

Impedance Spectroscopy with Battery Cell Sensors

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Universität Hamburg
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Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

- ① Battery Monitoring and Management**
- ② Sensor Measurements and Communication Methods**
- ③ Precise Measurements for Highly Dynamic Events**
- ④ Electrochemical Impedance Spectroscopy for State Determination**
- ⑤ Application Projects and Future Work**

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Challenges for Batteries

Requirements:

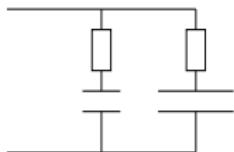
- Safe operation → fire risk, high voltage, environment issues ..
- Performance → energy/mass , power/mass ratio
- Life time → cycle numbers, calendar lifetime
- Costs → invest cost, 'total costs of ownership'

Solution Approaches:

- 1) Battery-Technology → New Materials and Combinations
- 2) Optimisation of the Battery-Operation in the Application
- 3) **Battery Management**

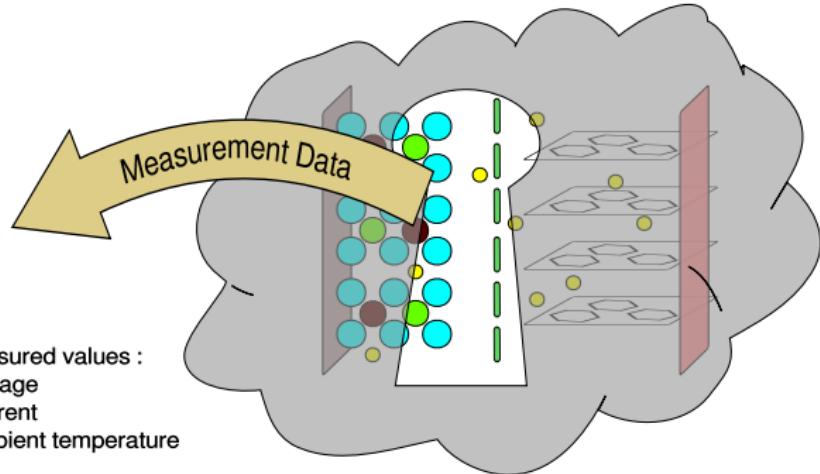
Battery Management: Sensors, Models, Control

Battery modell in
battery control unit
(microcontroller)

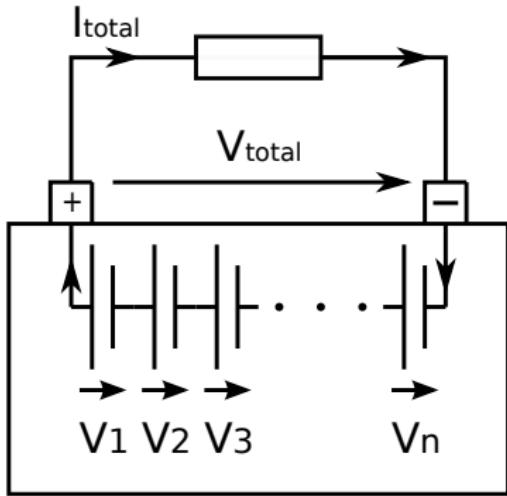


Chemical/physical parameters
inside a battery are hard to observe

Measured values :
-Voltage
-Current
-Ambient temperature
-Others ?

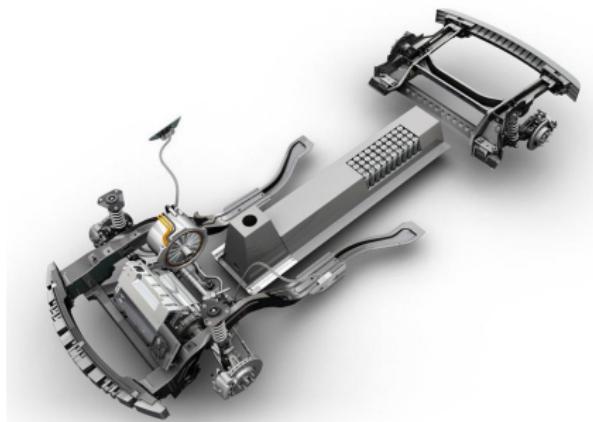


Multi Cell Batteries



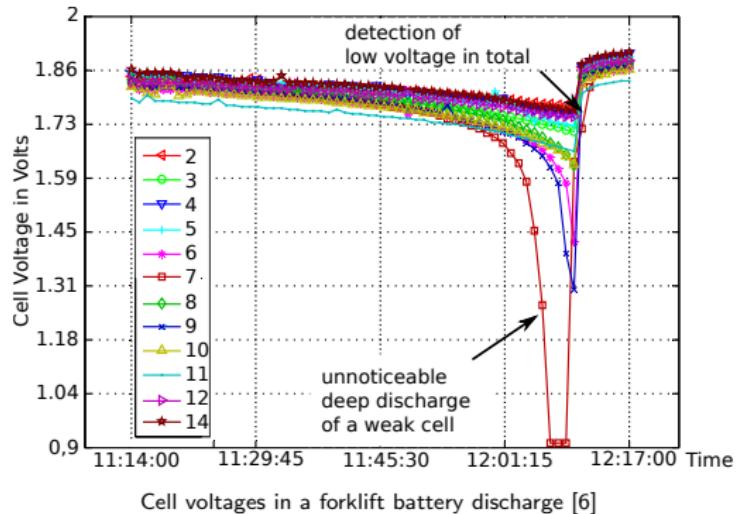
$$V_{total} = \sum_{i=1}^n V_i$$

$$I_{total} = I_1 = \dots = I_n$$



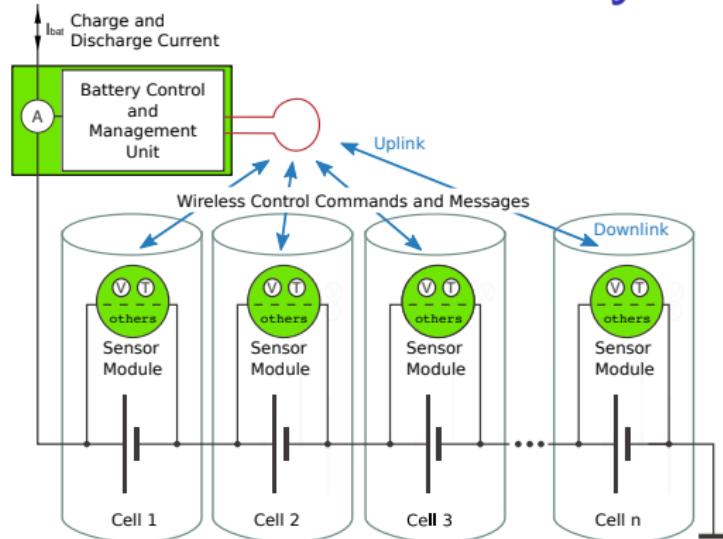
Opel Ampera Batteries with 288 Cells (3 parallel, 96 serial)

Undiscovered Cell Differences - a Lifetime Issue



- Root cause: production tolerances not avoidable and lifetime conditions differs slightly but over long time
- Differences in the individual **State of Charge (SoC)**
- Weaker cells reach the discharge/charge limits earlier
- Faster ageing of weaker cells:
⇒ reducing weak cells **State of Health (SoH)**

Our Approach: Sensors inside every Cell



- Voltage and temperature sensors located in every cell
- Wireless sensor data transmission
- Battery Control Unit:
central current measurement, data fusion, State of Charge and State of Health estimation, ...

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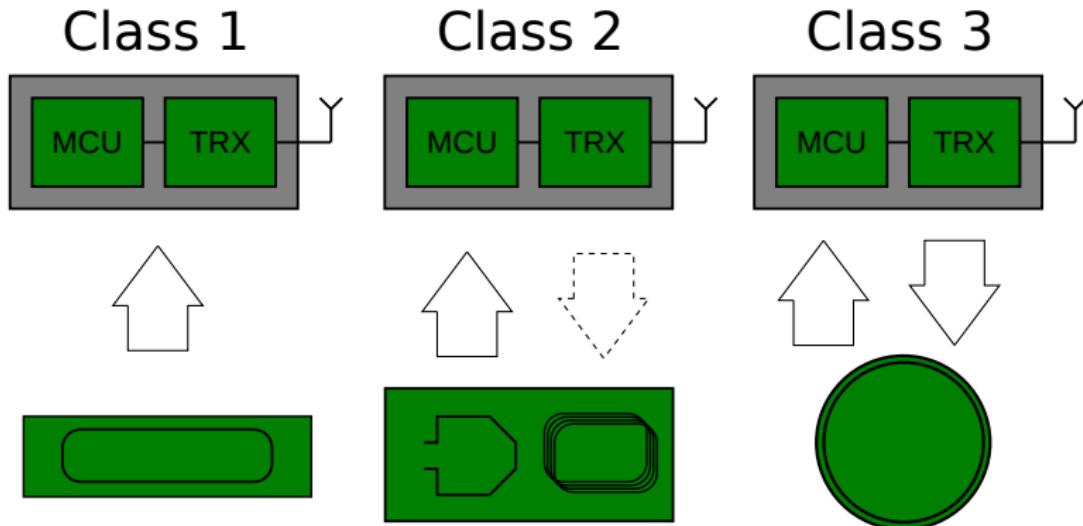
Cell Sensor Implementation

Sensor Hardware:

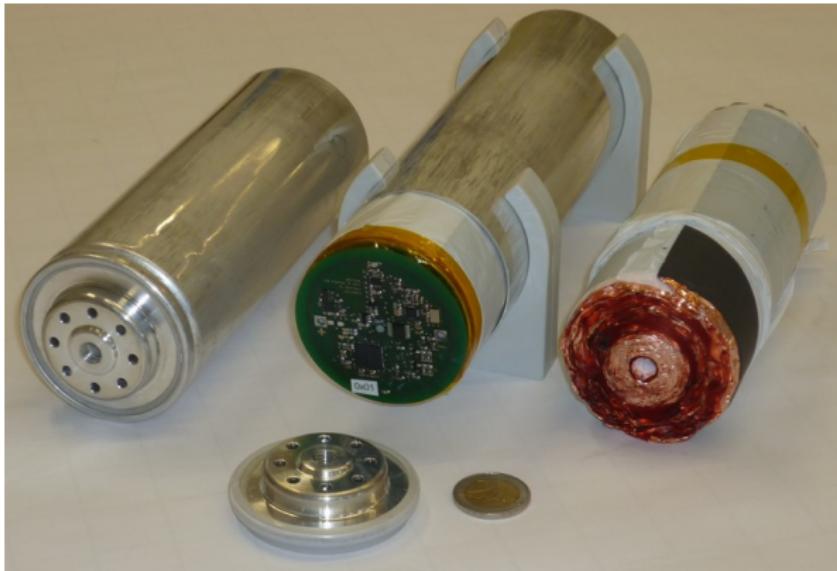
- Ultra-Low-Power Controller measures voltage and temperature
- Transmitter/Transceiver-Chip ISM Band 433 MHz

Controller software:

- Measurement and communication protocol

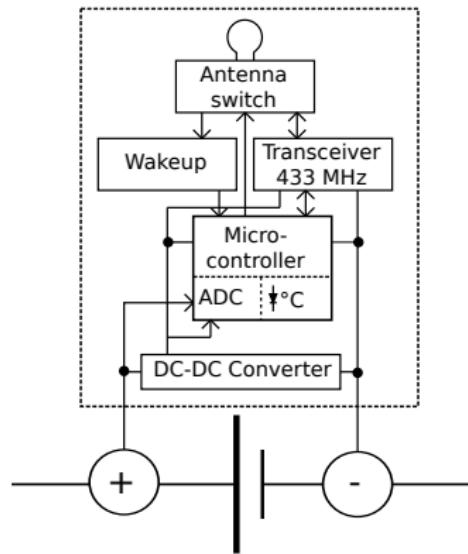
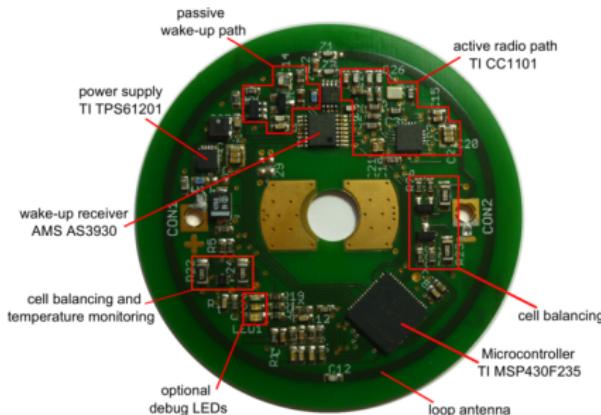


Sensor Class 3 - Target Application



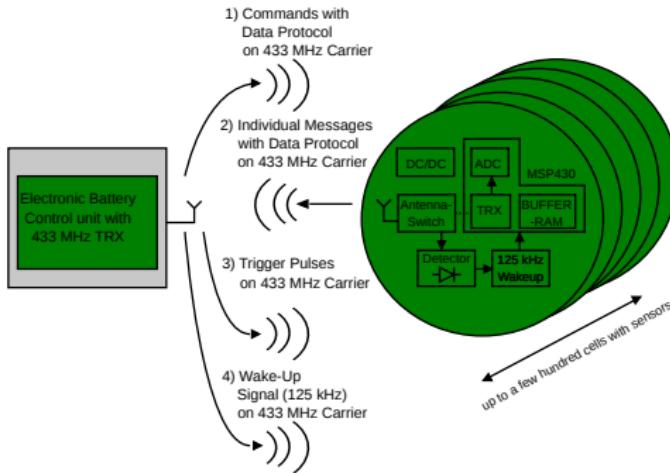
- Designed for large cylindric lithium cells > 40 Ah
- Target Application: Electric vehicle traction batteries and stationary storages
- Future: Encapsulation for placement inside of the battery cell

Sensor Class 3 - Components



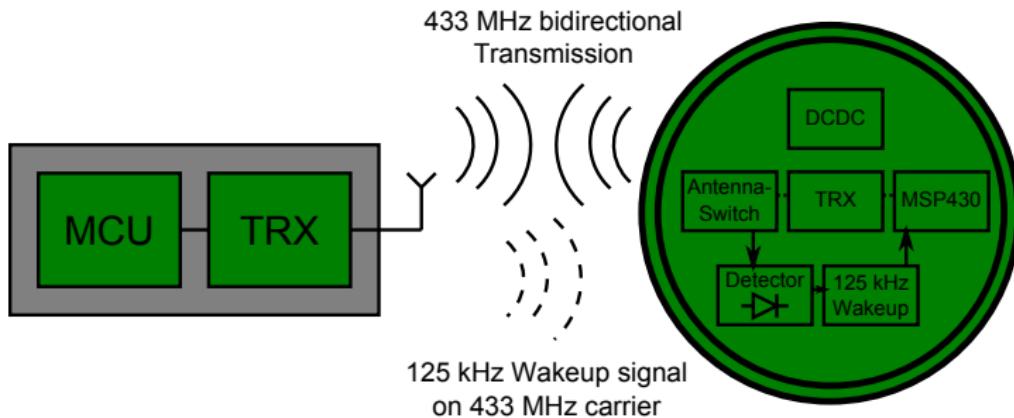
- Uplink and Downlink in the same radio frequency band 433 MHz
- Loop antenna on PCB is magnetic dominant
- Measures cell voltage and temperature
- and advanced modular functions

Sensor Class 3 - Communication Structures



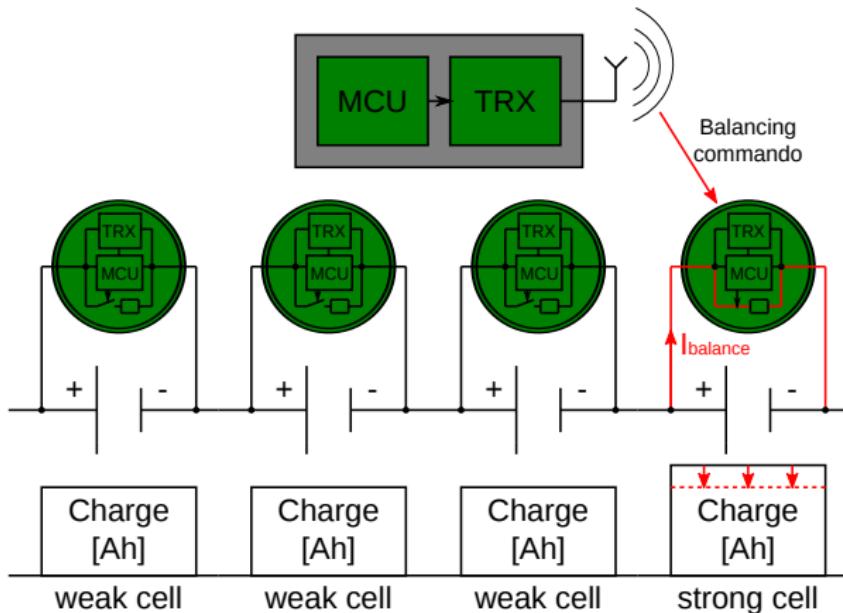
- ① Broadcast and addressed control commands (downlink+ data protocol)
- ② Individual messages (uplink + dataprotocol)
- ③ Broadcast Synchronization-pulses (downlink w./o.data protocol)
- ④ Broadcast of wake-wp-signals (downlink w./o. data protocol)

Advanced Sensor Function - Wake-Up



- Uplink and downlink in the same radio frequency band
- Optimal frequency band is to determine (433 MHz, 868 MHz, 2,4 GHz)

Advanced Sensor Function - Cell-Balancing



- Passive cell balancing in the sensor module
- MOSFET-switch for current path with time and voltage control
- Temperature monitoring

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Dynamic Measurement Requires: Precise Synchronization of Sampling

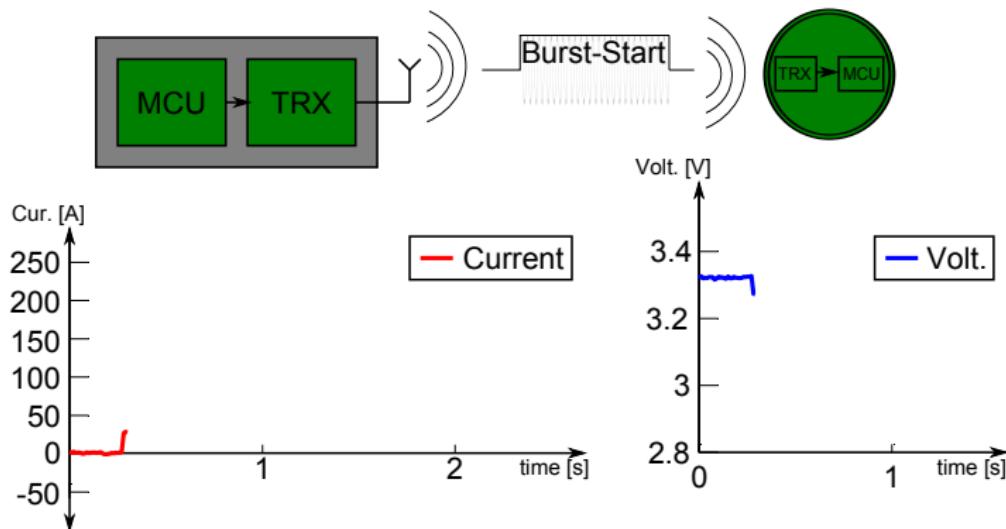
Synchronization Sensor to Sensor

- Synchronous voltage sampling of all sensors in high dynamic events
- Precise timed cell voltage comparison at high load
 - ⇒ Significant indicator of **cell differences**

Synchronization Battery Control Unit and Sensors

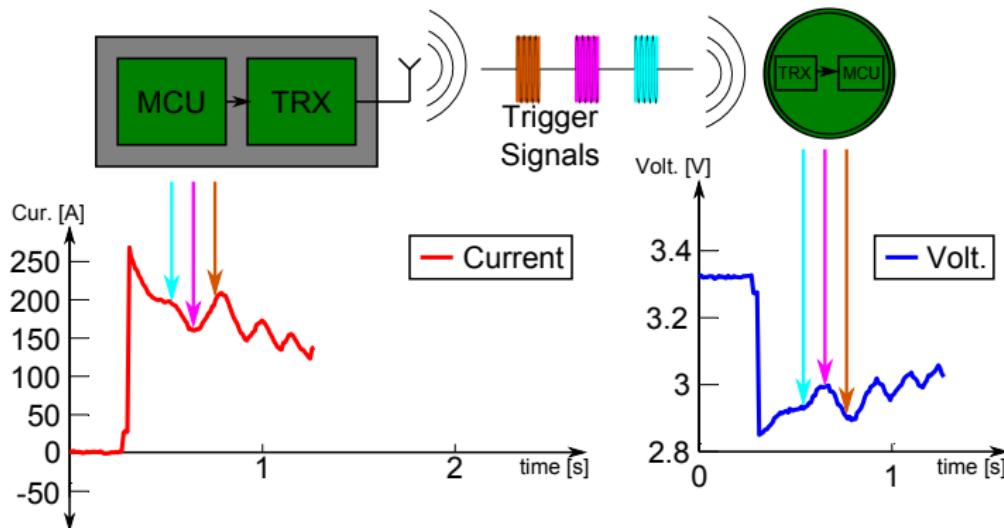
- Detecting time (resp. phase) difference between current (Control Unit) and cell voltages (Sensors)
- Can provides the complex impedance for each cell
 - ⇒ Significant indicator of **cell aging**, and more state information...

Synchronized Burst Sampling



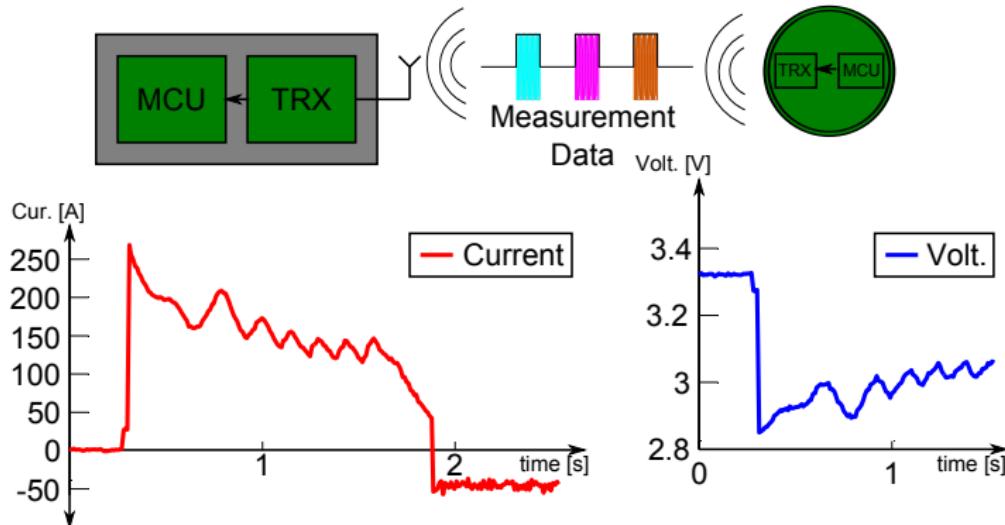
- Battery control unit (BCU) transmits a burst start command to sensor

Synchronized Burst Sampling



- Battery control unit (BCU) transmits a burst start command to sensor
- BCU triggers fast series of voltage measurements
- BCU performs synchronous current measurements

Synchronized Burst Sampling



- Battery control unit (BCU) transmits a burst start command to sensor
- BCU triggers fast series of voltage measurements
- BCU performs synchronous current measurements
- Stored / preprocessed measurements are transmitted to the BCU

Tests: Synchronized Burst Measurements on a Experimental LiFePO₄ Starter Battery

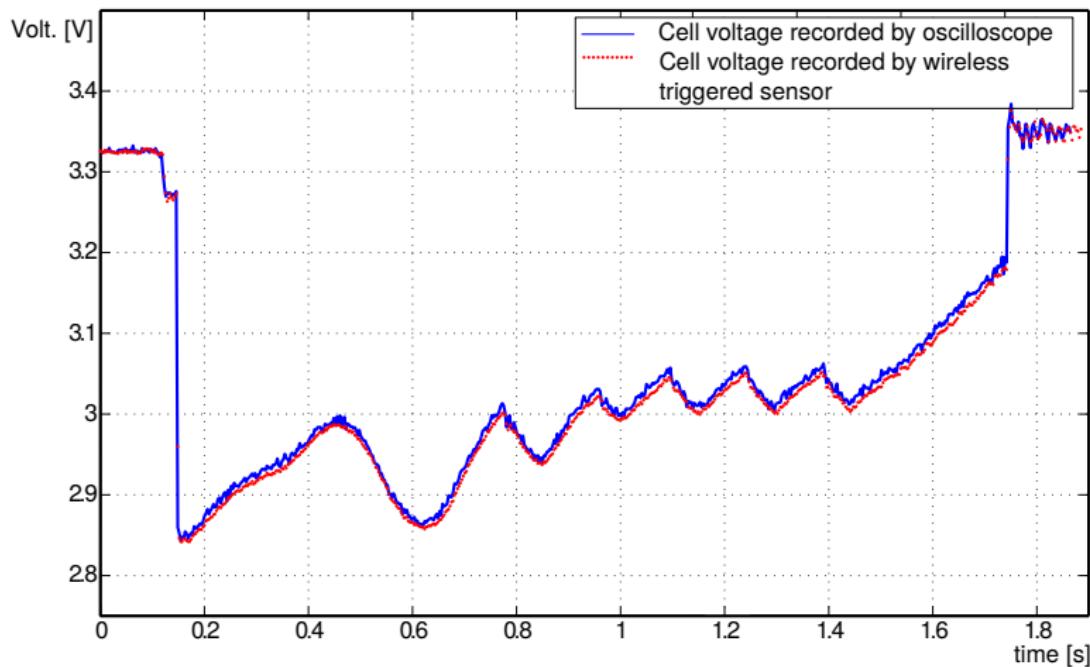


Four LiFePO₄ cells with BMS and safety circuits as a car starter battery



Engine start tests on a car

Functional Tests: High-Current & Highly Dynamic Event



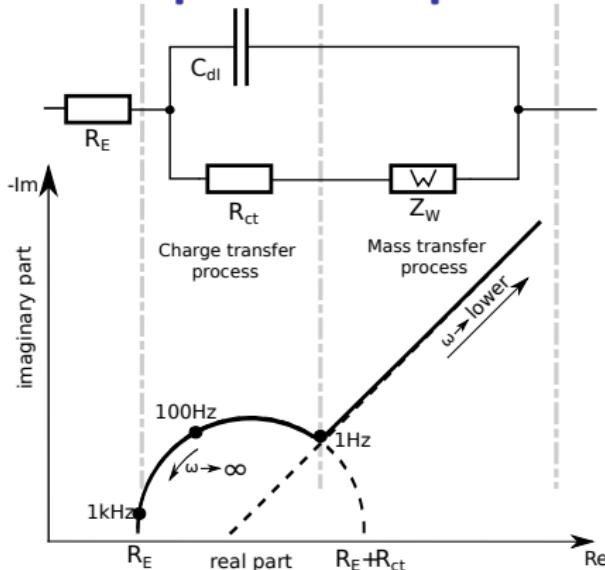
Sampling of 2500 data points during the engine start phase of the LiFePO₄ cell of the experimental starter battery

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Electrochemical Impedance Spectroscopy (EIS)

- EIS is a powerful method for battery state determination:
State of Charge, State of Health, Temperature, ...
- EIS can measure the complex impedance and capacitance of individual cell **components**, such as electrode surfaces and bulk electrolyte.
- EIS needs expensive laboratory instruments - up to now !

Electrochemical Impedance Spectroscopy (EIS)



- EIS determines the parameters for a complex battery model with resistors, capacitor(s) and "virtual" electric components (Warburg Impedance w. calculated behavior)
- The model (with parameters) characterizes the electrochemical dynamics which have a **nonlinear** system response

Basics for Impedance Spectrum Calculation

- Impedance = complex resistance: $\underline{Z} = |\underline{Z}| \cdot e^{j\varphi} = R + jX$ ¹
- Calculation: $\underline{Z}(\omega) = \frac{v(t)}{i(t)}$
- Practically implemented in 5 steps:

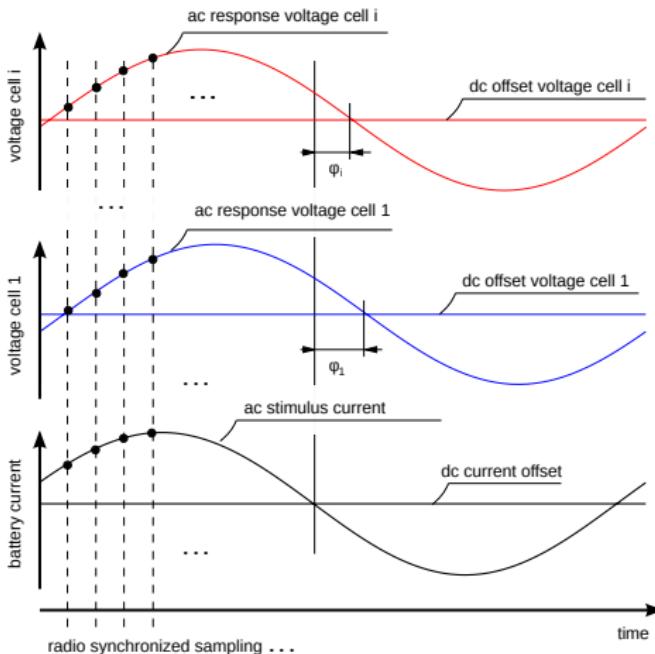
- 1: excitation stimulus $i(t)$: AC with $\omega_{ex} = 2\pi \cdot f_{ex}$ and DC offset
- 2: sampling $i(t)$ and sampling $v(t)$ synchronous
- 3: transform $i(t)$ to frequency domain: $i(t) \xrightarrow{\bullet} \mathcal{F}(i(t))$
- 4: transform $v(t)$ to frequency domain: $v(t) \xrightarrow{\bullet} \mathcal{F}(v(t))$
- 5: calculate complex $\underline{Z}(\omega)$ for $\omega = \omega_{ex}$: ² $\underline{Z}(\omega_{ex}) = \frac{\mathcal{F}(v(t), \omega_{ex})}{\mathcal{F}(i(t), \omega_{ex})}$

- Use a series of different excitation frequencies f_{ex_i} and repeat step 1-5 \implies impedance spectrum

¹ valid for a single frequency $\omega = 2\pi \cdot f$

² approximation with linearity assumption for small excitation

Electrochemical Impedance Spectroscopy: Phase Differences of Current and Cell Voltages

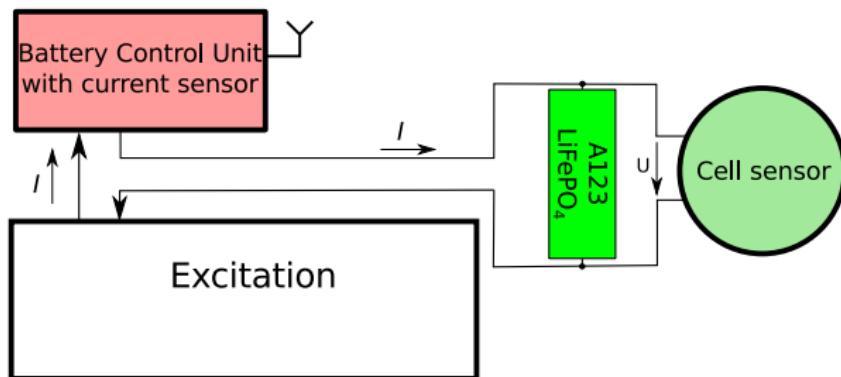


Response i

Response 1

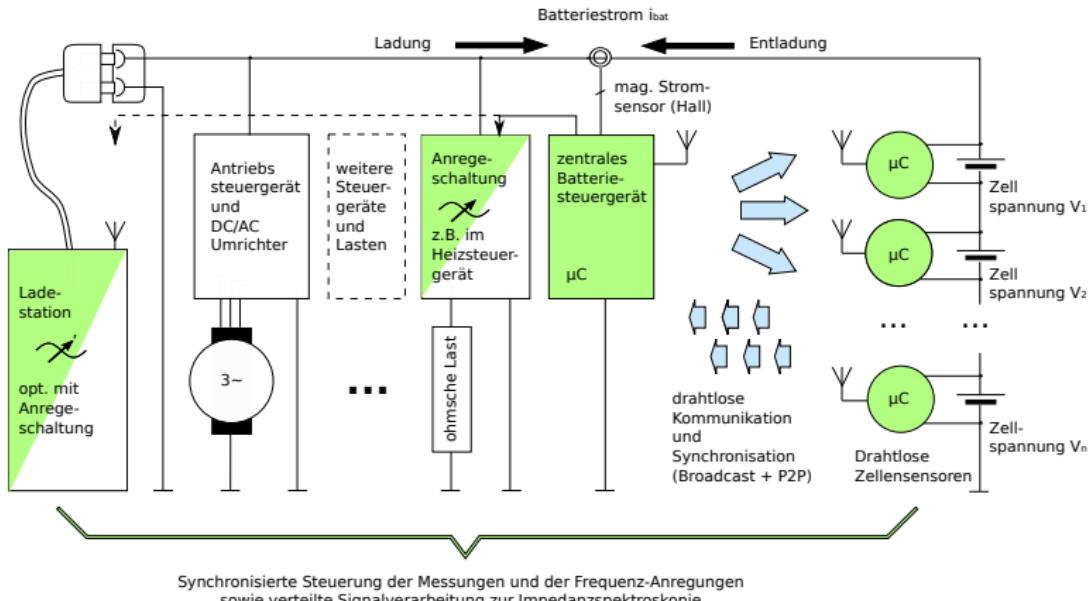
Excitation

Laboratory Test: Single Cell Impedance Spectroscopy



- Excitation current source: AC with arbitrary frequency plus preselected DC offset
- Current sampling: in the central battery control unit
- Voltage sampling: in the cell sensor (synchronous to the current sampling)
- Impedance calculation: in the central battery control unit

Concept: EIS & Excitation in Electrical Vehicles



EIS-excitation using charger components and/or in-vehicle load components

Frequency Transformations Algorithms for EIS

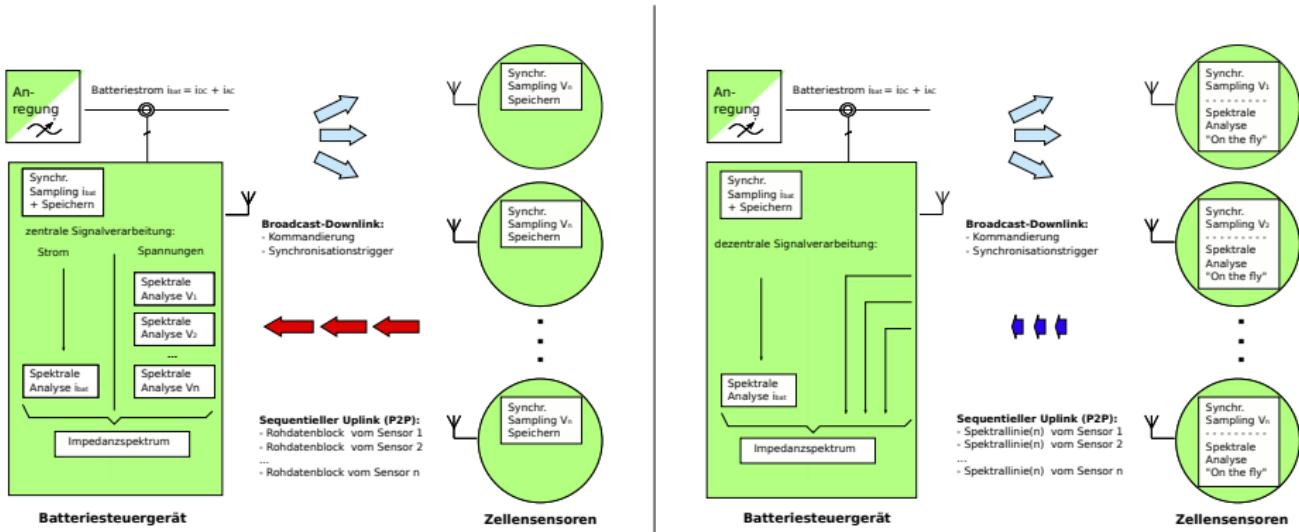
Alternatives:

- Discrete Fourier Transformation (DFT)
- Fast Fourier Transformation (FFT)
- Recursive Goerzel Filter ✓

| | Number of samples (N) | Number of spectral lines (S) | Computational costs | "On-the-fly"-calculation |
|---------|-----------------------|------------------------------|---------------------|--|
| DFT | arbitrary | arbitrary | typ. $O(N^2)$ | possible |
| FFT | power of 2 | power of 2 $S = N/2$ | $O(N * \log_2(N))$ | no, sample block size limited from sensor memory |
| Goerzel | arbitrary ✓ | 1 per filter ✓ | typ. linear $O(N)✓$ | possible ✓ |

The Goerzel Filter was chosen as efficient method for analysing the single and known frequency of the AC-excitation.

Distribution of Signal Processing



Left: Central signal processing the battery control unit

Right: Decentralized signal processing in battery control unit and the cell sensors

Comparision Examples of Central and Distributed Signal Processing

| | Zentrale Signalverarbeitung | Verteilte Signalverarbeitung |
|-------------|--|---|
| | 4 Zellen | 4 Zellen |
| Aufnahme | für 12 Freq. zus. $\approx 87\text{s}$ | für 12 Freq. zus. $\approx 87\text{s}$ |
| Übertragung | $12 \cdot 4 \cdot 6,98\text{s} \approx 335\text{s}$ | $12 \cdot 4 \cdot 40\text{ms} \approx 1,9\text{s}$ |
| Berechnung | $12 \cdot (4+1) \cdot 9,3\text{ms} \approx 500\text{ms}$ | $12 \cdot 1 \cdot 3,79\text{s} \approx 45\text{s}$ |
| Gesamtzeit | $\approx 422\text{s}$ | $\approx 137\text{s}$ |
| | 100 Zellen | 100 Zellen |
| Aufnahme | für 12 Freq. zus. $\approx 87\text{s}$ | für 12 Freq. zus. $\approx 87\text{s}$ |
| Übertragung | $12 \cdot 100 \cdot 6,98\text{s} \approx 8376\text{s}$ | $12 \cdot 100 \cdot 40\text{ms} \approx 48\text{s}$ |
| Berechnung | $12 \cdot (100+1) \cdot 9,3\text{ms} \approx 11,2\text{s}$ | $12 \cdot 1 \cdot 3,79\text{s} \approx 45\text{s}$ |
| Gesamtzeit | $\approx 8474\text{s}$ | $\approx 180\text{s}$ |

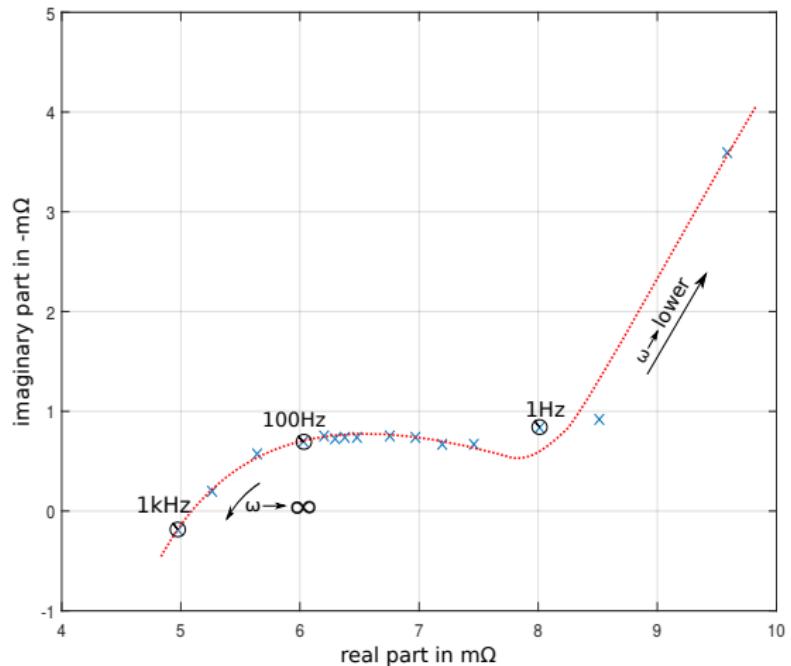
Solved Technical Problems

- 1:** Cell impedance in range of $m\Omega$ (typ. 0.1...10 $m\Omega$)
 - AC-Excitation in the range of Ampere for
 - AC-Voltage-Response in the range of mV
 - plus DC-Voltage of a Cell in range of 2...5 V
 - Problem: ADC with very high resolution needed

⇒ **Solution: separation of DC- and AC-voltage sampling**
with controlled analog offset subtraction and amplification for
AC-Sampling
- 2:** Effective time delay of current and voltage sampling
 - caused by trigger transmission, different ADC-timings, phase shift of current sensor and analog amplification
 - Problem: synchronisation up to submillisecond precision needed

⇒ **Solution: calibration procedure and compensation of time delays in the controller software**

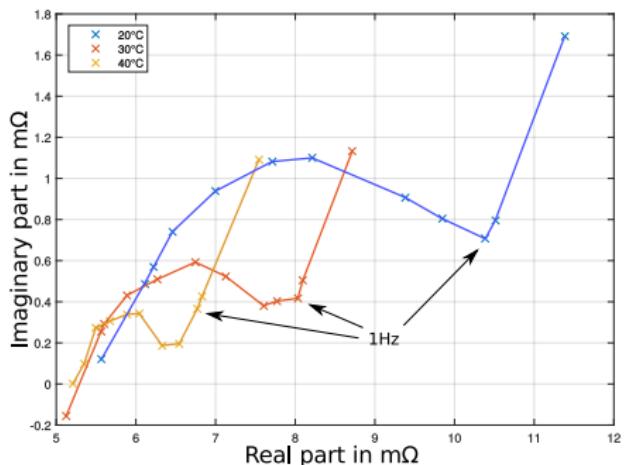
Functional Tests: EIS with Cell Sensors



Red: EIS-measurements from a commercial EIS meter

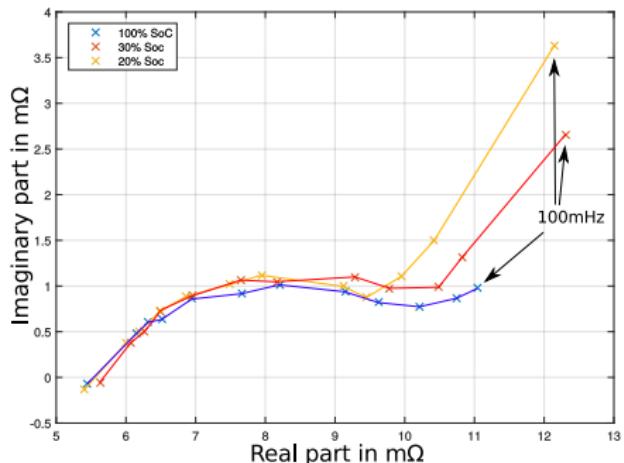
Blue: EIS-measurements with cell sensor prototypes

Tests: Cell State Determination with EIS

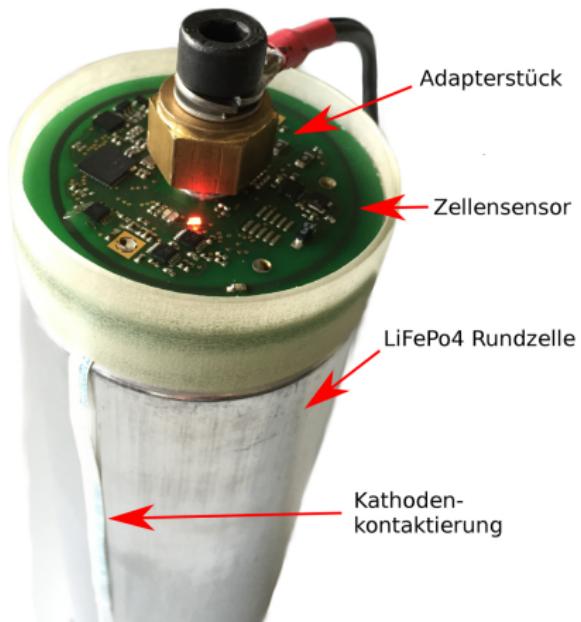


Left: EIS-measurement of impedance spectrum depending on temperature

Right: EIS-Measurement of State of Charge



Prototype Assembly: Cell Mounted Sensor



45 Ah LiFePO₄ Cylindic Cell with wireless Sensor

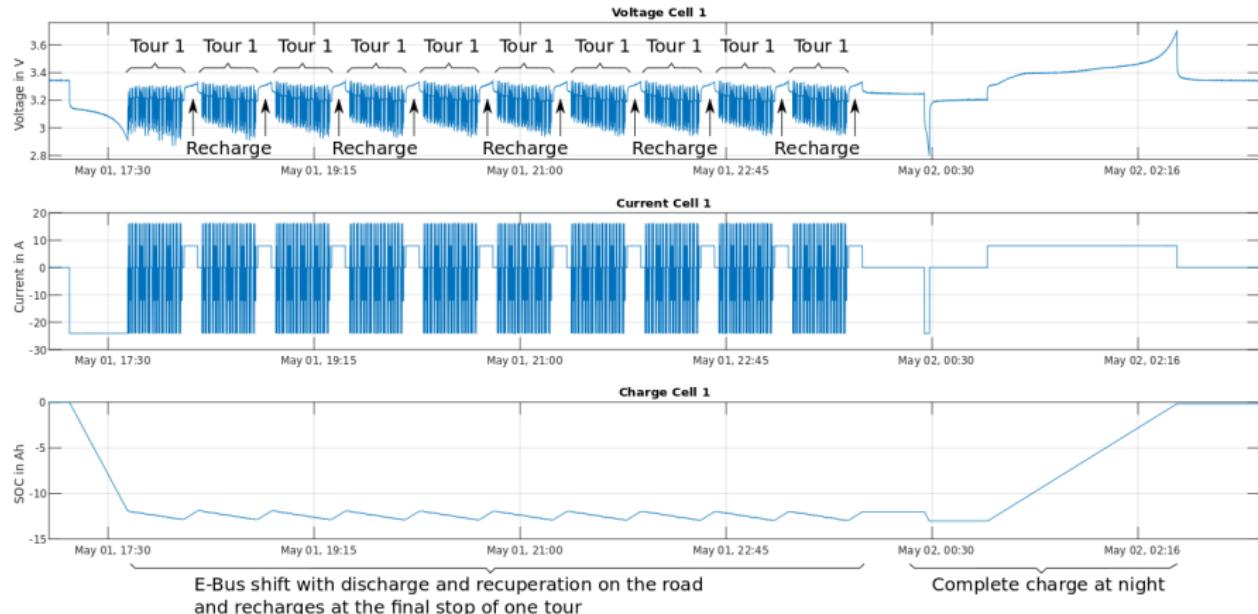
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Imaginable as Application: Electric Busses with > 1000 Cells



Political objective: a complete change to CO₂-free city-busses in Hamburg will start in 2020

Under Research at HAW: Optimization of Battery Cycles for Electric Busses



Recent Project BEEDel:
Battery lab cycle tests based on logged data of city-bus tours

E-Mobility Research at HAW Hamburg

- Wireless sensor system for real-time cell state observation including:
 - Cell balancing, wake-up functionality
 - Synchronized burst measurements for high dynamic events
 - Electrochemical impedance spectroscopy
 - Delivering an additional safety level
- Concept design for communication between battery, car and grid in a proposed EU Project application
- Data collection and lab tests for electric busses in Hamburg
- Basic research for real-time optical electrode observation

Acknowledgements

- Project 'BATSEN': German Federal Ministry of Education and Research BMBF





Bundesministerium
für Bildung
und Forschung

Interreg IVB North Sea project

e-mobility NSR



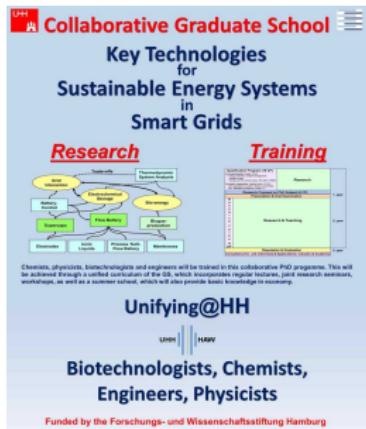
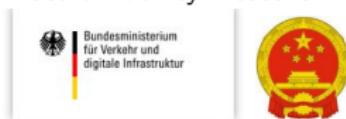
This project is part-financed by the EU

- E-Mobility NSR Interreg Project: EU Commission www.e-mobility-nsr.eu
 - Collaborative Graduate School with Univ. of Hamburg
 - Battery Test Laboratory HAW:

Environmental Authority City of Hamburg



- Project 'BEEDeL', Evaluation of E-Busses
 - Project 'SINGER' Sino-German Electromobility Research



Contributions of Students in the Research Team

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