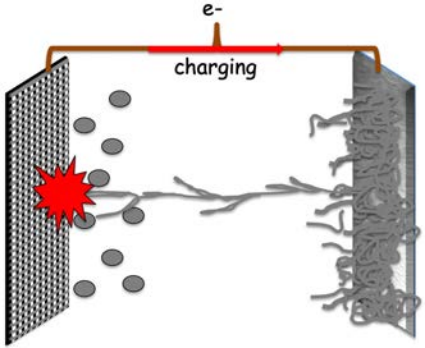
New opportunities for battery research and development from inside-out MRI and magnetometry

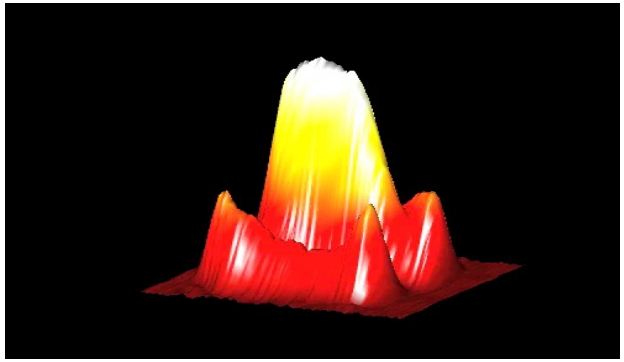
Alexej Jerschow

Battery Diagnostics Limited

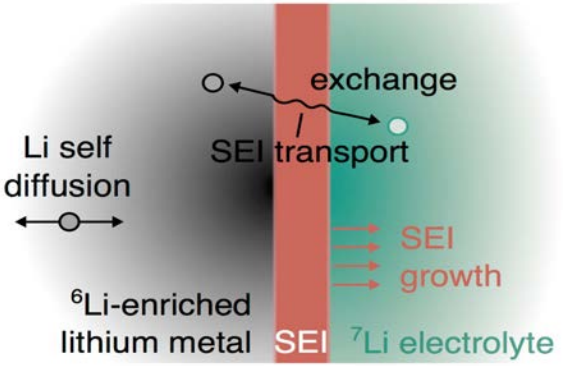
7Li MRI of dendrites



Nat. Mater., 11, 2012, 311

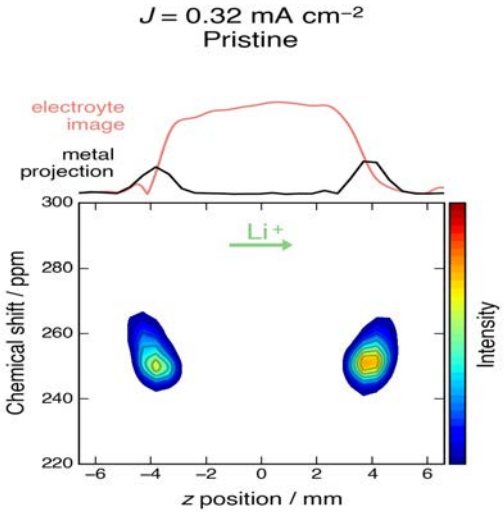


SEI growth 7Li/6Li



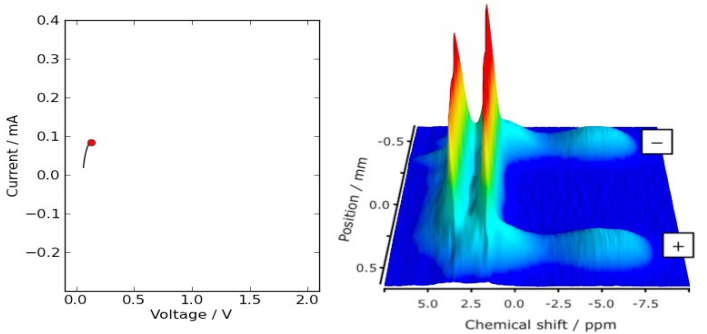
J. Phys. Chem. C. 2018, 122, 12598

In-situ (operando) NMR/MRI



Li dendrite growth
JACS 2015, 137, 15209

Ion localization, supercaps

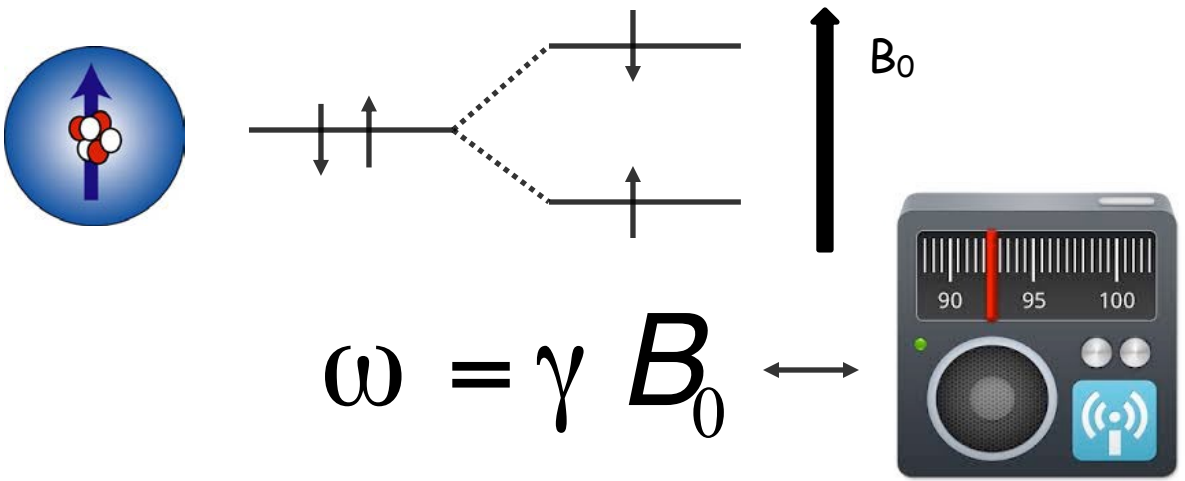


Nat. Comm., 5, 2014, 4536

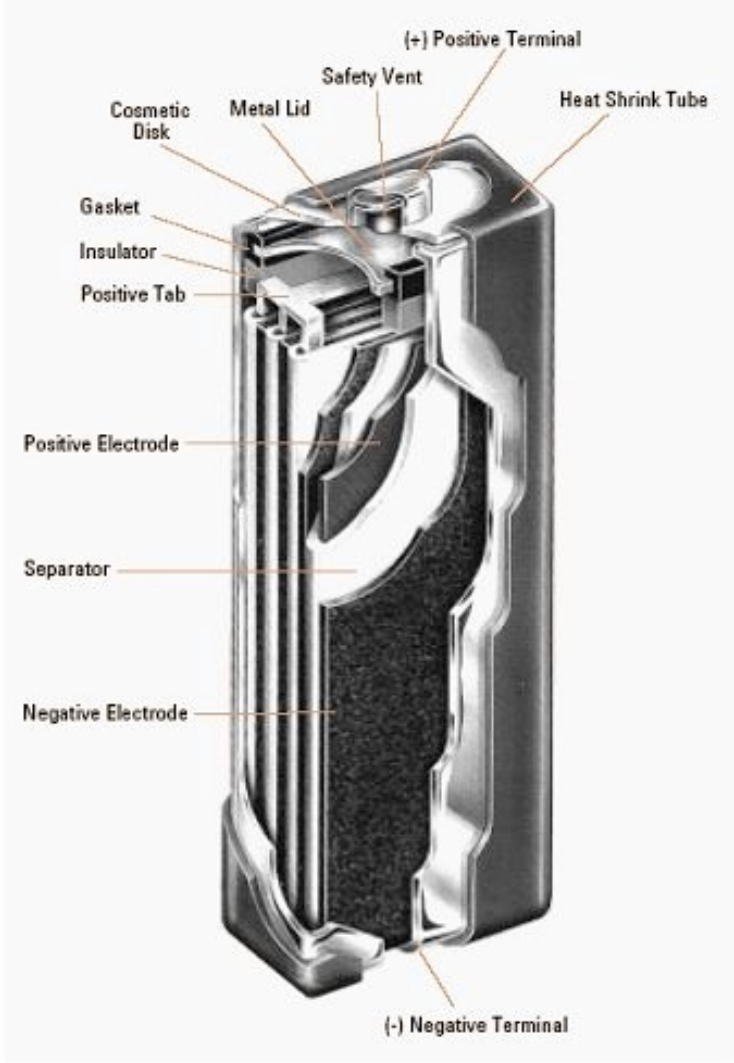
“In real life”

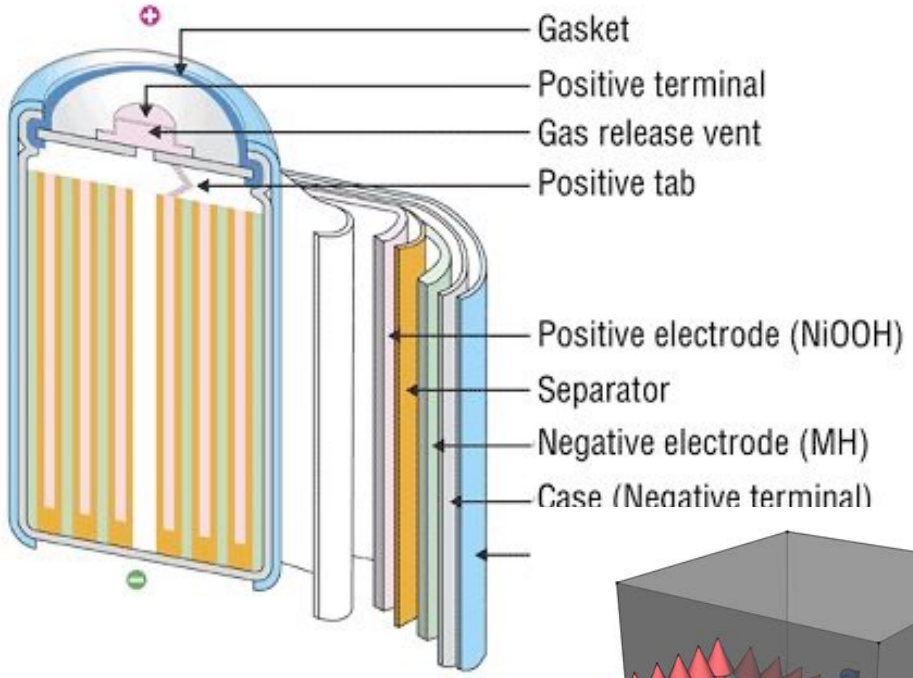
predict failures,
lifetimes
early
non-destructively
quickly

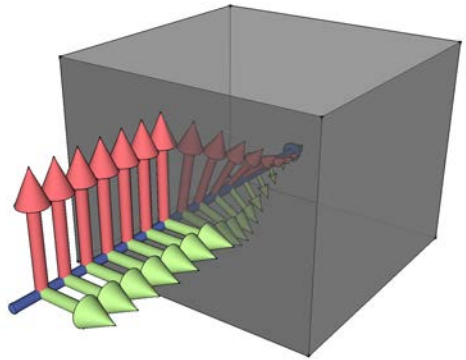
NMR



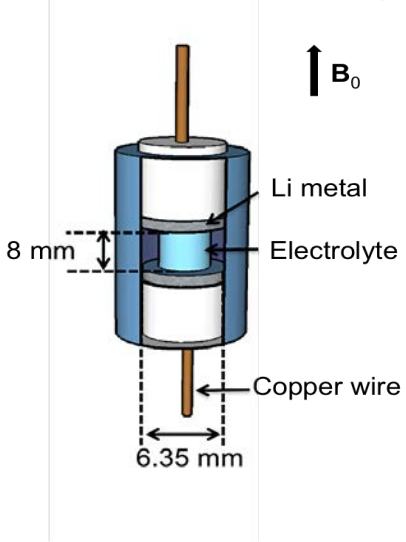
$$\omega = \gamma B_0$$

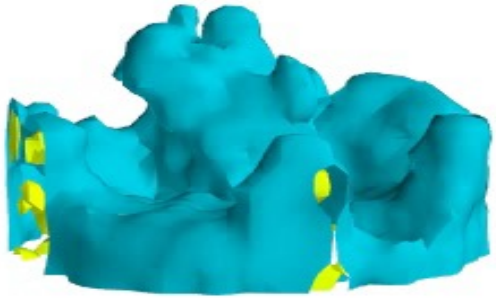

(+) Positive Terminal
Safety Vent
Heat Shrink Tube
Cosmetic Disk
Metal Lid
Gasket
Insulator
Positive Tab
Positive Electrode
Separator
Negative Electrode
(-) Negative Terminal


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



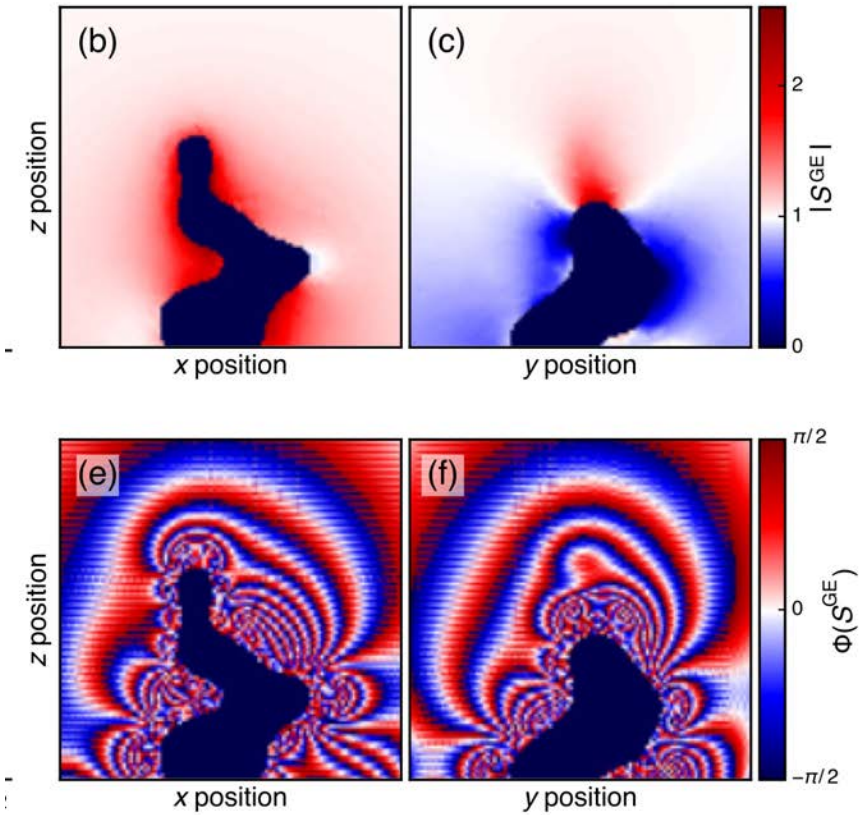
Indirect MRI of dendrite growth





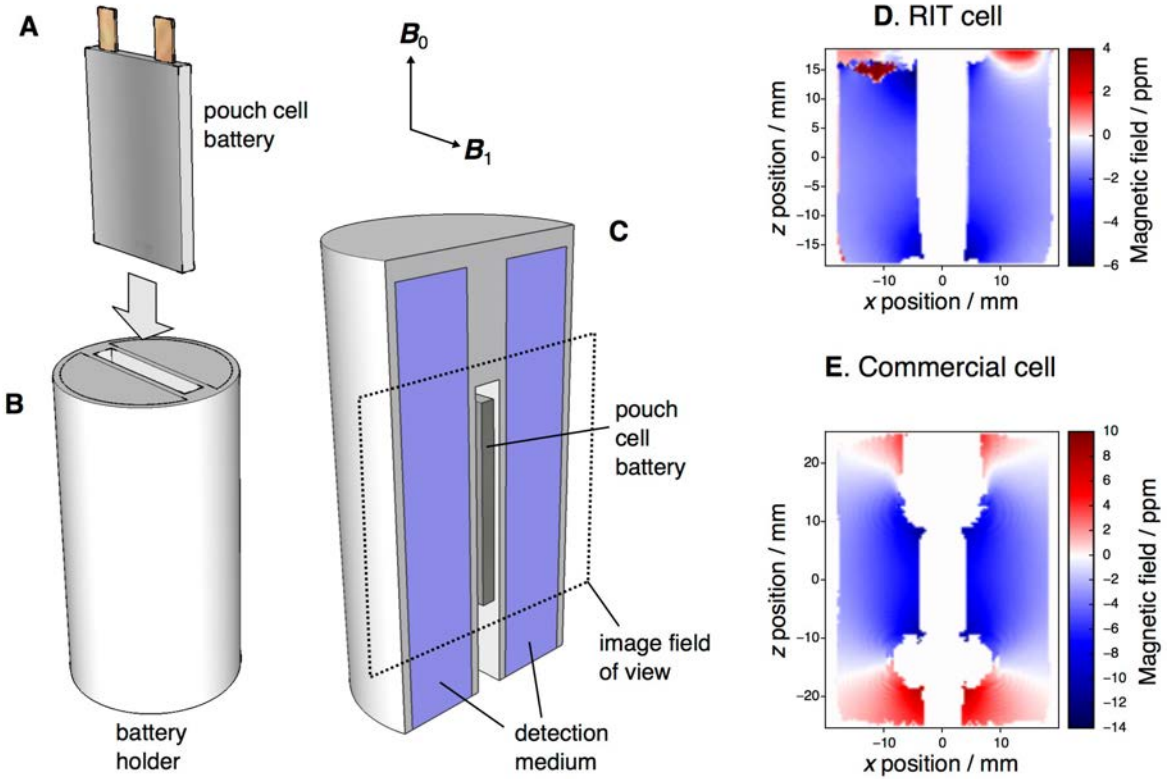
1H 3D FLASH 'negative' image

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



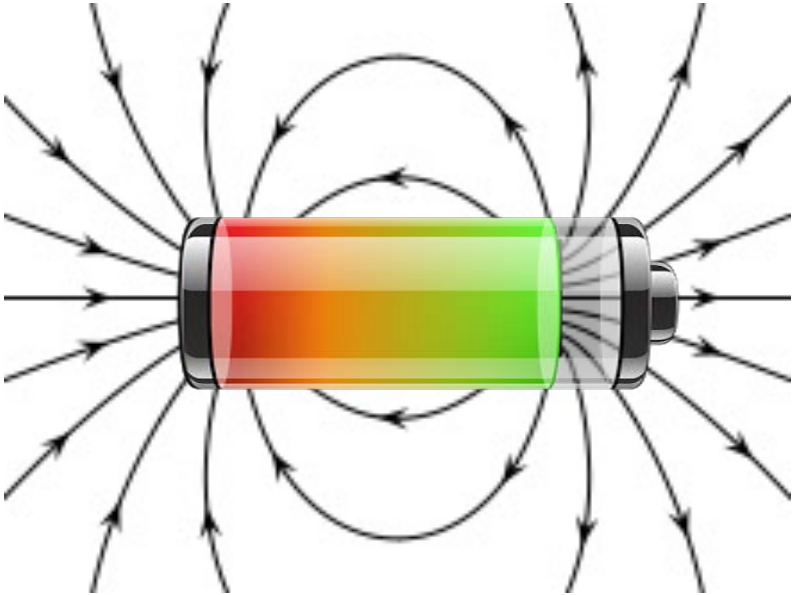
Ilott et al., PNAS, **2016**, 113, 10779-84

Inside-out MRI

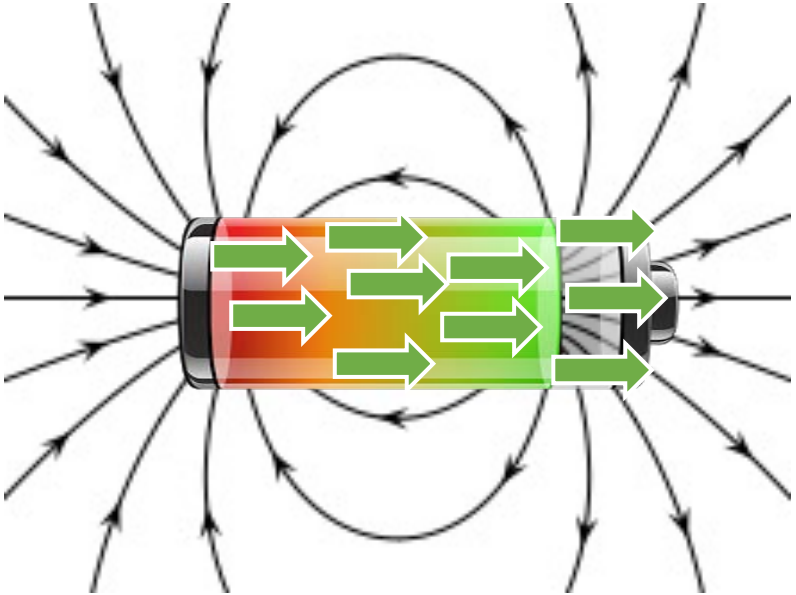


Ilott, et al, *Nat Comm* 9:1776, 2018

B_0



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]

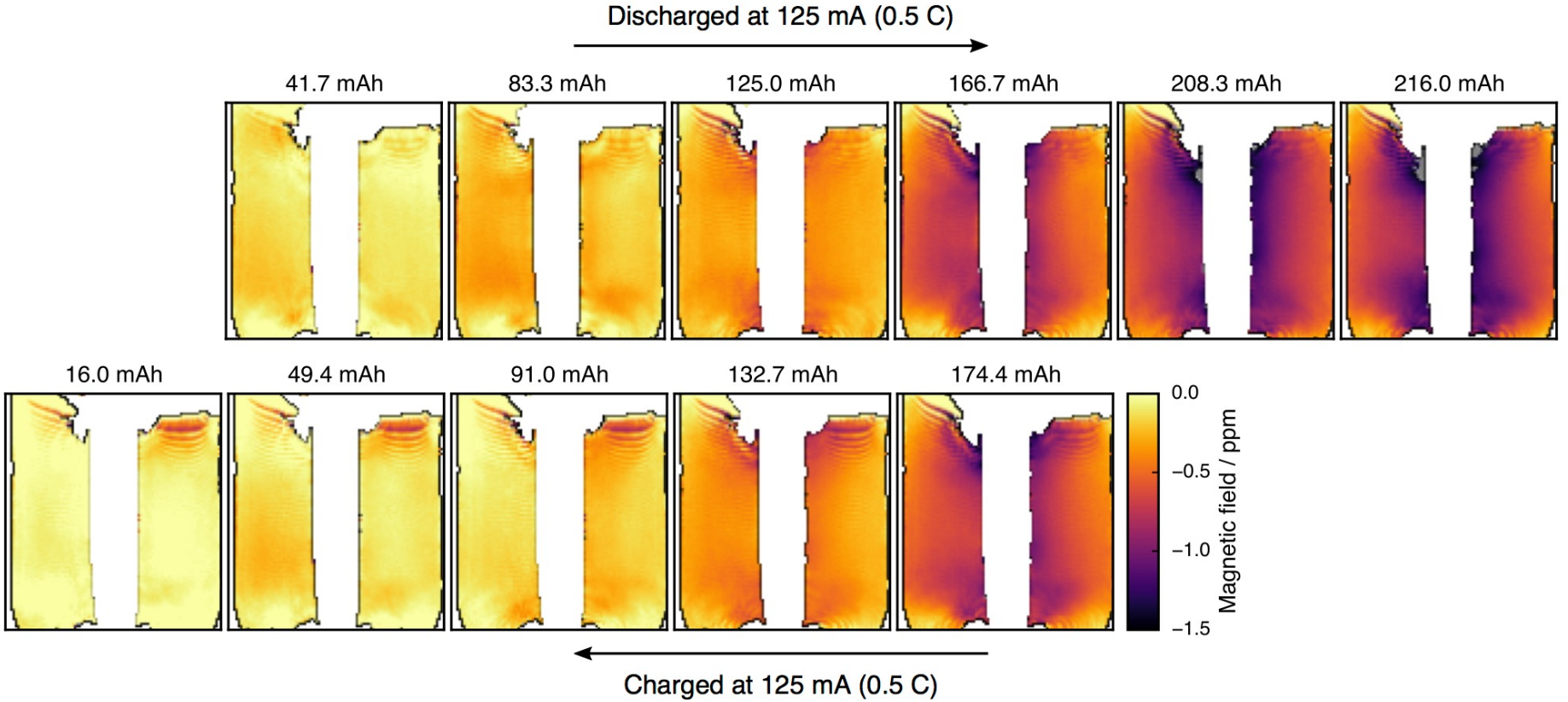
Chem. Mater. **2007,** *19,* 4682−4693

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‡

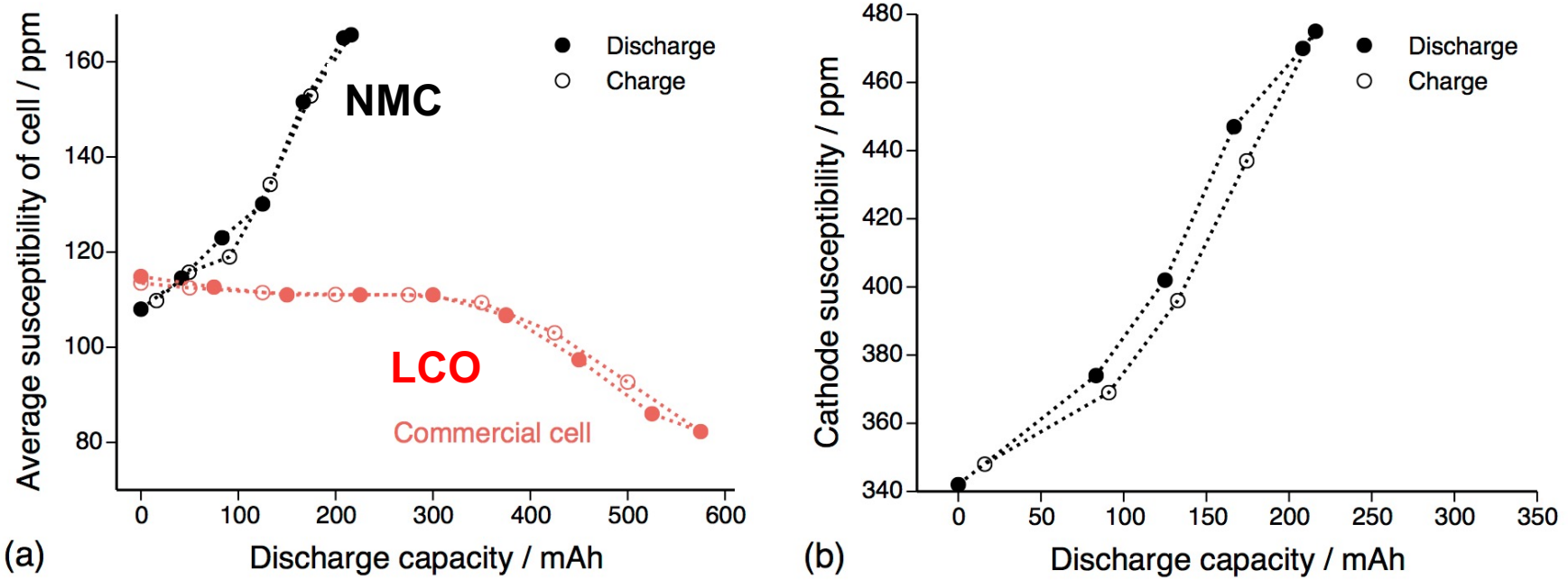

NITROGENN

Magnetic field maps during discharge



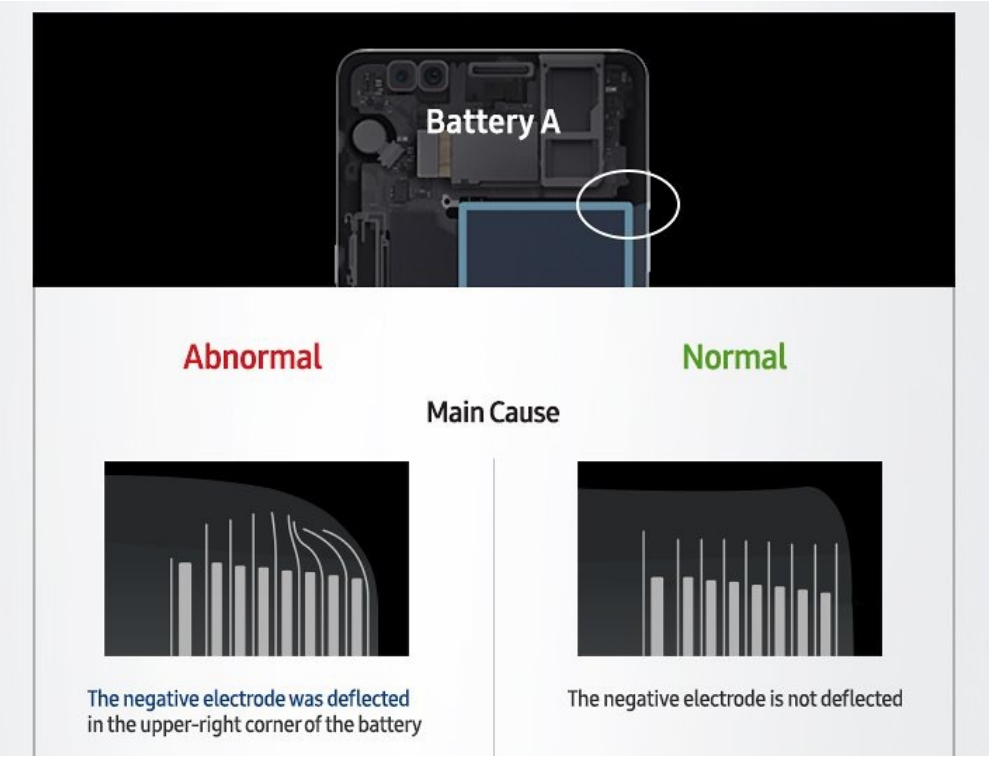
Ilott, et al, *Nat Comm* 9:1776, 2018

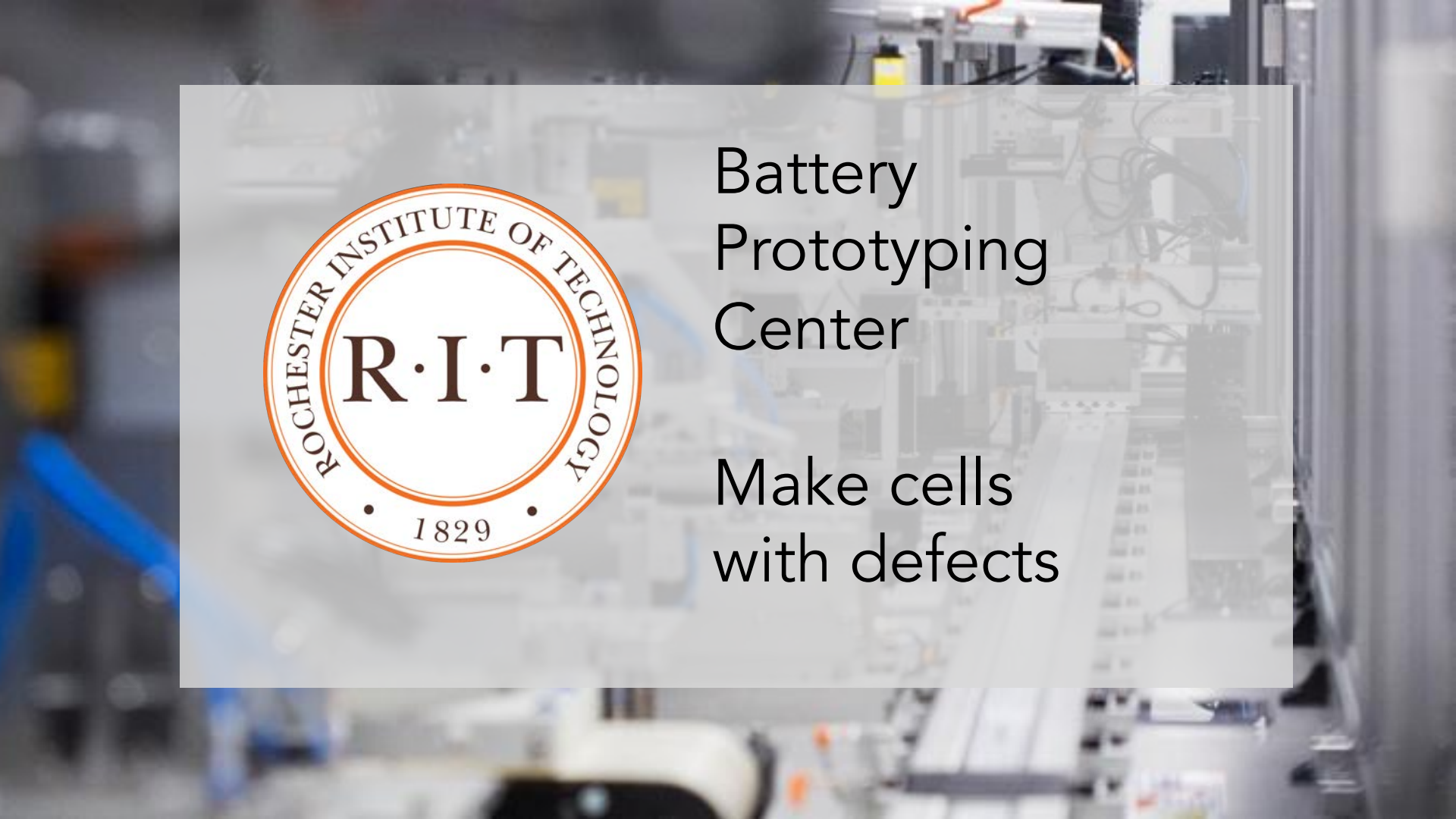
State of Charge from Susceptibility



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

Samsung battery defects Jan 2017 press release

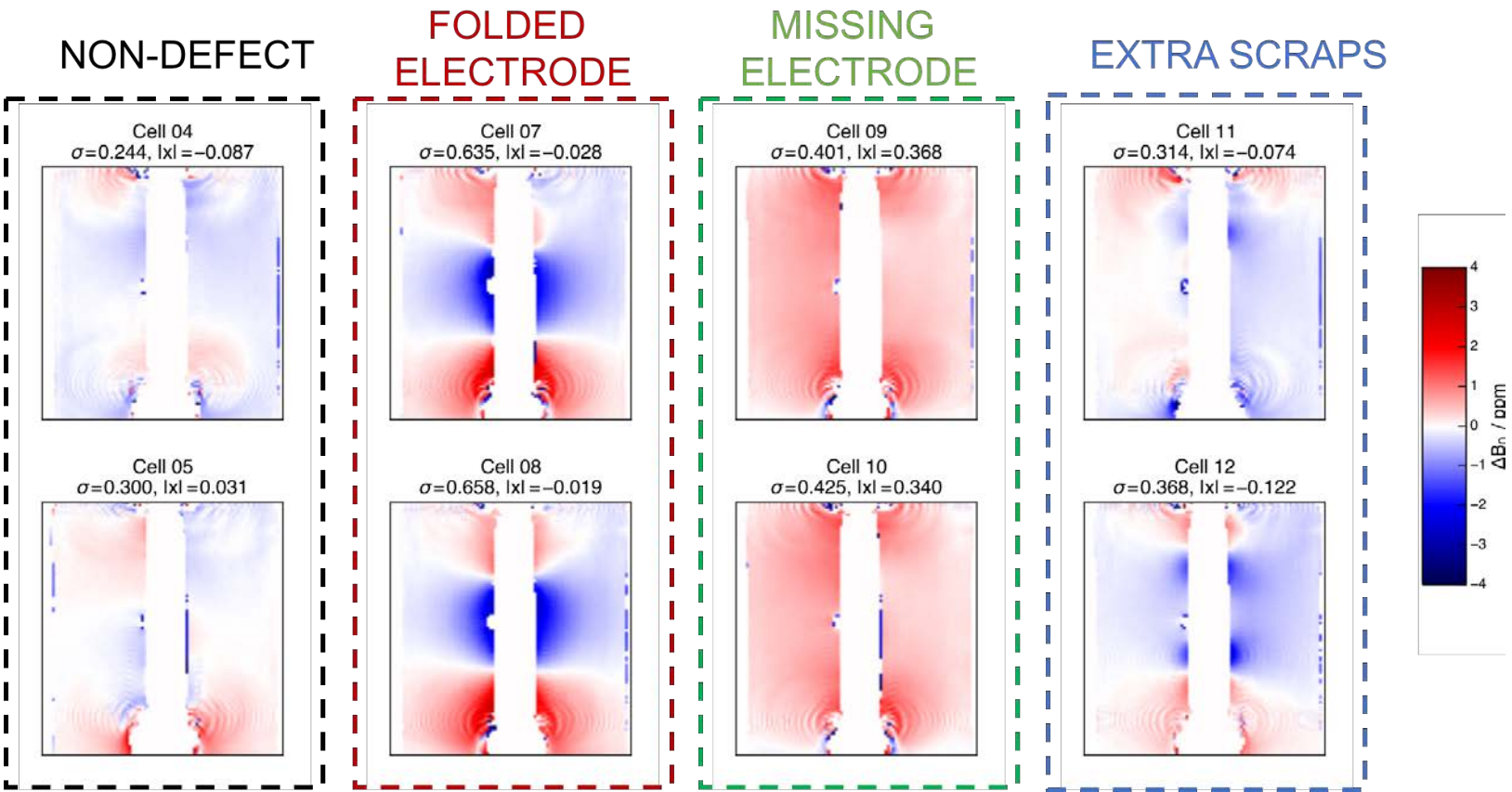


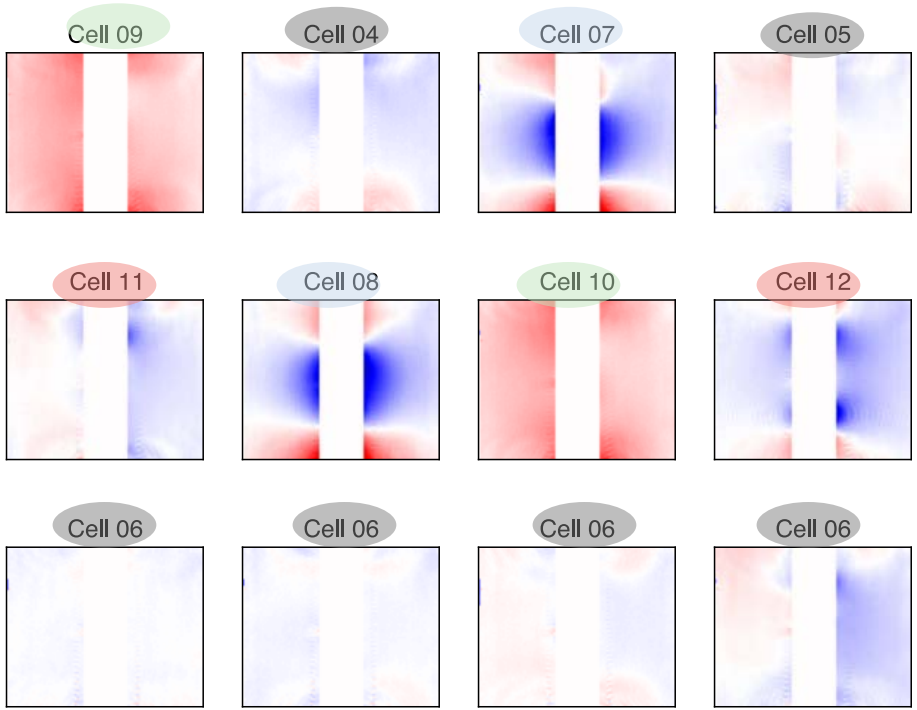


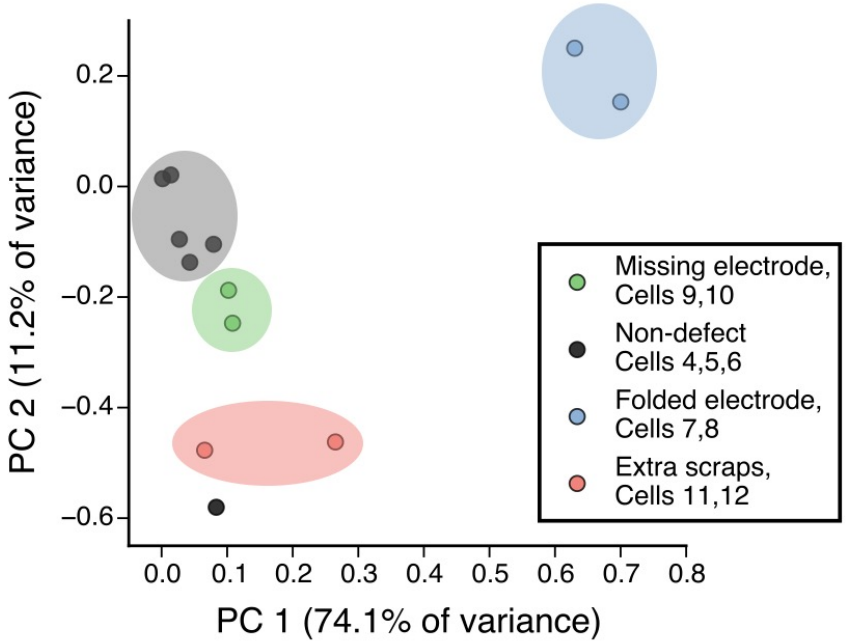
Battery Prototyping Center

Make cells with defects

Defective cells

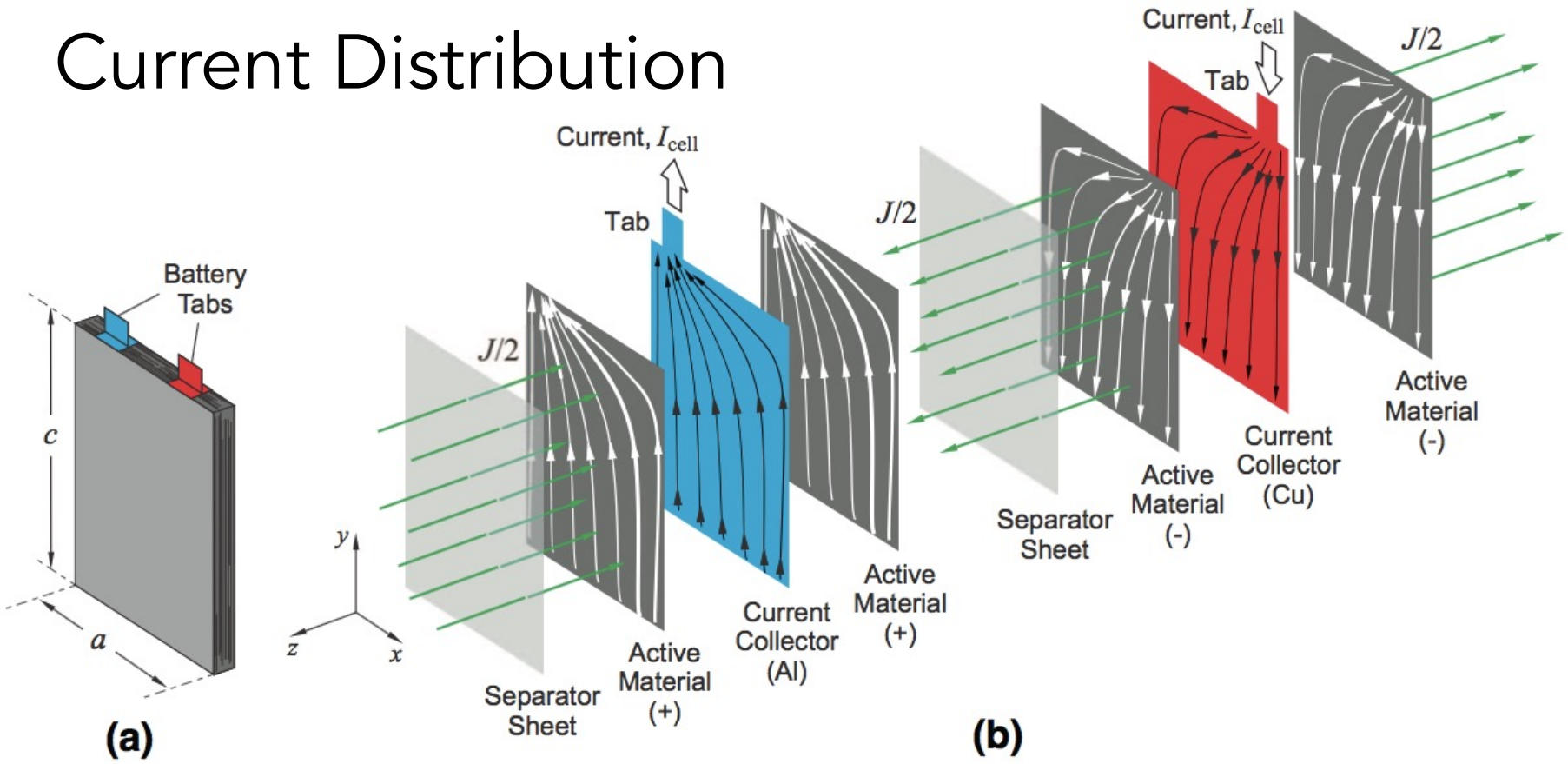






Ilott, et al, *Nat Comm* 9:1776, 2018

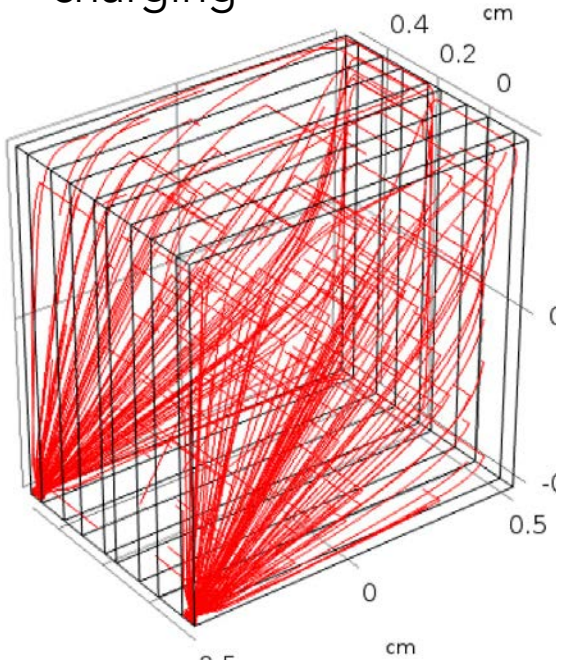
Current Distribution



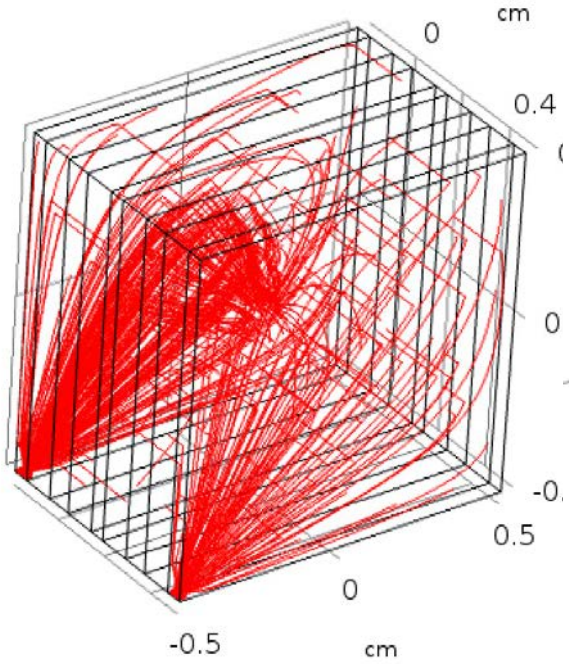
Yazdanpour, JECS, 161, 2014, A1953

Current distributions

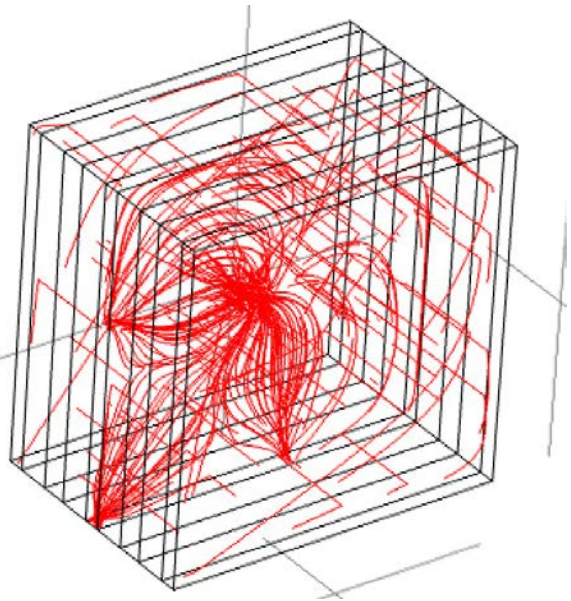
charging



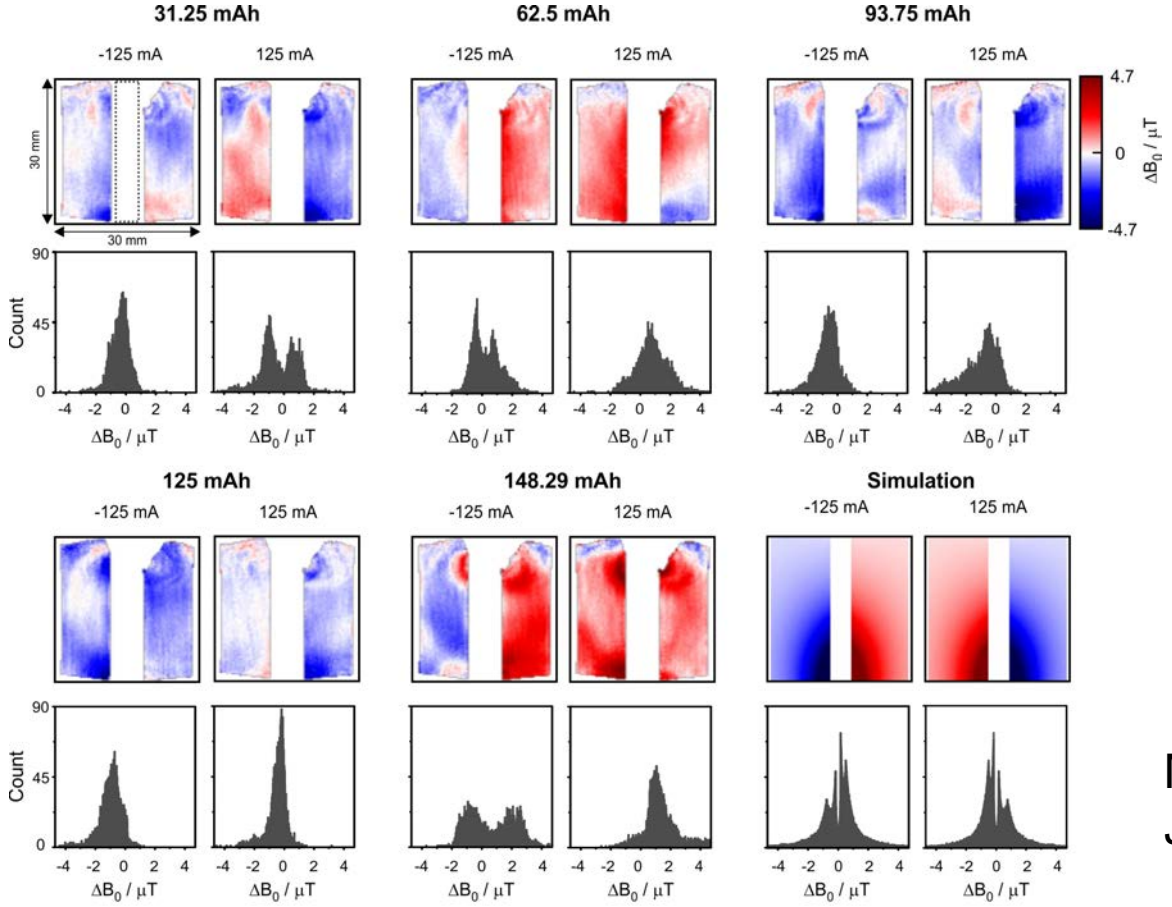
charging; short



discharging; short

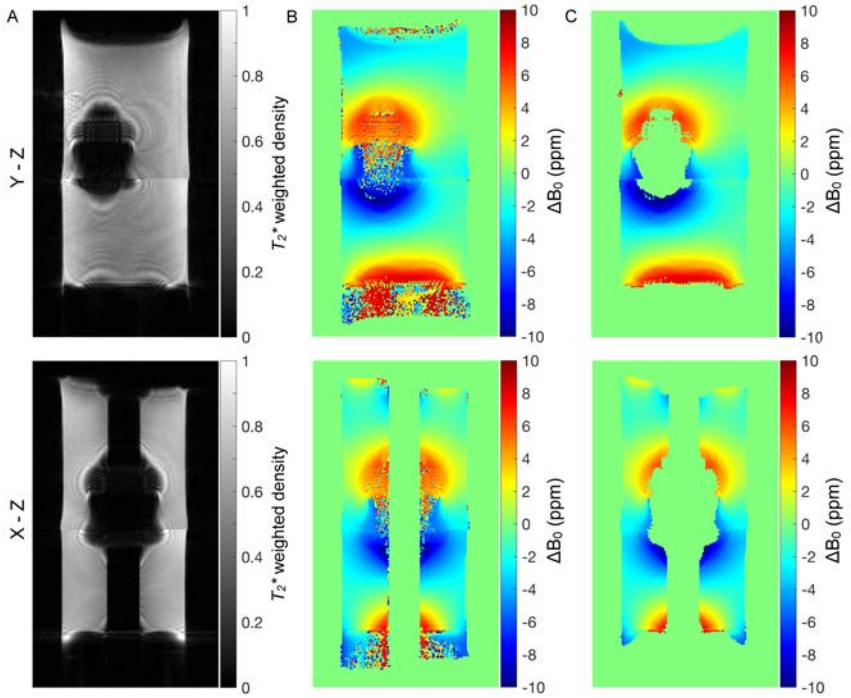


Current Imaging

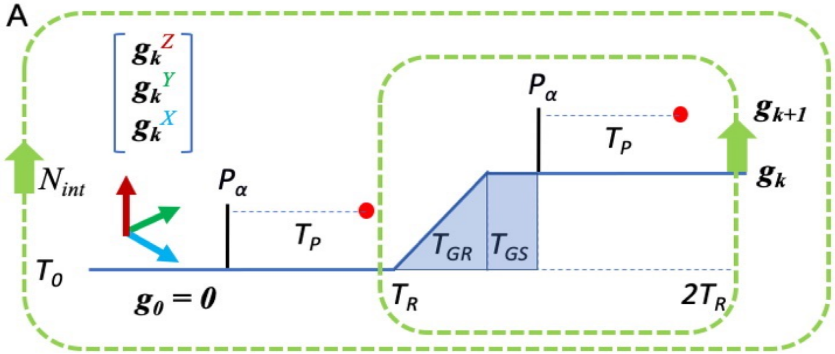


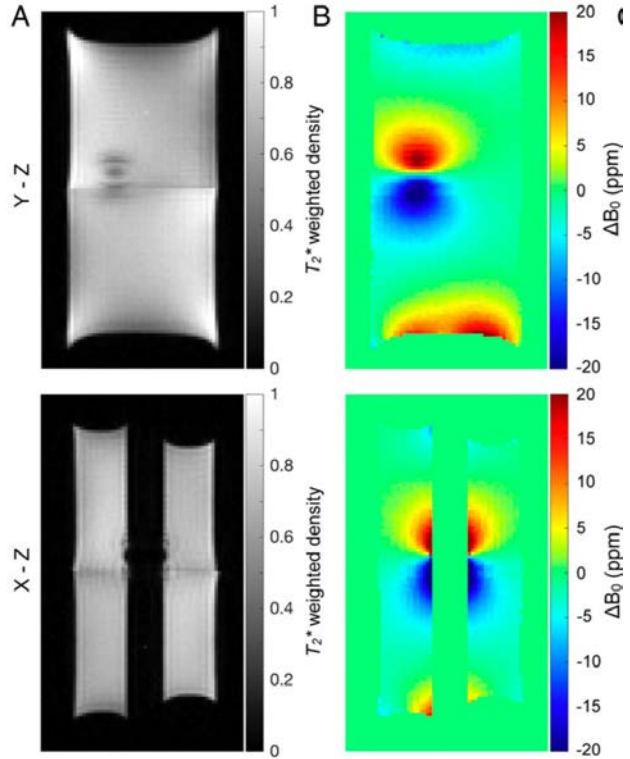
Mohammadi et al
JMR 2019

FLASH images



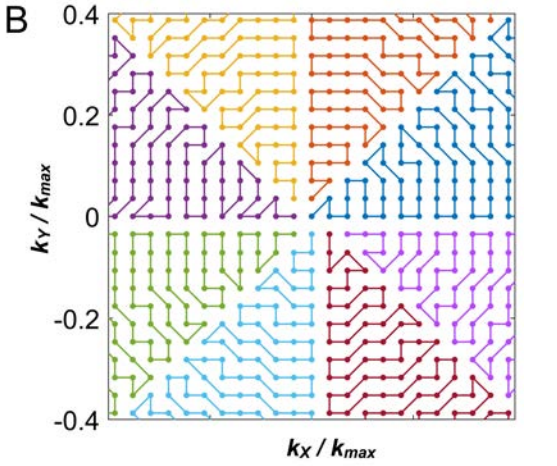
Single Point Imaging (SPRITE)

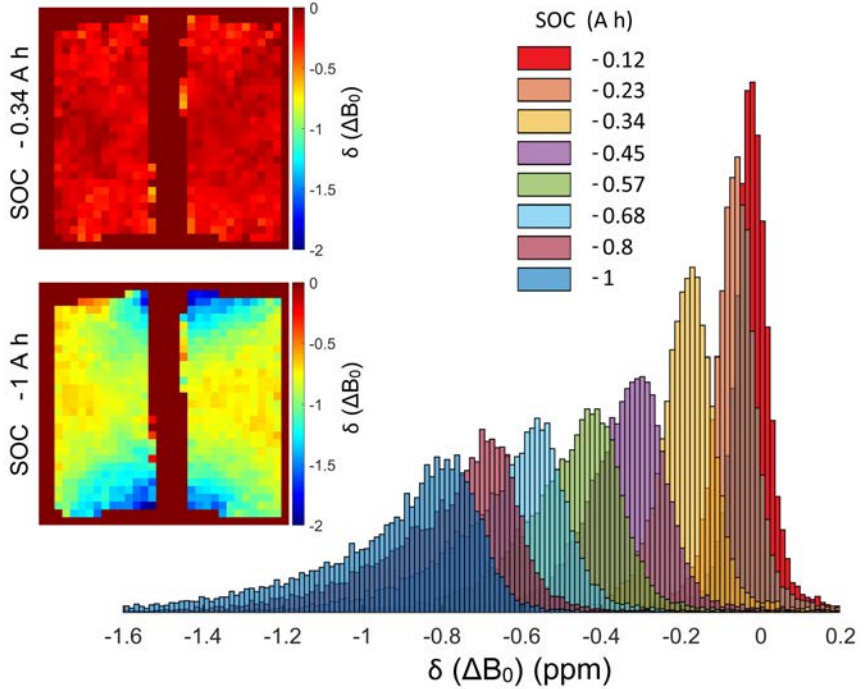




Romanenko, Jerschow, PNAS 2019

Single Point Imaging (SPRITE)





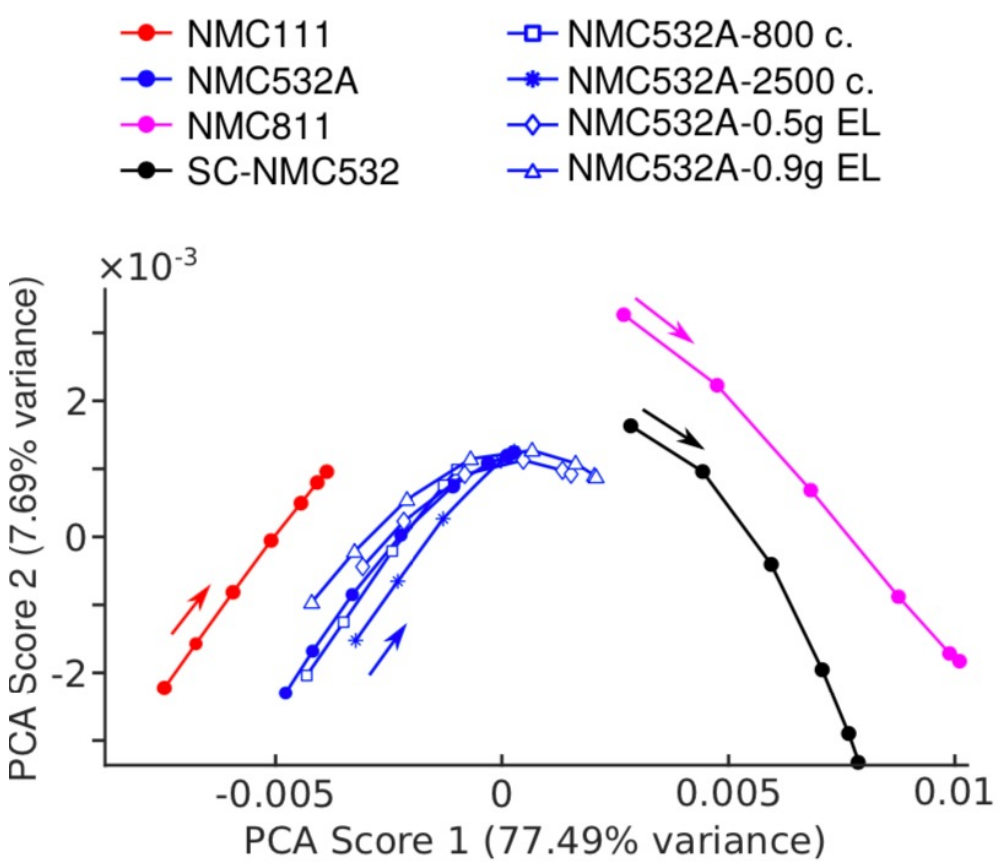
Romanenko, Jerschow, PNAS 2019

Ultrafast Cell Classification with NMR

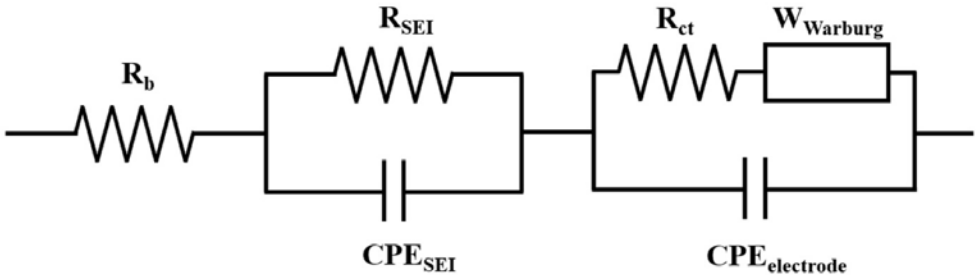
- Cell classification in under one second.
- SOC follows unique classifiable path.
- Each cathode material follows unique trajectory

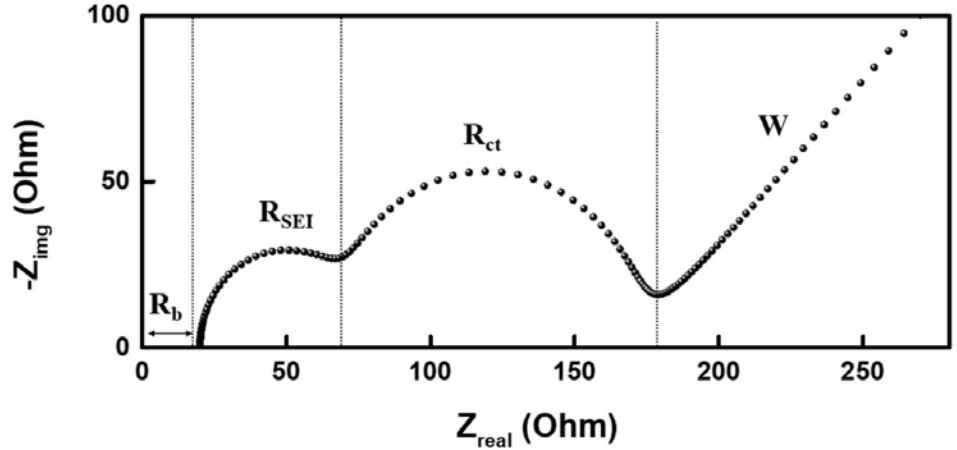
Batt&Supercap 2020

NYU



Electrical Impedance Spectroscopy

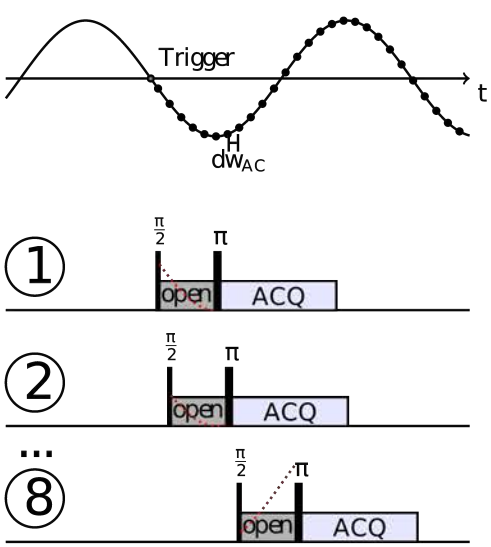




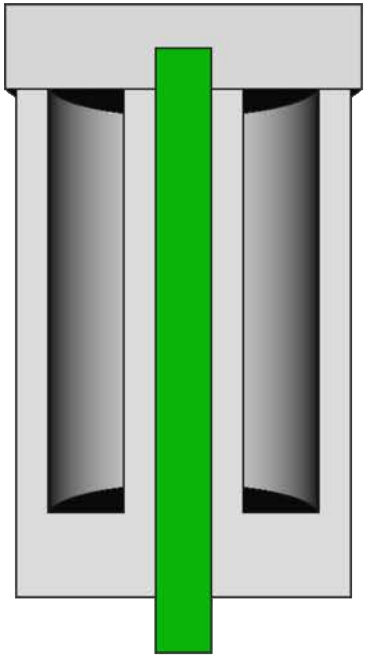
J Electrochem Sci Tech 2020, 11:1

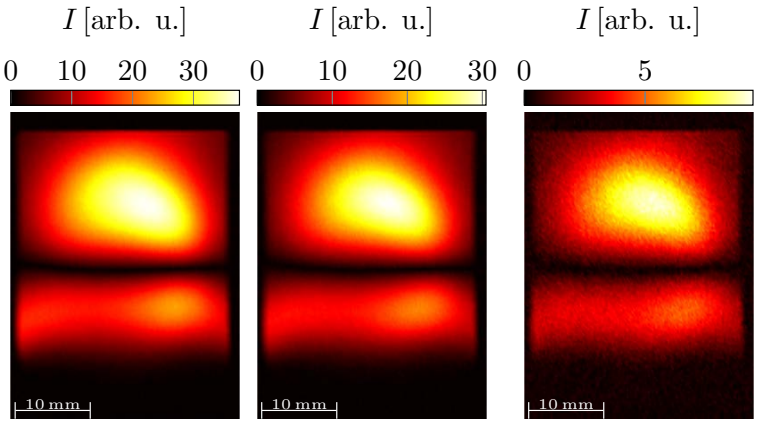
AC imaging: synchronized MRI acquisition

b)



c)



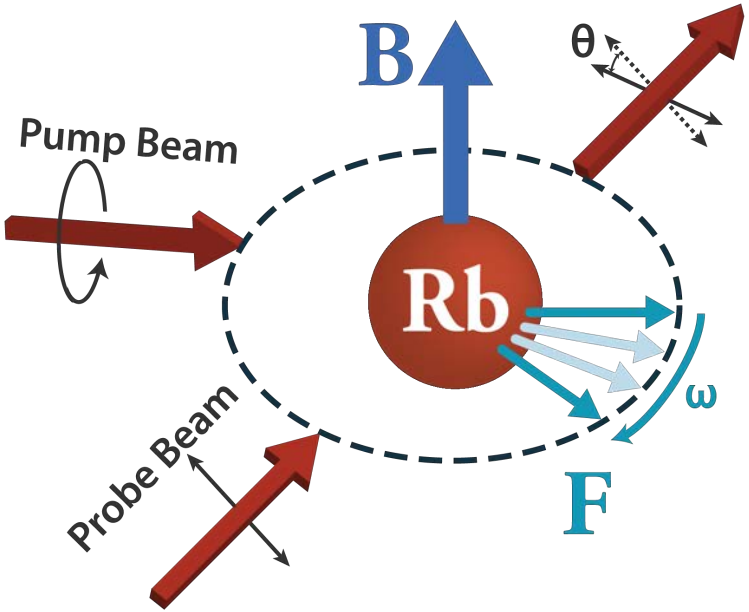


(a) 20 Hz (b) 140 Hz (c) 500 Hz

JMR 2020

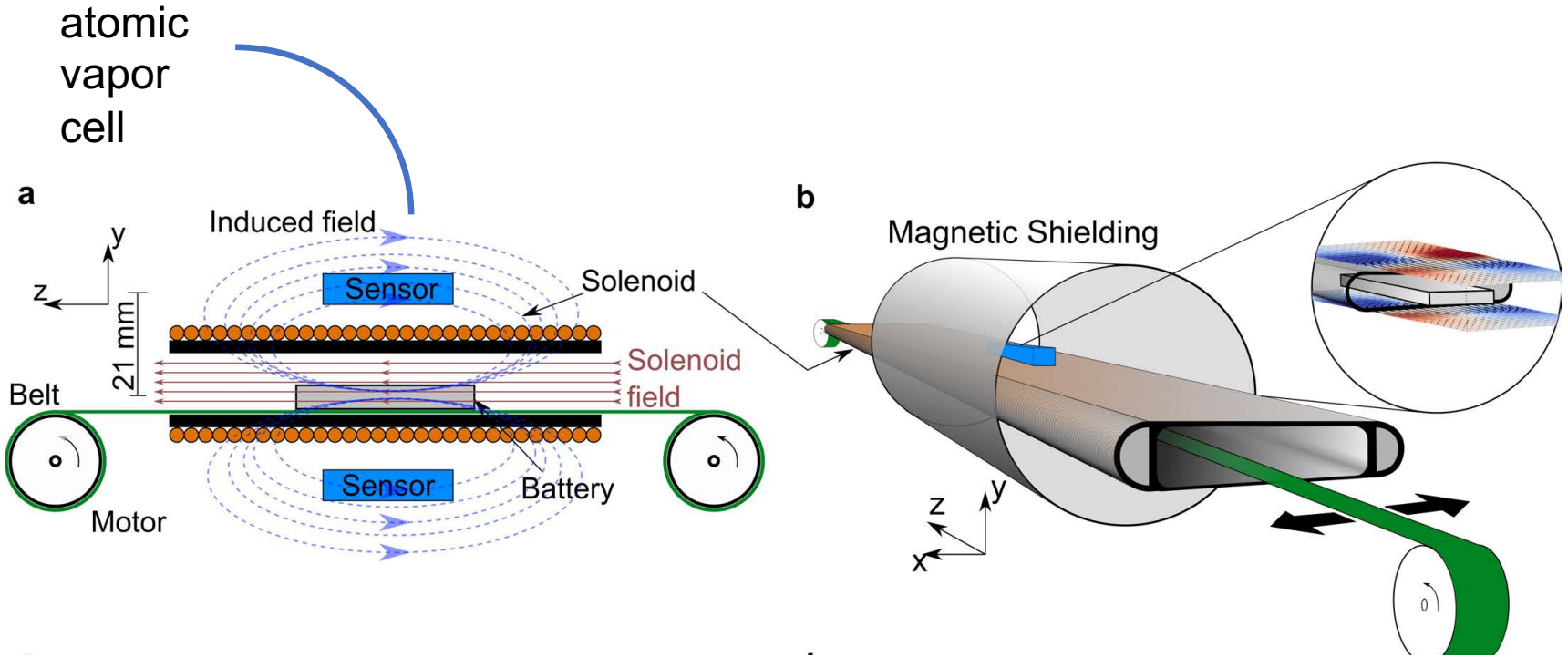
Magnetometry

atomic vapor magnetometer



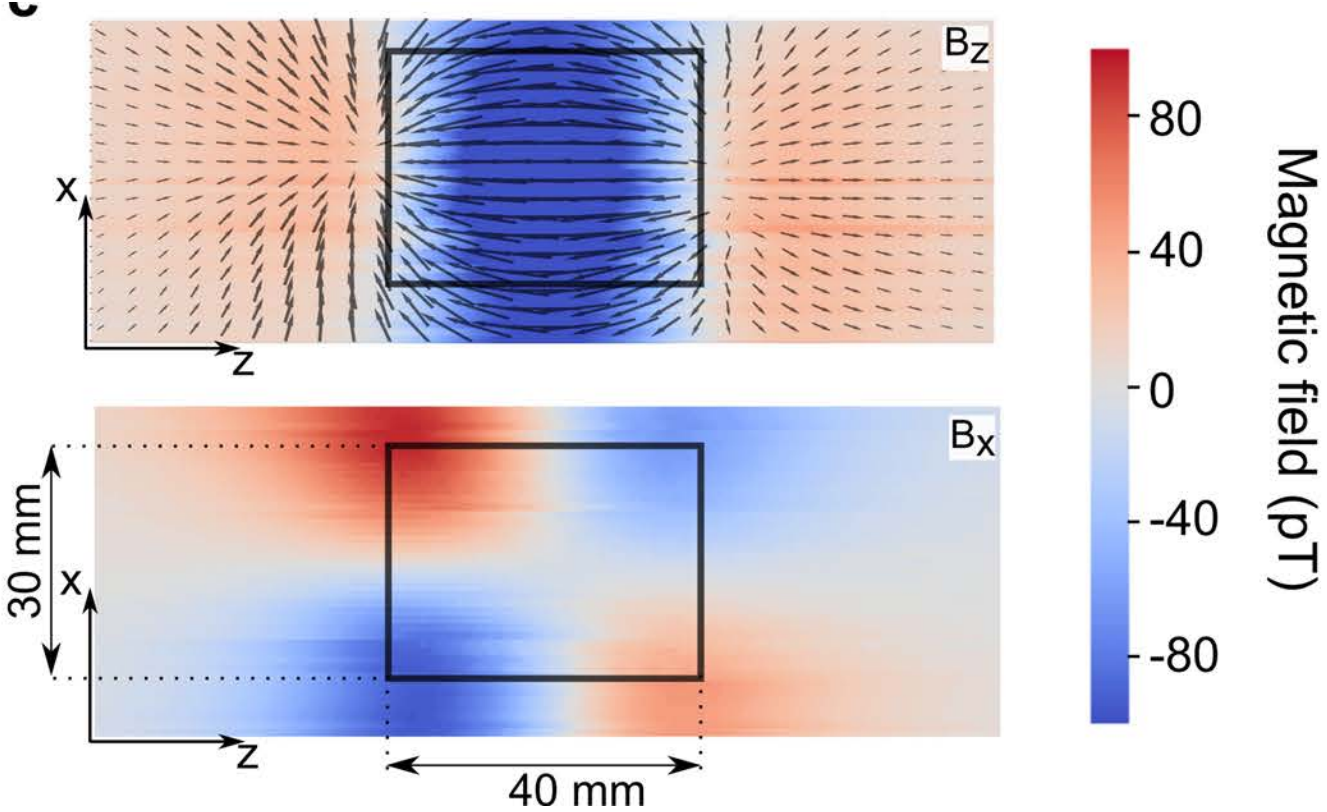
Geoffrey Iwata
Yinan Hu
John Blanchard
Arne Wickenbrock
Dima Budker
(JGU Mainz –Helmholtz Inst)

Magnetometry



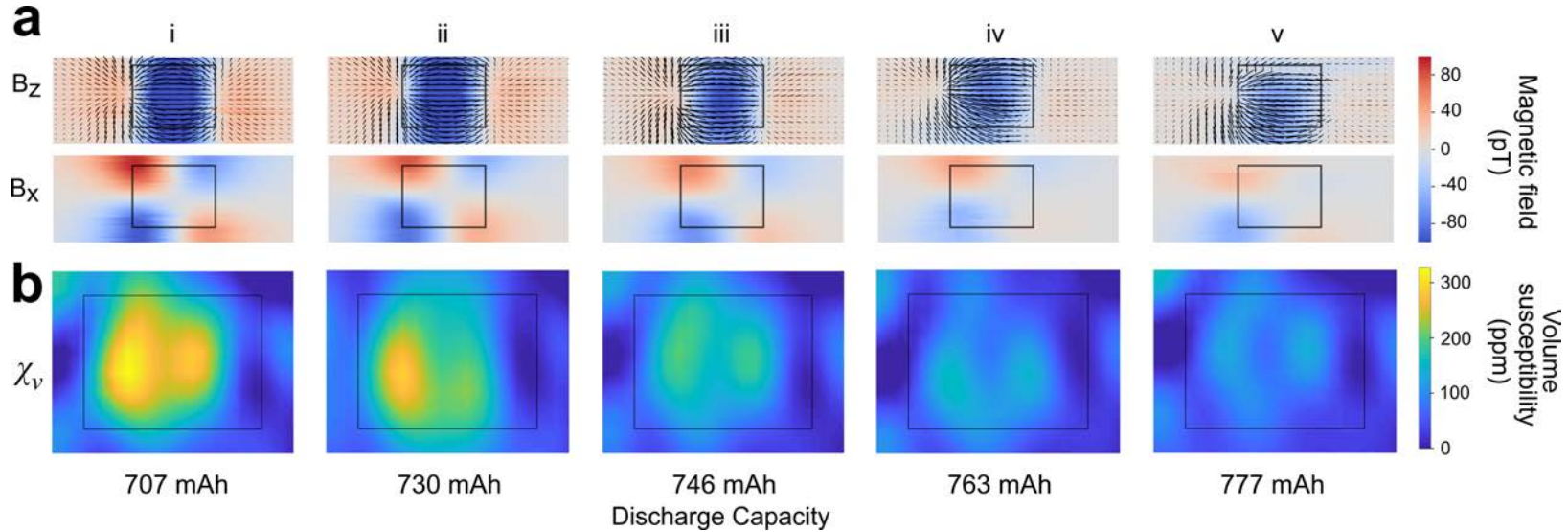
Hu et al. *PNAS* 2020

Magnetometry

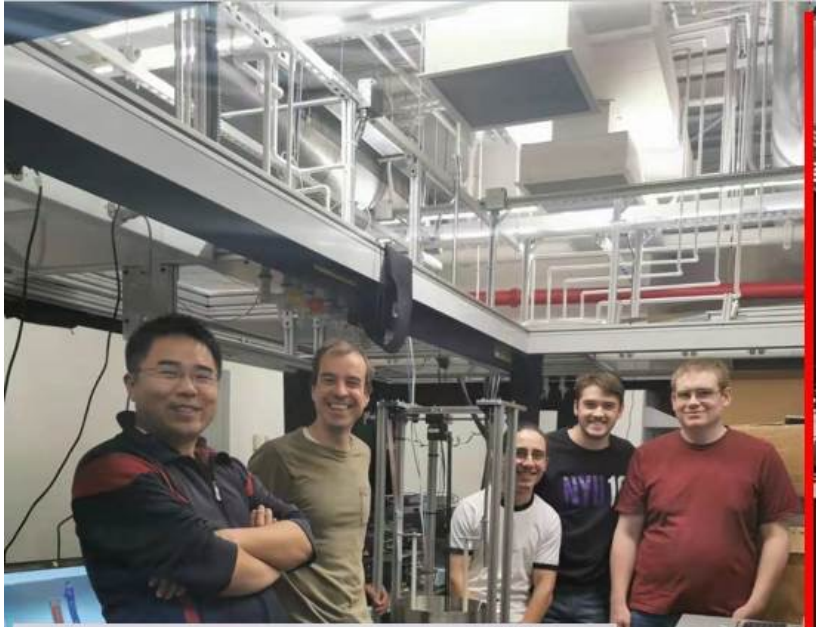


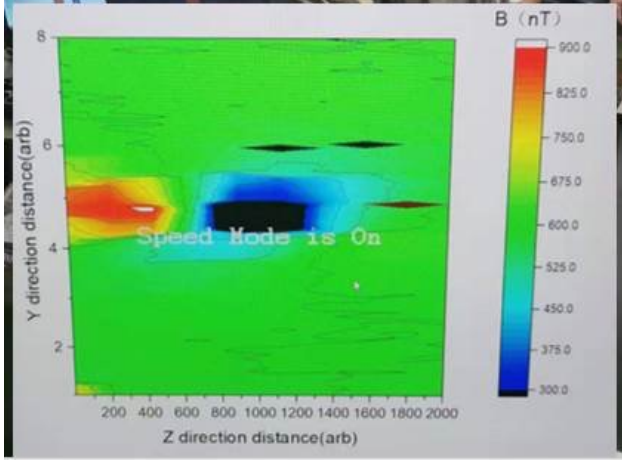
Hu et al. *PNAS* 2020

Magnetometry



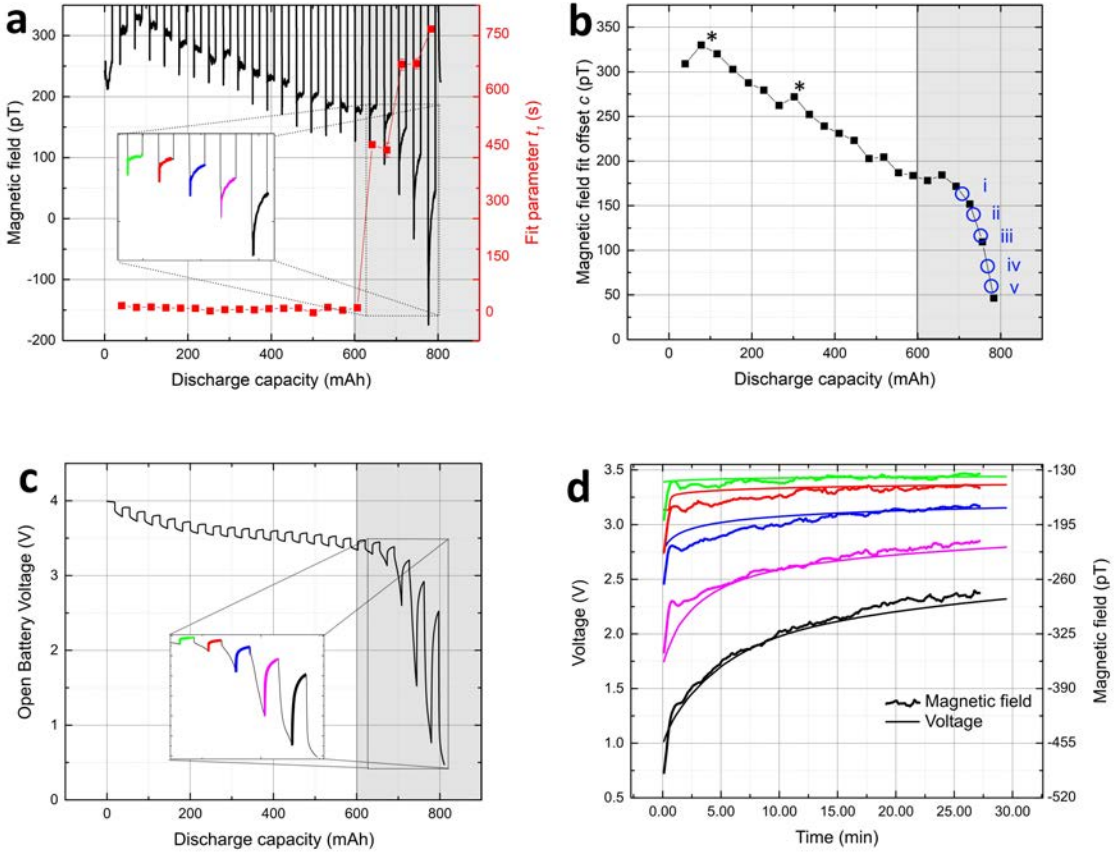
Hu et al. *PNAS* 2020
Hu et al, *Appl. Sci.* 2020




B (nT)
900.0
825.0
750.0
675.0
600.0
525.0
450.0
375.0
300.0
Speed Mode is On
Y direction distance(arb)
8
6
4
2
200 400 600 800 1000 1200 1400 1600 1800 2000
Z direction distance(arb)


Twinleaf
MS-2

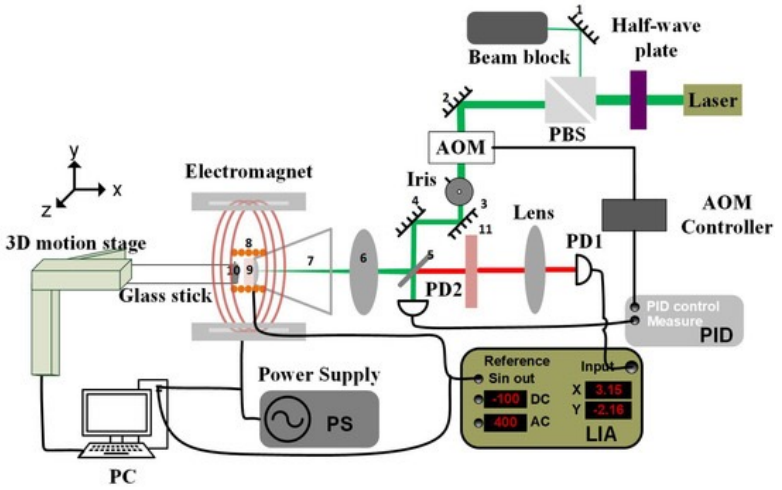
Magnetometry: diagnosing transient currents

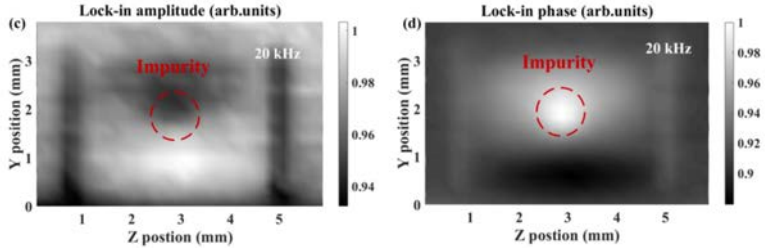


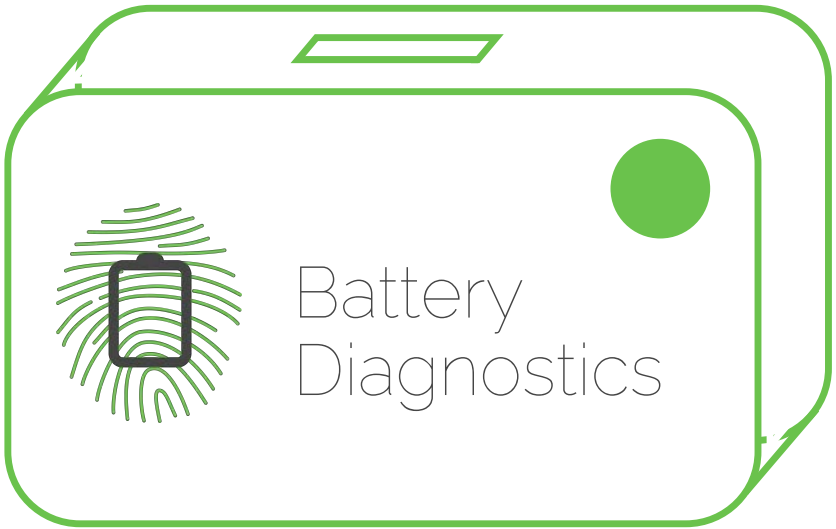
Hu et al. *PNAS* 2020

NV-center-based battery diagnostics

Zhang et al, Appl. Sci. **2021**






Battery
Diagnostics

"In real life"

Inside-out MRI

Magnetometry

Commercial-type cell analysis

- SOC
- SOH
- Current distribution

Acknowledgements

NYU

- Andy Ilott
- Mohaddese Mohammadi
- Stefan Benders
- Bret Schumacher
- Konstantin Romanenko
- Roberta Pigliapochi
- Emilia Silletta

Dalhousie University

- Jeff Dahn
- Stephen Glazier

RIT Battery Prototyping

- Christopher Schauerman
- Matthew Ganter

Helmholtz Institute Mainz, University Mainz

- Dmitry Budker, Arne Wickenbrock
- Geoffrey Iwata, Yinan Hu
- John Blanchard

NEW YORK UNIVERSITY

NSF

Mercedes-Benz

NY BES+ NEW YORK BATTERY AND ENERGY STORAGE TECHNOLOGY CONSORTIUM

POWERBRIDGE NY

NY-BEST BRIDGE PROGRAM

Relevant Publications

- 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
- Yinan Hu, Geoffrey Z. Iwata, Mohaddese Mohammadi, Emilia V. Silletta, Arne Wickenbrock, John W. Blanchard, Dmitry Budker, Alexej Jerschow, Sensitive magnetometry reveals inhomogeneities in charge storage and weak transient internal currents in Li-ion cells, Proc. Nat. Acad. Sci. USA, **2020**, https://doi.org/10.1073/pnas.1917172117.
- K. Romanenko, A. Jerschow, Distortion-free inside-out imaging for rapid diagnostics of rechargeable Li-ion cells, Proc. Nat. Acad. Sci USA, **2019**, https://www.pnas.org/content/early/2019/08/29/1906976116.
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