The 27th INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION

BARCELONA
17th-20th November 2013

Fast Charging Method Based on Estimation of Ion Concentrations using a Reduced Order of Electrochemical Thermal Model for Lithium Ion Polymer Battery

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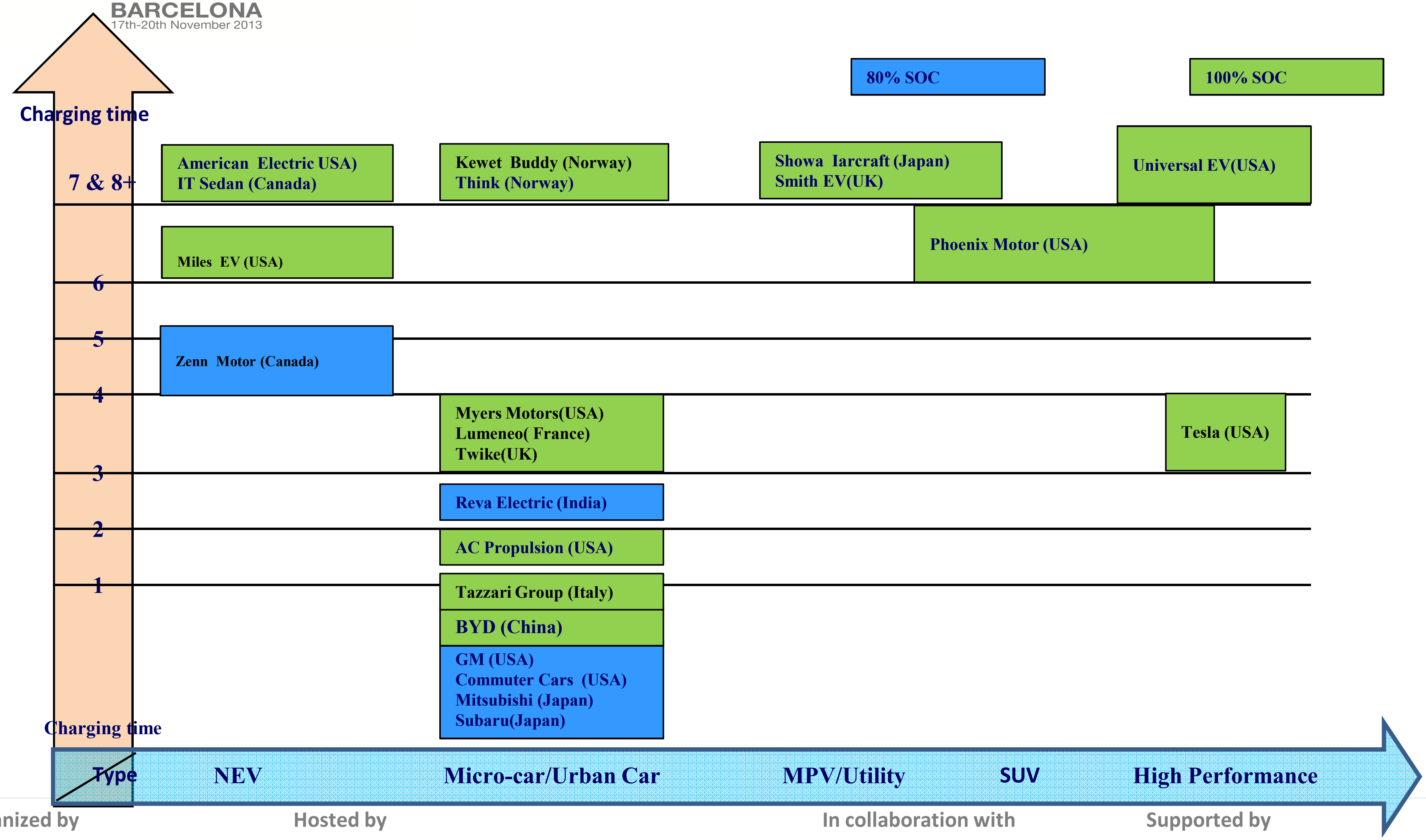
Background: Charging time of BEVs



Review: Charging Methodologies

- 1or 2-Step CC + CV charging
- Multi-Step CC Charging
- Multi-Step CC Charging + Taper Charging

- CC(Constant Current)
- CV (Constant Voltage)
- Taper Charging
- Constant Power Charging

Pulse Charging

- One-Directional Pulse
- Bi-Directional Pulse

Optimization for reduction of charging time, battery life or efficiency

1. **Experimental data:** Ant-Cycle System, Wolf Pack , Taguchi-based Algorithm, Sinusoidal Current Charging with the Minimum AC Impedance, Grey Prediction Technique
2. **Control theory and model:**
   - Fuzzy Controls, Residual Energy Evaluation, Built-in Resistance Compensator , Multiple Rate, Probabilistic Fuzzy Neural Network Control, integral linear programming algorithm, first order dynamic model, a single one-step prediction
3. **Cycle numbers or SOC**
   - Offline battery charger, Negative Pulse Discharge, Frequency- varied Technique

Proposed methods do not consider fundamental transport mechanism of lithium ions and their intercalation/de-intercalation in details

Limiting factors for high current Charging

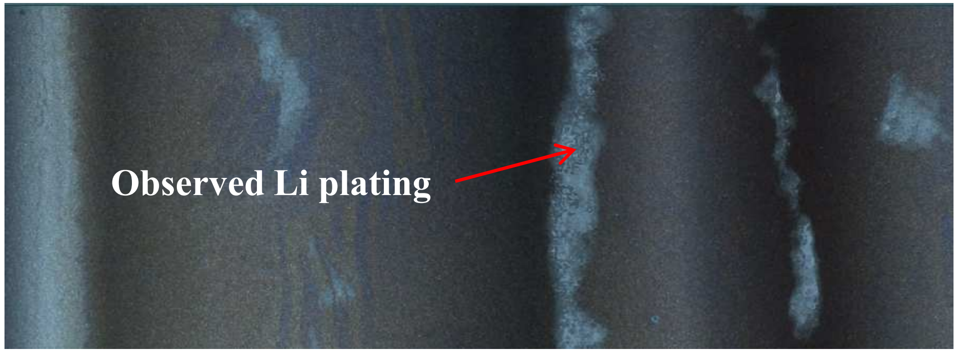
- The reaction on the negative electrode is described as: $C_6 + xLi^+ + xe^- \rightarrow Li_xC_6$
- When operated improperly, Li-ions are deposited on the anode surface instead of intercalating during charging: $Li^+ + e^- \rightarrow Li(s)$

Causes of Lithium plating:

- ✓ Large current rate during charging, especially at **high Li ion concentration**
- ✓ Low temperature

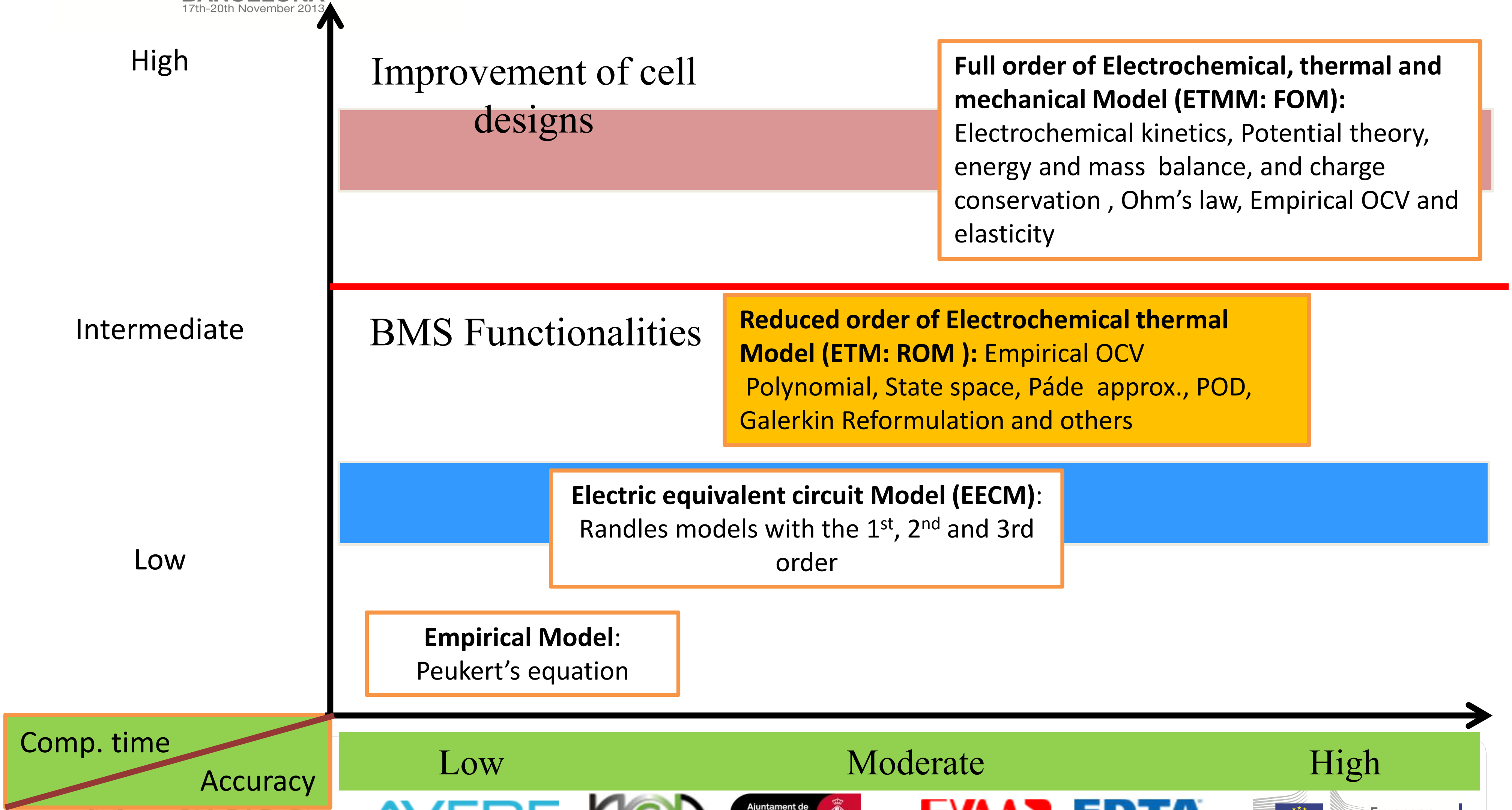
Effects of Lithium plating:

- ✓ Capacity
  - Irreversible loss of active Lithium
- ✓ Safety
  - Dendrites can cause shorts within the electrodes
- ✓ Heat generation
  - A mat of dead lithium and dendrites can increase the chances minor shorts will lead to thermal runway



Reference: C. J. Mikolajczak, J. Harmon, *From Lithium plating to Lithium – ion cell runaway* Exponent [E^x(40)]annual report, 2009

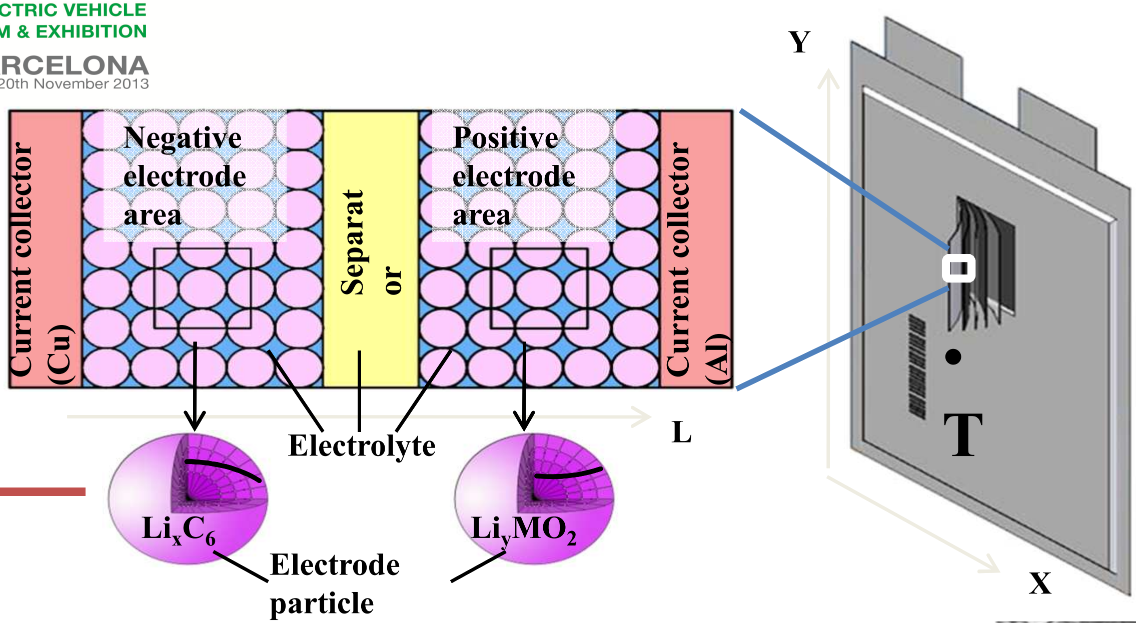
Models for Estimation ion concentrations



Modeling Approach for LiPB

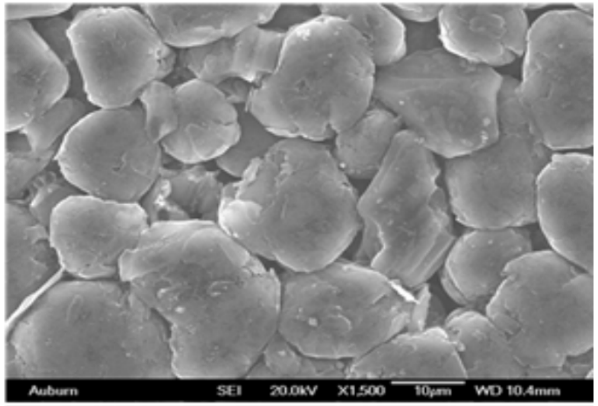
- c_e
- Φ_e
- Φ_s
- η_{SEI}

- c_s

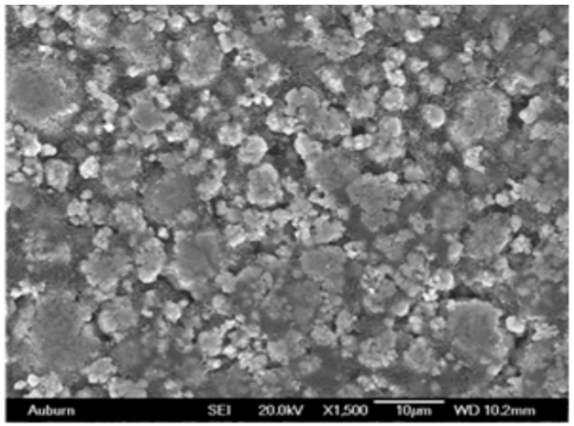


Cell specification	
Anode	Carbon
Cathode	Li[MnNiCo]O_2 (NMC),
Separator	polymer
Electrolyte	$LiPF_6$, EC/DMC
Size	164mm×250mm×5mm
Capacity	15.7Ah

SEM (anode side)



SEM (cathode side)



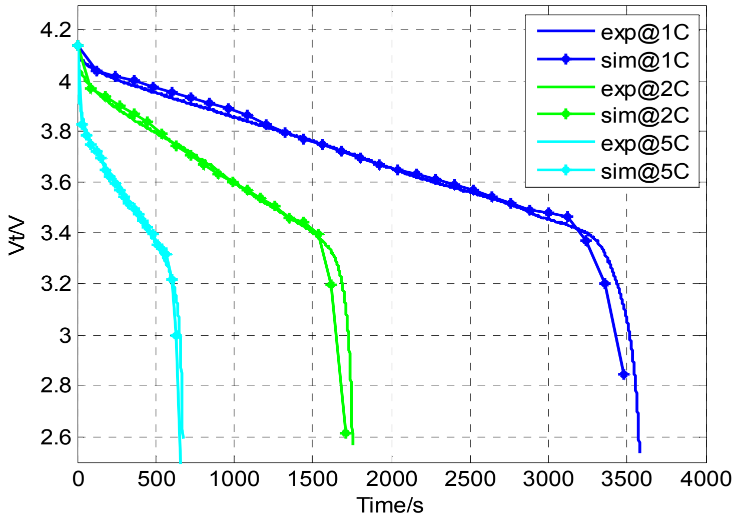
Models based on electrochemical and thermal principle

	Full Order Model (FOM)	Reduced Order Model(ROM)	Order reduction
Ion concentration in solid particles C_s → Polynomial approach	$\frac{\partial C_s}{\partial t} = \frac{D_s}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial C_s}{\partial r}\right)$	$\frac{d}{dt}C_{s,ave} + 3\frac{j^{Li}}{R_s a_s F} = 0$ $\frac{d}{dt}q_{ave} + 30\frac{D_s}{R_s^2}q_{ave} + \frac{45}{2}\frac{j^{Li}}{R_s^2 a_s F} = 0$ $35\frac{D_s}{R_s}\left(C_{s,surf} - C_{s,ave}\right) - 8D_s q_{ave} = -\frac{j^{Li}}{a_s F}$	**N_R*N_L to 3*N_L**
Ion concentration in electrolyte C_e → State space approach	$\dot{\mathbf{c}}_\mathbf{e} = \mathbf{A}\cdot\mathbf{c}_\mathbf{e} + \mathbf{B}\cdot I$ $\mathrm{y} = \mathbf{C}\cdot\mathbf{c}_\mathbf{e} + \mathbf{D}\cdot I$	$\dot{\mathbf{c}}_\mathbf{e} = \mathbf{A}^*\cdot\mathbf{c}_\mathbf{e} + \mathbf{B}^*\cdot I$ $\mathrm{y} = \mathbf{C}^*\cdot\mathbf{c}_\mathbf{e} + \mathbf{D}^*\cdot I$	**N_L to 3**
Potentials and current density → Parameters simplification	$\frac{\partial}{\partial x}\left(\sigma^{eff}\frac{\partial}{\partial x}\phi_s\right) - j^{Li} = 0$ $\frac{\partial}{\partial x}\left(k^{eff}\frac{\partial}{\partial x}\phi_e\right) + \frac{\partial}{\partial x}\left(k_D^{eff}\frac{\partial}{\partial x}\ln c_e\right) + j^{Li} = 0$ $j^{Li} = a_s i_0\left\{\exp\left[\frac{\alpha_a F}{RT}\eta\right] - \exp\left[-\frac{\alpha_c F}{RT}\eta\right]\right\}$	$\frac{\partial}{\partial x}\left(\frac{\partial}{\partial x}\phi_{se}\right) = j^{Li}\left(\frac{1}{\sigma^{eff}} + \frac{1}{k^{eff}}\right)$ $j^{Li} = \frac{a_s i_0 F}{RT}\left(\phi_{se} - U\right)$	**2*N_L to 1*N_L**
Energy equation and temperature dependence	$Q_{gen.} = \frac{1}{L}\int_L (\Delta U_{equ}^{+}\cdot i(r,l) - \Delta U_{equ}^{-}\cdot i(r,l))\,dl + \frac{I}{V}(U_{OCV} - V_T - T\cdot\frac{\partial U_{OCV}}{\partial T})$ $D_s = D_{s0}\cdot\exp(\frac{E_a}{R}(\frac{1}{T_0} - \frac{1}{T}))$		
SOC estimation	$SOC = \left[\frac{1}{L_-}\int_0^{L_-}\frac{(C_{s,ave} - C_{s,\max}\cdot x_0)}{C_{s,\max}\cdot(x_{100} - x_0)}\cdot dx\right]\cdot 100\%$		

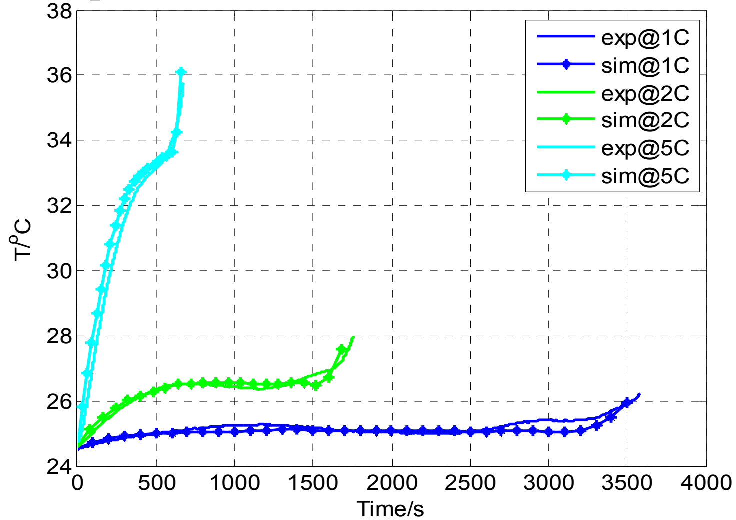
Validation of the Reduced Order Model

Test condition:
Mode: Depleting
Temperature: 25ºC
Current: 1C, 2C, 5C
Initial SOC: 100%

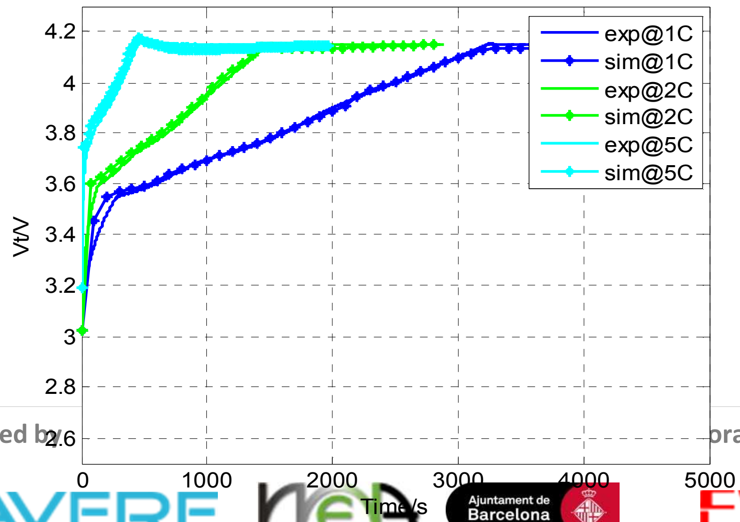
Terminal voltage:

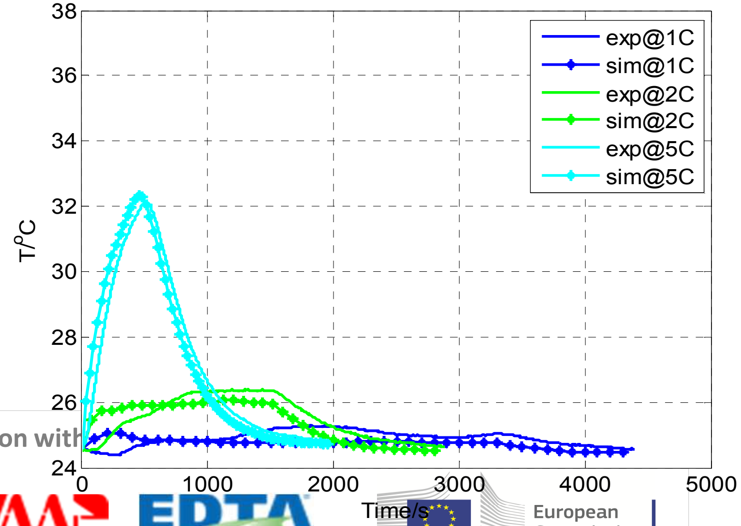


Temperature:

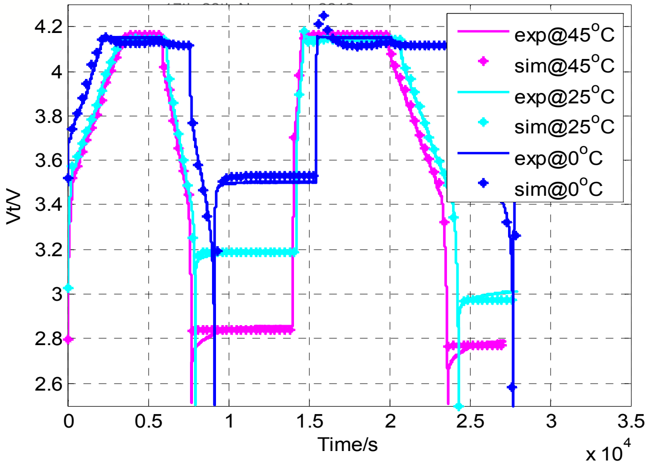


Test condition:
Mode: Depleting
Temperature: 25ºC
Current: 1C, 2C, 5C
Initial SOC: 0%

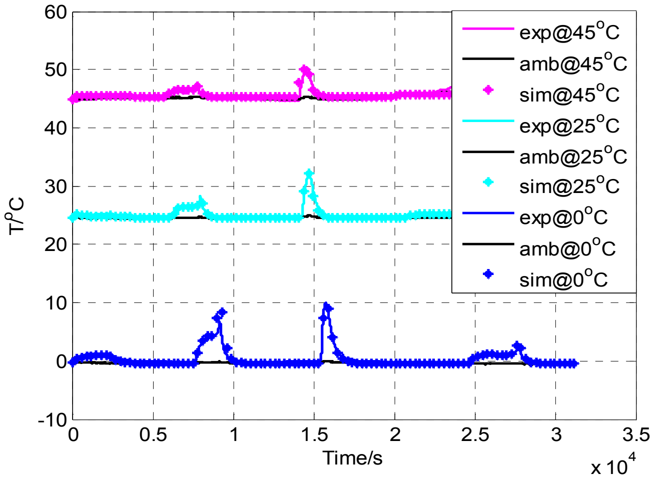




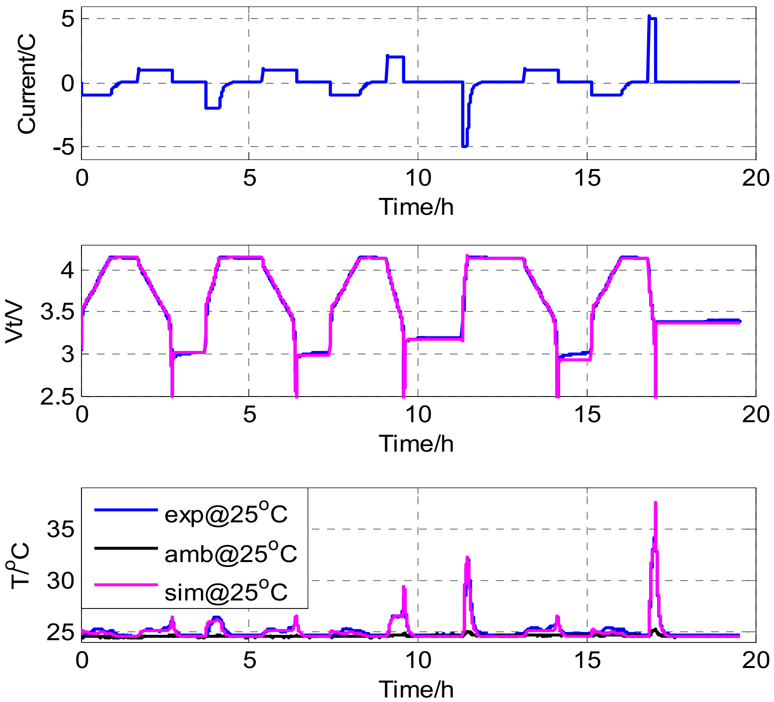
Validation of the ROM at multiple cycles



1. Test condition:
Mode: Depleting
Cycle #: 2
Temperature: 0ºC, 25ºC, 45ºC
Current: 1C, 2C, 5C
Initial SOC: 0%



2. Test condition:
Mode: Depleting
Cycle #: 5
Temperature: 25ºC
Current: 1C, 2C, 5C
Initial SOC: 0%



Model	Full dischar.@1C	Full dischar.@2C	Full dischar.@5C
FOM	79	45	26
ROM	8.7	3.9	2.7

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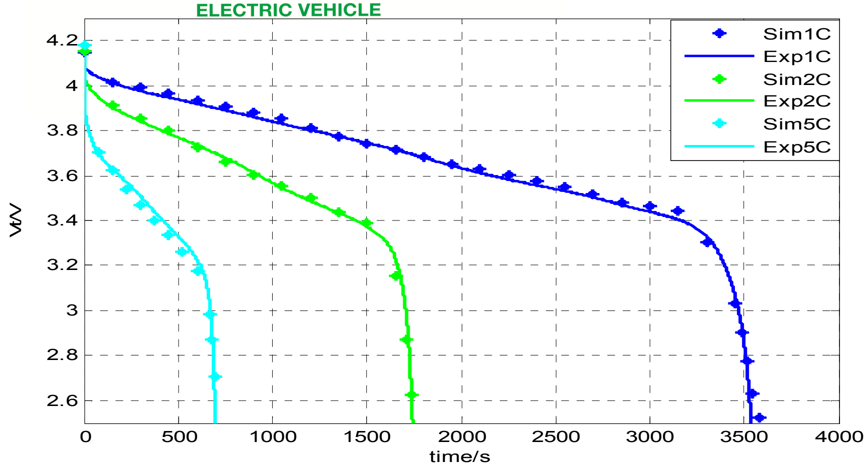
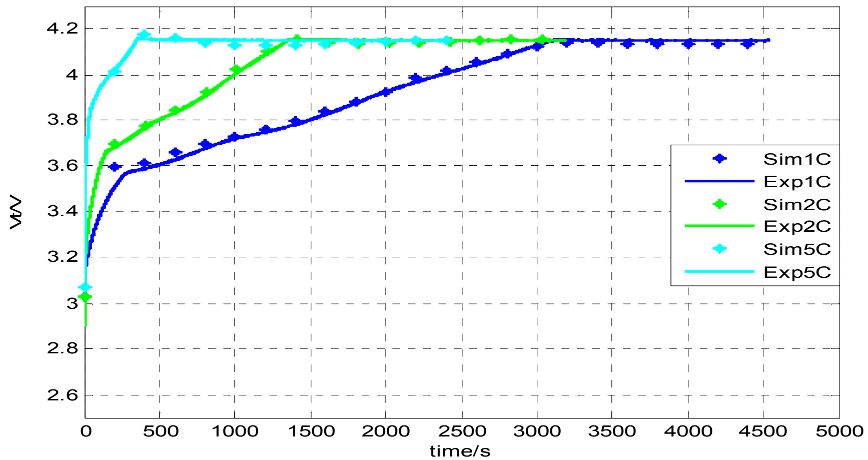
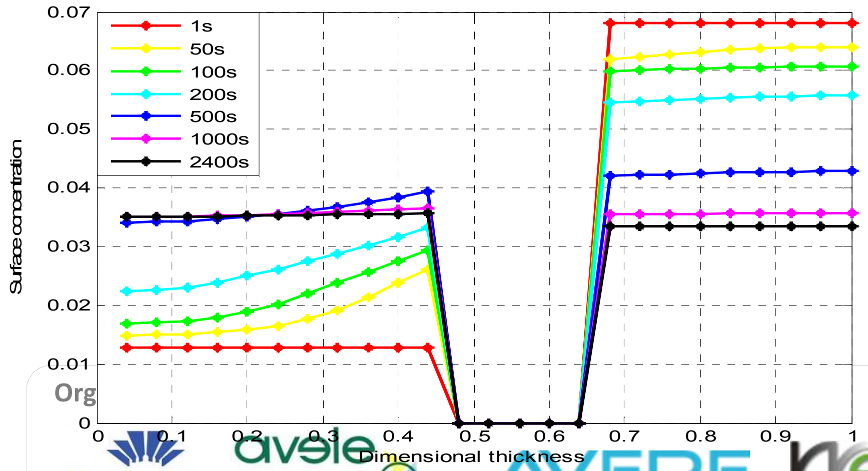
Analysis of the battery at Charging

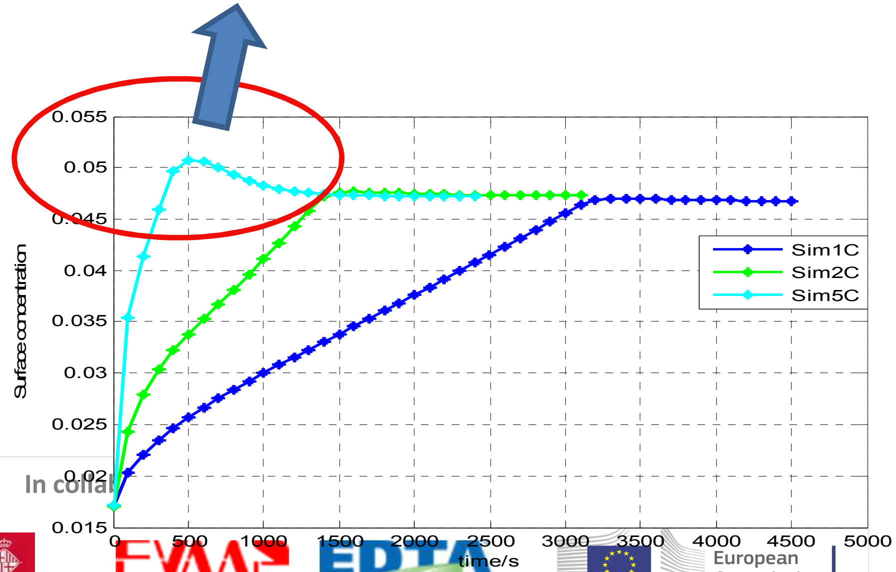




V_t @ 1/2/5C discharging at 25°C	$V_{t\,@}$ 1/2/5C discharging at 25°C
Cs @ 5C charging at 25°C	Cs @ 1/2/5C charging at 25°C

High ion concentration





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Estimation of SOC based on EKF and ROM

Model:	$\mathbf{x}_k = f\left(\mathbf{x}_{k-1}, \mathbf{u}_{k-1}, \mathbf{w}_{k-1}\right)$ $\mathbf{z}_k = h\left(\mathbf{x}_k, \mathbf{v}_k\right)$
Initialization:	Initial state estimation: $\hat{\mathbf{x}}_{k-1}$
	Initial error covariance : $\mathbf{P}_{k\text{-}1}$
	Initial process noise covariance : $\mathbf{W}_k$
	Initial measurement covariance : $\mathbf{V}_k$
Time update:	State prediction: $\hat{\mathbf{x}}_k^- = f\left(\hat{\mathbf{x}}_{k-1}, \mathbf{u}_{k-1}, 0\right)$
	Error covariance prediction: $\mathbf{P}_k^- = \mathbf{A}_k \mathbf{P}_{k-1} \mathbf{A}_{\mathrm{k}}^{\mathrm{T}} + \mathbf{W}_k \mathbf{Q}_{k-1} \mathbf{W}_{\mathrm{k}}^{\mathrm{T}}$
Measurement update:	Kalman gain: $\mathbf{K}_{\mathrm{k}} = \mathbf{P}_k^- \mathbf{H}_{\mathrm{k}}^{\mathrm{T}} \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_{\mathrm{k}}^{\mathrm{T}} + \mathbf{V}_k \mathbf{P}_{k-1} \mathbf{V}_{\mathrm{k}}^{\mathrm{T}}\right)^{-1}$
	State correction: $\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_{\mathrm{k}} \left(\mathbf{z}_k - h\left(\hat{\mathbf{x}}_k^-, 0\right)\right)$
	Error covariance correction: $\mathbf{P}_{\mathrm{k}} = \left(\mathbf{I} - \mathbf{K}_k \mathbf{H}_{\mathrm{k}}\right) \mathbf{P}_k^-$

The domain equation for averaged concentration in solid particles is

$$\frac{d}{dt} c_{\mathrm{s,ave}} + 3 \frac{j^{\mathrm{Li}}}{R_{\mathrm{s}} a_{\mathrm{s}} F} = 0$$

The domain equation for averaged concentration in negative electrode is

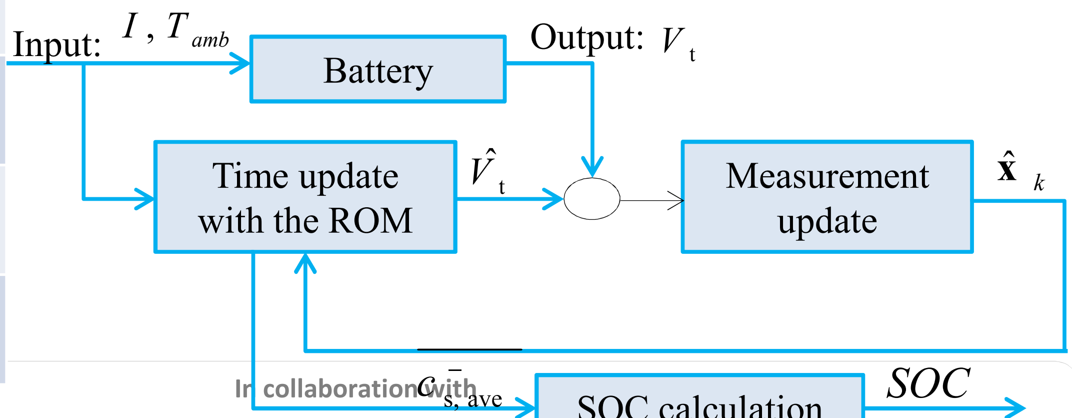
$$\overline{c_{\mathrm{s,ave}}^-}^{k} = \overline{c_{\mathrm{s,ave}}^-}^{k-1} - 3 \frac{\Delta t}{R_{\mathrm{s}} a_{\mathrm{s}} F} \frac{I}{A L^-}$$

The terminal voltage V_{t} is the difference between OCV and overpotential η;

$$V_{\mathrm{t}} = U_{\mathrm{OCV}}^+ \left(\overline{y}\right) - U_{\mathrm{OCV}}^- \left(\overline{x}\right) - \eta$$

$$\overline{x} = \frac{\overline{c_{\mathrm{s,ave}}^-}}{c_{\mathrm{s,max}}^-}, \quad \overline{y} = \frac{\overline{c_{\mathrm{s,ave}}^+}}{c_{\mathrm{s,max}}^+}$$

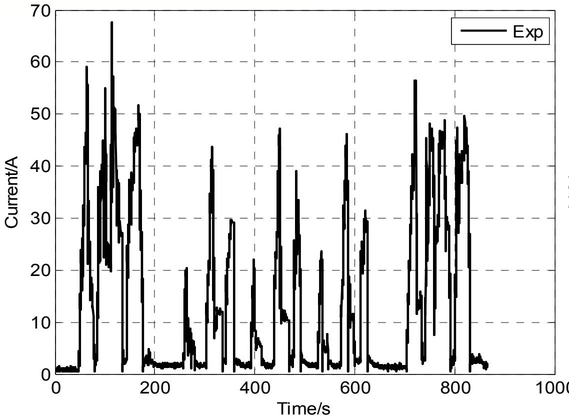
The block diagram of the EKF based ROM:



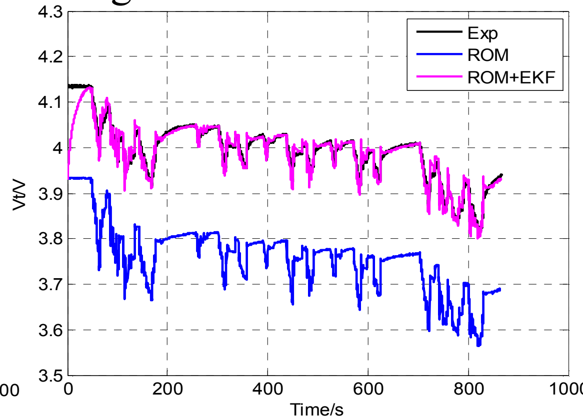
Results of the EKF based ROM

Test condition:
Mode: JS
Temperature: 25ºC
Initial SOC: 100%
Initial error: 0.2V
(30% SOC)

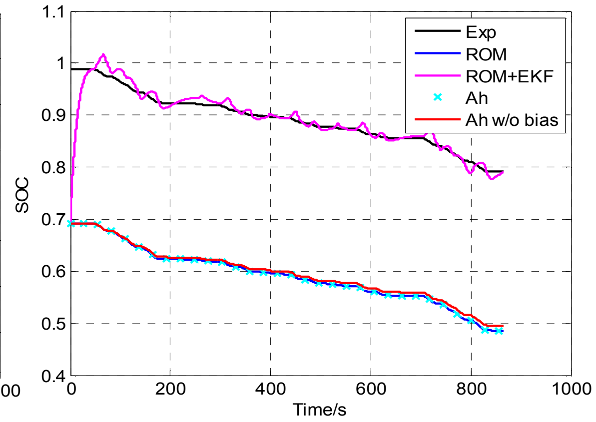
Current:



Voltage:

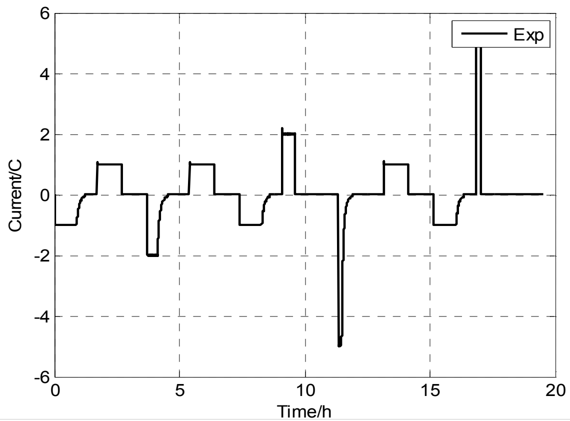


SOC:

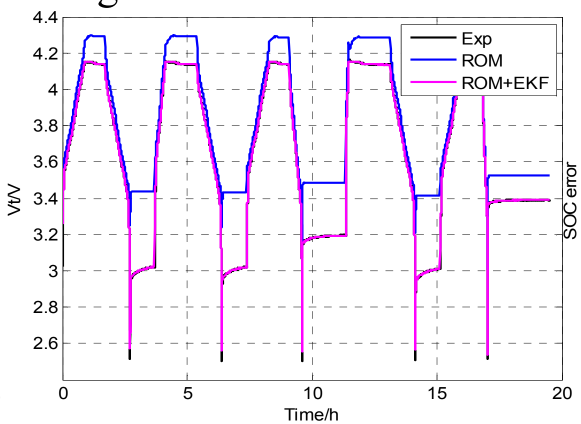


Test condition:
Mode: Depleting
Temperature: 25ºC
Initial SOC: 0%
Initial error: 0.5V
(6.5% SOC)

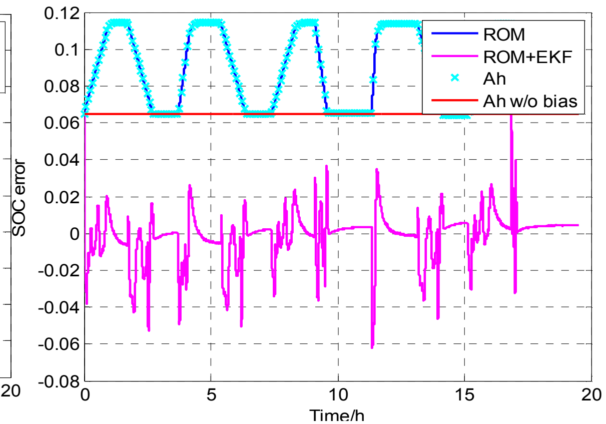
Current:



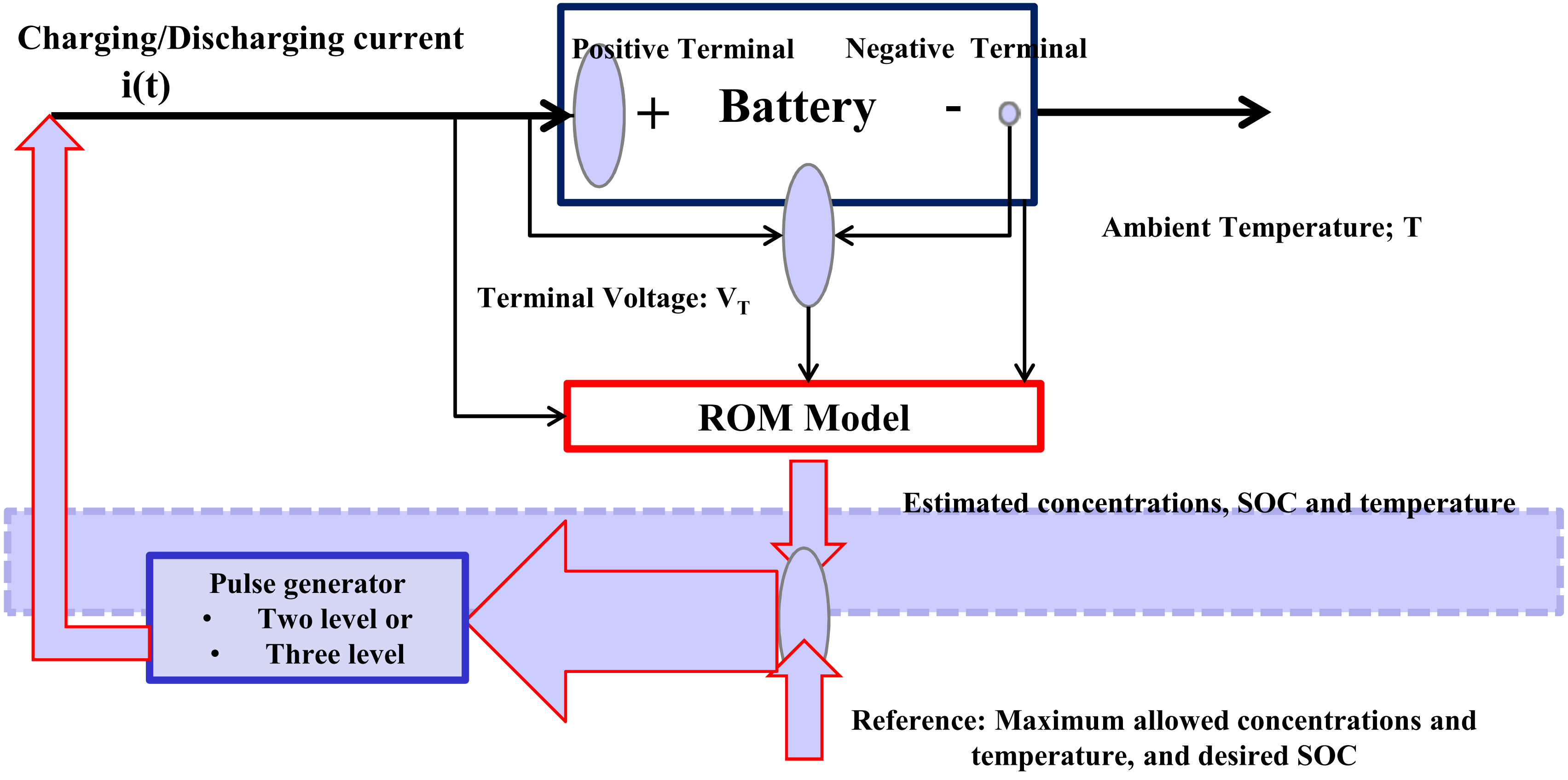
Voltage:



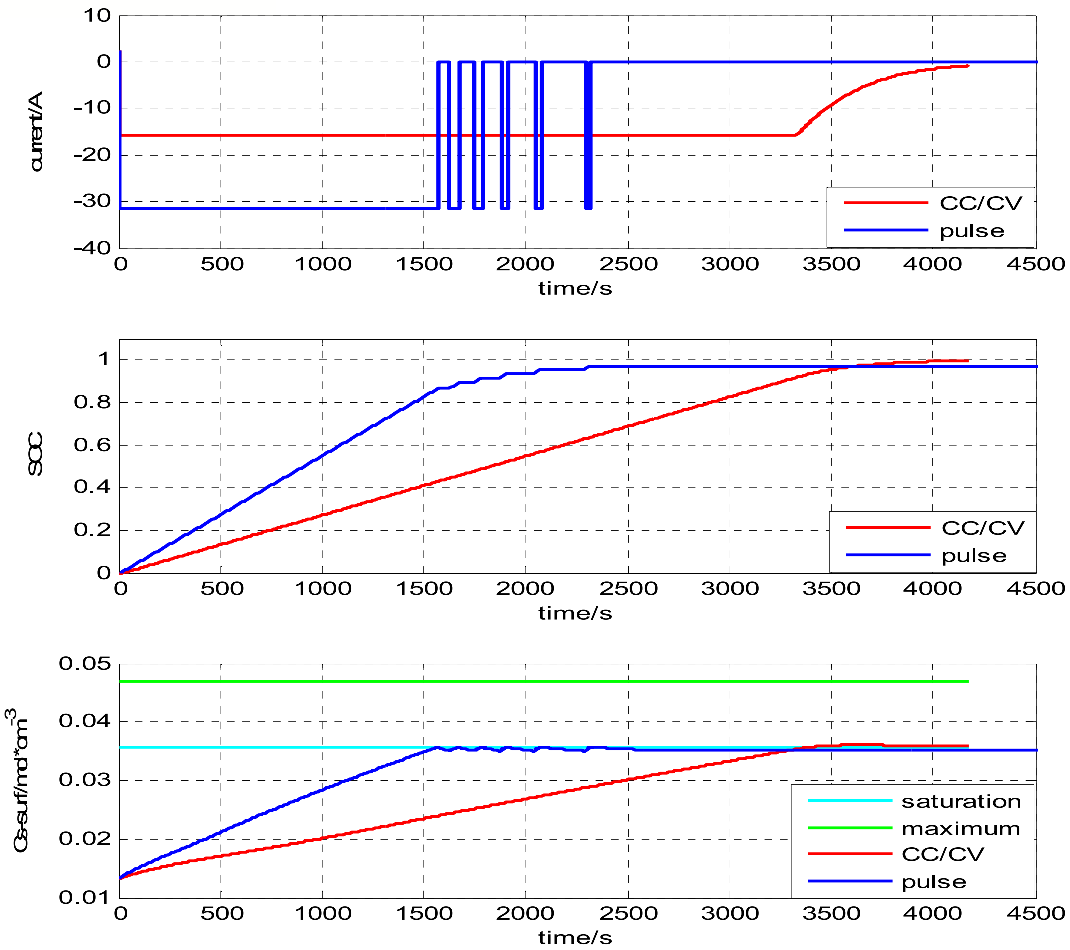
Error of SOC:



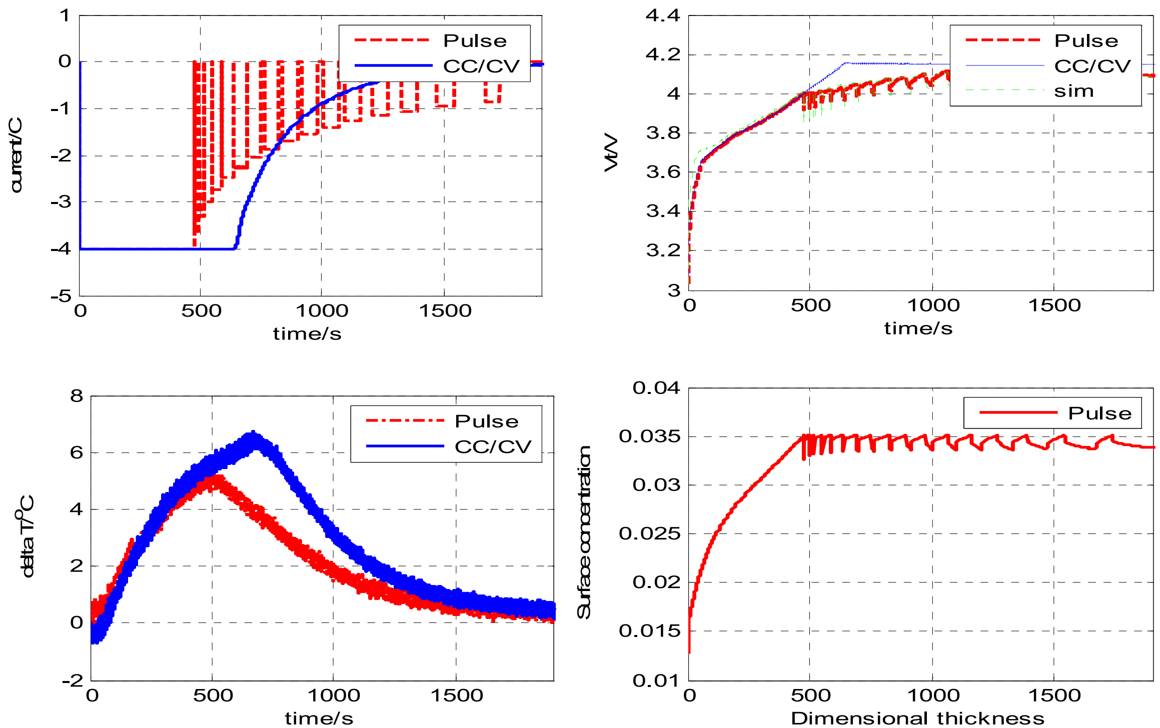
New Charging method



Simulation Results of Fast Charging method



Experimental results of the proposing Fast charging method



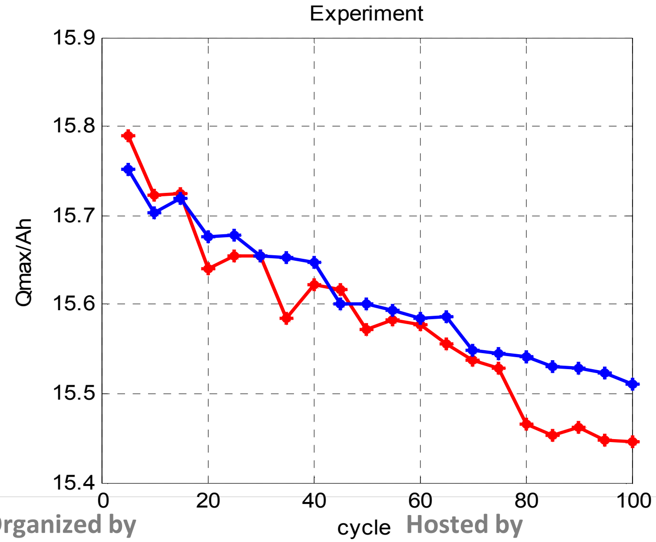
- **Reduction of Charging time in an amount of 30-40%**
- **Less heat is generated**
- **Surface concentration can be kept under upper limitation that slows down Lithium-plating**

Fast Charging Algorithm

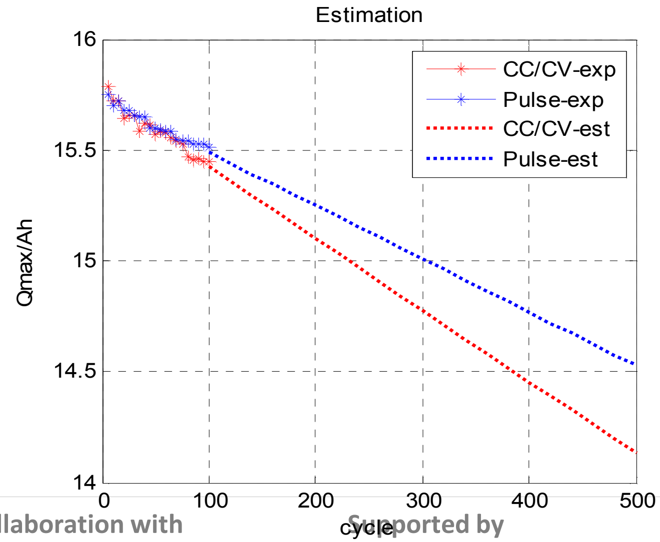
Test conditions:

Cell No.	1	2
Ambient temperature (°C)	25	25
Charging method	CC/CV	Pulse
Charging current (C)	4	4
Discharging current (C)	2	2
Rest time (min)	10	10
Cycles	100	100

- **Less capacity fade: 0.24Ah after 100 cycles compared to 0.34Ah by the CC and CV.**
- **Proof of limitation of the surface concentration of particles in the negative electrode and reduction of charging capacity losses by a relatively high charging current.**



If there is no significant



Summary

New fast charging algorithm is proposed

- **Development of a reduced Order Model based on electrochemical thermal model**
- **Design of SOC estimator based on EKF**
- **Validation of the model and SOC estimation at different current profiles**

Preliminary experimental results show;

- **Reduction of charging time up to 30-40%**
- **Reduction of capacity fade up to 6.3% at 100 cycles**
- **Less heat is generated**
- **SOC estimation errors less than 5 %**

Thanks for your attention.

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