Nondestructive Diagnostics of Battery Cells by MRI

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predict failures, lifetimes
early
non-destructively
quickly

Can we detect dendrites, soft shorts, electrolyte distribution, uneven SOC, metal particles …?

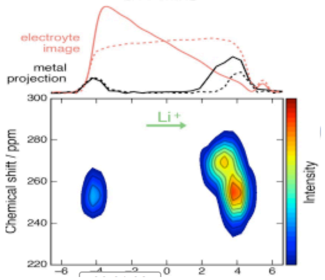
MRI

In-situ (operando) NMR/MRI

"In real life"

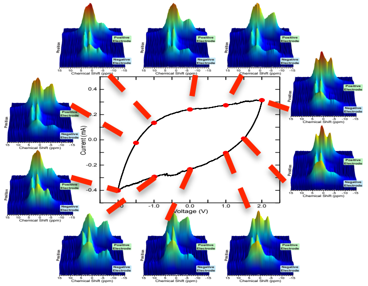
Li-dendrite visualization

- 7Li MRI / CSI
- 1H MRI



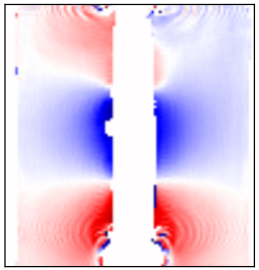
Supercapacitors

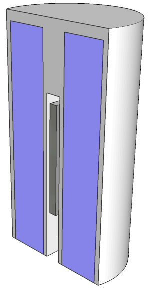
- 1H / 11B MRI



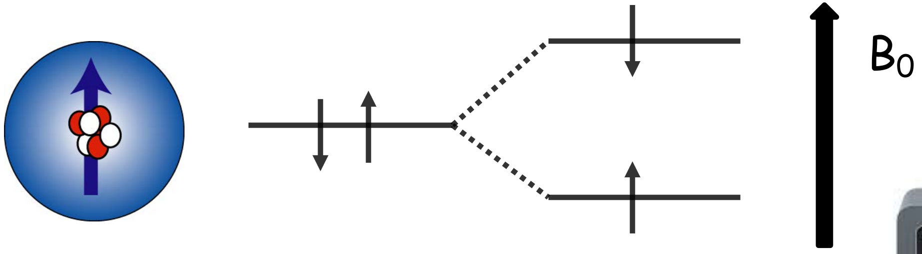
Commercial-type cell analysis

- SOC
- SOH
- Current distribution





NMR

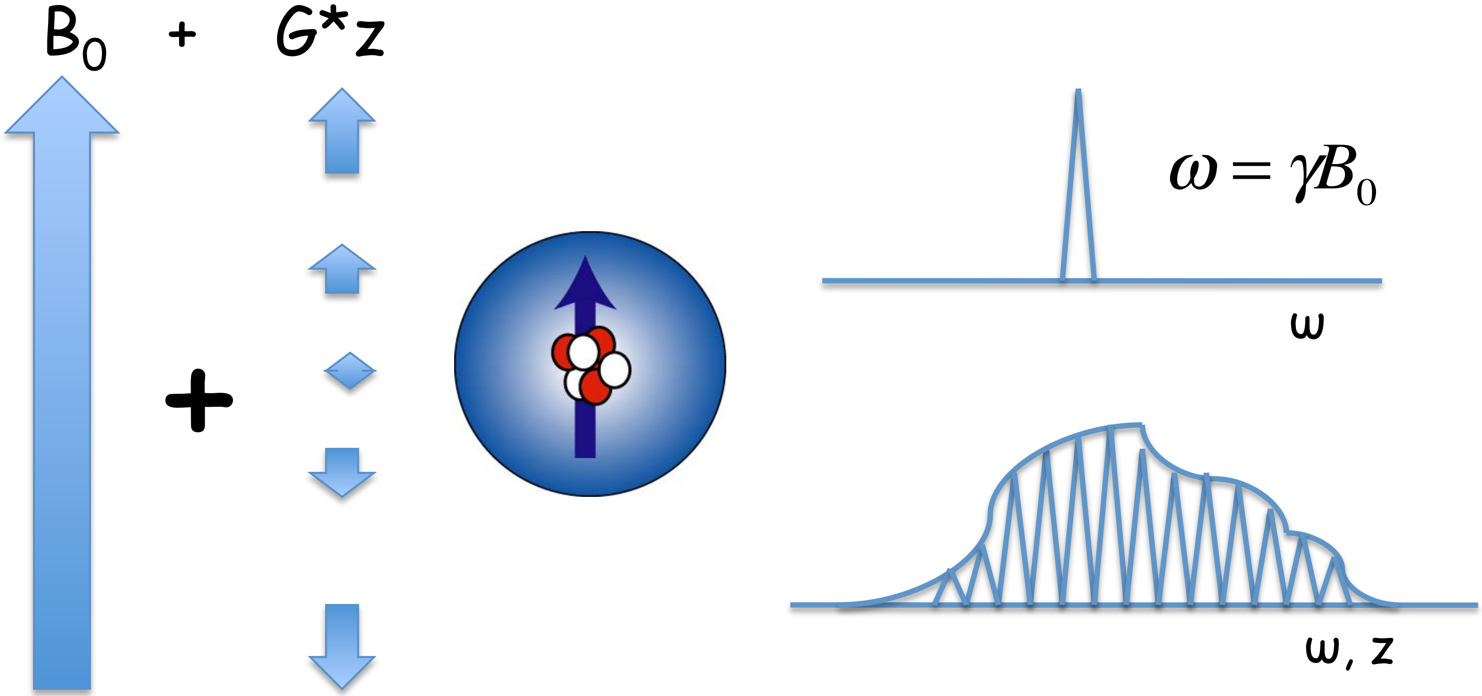


$$\omega = \gamma B_0$$

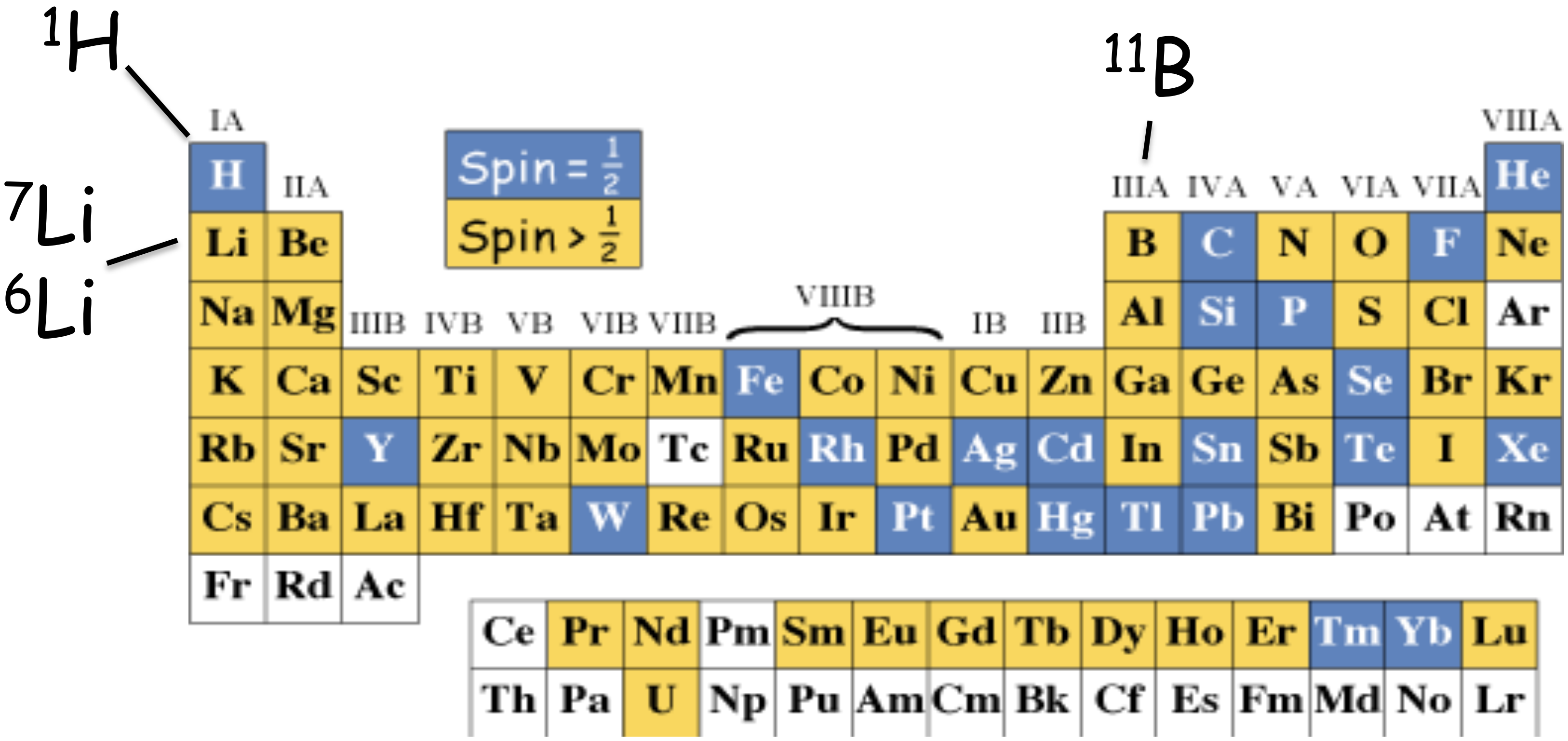
Chemical shift: varying electron density

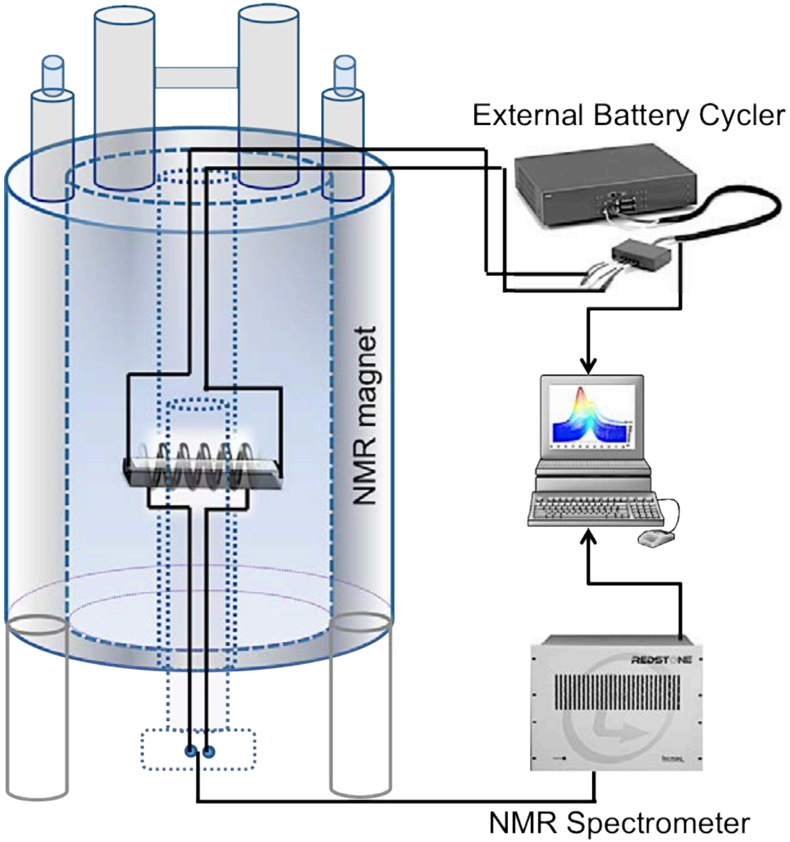
→ small changes in frequency

NMR and MRI



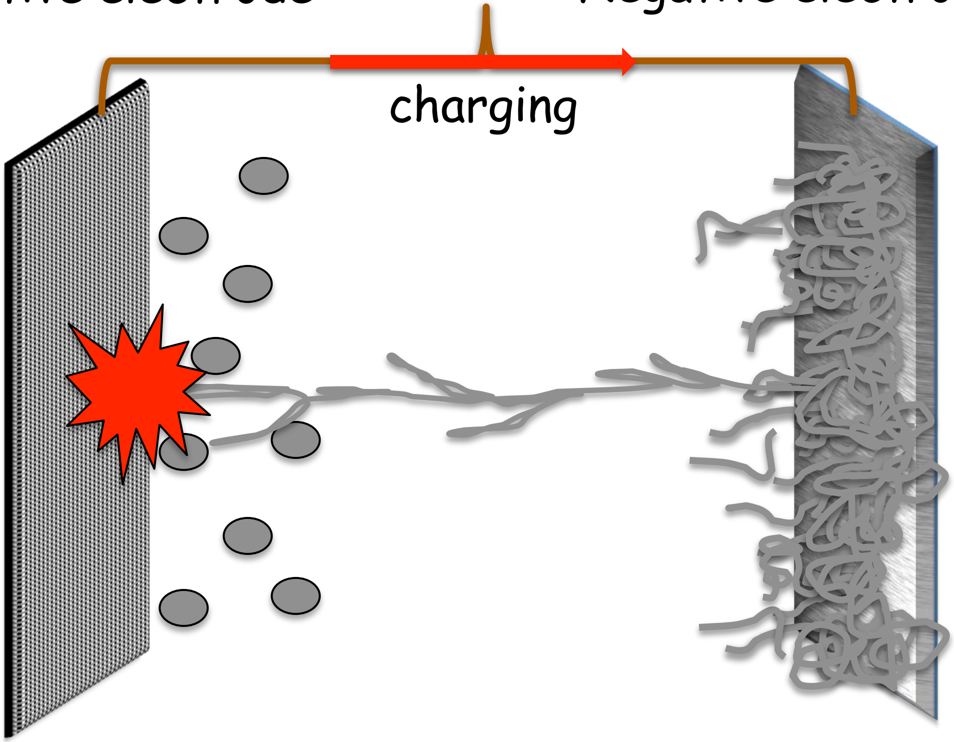
NMR accessible nuclei

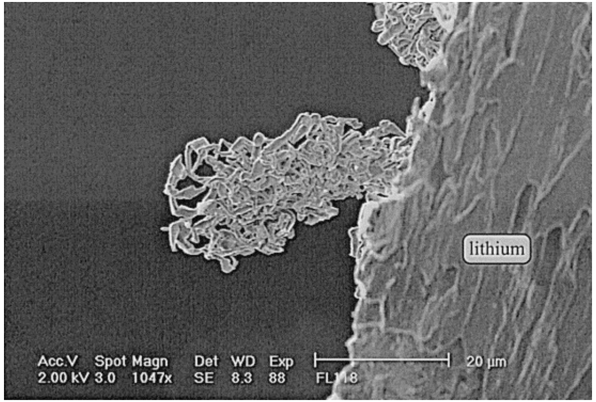



External Battery Cycler
NMR magnet
REDSTONE
NMR Spectrometer

Li plating / Li dendrites

Positive electrode e- Negative electrode (Lithium)

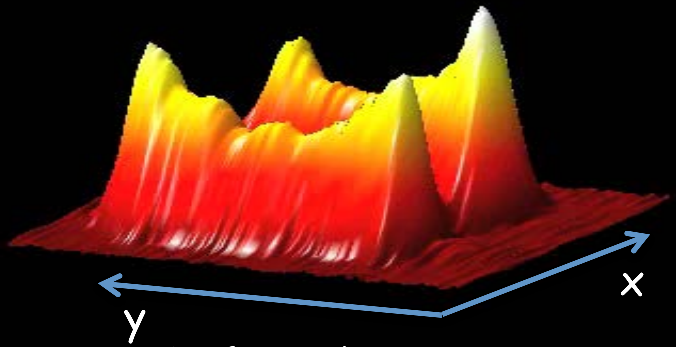




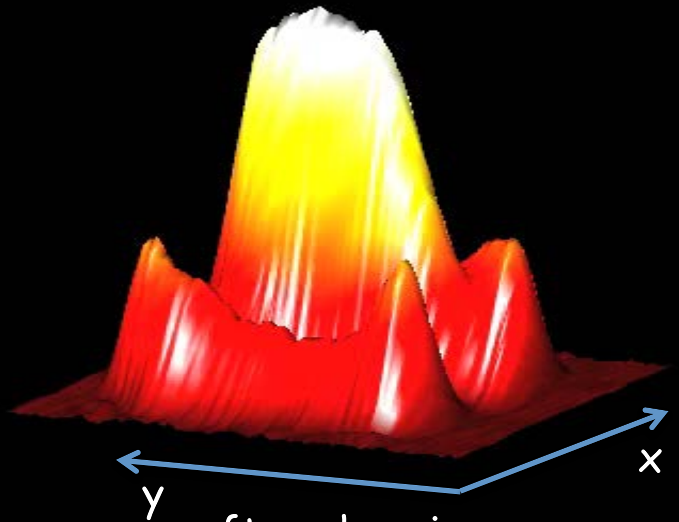
Orsini et al,
J Pow Src 76, 1998, 19

Hee Jung Chang

Lithium MRI of Batteries



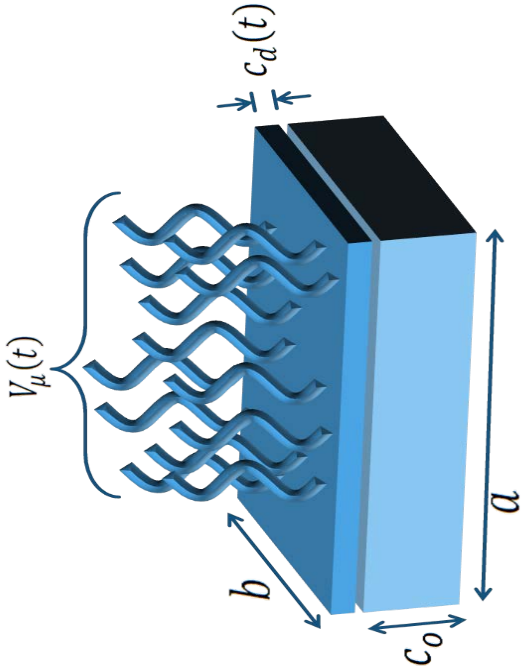
before charging



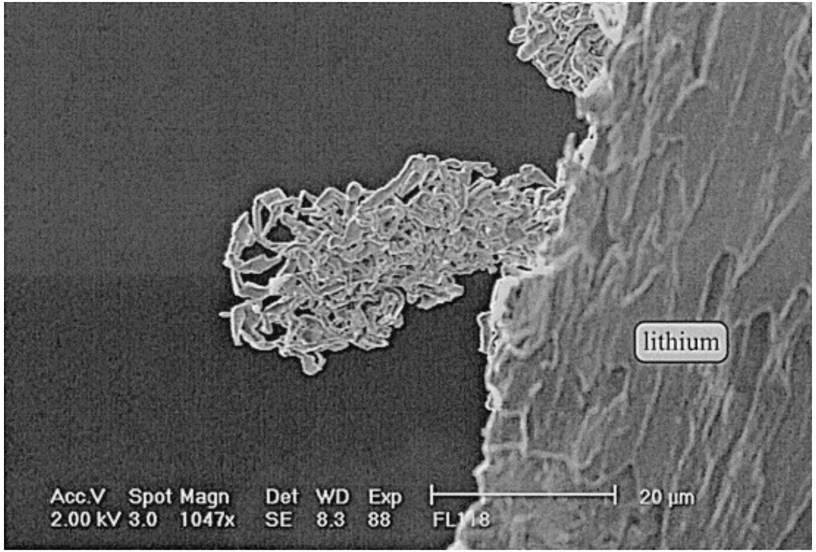
after charging

Chandrashekar et al.
Nat. Mater., *11*, 2012, 311

Li-dendrites on electrode



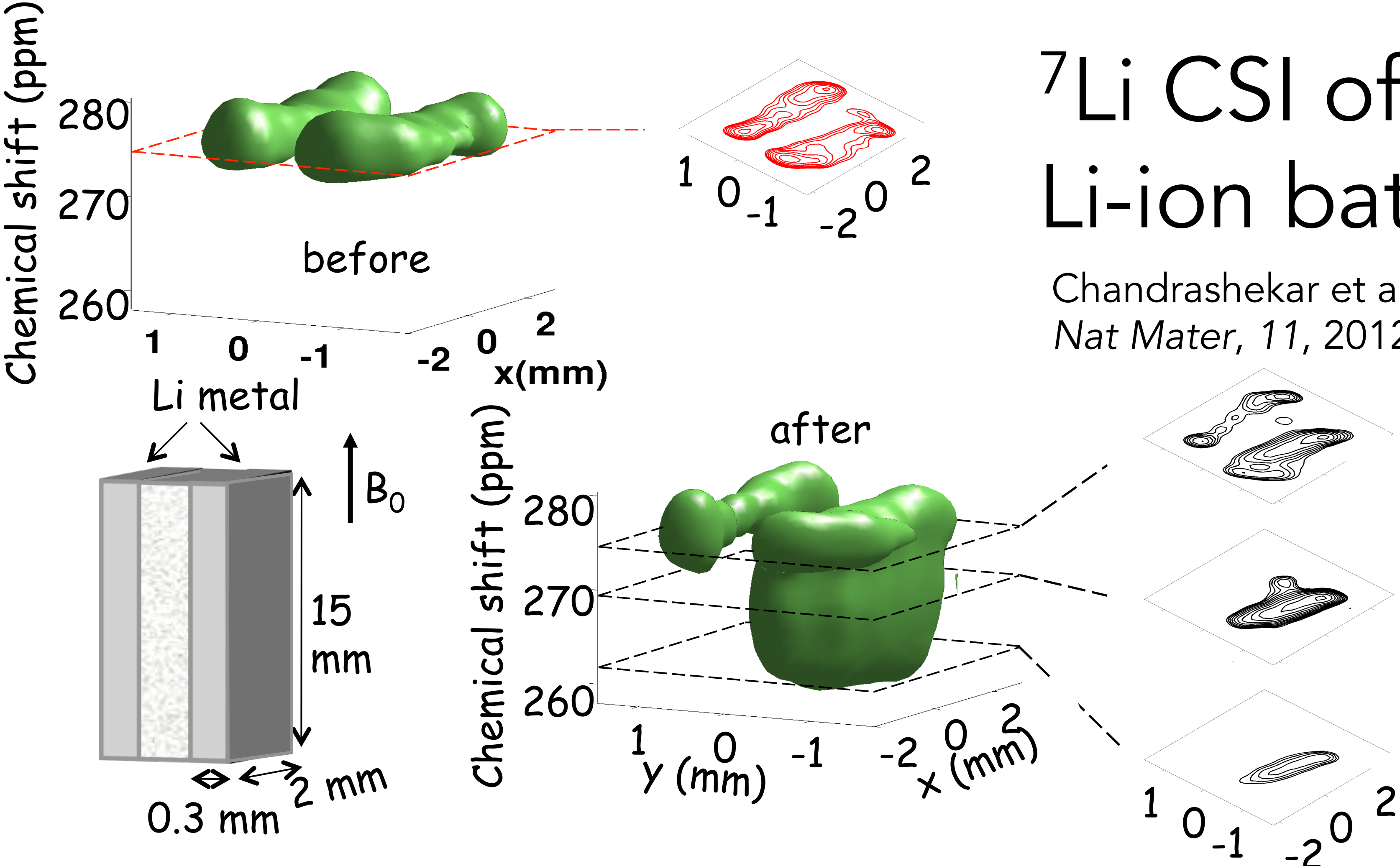
Bhatacharya et al,
Nat. Mat. 9, 2010, 504



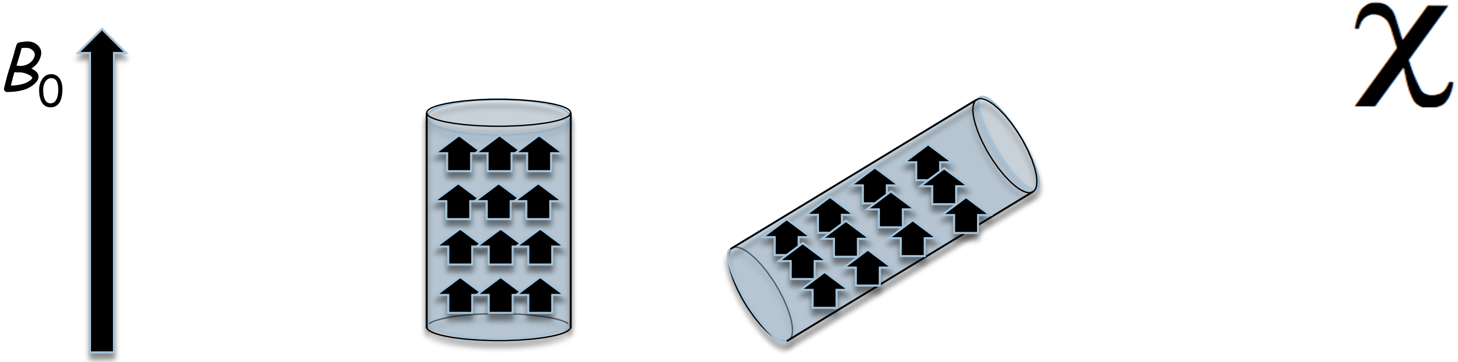
Orsini et al,
J Pow Src 76, 1998, 19

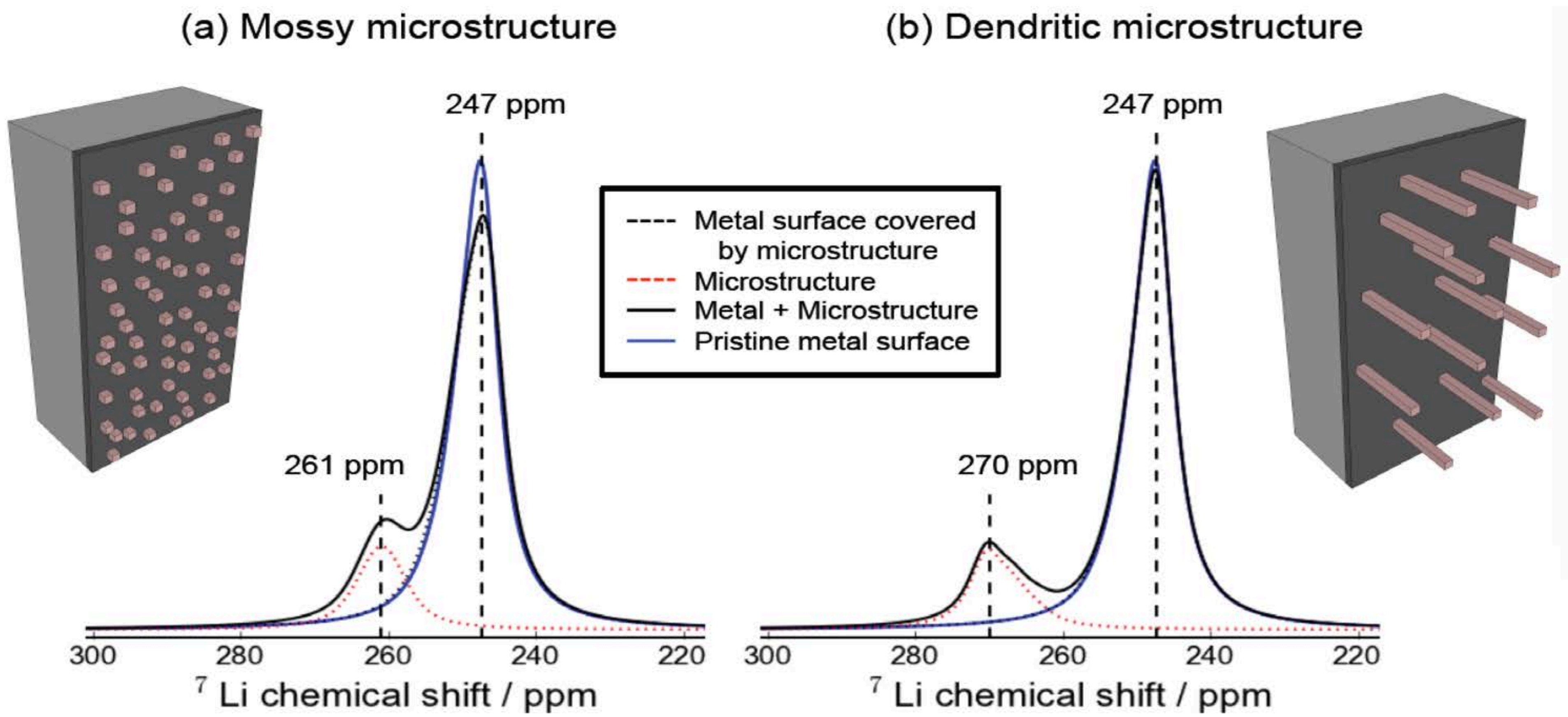
^{7}Li CSI of Li-ion batt.

Chandrashekar et al.
Nat Mater, *11*, 2012, 311



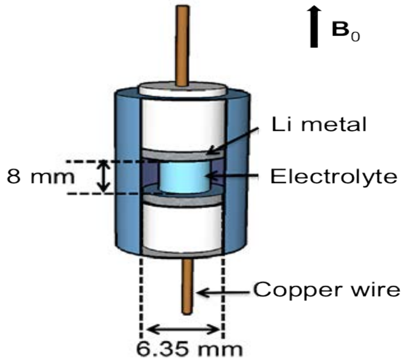
Superresolution Information: Chemical and Susceptibility shifts

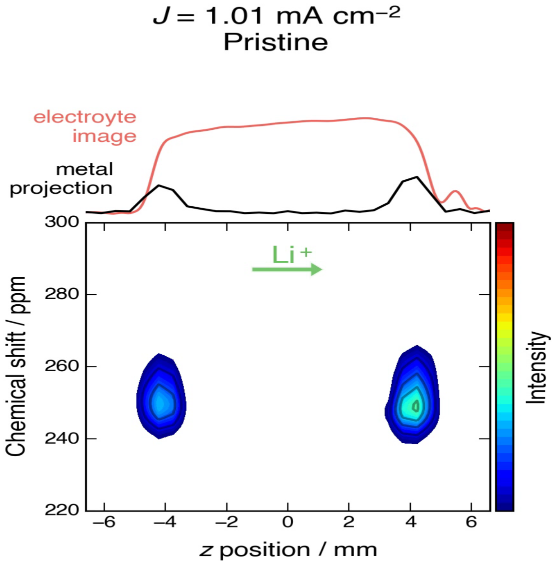




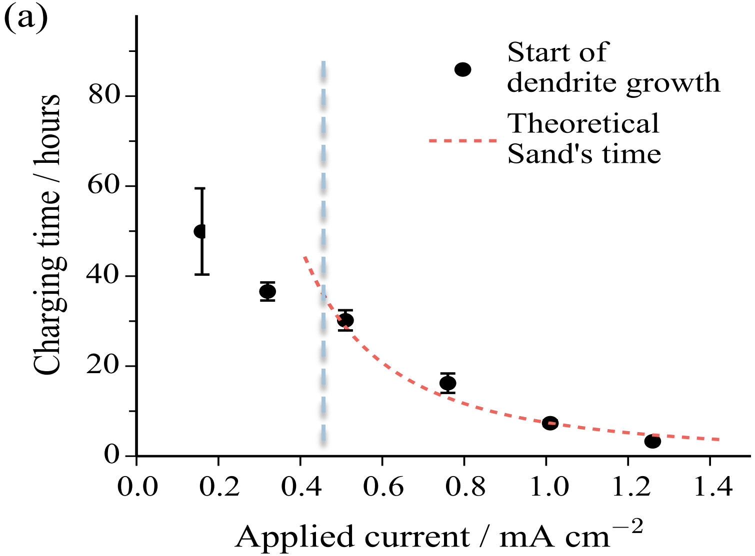
HJ Chang et al., J Phys Chem C, 119 (2015) 16443

Studying dendrite growth models



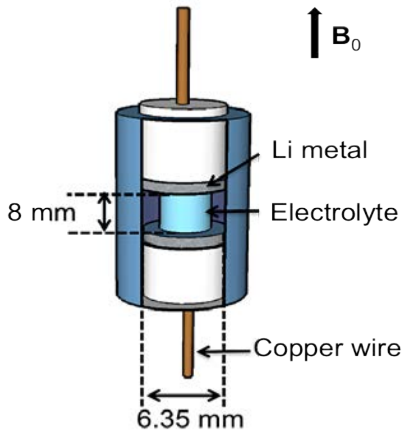


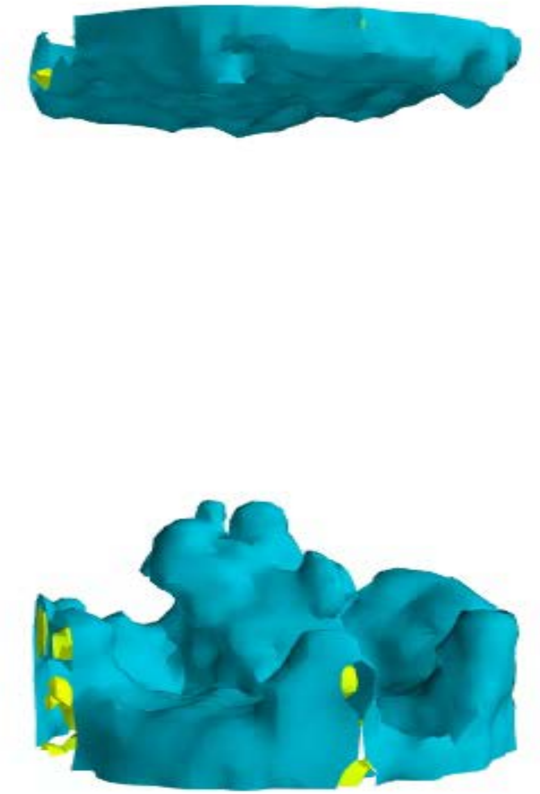
$$\tau = \pi D \left(\frac{C_0 e}{2 J t_a} \right)^2$$



H.J. Chang et al, JACS **2015**, 137, 15209

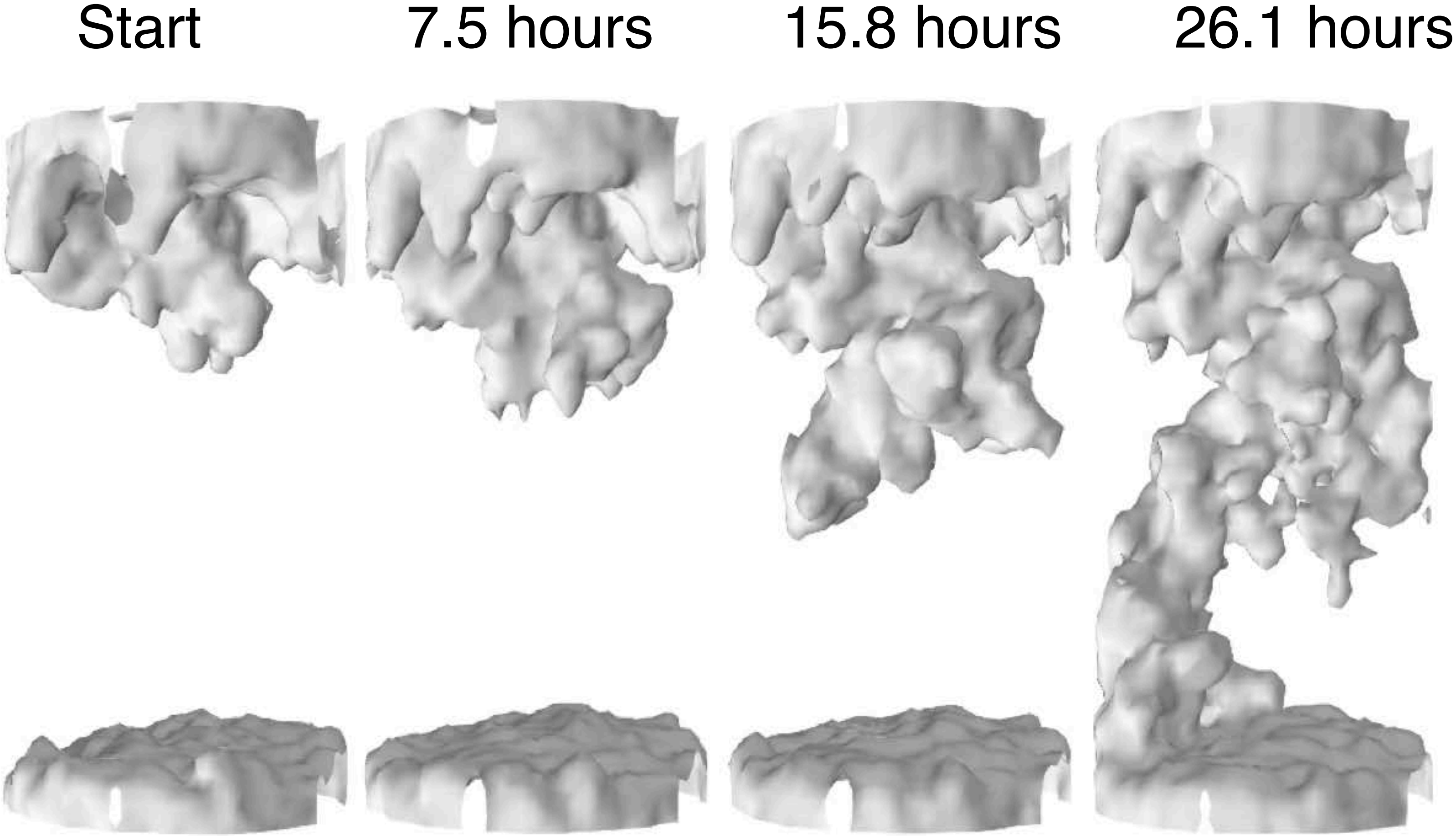
Indirect MRI of dendrite growth



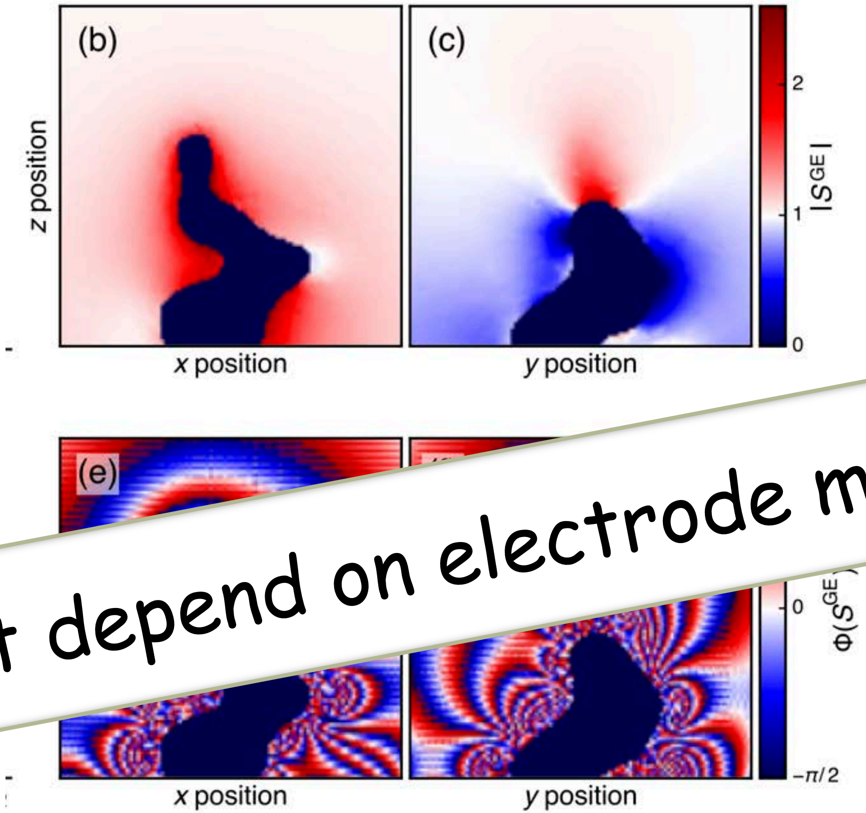


1H 3D FLASH
'negative'
image

Ilott et al.,
PNAS, **2016**,
113, 10779-84


Start
7.5 hours
15.8 hours
26.1 hours

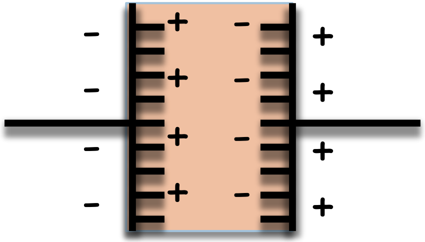
~20-fold amplification from field distortions!

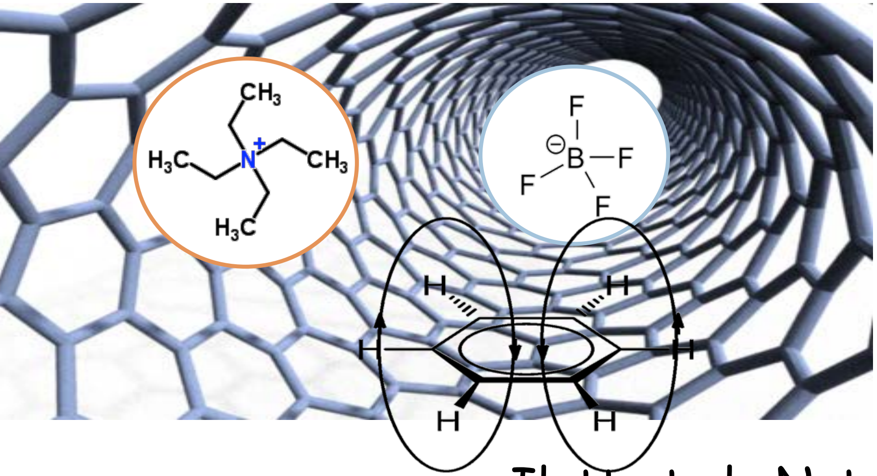


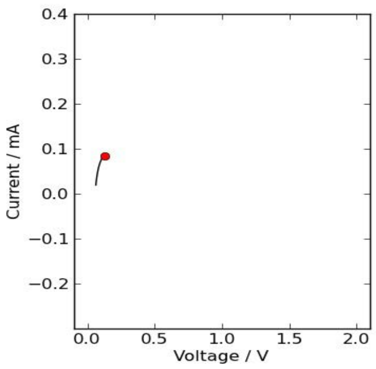
Does not depend on electrode material

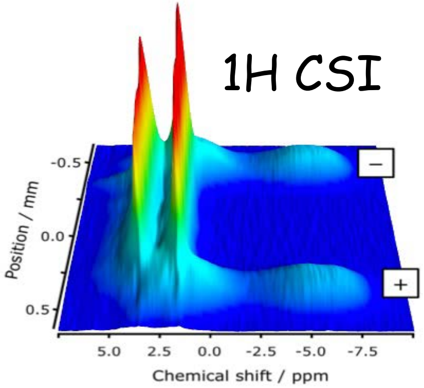
Ilott et al., PNAS, **2016**, 113, 10779-84

Supercapacitors



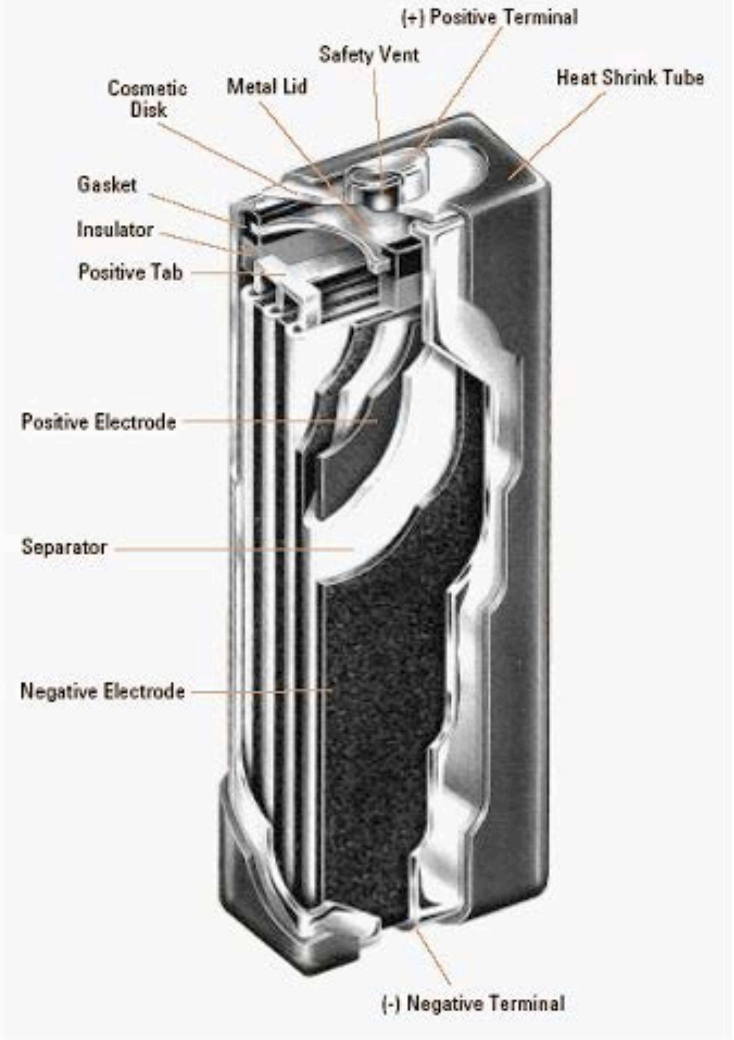


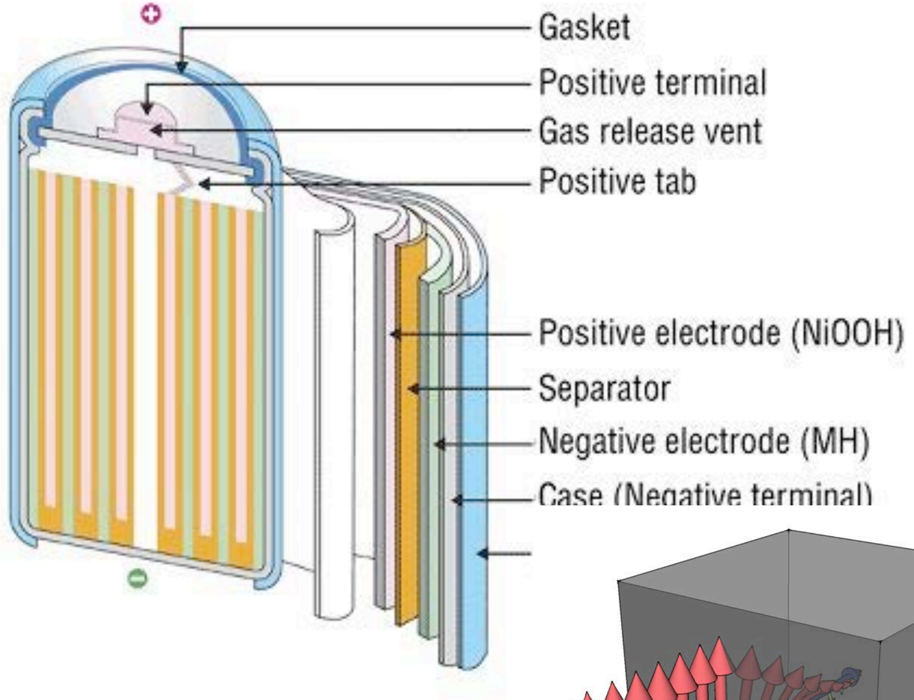


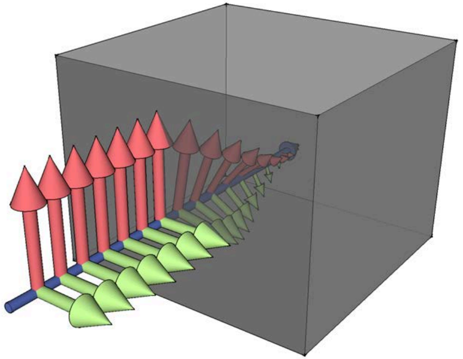


Ilott et al., Nat. Comm., 5, **2014**, 4536

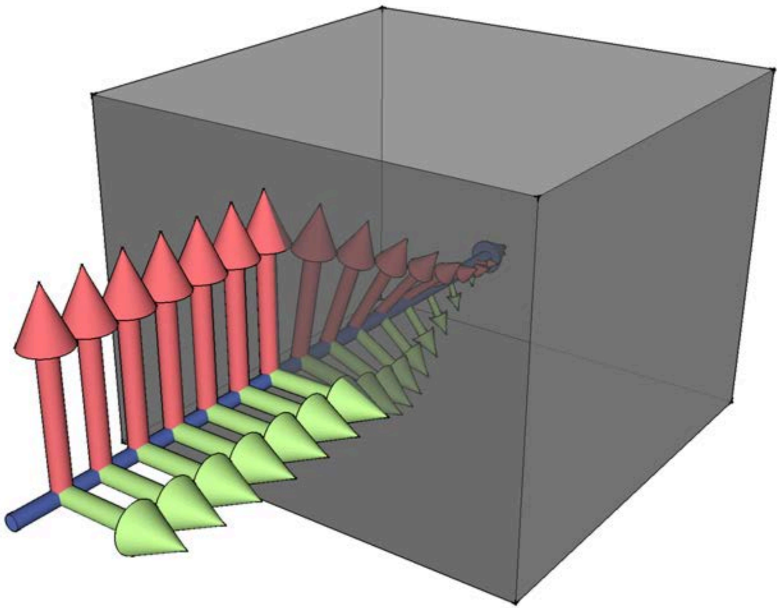
“In real life”

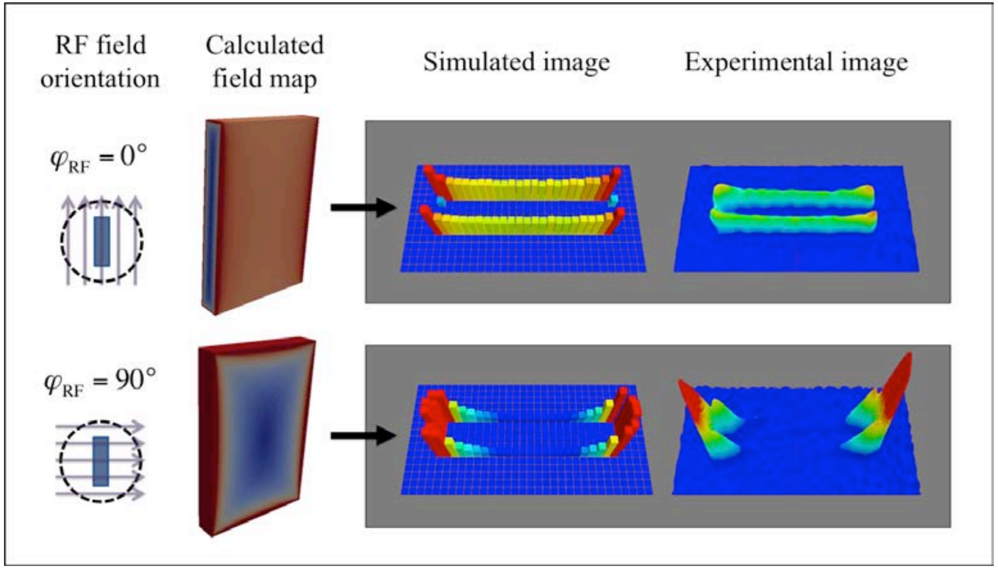

(+) Positive Terminal
Safety Vent
Heat Shrink Tube
Cosmetic Disk
Metal Lid
Gasket
Insulator
Positive Tab
Positive Electrode
Separator
Negative Electrode
(-) Negative Terminal


Gasket
Positive terminal
Gas release vent
Positive tab
Positive electrode (NiOOH)
Separator
Negative electrode (MH)
Case (Negative terminal)



RF penetration into metal: skin effect

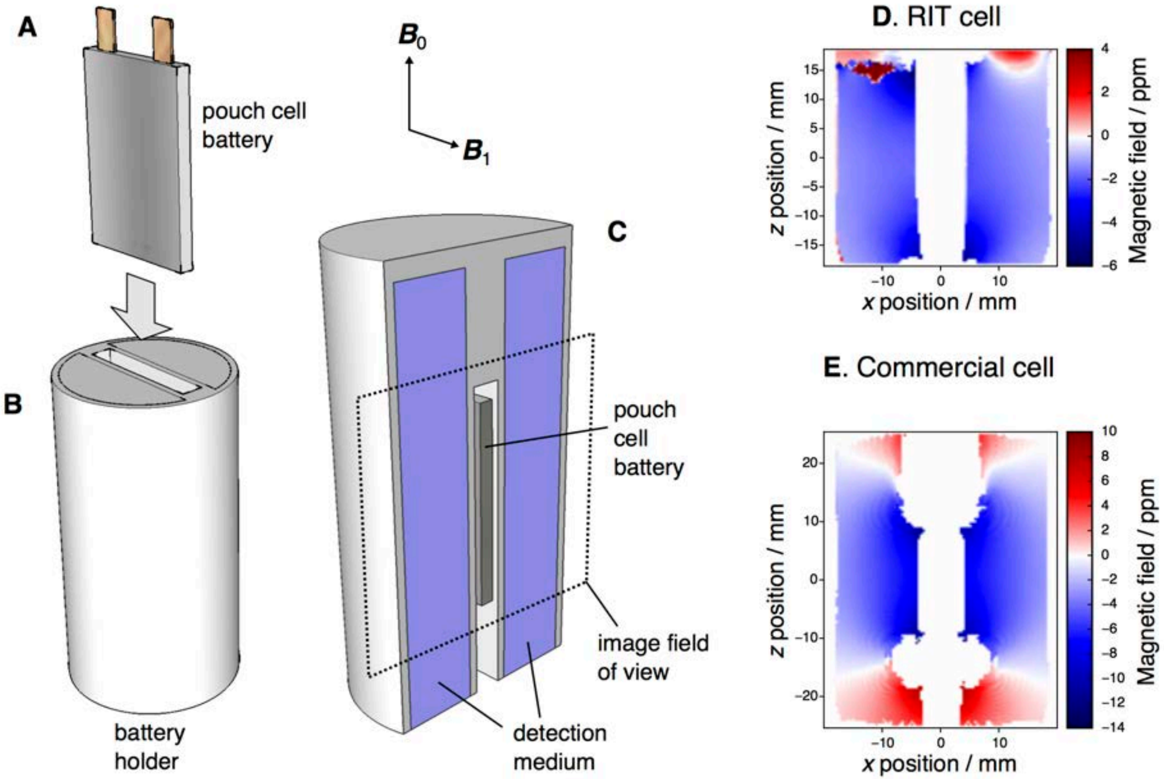




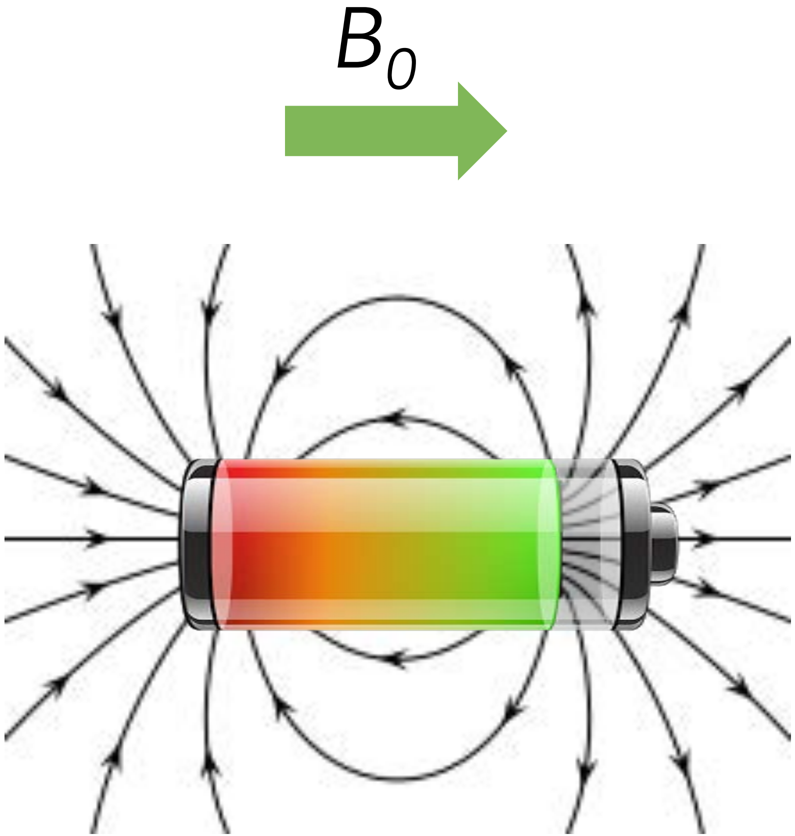
$$\delta = \frac{1}{\sqrt{\pi \mu_r \mu_0 \sigma f}}$$ skin depth

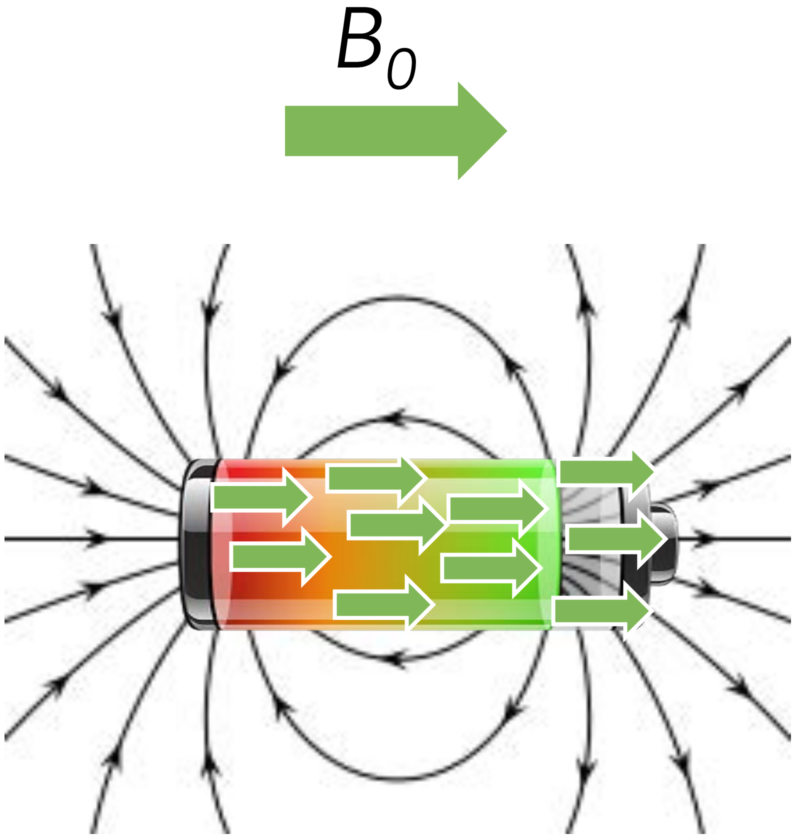
Ilott et al., JMR, 245, 2014, 143-149

Inside-out MRI



Ilott, et al, *Nat Comm* 9:1776, 2018


B_0



Magnetic Susceptibility

PHYSICAL REVIEW B **77**, 075119 (2008)

Magnetism and structure of Li_xCoO_2 and comparison to Na_xCoO_2

J. T. Hertz,[1] Q. Huang,[2] T. McQueen,[1] T. Klimczuk,[3,4] J. W. G. Bos,[5] L. Viciu,[1] and R. J. Cava[1]

Chem. Mater. **2007**, *19*, 4682−4693

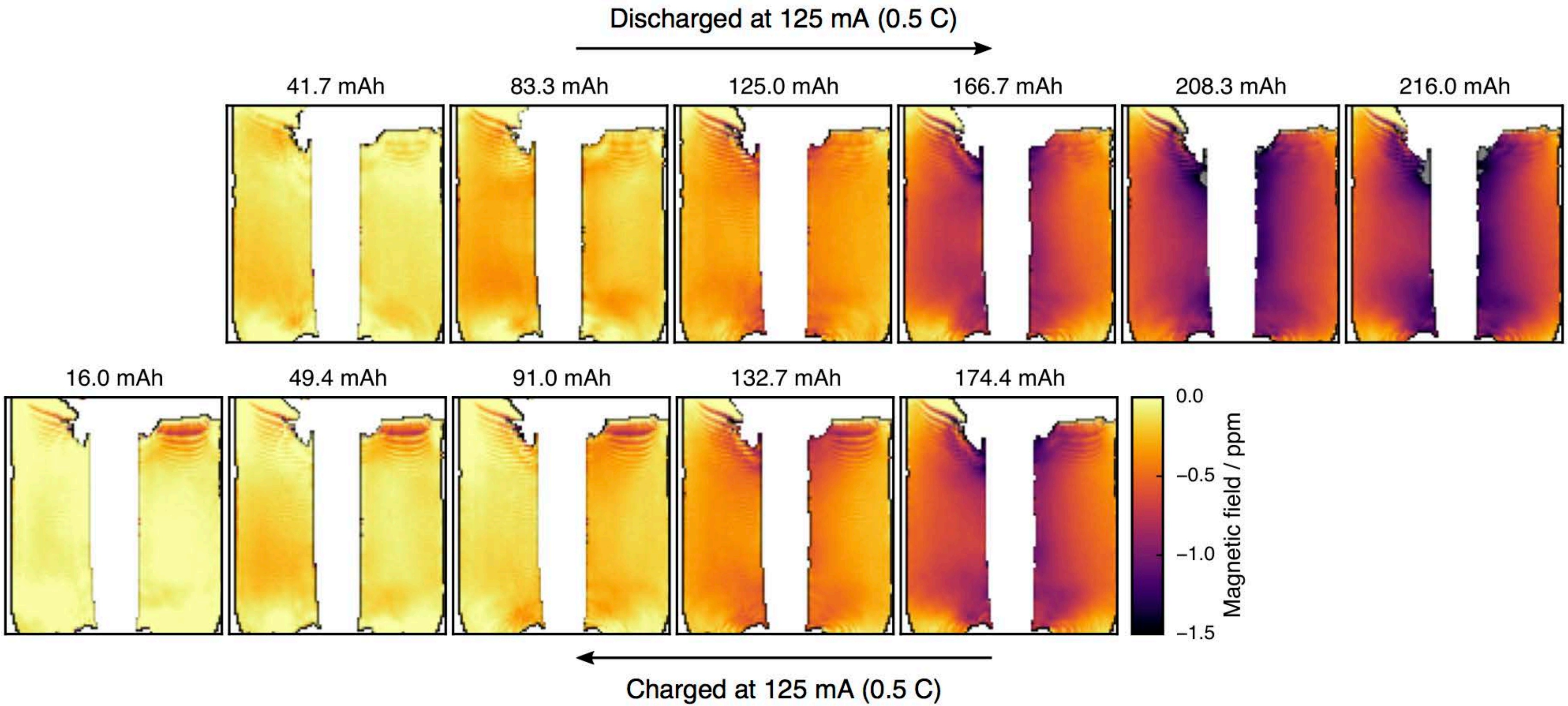
Layered $Li_xNi_yMn_yCo_{1-2y}O_2$ Cathodes for Lithium Ion Batteries: Understanding Local Structure via Magnetic Properties

Natasha A. Chernova,*,† Miaomiao Ma,† Jie Xiao,† M. Stanley Whittingham,†
Julien Breger,‡ and Clare P. Grey‡

Magnetic Susceptibility effects

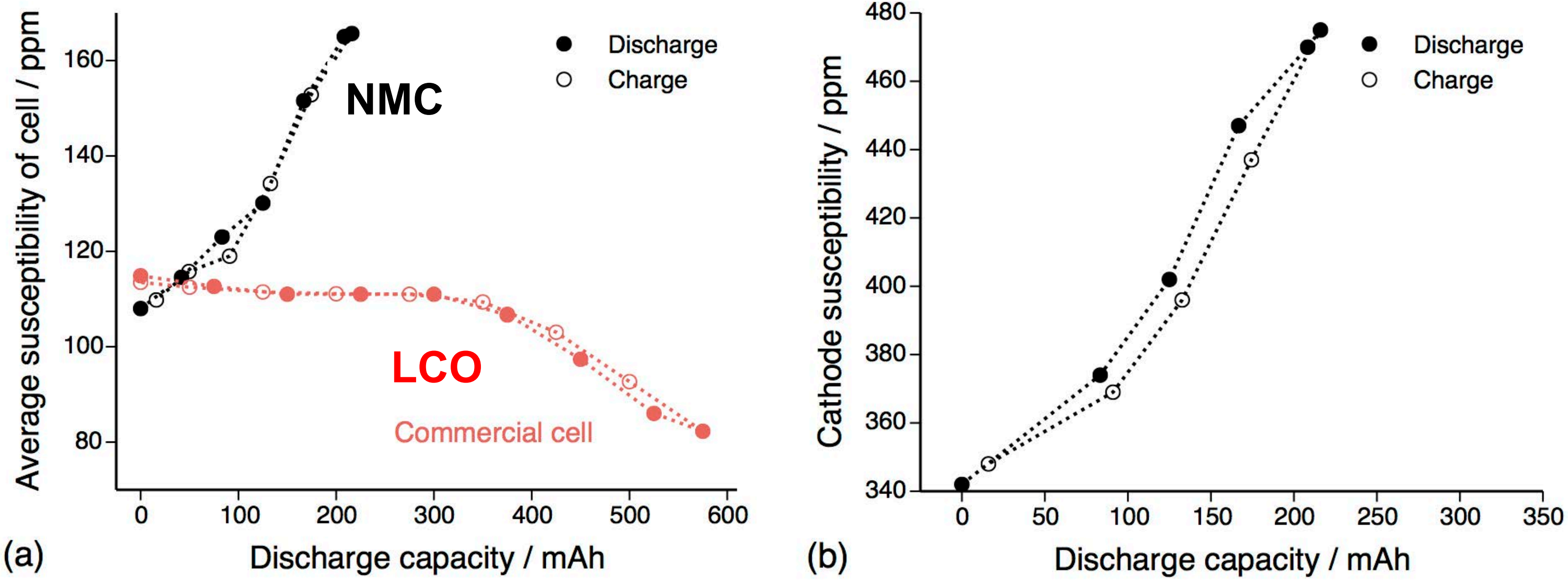

NITROGENN

Magnetic field maps during discharge



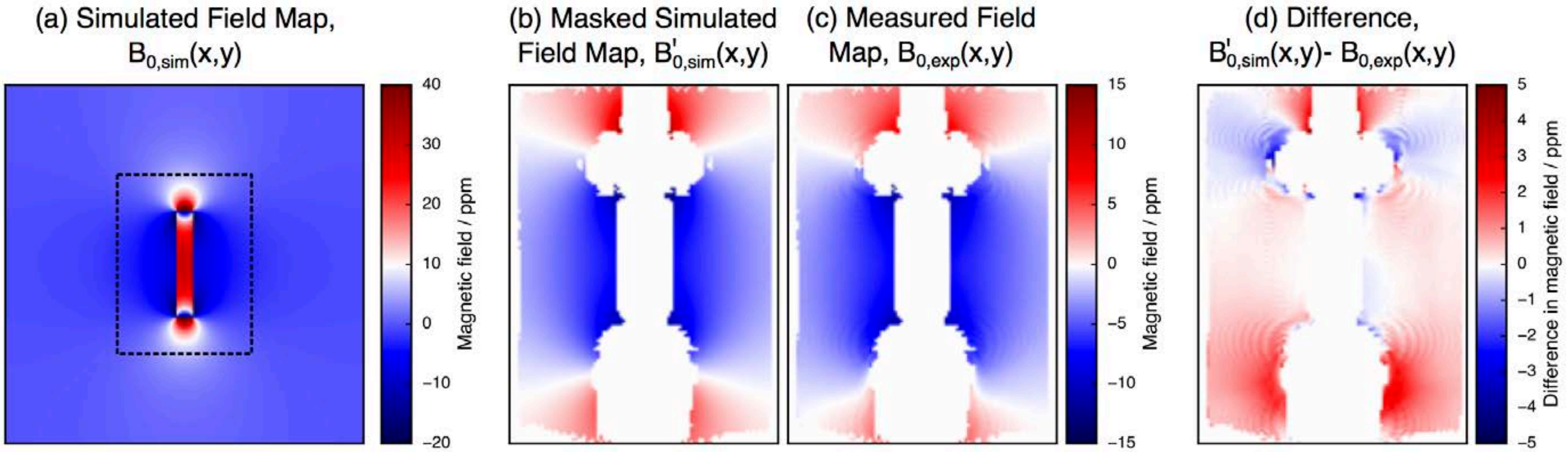
Ilott, et al, *Nat Comm* 9:1776, 2018

State of Charge from Susceptibility



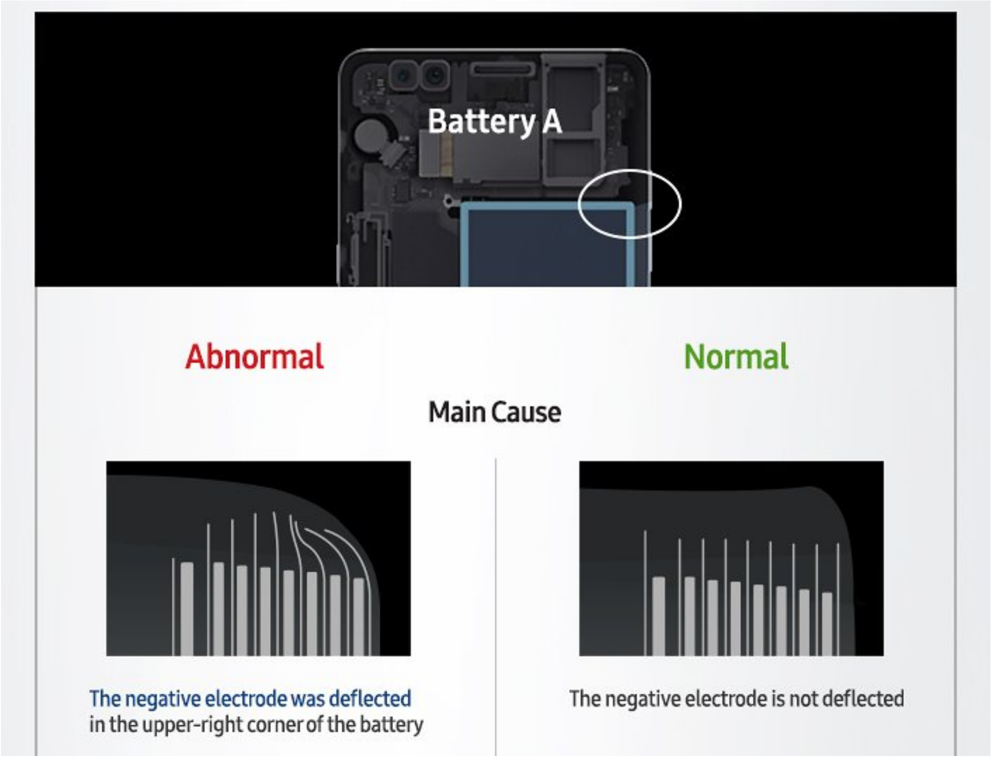
Ilott, et al, *Nat Comm* 9:1776, 2018

Susceptibility Inversion



Ilott, et al, *Nat Comm* 9:1776, 2018

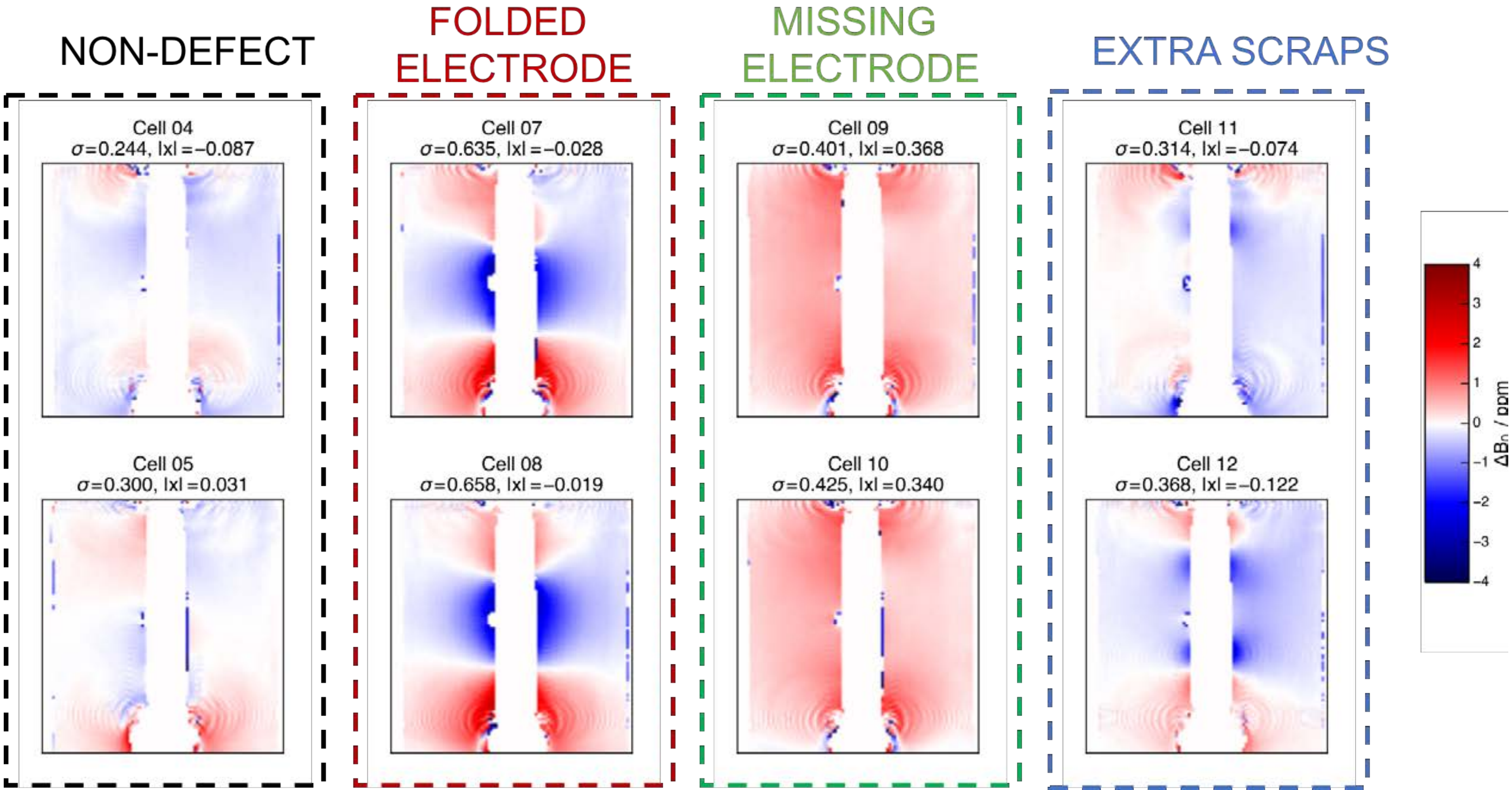
Samsung battery defects
Jan 2017 press release

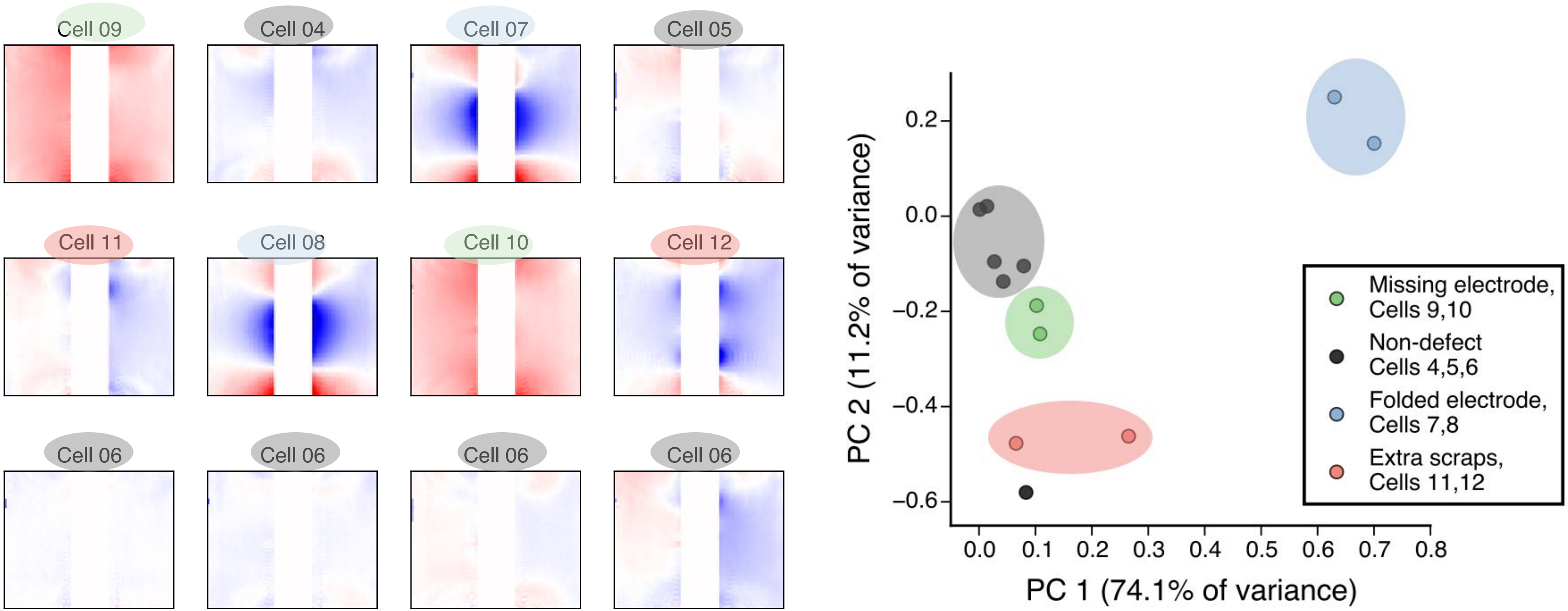


Battery
Prototyping
Center

Make cells
with defects

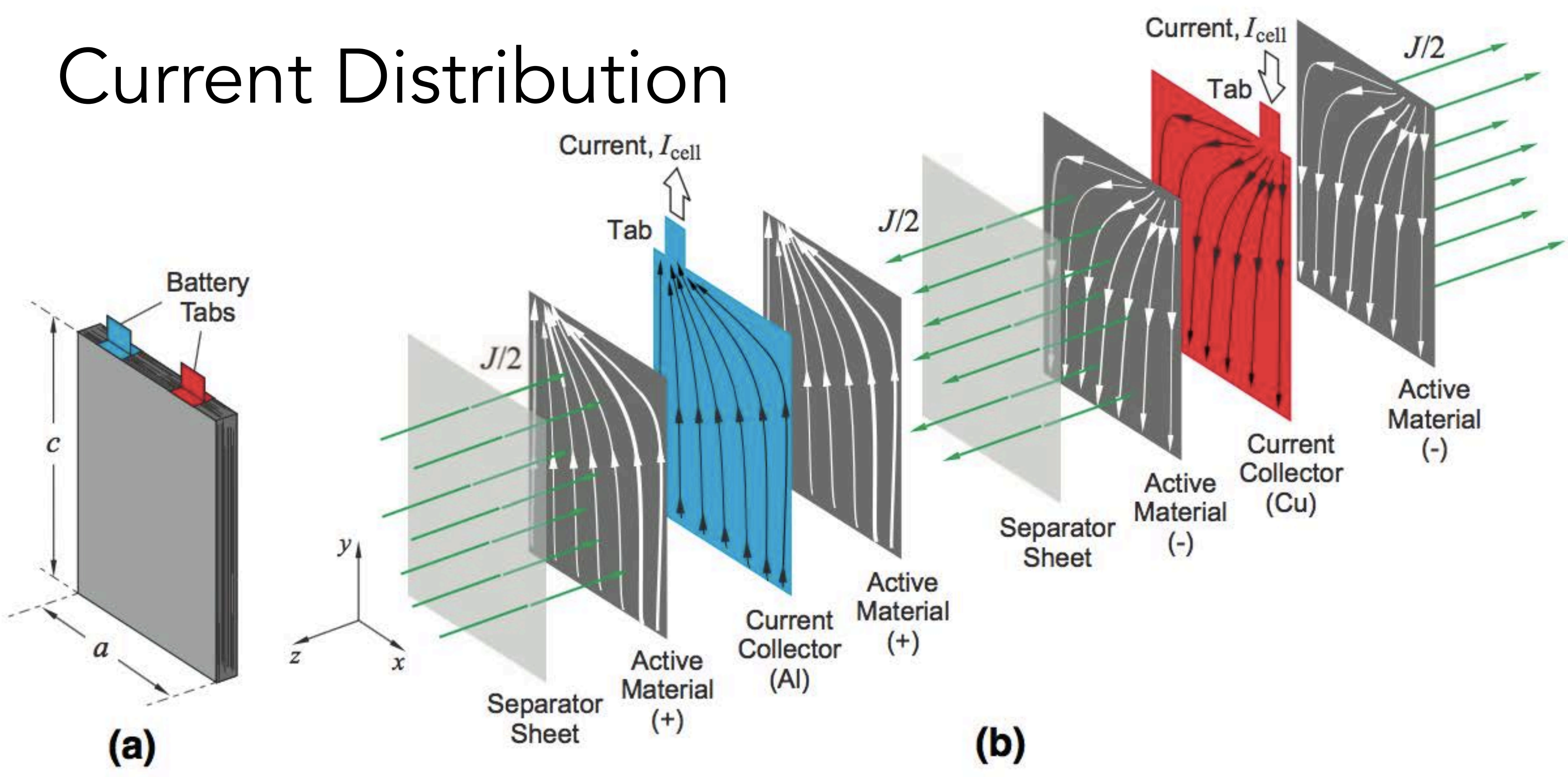
Defective cells





Ilott, et al, *Nat Comm* 9:1776, 2018

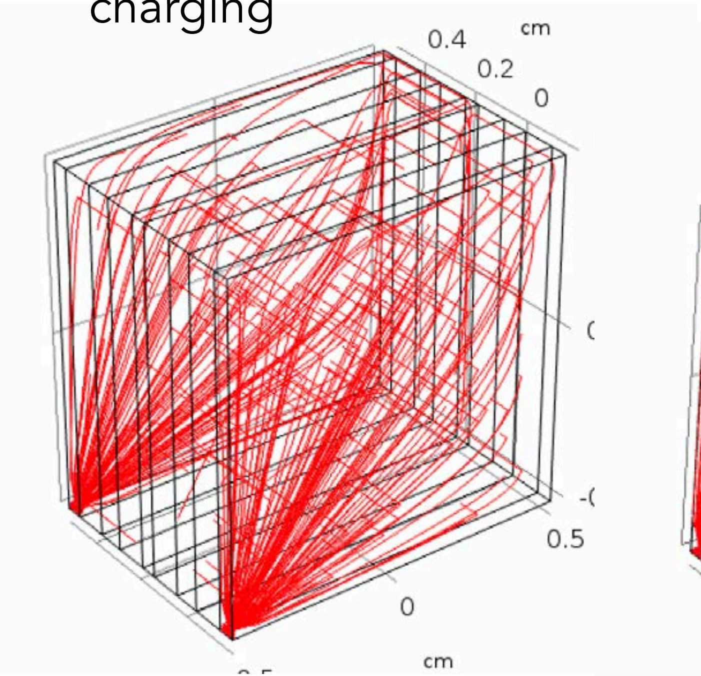
Current Distribution



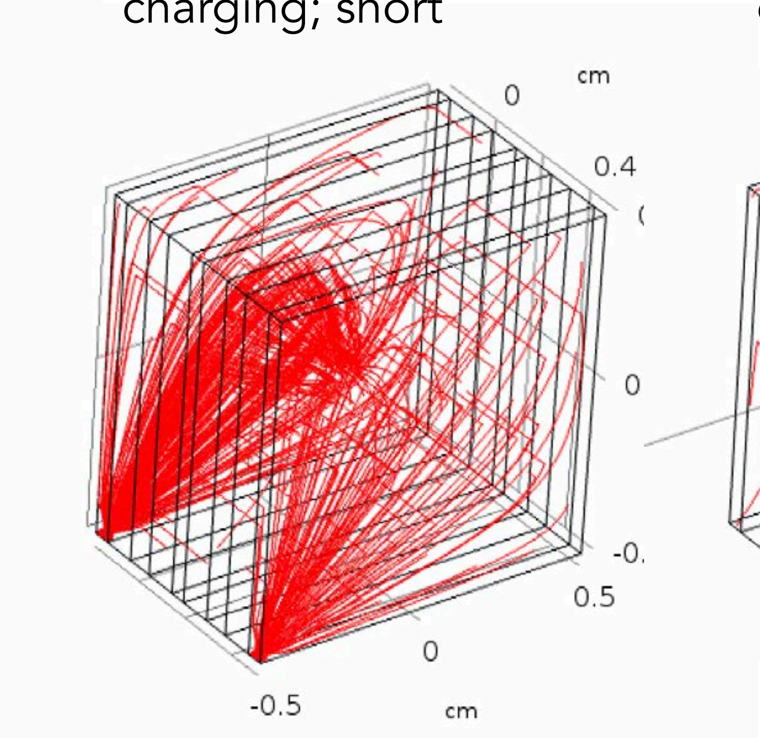
Yazdanpour, JECS, 161, 2014, A1953

Current distributions

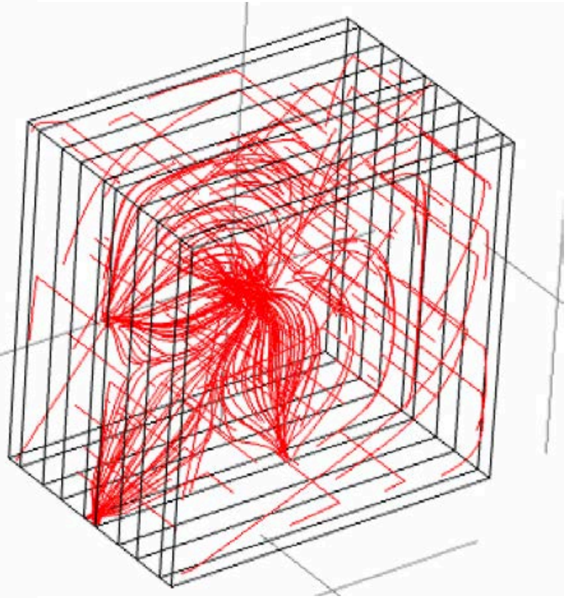
charging



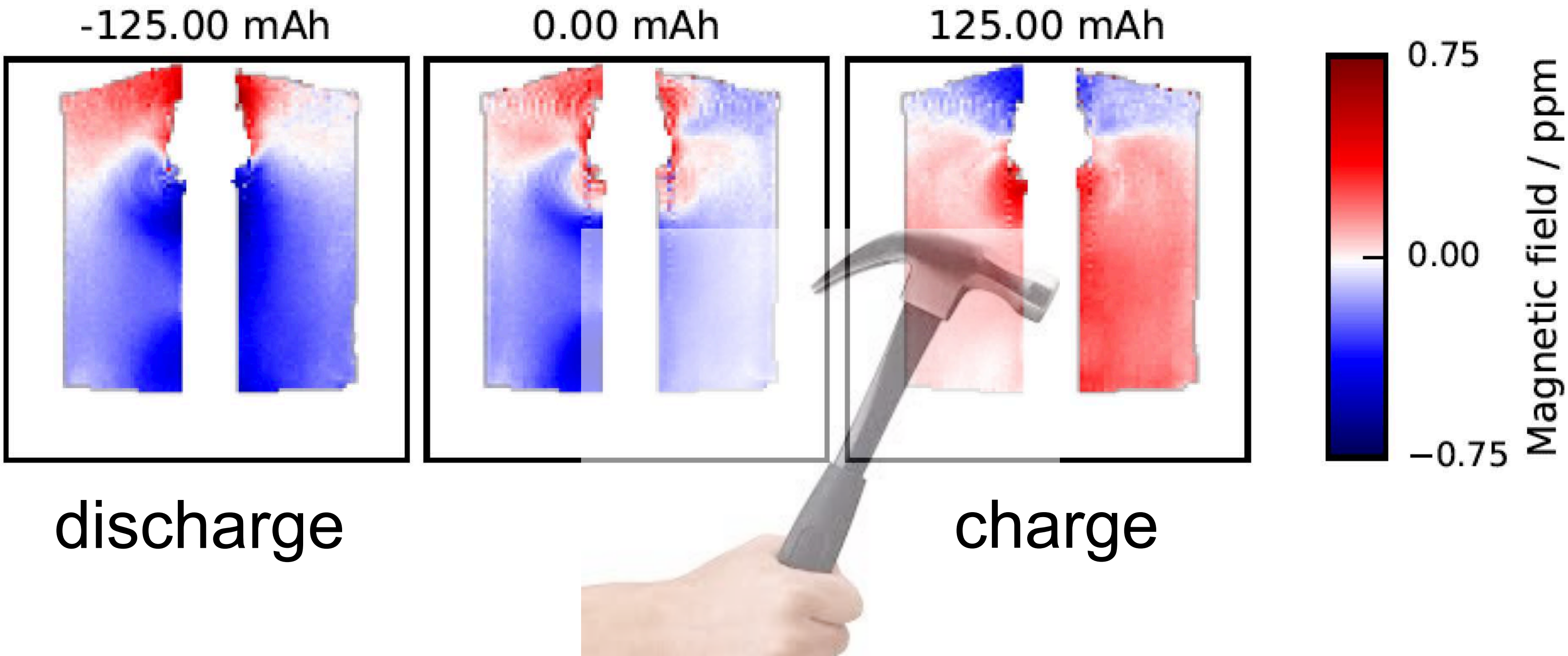
charging; short



discharging; short



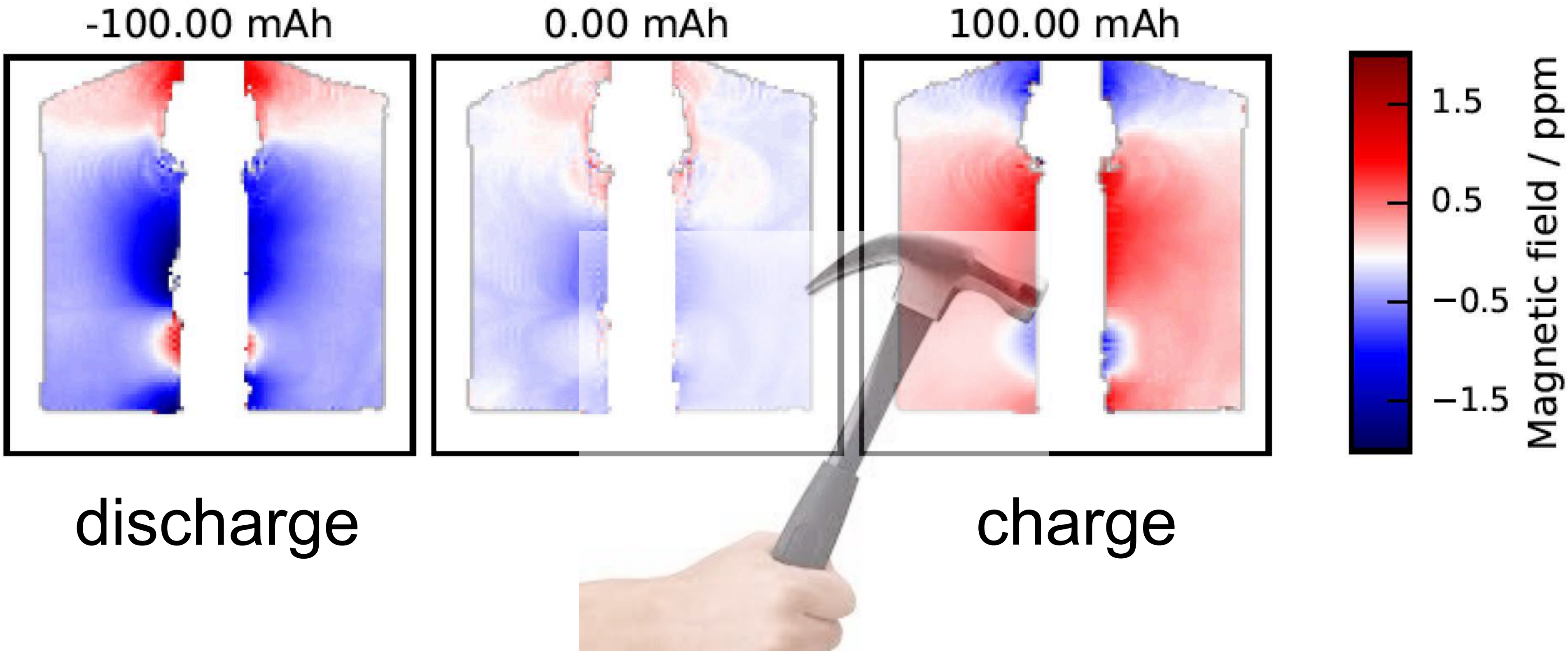
Current distributions with MRI

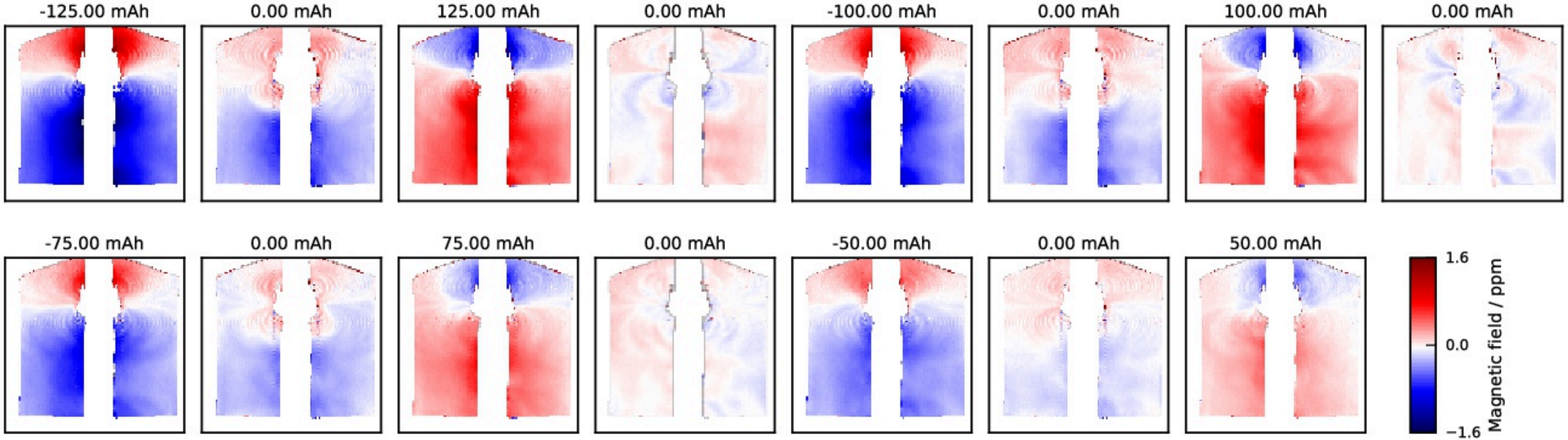


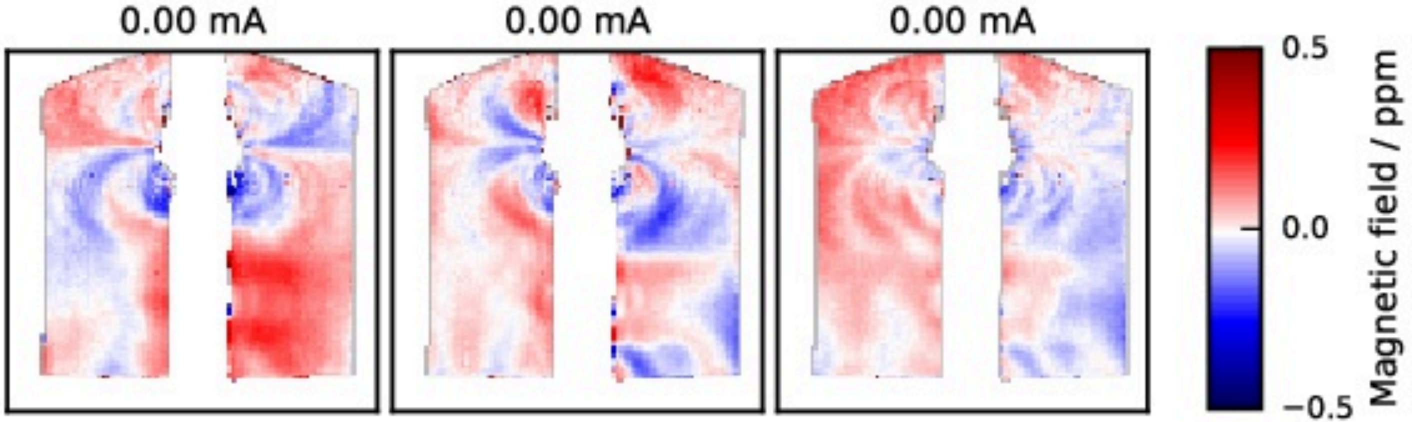
discharge

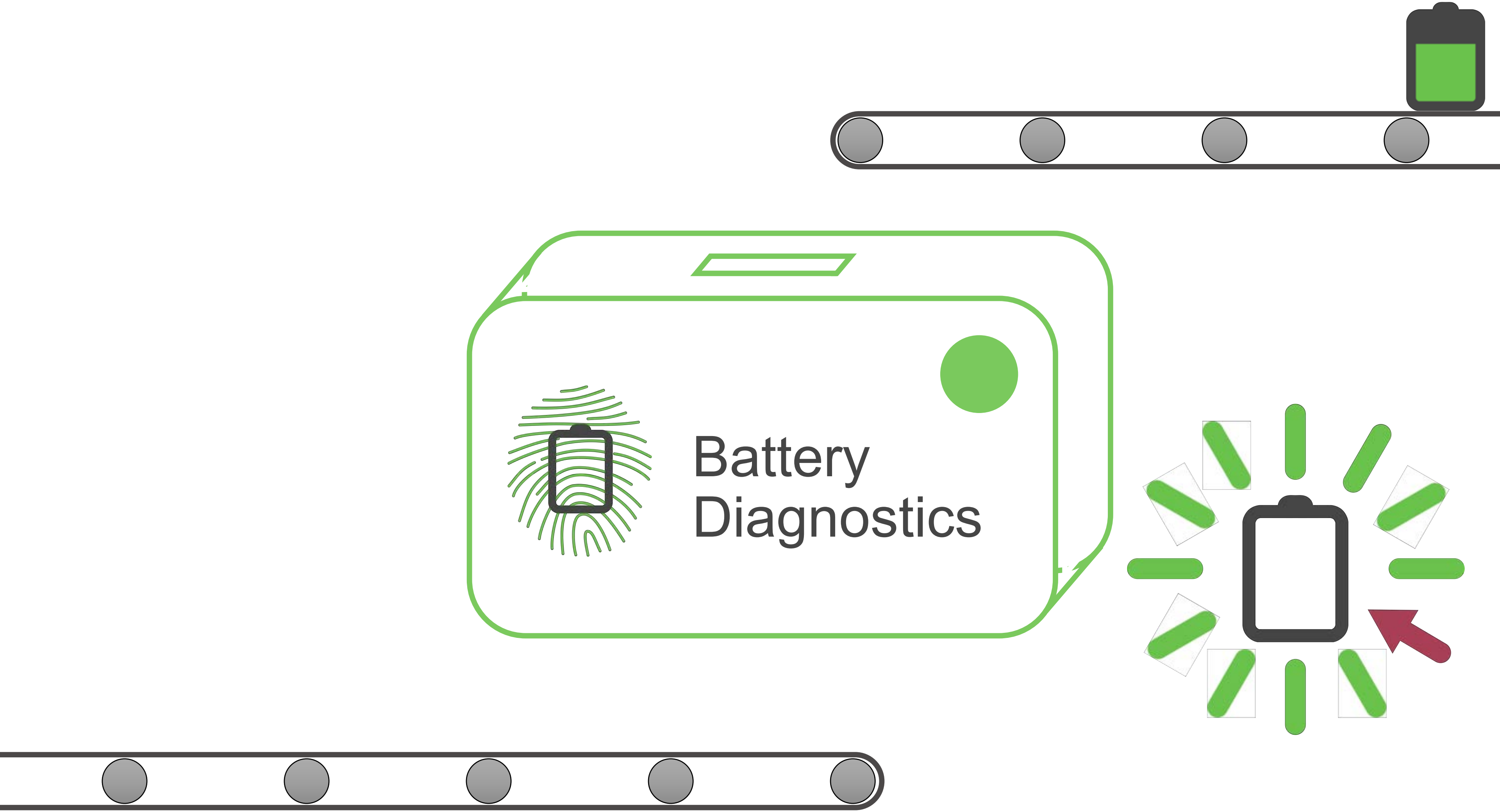
charge

Current distributions with MRI




-125.00 mAh
0.00 mAh
125.00 mAh
0.00 mAh
-100.00 mAh
0.00 mAh
100.00 mAh
0.00 mAh
-75.00 mAh
0.00 mAh
75.00 mAh
0.00 mAh
-50.00 mAh
0.00 mAh
50.00 mAh
1.6
0.0
−1.6
Magnetic field / ppm

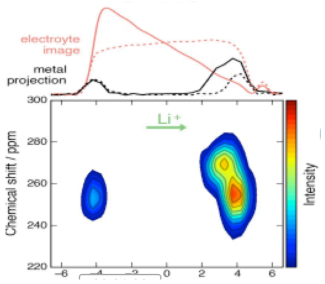

0.00 mA
0.00 mA
0.00 mA
0.5
0.0
−0.5
Magnetic field / ppm


Battery
Diagnostics

In-situ (operando) NMR/MRI

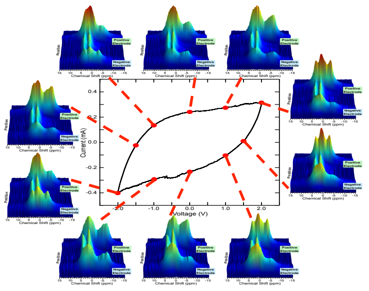
Li-dendrite visualization

- 7Li MRI / CSI
- 1H MRI



Supercapacitors

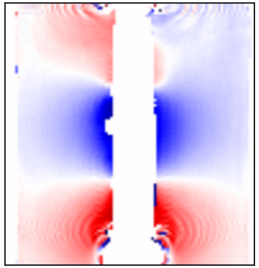
- 1H / 11B MRI

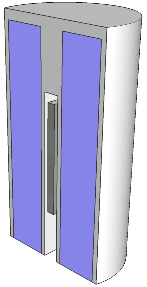


"In real life" Inside-out MRI

Commercial-type cell analysis

- SOC
- SOH
- Current distribution





Relevant Publications

- S. Chandrashekar, N. M. Trease, H. J. Chang, L.-S. Du, C. P. Grey, A. Jerschow, *7Li MRI of Li batteries reveals location of microstructural lithium*, Nature Mater., *11*, 311-315, **2012**, http://www.nature.com/doifinder/10.1038/nmat3246.
- A. J. Ilott, S. Chandrashekar, A. Klöckner, H. J. Chang, N. M. Trease, C. P. Grey, L. Greengard, A. Jerschow, *Visualizing skin effects in conductors with MRI: 7Li MRI experiments and calculations*, J. Magn. Reson, *245*, **2014**, 143-149, http://dx.doi.org/10.1016/j.jmr.2014.06.013.
- A. J. Ilott, N. M. Trease, C. P. Grey, A. Jerschow, *Multinuclear in situ magnetic resonance imaging of electrochemical double-layer capacitors*, Nat. Comm. *5*, **2014,** 4536, http://dx.doi.org/10.1038/ncomms5536**.**
- H. J. Chang , N. M. Trease , A. J. Ilott , D. Zeng , L.-S. Du , A. Jerschow, C. P. Grey, *Investigating Li Microstructure Formation on Li Anodes for Lithium Batteries by In Situ 6Li/7Li NMR and SEM*, J. Phys. Chem. C, **2015**, 119, 16443–16451, http://dx.doi.org/10.1021/acs.jpcc.5b03396.
- H.J. Chang, A. J. Ilott, N. M. Trease, M. Mohammadi, A. Jerschow, C. P. Grey, *Correlating Microstructural Lithium Metal Growth with Electrolyte Salt Depletion in Lithium Batteries using ^{7}Li MRI*, J. Am. Chem. Soc., **2015**, 137, 15209–15216, http://dx.doi.org/10.1021/jacs.5b09385.
- A. J. Ilott, H.-J. Chang, C. P. Grey, A. Jerschow, *Real time 3D imaging of microstructure growth in battery cells using indirect MRI*, Proc. Natl. Acad. Sci. USA, **2016**, 113, 10779-84, http://www.pnas.org/content/early/2016/09/06/1607903113.abstract.
- A. J. Ilott and A. Jerschow, *Super-resolution Surface Microscopy of Conductors using Magnetic Resonance,* Sci Rep. **2017**, 7, 5425, http://rdcu.be/ubQl, https://www.nature.com/articles/s41598-017-05429-3
- A. J. Ilott, M. Mohammadi, C. M. Schauerman, M. J. Ganter, A. Jerschow, Rechargeable lithium-ion cell state of charge and defect detection by in-situ inside-out magnetic resonance imaging, Nat Comm 9:1776, 2018, http://dx.doi.org/10.1038/s41467-018-04192-x

Acknowledgements

NYU

- Andy Ilott
- Mohaddese Mohammadi
- S. C. Shekar
- Emilia Silletta

RIT Battery Prototyping

- Christopher Schauerman
- Matthew Ganter

NEW YORK UNIVERSITY

NSF

Mercedes-Benz

NY BEST

NEW YORK BATTERY AND ENERGY STORAGE TECHNOLOGY CONSORTIUM

POWERBRIDGE NY

NY-BEST BRIDGE PROGRAM