# The Lithium-Ion Cell: Model, State Of Charge Estimation and Battery Management System


Carmelo Speltino

Tutor Giovanni Fiengo — Università del Sannio, Benevento, IT

Co-Tutor Anna Stefanopoulou — University of Michigan, Ann Arbor, MI, USA


Grace — Group for Research on Automatic Control Engineering

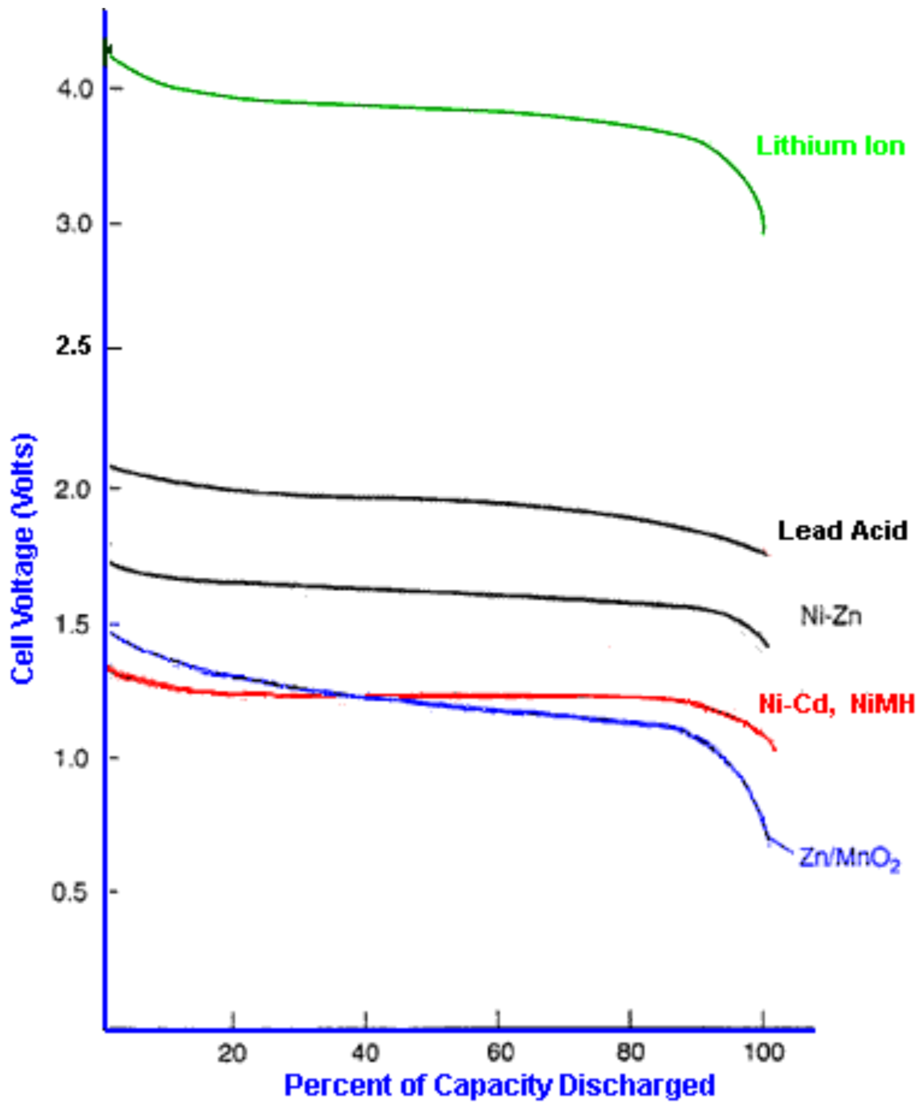
MICHIGAN

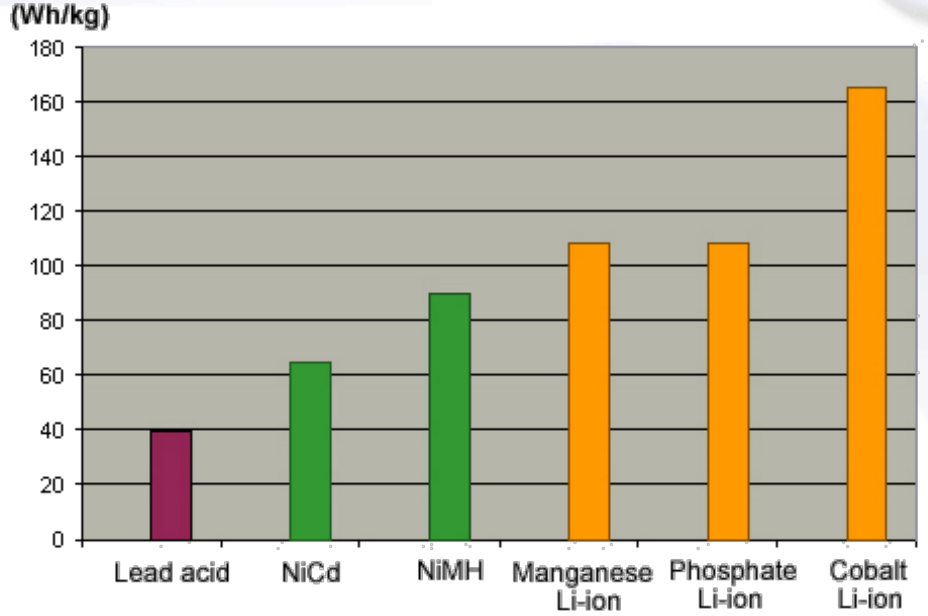
Università degli Studi del Sannio

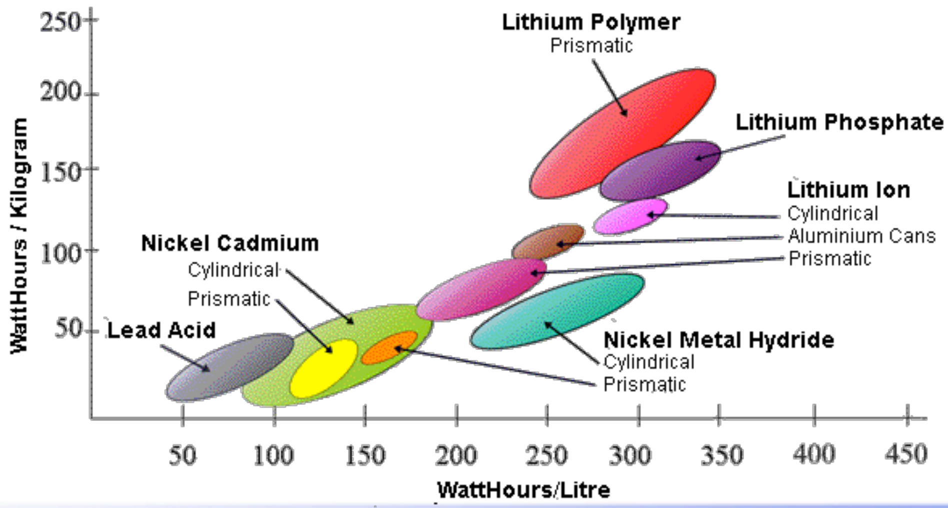
# Outline

- ✓ Cell Generalities
- ✓ Principle of Functioning
  - ❑ Electrochemical Model
  - ❑ Reduced Order Model
  - ❑ Parameter Identification
- ✓ State of Charge Estimation
  - ❑ Extended Kalman Filter
  - ❑ Critical SOC Definition
- ✓ Cell SOC Equalization
  - ❑ Battery Management System
- ❖ Neutron Scattering Analysis
  - ❑ Custom Designed Case
  - ❑ Preliminary Results

# Lithium-ion battery: Why choose it?

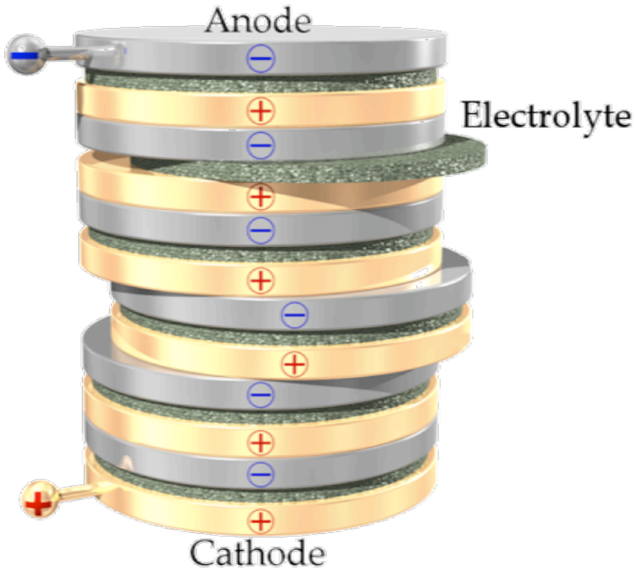


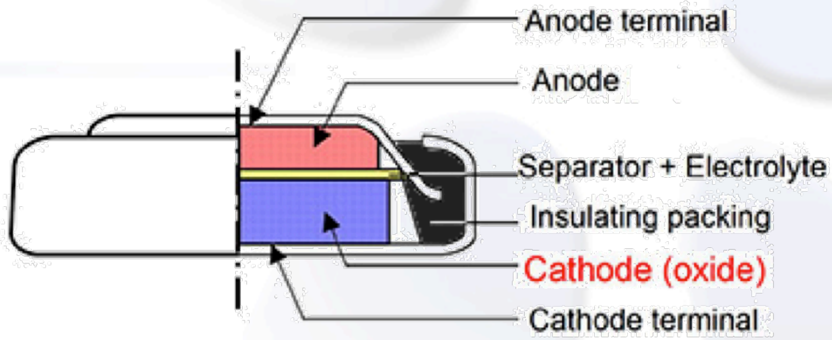



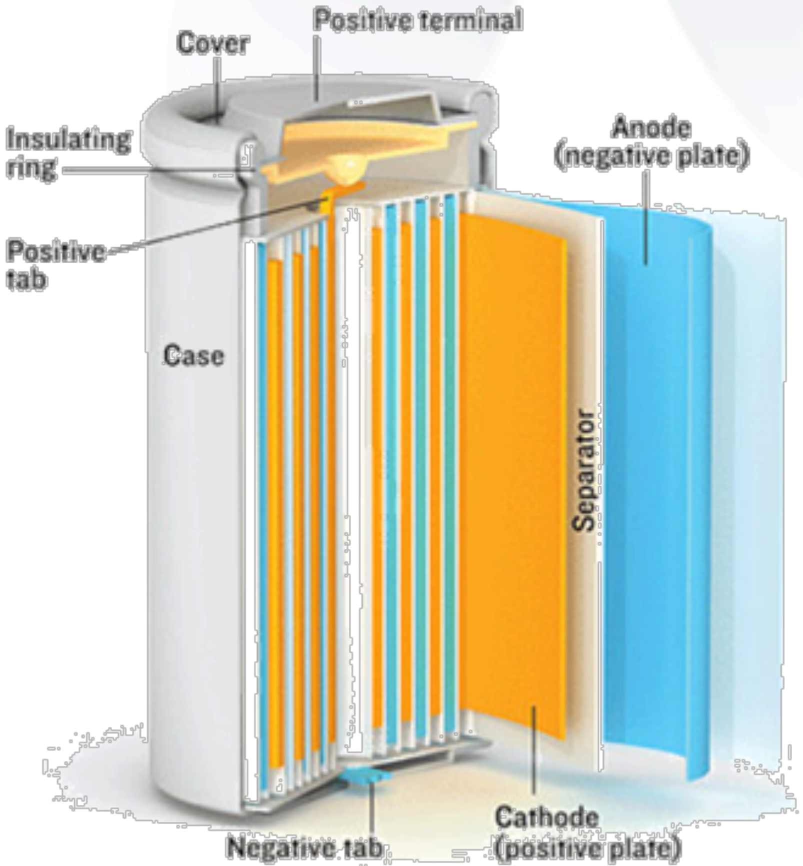

Grace

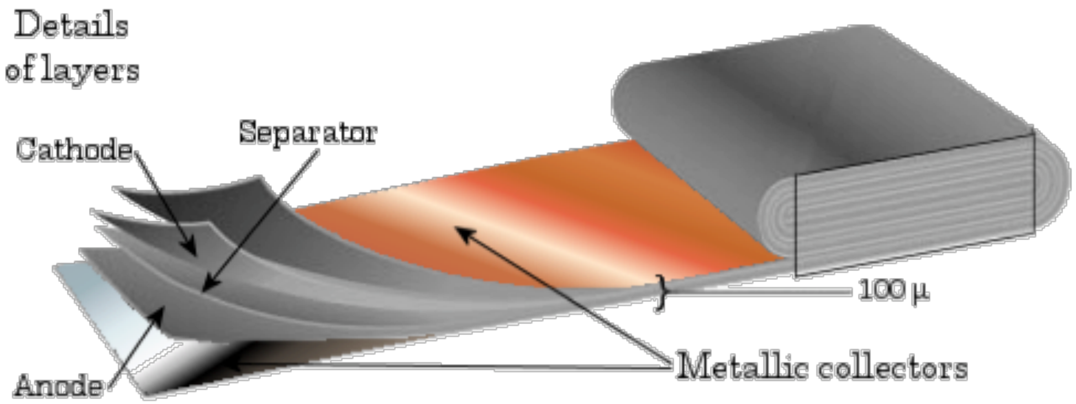
# Lithium-ion battery: Cell build



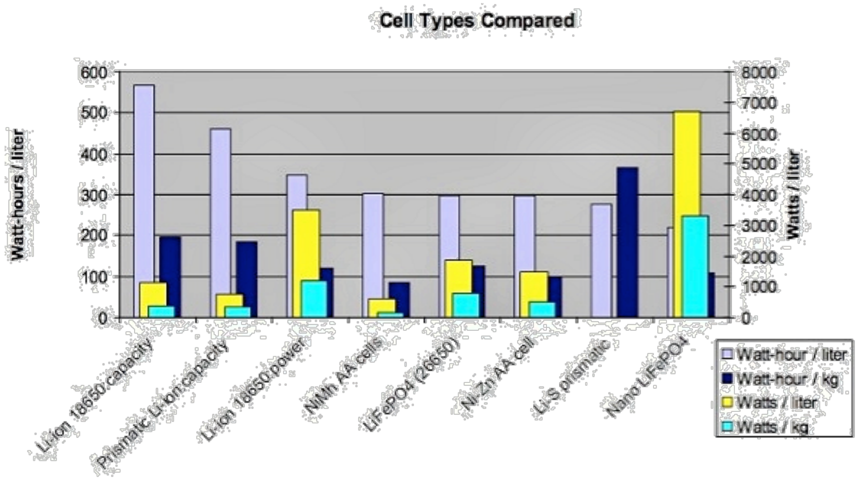


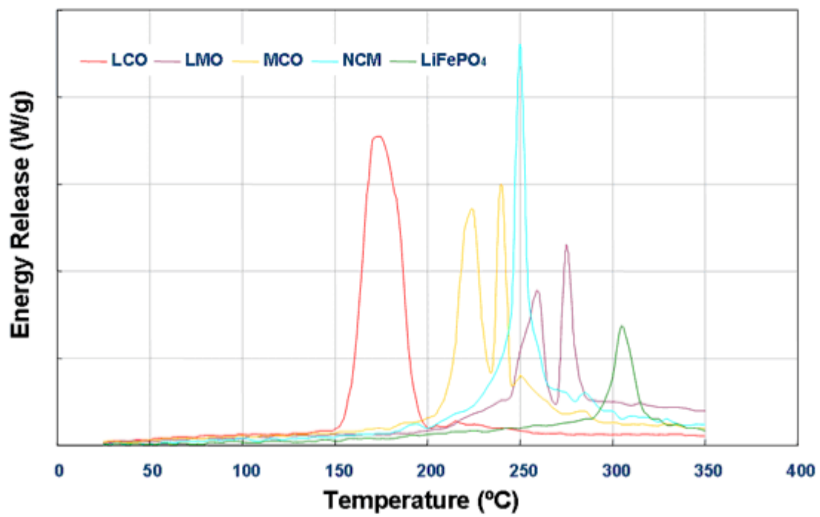


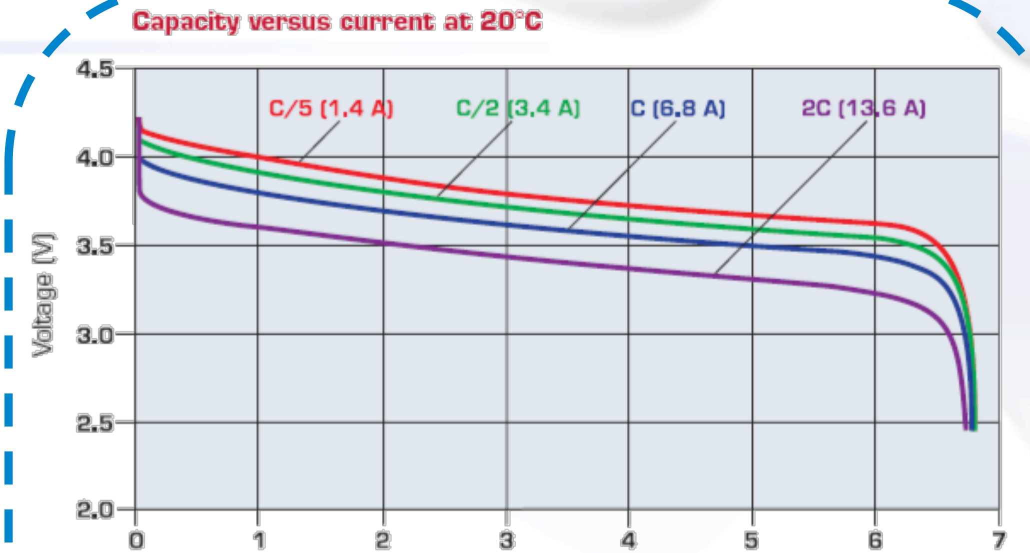



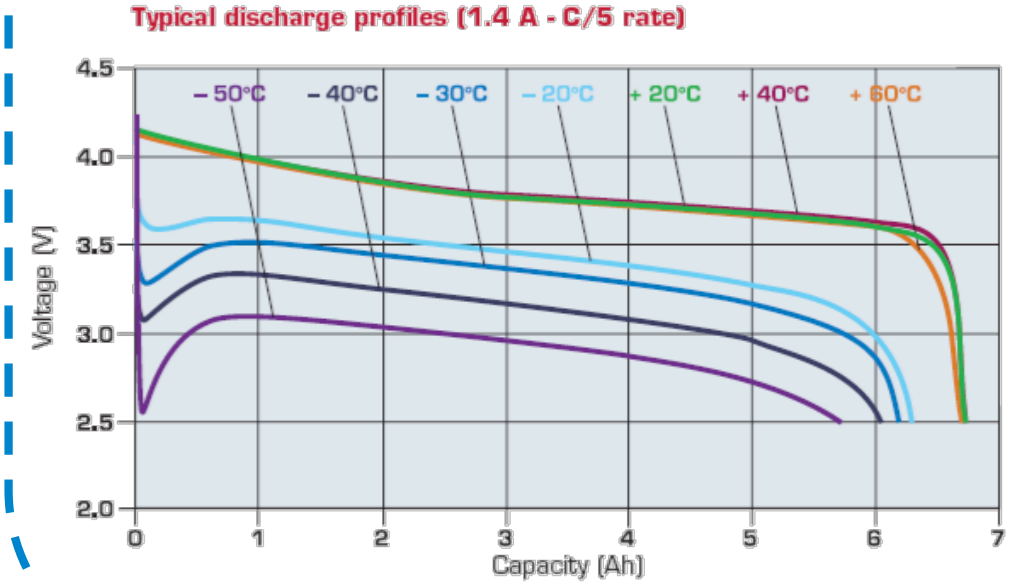



# Lithium-ion battery: Cell behavior



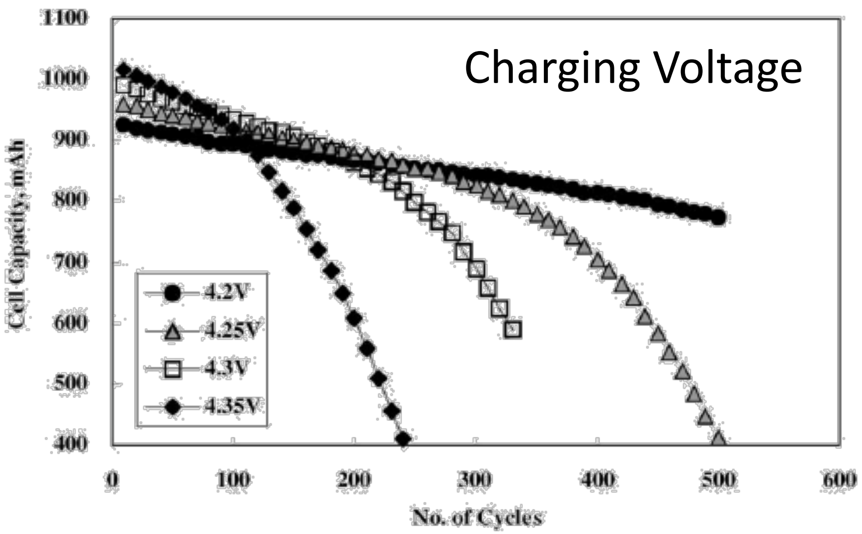



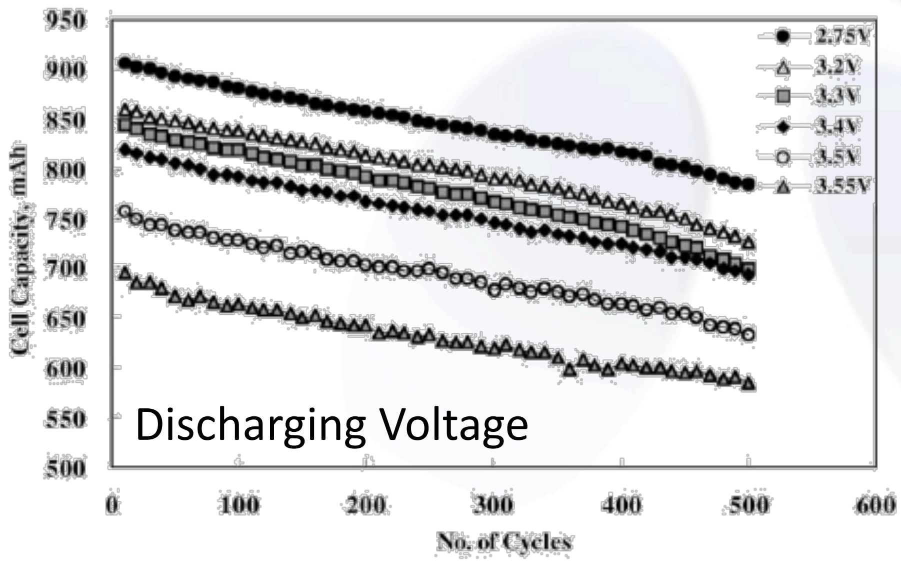



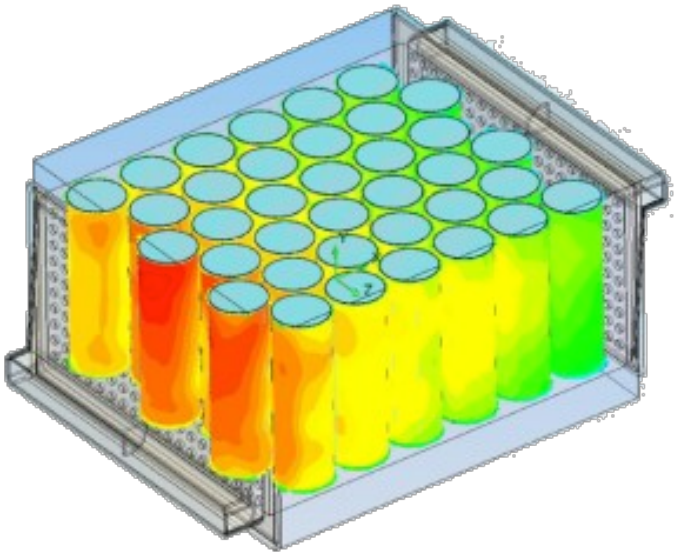

SAFT, **“MP176065”** Datasheet

Grace

# Lithium-ion battery: Cell degradation profiles



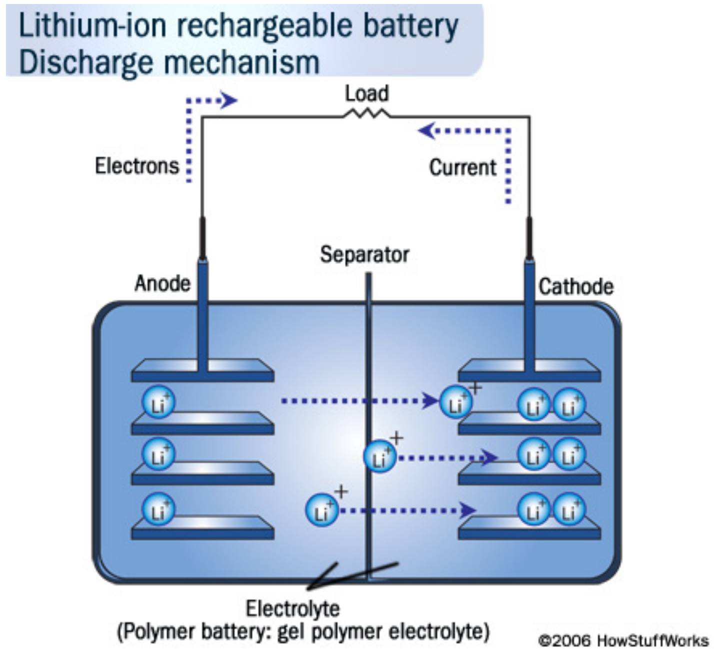



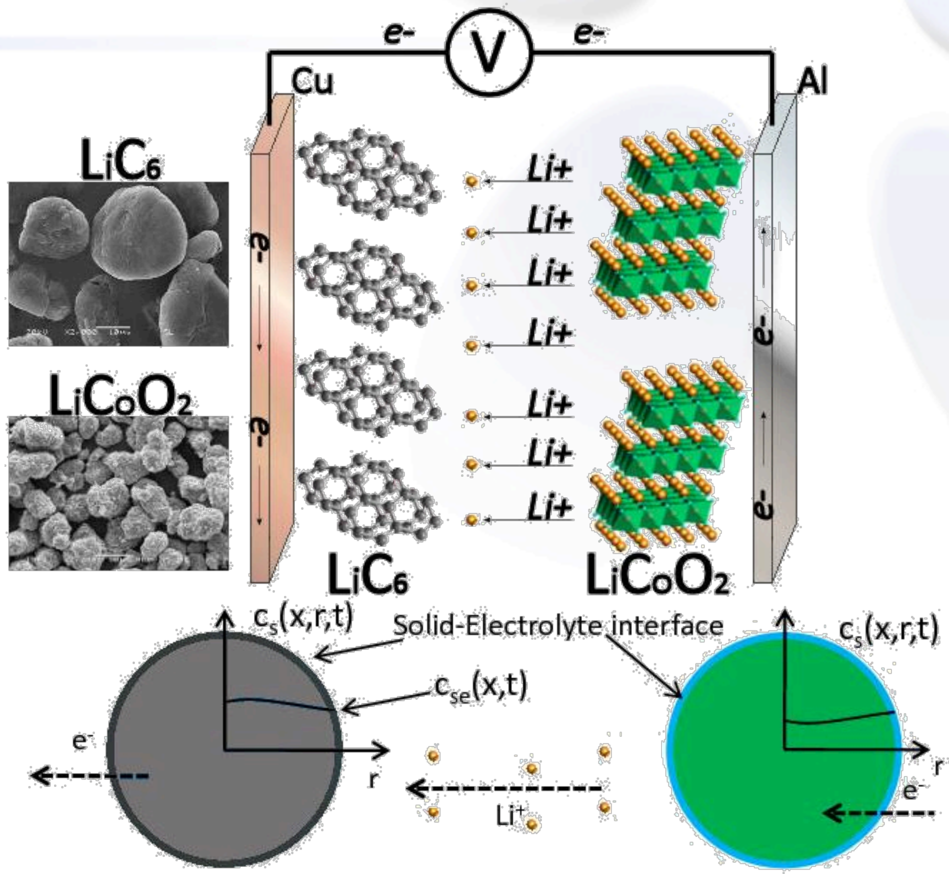



Battery pack thermal image

S. Choi and H. S. Lim, "*Factors that affect cycle-life and possible degradation mechanisms of a Li-ion cell based on LiCoO2",* Journal of Power Sources

# Lithium-ion battery: Cell internal structure



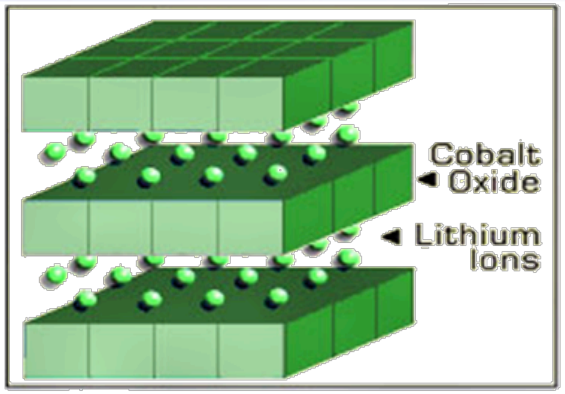



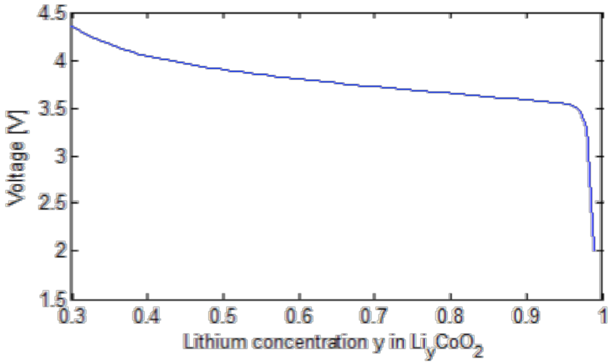

Lithium ions and $e^-$ are produced in the anode. The $e^-$ produce current in the external circuit, while lithium ions travel via diffusion through the solution to the cathode, where the external circuit $e^-$ are adsorbed.

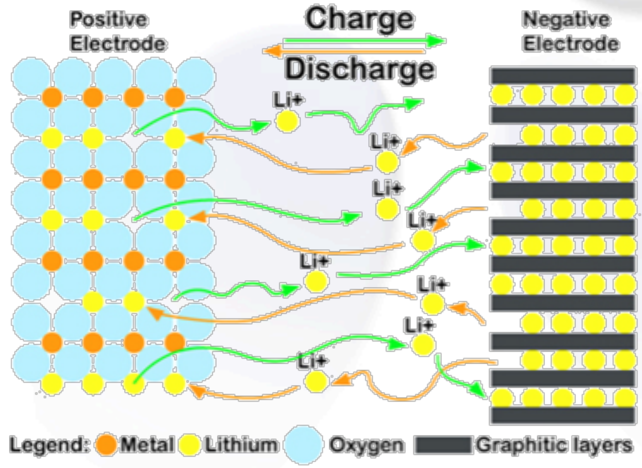
At anode, the solid active material diffuses through the spherical particles toward surface (electrolyte-solid interface) where it reacts due to the over-potential, transferring lithium-ions into the solution and $e^-$ to collector. At the cathode lithium ions and $e^-$ react and insert into metal solid particles.

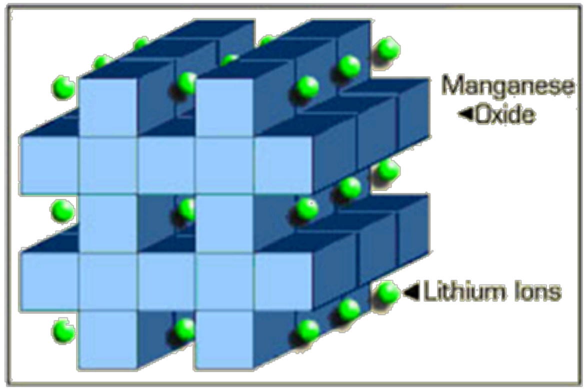
Grace

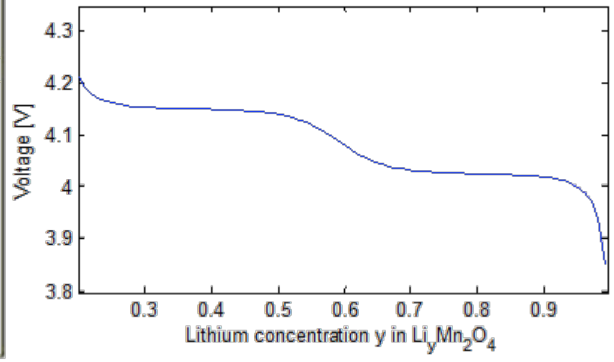
# Lithium-ion battery: Cathodic Intercalation

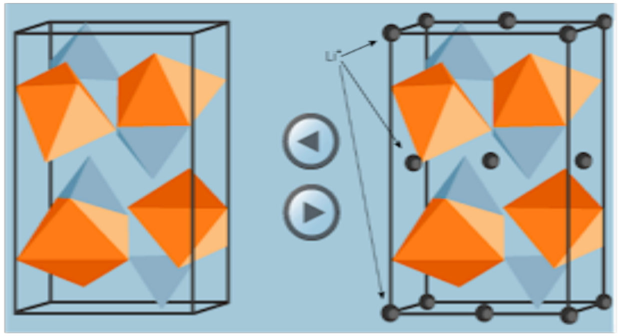


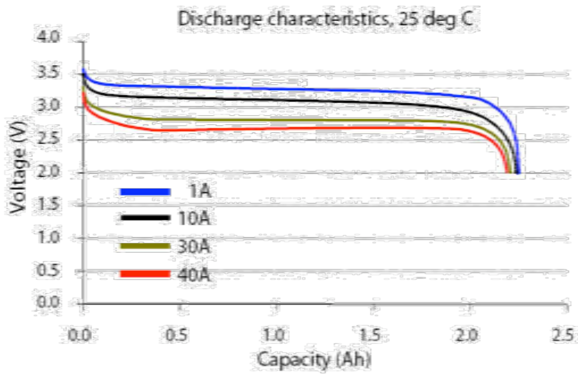



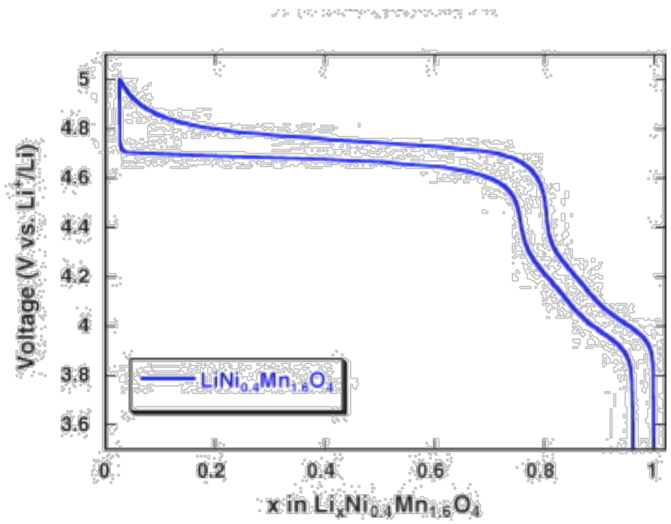





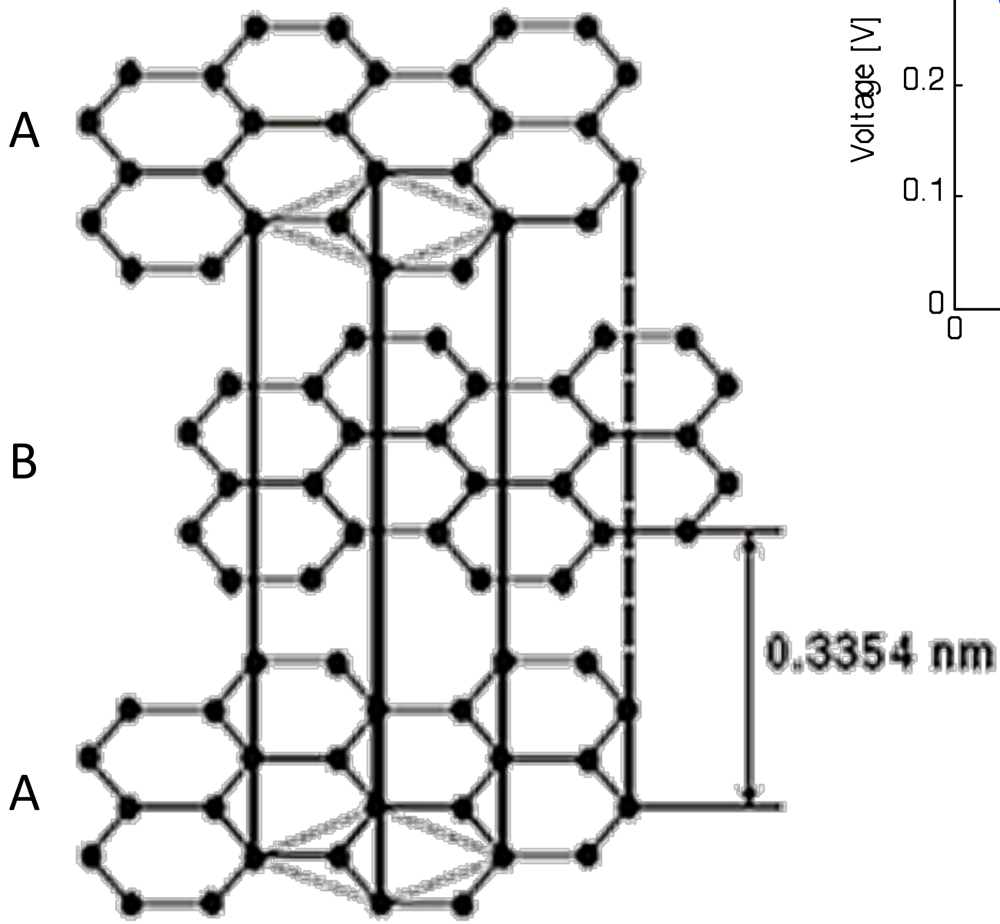



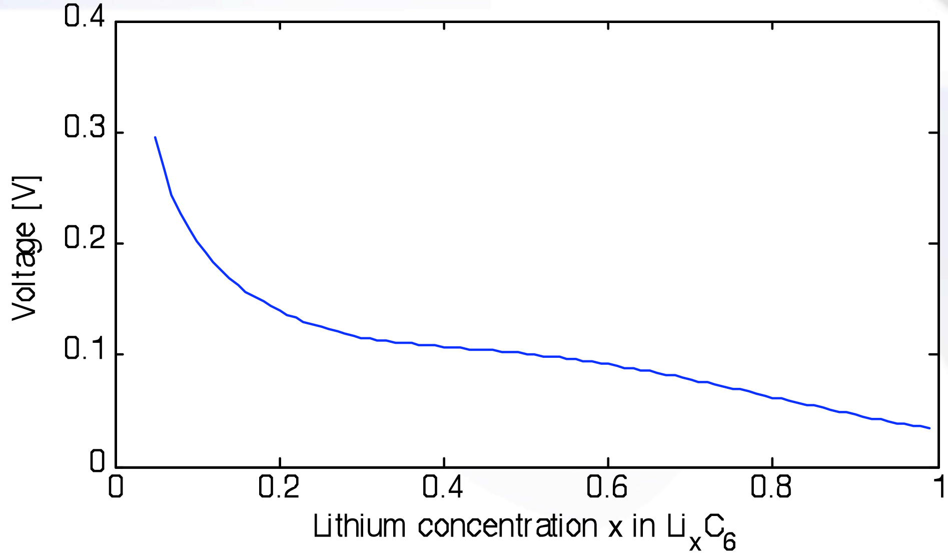

Grace

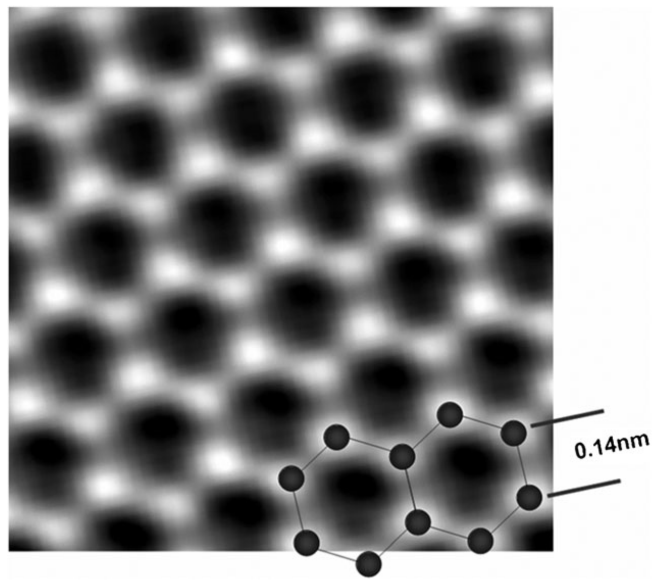
M. Doyle and Y. Fuentes. *Computer simulations of a lithium-ion polymer battery and implications for higher capacity next-generation battery designs*. J. Electrochem. Soc., 150:A706–A713, 2003.

# Lithium-ion battery : Anodic intercalation

Basal Surface Plan




Grace

## Electrodes

$$\frac{di_s}{dx} = j^{Li}$$

$$\sigma\varepsilon_s \frac{d\phi_s}{dx} = -i_s$$

$$\int_0^{\delta} j^{Li}(x)dx = \frac{I}{A}$$

$$\frac{di_e}{dx} = -j^{Li}$$

$$k\varepsilon_e \frac{d\phi_e}{dx} = -i_e$$

$$j^{Li} = a_{sn} j_0 \left[ \exp\left( \frac{\alpha_a F}{RT}\eta \right) - \exp\left( -\frac{\alpha_c F}{RT}\eta \right) \right]$$

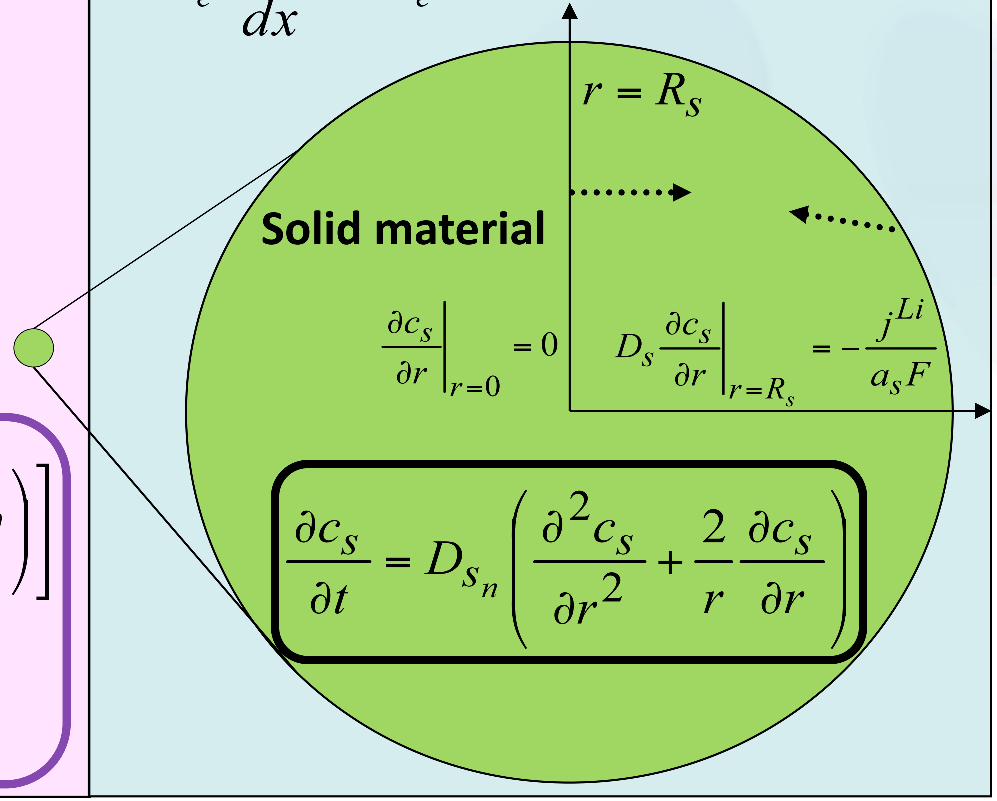
$$\eta = \phi_s - \phi_e - U(c_{se})$$

$$j_0 = j_0(c_{se})$$

## Separator

$$\frac{di_e}{dx} = 0$$

$$k\varepsilon_e \frac{d\phi_e}{dx} = -i_e$$




$$\left.\frac{\partial c_s}{\partial r}\right|_{r=0} = 0 \qquad \left. D_s \frac{\partial c_s}{\partial r}\right|_{r=R_s} = -\frac{j^{Li}}{a_s F}$$

$$\frac{\partial c_s}{\partial t} = D_{s_n} \left( \frac{\partial^2 c_s}{\partial r^2} + \frac{2}{r}\frac{\partial c_s}{\partial r} \right)$$

-- Charge Conservation, Solid Phase

-- Charge Conservation, Electrolyte Phase

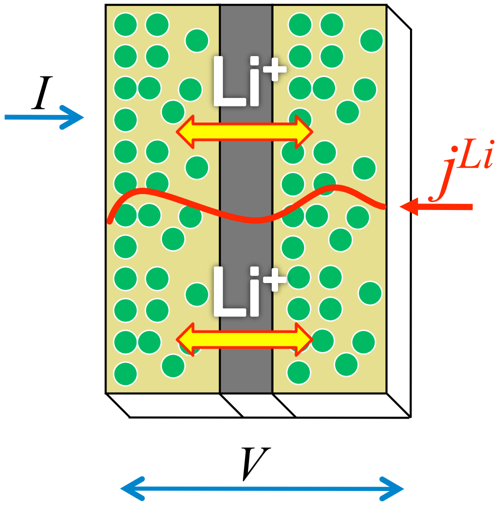
-- Solid Diffusion Equation

-- Butler-Volmer Equation

Grace

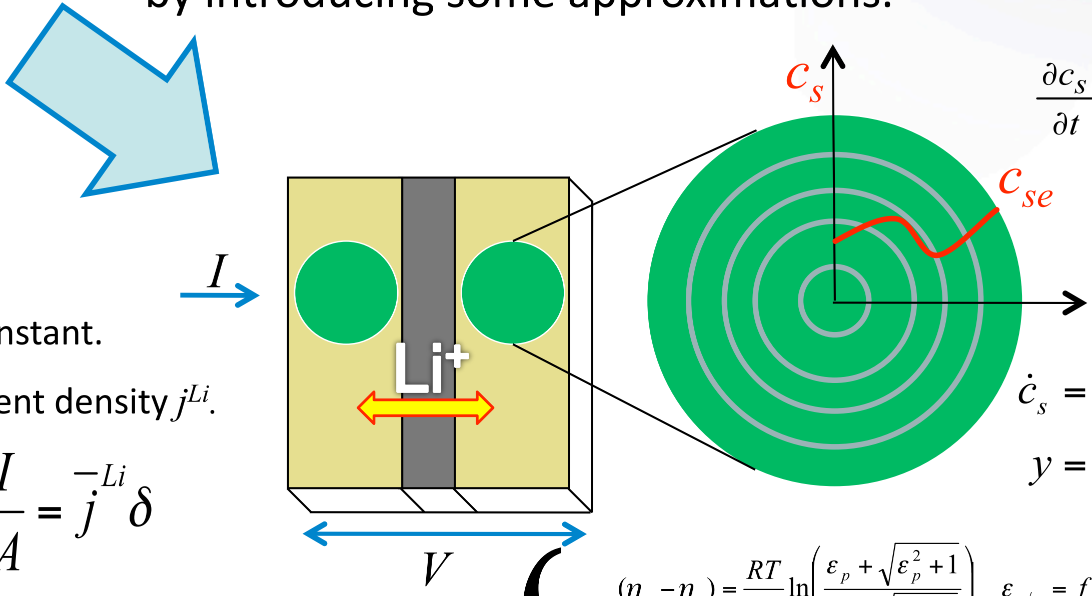
K. Smith and C.Y. Wang. *Solid-state diffusion limitations on pulse operation of a lithium-ion cell for hybrid electric vehicles*. Journal of Power Sources, 161:628–639, 2006

# Lithium-ion battery: Cell reduced order model




PDEs based systems are not useful for control applications and cannot be used for real time simulations.

A model reduction is necessary in order to derive a set of classical ODE based system. Typically this is accomplished by introducing some approximations.




$$\frac{\partial c_s}{\partial t} = D_{s_n}\left(\frac{\partial^2 c_s}{\partial r^2} + \frac{2}{r}\frac{\partial c_s}{\partial r}\right)$$

$$\dot{c}_s = \mathbf{A}c_s + \mathbf{B}u \qquad u = \bar{j}^{Li}$$

$$y = \mathbf{C}c_s + \mathbf{D}u \qquad y = c_{se}$$

✓Electrolyte concentration $c_e$ constant.

✓Average solution of micro-current density $j^{Li}$.

$$\frac{\partial j}{\partial x} = 0 \Rightarrow \int_0^{\delta} j^{Li}(x)dx = \frac{I}{A} = \bar{j}^{Li}\delta$$

$$V = (\eta_p - \eta_n) + (\phi_p - \phi_n) + (U_p - U_n) - \frac{R_f}{A} I \quad \begin{cases} (\eta_p - \eta_n) = \frac{RT}{2F}\ln\left(\frac{\varepsilon_p + \sqrt{\varepsilon_p^2 + 1}}{\varepsilon_n + \sqrt{\varepsilon_n^2 + 1}}\right) & \varepsilon_{p/n} = f(I, c_{se,p/n}) \\ (\phi_p - \phi_n) \cong -\frac{I}{2AK^{eff}}(\delta_n + 2\delta_{sep} + \delta_p) = -\frac{I}{A}K_t & \\ (U_p - U_n) = f(c_{se,p}) - f(c_{se,n}) & \end{cases}$$



D. Di Domenico, A. Stefanopoulou, and G. Fiengo., *Reduced Order Lithium-ion Battery Electrochemical Model And Extended Kalman Filter State Of Charge Estimation*. ASME JDSMC, 2008

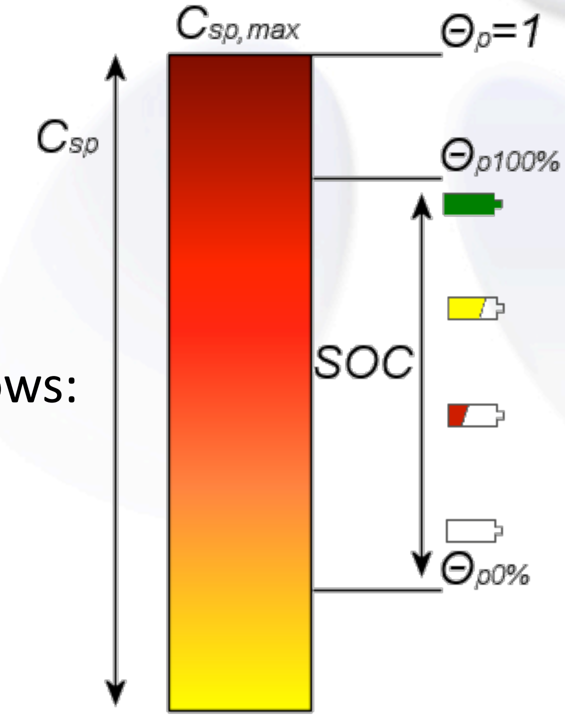
# Lithium-ion battery: Critical SOC definition

By defining solid surface concentration stoichiometry (also indicated as normalized concentration) as:

$$\theta = \frac{c_s}{c_{s,\max}}$$

the battery critical SOC can be conveniently defined as follows:

$$SOC = \frac{\theta_p - \theta_{0\%}}{\theta_{100\%} - \theta_{0\%}} \qquad \theta_p = \frac{C_{se,p}}{C_{se,p/\max}}$$




Where $\theta_{100\%}$ and $\theta_{0\%}$ are respectively the positive solid surface concentration stoichiometry of a full charged and a full discharged battery.

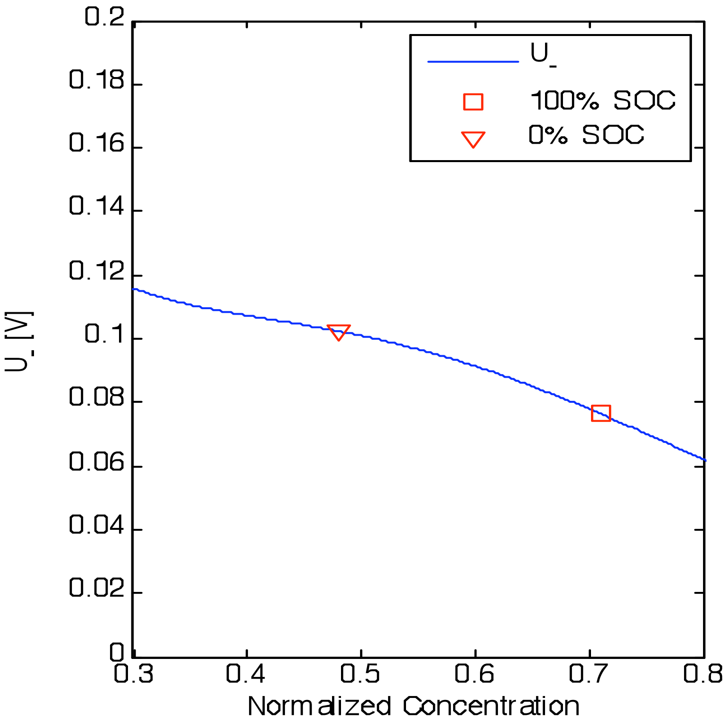
The SOC can be defined equivalently on the positive or negative solid concentration, but is defined on the positive because of its greater range of variation during battery charge and discharge operations.

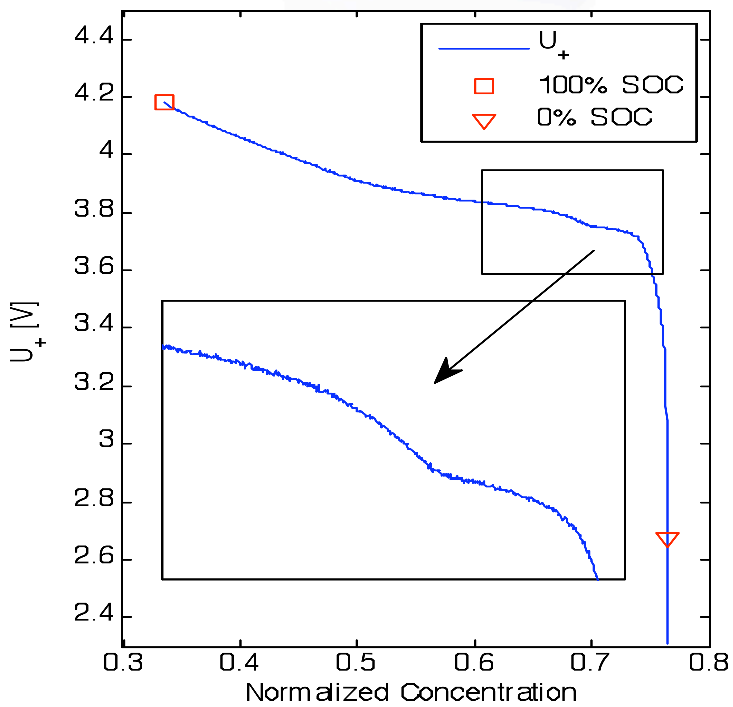
Grace

# Lithium-ion battery: OCP identification

The negative electrode is composed of graphite ($LiC_6$), so it is possible to utilize the empirical relationship between the solid concentration and OCP from Doyle *et al.*

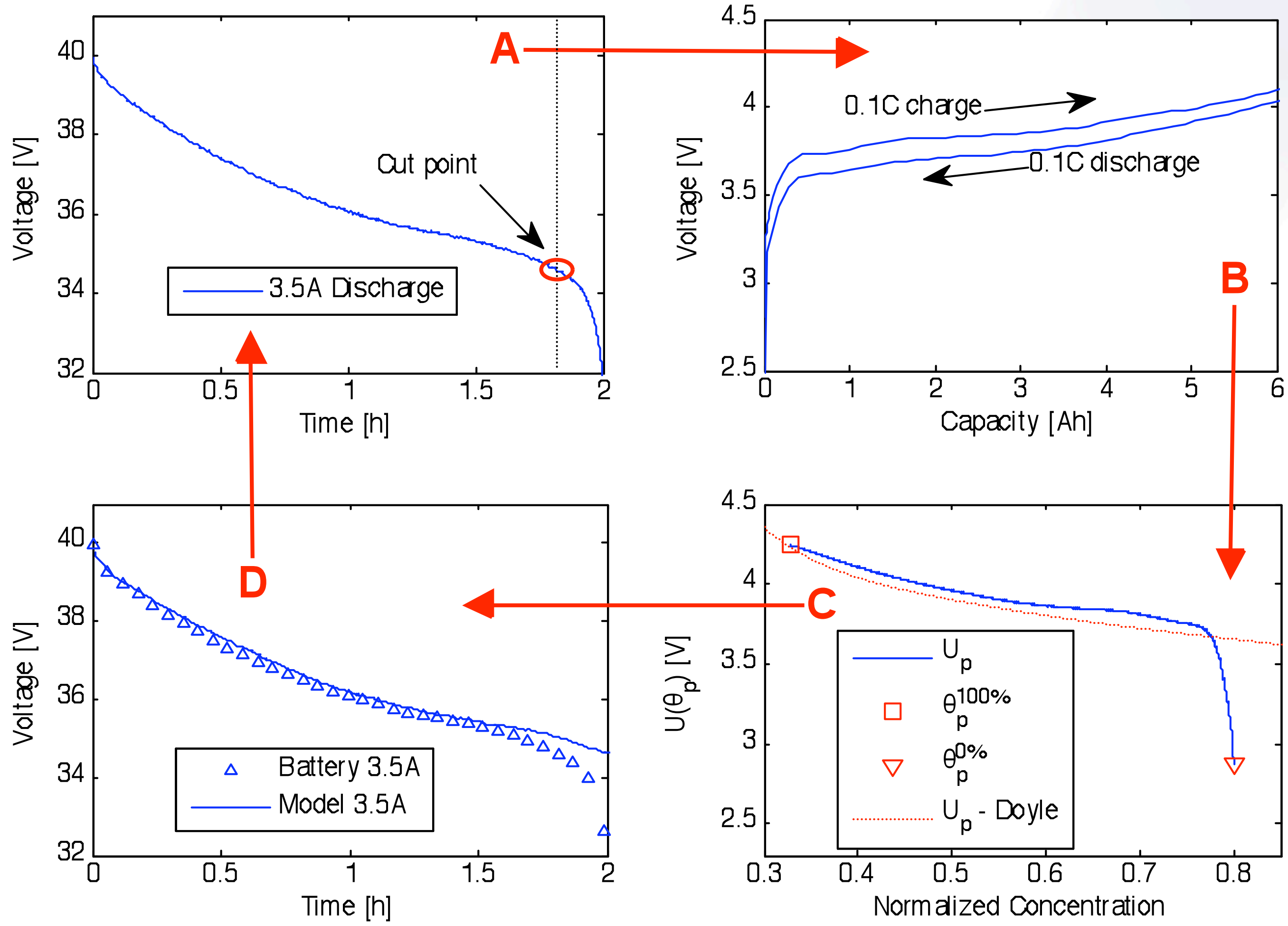
The positive electrode instead, is composed of a mixture of Lithium metal oxides, so the correlation function $U_p$ needs to be identified as well.



# Lithium-ion battery: OCP identification

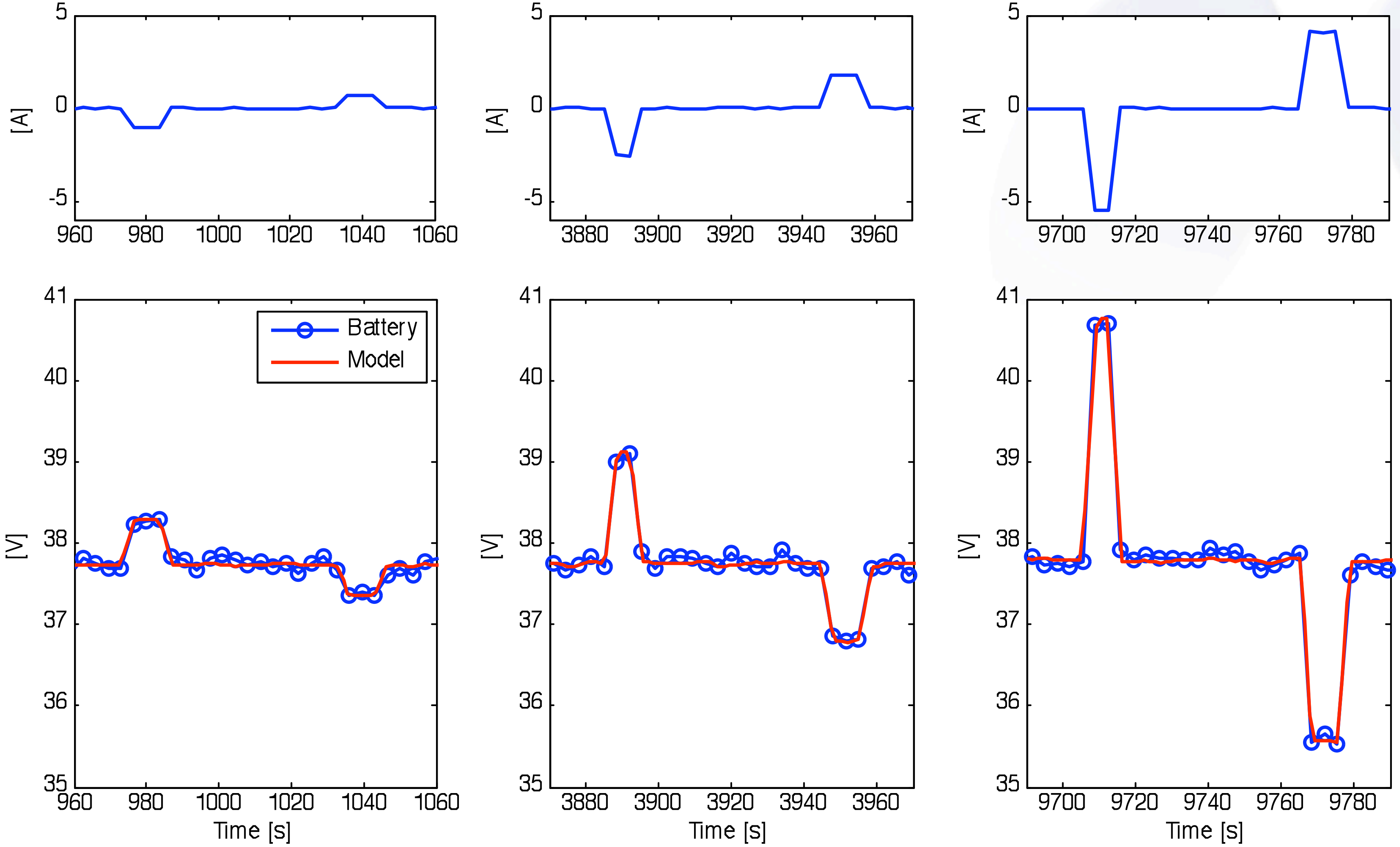
The identification of the $U_p$ function is part of the global identification procedure and it is obtained through a series of iterative refinements as shown below:




Grace

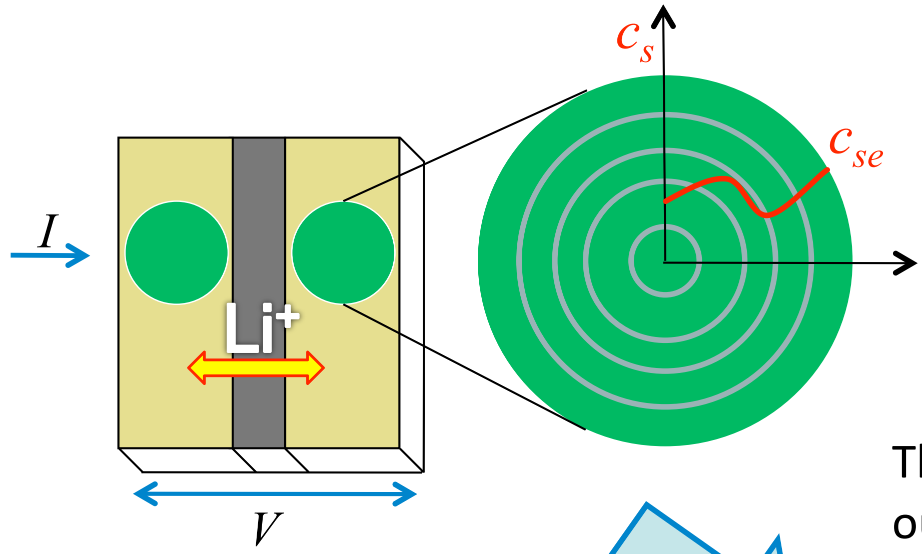
# Lithium-ion battery: Validation results

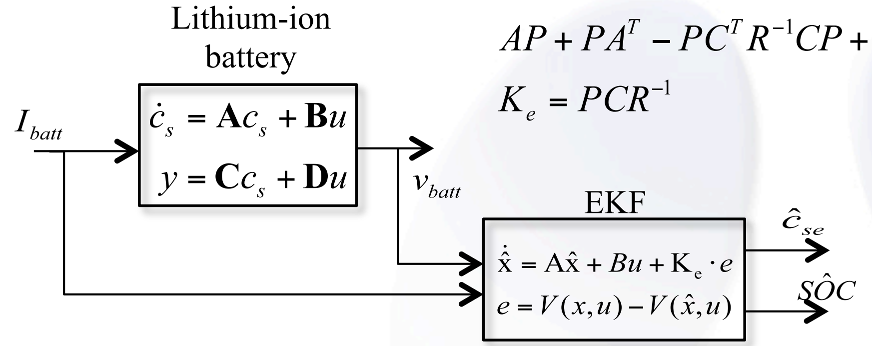
Validation test results – Increasing amplitude HPPC profiles




Grace

# Lithium-ion battery: Extended Kalman Filter



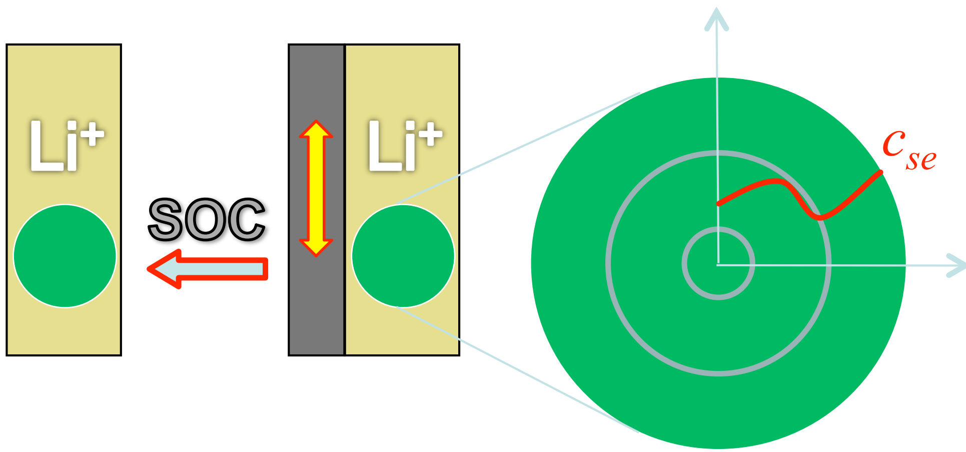

$$AP + PA^T - PC^T R^{-1} CP + Q = 0$$

$$K_e = PCR^{-1}$$

The system has a poor observability because the output is the difference of two sub-systems!

A further reduction:
The single electrode model.

The negative electrode quantities are estimated through inversion of the positive SOC calculation.

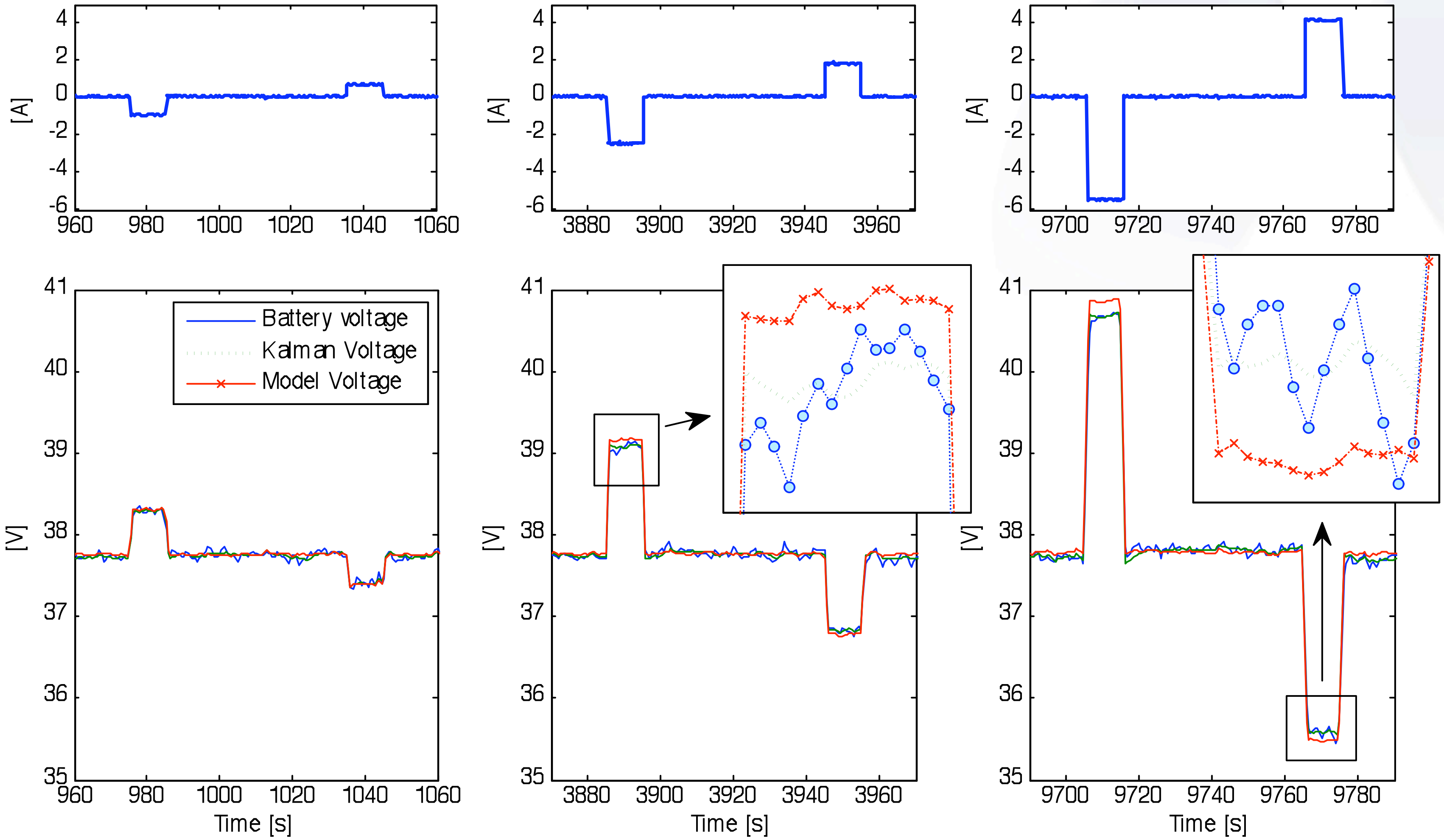



Grace

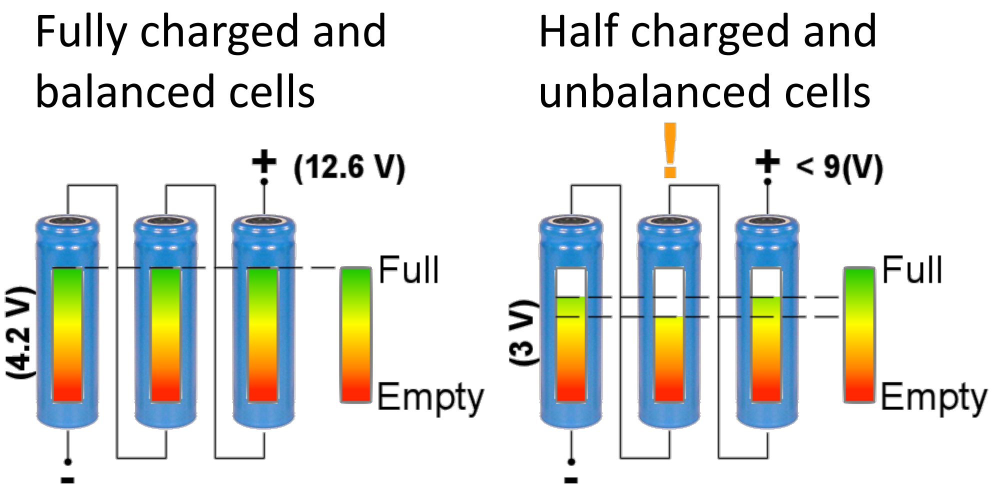
C.Speltino, D. Di Domenico, A. Stefanopoulou, and G. Fiengo., *Experimental Validation of a Lithium-Ion Battery State of Charge Estimation with an Extended Kalman Filter*, ECC 09.

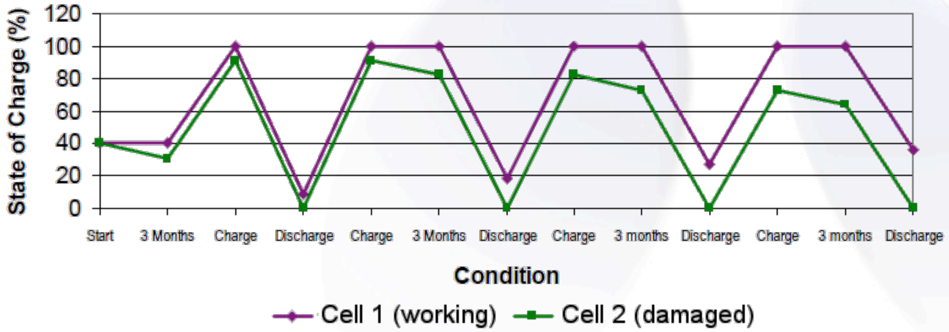
# Lithium-ion battery: EKF results

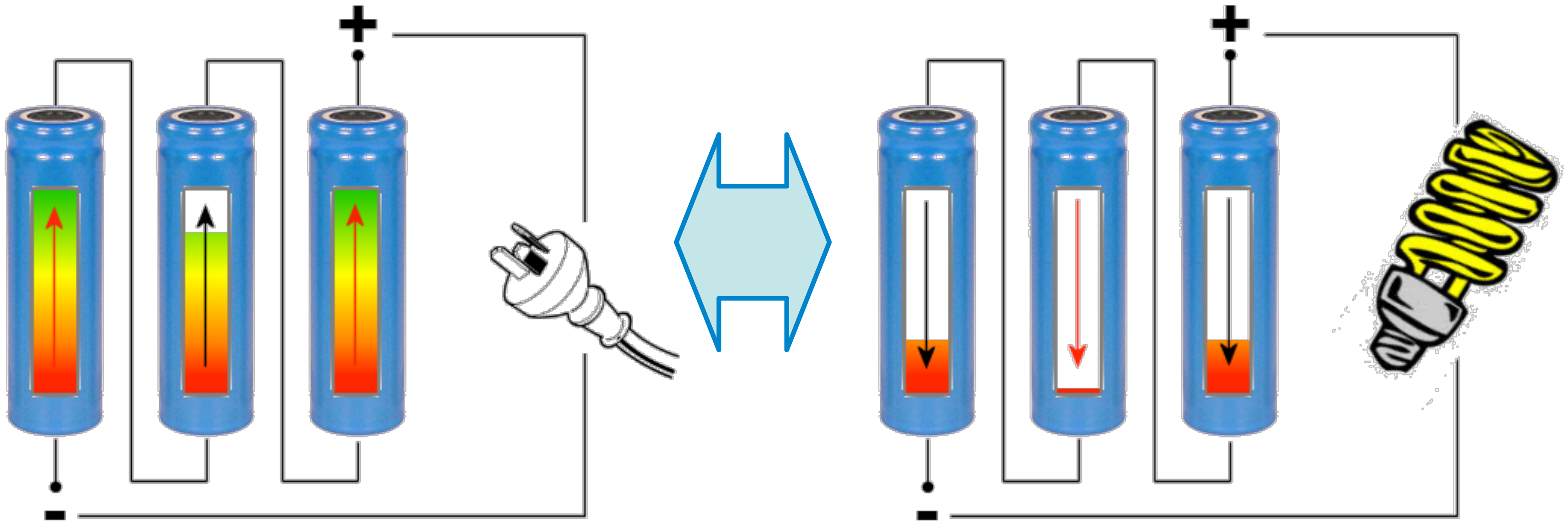
HPPC profiles, with increasing reference current charge and discharge.



# Lithium-ion battery: Cell balancing



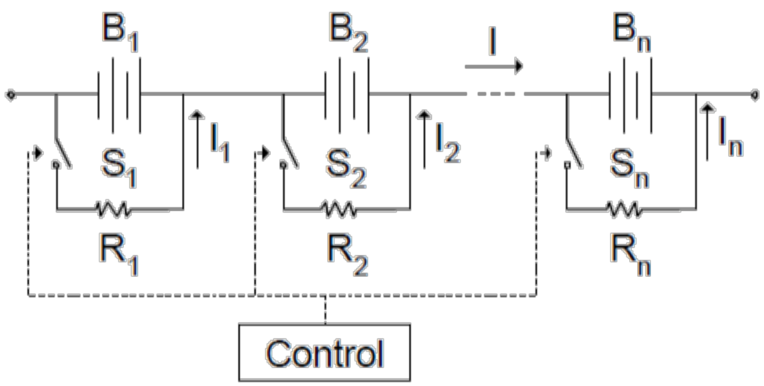



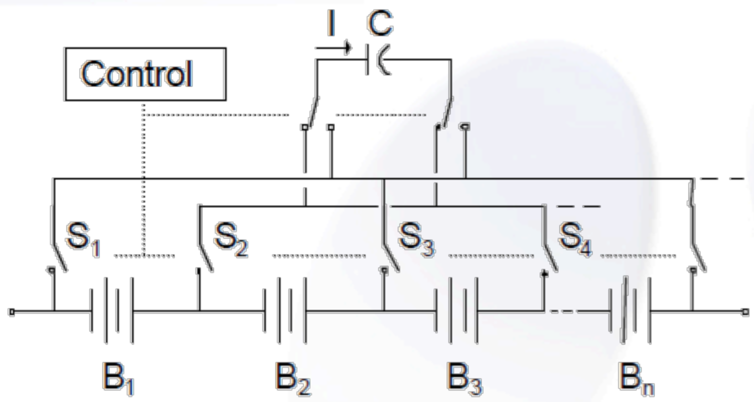

Grace

A. Jossen, V. Spath, H. Doring and J. Garche, *"Reliable Battery Operation — A Challenge For The Battery Management System"*, Journal of Power Sources

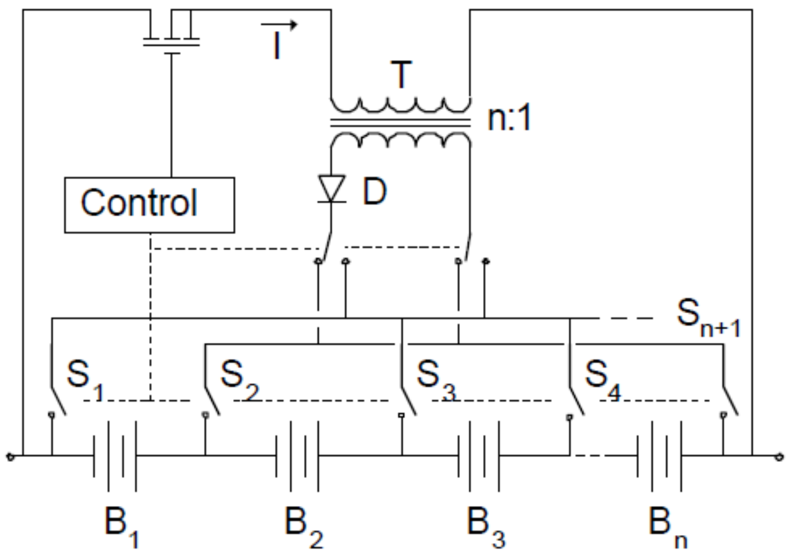
# Lithium-ion battery: Cell balancing



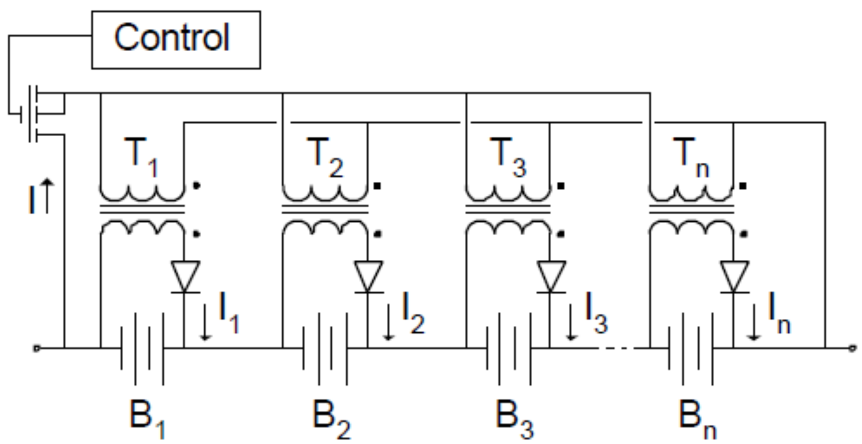

Charge Shunting




Charge Shuttling




Switched Transformer




Multiple Transformer



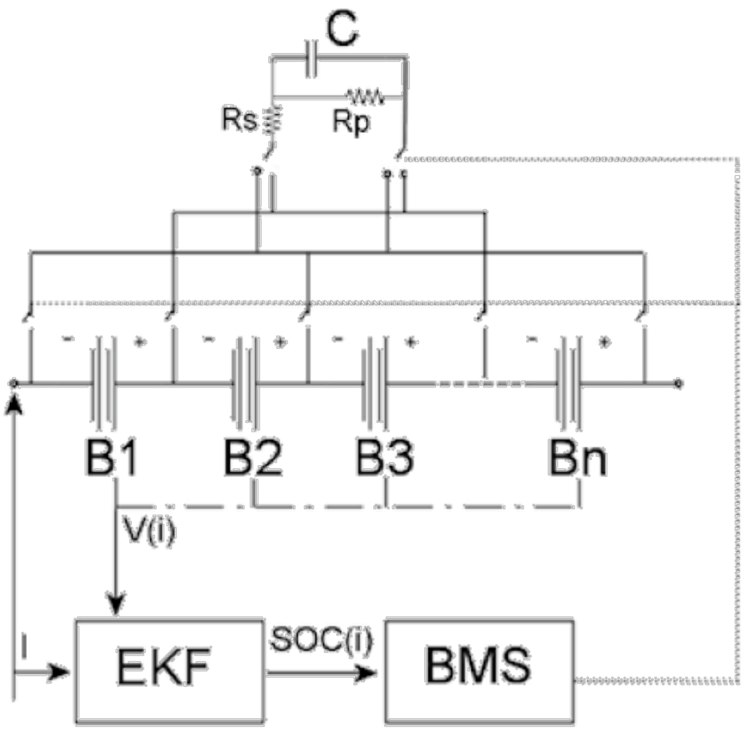
S. Moore and P. Schneider, *" A Review of Cell Equalization Methods for Lithium Ion and Lithium Polymer Battery Systems "*, SAE, 2001-01-0959

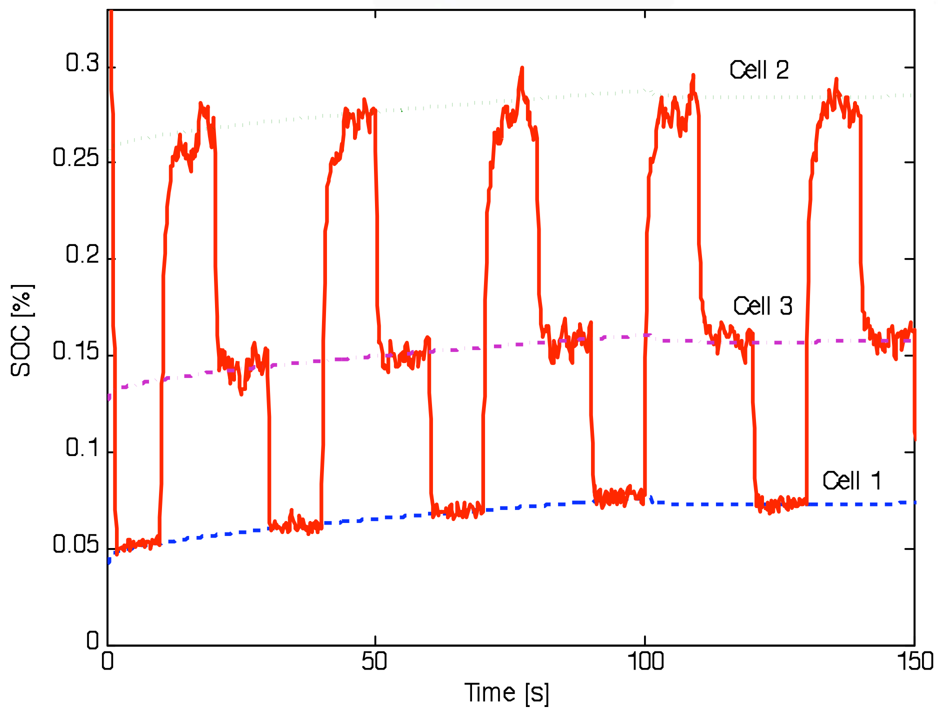
# Lithium-ion battery: Cell balancing

The charge equalization circuit is a modified version of the charge shuttling method.

A switched capacitor drains energy from the battery pack and releases energy on the weaker cell, raising its SOC to equalize the battery.

The BMS algorithm utilizes the EKF estimation to select the weaker cell in the pack.





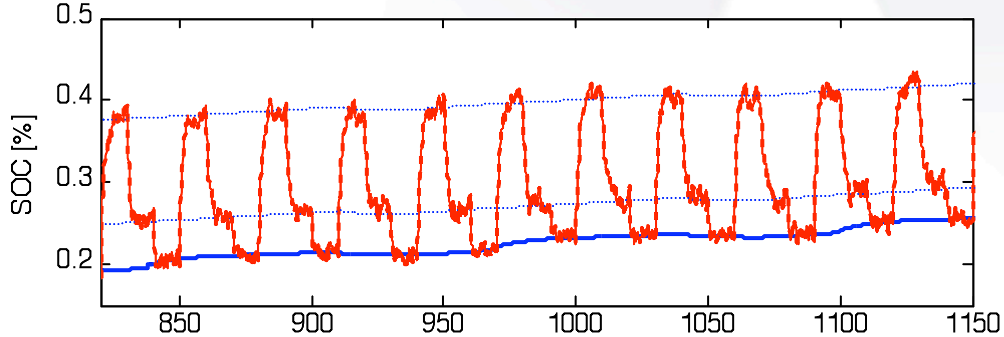

Carmelo Speltino, Anna Stefanopoulou and Giovanni Fiengo, *"Cell Equalization In Battery Stacks Through State Of Charge Estimation Polling"* Proceedings of CDC

# BMS – Cell equalization algorithm

✓Each cell is polled by the EKF for 10 s. The gain of the filter have been chosen in order to ensure the estimation convergence in less than 5 s.

✓The SOC of the cells that are not polled by the EKF are tracked by simple coulomb counting integrator models:

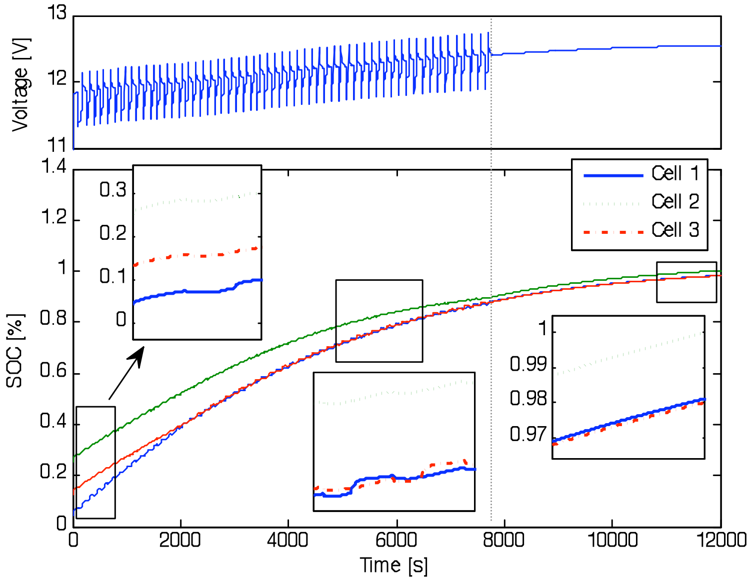
$$SOC(i) = \frac{1}{C}\int I(t)dt + SOC(i)_0$$

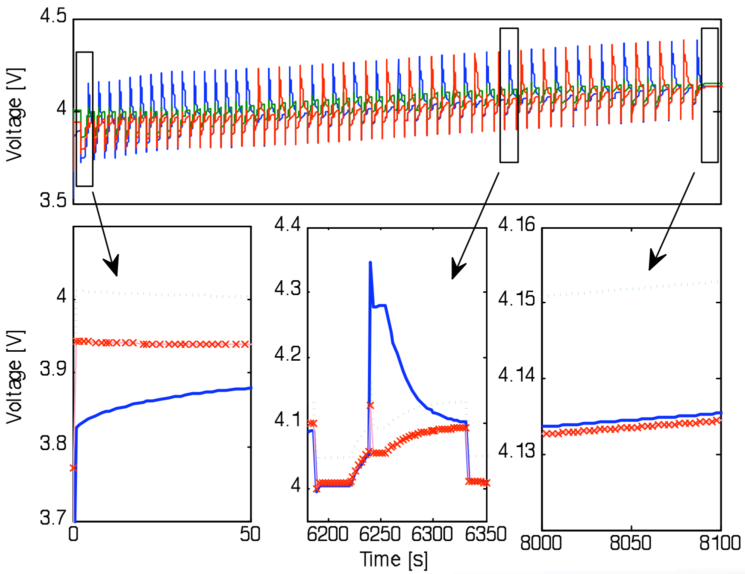



The cell equalization procedure is the following:

1. Identify the lowest charged cell while charging the capacitor up to a fixed threshold *HV;*
2. Discharge the capacitor over the selected cell until its voltage goes under a fixed threshold *LV;*
3. Check SOC difference for all the cell;
4. Repeat step 1, 2 and 3 until maximum difference in SOC becomes lower than 2%.

# Lithium-ion battery: BMS results

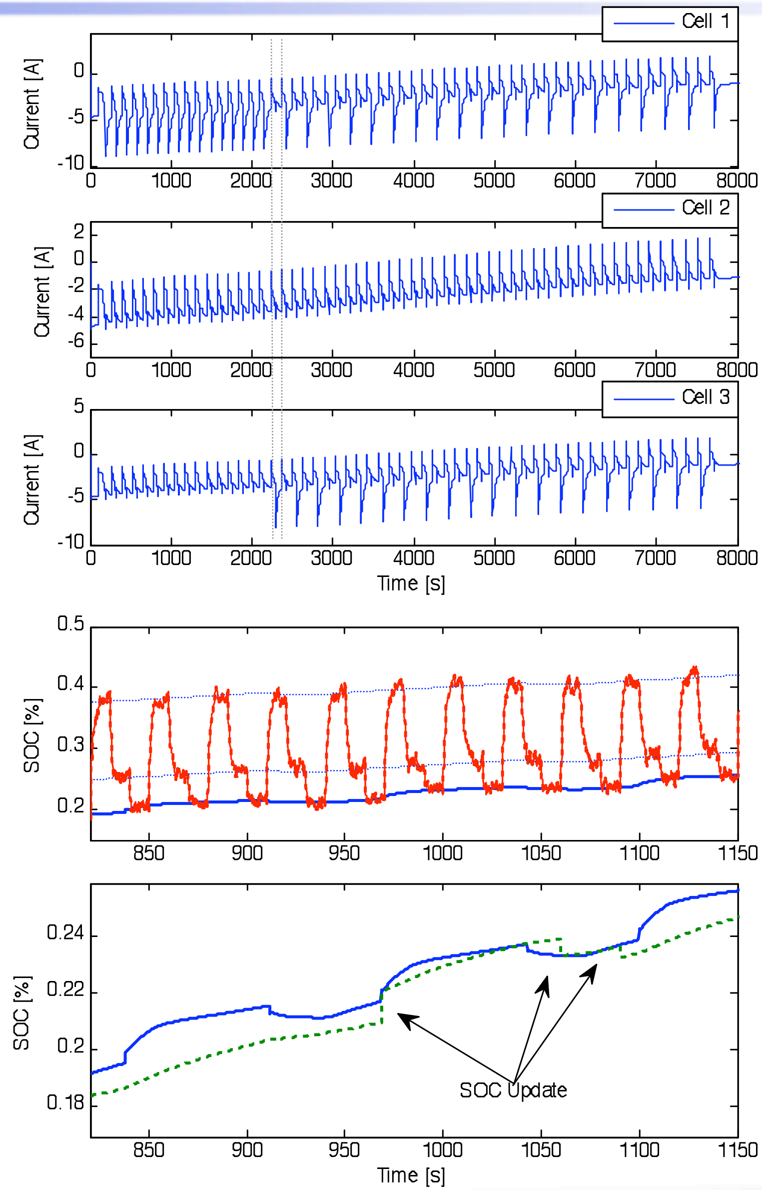



- ✓ Cells start with a strong unbalance.
- ✓ Cell 1 is the first to be selected.
- ✓ When cell 1 and cell 3 have the same SOC they start to be alternatively selected.
- ✓ The equalization process ends at 8000 s.
- ✓ High initial voltage difference because cell 1 and 3 are almost totally discharged.
- ✓ When a cell is selected by the BMS, it receives a charge injection, raising its SOC.
- ✓ Final voltage difference is less than 0.02V. Final SOC difference is less than 1%.

Grace

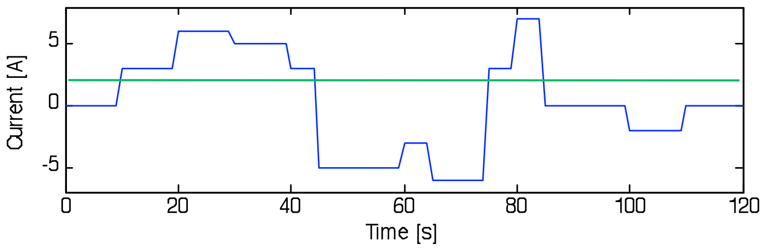
# Lithium-ion battery: BMS results

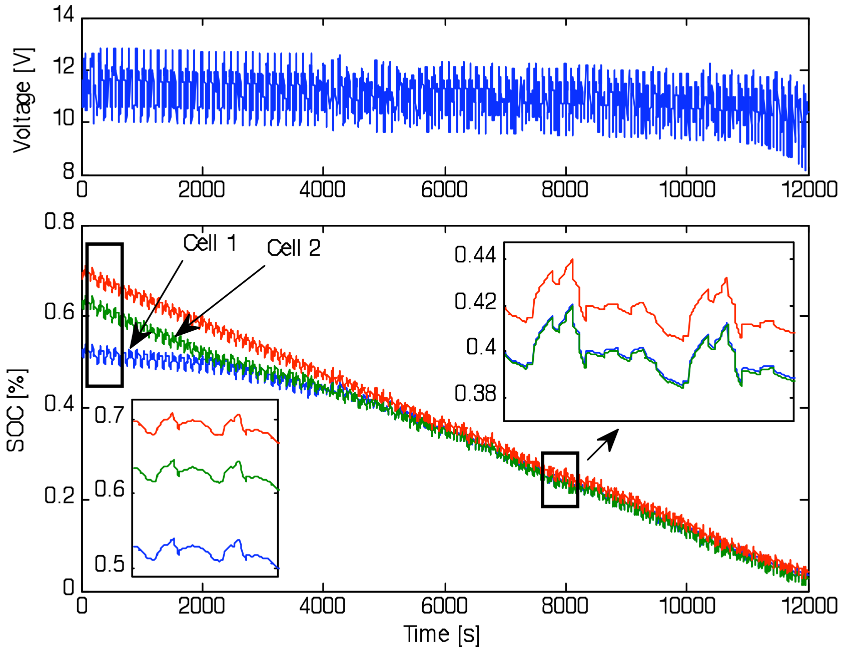


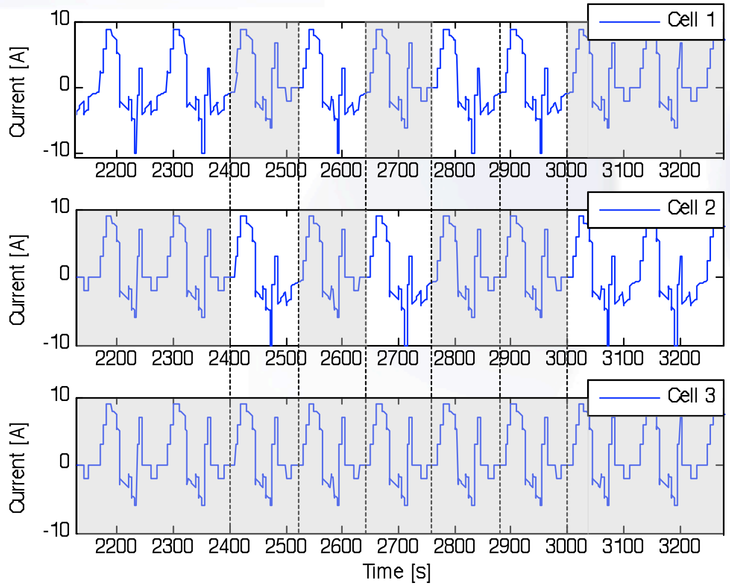

- ✓ Current spikes correspond to an energy extraction from the capacitor. Valleys instead correspond to energy injection from the capacitor.
- ✓ Cell 1 receives all the injections until its SOC becomes equal to cell 3 SOC, at 2400 s.
- ✓ Cell 2 is never selected for injection because its higher SOC respect to cell 1 and 3.
- ✓ Red line is the Kalman Filter polling.
- ✓ Solid blue line is cell 1 SOC.
- ✓ The green dot line is the cell 1 simple coulomb counting model. The initial value of the integral is updated only when the cell is not selected for charge injection.

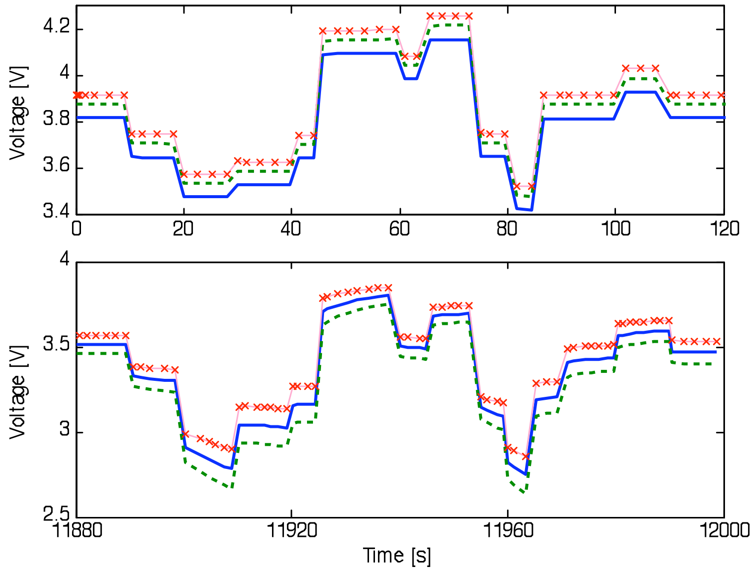
# Lithium-ion battery: BMS results

## Bi-directional current input

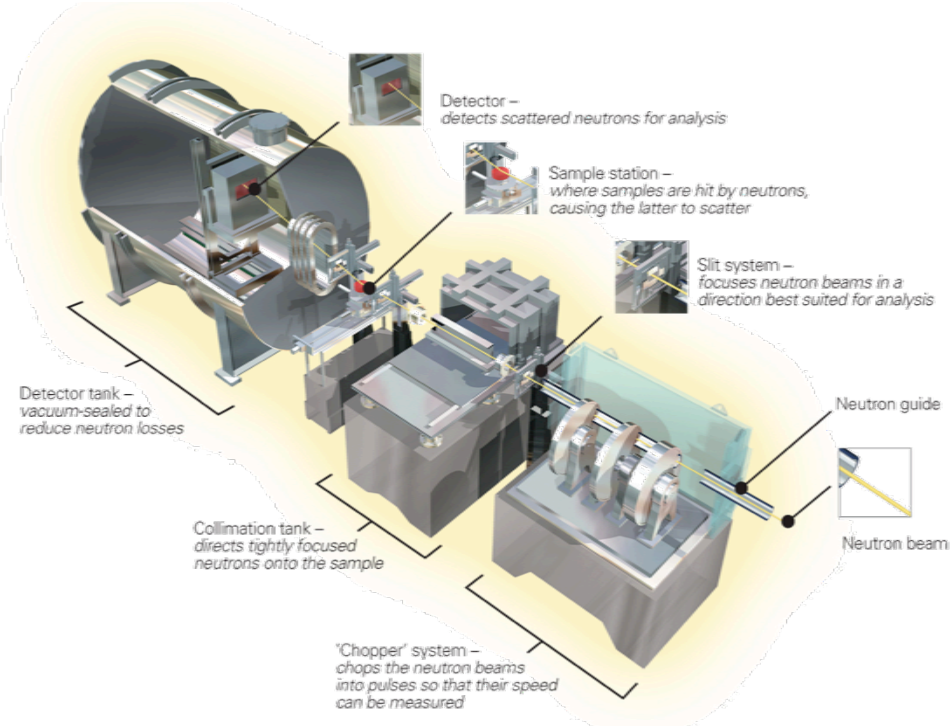


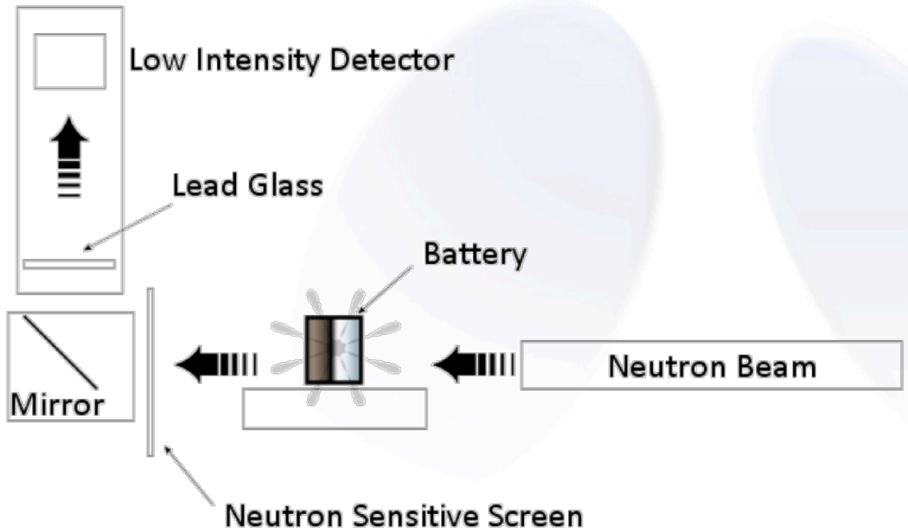



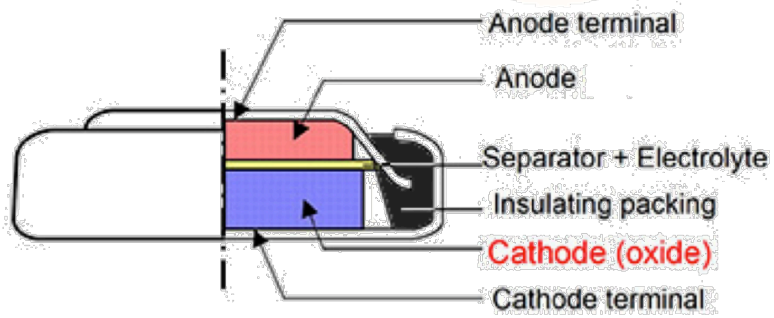



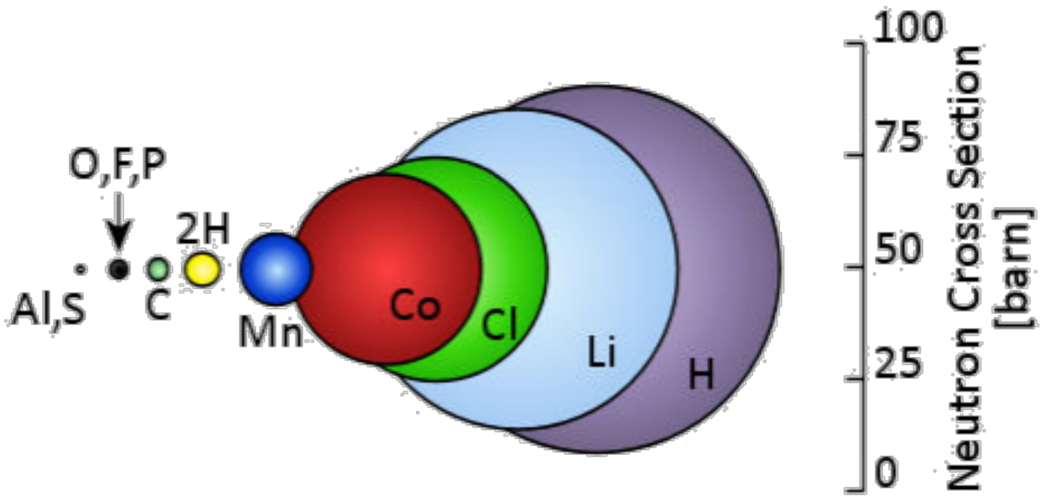
# Neutron scattering analysis



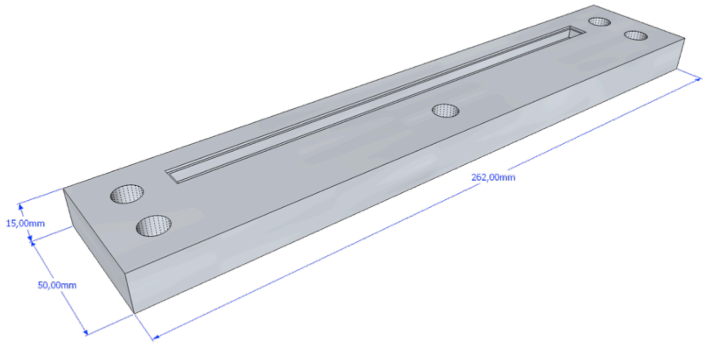



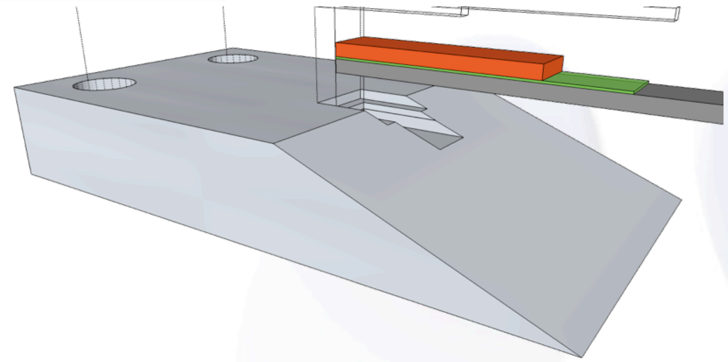

Rubber + *EC:DMC* solvent

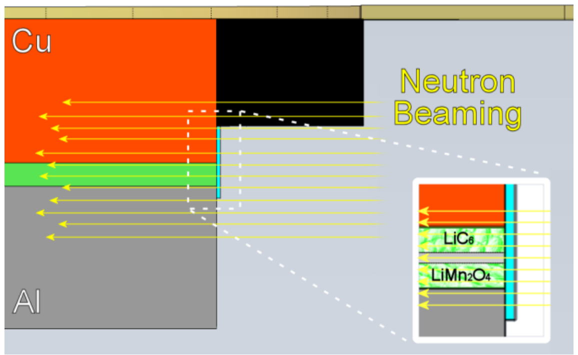


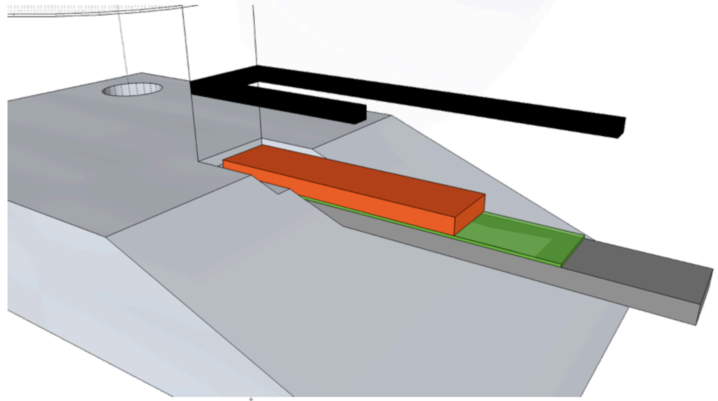

Grace

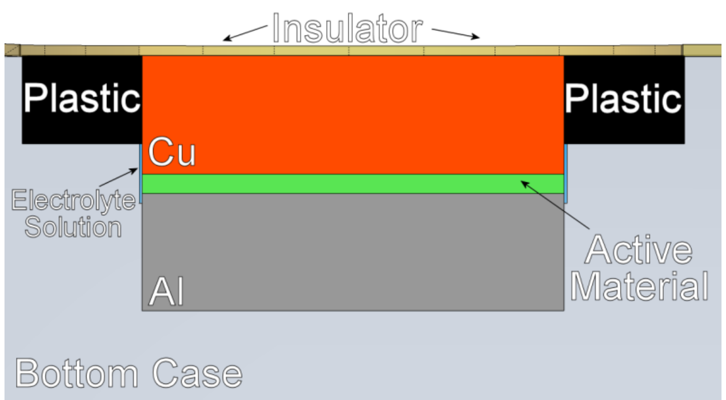
# Neutron scattering analysis

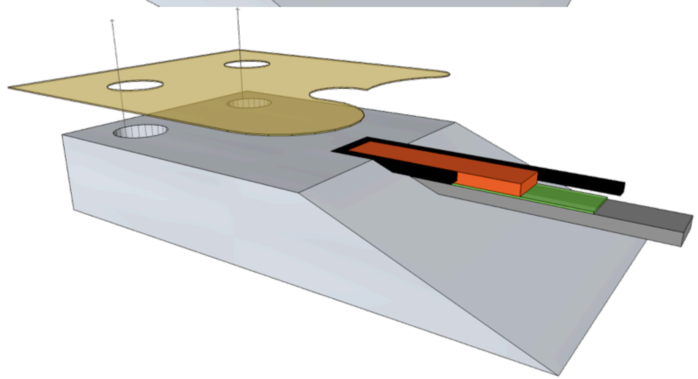


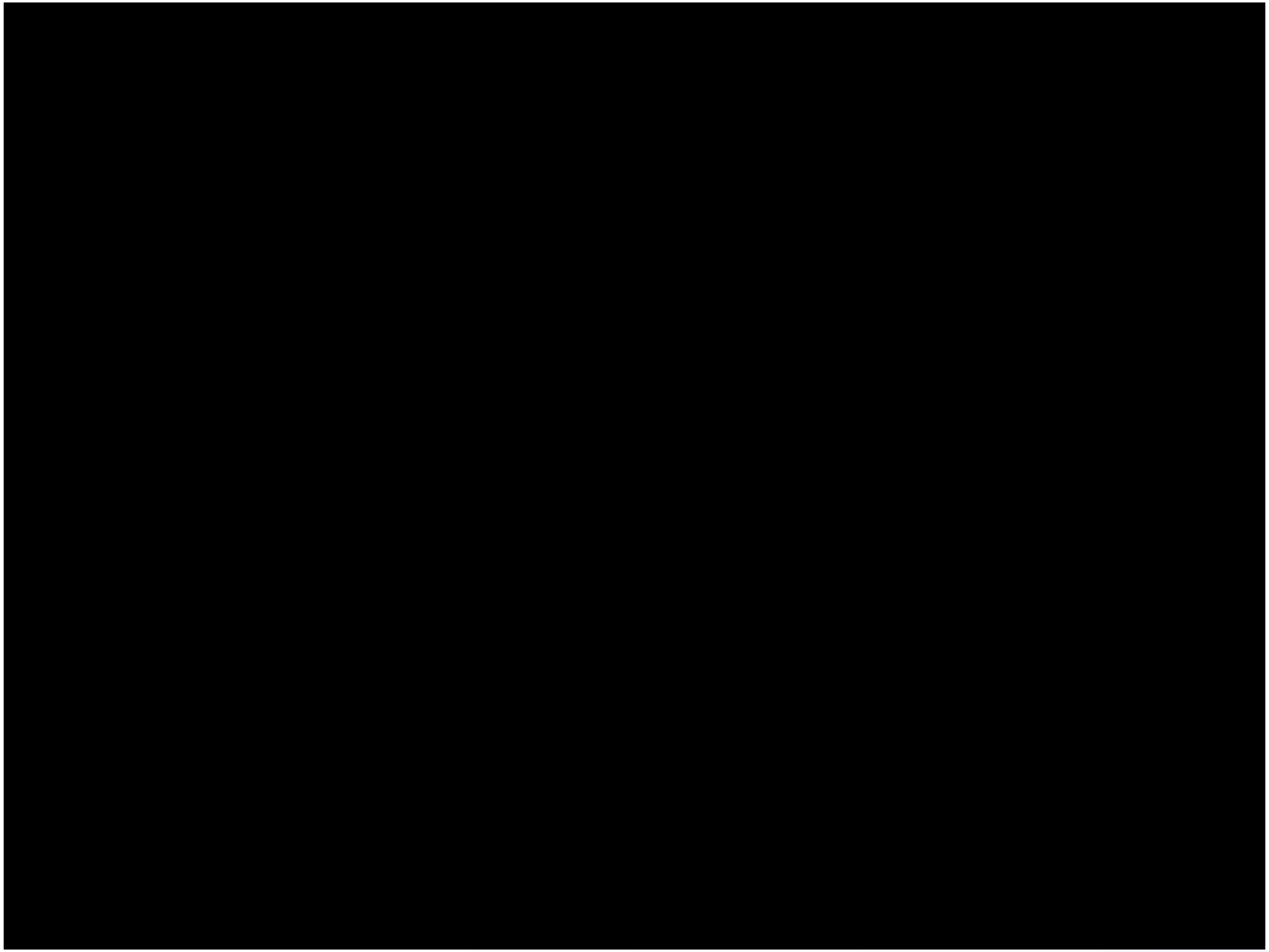




# Neutron scattering analysis



# Conclusions

| |
|---|
| *International publications* |
| C. Speltino, D. Di Domenico, G. Fiengo and A. Stefanopoulou, **Comparison of Reduced Order Lithium-Ion Battery Models for Control Applications**, *Proceedings of Conference on Decision and Control*, Shanghai, 2009. |
| C. Speltino, D. Di Domenico, G. Fiengo and A. Stefanopoulou, **Experimental Identification and Validation of an Electrochemical Model of a Lithium-Ion Battery,** *Proceedings of European Control Conference*, Budapest 2009. |
| C. Speltino, D. Di Domenico, G. Fiengo and A. Stefanopoulou, **Experimental Validation of a Lithium-Ion Battery State of Charge Estimation with an Extended Kalman Filter**, *Proceedings of European Control Conference*, Budapest 2009. |
| C. Speltino, D. Di Domenico, G. Fiengo and A. Stefanopoulou, **A Decoupled Controller for Fuel Cell Hybrid Electric Power Split, "**Advances in Hybrid Powertrains", *IFP International Conference*, Lyon, 2008. |
| C. Speltino, A. Stefanopoulou and G. Fiengo, **Cell Equalization in Battery Stacks through State of Charge Estimation Polling**, *Automatic Control Conference*, Invited paper, Baltimore, 2010. |
| *In submission* |
| C. Speltino, A. Stefanopoulou and G. Fiengo, **Identification and Validation a Lithium Battery Reduced Model Based Extended Kalman Filter for State Of Charge Estimation**, *IEEE Transactions on System Control Technology*. |
| G. Rizzo, M. Sorrentino, C. Speltino, I. Arsie, G. Fiengo, F. Vasca, **Converting Conventional Cars in Mild Hybrid Solar Vehicles**, *18$^{th}$ IFAC World Congress, 2011, Milano.* |
| C. Speltino, A. Stefanopoulou and G. Fiengo, **Battery Management Systems**, *IEEE Control System Magazine,* Feb. 2012 |
| *Current activities* |
| •Experimental research on Power Split Control aimed to validate the previous results obtained in simulation;<br>•On-line parameter identification for cell aging and deterioration estimation;<br>•Multi-cell BMS control strategy. |