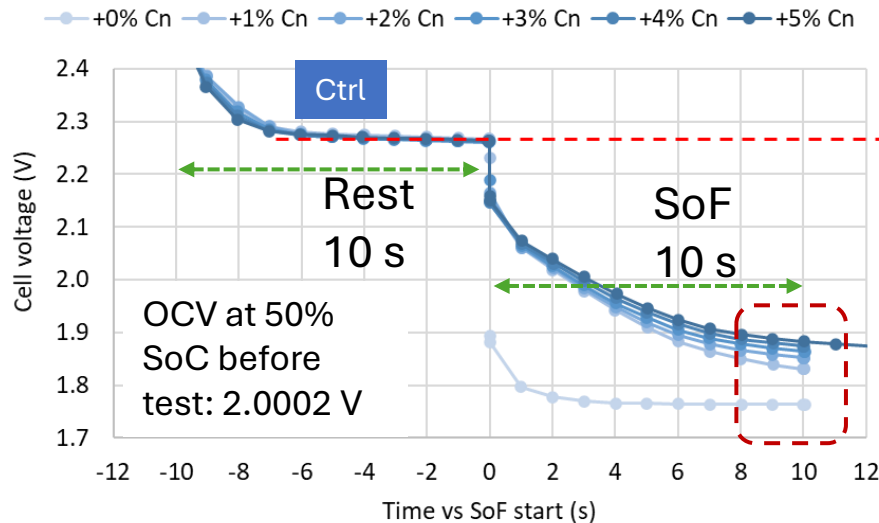
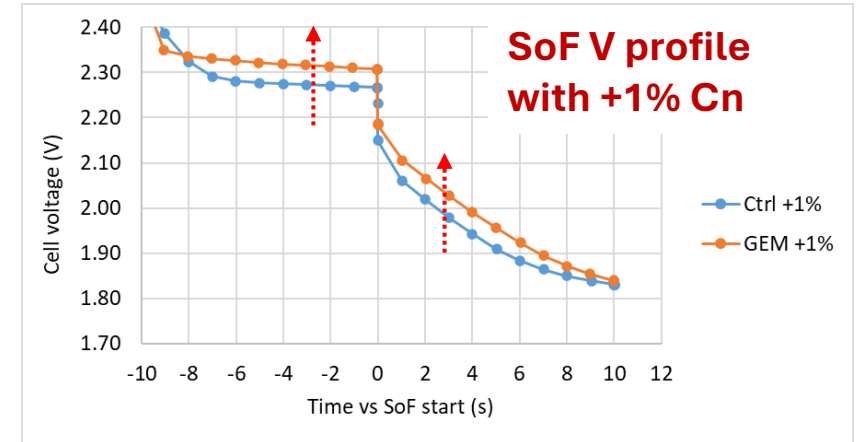
60 Ah 2V AGM cell  
CR weekend, -18 C

**Ah-ctrl charge (test #2)**

Same Ah return

- Higher GEM Cell V in rest
- Higher GEM initial V in SoF

GEM's high  $V_{POS}$  leads to strong SoF



### Test #2

A fair comparison at same SoC recovery

60 Ah 2V AGM cell

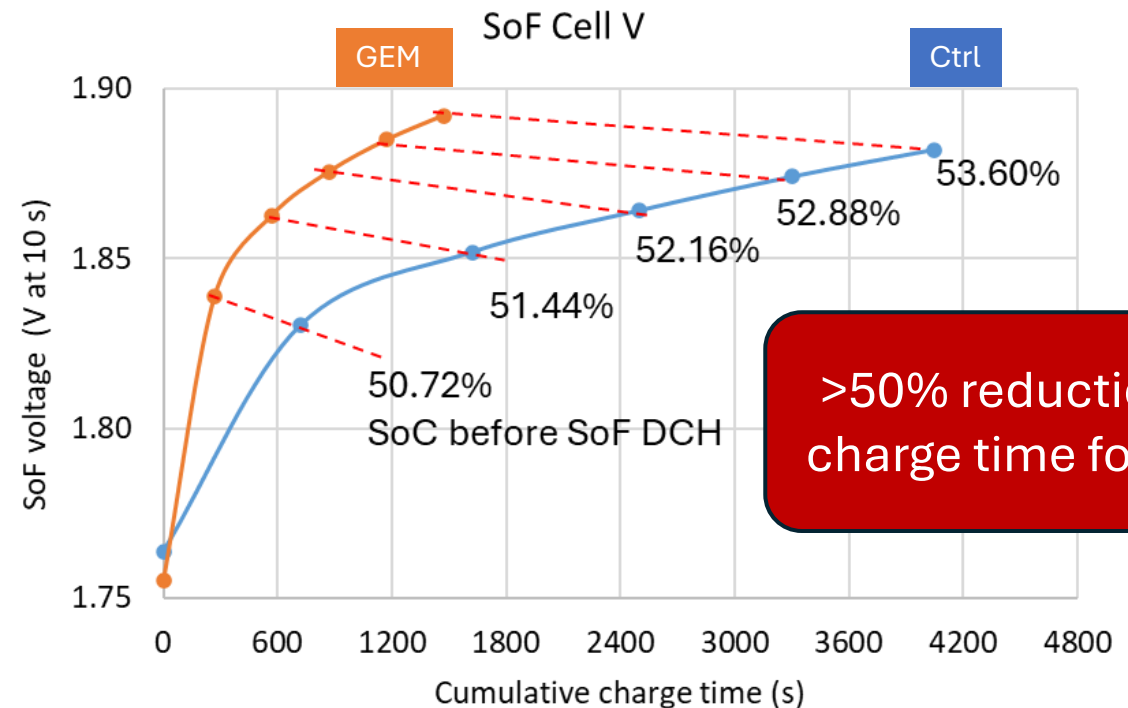
CR weekend, -18 C

**Ah-ctrl charge (test #2)**

Same Ah return: 1% Cn (0.6 Ah each CHA)

- Ctrl needs longer recharge time
- GEM **higher voltage** in SoF **at same SoC** with **shorter recharge time**
- **Higher Vpos in GEM cell**

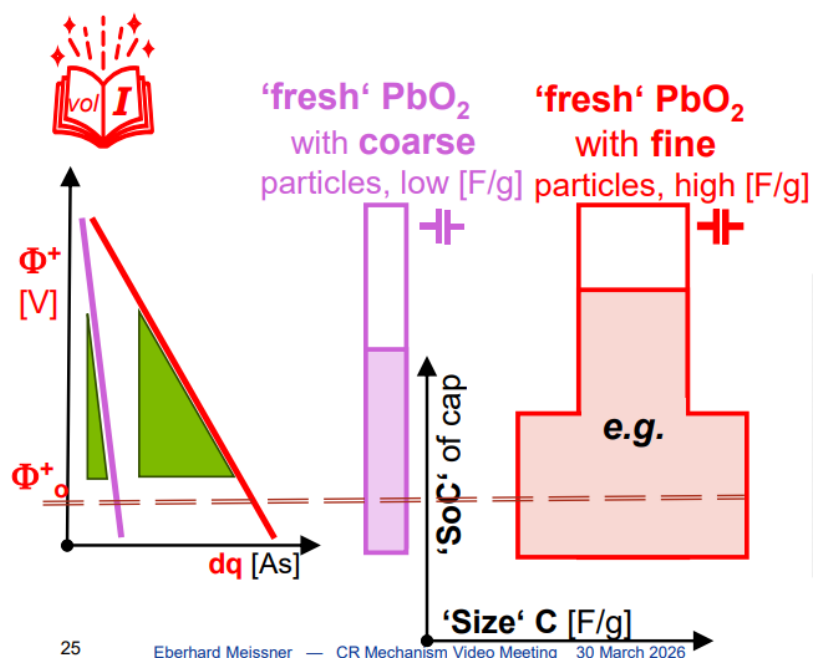
“SoF-time-SoC” curve



>50% reduction in charge time for SoF

How is extra energy stored ?

Inspired by Eberhard's model: **CR11**



**C.I Mechanisms** behind ‘pseudo-capacitance’ Slope

a) .. **PSEUDO-Capacitor** has **two** INDEPENDENT **dimensions** !

- (i) “Size C” of capacitance [F], related to total surface area of all types of PbO<sub>2</sub> material
- (ii) “SoC” of capacitance [%], related to actual potential  $\sim (\Phi^+ - \Phi^+_o)$

↑ **Size C** : “more pseudo-capacitors”

Finer surface, more active surface (+ **Cn%**)

↑ **SoC**: “charging the pseudocaps to high V”

$$E = 1/2CU^2 \quad (\uparrow V_{pos})$$

- GEM enables more SoC ++ in same CHA time
- And always higher positive electrode polarization

$$dG = \overset{\text{Enthalpy}}{V}dp - \overset{\text{Entropy}}{S}dT + \mu dN \quad \mu = \frac{\partial G}{\partial N}(T, V) \quad \Delta V_{pos} = \frac{|\Delta\mu|}{2F}$$

More energy per “PbO<sub>2</sub>” redox =  
Higher P electrode voltage in SoF

60 Ah 2V AGM cell  
CR weekend, -18 C

| Time-ctrl charging (1, 10, 30, 120 min) |                    | Ah-ctrl charging (1% Cn step)       |                        |
|-----------------------------------------|--------------------|-------------------------------------|------------------------|
| Short rest                              | Long rest (10 min) | Short rest                          | Long rest (10 min)     |
| POS polarization<br>SoC                 | SoC                | POS polarization<br>GEM time saving | SoC<br>GEM time saving |

Time saving!

Avg charge time for 1% Cn  
Ctrl: >12 min  
GEM: 5-7 min

Test #1  
Time-ctrl

GEM  
Stronger SoF

Test #2  
Ah-ctrl

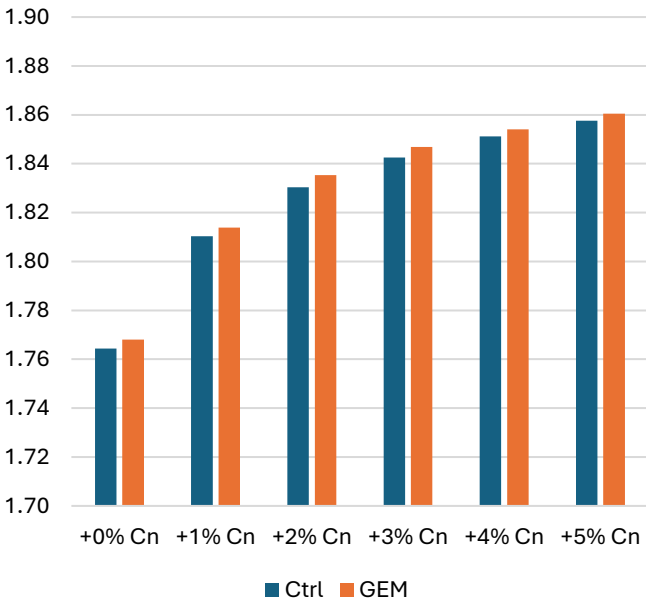
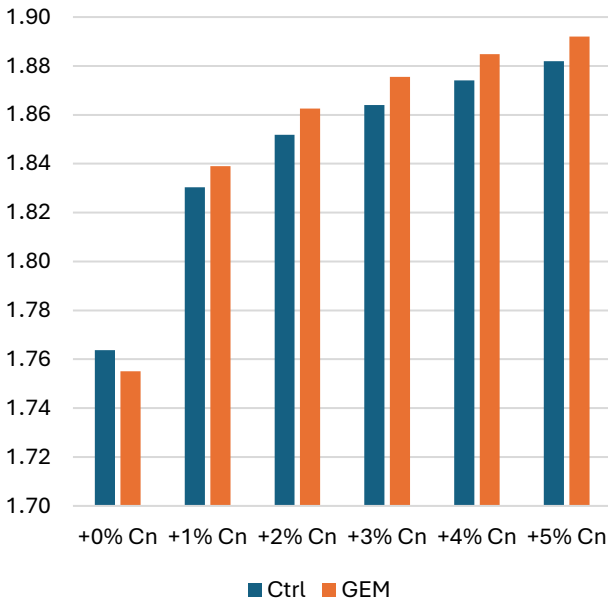
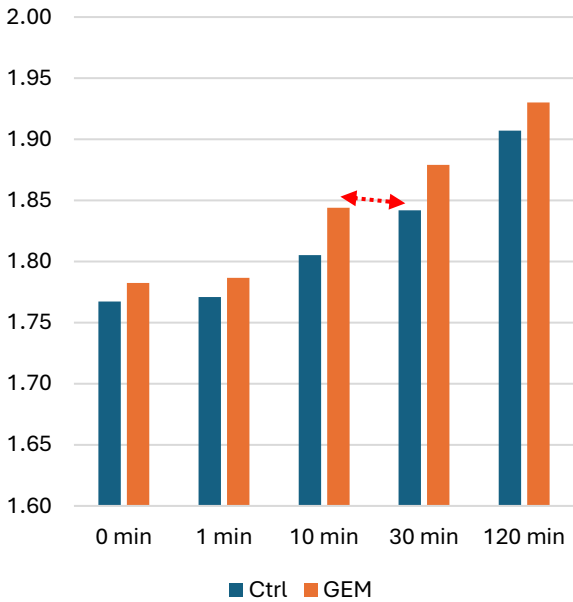
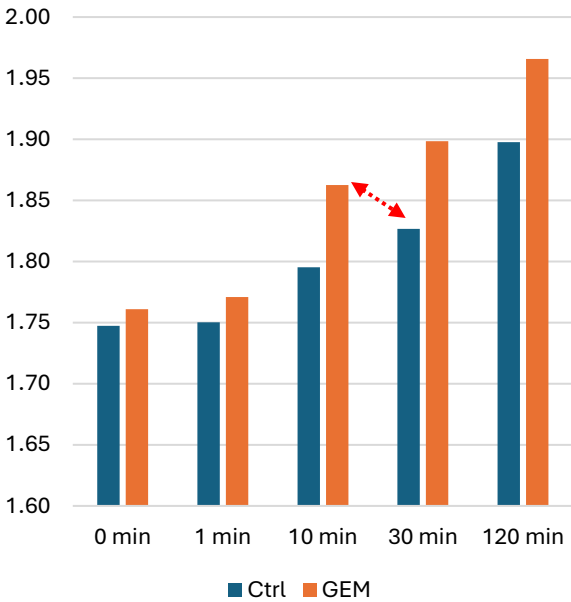
GEM Faster  
recovery

V SoF, time-ctrl no PAU

V SoF, time-ctrl + 10 min PAU

V SoF, Ah-ctrl no PAU

V SoF, Ah-Ctrl + 10 min PAU





GEM technology enables more Electro-Chemically active Surface Area (ECSA) in the negative electrode

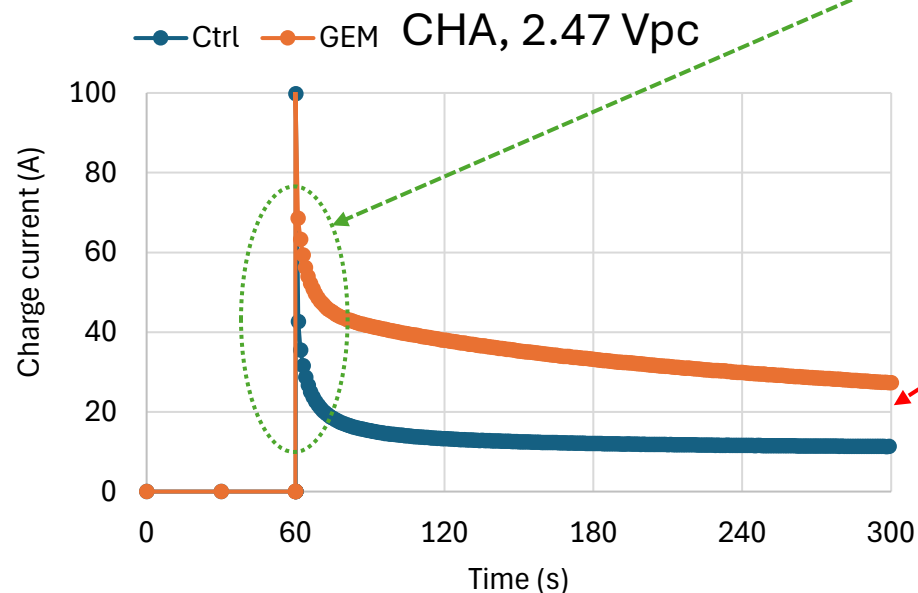
$$-\frac{d[\text{Pb}^{2+}]}{dt} = \frac{j_{\text{elec.}}}{2F} = A \cdot \exp\left(-\frac{E_A^0 - 2F \cdot \alpha \cdot \Delta V}{RT}\right) \cdot [\text{Pb}^{2+}]$$

Pb<sup>2+</sup> consumption >> supply: polarization- kinetics control

$$I_{\text{cell}} = I_{\text{Positive}} = I_{\text{Negative}} = j_{\text{neg}} \cdot \text{ECSA}$$

More active surface area (ECSA),  
higher “transient” current

Pb<sup>2+</sup> consumption ≈ supply: Mass transport of Pb<sup>2+</sup> control



$$\frac{j_{\text{elec.}}}{2F} = -\frac{d[\text{Pb}^{2+}]}{dt} (\text{consump.}) = \text{supply}$$

More ECSA, smaller crystals formed during  
discharge, higher dissolution rate

## The Findings:

Positive/Cell CR performance is limited by sluggish negative kinetics

- $V_{pos}$  is the key
- Higher P electrode polarization increases “pseudo-capacitance” for stronger SoF -- more energetic “fresh PAM”
- Higher SoC not always necessary: SoF GEM 10 min > Ctrl 30 min

## GEM advantages:

GEM technology enables a **high ECSA** (electrochemically active surface area) of the negative electrodes

- Performing the N electrode electrochemistry on a larger active surface
- Greatly reduced mass transport limitation: less overpotential but higher recharge current

## Continuing Work:

- CR performance after aging (80 units 17.5% PSoC, 36 weeks DCRss, 360 50%DoD)
- Neg electrode charge-transfer kinetics at different SoC
- Other specific applications with opportunity charging

