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*Embedding smart functionalities into battery cells (embedding sensing and self-healing functionalities to monitor and self-repair battery cells)
(Batteries Partnership)*



PHOENIX

Building more reliable and performant batteries by embedding sensors and self-healing functionalities to detect degradation and repair damage via advanced Battery Management System

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SHORT ABSTRACT FOR DISSEMINATION PURPOSES

Abstract

This deliverable focuses on the detection of degradation in lithium-ion cells using ultrasound. A sensor system with piezoelectric disks for an ultrasonic sensor mat was developed. Time-of-flight (ToF) measurements serve as a direct indicator of the state of health (SoH) and correlate with the degree of degradation. An indirect proportionality between ToF and SoH was demonstrated in a series of tests. By integrating these measurements, the work package aims to enhance battery health monitoring and optimize maintenance strategies.



TABLE OF CONTENTS

DOCUMENT INFORMATION	2
DOCUMENT CHANGE HISTORY.....	3
SHORT ABSTRACT FOR DISSEMINATION PURPOSES	4
TABLE OF CONTENTS	5
LIST OF PARTNERS.....	6
ABBREVIATIONS	7
LIST OF FIGURES.....	8
LIST OF TABLES	8
EXECUTIVE SUMMARY	9
1. SETUP OF ULTRASONIC SENSORS.....	10
1.1 Measurements of the ultrasound	10
1.2 Ultrasonic sensor system	11
1.3 Sample preparation	11
1.4 Initial testing	12
1.5 Improvements to the sensor system	13
2. AGEING MEASUREMENT WITH ULTRASONIC SENSORS	15
2.1 Measurement Setup	15
2.2 Measurement Results.....	16
2.3 Conclusion.....	19
ANNEX.....	21



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4		ENWAIR ENERJI TEKNOLOJILERI ANONIMSIRKETI	ENW	Turkey
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ABBREVIATIONS

Acronym	Description
C-Rate	Charge/Discharge-Rate according to nominal capacity 1 C @ Q.n = 1,2 Ah -> 1,2 A
CC	Constant Current
CCCV	Combined Constant Current and Voltage
CEI	Cathode Electrolyte Interphase
CV	Constant Voltage
Digatron	Battery tester manufacturer
LIB	Lithium Ion Battery
NDT	None-destructive testing
PCUS	Measurement electronics, Frontend for the ultrasonic testing
SEI	Solid Electrolyte Interphase
SoC	State of Charge [%]
SoH	State of Health [%]
ToF	Time-of-Flight



LIST OF FIGURES

Figure 1: PCUS Measurement Frontend	11
Figure 2: Piezo disc preparation	12
Figure 3: Flex PCB with piezo disc (top) and without (bottom).....	12
Figure 4: Casting mold (left), with flex PCB (middle), finished sensor mat with cell (right).12	
Figure 5: Initial cycle measurement	13
Figure 6: Exemplary photography of the clamping setup. (Fraunhofer ISC)	15
Figure 7: Cell from CIDETEC ID 002 (left), cell pressed with piezo disc (right)	16
Figure 8: Cell capacity over number of cycles for 1C cyclisation of CIDETEC cell 002.....	16
Figure 9: SoH over number of cycles for 1C cyclisation of CIDETEC c cell 002	17
Figure 10: Zoom of voltage, current, ToF and amplitude over time	18
Figure 11: Ageing measurement, ToF, amplitude and SoH over time	19

LIST OF TABLES

Table 1: Cycling procedure for aging measurement.....	15
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EXECUTIVE SUMMARY

This deliverable focuses on the detection of degradation in lithium-ion cells using ultrasound. A sensor system with piezoelectric disks for an ultrasonic sensor mat was developed. Time-of-flight (ToF) measurements serve as a direct indicator of the state of health (SoH) and correlate with the degree of degradation. As a contribution, we received test cells from our partner CIDETEC, which we used to start a series of measurements. In this test series, the sample cell was cycled and ultrasound measurements were carried out simultaneously. As a result, an indirect proportionality between ToF and SoH could be demonstrated. Thus, the detection of degradation by ultrasonic measurements could be proven.

The goal of the work was to achieve a form factor increase of less than 10% and an energy consumption of under 50 Wh/kg, corresponding to KPI2 defined in the grant agreement. Achieving the specified form factor with relatively small sample cells (1.2 Ah) presents a significant challenge. The dimensions of the sensors remain unchanged regardless of using larger or thicker cells, resulting in a substantial reduction in form factor for the small test cells.

The technical drawing in the annex illustrates that the cell measures 95 mm x 145 mm, with a thickness of 1.65 mm, yielding a theoretical volume of 22.7 cm³. This division leaves only 2.27 cm³ for the sensor mats. Although it seems feasible to use two individual piezo discs (each approx. 0.4 cm³), this is impractical as uniform pressure distribution is required in the cell. We have therefore developed a sensor mat that corresponds to the active area of the cell and measures 105 mm x 66 mm. The height of the mat, which is determined by the silicone volume, ensures that the discs are sufficiently covered, resulting in a thickness of 1.5 mm. The total volume of the two sensor mats is therefore 20.8 cm³.

Given the size constraints of the here tested cells, fulfilling this KPI is not feasible. The sensor mat must cover at least the active area of the cell, establishing a critical relationship between cell thickness and sensor mat thickness; the mats' thickness is limited to 5% of the cell's thickness, particularly as two mats are required.

In today's battery modules and packs, tolerance compensation mats are typically employed to ensure uniform pressure on all pouch lithium-ion cells. Integrating sensors into these mats is the key to mitigate the impact on form factor. Additionally, the possibility of incorporating multiple sensors within a single mat may further reduce the increase in form factor while enhancing overall functionality.

Another KPI is the maximum energy consumption. The sensor system should consume less than 50 Wh/kg in relation to the cell weight. The sample cell was weighed at 29.3 g. This translates to a maximum energy consumption of 1.5 Wh for our specific test setup. During our testing series, ultrasound measurements were conducted every two minutes. In future iterations, it is anticipated that the Battery Management System (BMS) will initiate measurements at longer intervals. For the purposes of this analysis, we will assume continuous measurement. The power consumption of our microcontrollers, measured at 500 mW, resulting in an energy consumption of 15 Wh/kg, based on the sample cell weight.



1. SETUP OF ULTRASONIC SENSORS

Ultrasound refers to sound waves with frequencies above the audible range for humans, typically above 20 kilohertz (kHz). In non-destructive testing (NDT) applications related to batteries, frequencies ranging from hundreds of kHz to several megahertz (MHz) are commonly used. When ultrasound waves propagate through a material, they interact with its internal structures, and changes in the material properties affect the waves' propagation characteristics. By analysing parameters such as time-of-flight (ToF) and amplitude it is possible to infer information about the material's mechanical and structural state, such as Young's modulus, density, and the presence of defects or electrode degradation.

Understanding the fundamentals of ultrasound and its application to Lithium-Ion Batteries (LIB) cell diagnostics could prove to be extremely beneficial for advancing battery monitoring and enhancing performance and safety. Two primary measurement variables are commonly employed: ToF measurements and amplitude measurements.

1.1 Measurements of the ultrasound

Time-of-Flight (ToF) Measurements

ToF measurements determine the time an ultrasound wave takes to travel from a transmitter to a receiver through a material. In LIB diagnostics, ToF can be used to assess changes in the mechanical properties of the battery components. The velocity (v) of the ultrasound wave is related to the material's elastic modulus (E) and density (ρ) by $v = \sqrt{E\rho}$.

As the battery undergoes aging and degradation, changes in the electrodes alter the elastic modulus and density. These changes result in variations in the ultrasound wave velocity, which can be detected through shifts in the ToF. In addition to the propagation velocity, the ToF also strongly depends on the distance travelled by the sound wave. The cell thickness and its variation during charging or during aging therefore also affects the ToF. To differentiate between changes in elastic modulus and density versus swelling, a direct distinction could be possible by incorporating an expansion measurement, such as laser-based distance measurement or pressure sensors.

Amplitude Measurements

Amplitude measurements assess the reduction in the ultrasonic wave's amplitude as it propagates through the material, which is influenced by scattering, absorption, and reflection caused by internal features like boundaries between materials or components, defects, or the formation of new phases (e.g., SEI and CEI). In LIB cells, this attenuation reveals microstructural changes related to aging, such as increased porosity, cracks, or layer delamination. By correlating the amplitude reduction with these changes, the integrity of electrode materials and the extent of mechanical degradation can be evaluated.



As part of this project, low-cost, commercially available piezo elements will be used. These can be electrically contacted and excited to vibrate using a voltage pulse, thereby emitting an ultrasound pulse. The choice of this transmitter provides a cost-effective and space-saving method for evaluating the aforementioned parameters. However, due to the somewhat inferior response and damping behaviour compared to high-performance ultrasonic probes, only the qualitative change in the ultrasound signal caused by the cell during aging will be considered in the following. This qualitative change can also provide insight into the aging process.

1.2 Ultrasonic sensor system

The ultrasonic sensor system uses piezo discs, which can be used both as receivers and transmitters for the ultrasonic signal. The transmission method is used for this, which means that we attach a receiver and a transmitter directly opposite of each other on each side of the pouch cell. The echo measurement with only one ultrasonic transducer on the cell has not shown promising results and is therefore not considered further in this project.



Figure 1: PCUS Measurement Frontend

The piezo discs are connected to a commercially available ultrasonic front end named PCUS via a soldered connection using a shielded cable. By using this front end, it is possible to control the excitation of the transmitting piezo as well as to log the received signal of the receiving piezo transducer. The control as well as the data logging of this PCUS is done via a python script developed by Fraunhofer for this purpose.

1.3 Sample preparation

The first samples have been prepared so that the general function can be verified. These were casted in epoxy to ensure mechanical stability during handling. Static measurements were then carried out on a mono-layer NMC cell to ensure basic functionality first. This monolayer cell comes from battery production at Fraunhofer ISC. The cell is not identical to the cells later used, manufactured by our partner CIDETEC, but similar enough in structure, mono-layer and chemistry to carry out initial measurements for verification.



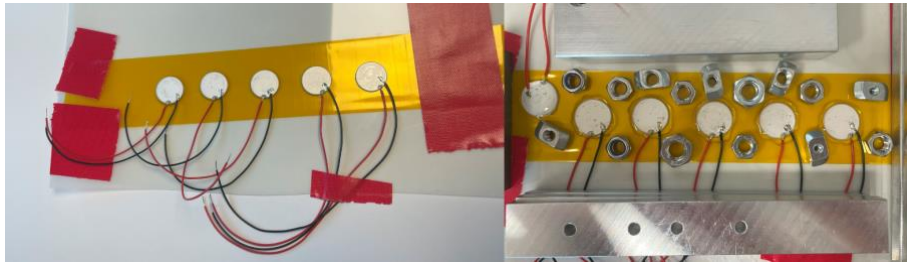


Figure 2: Piezo disc preparation

1.4 Initial testing

The first CIDETEC sample cells were delivered in July 2024 which allowed first static measurements on a CIDETEC cell on site. The cell has an average thickness of only 1.65 mm, which makes it challenging to probe with ultrasound. A flex PCB was designed to contact the two transducers. The PCB design represents a loop between the two sensors and goes from the transmitter to the receiver and vice versa, in the middle of the PCB a connection for the measuring electronics is located.



Figure 3: Flex PCB with piezo disc (top) and without (bottom)

Initial tests with this sensor exhibited that the electrical connections and solder joints must be encapsulated, in order to ensure mechanical stability. However, for optimum cell operation a flat and slightly compressible surface is needed for the sensor mat to ensure uniform pressure distribution over the cell. A pressure of 50 kPa is recommended by CIDETEC for pressing the cell. A mold was constructed for casting the sensor into a silicone mat. This mat has dimensions greater than or equal to the active area of the cell and is therefore also suitable as a tolerance compensation mat for evenly bracing the sample cells.

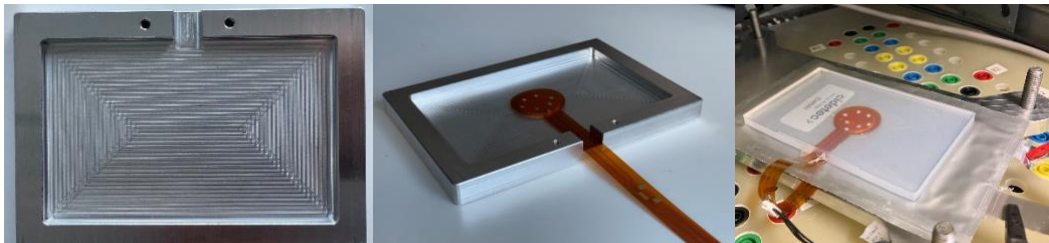


Figure 4: Casting mold (left), with flex PCB (middle), finished sensor mat with cell (right)

The silicone mat was very suitable for levelling out height differences and worked well as a tolerance compensation. Unfortunately, the mechanical stability is not sufficient due to the soft material. For this reason, the sensors are now enhanced with epoxy at the problematic

points (solder joints) before casting in silicone. This protects the solder joints in particular from cracking and provides good mechanical stability.

1.5 Improvements to the sensor system

The first assembly was compressed with a sample cell from CIDETEC. The cell was cycled at 0.5 C according to CIDETEC’s specifications. The ultrasonic measurement successfully showed the characteristic behaviour of the calculated variables “Time of Flight” (ToF) and the amplitude behaviour during cycling.

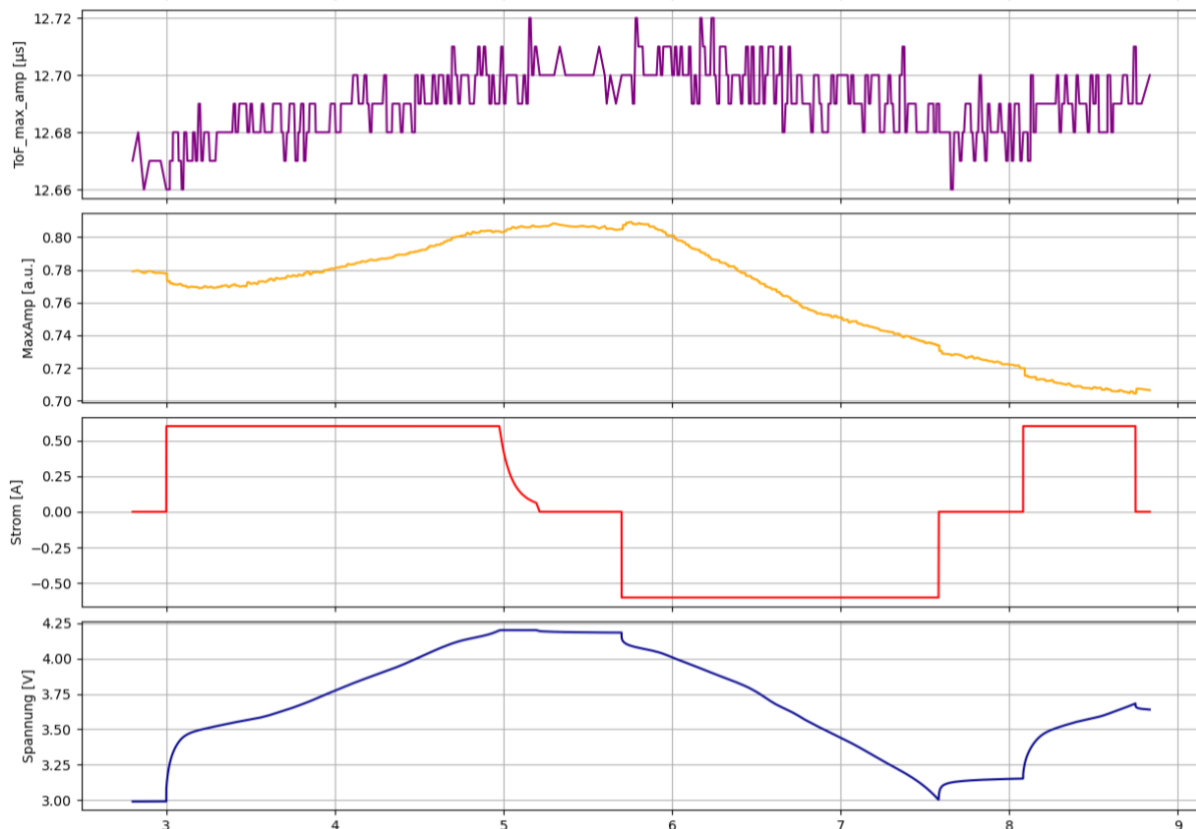


Figure 5: Initial cycle measurement

A clear dependency between the calculated ToF value and the SoC has already been established. This suggests that detecting aging-related effects is highly likely. We anticipate a change in the magnitude of order of the measured variables as the cell transitions from Beginning of Life (BoL) to the End of Life (EoL), spanning from SoC 0% to SoC 100% for one cycle. Although the small cell thickness presents a significant challenge for ultrasound sensing, we have already conducted valid measurements on the cell with this first prototype sensing system.

The maximum amplitude shows hardly any change here. In simple terms, it is mainly influenced by the cell thickness (damping factor). The change in thickness of the cell during charging and discharging automatically also changes the damping factor. However, this is dependent on the delta of the thickness change. The thinner a cell is, the less pronounced this effect can be observed. For this reason, we still tend to see the trend of an increasing



maximum amplitude when charging and a decreasing one when discharging. However, the effect is too small with such thin cells to be of any real significance.

In the battery testing lab, the setup showed a measurement noise that could not be observed before, suggesting some electromagnetic interference. For this reason, the electrical connection to the measurement electronics was shielded with copper foil. The results showed a significant reduction in noise. With these results, a long-term measurement accompanying the cycling of the cell was started. The aim is to continuously record ultrasonic data while the cell is cycled. In this way, the aging (decreasing SoH) of the cell can be linked to the results (ToF, amplitude) of the ultrasound measurement.



2. AGEING MEASUREMENT WITH ULTRASONIC SENSORS

2.1 Measurement Setup

The measurement setup consists of a clamping device for the cell, the ultrasonic sensors and measuring electronics as well as the sample cell from CIDETEC and a battery tester. The battery tester used is a Digatron MCT-HD device. The voltage range is 0.7-6V and the maximum current is 5 A. Cyclization with a C-rate of 1 C was selected as the test procedure for both charging and discharging. The cycling is briefly explained in the table below. There was no termination criterion defined for the end of the cycling, because this experiment gave the opportunity to reveal the evolution of the ultrasonic signal behaviour after the end-of-life (EoL) of the battery cell is reached. However, the main focus is on the correlation between the decline in SoH and the ToF.

Table 1: Cycling procedure for aging measurement

Step	Action	Comment
1	Rest 60 min	initial tempering
2	Charge 1C	CC charging with 1 C (1.2A) up to 4.2 V
3	Charge 4,2 V	CV charging at 4.2V until $I < 0.05$ C
4	Rest 10 min	rest between charge and discharge
5	Discharge 1C	CC discharge until 2.8 V
6	Rest 10 min	rest between discharge and charge
7	loop	loop steps 2-6

The clamping device used in this experiment is a device made of aluminium profiles and plates, in which two plates are mounted on a rail, which can be clamped with the help of a threaded screw. This measurement setup not only has the appropriate dimensions for the test cell and the load cell allows to set the bracing to the defined preload of 50 kPa, by using a preload spring.

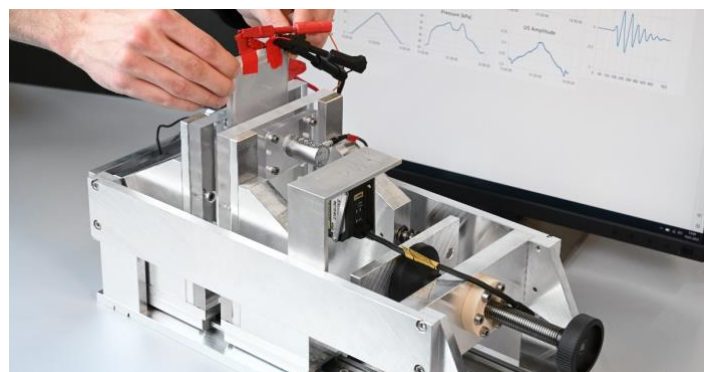


Figure 6: Exemplary photograph of the clamping setup. (Fraunhofer ISC)

The battery cell and ultrasonic sensors were pressed between the two clamping plates. and the two piezo transducers are positioned in the middle of the cell.





Figure 7: Cell from CIDETEC ID 002 (left), cell pressed with piezo disc (right)

2.2 Measurement Results

Until February 24.02.2025, the aging measurement has already completed 600 cycles. There was an interruption in the tests lasting several days during the 2024-2025 Winter break, but otherwise the tests ran without any abnormalities or interruptions. This interruption took place at cycle 100, the recovery of the capacity after this break can therefore be seen in all ageing plots. Figure 8 and 9 show the curves of discharge capacity and SoH over cycle number indicating the aging of the cell in this 1C cyclization test.

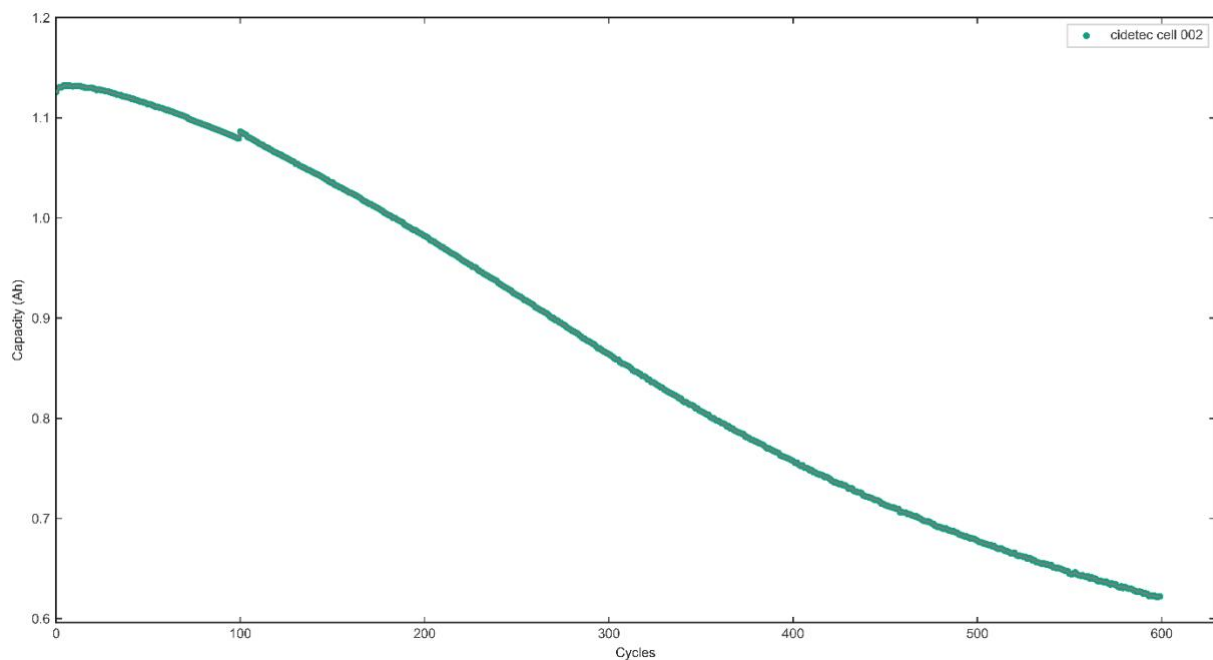


Figure 8: Cell capacity over number of cycles for 1C cyclisation of CIDETEC cell 002



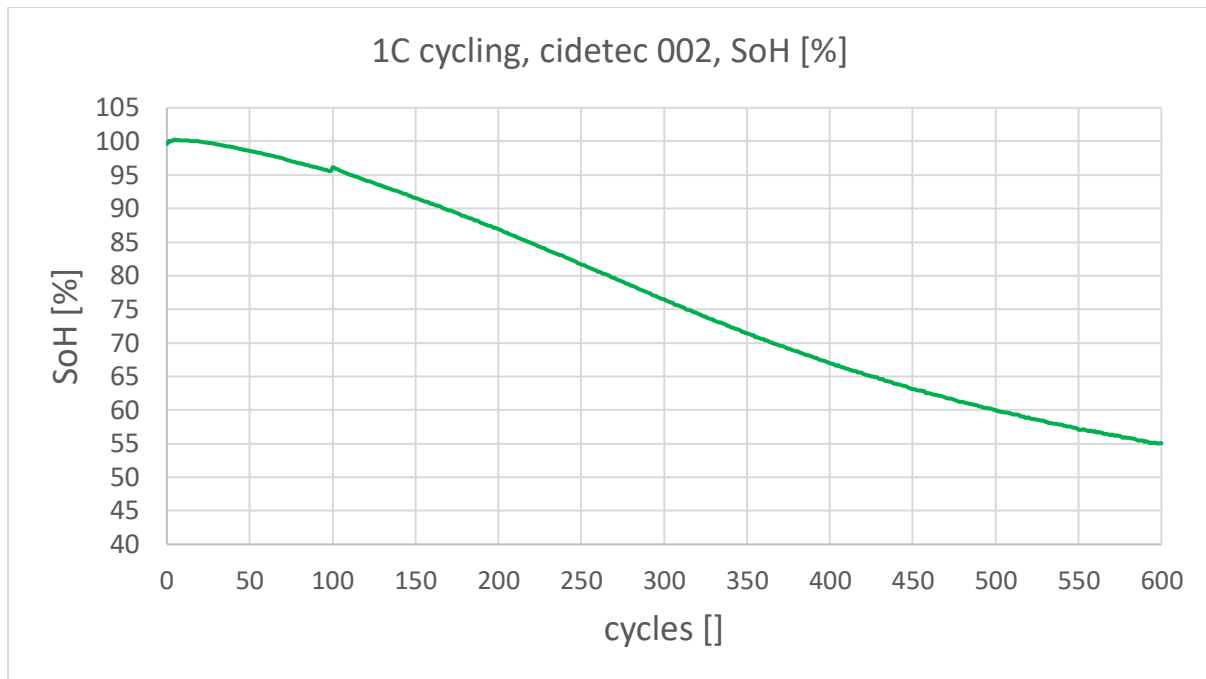


Figure 9: SoH over number of cycles for 1C cyclisation of CIDETEC c cell 002

For the calculation of the SoH, the discharge capacity of the third cycle was used as a reference for the nominal capacity which is 1.13 Ah. As can be seen from Figure 8, the SoH of 80% is reached after 267 cycles, while the SoH of 60% is achieved exactly at cycle 500. In the current cycle 600, the cell has a SoH of 55 % which clearly shows the aging (decrease of capacity) over cycling as expected.



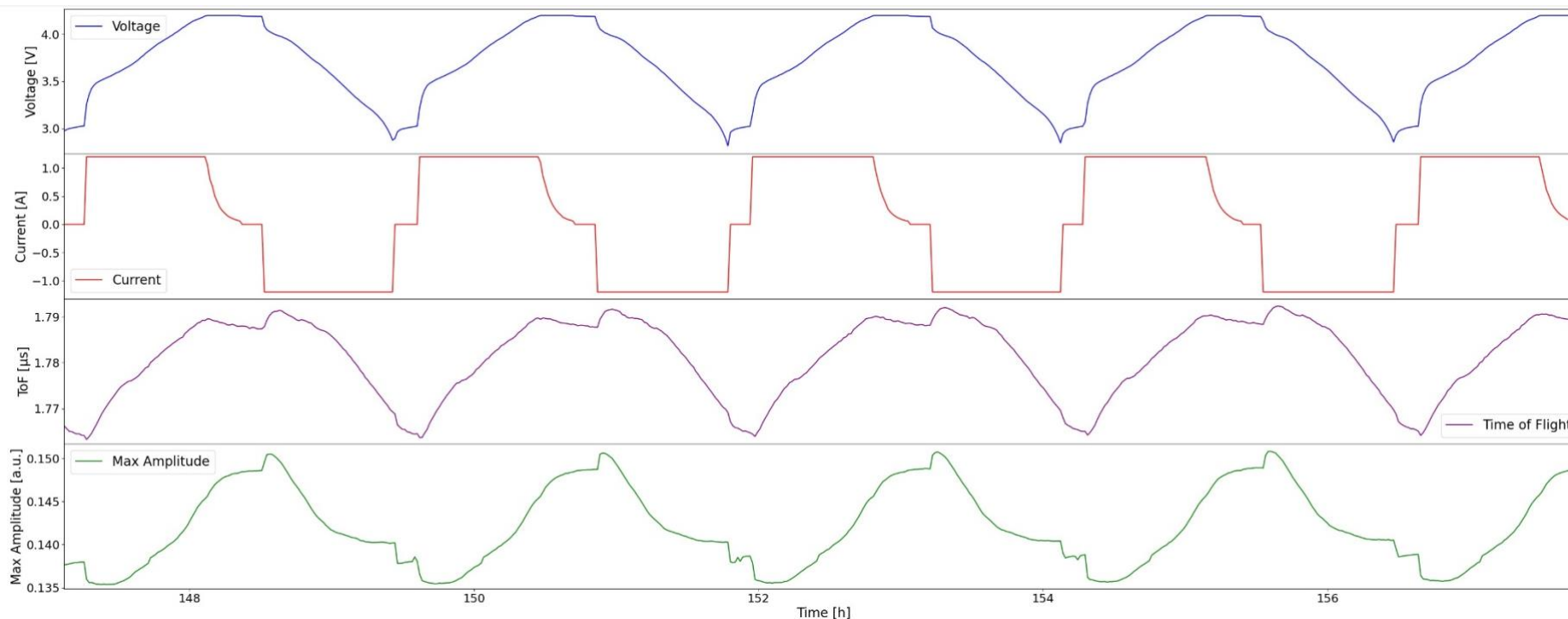


Figure 10: Zoom of voltage, current, ToF and amplitude over time

Figure 10 shows a zoom in over 4 cycles. The two top plots show shows that the current and voltage of the cell. The 3rd plot is the ToF. As expected, the ToF (threshold) increases during charging and decreases during discharging. This behaviour is not only related to the change of the cell thickness, but is more prominently caused by the change in the density of the graphite anode, which changes with the level of lithium intercalation.



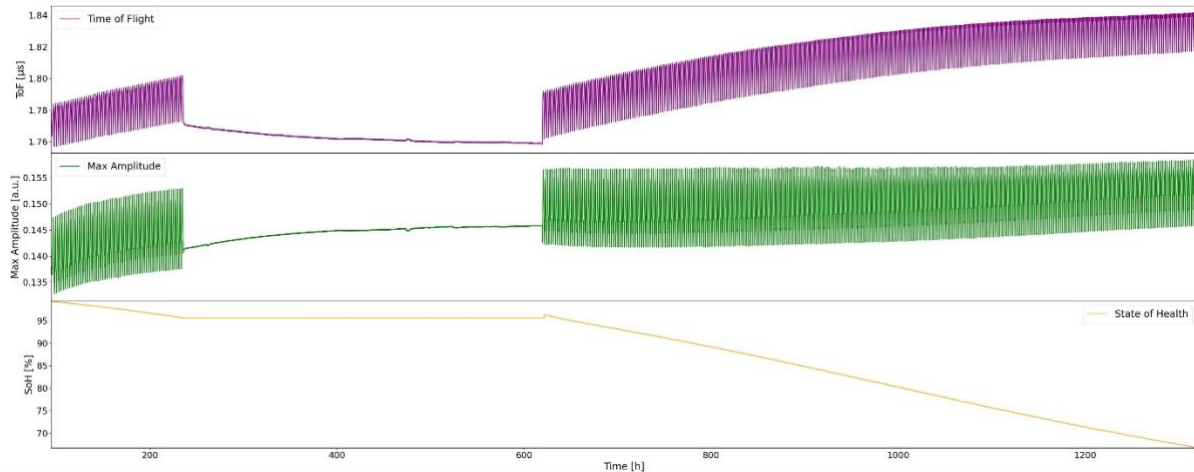


Figure 11: Ageing measurement, ToF, amplitude and SoH over time

As seen in figure 11, the ToF over the entire cycling steadily increases, with each new cycle. We anticipate that the ToF values are inversely proportional to the SoH. For clarification: at cycle 100, there was a one-week break, as shown in the graph due to closure of the institute over the holidays. After the pause, the ToF signal starts at a lower value compared to the last cycles before interruption. This behaviour complies with the short-term recovery of the cell's capacity which, however, reverts to its original level after a few cycles. This also indicates that there is no significant drift in the measurement results indicating a long-term stability of the measurement.

The 4th plot in figure 10, shows the amplitude curves. The pattern of the maximum amplitude of the ultrasonic signal is similar to the ToF behaviour. The amplitude rises during charging and subsequently decreases during discharging which can be attributed to the increasing and decreasing attenuation for the sound wave. In terms of the correlation with degradation, the relationship to the state of health (SoH) is not as clearly defined as it is with the ToF.

The aging measurement of the CIDETEC sample cell successfully completed 600 cycles, demonstrating consistent performance throughout the testing period with no significant anomalies. The results reveal a clear degradation in capacity, as the State of Health (SoH) reached 80% after 267 cycles and decreased to 60% by cycle 500. At cycle 600, the SoH has further declined to 55%.

2.3 Conclusion

The ultrasonic measurements further illustrate the cell's behaviour during the cycling and over cycle life. The Time of Flight (ToF) shows a predictable pattern, increasing during charging and decreasing during discharging, primarily due to changes in the density and the Young's Modulus of the graphite anodes and the cell. Despite a one-week pause at cycle 100, the ToF signal returned to a lower initial value but stabilized, demonstrating the measurement's long-term reliability. This can also be seen very clearly in the SoH values



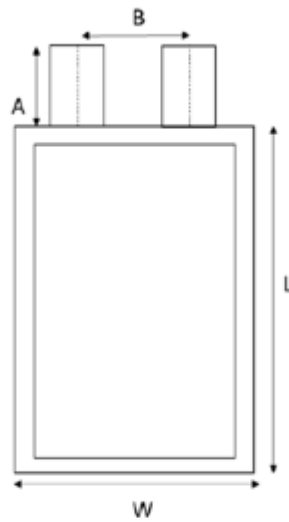
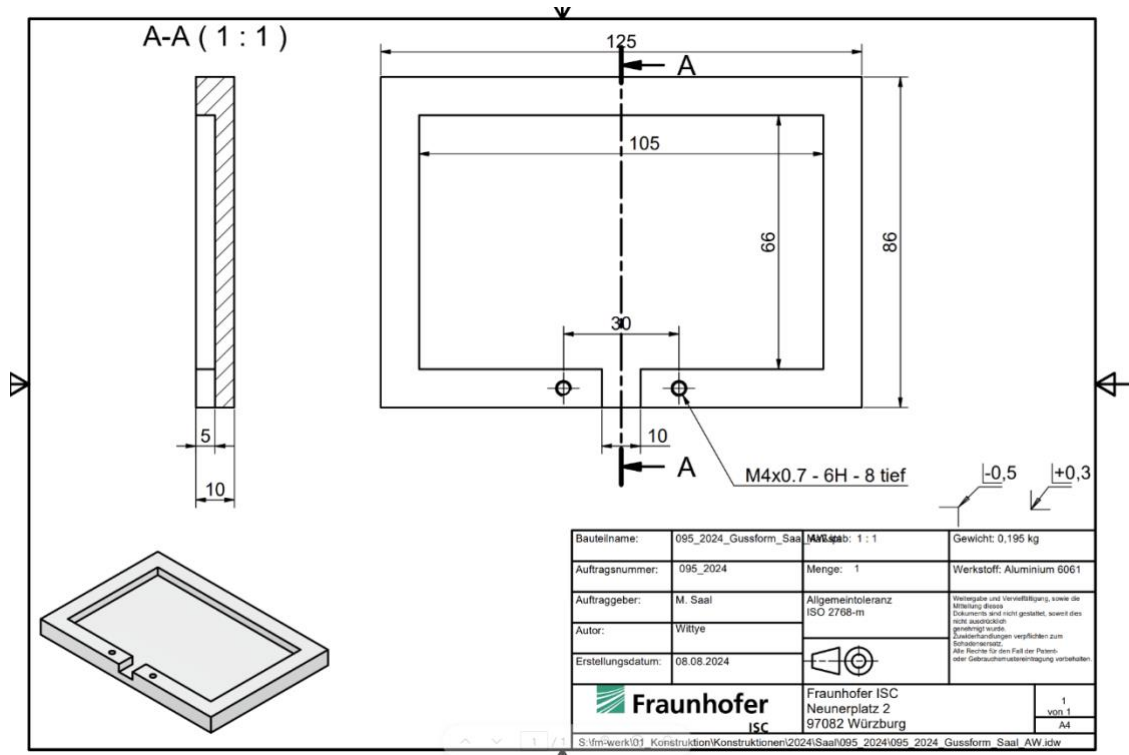
after the break, as there is an increase in capacity after cycle 100 at the end of the break, which is also reflected in the ToF.

The behaviour of the ToF highlights its inverse relationship with the State of Health (SoH) and thus the degradation of the cell. As ToF values increase—indicating longer transit times for the ultrasonic signal—the SoH decreases. This trend suggests that as the cell degrades, reflected in lower SoH values, the ToF rises, reinforcing the notion that a higher ToF is associated with a lower SoH. This inverse proportionality emphasizes the utility of ToF measurements in effectively monitoring cell health and evaluating its degradation over time.

Additionally, the maximum amplitude of the ultrasonic signal mirrored the ToF behaviour, highlighting the relationship between charging and discharging processes. However, the correlation between degradation and SoH remains less pronounced compared to the ToF. We therefore consider the ToF to be the better parameter for assessing degradation. Overall, these findings contribute valuable insights into the aging dynamics of the cell, reinforcing the expected trends in capacity degradation over the cyclization period.



ANNEX



Cell dimensions (mm)	Specification
Width (W)	90
Length (L')	200
Length (L)	160
Length (mm), (A)	35
Distance (mm), (B)	40



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