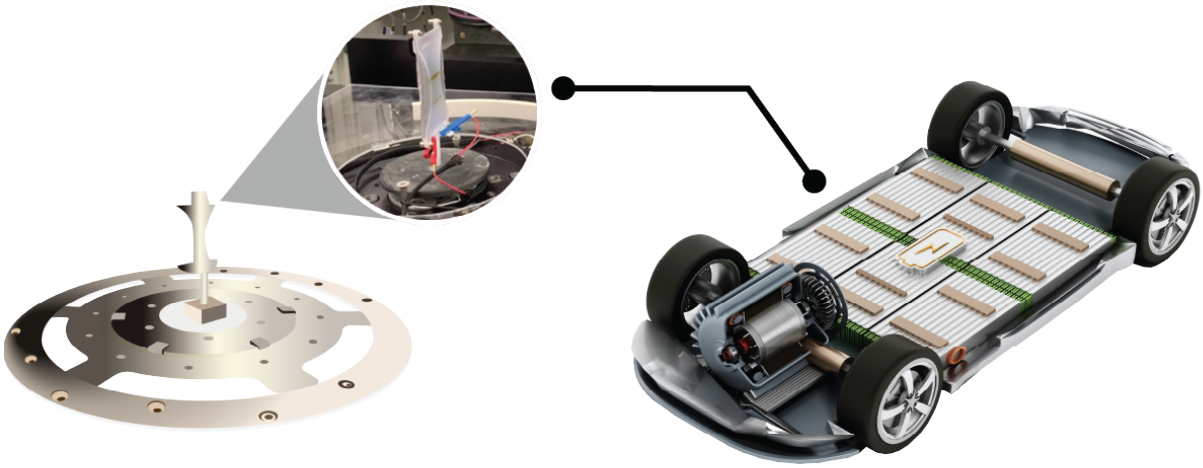
Hi ACTS | Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions

IMPACT STUDY OF THE SOCIO-ECONOMIC BENEFITS FROM THE HI-ACTS USE CASE INITIATIVE

Test Stand for Operando Battery Investigation



FINAL REPORT

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AS THE DEMAND FOR ELECTRICITY STORAGE SOLUTIONS GROWS, BATTERY INNOVATION AND TESTING MUST KEEP PACE...

In the transition to clean energy and digitalisation, there is rapidly increasing demand for efficient, sustainable, and scalable energy storage. This growth is driven by renewable energy integration, the electrification of transport - such as electric vehicles (EVs) - grid-scale storage solutions, and the growing reliance on portable electronics. As outlined in the Federal Ministry for Economic Affairs and Climate Action *Electricity Storage Strategy*, Germany is anticipated to be almost entirely powered by renewable energy by 2035,[i] while the Fraunhofer Institute forecasts that Germany will provide batteries for 6.5 million electric cars by 2030.[ii]

Meeting this demand requires deep scientific understanding of battery performance, failure modes, and safety risks under realistic operating conditions - otherwise known as operando tomography. However, conventional laboratory tools are often inadequate for this measurement technique, as they are unable to measure internal structural changes within batteries in real time, and must instead infer where failures have occurred indirectly. This is where large-scale research infrastructures, such as synchrotrons and neutron sources, can play a transformative role in driving innovation in battery technology. To realise this ambition, hardware and software at synchrotron beamlines must be optimised to ensure that all variables can be controlled throughout an experiment, and that software is tailored and accessible to users who are more familiar with conventional laboratory-based measurements.

...HENCE UCI FUNDING IS SUPPORTING FASTER AND MORE ACCESSIBLE BATTERY IMAGING AT ACCELERATOR FACILITIES

Helmholtz-Zentrum Berlin (HZB) is a research centre focused primarily on climate-neutral energy materials and technologies, such as solar cells, catalysts, advanced batteries and green hydrogen generation. . In 2023, HZB received €78,000 through the Helmholtz Innovation Platform for Accelerator-Based Technologies (Hi-Acts) to develop a ‘test stand for operando battery investigation’ over an 8-month period. This initiative formed part of a broader Hi-Acts strategy to open up accelerator-based techniques to industry and enable translational research at scale.

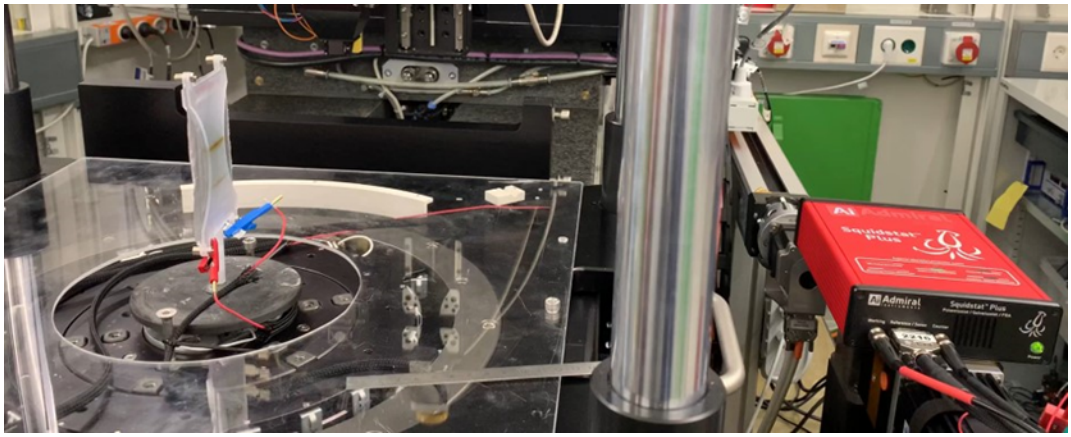
The UCI-funded hardware developed was a flexible, multi-purpose battery test bench with cyclers to enhance in-situ synchrotron tomography facilities.[1] The test bench is a crucial component in enabling 3D imaging of batteries at synchrotron facilities to investigate their inner dynamics. While synchrotron facilities offer unique imaging capabilities, they remain underutilised by industry due to operational complexity, specialised hardware requirements, and steep learning curves for external users. Whilst accelerators can provide significant benefits compared to experiments conducted at electrochemical laboratories, the latter is the current status quo in industry. This Hi-Acts-funded flexible test bench aims to unlock the benefits of accelerators in an industrial research context.

The project integrated this battery test bench with existing x-ray beamlines, focusing initially on BAMline at the BESSY II facility at HZB and two beamlines (P05 and P07) at the DESY PETRA III facility. The test bench is compatible with batteries ranging from coin cells to larger prismatic, pouch and round cell batteries – including lithium-ion batteries, which are used in energy storage systems and EVs, alongside other applications. This compatibility, coupled with integrated Python-programmable software, supports more efficient, standardised, and scalable battery testing, which could make battery research at synchrotron accelerators faster, more reliable, and more accessible to

[1] Synchrotron tomography is an imaging technique which uses high-energy x-rays to penetrate through thicker materials, to create detailed, 3D images of a sample’s internal structure.

industry. Over the longer term, this also unlocks the potential for AI-controlled experiments, further lowering barriers to entry for industrial users.

Figure 1: The pouch cell stack (left) and battery cyclers (right) used at the P07 beamline at DESY



Source: DESY

TECHNOLOGY DEVELOPMENT AND INNOVATION

Hi-Acts UCI funding enabled technology maturity progression of the test bench hardware from an estimated Technology Readiness Level (TRL) 5 to TRL 9. It has been fully integrated into several synchrotron beamlines.

Hi-Acts funding has accelerated the development of the flexible test bench, taking the hardware from an estimated TRL 5 to TRL 9, as it has been fully integrated into beamline operations. In doing so, the project team has developed informal IP in electrochemistry. In the future, this test bench could be sold to other synchrotron accelerator facilities, representing revenue and export opportunities which are discussed below. Alongside the pouch cell stack and battery cyclers, the scientists also worked on implementing a standardised software interface, supporting widespread useability. The flexible software control platform, Bluesky, was adopted to control instruments throughout experiments using Python script, building expertise in API-controlled cyclers. Currently, the scientists are looking to further enhance the test bench with the addition of a robotic arm, which (whilst not funded directly by Hi-Acts) will support the automation of sample cycling and further enhance throughput at accelerator facilities in the future. These activities have already begun, and will be fully demonstrated over the next year (2025).

ENHANCED PERFORMANCE, THROUGHPUT, AND COST SAVINGS

The test bench enables unique operando tomography capabilities and achieves a threefold increase in experimental throughput, significantly reducing access costs to industry.

Imaging at synchrotron facilities, supported by this UCI-funded hardware, has the potential to bring significant value-add to industry compared to typical laboratory experiments. For instance, soft x-ray imaging techniques used at beamlines enable non-destructive monitoring of samples. This means that battery charging and discharging cycles can be fully assessed with lower radiation damage to the sample battery. In doing so, the performance of batteries can be explored in real time and conditions to understand internal processes and key failure mechanisms which contribute to battery degradation and safety risks. This means better, more resilient batteries can be developed from these insights.

The test bench can also increase experimental throughput, offering significant efficiency advantages in beamline measurements of batteries. The new test sample holder acts like a small assembly line for series measurements, meaning the process can be sped up significantly – more than 3 times faster relative to an experiment without the test bench. Compared to conventional electrochemical laboratory experiments, one measurement (which takes 2-3 hours in the laboratory), can take as little as 20 minutes at an accelerator, using the flexible test bench. Not only does this make experiments more efficient, but it also raises the appeal of accelerator-based battery research to industry. Access to beamtime is highly competitive and is priced conservatively at approximately €10,000 per day. However, the test bench can introduce cost savings in the tens of thousands of euros, with the exact figure depending on the number of measurements required in the experiment. With enhanced resolution, higher experimental throughput, and the ability to undertake operando measurements, the test bench could unlock new industry insights and innovation relating to battery performance, delivering unique capabilities and enhanced value for money to industry users.

INDUSTRIAL ENGAGEMENT AND BENEFITS TO INDUSTRY

Two confidential partners from the automotive sector have engaged with the project, reflecting wider industry interest.

As part of the first round of Hi-Acts UCI funding, the project began without a defined industry partner. However, there has been significant industry interest in the research breakthroughs unlocked by the test bench. For instance, the scientists have performed measurements for two large automotive companies (who cannot be named, for confidentiality reasons). These early engagements highlight the potential value of the technology in driving innovation in battery capacity and safety, especially with regard to EVs. For example, the test bench supports investigation of dendrite[2] buildups of lithium within batteries – a major cause of performance degradation and safety hazard in lithium-ion batteries. Dendrite buildups can potentially cause short circuits and fires, and are considered a key barrier in the commercial deployment of solid-state lithium batteries.[iii] The test bench enables 3D, non-destructive imaging of the chemical composition (including the materials, thickness, and density) inside a battery throughout a charging cycle. By unlocking measurement capabilities which show how dendrite buildups occur in real-time, the test bench could enable industry to develop safer and better performing batteries in the future, in turn enhancing their commercial viability.

COLLABORATIONS AND STRATEGIC POSITIONING

The UCI-funded activity has strengthened collaborations with accelerator facilities in France, Japan, and the UK, leading to enhanced visibility at the leading edge of tomography.

The project team implemented the test bench in experiments across other international synchrotron beamline facilities. Beyond beamlines at DESY and HZB, the test bench was trialled at Diamond Light Source (UK), Institut Laue–Langevin (ILL, France), and the Japan Proton Accelerator Research Complex (J-Parc). Hi-Acts funding has reinforced HZB's role as a key player in the European and international research landscape and underscores the widespread demand for enhanced battery characterisation.

Beyond its technical achievements, the project has contributed to HZB's visibility and international reputation as a leader in operando battery investigations. While HZB is already well-recognised globally, cooperation with other leading facilities has helped to demonstrate their expertise specifically in operando tomography experiments. The test bench, alongside the robotic arm and associated

[2] Dendrites are branch-like microstructures which form on electrodes, which can grow and create short circuits and fires.

software, also demonstrate HZB's pioneering role in enhancing the user interface for synchrotron accelerator research. By showcasing these capabilities internationally, the project supports standardisation and common approaches to experiments, which could further benefit industry uptake.

FOLLOW-ON COMMERCIALISATION POTENTIAL

The Hi-ACTS project has catalysed early commercialisation pathways for the project team, with several products and services currently being explored, including the test bench device, associated support services, and an AI Large Language Model (LLM) to support accelerator-based research.

Following successful demonstrations at other international accelerator facilities, there is potential for the battery test bench, robotic arm, and associated support services to be offered commercially to other facilities and research centres. These systems present an opportunity to create bespoke revenue and export opportunities. While still at an exploratory stage, the project team is currently investigating pathways to commercialisation, with indicative pricing estimated at €250k-300k per device. If the facilities which hosted demonstrations of this new technology purchased the test bench, this could catalyse approximately €750k to €900k in revenue exclusively from sales of the devices. Coupled with ongoing commercial support services for operations and maintenance, the prospect for revenues could be considerably higher. A continuation project is underway to further refine the system and its capabilities. If successful, this could lay the groundwork for commercial opportunities in the longer term, with HZB offering both the devices and associated support services commercially.

While not directly funded under the Hi-Acts project, the project team are also exploring pathways to develop and commercialise an LLM AI chatbot for researchers. Development of an LLM-supported consultancy is already underway, with a pilot demonstrator targeted for launch in September 2025. This development was linked to the project team's investigations into developing an automated and standardised user interface for synchrotron accelerator research, which could support the use of AI controlled measurements. The project team is developing this LLM-supported service to guide scientists and industry towards the most suitable beamlines for their research objectives, and to highlight other relevant research papers in the field. Like the test bench, this development is part of a wider strategy to make accelerator research more visible, accessible, and user-friendly to industry. Currently, the project team are training this model using publications produced at the BESSY beamline and have delivered promising initial results. This model is also scalable and could include a larger data set of open access papers from other international accelerator facilities. The project team are liaising with HZB's Department for Technology Transfer and Innovation to progress this concept, and intend to pursue future rounds of Hi-Acts funding. In the longer-term, the LLM-supported consultancy has the potential to generate significant licencing or subscription-based revenues.

GENERATING NEW SCIENTIFIC PUBLICATIONS

The project team are currently developing several (3 to 4) academic publications linked to the Hi-Acts funded activities, which will outline the results of the operando experiments through the project.

Whilst the project team focused on experimental demonstrations of the test bench concept through the duration of their project, they now intend to disseminate the findings of these activities to the scientific community. Currently, 3 to 4 scientific publications are in development, which are linked to Hi-Acts funded activities. These publications could raise visibility of the performance and throughput-related enhancements associated with the test bench to the wider research community, in turn bringing authoritativeness and recognition which could help raise industry awareness and uptake of accelerator-based battery research, supported by the test bench.

GERMAN COMPETITIVENESS AND SOVEREIGNTY IN BATTERIES AND THE AUTOMOTIVE SECTOR

The Hi-ACTS funding is relatively small-scale, but it contributes to innovation in strategically important sectors to the German economy, such as batteries and the automotive sector.

Though modest in scale, the development of the operando battery test bench and associated robotic arm represents a strategic contribution to Germany and Europe's battery sovereignty, which has key implications for Germany's automotive sector. China currently produces over 75% of batteries sold globally, which are approximately 30% cheaper than those made within the European Union.[iv] These cost advantages are a significant factor behind China's growing dominance in the EV market, as the cost of batteries represent between 25% to 40% of the total cost of an EV,[v] and Chinese automotive companies now account for over 50% of global EV production.[vi] In the context of a global energy transition to electrification, innovation in battery technologies is a core strategic factor influencing German competitiveness in EVs, and the automotive sector more broadly.

This pressure is compounded by regulatory shifts within the EU, with the European Commission and Parliament approving the adoption of 'Fit for 55' proposals to deliver the European Green Deal. This legislation states that cars and vans must be zero-emission by 2035, effectively phasing out new internal combustion and hybrid vehicles.[vii] This is expected to significantly increase demand for lithium-ion batteries, with the European Commission expecting battery production capacity in the EU to grow from 44GWh in 2020 to 1200GWh by 2030 - a more than 25-fold increase.[viii] If European supply does not meet this projected demand, this could introduce challenges to battery sovereignty. In turn, this risks undermining German automotive competitiveness in the transition to EVs, alongside public support for the 2035 mandate and the energy transition required to tackle the climate crisis.

Germany - home to globally leading automotive companies such as Mercedes-Benz, BMW, Volkswagen, Porsche and Audi - must expand battery innovation and production capacity to remain competitive in the global EV market. In a landscape shaped by scale, speed, and technological agility, the capacity to develop safer and better performing batteries, and bring them to market, will be crucial to compete. The operando test bench, while a focused research effort, is an essential tool for enabling earlier, faster, and more accurate insights into battery behaviour in realistic conditions. By embedding advanced diagnostic capabilities and automation into Germany's accelerator research infrastructure, the test bench could unlock innovation in battery technology, strengthen national sovereignty in battery technology, and support the long-term competitiveness of the battery and automotive sectors.

ATTRIBUTABILITY OF THESE BENEFITS TO HI-ACTS FUNDING

Hi-Acts UCI funding was central in developing the test bench, including the pouch cell stack and cyclers. These core technologies have been developed in parallel with broader advancements achieved during this project, including progress in software development to create a user-friendly interface with the potential for future AI integration. The project team highlighted how without UCI funding, this project would have faced significant delays and may have been less aligned to the needs of industry, potentially limiting the benefits associated with industry engagement.

The robotic arm (which brings additional throughput enhancements) is not directly funded under this project, and costs approximately €20k. Whilst strongly interlinked with the test bench, this means future automation benefits are not solely attributable to UCI funding. Likewise, early progress in the LLM is linked to the project, but is also influenced by wider activities at HZB. Moreover, whilst the test bench is a valuable tool for driving innovation in battery diagnostics, there are wider political and

economic factors driving trends in the global battery market and automotive and energy sectors. The test bench could be a valuable disruptor to the industry status quo, but further project continuation will be needed to fully realise more significant commercial and strategic benefits to these sectors.

IMPACT SUMMARY

Test Stand for Operando Battery Investigation

Organisation	Industry	Society
Technical: • TRL progression: raised test bench maturity from TRL 5 to 9, demonstrating real -time 3D in-situ battery measurements under realistic (while charging) conditions • Python programmable software implemented to simplify user interface and enable AI integration **Competitiveness and Reputation:** • International partnerships: strengthened through demonstrations at 3 accelerator facilities (Diamond, ILL, J -Parc), showcasing HZB leadership in operando tomography • Partnerships with industry: links with 2 automotive companies developed/strengthened through the project **Commercial:** • Cost savings: provides 3 times faster experimental throughput, saving industry users €10,000s per experiment • New products / services: devices (priced at ~ €250 -300k) and consultancy support have export potential, spin out opportunities include an LLM chatbot for accelerator research **Science and Knowledge:** • Research output: 3 -4 publications currently in development • New informal IP developed in API controlled cyclers	The test bench could help drive innovation in the German battery industry, crucial for retaining global leadership in the automotive sector in the global energy transition. Relevant for: • Economy • Knowledge & Technology • German / European Competitiveness, sovereignty & resilience • Improved attractiveness of the local area / Germany / Europe for investment • Regulation & policy -making • Entrepreneurship & innovation	By supporting measurements of failure modes, the test bench is a crucial tool in discovering structural changes within batteries as they charge. These discoveries could improve the performance of batteries, while also making them safer and more reliable. Relevant for: • Scientific knowledge • Environment & sustainability • National security & safety

Granularity of evidence

Attribution to UCI support

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