KEYSIGHT

Advancing Cell and Pack Characterization with Novel Metrology and Calibrated Impedance Spectroscopy for Accurate Field Testing

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Keysight Technologies GmbH- Austria
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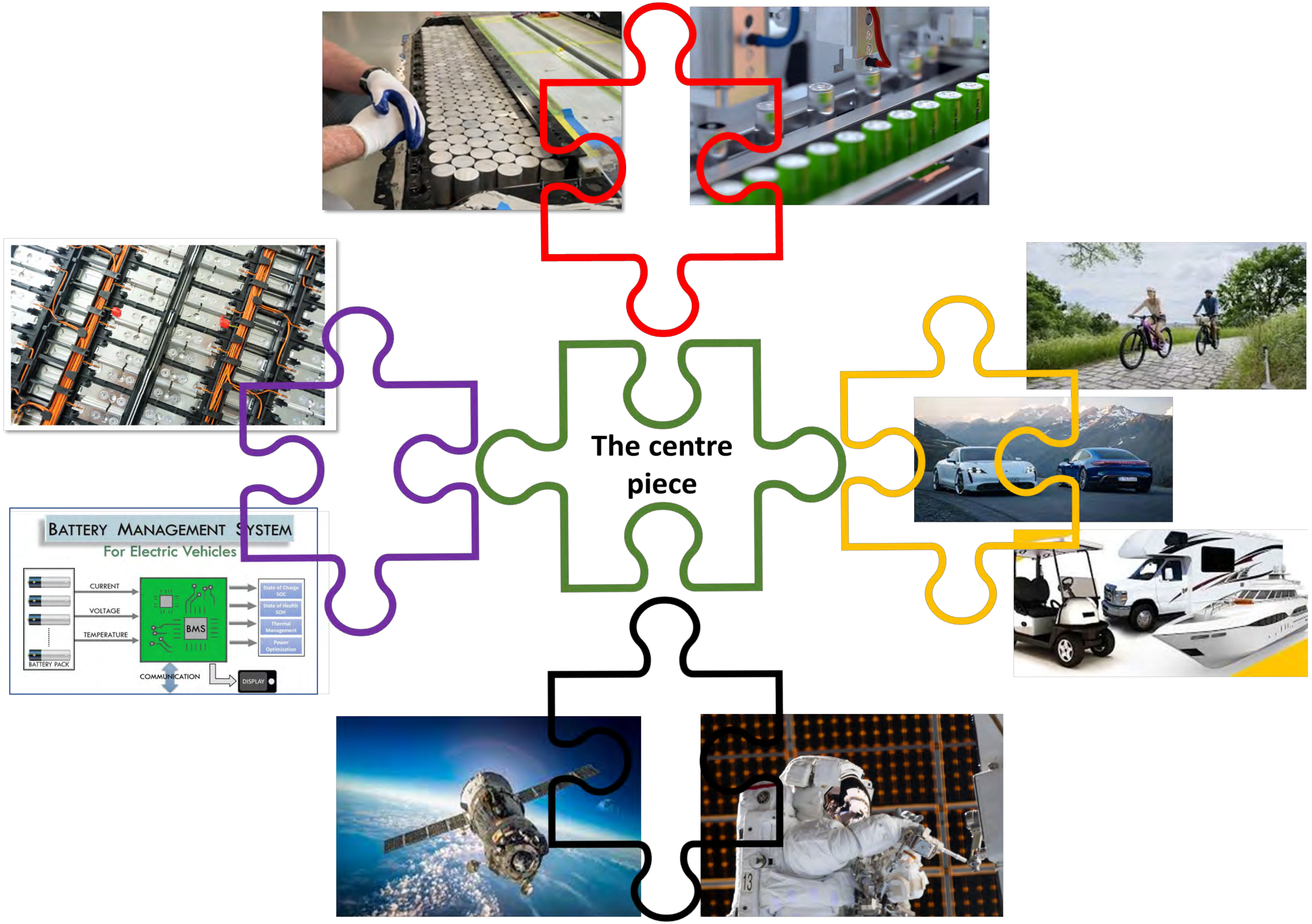
The Battery Show Europe 2023 – Open Tech Forum

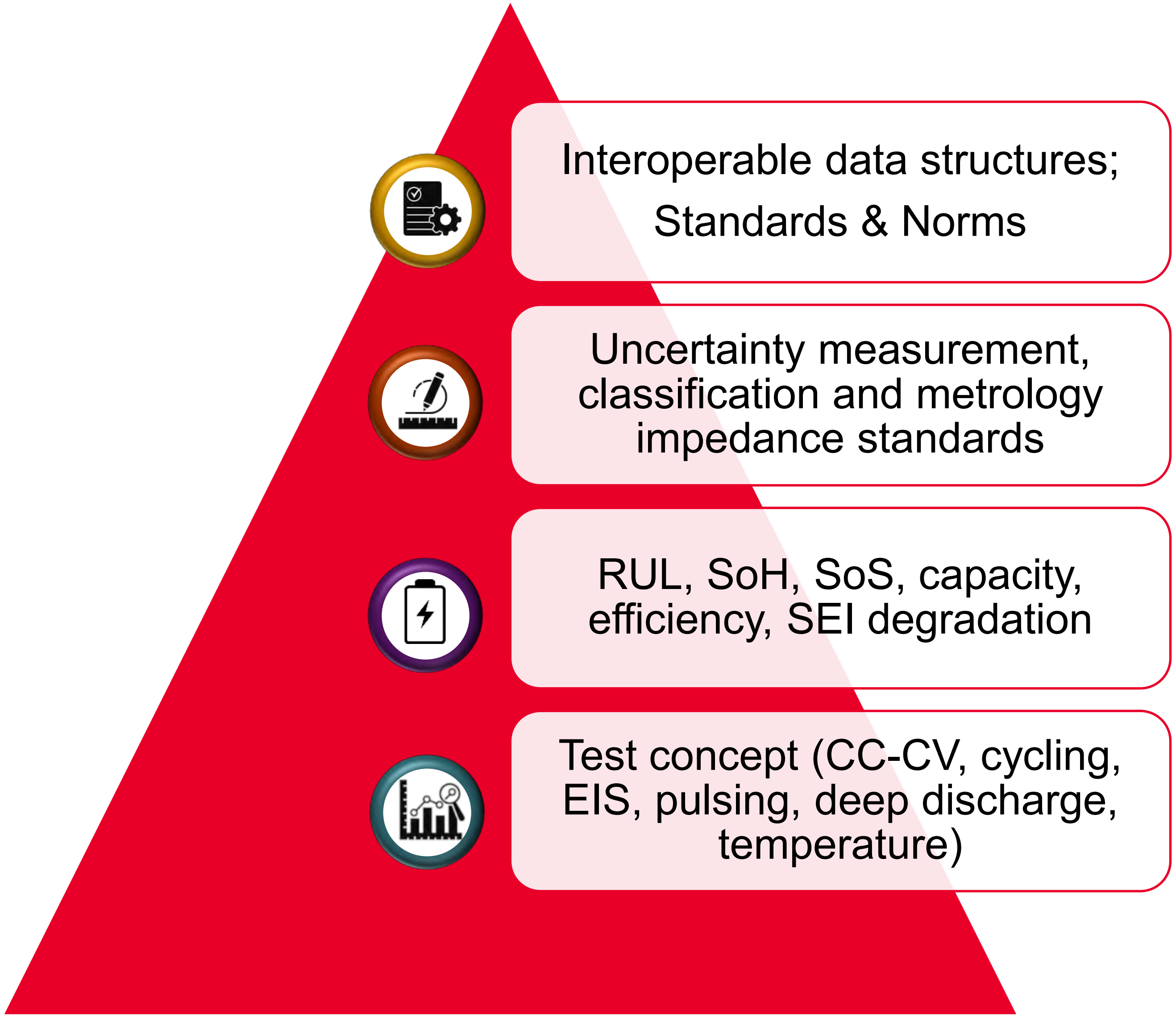
Outlook

1. Keysight battery measurement solutions and structured data concept
2. Metrologic and calibrated EIS for cell and pack tests
3. Measurement uncertainty and confidence levels in battery tests
4. Applications and use cases
5. Conclusions

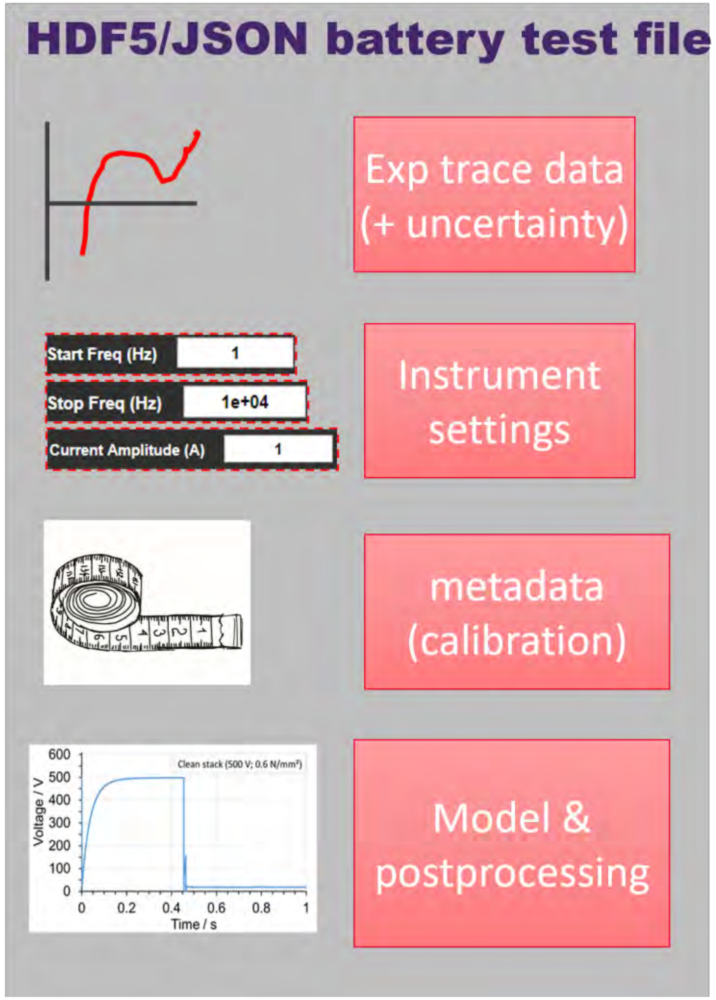
Interoperable and structured battery test data



Keysight battery strategy for interoperable data standards in agile manufacturing and field tests



Hierarchical data file for interoperable battery test



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Error sources in low impedance EIS for good practice measurement

Error source	Physical process	Relative importance	Frequency behavior	Typical values
Fixture DUT position accuracy	DUT current path changes with position: inductance changes, eddy currents in conductive structures.	*****	Linear with frequency	$\Delta Re = 80\ \mu\Omega/mm$ $\Delta Im = 400\ \mu\Omega/mm$
Cable movement	Changed mutual coupling between sense and force.	**** (single wires) ** (coaxial)	Linear with frequency	$\Delta Re = 80\ \mu\Omega$ $\Delta Im = 400\ \mu\Omega$ $\Delta Re = 4\ \mu\Omega$ $\Delta Im = 5\ \mu\Omega$
Fixture contact repeatability	Variying contact resistance (pressure, oxide layers), current distribution in DUT contact pad.	**	Typically constant	$\Delta Re = 10\mu\Omega$
Instrument noise	Random noise.	**	Typically constant above 1 - 10 Hz	$\Delta Z = 5\ \mu\Omega$
Instrument drift	Low frequency noise, typically not Gaussian.	**	Increase at lower frequencie	$\Delta Z = 5\ \mu\Omega$
Instrument nonlinearity	Signal level dependent response error.	*	Typically c	
contact thermal voltages	thermoelectric DC offset due to temp. gradients.	*	DC resistar	

- Best measurement practices are considered to correct errors via calibration and to maintain errors at low levels. A summary of individual contributions from systematic errors and random errors is given in Table 1.

M. Kasper, A. Leike, J. Thielmann, C. Winkler, N. Al-Zubaidi R-Smith, F. Kienberger, J. of Power Sources, vol. 536, 2022, no. 231407.

Journal of Power Sources 536 (2022) 231407

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journal homepage: www.elsevier.com/locate/jpowsour

ELSEVIER

Electrochemical impedance spectroscopy error analysis and round robin on dummy cells and lithium-ion-batteries

Manuel Kasper [a,*], Arnd Leike [b], Johannes Thielmann [c], Christian Winkler [c], Nawfal Al-Zubaidi R-Smith [a], Ferry Kienberger [a]

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[c] Infineon Technologies Austria, 9500, Villach, Austria

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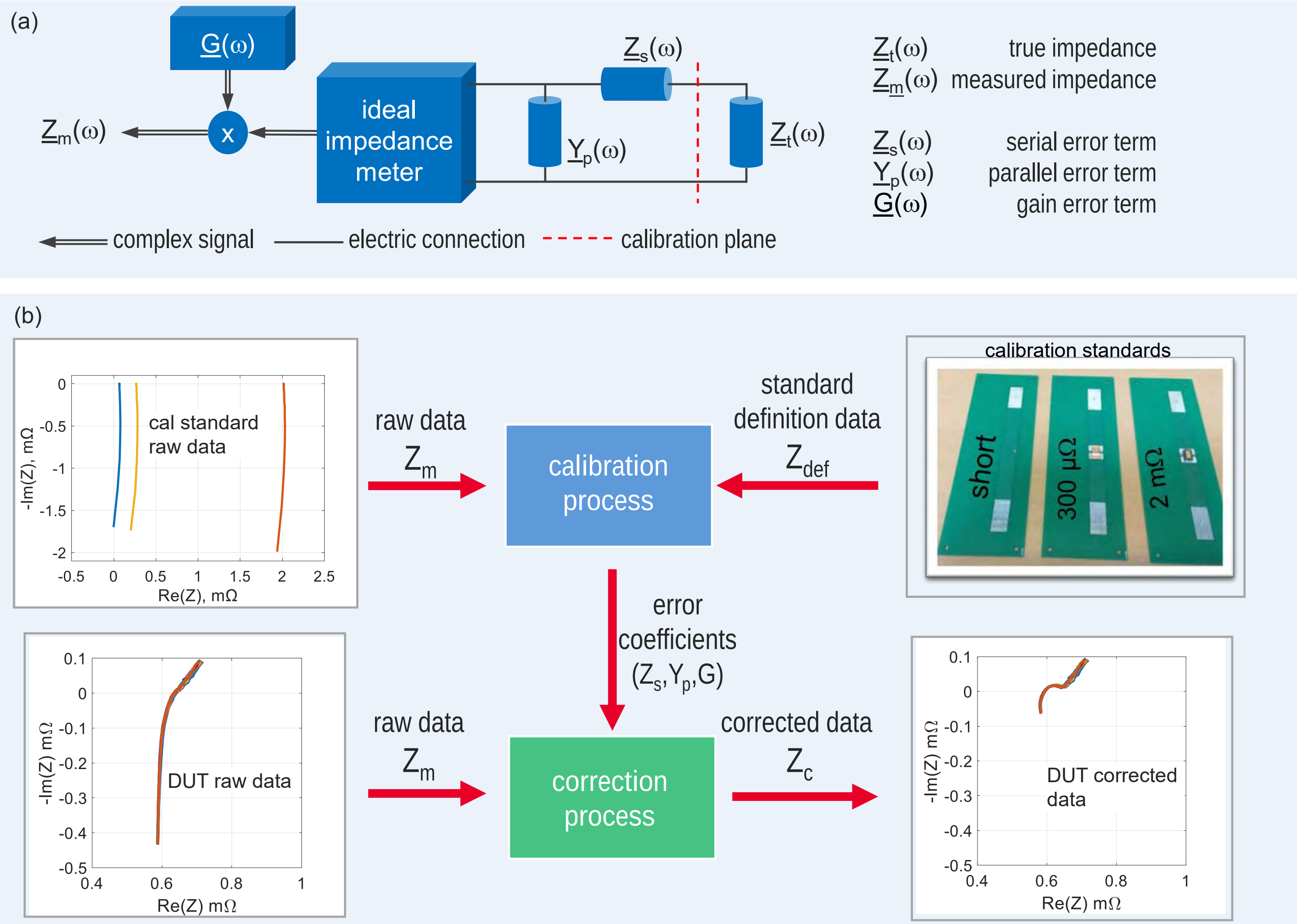
Impedance calibration workflow and calibration standards to obtain the true complex impedance of a battery



- EIS calibration workflow is employed allowing for precise measurements of low micro-Ohm impedances in a broad frequency range of 50 mHz to 10 kHz.

$$Z_m = \frac{Z_t * G + Z_s * G}{Z_t * Y_p + Z_s * Y_p + 1}, \tag{4}$$

where Z_s, Y_p, and G are the error coefficients, and Z_t the true impedance. By introducing the following substitutions,

$$k_1 = Z_s + \frac{1}{Y_p}, \quad k_2 = \frac{G}{Y_p}, \quad \text{and} \quad k_3 = \frac{Z_s * G}{Y_p} \tag{5}$$

the calibration equation system can be obtained as,

$$\begin{bmatrix} Z_{m1} & -Z_{def1} & -1 \\ Z_{m2} & -Z_{def2} & -1 \\ Z_{m3} & -Z_{def3} & -1 \end{bmatrix} * \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} = \begin{bmatrix} -Z_{m1} * Z_{def1} \\ -Z_{m2} * Z_{def2} \\ -Z_{m3} * Z_{def3} \end{bmatrix}. \tag{6}$$

$$Z_c = \frac{Z_m}{(G - Y_p * Z_m)} - Z_s \tag{7}$$

where Z_m and Z_c are the measured and the corrected DUT impedances, respectively.

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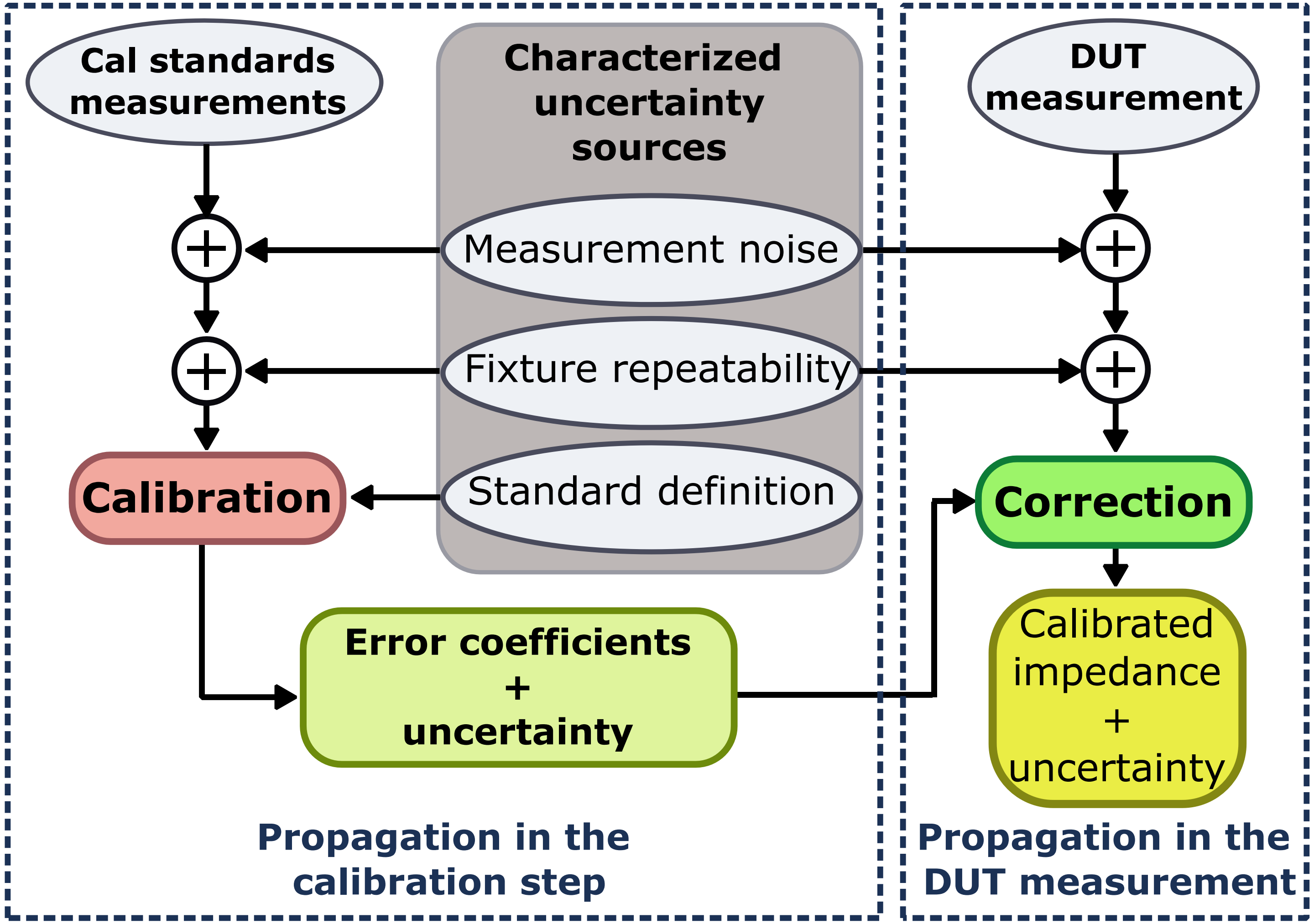
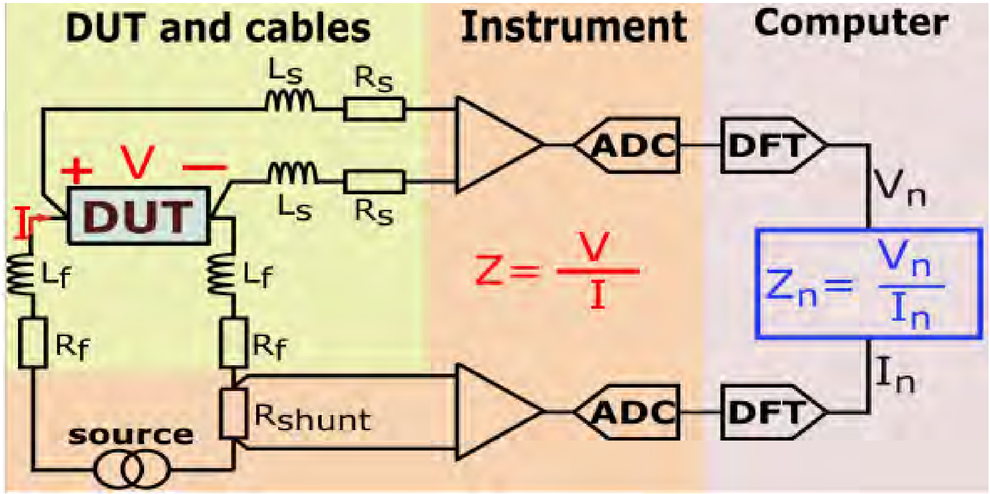
Measurement uncertainty in battery tests – Keysight (Austria) & METAS (Swiss)





$$Z_{E_{\text{shunt\_real}}} = \frac{1}{n}\sum_{k=1}^{n} Z_{R_{\text{shunt\_real}}}{}_{k}$$
$$Z_{E_{\text{short\_real}}} = \frac{1}{n}\sum_{k=1}^{n} Z_{R_{\text{short\_real}}}{}_{k} \quad (5)$$

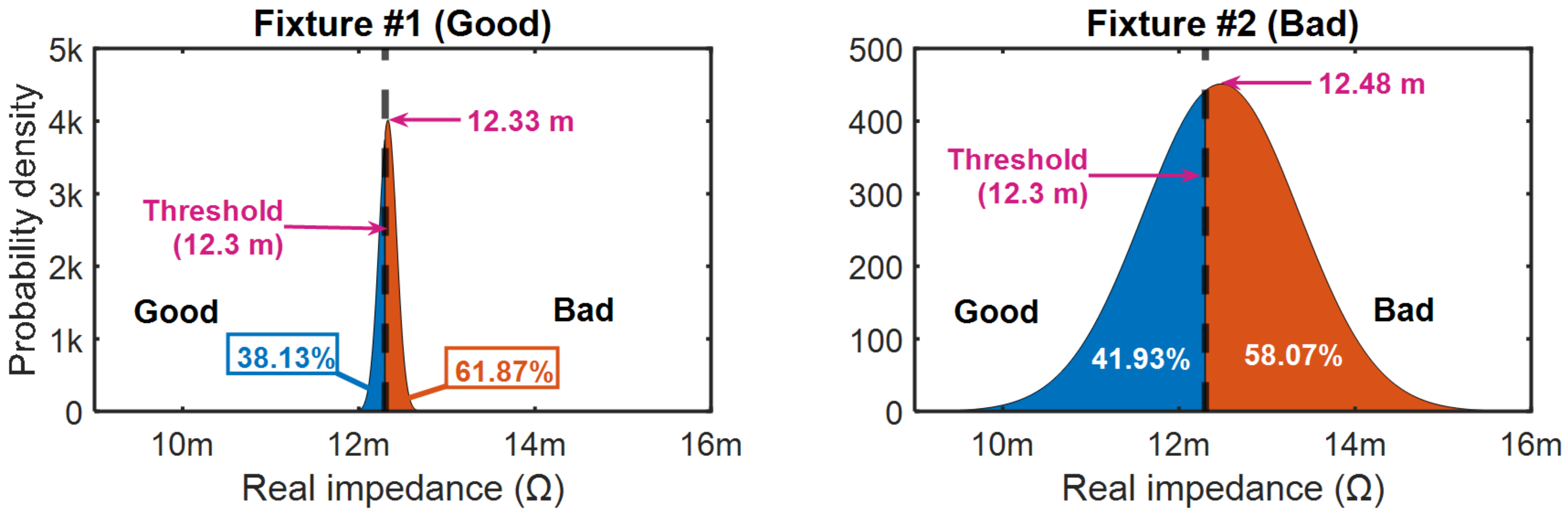
Here, n is the number of measurements on each standard. By converting equation (4) to the matrix equation, the variances of model parameters can be calculated as the following:

$$\begin{bmatrix} \sigma^2_{\delta R1_{real}} \\ \sigma^2_{\delta R2_{real}} \end{bmatrix} = \begin{bmatrix} Z^2_{E_{\text{shunt\_real}}} & 1 \\ Z^2_{E_{\text{short\_real}}} & 1 \end{bmatrix}^{-1} \begin{bmatrix} \sigma^2_{ZR_{\text{shunt\_real}}} \\ \sigma^2_{ZR_{\text{short\_real}}} \end{bmatrix} \quad (6)$$

A. Moradpour, M. Kasper, J. Hoffmann and F. Kienberger, IEEE TIM, vol. 71, pp. 1-9, 2022, no. 1006209.

Measurement uncertainty and confidence levels in battery tests

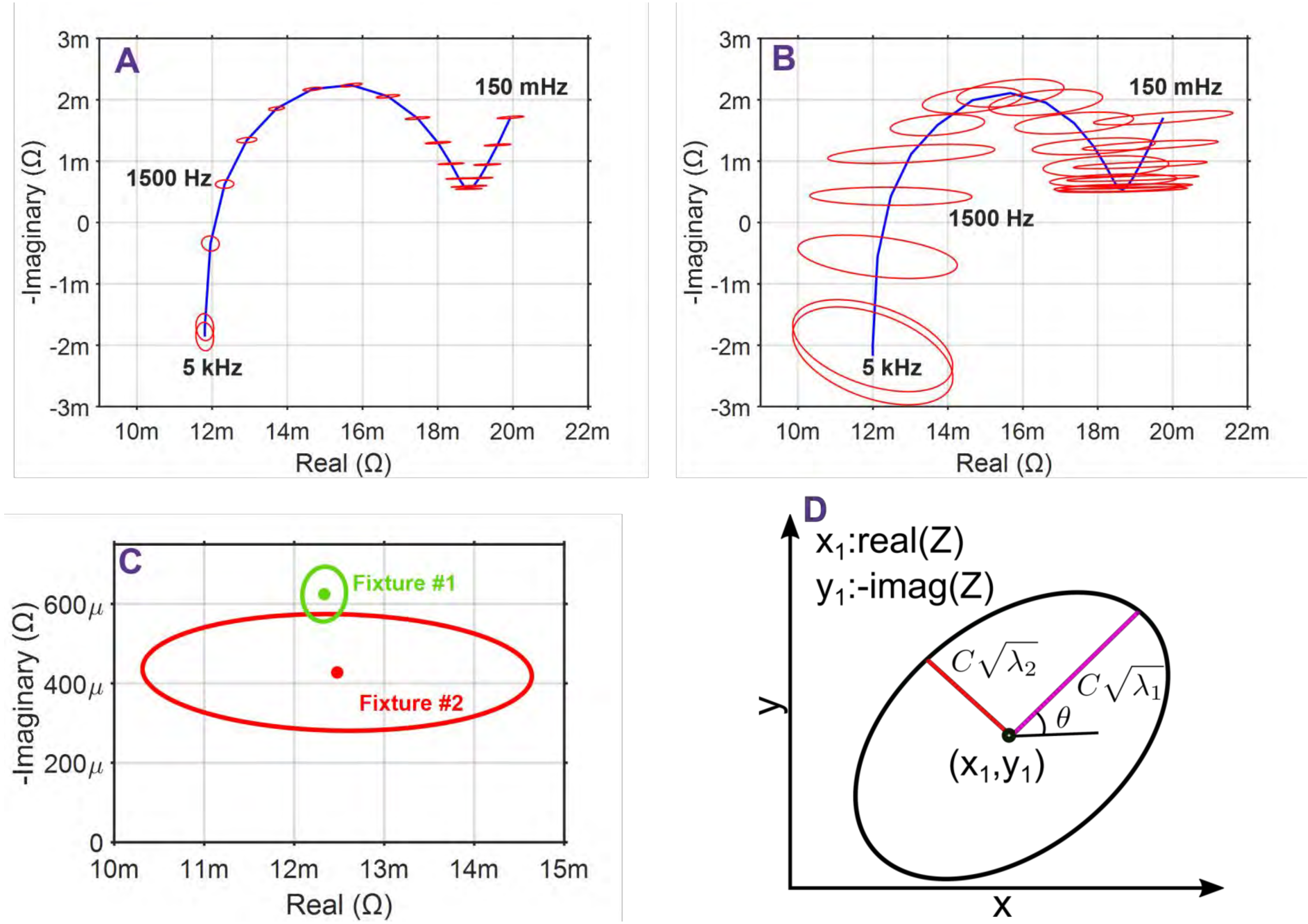
- Demonstration of uncertainty evaluation of the calibrated impedance of a single cylindrical cell at 1500 Hz using two types of fixtures:



- ➢ The good fixture shows a narrow error bound centered on the calibrated mean value of 12.33
- ➢ The bad fixture shows a broader distribution with a calibrated mean value 12.48

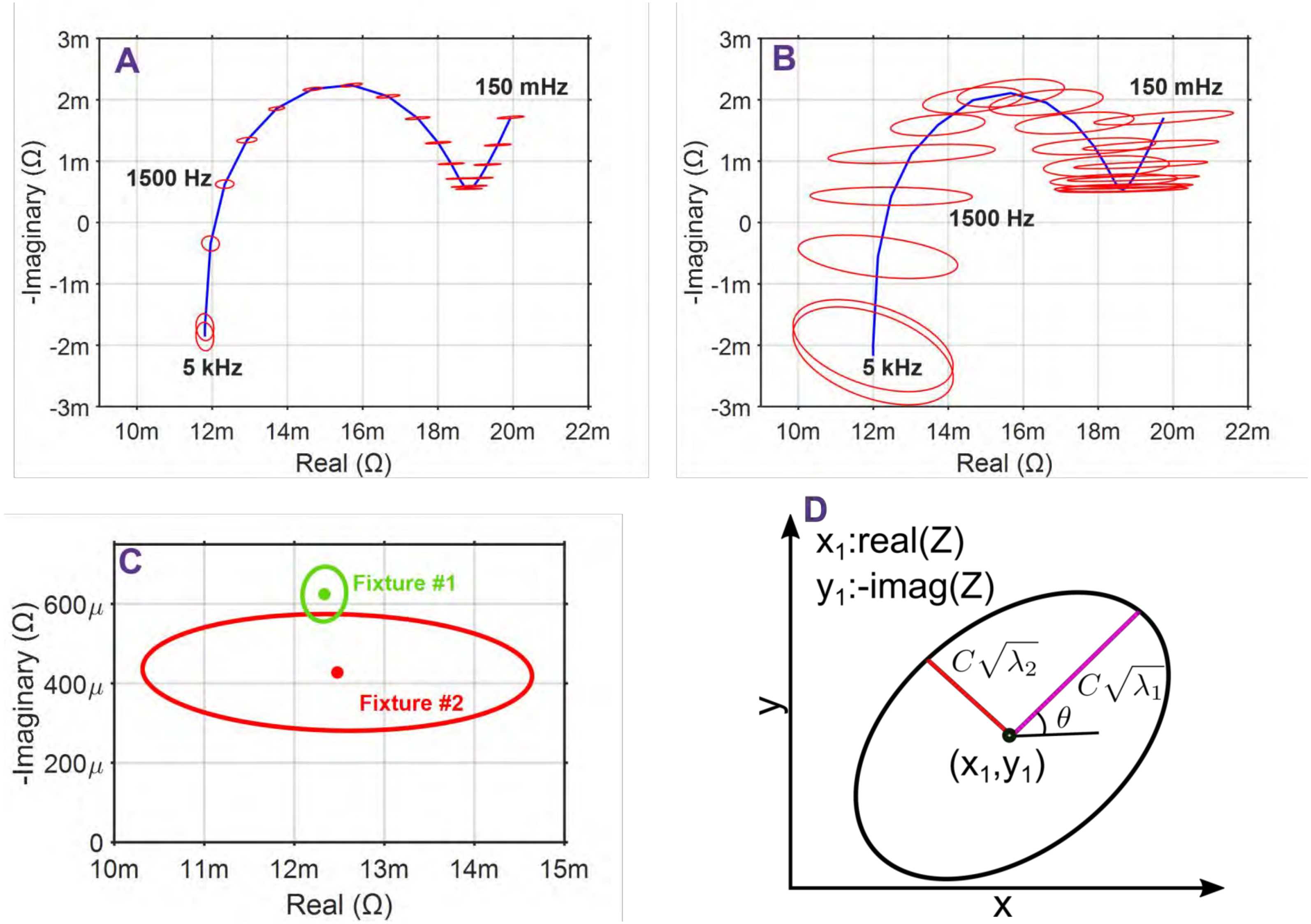
Moradpour, A., Kasper, M., Kienberger, F., Batteries & Supercaps 2023, 6, e202200524.

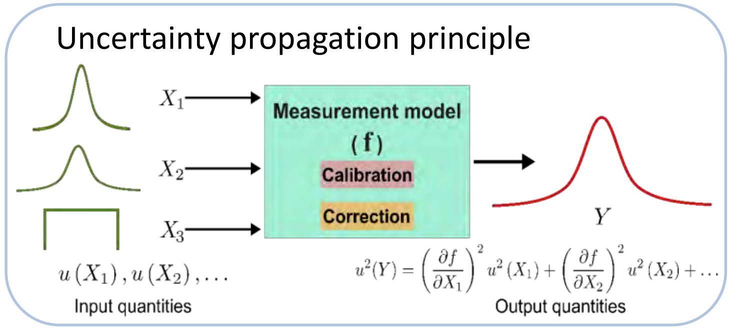
Measurement uncertainty and confidence levels in battery tests



- Battery EIS uncertainty over the full frequency range of 150 mHz to 5 kHz at 95% confidence level

Measurement uncertainty and confidence levels in battery tests





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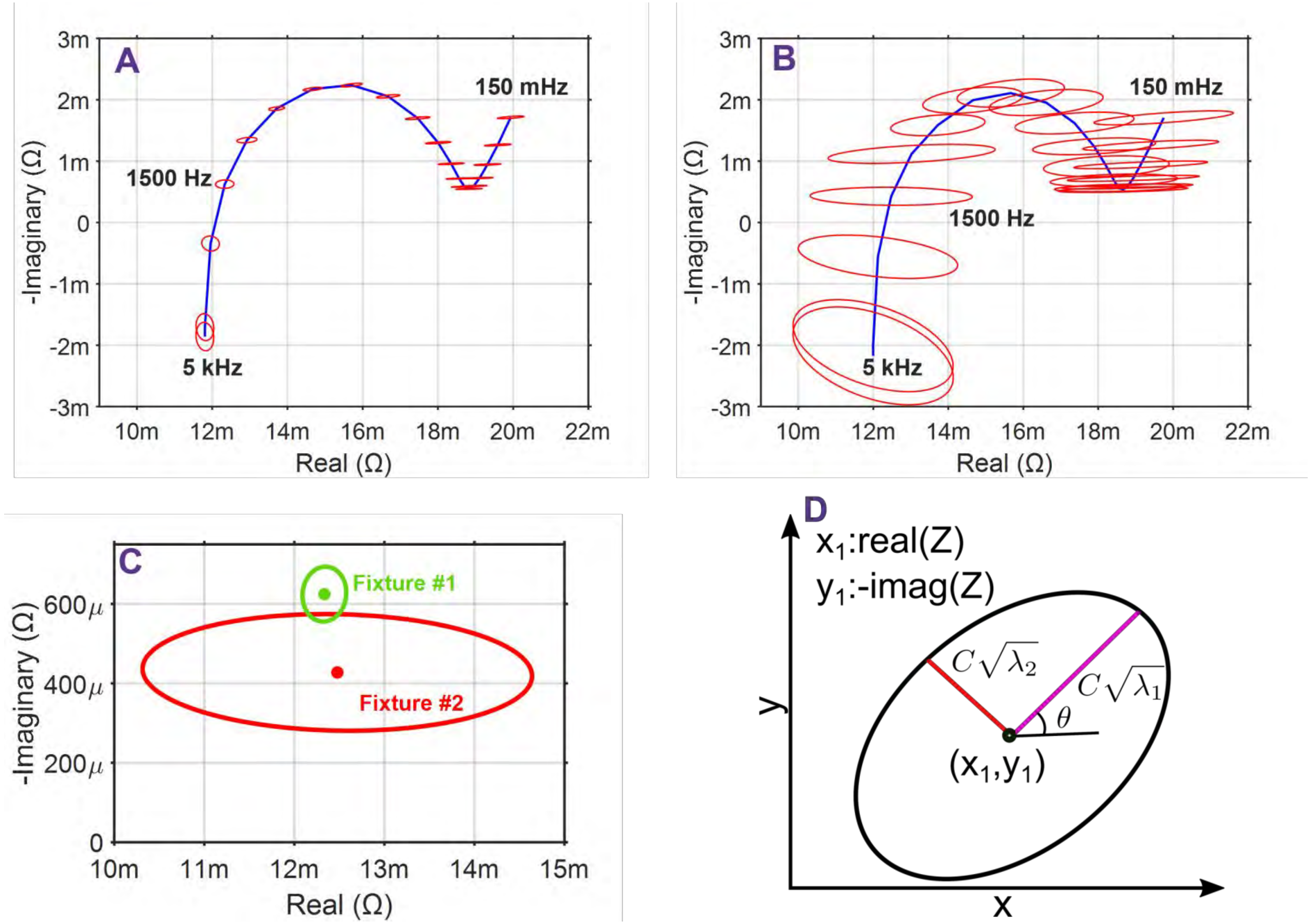

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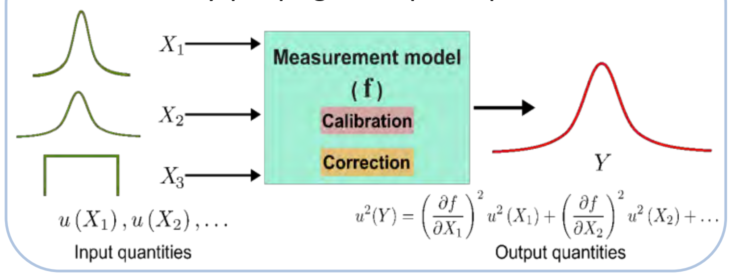
Uncertainty propagation principle



Error ellipse visualization in the Nyquist plot

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = R \begin{bmatrix} C\sqrt{\lambda_1}cos(t) \\ C\sqrt{\lambda_2}sin(t) \end{bmatrix} + \begin{bmatrix} real(Z) \\ -imag(Z) \end{bmatrix}$$

$$R = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix}$$

$$t = 0, . . . , 2\pi \quad and \quad \theta = atan2(u_2, u_1)$$

- *U* is the largest eigenvector of the covariance matrix.
- *C* is the parameter of the Chi-squared distribution with two degrees of freedom
- *Z* is the measured impedance, and λ_1 and λ_2 are the covariance matrix largest and smallest eigenvalues.
- R is the rotation matrix which depends on the values of *U.*

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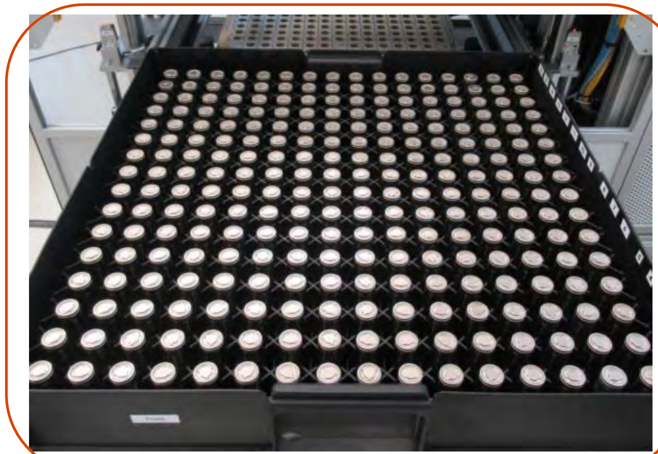
Metrologic and calibrated impedance for cell measurement and ageing analysis

- Cell classification based on calibrated AC-IR based on batch or cycle numbers



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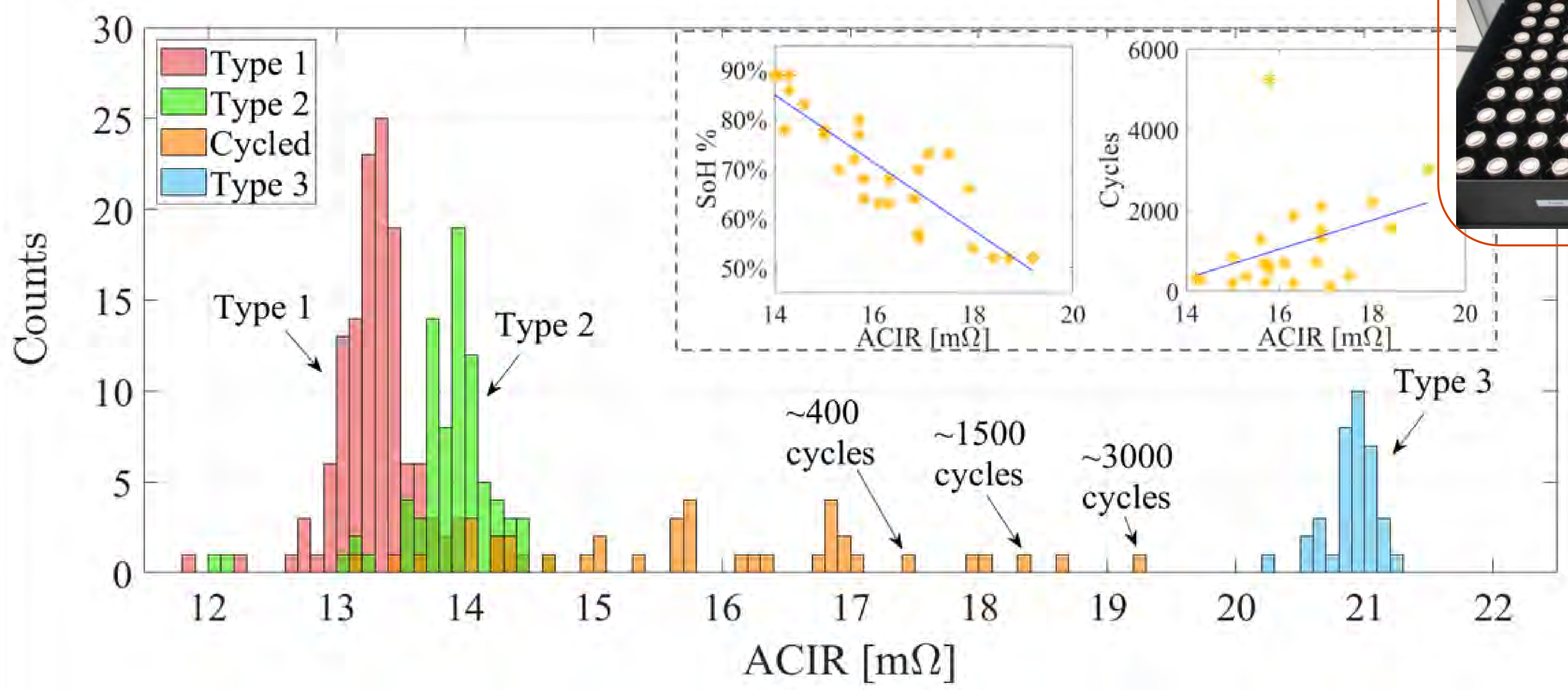

N. A. -Z. R-Smith et al., IEEE TIM, vol. 70, pp. 1-9, 2021,no. 2006109

Metrologic and calibrated impedance for cell measurement and ageing analysis

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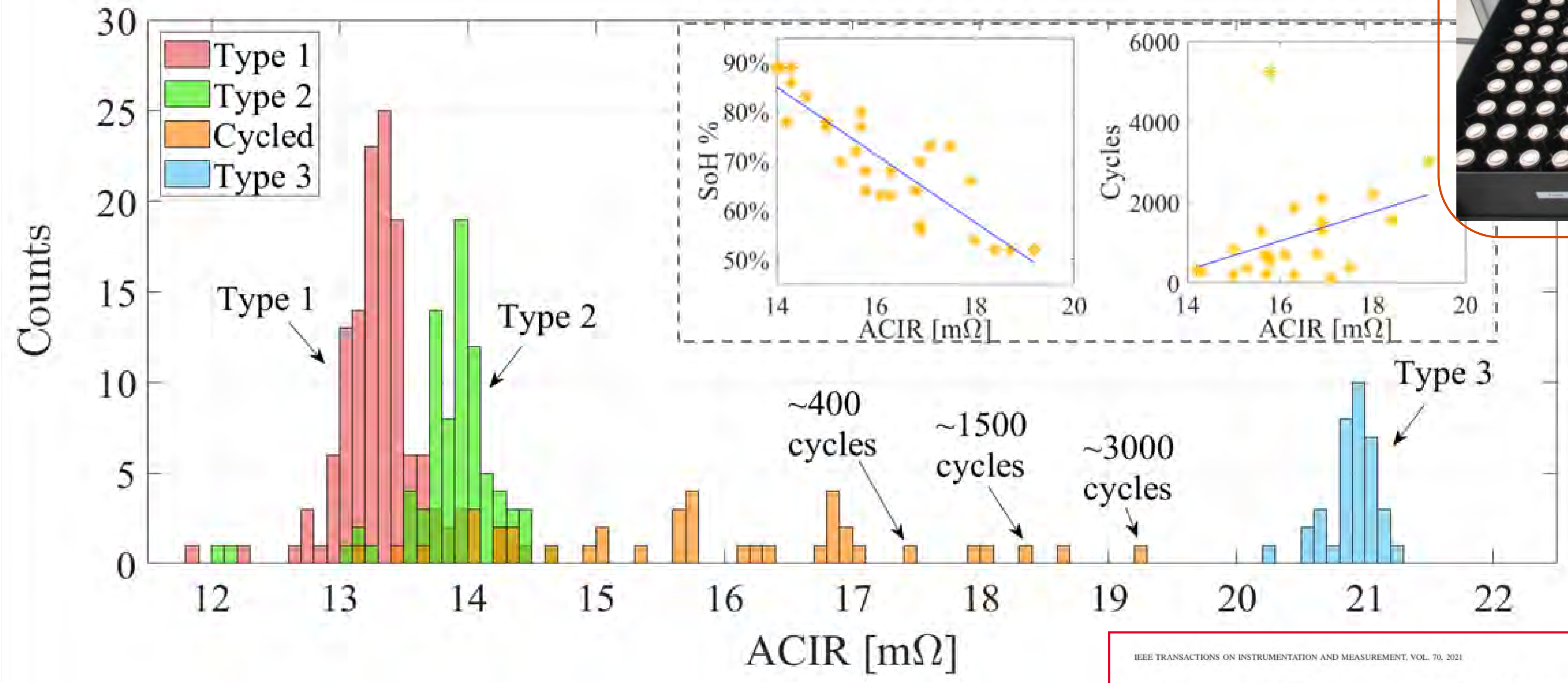
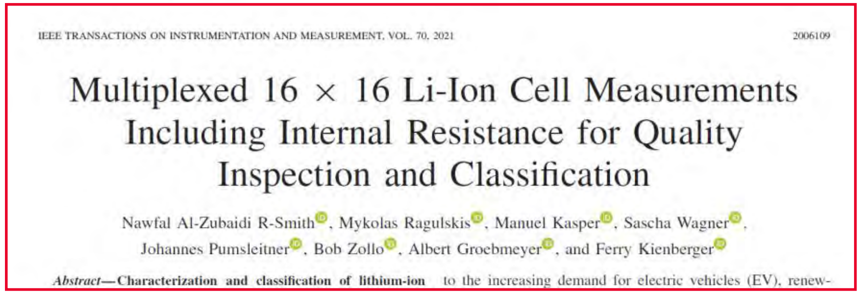


N. A. -Z. R-Smith et al., IEEE TIM, vol. 70, pp. 1-9, 2021,no. 2006109



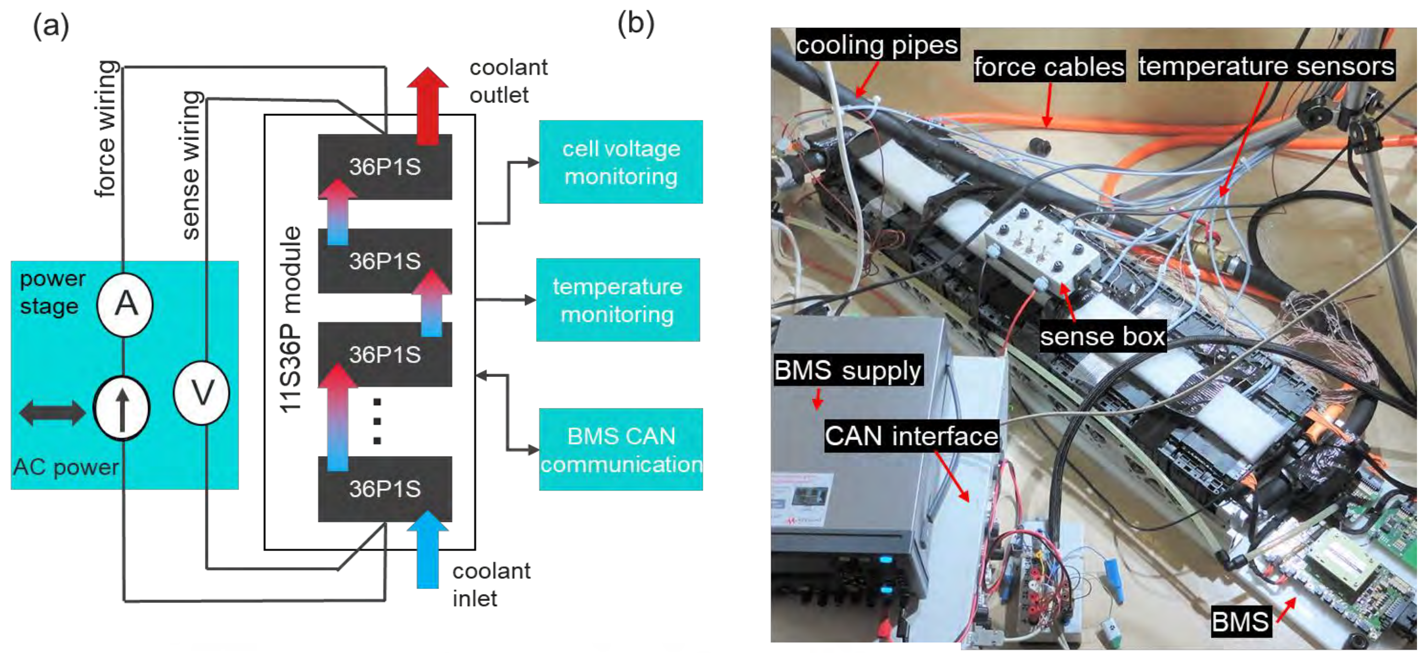
IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 70, 2021 2006109

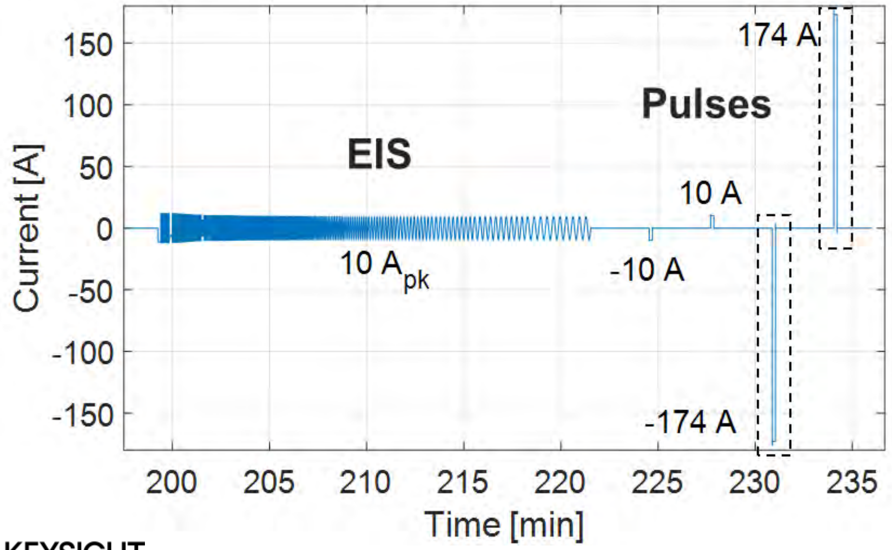
Multiplexed 16 × 16 Li-Ion Cell Measurements Including Internal Resistance for Quality Inspection and Classification

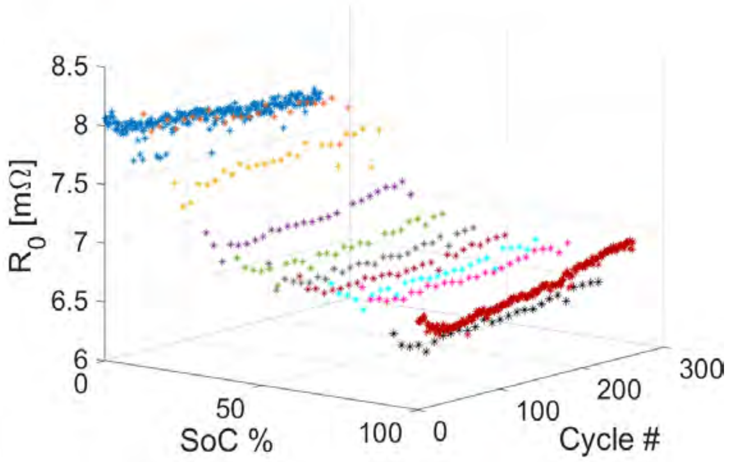
Nawfal Al-Zubaidi R-Smith, Mykolas Ragulskis, Manuel Kasper, Sascha Wagner, Johannes Pumsleitner, Bob Zollo, Albert Groebmeyer, and Ferry Kienberger

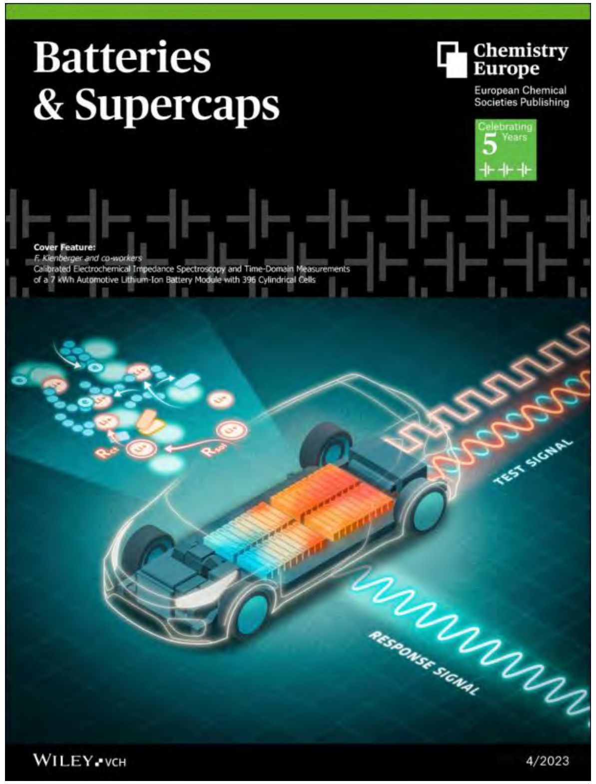
Abstract—Characterization and classification of lithium-ion to the increasing demand for electric vehicles (EV), renew-

Metrologic and calibrated impedance for automotive battery tests









Kasper, M., et. al., Batteries & Supercaps 2023, vol. 6, no. 2, pp. 1-9, id: e202300114.

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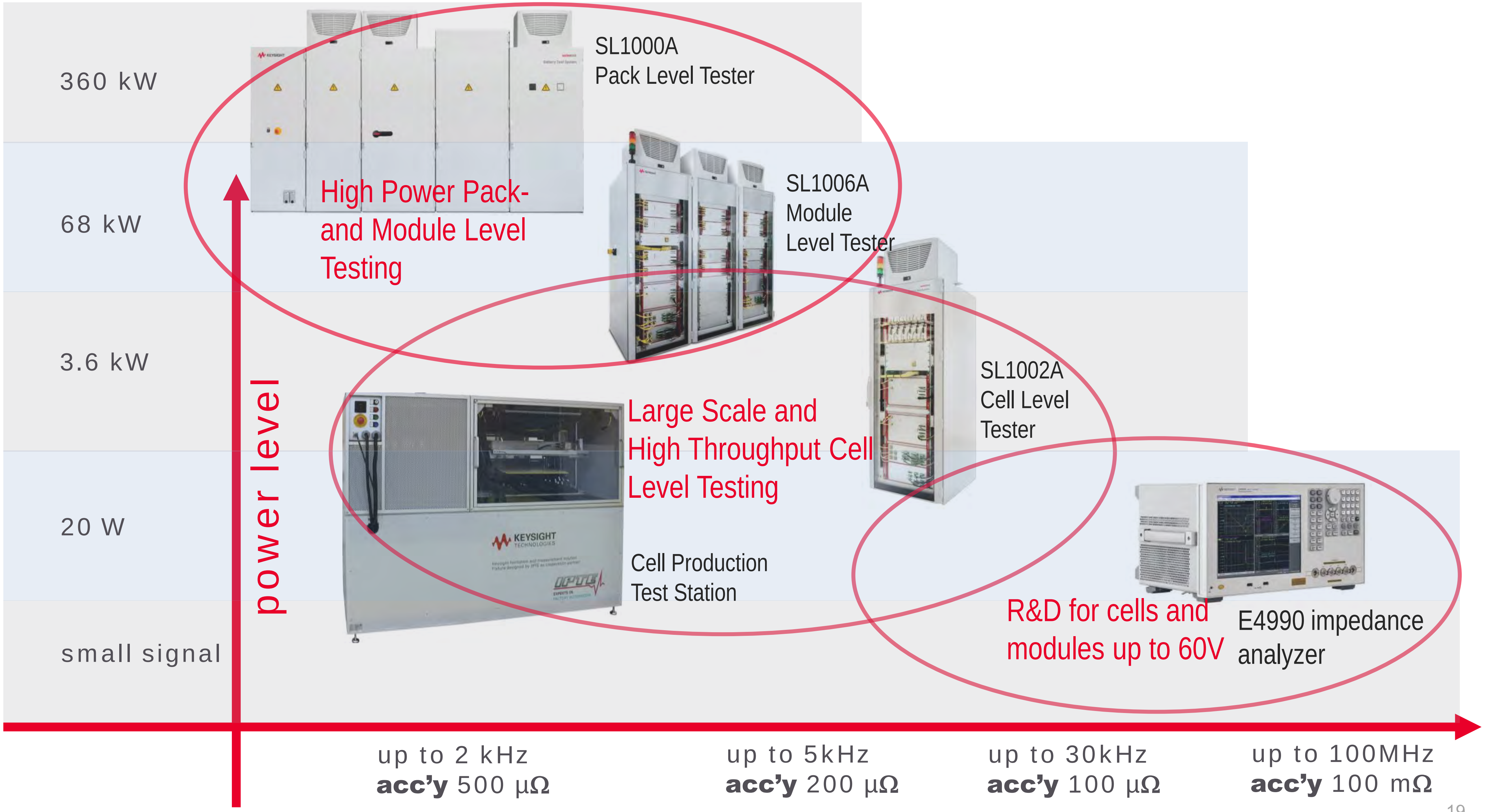
Instrumentation: from R&D to industrial and filed applications



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Conclusions

- Electrical impedance calibration and metrological uncertainty analysis improves cell classification and makes it quantitative including a confidence level.

- Significant systematic-error corrections are obtained from the calibration, especially for low micro-Ohm impedances in a broad frequency range of 50 mHz to 10 kHz.

- Metrologic and calibrated impedance measurements are effectively used to characterize battery modules and pack with hundreds of interconnected cells.

- Based on EIS and time domain pulsing, robust model parameters are extracted, providing insights into the electrochemical processes of battery modules at different SoC and cycling ageing.

- The application of uncertainty for the evaluation of automotive battery packs is important for improved quality assessment and prediction, and 2nd life applications

Moradpour, A., Kasper, M., Kienberger, F., Batteries & Supercaps 2023, vol. 6, no. 5, id: e202200524.

Recent scientific publications

1. *M. Kasper et al, Calibrated Electrochemical Impedance Spectroscopy and Time-Domain Measurements of a 7 kWh Automotive Lithium-Ion Battery Module with 396 Cylindrical Cells. Batteries & Supercaps, vol. 6, March 2023. Cover feature.*

2. *A. Moradpour et al, Quantitative Cell Classification Based on Calibrated Impedance Spectroscopy and Metrological Uncertainty. Batteries & Supercaps, vol. 6, March 2023. Profile cover.*

3. *A. Moradpour et al, "Measurement Uncertainty in Battery EIS", IEEE Transaction Instrument & Measurements, vol. 71, no. 1006209, 2022.*

4. *M. Kasper et al., "Electrochemical impedance spectroscopy error analysis and round robin on dummy cells and lithium-ion-batteries", J. Power Sources, vol. 536, no. 231407, 2022.*

5. *N. Al-Zubaidi R-Smith et al., "Multiplexed 16 × 16 Li-Ion Cell Measurements Including Internal Resistance for Quality Inspection and Classification," in IEEE Transaction Instrument & Measurements, vol. 70, no. 2006109, 2021.*

6. *N. Al-Zubaidi R-Smith et al., "Advanced EIS of Industrial Ni-Cd Batteries," MDPI Batteries, vol. 8, no. 6, May 2022.*

7. *N. Al-Zubaidi R-Smith et al., "Assessment of lithium-ion battery ageing by combined impedance spectroscopy, functional microscopy and finite element modelling", J. Power Sources, vol. 512, no. 230459, 2021.*

8. *L. Hoffmann et al., "High-Potential Test for Quality Control of Separator Defects in Battery Cell Production," MDPI Batteries, vol. 7, no. 4, Sep. 2021.*

Thank you