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

Final Report for Hi-ACTS

FINAL REPORT

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August 2025

CONTENTS

INTRODUCTION

Established in 2022, Hi-Acts brings together several Helmholtz Centres[1] to expand access to accelerator-based technologies for industry, science, and society. Its goals include improving industrial access, developing market-ready solutions in areas such as medicine and energy, and optimising accelerator systems for diverse applications. As part of the Helmholtz association, which is ranked 2nd in Germany and 14th worldwide in the *Nature Index*[2], Hi-Acts builds on a strong scientific foundation to advance accelerator innovation.

A core element of Hi-Acts is the Use Case Initiative (UCI), an annual funding programme designed to strengthen industry collaboration. UCI projects address short-term R&D or production challenges aligned with Hi-Acts' broader objectives. They focus on advancing accelerator-related technologies or methods to meet industrial needs such as cost-efficiency and reliability. Funding ranges from €20,000 to €150,000 per project, funded from UCI's annual budget of €500,000 and includes a one-year implementation timeline from 2023 to 2025; this will be followed by a €950,000 annual budget from 2026 onwards.

Eligible UCI projects must improve accelerator-based setups, target high-impact industrial applications, or enhance service offerings. They may also foster stronger communication and knowledge exchange between science and industry. Projects must demonstrate measurable impact and may also lead to increased industry funding, co-financing, or licensing agreements.

Hi-Acts and the UCI aim to bridge cutting-edge research with industrial innovation. It is therefore essential to assess the socio-economic benefits of funded activities, in order to track and improve programme performance. To support this, Hi-Acts commissioned **know.**space to conduct a pilot project, developing and testing a framework for assessing the socio-economic impact of selected UCI projects. This pilot study has produced four case studies based on the 2023 UCI cohort, presenting robust quantitative and/or qualitative evidence in a concise, visual, and accessible format. Findings from this project will feed into the Hi-Acts platform evaluation scheduled for September 2025.

METHODOLOGY

During the inception phase of the study, we developed an initial analytical framework based on secondary research (i.e., evidence review and desk-based research). This framework was designed to capture socio-economic benefits of selected UCI activities across different levels (i.e., organisational, industry, societal) and impact areas (e.g., commercial, technical, jobs & skills, competitiveness & reputation, and scientific & knowledge) – see To capture organisation-level impacts, we have developed a comprehensive list of indicators, including both quantitative and qualitative metrics to support clear and consistent assessment. Since the relevance of specific indicators depends on the nature of each case study, impact is not expected to be observed across all indicators in every case. For each case study, a tailored subset of relevant indicators is selected from the comprehensive list.

We have also defined higher-order impact areas of inquiry at the industry- and societal-level to account for broader effects beyond impacts for organisations. These areas reflect wider value while maintaining a realistic view of attribution, ensuring clarity and avoiding overstatement.

[1] DESY, HZDR, GSI, Helmholtz-Zentrum Hereon, HZB

[2] Nature Index. 2025. Institution Tables. Available at: https://www.nature.com/nature-index/institution-outputs/generate/all/countries-Germany/all

Figure 1.

To capture organisation-level impacts, we have developed a comprehensive list of indicators, including both quantitative and qualitative metrics to support clear and consistent assessment. Since the relevance of specific indicators depends on the nature of each case study, impact is not expected to be observed across all indicators in every case. For each case study, a tailored subset of relevant indicators is selected from the comprehensive list.

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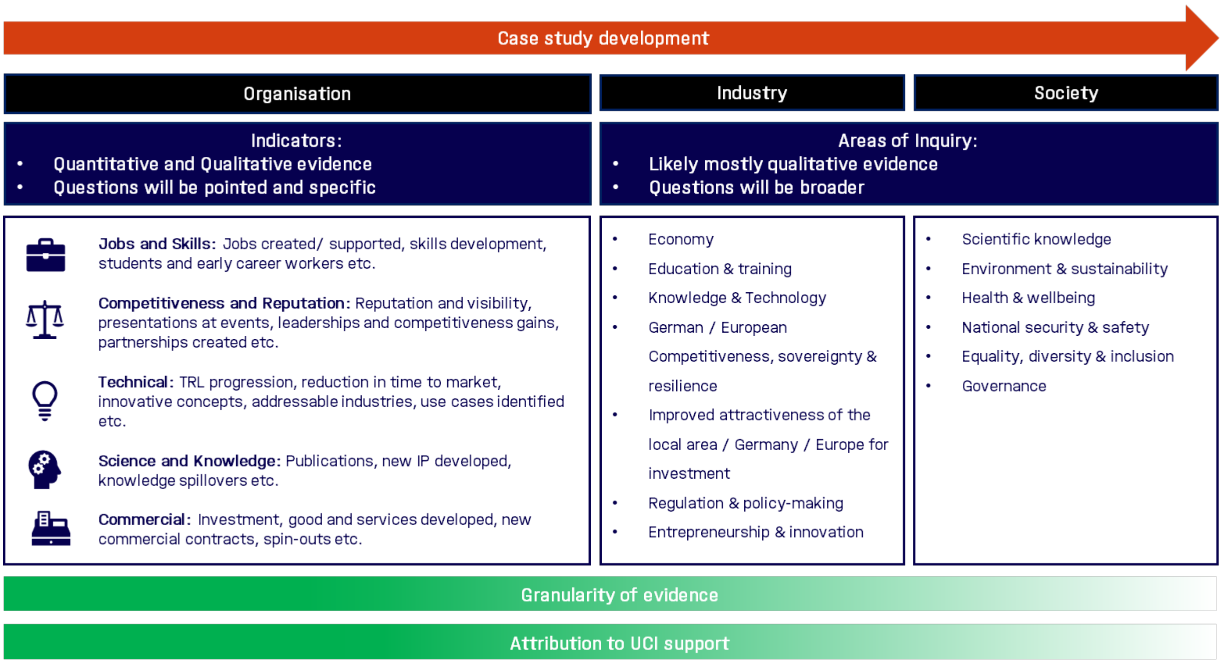
Figure 1: Indicators and areas of inquiry schematic



Source: know.space

Leveraging the framework, we conducted semi-structured interviews with key stakeholders, including Innovation Managers, project scientists and industry partners, to gather primary data to inform the indicators and areas of inquiry. Insights from secondary research and interviews were then thematically synthesised to build an evidence base for each benefit type. We have quantified impacts where feasible, and otherwise providing robust qualitative assessments. Findings were presented both in detailed case study reports and in accompanying infographics that visually and concisely highlight key insights.

Two initial case studies were developed as pilots to test and refine the framework, incorporating feedback from Hi-Acts. Lessons learned from these pilots informed the following two case studies and minor revisions to the framework, to ensure that it is fit-for-purpose and usable beyond the life of the study.

CASE STUDY 1: HIGH-THROUGHPUT PHARMACEUTICAL SCREENING AT ROOM TEMPERATURE

ACCELERATING EARLY-STAGE DRUG DEVELOPMENT…

Public health resilience depends on our ability to respond rapidly to emerging and re-emerging diseases, as highlighted during the COVID-19 pandemic. There is an urgent need for faster development of drugs, especially for underfunded or neglected infectious diseases[i]. Structural insights into protein-ligand interactions are crucial for drug discovery, with macromolecular X-ray crystallography remaining a cornerstone technique in identifying and optimising potential therapeutics.

The High-throughput Pharmaceutical X-ray screening instrument (HiPhaX) was developed at DESY[3] in 2021 to meet the growing demand for high-throughput pharmaceutical screening. It is located at the PO9 beamline at DESY PETRA III[4]. HiPhaX is a valuable tool for drug discovery, helping scientists quickly test thousands of potential medicines against disease-related proteins. Unlike traditional methods, it does not just confirm whether a drug binds, but shows exactly how it interacts at the atomic level, making it easier to design more effective treatments. Designed for full automation, HiPhaX aims to deliver over 1,000 structure determinations per day and ultimately provide fully autonomous data collection and analysis, speeding up early-stage drug development. It can operate at both ultra-cold and room temperatures, allowing for a wide range of experiments.

… THROUGH UCI-FUNDED HARDWARE ENABLING HIGH-THROUGHPUT ROOM TEMPERATURE SCREENING, A GLOBALLY UNIQUE CAPABILITY

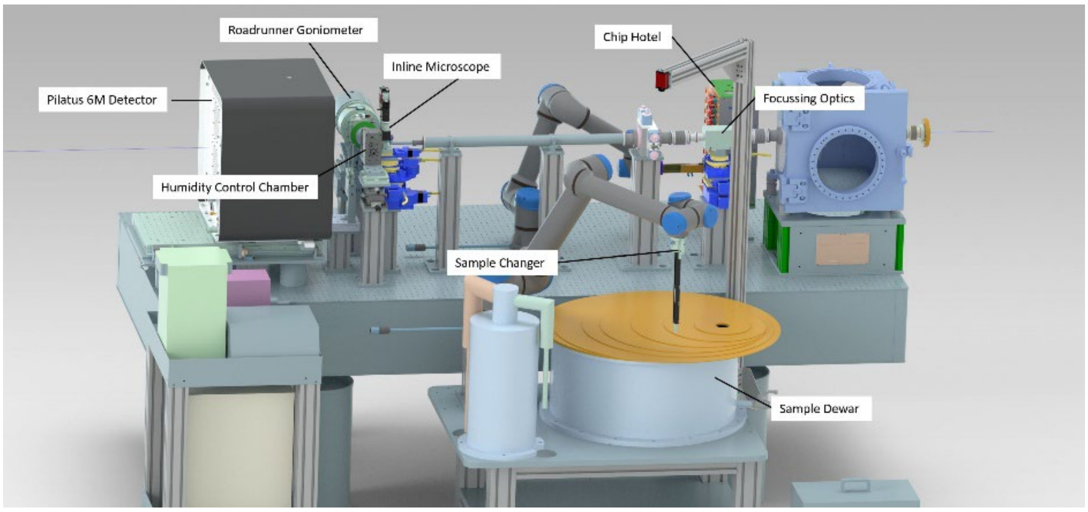
To enable room-temperature capability in the HiPhaX instrument, the 'High-throughput pharmaceutical screening at room temperature' activity received €60,000 in funding from Hi-Acts' Use Case Initiative (UCI). This was used to develop a measurement chamber with humidity and temperature control and a robotic arm for automatic sample exchange. The project sought to design a fragment screening beamline for rapid screening at physiologically-relevant conditions with applications in structure-based drug development. The 8-month long activity was led by DESY (specifically by the FS-CFEL-1-BMX research group, which focuses on advancing automated, high-throughput methods for structural biology and drug discovery), with Suna-Precision GmbH (a DESY spin-out organisation supplying hardware for serial crystallography, imaging systems and sample environments and handling) as an industry partner, concluding in late 2023.

The UCI-funded hardware developed enables faster, more cost-effective investigation of biologically relevant protein crystals (e.g., from viruses or bacteria) in combination with potential drug compounds. As room temperature more closely reflects physiological conditions, it may reveal biologically-relevant structural states obscured at cryogenic temperatures – an area still at the cutting edge of structural biology. The instrument's fully automated operation supports high-throughput screening, while room-temperature capability simplifies sample handling compared to cryogenic methods. All planned

[3] Deutsches Elektronen-Synchrotron (DESY) is a premier German research institute specialising in particle accelerator technology and fundamental investigations into the structure and behaviour of matter.
[4] PETRA III is a high-brilliance synchrotron X-ray source at DESY in Hamburg, used for cutting-edge research in fields like materials science and biology. In this context, a beamline is the path along which synchrotron-generated X-rays travel to experimental stations for scientific investigation.

technical developments have successfully been completed, with next steps focusing on refining the software to enhance automation capabilities and AI-supported analysis.

Figure 2: HiPhaX experimental hutch overview



Source: DESY

Further developments to the HiPhaX instrument are planned. The addition of a sample dewar[5] holding up to 860 samples will enable near-continuous 24-hour data collection for cryogenic samples. A SampleDB-based database (developed by Helmholtz Center FZ Jülich) is also being implemented to support full automation.

The performance of the HiPhaX instrument is influenced by the frame rate of the Pilatus 6M detector, which affects fast X-ray centring and high-speed serial data collection. Enhancing its capabilities would involve incorporating a faster detector and refining X-ray optics to increase flux at the sample, though implementing these improvements would require additional funding beyond the original UCI support.

This activity supported by Hi-Acts UCI has already resulted in benefits for the organisations involved, and is anticipated to contribute to industry- and society-level impacts, as explored in the following sections.

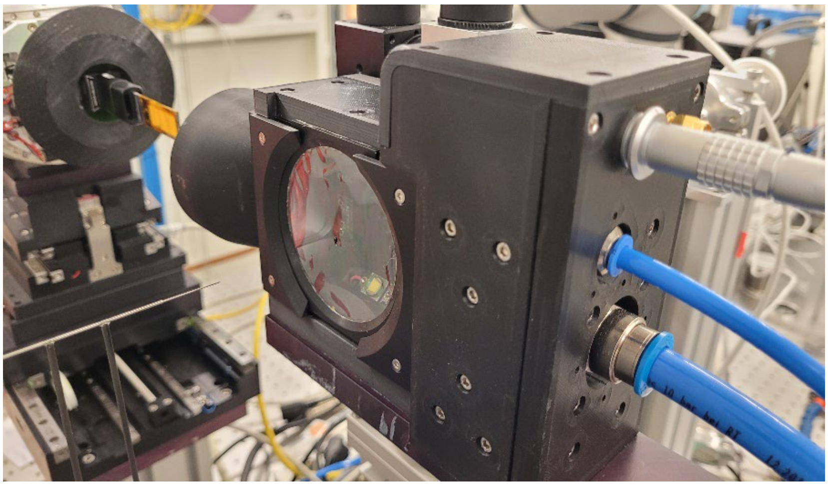
TECHNOLOGY MATURITY PROGRESSION

Hi-Acts UCI funding has enabled the technology maturity progression of critical hardware of the HiPhaX instrument, from Technology Readiness Level (TRL) 7 to TRL 9, with the equipment now operational.

Hi-Acts UCI funding has enabled technology maturity progression, from an estimated TRL 7 to TRL 9. The hardware is now fully integrated into the operation of the beamline, along with a room temperature storage container (funded by an alternative source). The science team highlighted that the equipment is operational, used regularly, and is working reliably.

[5] A dewar is a container designed to maintain the temperature of its contents, in this case, at cryogenic temperatures.

Figure 3: Sample and environmentally controlled measurement chamber



Source: DESY

Temperature and humidity stability and accuracy exceed the baseline requirements (+/- 0.5 % rH and +/- 0.1°C), which is critical to producing relevant and reliable measurement results. This allows multi-dimensional crystallography experiments to be conducted, to study protein flexibility and conformational space under varying external conditions. Fully remote and automated operations are also now possible, which is particularly beneficial, as it enables high throughput. The science team highlighted that one sample can now be measured in 1 to 2 minutes, significantly faster than the 10 to 15 minutes required prior to automation. This represents a reduction in measurement time of up to 93% (i.e., up to 15 times faster). The development of this technology thus presents an opportunity for significant benefits to DESY and the German industry, the magnitude of which will depend on user uptake. Room-temperature crystallography is a globally unique capability, positioning DESY as a leader and establishing German sovereignty in this field.

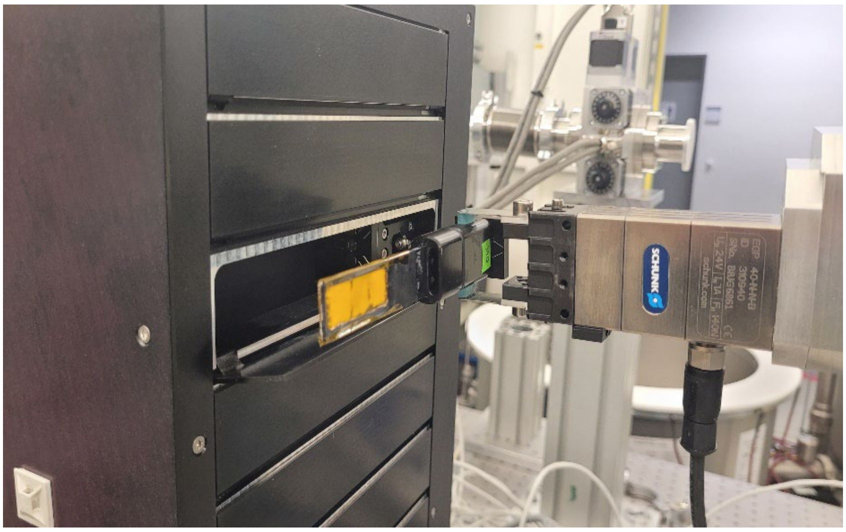
SCIENTIFIC BREAKTHROUGHS

HiPhaX, equipped with UCI-funded hardware, has already delivered key scientific breakthroughs, contributing to building public health resilience by accelerating drug development and reducing costs.

The HiPhaX instrument, leveraging the hardware developed through this UCI-funded activity, has already enabled several scientific breakthroughs in its first three years. The science team advanced fixed-target serial crystallography to enable high-throughput fragment screening at room temperature (RT), systematically comparing results with conventional cryogenic single-crystal data for ‘FosAKP’, an antibiotic resistance-related enzyme. RT serial crystallography achieved 1.5 Å resolution[6], comparable to cryogenic methods and significantly better than RT single-crystal data (1.9 Å). This approach revealed a previously unobserved active-site conformation, offering new starting points for drug design. By uncovering structural features that are likely to be functionally relevant under physiological conditions, this work provides critical insight into how resistant enzymes adapt, and opens a path to developing inhibitors capable of overcoming antibiotic resistance in high-priority pathogens. For the seven ligands identified at both temperatures, binding modes remained unchanged. While more binders were detected at cryogenic temperatures, these were mostly at physiologically less-relevant sites. The ability to access alternative protein conformations through RT serial crystallography, especially when combined with HiPhaX automation, can enhance drug development by expanding the conformational space available for screening.

[6] Ångström (Å): A unit of length used to express molecular dimensions. 1 Ångström equals 10^{-10} metres or 0.1 nanometres.

Figure 4: Gripper tool moving sample from the room temperature storage container



Source: DESY

The science team also conducted experiments focusing on protein dynamics. They investigated protein conformational changes through controlled modulation of relative humidity and temperature. Lysozyme data at 1.4 Å resolution revealed water network changes and an active-site peptide flip. Additionally, user experiments explored the effects of relative humidity on the 2'-5'-Oligoadenylate synthetase 1 (OAS1) enzyme, which belongs to a family of essential proteins involved in the innate immune response to viral infections. Findings revealed the significant role of hydrodynamic effects in modulating enzymatic function under conditions of changing relative humidity. These experiments provide critical insight on protein flexibility in crystal structures, essential for the effective development of drugs.

The scientific breakthroughs enabled by the HiPhaX instrument can play a pivotal role in enhancing resilience to (re-) emerging diseases[7], ultimately driving down costs and saving lives[8] by accelerating drug development and improving therapeutic outcomes [ii,iii,iv].

NEW SKILLS, KNOWLEDGE, AND TECHNOLOGY TRANSFER

Developing the environment-controlled chamber and robotic arm has built new skills within the science team, while also facilitating knowledge and technology transfer across DESY and to international partners.

The UCI-funded activity has enabled the upskilling of all three senior individuals involved as part of the scientific team. They acquired valuable technical skills associated with the development of innovative precise temperature control processes to meet the demanding requirements of the technology.

The knowledge and experience acquired in room temperature fixed-target serial crystallography is being transferred to other parts of DESY and US-based SLAC National Accelerator Laboratory (SLAC), as part of a Helmholtz Institute-funded activity focusing on serial-femtosecond crystallography (SFX) experiments. This work, carried out at the European XFEL (X-Ray Free-Electron Laser Facility) and SLAC, depends on competitive beamtime access. The technological

[7] The World Health Organization (WHO) released an updated list of (re-) emerging pathogens with epidemic and/or pandemic potential in 2024. It can be consulted here.

[8] For example, the indirect costs associated to the COVID-19 pandemic constituted 10.53% of the global GDP. The WHO highlights that over 7 million COVID-19 deaths were reported globally.

developments and pre-tests conducted with HiPhaX have been crucial in enabling this follow-on activity, particularly due to the instrument's high-throughput capability. Future plans include expanding collaboration with XFEL facilities to support sample pre-testing, delivery, and training for users and beamline staff.

Additionally, the UCI-funded hardware is also being leveraged for the experiments ran under a follow-on international collaboration (explored in more detail below) and in the field of catalysis. The robotic arm device drivers have been transferred to PETRA III Beamline 65, which uses the same robot, and will be extended to additional beamlines in the future.

Hi-Acts UCI funding has fostered the development of new skills, valuable knowledge, and technology transfers within DESY and beyond, both nationally and internationally. This highlights that the funding's impact footprint reaches beyond the direct contractors and application domains. It also strengthens the science team and DESY's technological leadership in the field.

VISIBILITY AND REPUTATION

The UCI-funded activity has raised the profile of the hardware and highlighted the advantages of the room-temperature screening technique.

While DESY and the research team are already well-recognised globally, the UCI-funded activity has significantly increased visibility for the hardware developed and the benefits of room-temperature macromolecular synchrotron X-ray crystallography. Presentations at numerous conferences have raised awareness of these innovations and the new capability now available.

Further work is needed to enhance industry's understanding of the added value of this measurement technique, though the science team anticipates that their upcoming high-profile publications in *Nature Communications* and *Science* will help demonstrate the hardware and concept, building confidence for commercial end users, and fostering uptake.

FOLLOW-ON COLLABORATION

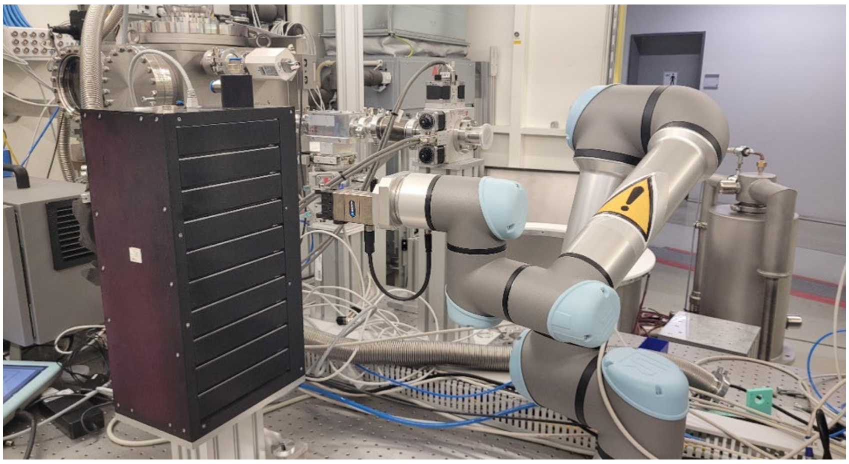
The development of the enabling hardware has resulted in follow-on international collaboration, driving innovation in structure-based drug discovery to enhance resilience against outbreaks, saving lives and reducing costs.

Hi-Acts UCI funding has directly led to a follow-on international collaboration with eight partners (through a Block Allocation Group, BAG), including the University of Hamburg (Germany), DESY (Germany), the Centre for Structural Systems Biology (Germany), the University of São Paulo (Brazil), the Hanover Medical School (Germany), and the Brazilian Synchrotron Light Laboratory (Brazil). The science team had worked with some of these organisations before, though around half of them were new partners. This work is funded by the German Federal Ministry of Research, Technology and Space (BMFTR) and leverages the equipment developed for structure-based drug discovery, focusing on emerging diseases as well as existing diseases that scientists regard as being underfunded in pharmaceutical research.

Sub-projects within this framework target diverse scientific goals. Three explore new starting points for antiviral drug development against influenza A (i.e., H5N1, a highly virulent strain with pandemic potential). Others focus on fundamental research into magnetoreception and pathogen defence mechanisms in humans and bacteria. Additional efforts aim to establish a Ca^{2+}-dependent enzyme as a benchmark for time-resolved mix-and-diffuse serial crystallography and to extend basic room-temperature measurements at HiPhaX to time-resolved studies. Under this framework, one experiment has successfully been concluded to date (with Prof. Dr. Matthias Rarey's group of the

University of Hamburg), targeting the Lassa virus (LASV), an arenavirus that causes Lassa haemorrhagic fever in humans and primates.

Figure 5: Robotic arm approaching the sample container



Source: DESY

The science team is also collaborating with the Centre for Bioinformatics at the University of Hamburg on a joint BMFTR-funded project focused on developing AI-based software for automated ligand hit identification and position refinement from electron density maps. In addition to full automation, this will save the time typically spent manually identifying ligands across hundreds or thousands of datasets, increasing the speed of screening.

As an enabling equipment of these follow-on collaborations, the UCI-funded hardware is contributing to cutting-edge research in structure-based drug discovery, which could enhance resilience to future outbreaks, saving lives and minimising economic costs. Being able to collaborate with leading research institutes globally is also an opportunity to build new partnerships, strengthen existing ones, and benefit from knowledge transfers, overall fostering innovation.

COMMERCIAL POTENTIAL

The HiPhaX instrument, equipped with UCI-funded hardware, offers significant value for research and industry, with strong revenue potential. High uptake could lead to the creation of a spin-out organisation to support commercialisation.

The HiPhaX instrument can be valuable for both research and industry customers, and is now accepting users for pharmaceutical screening experiments with both conventional cryo-crystallography and room temperature serial-crystallography. Several research institutions, especially based in Germany, have already been using the UCI-funded hardware, notably as part of the follow-on international collaboration highlighted earlier. Members of the BioMAX group at the MAX IV Laboratory (Sweden) have also been conducting humidity studies at room temperature using the equipment developed. This is helping build heritage for this capability and demonstrate its effectiveness and benefits to a wider customer base.

Another anticipated customer group is the measurement service providers for pharmaceutical companies. Pharmaceutical companies directly could also constitute a customer segment, though service providers are more likely. Cryogenic macromolecular synchrotron X-ray crystallography is the current status quo, meaning that the benefits of the room temperature equipment developed will have to be convincingly demonstrated to trigger a change in processes for these customers. As highlighted previously, the science team anticipates that this will be achieved through the dissemination of the three articles currently in the publication process for prestigious journals. However, as highlighted earlier, while the Pilatus 6M detector used in the equipment developed still offers high performance, it is not state-of-the-art, which could potentially deter some industry customers.

There is a notable revenue potential for this equipment. According to the science team, the market rate price to measure one cryogenic sample at a synchrotron facility in Europe is around €50. To encourage a shift toward room-temperature macromolecular synchrotron X-ray crystallography and increase adoption, we explored, for illustrative purposes, a cost-competitive pricing model of €35 per sample. Under this conservative hypothetical scenario, processing 1,000 samples (i.e., in 1 day with this new equipment) would generate €35,000 in revenue. However, due to high operating costs, profit margins are expected to remain low – estimated at only a few percent. Assuming a conservative 3% margin, the resulting profit would be approximately €1,050 per day. The science team indicated that if uptake is high, a spin-out organisation could be created to support commercialisation endeavours.

PUBLIC HEALTH RESILIENCE

The UCI-funded HiPhaX hardware helps accelerate drug development for high-risk and underfunded diseases, contributing to saving lives and reducing the considerable economic burden of future pandemics.

By enabling high throughput screening at room temperature, the hardware developed with UCI funding is contributing to speeding up the development of effective drugs. As noted, follow-on projects leveraging the equipment are principally focused on (re-) emerging and underfunded diseases, areas where rapid therapeutic development is critical for global health preparedness and resilience.

These diseases, such as pandemic-prone viruses or neglected tropical infections, can place significant strain on healthcare systems and economies. For example, in Germany alone, the COVID-19 pandemic[9] resulted in economic losses amounting to €330 billion over 2020 and 2021, representing approximately 10% of the country's 2019 GDP[v]. Across the European Union, the pandemic led to a 6.1% contraction in GDP in 2020[vi]. The ability to accelerate early-stage drug development not only helps save lives but also reduces the long-term economic burden associated with delayed treatments, containment efforts, and healthcare costs. In this way, the HiPhaX instrument, and its UCI-funded hardware, support both public health and economic resilience, contributing to the United Nations' Sustainable Development Goals[10].

ATTRIBUTABILITY OF THESE BENEFITS TO HI-ACTS FUNDING

Hi-Acts UCI funding was critical in enabling the development of the measurement chamber with controlled temperature and humidity, as well as the robotic arm for automatic sample exchange as part of the HiPhaX instrument. The science team noted that securing funding for this hardware elsewhere would have been challenging, although they did obtain alternative DESY internal funding for the room temperature storage container, which was initially included in the UCI proposal but ultimately not funded. They highlighted that they could have accessed resources through a larger project, but those are more complex to design and more difficult to fund, as they typically require larger budgets.

[9] DESY's PETRA III X-ray source contributed to research on improving RNA vaccines, specifically supporting BioNTech's development efforts for the BioNTech-Pfizer COVID-19 vaccine. Further details can be found here.

[10] Notably Goal 3 (Ensure healthy lives and promote well-being for all at all ages), Goal 8 (Promote sustained, inclusive and sustainable economic growth), and Goal 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation).

UCI thus provided a rapid and flexible funding source to develop this enabling hardware. Most of the benefits outlined in the previous sections would consequently not have occurred without UCI support, notably the follow-on collaborations and scientific breakthroughs. Wider societal impact, such as accelerating the development of effective therapeutics (including those targeting antibiotic-resistant pathogens) and the subsequent strengthening of public health resilience, remain contingent on the broader uptake of room temperature measurement techniques, sustained research investment, and coordinated efforts across the drug development pipeline.

While the UCI-funded hardware represents an essential enabling step, it is important to note that realising its full impact will depend on many additional scientific, funding and policy factors.

IMPACT SUMMARY

High-Throughput Pharmaceutical Screening at Room Temperature

DESY / Suna-Precision	Industry	Society
Competitiveness and Reputation: • Partnerships: new follow-on collaborations (including internationally) • Visibility: raised profile of the hardware and highlighted the advantages of the room-temperature screening technique **Technical:** • TRL progression: TRL 7 to TRL 9 (hardware operational) • Reduction in measurement time of up to 93% (i.e., up to 15 times faster) • Addressable industries: pharmaceuticals, catalysis • Technology transfers: hardware being used by other teams across DESY, German research organisations, and international partners (Brazil, USA) **Science and Knowledge:** • Publications: 3 in progress (Nature Communications, Science) • Supported scientific breakthroughs for (re-) emerging diseases • Skills: development of innovative precise temperature control processes **Commercial:** • Revenue: significant commercial potential, with anticipated profits of ~€1,000 per day of beamline access • Spin-out: possible creation of a new organisation to support commercialisation endeavours	Accelerates the development of effective drugs for (re-) emerging diseases. Relevant for: • Economy • Knowledge & Technology • German / European Competitiveness, sovereignty & resilience • Improved attractiveness of the local area / Germany / Europe for investment • Regulation & policy-making • Innovation	Increased public health resilience to (re-) emerging diseases, contributing to lower economic costs and mortality. Relevant for: • Scientific knowledge • Health & wellbeing • Governance

Granularity of evidence

Attribution to UCI support

[i] WHO (2025). *World Health Statistics 2025*. Available from: https://iris.who.int/bitstream/handle/10665/381418/9789240110496-eng.pdf?sequence=1

[ii] Faramarzi, et al. (2024). *The global economic burden of COVID-19 disease: a comprehensive systematic review and meta-analysis.* Systematic Reviews 13, 68. https://doi.org/10.1186/s13643-024-02476-6

[iii] WHO (2025). *Number of COVID-19 deaths reported to WHO (cumulative total).* Available from: https://data.who.int/dashboards/covid19/deaths

[iv] WHO (2024). *Pathogens Prioritization – A scientific framework for epidemic and pandemic research preparedness*. Available from: https://cdn.who.int/media/docs/default-source/consultation-rdb/prioritization-pathogens-v6final.pdf?sfvrsn=c98effa7_7&download=true

[v] ifo Institute (2022). *Coronavirus Pandemic Caused EUR 330 Billion in Economic Losses for Germany*. Available from: https://www.ifo.de/en/press-release/2022-02-17/coronavirus-pandemic-economic-losses-germany

[vi] European Parliament (2022). *How have major economies responded to the COVID-19 pandemic?*. Available from: https://www.europarl.europa.eu/RegData/etudes/STUD/2022/699531/IPOL_STU(2022)699531_EN.pdf

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

DESY. HZDR GSI hereon HZB Helmholtz Zentrum Berlin

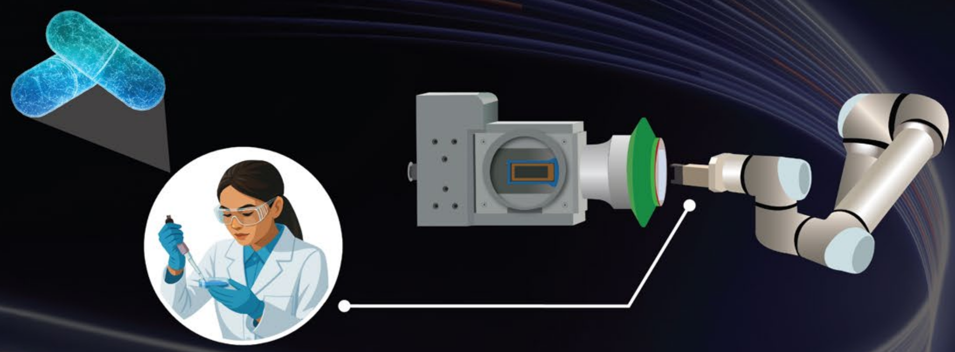
HIGH-THROUGHPUT PHARMACEUTICAL SCREENING AT ROOM TEMPERATURE

PIONEERING NEW MEASUREMENT TECHNIQUES TO FACILITATE THE DEVELOPMENT OF DRUGS AGAINST NEW & UNDERFUNDED DISEASES

Hi-Acts UCI funding enabled critical hardware development for the HiPhaX instrument, allowing groundbreaking automated room-temperature testing to accelerate early-stage drug development, while fostering collaborations, powering cutting-edge science, and strengthening pandemic resilience.

ORGANISATION • FIRST-MOVER ADVANTAGE FOR A GLOBALLY UNIQUE CAPABILITY

- Developed a temperature- and humidity-controlled measurement chamber and a robotic arm, progressing from **TRL 7 to TRL 9**
- **Upskilled team** in innovative precise temperature control processes
- **Unlocked revenue potential** across research and industry
- 3 publications in **high-profile journals** (*Nature Communications and Science*)



INDUSTRY • BENEFITING WIDE-RANGING STAKEHOLDERS

- Catalysed a **follow-on international collaboration**, building strong partnerships
- Led to **knowledge and technology transfers** within DESY, and with German and international research organisations
- Enabled users to conduct high-throughput room temperature experiments, leading to **scientific breakthroughs** and building visibility and heritage for both room-temperature testing and the hardware

SOCIETY • SIGNIFICANT PUBLIC HEALTH IMPACT

- **Speeding up** testing up to 15 times, accelerating the development of effective drugs
- **Strengthening public resilience** to emerging and underfunded diseases, saving lives and reducing economic costs

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CASE STUDY 2: WAFER-SCALE CMOS TECHNOLOGY FOR ROOM-TEMPERATURE EXTENDED SHORT-WAVE INFRARED GESN PHOTODETECTORS BASED ON ION IMPLANTATION AND FLASH LAMP ANNEALING

INFRARED PHOTODETECTORS ARE VALUABLE FOR MANY DOMAINS OF MODERN TECHNOLOGY...

Infrared imaging plays a crucial role across many sectors, including healthcare, transportation, and environmental monitoring - ultimately enhancing the safety, efficiency, and security of modern life. Short-wave infrared (SWIR) photodetectors are an important technology that enable infrared imaging in the SWIR wavebands. For example, SWIR imagery enhances visibility in poor conditions such as fog, making it a valuable component for Light Detection and Ranging (LiDAR) for vehicle safety.[vii] It can also be leveraged for remote sensing and soil monitoring, supporting valuable applications in agriculture and more general environmental and sustainability efforts.

Complementary Metal-Oxide-Semiconductor (CMOS) is the standard technology used to manufacture microchips, forming the foundation of nearly all modern electronics. Due to this, well-established, large-scale manufacturing processes and infrastructure already exist to produce CMOS-compatible devices. Today, SWIR photodetectors[11] are often made from semiconductors such as indium gallium arsenide (InGaAs) and indium antimonide (InSb) as they can be tuned to detect specific wavelengths with high sensitivity. These, however, are *not* CMOS-compatible. As a result, their production cannot take advantage of the standard CMOS manufacturing infrastructure and instead relies on expensive, specialised processes. Therefore, CMOS-compatible SWIR photodetectors, made from materials that align with the silicon-based components used in CMOS technologies are advantageous, as they can be manufactured using standard CMOS processes and facilities. The compatibility also enables the integration of photodetectors and the electronics (like amplifiers or processors) on the same chip.

... AND HI-ACTS FUNDING HAS ENABLED THEIR DEVELOPMENT TO INDUSTRY STANDARD SIZE

Helmholtz-Zentrum Dresden Rossendorf (HZDR) is a Dresden-based research facility focused on health, energy and matter. Under the Hi-Acts Use Case Initiative, HZDR's Semiconductor Materials department received €89,000 in funding to scale-up its in-house CMOS-compatible technology.

This project built on HZDR's pre-existing in-house CMOS-compatible photodetector technology. The institution's approach, which was a first-of-a-kind innovation, used ion implantation and flash lamp annealing[12] to alloy Germanium-Tin (GeSn), creating a 10mm x 10mm CMOS GeSn photodetector (the standard size for research purposes).

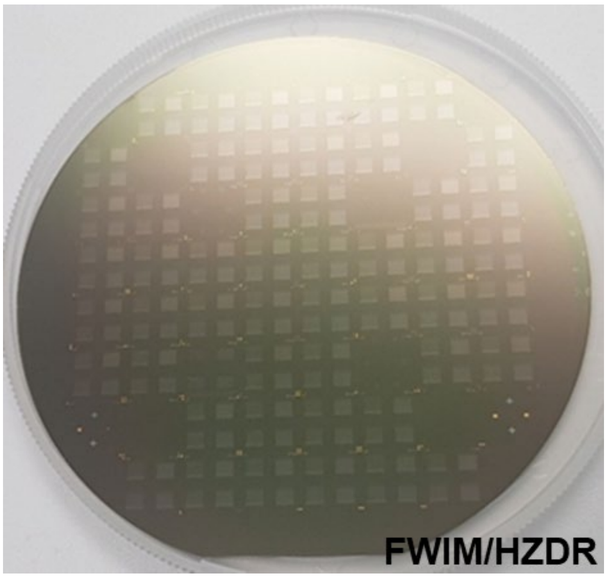
The aim of the 8-month long Hi-Acts project was to scale 10mmx10mm single photodetector fabrication process to a lateral array of photodetectors on 3-inch commercial wafers. This scaling enables cost-effective mass-produced GeSn SWIR photodetectors for industry, supporting

[11] Hereafter referred to as 'photodetectors'.

[12] Ion implantation combined flash lamp annealing is a non-equilibrium technique used to introduce impurities into semiconductors at concentrations higher than their natural solubility limit.

manufacturing efficiency and affordability across the wider semiconductor value chain - from sensor manufacturers to end users.

Figure 6: 3-inch GeSn wafer with array of SWIR sensors



Source: HZDR

TECHNOLOGICAL INNOVATION

High-acts funding has enabled technological innovation, raising the technology maturity from Technological Readiness Level (TRL) 3 to TRL 4, by further refining highly innovative processes for wafer development.

Over the course of the project, HZDR progressed the GeSn wafers from TRL 3 to TRL 4. This indicates a shift from proof-of-concept to laboratory testing to validate the feasibility of a 3-inch GeSn wafer. This progress involved scaling up HZDR's novel ion implantation and flash lamp annealing process for GeSn alloying, from a 10mm x 10mm photodetector to a 3-inch wafer, pushing the limits of the already innovative technique.

This success helps position HZDR as a pioneer in the integration of photonics and CMOS technology. Demonstrating scalability is a key step toward commercialising the CMOS technology, proving that a lab-scale innovation can be adapted to industry-standard sizes and brought to market. In doing so, it also enables industry to unlock the benefits of efficient production and lower energy usage associated with CMOS-compatible photodetectors, while also supporting the European Chips Act, which aims to bolster Europe's strength in semiconductors by increasing resilience and reducing reliance on external suppliers.[viii] These benefits are discussed in further detail below.

DRIVING EFFICIENCY IN SENSOR MANUFACTURING

By showcasing the scalability of GeSn photodetectors to an industry standard 3-inch wafer, the project has supported efforts towards lower costs, reduced energy demand, and improved efficiency across the photodetector supply chain.

The advancements in HZDR's wafer-scale CMOS technology present an opportunity for increased efficiency in commercial photodetector manufacturing, as photodetectors can be manufactured using standard CMOS manufacturing and facilities. This compatibility allows industry actors to integrate photonic components into existing semiconductor manufacturing lines, increasing production efficiency, lowering costs, and reducing the need for highly specialised and costly techniques associated with conventional photodetectors (based on InGaAs and InSb).[13] This has the potential to accelerate the prototyping and development of sensors, which could reduce the time to market for photodetector products. Moreover, it enables manufacturers to respond more quickly to emerging demand and increase production capacity.

The project is also progressing towards a competitively priced wafer with high-temperature resilience for industry. Unlike the InGaAs SWIR sensors commonly used for comparable applications, the GeSn sensors function without the need for cooling. This means that end-user applications, especially those in agriculture and biomedical products, could benefit from operation under high temperatures with reduced energy consumption and without the need for active cooling systems, leading to simpler designs and lower operational costs. While research is underway to understand the exact energy cost savings, stakeholders currently estimate 40-50% in energy savings between the GeSn sensor and those like the InGaAs SWIR sensors. Through a reduced need for cooling, HZDR's wafers could aid industry in the deployment of durable and cost-effective photodetectors for a broad range of applications.

In addition to this, HZDR shared that the 3-inch GeSn wafer is currently estimated to cost around €1 per sensor, with an estimated market price for the encapsulated photodetector at around €10. This is a significantly reduced cost compared to market-available alternatives, which HZDR stakeholders noted were typically priced at €500 per sensor, meaning a potential cost saving of 98%. As various technologies may have multiple sensors (e.g. 10 sensors for one product), this could result in significant cost savings within the supply chain (e.g. 10 sensors at €10 would be €100, compared to 10 sensors at €500, totalling €5,000). In recent conversations with potential customers, an HZDR stakeholder was told that the price of sensors is a key inhibitor to the scaling of technologies supporting tomography[14] for the public healthcare system. Offering a cost-effective alternative not only strengthens the industrial supply chain but also delivers broader societal benefits by reducing the overall cost of equipment used in healthcare and other sectors, such as agriculture. At the same time, it positions HZDR as a competitive supplier of wafers in the commercial market.

CONTRIBUTING TO EUROPEAN CIRCULARITY

By developing a photodetector using non-toxic elements, the project supports wider European Union and Commission goals towards circularity, strategic autonomy and climate neutrality.

The GeSn SWIR photodetectors offer a more sustainable option to current alternatives, as they are composed of non-hazardous elements. This is particularly relevant in Europe, where regulations increasingly restrict hazardous substances in electronic equipment.[15,ix,x] Notably, current sensors on the market may contain toxic elements like Indium and Gallium, which are not only hazardous but also challenging to recycle.

In contrast, GeSn sensors offer potential advantages in addressing recycling challenges, as they are made from materials that are more commonly recycled. Recycling infrastructure - particularly for Germanium - is actively being developed, driven by increasing interest and investment from various

[13] Indium Gallium Arsenide (InGaAs) and Indium Antimonide (InSb) are both semiconductor compounds.

[14] A method used to create an image of a cross-sectional slice of the human body or another solid object by employing X-rays or ultrasound.

[15] This includes the REACH (registration, evaluation, authorisation, and restriction of chemicals) Regulation (2007), as well as the Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) (2002), and ROHS2 (2011) and its 2017 amendment.

industries, including the space sector, with support from organisations such as the European Space Agency (ESA).[16xi]

By comparison, elements and compounds such as indium and gallium arsenide have extremely limited capacity for recycling in Europe and, due to regulatory constraints, including their listing under REACH (registration, evaluation, authorisation, and restriction of chemicals) as restricted substances, may require complex processes in order to comply with the regulation.[xiixiii] When such materials are not recycled, they often end up in general waste streams, where they may be added to landfills or incinerated, releasing toxic substances into the environment that can negatively impact human health and the broader ecosystem.[xiv] For example, studies have shown that prolonged exposure to indium has been linked to elevated levels of the element in the bloodstream,[xv] and that gallium-based compounds may pose health risks, including skin irritation and reduced blood cell production.[xvi]

In line with this, initiatives aimed at reducing environmental impact in the semiconductor manufacturing process are a key priority under the EU Chips Act.[xvii] By supporting a more efficient and cleaner product, the UCI funding supports wider EU initiatives aimed at promoting European autonomy and environmental protection.

Although precise recycling costs for hazardous materials are hard to quantify, the European Commission is increasingly placing requirements on electronics to be recyclable. One stakeholder even reported that an international supplier for sensors faced export challenges due to these restrictions. As such, GeSn SWIR photodetectors present a compliant and forward-looking solution focusing on circularity, which may become increasingly important in the European market should international suppliers face continued constraints.

SUPPORTING END USER APPLICATIONS

Follow-on activities, such as early market engagement, are helping ensure that the technology is leveraged effectively by end users to support safety and sustainability applications.

While commercialisation was beyond the scope of this specific Hi-Acts project, HZDR's focus on industry-standard CMOS technology has laid the foundations for early exploration of target markets. Since the project's conclusion, the team at HZDR has conducted market research and engaged with end users to identify where their wafer-scale CMOS technology can deliver the greatest value. These insights are helping to pinpoint the most promising opportunities for adoption, guiding the development of a business model and a strategic path to commercialisation.

The shortwave infrared market was valued at €147m ($167m) in 2021, with an expected compound growth rate of 8.7% until 2030.[xviii] HZDR's advancements of their wafer-scale CMOS technology has the potential to provide value in several application fields within this market. LiDAR and agriculture were identified as particularly suitable due to the strong match between HZDR's technology and the applications' key requirements, including spectral range, bandwidth and sensitivity.[17] LiDAR, often used in autonomous vehicles and environment mapping, presents an enhanced form of imaging that can enable safer systems. However, the GeSn wafer, as noted by stakeholders, would still require additional technical development to prove its compatibility.

Alternatively, infrared photonics in agriculture can offer increased precision for monitoring crop health, soil moisture or other activity supporting efficient farming and food security, demonstrating the diverse

[16] Notably, there are initiatives for recycle germanium include the Belgian-based Umicore germanium recycling programme.

[17] Several other applications were identified during market research activities, including biomedical sensors, chemical spectroscopy for food and pharmaceuticals, and motion and proximity sensors. Other potential applications are still being investigated, such as consumer electronics and monitoring of industrial processes.

range of user-applications. This market research, which took place as a follow-on from the Hi-Acts project, indicates the potential to drive progress towards low-cost and energy-efficient technologies that can, in turn, support safer systems and sustainability efforts. However, as the technology is in the early stages of development, it is difficult to predict the extent of industry uptake, and thus materiality of this impact.

FOLLOW-ON COMMERCIAL OPPORTUNITIES

The project's success is paving the way for commercialisation, backed by plans for a spin-out company, and improved business know-how.

The project's advancements under Hi-Acts UCI have enabled a path to commercialisation for HZDR's wafer-scale CMOS technology. HZDR representatives noted that plans are underway to establish a spin-out company for the GeSn wafer, as well as another sensor developed by the team (developed separately from the Hi-Acts project). While the spin-out will focus on two technologies, a stakeholder noted that it would not be possible without the GeSn wafer. This could provide the opportunity to capture commercial value from the infrared photodetector market through product sales. The nascent spin-out intends to operate as a fabless company,[18] enabling resources and time to be focused on technology design while outsourcing manufacturing. This presents an opportunity for continued research, development, and innovation beyond the Hi-Acts project, while also supporting the creation of a spin-out company with a novel product positioned to enter the photodetector market.

Alongside the development of these commercial opportunities, a HZDR scientist noted that the project played a significant role in supporting their understanding of the sensor market, as well as their skill set related to business and commercialisation. In shifting focus toward a commercially viable product rather than one intended for a scientific audience, the scientist gained valuable insight into the sensor market and commercialisation processes that would have otherwise remained outside their typical scope.

These developments represent important progress towards commercialisation and demonstrate the strong potential for bringing a CMOS-compatible photodetector to the industrial market - progress that is highly attributable to the work supported by Hi-Acts UCI funding.

SUPPORTING THE LOCAL ECONOMY

The project is supporting Dresden's semiconductor ecosystem with potential for leveraging local expertise, enhancing the region's reputation, and catalysing work for a local research services company.

Stakeholders noted that HZDR's work under Hi-Acts aligns with and supports the local industry's strengths in semiconductors. Dresden, where HZDR is based, has a growing semiconductor ecosystem, with a concentration of organisations involved across the supply chain.[xix] By advancing CMOS compatible photodetector technology, the project added to this regional expertise in semiconductor innovation and manufacturing.

Furthermore, if the spin-out achieves its goal of becoming a fabless company by leveraging local facilities and manufacturers, the innovation developed through the Hi-Acts programme could continue to enhance regional expertise. This would help position the region as a specialist in this unique technology, while also securing contracts for local industry.

[18] Fabless describes a company that designs and sells semiconductors but outsources the manufacturing (fabrication) to a third party.

Follow-on work from the Hi-Acts project also stimulated a market study and technical evaluation undertaken by local Dresden-based research services companies, KETmarket and Finnoval. The €4,500 contract was funded outside of the Hi-Acts project by the Free State of Saxony. As part of this work, the team delivered a report assessing the TRL of the technology, identifying the applications, exploring the interest of the potential users, and supporting meetings with potential users and planning the next steps of commercialisation. The study identified pulse oximetry[19] as one of the potential applications for the wafer-scale CMOS technology, due to the alignment in bandwidth required and low-cost potential. In doing so, the Hi-Acts project was able to catalyse an additional contract, contributing to the local economy. At the same time, this contract offered value to the HZDR team in supporting their knowledge of the potential market applications for the novel sensor.

ATTRIBUTABILITY OF THESE BENEFITS TO HI ACTS FUNDING

The Hi-Acts UCI funding was regarded as crucial for HZDR's success in demonstrating the scalability of CMOS technology for infrared photodetectors, as well as the follow-on activities and the associated socio-economic impacts. Stakeholders noted that there were no other funding opportunities to progress the project, and thus, Hi-Acts funding was an instrumental enabler. UCI funding has directly contributed to progress in developing an innovative and increasingly efficient infrared photodetector, as well as a clear route to commercialisation. The broader socio-economic impacts, such as improved industrial efficiency across the supply chain and a range of potential environmental and societal benefits, are promising and expected to grow as industry uptake and manufacturing capabilities continue to advance.

Attributing the ultimate success of the 3-inch GeSn wafer solely to the Hi-Acts UCI funding will become increasingly difficult over time, as many factors may influence successful commercialisation and the uptake of the product. However, it is important to recognise that without this initial funding support, the project may never have been pursued, potentially preventing the development of the wafer-scale CMOS technology as well as any path to commercialisation from emerging at all.

While the UCI-funded hardware represents an essential enabling step, realising its full impact will depend on several additional technological, funding and policy factors.

[19] Pulse oximetry is a biomedical technology that measures blood oxygen levels.

IMPACT SUMMARY

Wafer-scale CMOS technology for room-temperature extended short-wave infrared GeSn photodetectors

HZDR	Industry	Society
Jobs and Skills: • Commercial skills: Business know-how developed/increased for scientists • Market knowledge: Sensor-market knowledge and commercial application developed through follow-on work **Technical:** • TRL progression: TRL 3 to TRL 4 (laboratory validation and testing) • Development of a solution that is better for the environment (in terms of toxicity and recycling potential) • Addressable industries: agriculture, biomedicine **Commercial:** • Cost savings: ability to leverage CMOS cost effective manufacturing processes and infrastructure, leading to energy savings estimated at 40-50% and cost savings of ~98% for GeSn sensors. • Revenue: significant commercial potential, with potential to break into a €147m (valued in 2021) shortwave infrared market • Spin-out: possible creation of a new organisation to support commercialisation endeavours	Potential strengthening of regional expertise, capability, and reputation. Relevant for: • Economy • Knowledge & Technology • German / European Competitiveness, sovereignty & resilience • Improved attractiveness of the local area / Germany / Europe for investment • Innovation	Sustainable, low-cost sensor alternatives aligned with EU standards and circular economy goals. Relevant for: • Scientific knowledge • Environment & sustainability • Health & wellbeing • National security & safety • Governance

Granularity of evidence

Attribution to UCI support

[vii] Cao, F., Liu, L. and Li, L. (2023). 'Short-wave infrared photodetector', *Materials Today*, 62, pp.327-359. DOI: https://doi.org/10.1016/j.mattod.2022.11.003

[viii] European Commission (n.d.). *European Chips Acts.* Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en

[ix] European Commission (n.d.). *REACH Regulation.* Available at: https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en

[x] European Union (2017). *Directive of the European Parliament an of the Council amending Directive 2011/65/EU of the restriction of the use of certain hazardous substances in electrical and electronic equipment.* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1485526057244&uri=CELEX:52017PC0038

[xi] European Space Agency (2022). *Effective recycling for Germanium.* Available at: esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Effective_recycling_for_Germanium

[xii] European Chemicals Agency (n.d.). *Substances restricted under REACH.* Available at: https://www.echa.europa.eu/substances-restricted-under-reach

[xiii] De Tandt, Ellen, Cody Demuytere, Elke Van Asbroeck, Hiram Moerman, Nicolas Mys, Gianni Vyncke, Laurens Delva et al. (2021) "A recycler's perspective on the implications of REACH and food contact material (FCM) regulations for the mechanical recycling of FCM plastics." *Waste Management* 119: 315-329. Available at: https://doi.org/10.1016/j.wasman.2020.10.012

[xiv] Haiying, Zhang, Zhao Youcai, and Qi Jingyu (2010). "Characterization of heavy metals in fly ash from municipal solid waste incinerators in Shanghai." *Process Safety and Environmental Protection* 88, no. 2:114-124 Available at: https://doi.org/10.1016/j.psep.2010.01.001

[xv] Nakano, Makiko, Kazuyuki Omae, Akiyo Tanaka, Miyuki Hirata, Takehiro Michikawa, Yuriko Kikuchi, Noriyuki Yoshioka, Yuji Nishiwaki, and Tatsuya Chonan (2009). "Causal relationship between indium compound inhalation and effects on the lungs." *Journal of occupational health* 51,6: 513-521. Available at: https://doi.org/10.1539/joh.L9077

[xvi] Zhan, Lu, Fafa Xia, Qiuyu Ye, Xishu Xiang, and Bing Xie (2015). "Novel recycle technology for recovering rare metals (Ga, In) from waste light-emitting diodes." *Journal of Hazardous Materials* 299:388-394. Available at: https://doi.org/10.1016/j.jhazmat.2015.06.029

[xvii] European Union (2023). *Regulation (EU) 2023/1781 of the European Parliament and of the Council of 13 September 2023 establishing a framework of measures for strengthening Europe's semiconductor ecosystem and amending Regulation (EU) 2021/694 (Chips Act).* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.229.01.0001.01.ENG

[xviii] Polaris Market Research. (2022). *Shortwave Infrared (SWIR) Market Share, Size, Trends, Industry Analysis Report, By Type; By Technology (Cooled Infrared Imaging, Uncooled Infrared Imaging); By End-User; By Region; Segment Forecast, 2022 – 2030.* Available at: https://www.polarismarketresearch.com/industry-analysis/shortwave-infrared-swir-market/toc

[xix] McKinsey & Company. (2024). *Exploring new regions: The greenfield opportunity in semiconductors*. Available at: https://www.mckinsey.com/industries/semiconductors/our-insights/exploring-new-regions-the-greenfield-opportunity-in-semiconductors

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

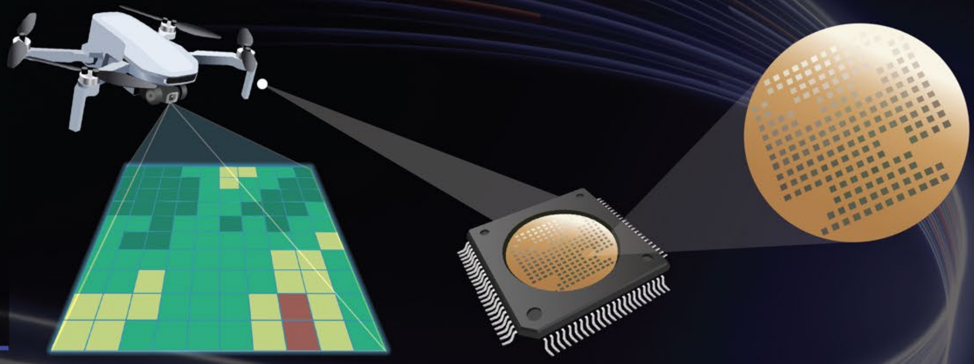
WAFER-SCALE CMOS TECHNOLOGY FOR INFRARED PHOTODETECTORS

SHOWCASING THE SCALABILITY OF CMOS COMPATIBLE SHORT-WAVE INFRARED PHOTODETECTORS FOR INDUSTRIAL EXPLOITATION

Hi-Acts UCI funding enabled the scaling-up of Complementary Metal-Oxide-Semiconductor (CMOS) compatible Germanium-Tin photodetectors to an industry standard 3″ wafer scale, demonstrating a cost-effective and mass producible photodetector to support the wider commercial infrared photodetector value chain.

ORGANISATION • ENHANCING INNOVATIVE CMOS TECHNOLOGY

- Progressed CMOS technology from **TRL 3 to TRL 4**, validating the feasibility of a 3″ wafer
- Transitioned from a novel research-grade photodetector to a full industrial-scale wafer, bridging lab-scale innovation and potential for **industrial manufacturing**
- Demonstrated the **scalability** of HZDR's innovative ion implantation and flash annealing processes for Germanium-Tin alloying
- Laid the foundation for a path towards **commercialisation via a spin-out company**



INDUSTRY • DRIVING EFFICIENCY IN PHOTODETECTOR MANUFACTURING

- Advancing a photodetector for industry that can leverage standard CMOS manufacturing procedures, reducing energy costs of between 40-50% due to improved cooling, and **improving efficiency** of infrared photodetector production
- Progressing a low-cost wafer-scale technology, **improving potential market competitiveness** of HZDR and aiding **potential cost reductions of 98%** through the photodetector supply chain through to end users
- **Supporting Germany's semiconductor industry** with plans to outsource production and increase regional expertise

SOCIETY • SUPPORTING END USER APPLICATIONS

- Potential to support **advanced applications** including agricultural monitoring and biomedical devices, by delivering stable performance in demanding environments without the need for cooling
- Offering a **non-toxic alternative** to current market options, aligning with broader EU objectives
- Engaging end users and stakeholders to inform follow-on plans for further technology development

SCAN HERE FOR MORE INFORMATION

CASE STUDY 3: STANDARDISED STATION FOR HIGH-ENERGY HEAVY ION RADIATION ON ELECTRONICS

MEETING THE DEMANDS OF SPACE RADIATION ENVIRONMENTS...

Satellites and other space technologies must operate in an environment filled with high-energy heavy ion radiation from sources such as solar flares, cosmic rays, and trapped charged particles in Earth's orbit.[xx] This radiation can cause significant damage to onboard electronics, as high-energy ions can pass through a spacecraft's outer shielding and interact with electronic circuit boards. The charged ions can release energy in the circuit boards and lead to short or long-term failures, potentially leading to a complete failure of the electronic component, which can result in mission failures. As these components are critical to spacecraft operations, ranging from navigation and communication to power and data processing, it is essential to understand how radiation affects their performance. To ensure reliable performance and mission success, space hardware must be designed to withstand and quickly recover from disturbances caused by high-energy particles, such as protons or heavy ions, passing through its electronic systems.[xx]

Irradiation testing plays a vital role in space technology development by simulating the space environment on Earth, enabling engineers to assess component resilience, predict failure modes, and design systems with sufficient protection or redundancy – the practice of radiation hardening. Without such testing, the reliability and success of space missions would be severely compromised.

Ionising radiation, particularly galactic cosmic rays (GCR) and solar wind, poses a major challenge to the reliability of electronic systems. To test radiation resistance, components have to be exposed on the ground, before the flight, to simulated space conditions to ensure their performance and reliability. Whilst tests on custom-made electronic chips are traditionally performed at low-energy particle accelerators, the recent widespread use of Components-Off-The-Shelf (COTS) requires very high-energy and charged ions to test radiation hardness.

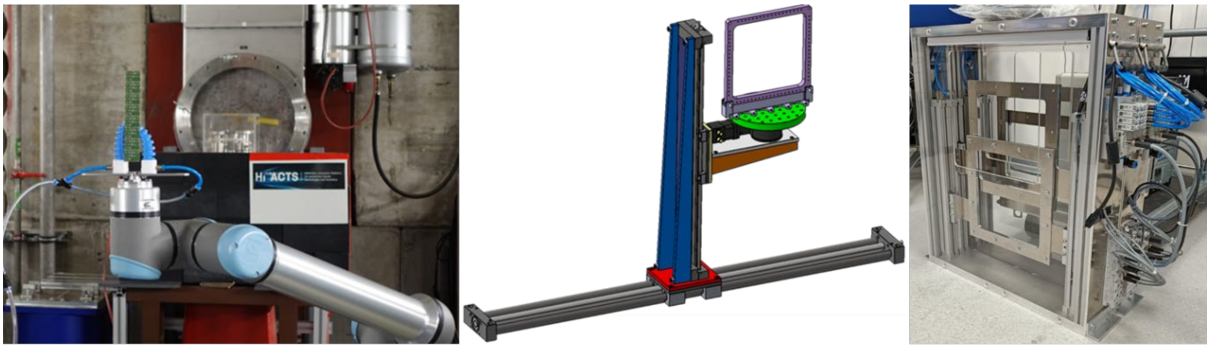
Testing electrical equipment against very high-energy heavy ion radiation demands highly specialised facilities, which are rare worldwide. The GSI Helmholtzzentrum für Schwerionenforschung GmbH, based in Darmstadt (Germany), addresses this challenge with its powerful heavy ion accelerator, originally developed for advanced scientific research. GSI has historically focused on fundamental nuclear and atomic physics research, while also pursuing applied studies in materials science, plasma physics, biophysics, and nuclear medicine.[xxi] GSI's accelerator uses electric fields to speed up ions and magnets to steer and focus them through its beamline, accelerating the ions to nearly 90% of the speed of light (about 270,000 km/s).[xxii]

...WITH UCI-SUPPORTED ENHANCEMENTS FOR ACCELERATOR-BASED ELECTRONICS TESTING

GSI has one of the few high-energy heavy ion accelerator facilities in the world, and one of only two in Europe, which can mimic the level of irradiation relevant for the space environment. Hi-Acts provided €68,000 to the institution to enhance this facility over 8 months by developing a standardised station for testing space electronics for radiation hardness. An ion-accelerator can precisely target and bombard equipment with high-energy particles, simulating the radiation conditions that spacecraft electronics must endure in orbit (and beyond). While GSI already had the beamline capability, the project was instrumental in developing a standardised station to facilitate industry use.

As part of the station, GSI installed a robotic arm, linear axes with a standardised frame (also used at CERN, UCL and others, where it is known as the European Space Agency (ESA) frame), modular target exchangers, and alignment lasers and cameras in the irradiation facility, Cave A of the heavy ion synchrotron SIS-18. By bringing together the various equipment (see Figure 7), the station will be able to support a variety of applications without the need for customisation. For example, the robotic arm can hold non-standard size electronics, while the standardised frame on the linear axes will allow users familiar with other electronics testing facilities to mount their samples with increased ease and speed. Meanwhile, the modular target exchangers allow for additional beam manipulation options for more diverse applications, which adds flexibility, efficiency and user-friendly handling, as more complicated structures can also be mounted to them (including modulators).

Figure 7: Three of the new elements added to the standardised station funded under UCI



Robotic arm | **Linear axes with standardised frame** | **Module range shifters**

Source: GSI

Alongside the Hi-Acts UCI activity, GSI is also involved in other projects that support industry access to the facility, including the High-Energy Accelerators for Radiation Testing and Shielding (HEARTS) project[20] and the RADiation facility Network for the EXploration of effects for indusTry and research (RADNEXT).[21] Both projects aim to enhance industrial access to heavy ion irradiation facilities, such as GSI and CERN, by providing available beam time for industry use and improving the facility further.[xxiii, xxiv]

CAPABILITY ENHANCEMENT FOR COMMERCIAL ACCESS

By developing a standardised station for irradiating electronics, the project supports a user-friendly testing facility ready for industry access.

To support GSI's broader efforts to attract industrial users and facilitate the transition from a facility predominately used by scientific researchers, GSI needed to enhance its infrastructure. A central element was the creation of a standardised station, designed for ease of use and minimal customisation. This included a robotic arm for handling non-standard electronics and a standardised frame on new linear axes, ensuring compatibility with testing setups that users are familiar with at other facilities.

With this setup, GSI conducted a pilot run (outside of the Hi-Acts project) involving companies from the USA, UK, and Germany. Participants successfully irradiated their electronics, supporting validation efforts toward space qualification. The pilot also served to trial new access models for

[20] The HEARTS project is funded by the European Union through the Space Work Programme of the European Commission.

[21] The RADNEXT project is funded through the European Union's Horizon 2020 research and innovation programme.

commercial users, who may have different expectations and workflows than scientific users, demonstrating the viability of industry engagement.

This initiative marks a strategic shift for GSI, introducing a new capability focused on industrial space applications testing. While the facility has historically centred on biomedical and fundamental science research, it can now tap into a new application area and potential revenue stream. However, access models for industry use are still under development. The pricing structure for the coming years will be based on corresponding operating costs. As demonstrated in the pilot runs, it can be assumed that GSI will be able to offer competitive prices compared to international alternatives. As informed by stakeholders, alternatives are currently priced between around €3,400 - €4,700 per hour of use.[22] [xxv]

It is not yet possible to make concrete revenue forecasts for the coming years, as the availability of industrial beam time is still to be determined – a limiting factor. Furthermore, GSI is currently commissioning its new FAIR accelerator, which will connect to the GSI facility in future. This will lead to longer shutdown phases without user operation until 2028.

INCREASING EFFICENCY

In developing a standardised station, the facility can help save on personnel time and maximise beam-time, leading to cost savings and increased revenue opportunities.

To safely irradiate electronic components, it is essential that the tested device is securely mounted and precisely positioned throughout the exposure. The heavy ion beam must be delivered with high accuracy to ensure controlled and consistent results. Any instability can lead to uneven exposure, compromised data, or potential damage to both the sample and the beamline. A stable setup is therefore critical for both safety and experimental integrity.

Creating custom setups for each experiment is time-intensive, requiring careful design, alignment, and validation to ensure compatibility with the beamline. This process can delay testing and place a significant burden on GSI's engineering resources. The Hi-Acts project enabled GSI to develop a standardised station, providing a reliable, ready-to-use setup for a wide range of users. This reduces the labour and preparation time needed for GSI, improving facility efficiency and lowering the barrier for industry access, where speed and predictability are especially important.

The GSI team estimates the standardised setup can save GSI around 3 to 4 workdays per experiment, or more for complex cases, by removing the need for custom design and validation. In the first half of 2025 alone, a GSI stakeholder noted that over 10 users have already used the station, resulting in a collective saving of at least 30 to 40 workdays.

This efficiency has made it possible to support industry access without placing a heavy demand on scientific staff time. Importantly, moving to standardisation also helps to conserve beam-time, which is both costly and limited. Automated positioning can expedite sample alignment, while the modular design enables quick transitions between experiments with minimal reconfiguration.

With these improvements, the facility can support more experiments or samples in the same timeframe. GSI stakeholders roughly estimate an overall efficiency gain of 10% to 15% for GSI operations, enabling additional test campaigns / scientific experiments, many of which might not have been possible under the previous setup.

[22] This access fee range of €3,400 - €4,700 was estimated for the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory, alongside an access fee of around €3,800 estimated for CERN.

BRIDGING SCIENCE AND INDUSTRY

Expanding GSI's user reach to industry has increased commercial understanding for GSI staff, and has the potential to support two-way knowledge transfers in the future.

Through the development and delivery of this project, the GSI team has gained insight into industry practices and expectations. Working directly with industrial partners during the pilot phase - including Astranis, a US-based company which builds geostationary communications satellites, and RadTest Ltd, a UK-based radiation testing and support company, has helped shift the team's perspective toward a more commercial customer-focused mindset. This shift was directly enabled through Hi-Acts funded activities, and can support the successful commercialisation of this new radiation testing service for industry users in the future. It also builds internal capabilities for more effective engagement with non-academic users in future projects.

While initiatives like RADNEXT and HEARTS have played a significant role in raising the profile of GSI and increasing industry awareness through various workshops, these reputational increases are partly enabled through the UCI-funded development of the standardised station.

Exposure to industry requirements has also allowed for reflection and further iteration on internal processes / the commercial access model, which will allow GSI staff to adapt their approaches to better align with the needs of commercial partners. This organisational cultural shift is a crucial step toward establishing the facility as a trusted and reliable partner for applied research and commercial irradiation services.

Looking ahead, there is also potential for two-way industry-research organisation knowledge transfers. As industrial users become more involved, their willingness to share challenges, methods, or feedback could lead to deeper collaborations and mutual learning. Such engagement may unlock new opportunities for scientific research informed by real-world application needs, while offering industry users access to cutting-edge expertise and infrastructure. This convergence of scientific and industrial perspectives could strengthen both communities and support the long-term sustainability and relevance of the facility.

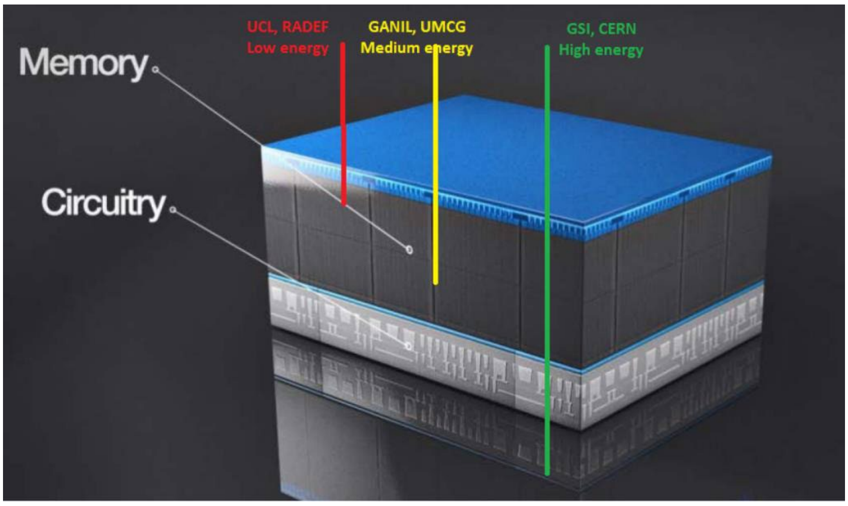
LOWERING BARRIERS TO ACCESS FOR INDUSTRY

By providing access to very heavy ion radiation for industry, GSI has increased the international capacity of this specialised testing, enabling faster innovation for the space sector.

Globally, there are only a handful of facilities offering similar capabilities, such as the NASA Space Radiation Laboratory (NSRL) at the Brookhaven National Laboratory in the USA and the CERN Highly-Accelerated Mixed Field Facility (CHARM) at CERN in Switzerland. Both of these facilities experience high demand. Through GSI providing an alternative test facility, availability of beam time for industrial users significantly increases. This can help drive product development, supporting the acceleration and growth of innovation in the European space sector.

GSI's irradiation testing also helps reduce cost and technical risk. Many companies aim to use commercial off-the-shelf radiation-hardened chips, but without access to a facility capable of penetrating deep into electronic packages, they would need to physically de-lid or thin the chip, which carries a significant risk of damaging or destroying these high-value parts. A pilot-user noted that they can cost anywhere from €8,500 (US$10,000) to €42,000 (US$50,000) each. The ability of GSI's facility to perform precise deep-penetrating irradiation without the need for such destructive preparation eliminates that concern (see Figure 8 for a comparison of various European facilities and their penetration capabilities). Testing can be conducted on fully assembled boards, preserving the integrity of the components and removing a major financial and technical barrier.

Figure 8: Penetration capabilities of ions with various energies at European facilities in the context of a 176-layer FLASH memory



Source: GSI and EETimes [xxvi, xxvii]

By making these testing services more affordable and more accessible, GSI is helping to open space electronics development to companies of all sizes. In particular, increased access to satellite validation and component testing supports shorter development cycles and reduces time-to-market. For companies working within limited funding windows, this kind of efficiency can mean the difference between staying on track or missing key market opportunities. Ultimately, by filling a critical infrastructure gap, GSI is helping accelerate innovation in the space sector and possibly enabling broader participation in space missions. Satellites that undergo irradiation testing can serve various purposes, from communication to Earth observation. These applications offer significant benefits for the planet, such as climate monitoring and support for global banking systems.

ENHANCING EUROPEAN COMPETITIVENESS

By enabling industry access to very heavy ion beam time, UCI funding has enabled GSI to position itself as key infrastructure in Europe, supporting German and European industry and contributing to European innovation goals.

This project has positioned GSI as a leader in advanced space environment testing, significantly enhancing its competitive edge and reputation within the European research and innovation landscape. Notably, GSI is now one of the first facilities in Europe to offer testing under simulated Galactic Cosmic Ray (GCR) conditions. GCR represent a continuous, low-dose background radiation environment composed of high-energy particles from outside our solar system. These conditions are particularly relevant for long-duration space missions, such as deep space probes or lunar infrastructure, and replicating them is technically challenging.

Prior to this project, space companies might have been unaware of GSI’s potential for radiation hardness testing. One pilot user noted that they had searched in previous years for heavy ion test facilities and had found GSI by chance when searching for alternatives in 2025. The standardised station, combined with the pilot initiative, has increased the visibility of the facilities. While the pilot initiative was not funded through Hi-Acts, pilot users would not have had access to the facility without the standardised station, allowing for a degree of attributability to the UCI funding.[23]

GSI noted that the standardised station project lowers the barrier to access for small and medium-sized enterprises (SMEs), which is critical in the German economy, where SMEs make up a significant portion of the industrial ecosystem, accounting for 55% of the country's employed population.[xxviii] Additionally, offering commercial access to heavy ion testing within Europe could act as a key enabler for European space companies, taking away the need to travel to the USA (see Figure 8 for a comparison of European facilities). By supporting access to cutting-edge testing infrastructure, the facility may directly contribute to national and European innovation goals. It aligns with Horizon Europe's Pillar Two (Cluster 4) by advancing next-generation space technologies and strengthening Europe's competitiveness in space infrastructure.[xxix] It also contributes to strategic autonomy in space by reducing reliance on non-EU testing facilities and supports the EU Chips Act by reinforcing Europe's capacity to test and validate microelectronics.[xxx] Making advanced services available to a broader user base is not only a technology transfer goal but also a strategic effort to support long-term economic growth and security for Europe.

In lowering barriers to access, the project also supports companies looking to spin-in to the space sector, reducing the costs and complexity of testing space electronics. The increased availability of such testing capabilities furthers this support, increasing accessibility which can help bring new players, ideas, and technologies into Europe's space ecosystem.

GSI stakeholders also noted that these achievements are expected to generate political goodwill, strengthening GSI's position for future funding and infrastructure development. With greater visibility, increased service offerings, and demonstrated value to both science and industry, GSI is now better placed to evolve as a national asset supporting space technology development, innovation, and economic resilience.

ATTRIBUTABILITY OF THESE BENEFITS TO HI-ACTS FUNDING

The Hi-Acts UCI funding was highlighted as a key enabler for supporting the direct industrial use of GSI's very heavy ion beam in Cave A. In the absence of funding, GSI stakeholders noted that they would not have developed the standardised station nor the capacity to support direct commercial access. Without the standardised station, the amount of labour required to prepare for each customer would make direct commercial industry access not possible. GSI also noted that the project was important for increasing the facility's visibility and for demonstrating to internal stakeholders the value of attracting commercial users.

Future impacts resulting from industry access to the facility, including potential knowledge transfers between industry and GSI scientists, can be attributed to Hi-Acts funding to a limited extent, as the facility could have potentially secured alternative support for such developments over time. GSI stakeholders noted that no immediate alternative funding sources were available at the time; however, the facility may have pursued other funding routes as they emerged. In the short term, the benefits to industry, such as faster access to irradiation testing and associated time savings, are highly attributable to Hi-Acts.

The facility and the region's reputation increased as a result of the project, though it is important to acknowledge that the Hi-Acts funding is part of a larger initiative to support industry access to

[23] The facility's competitive testing offering has also expanded with the addition of the heavy ion microprobe, developed under a separate UCI project titled *Microprobe 2.0*. This project will enable users to conduct highly targeted fault analysis and material studies, using a finely focused ion beam with spatial resolution down to 500 nanometres. This capability is particularly valuable for identifying the precise origin of faults in microelectronics, which is essential for both failure analysis and component qualification.

advanced scientific facilities. As with HEARTS and RADNEXT,[24] this UCI-funded project is expanding GSI's user community, and developing an access model to include industry alongside scientists and researchers. Nonetheless, the Hi-Acts platform has been an essential enabler to support industry access by increasing the efficiency of testing setup, minimising the technical and financial risks of increased testing duration and complexity.

IMPACT SUMMARY

Standardised Station for High-energy Heavy Ion Radiation on Electronics

GSI	Industry	Society
Jobs and Skills: • Increased understanding of industry needs and business know-how for GSI staff • Potential for further cross industry-academia knowledge transfer **Competitiveness and Reputation:** • International standing: leveraged reputation as one of the few facilities internationally to provide access to very-heavy ion radiation testing • Visibility: raised profile of the services available at GSI **Technical:** • New services: Standardisation station facilitates industrial access which was not previously available • New industries addressable: Commercial space sector with international market access already established in the UK and USA, as well as domestic use from Germany • Additional use cases: Scientific applications including biomedical, with over 10 experiments demonstrated in 2025 at GSI **Commercial:** • Increased revenue opportunities • New potential users: Unlocking full operational potential, from no prior industry users to scalable growth	Enables easier access internationally to crucial testing and validation infrastructure for space electronics. Relevant for: • Economy • Knowledge & Technology • German / European Competitiveness, sovereignty & resilience • Improved attractiveness of the local area / Germany / Europe for investment • Regulation & policy-making	Scaling international testing enables faster fault finding, quicker validation, and reduced time to space launch, while supporting EU policy / strategy. Relevant for: • Scientific knowledge • Environment & sustainability • National security & safety • Governance

Granularity of evidence

Attribution to UCI support

[xx] Brookhaven National Laboratory (n.d.). *Towards Safer Spaceflight.* Available at: https://www.bnl.gov/nsrl/
[xxi] GSI (n.d.). *Research at GSI – An Introduction.* Available at: https://www.gsi.de/en/researchaccelerators/research_an_overview
[xxii] GSI (n.d.). *Accelerator.* Available at: https://www.gsi.de/en/researchaccelerators/accelerator_facility
[xxiii] RADNEXT (n.d.). *About RADNEXT.* Available at: https://radnext.web.cern.ch/#about
[xxiv] HEARTS (n.d.). *High-energy heavy ion testing for space in Europe.* Available from: https://hearts-project.eu/
[xxv] HEARTS (n.d.). *HEARTS@CERN 2025 user campaign*. Available from: https://indico.cern.ch/event/1548956/
[xxvi] This image is courtesy of the Hi-Acts Academy presentation *Radiation Hardness Testing at GSI and HZB – Unique Capabilities to Test Modern Electronics*, which utilises an image courtesy of Micron Technologies (see below)
[xxvii] EETimes (2020). *Micron Leapfrogs to 176-Layer 3D NAND Flash Memory.* Available at: https://www.eetimes.com/micron-leapfrogs-to-176-layer-3d-nand-flash-memory/
[xxviii] Statistisches Bundesamt DESTATIS (2024). *Shares of small and medium-sized enterprises in selected characteristics 2022 by size class*. Available at: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Unternehmen/Kleine-Unternehmen-Mittlere-Unternehmen/Tabellen/wirtschaftsabschnitte-insgesamt.html
[xxix] Horizon Europe NI (n.d.). *Pillar Two.* Available at: https://www.horizoneuropeni.com/pillar-two
[xxx] European Commission (n.d.). *European Chips Act.* Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en

[24] Funded under separate European Union initiatives.

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

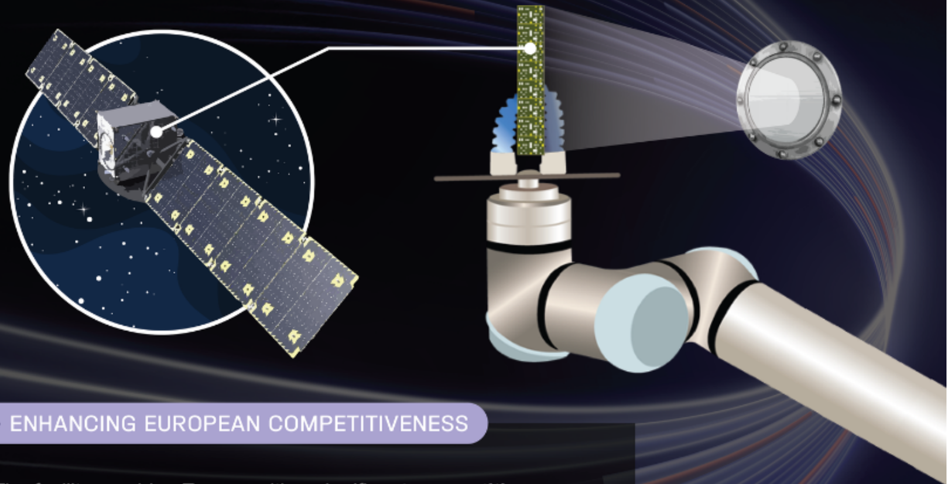
STANDARDISED STATION FOR HIGH-ENERGY HEAVY ION RADIATION ON ELECTRONICS

CREATING A STANDARDISED STATION TO EXPAND INDUSTRY ACCESS TO CRITICAL RADIATION TESTING FOR SPACE ELECTRONICS

Hi-Acts UCI funding has supported the development and installation of a standardised testing station, featuring a robotic arm for handling non-standard components, linear axes for precise positioning of detectors, shielding or samples, modular range shifters for rapid energy adjustments, and integrated alignment lasers and cameras - all designed to provide industry-friendly access.

ORGANISATION • INCREASING EFFICIENCY & DEVELOPING COMMERCIAL ACCESS

- Standardisation allows for industry actors to access the heavy ion beam by **eliminating the need for customised solutions**
- Catalysed the development of an access model for industry access to enable and expand **revenue generating opportunities** for GSI
- The standardised approach supports greater industrial participation, whilst **reducing workload pressures** on the existing team, saving an estminated 3 to 5 workdays per experiment
- The station has hosted a **successful pilot** with space companies from Germany, the UK (RadTest Ltd), and the US (Astranis) qualifying their electronic components



INDUSTRY • LOWERING BARRIERS TO ACCESS

- Supports both **domestic and international demand**, exceeding the current capacity of existing facilities
- De-risking space technology development through providing industry with deep-penetrating irradiation without the need to de-lid electronic chips which can be damaging
- Expanded access to satellite and space electronics manufacturers, allowing them to **accelerate space deployment**

SOCIETY • ENHANCING EUROPEAN COMPETITIVENESS

- The facility provides Europe with a significant **competitive advantage in testing capabilities**, complementing CERN and NSRL in the US
- Strengthened Germany's space testing ecosystem by **bolstering the technical reputation** of Darmstadt and the country, shifting from a purely scientific facility towards greater industry accessibility

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CASE STUDY 4: TEST STAND FOR OPERANDO BATTERY INVESTIGATION

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,[xxxi] while the Fraunhofer Institute forecasts that Germany will provide batteries for 6.5 million electric cars by 2030.[xxxii]

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

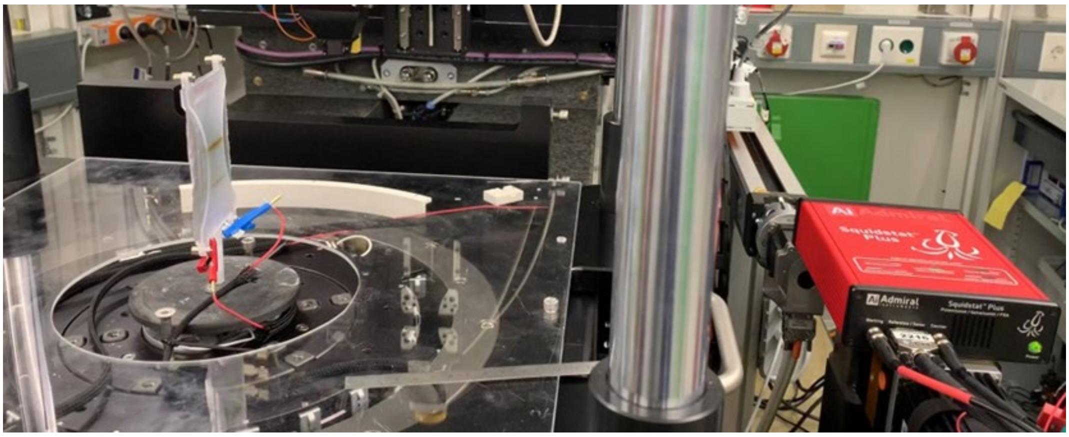
Helmholtz-Zentrum Berlin (HZB) is a research centre focused primarily on climate-neutral energy materials and technologies, such as solar cells, catalysts, advanced batteries and green hydrogen generation. In 2023, HZB received €78,000 through the Helmholtz Innovation Platform for Accelerator-Based Technologies (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 in cooperation with Hi-Acts partner Helmholtz-Zentrum Hereon, was a flexible, multi-purpose battery test bench with cyclers to enhance in-situ synchrotron tomography facilities.[25] 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.

[25] 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.

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

Figure 9: The pouch cell stack (left) and battery cyclers (right) used at Hereon's P07 beamline at DESY



Source: Hereon/ 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[26] 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.[xxxiii] 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

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

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 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.[xxxiv] 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,[xxxv] and Chinese automotive companies now account for over 50% of global EV production.[xxxvi] 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.[xxxvii] 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.[xxxviii] 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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xxxi Federal Ministry for Economic Affairs and Climate Action, 2023. Electricity Storage Strategy. Available at: https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/electricity-storage-strategy.pdf?__blob=publicationFile&v=6

xxxii Deutschland.de. 2024. Germany ramps up battery production. Available at: https://www.deutschland.de/en/topic/business/batteries-from-germany-production-ramping-up

xxxiii Zhou, Y., Wang, P., Wang, K., Fang, X., Li, W., Nai, J., Liu, Y., Wang, Y., Zou, S., Yuan, H. and Tao, X., 2025. Developing High-Performance Anode-Free Lithium Batteries: Challenges, Strategies, and Opportunities. *Advanced Functional Materials*, 35(27).

xxxiv International Energy Agency, 2025. The battery industry has entered a new phase. Available at: https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase

xxxv European Parliamentary Research Service. 2025. Powering the EU's future: Strengthening the battery industry. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2025/767214/EPRS_BRI(2025)767214_EN.pdf

xxxvi World Economic Forum, 2024. China has an electric vehicle advantage but can it maintain its edge? Available at: https://www.weforum.org/stories/2024/06/china-electric-vehicle-advantage/

xxxvii Directorate-General for Climate Action. 2023. Fit for 55: EU reaches new milestone to make all new cars and vans zero-emission from 2035. Available at: https://climate.ec.europa.eu/news-your-voice/news/fit-55-eu-reaches-new-milestone-make-all-new-cars-and-vans-zero-emission-2035-2023-03-28_en

xxxviii European Commission. 2023. Special report 15/2023: The EU's industrial policy on batteries – New strategic impetus needed. Available at: https://www.eca.europa.eu/en/publications?ref=sr-2023-15

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

DESY. HZDR GSI hereon HZB Helmholtz Zentrum Berlin

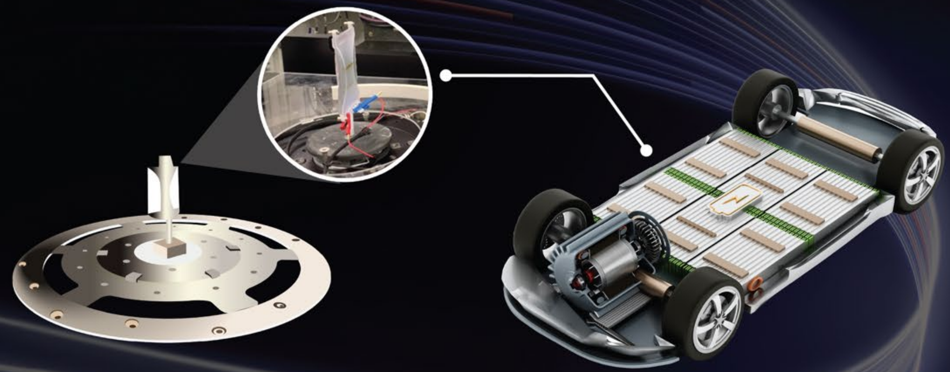
TEST STAND FOR OPERANDO BATTERY INVESTIGATIONS

ENABLING REAL-TIME 3D IMAGING OF BATTERIES AT ACCELERATOR FACILITIES TO DRIVE INDUSTRY INNOVATION IN BATTERY TECHNOLOGIES

Hi-Acts UCI funding supported the development and demonstration of a flexible battery test bench that reveals new insights into the internal conditions of batteries as they charge. This could spark innovation in battery performance and safety, helping Europe remain competitive in a fast-growing global battery market during the energy transition.

ORGANISATION • PIONEERING A FIRST-OF-A-KIND TESTING PLATFORM IN EUROPE

- Raised maturity of the test bench from **TRL 5 to TRL 9**, demonstrating promising real-time 3D in-situ battery measurements
- Developed a Python-programmable user interface to support **AI integration** alongside an AI LLM for researchers with **spin-out product potential**
- Created a commercial valuable asset, indicitively priced at **€250k - €300k per unit**, alongside potential for associated support services
- HZB leadership in operando tomography showcased through demonstrations at **3 international accelerator facilities** in the UK, France, and Japan



INDUSTRY • LOWERING BARRIERS TO ENTRY

- Increased experimental throughput by **3x**, saving users **€10,000s per experiment**
- Strengthened ties with **2 automotive companies**, supporting early-stage testing and **demonstrating industry 'buy-in'**
- Could **unlock new insights** into lithium dendrites within batteries, which cause safety risks and are a major barrier to the commercial deployment of lithium-ion batteries

SOCIETY • STRENGTHENING GERMAN COMPETITIVENESS

- Contributes to **German and European battery non-dependency**, reducing reliance on imports
- Supports the **automotive energy transition** by accelerating innovation in **battery safety and performance**

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DISCUSSION

The four case studies developed highlight that Hi-Acts UCI funding has delivered a wide range of benefits, with more expected to materialise in the coming months and years. Impact was particularly strong at organisation-level, which is to be anticipated given the relatively limited timeline and budget awarded for each activity. Additionally, the case studies reveal that the funded activities inscribe themselves in a wider industry and societal context, therefore contributing to higher order impact. It should be noted that there might be a selection bias, as activities were chosen for case study development where Hi-Acts anticipated that progress had already taken place.

At organisation level, a strong early commercial storyline emerged across the case studies, though at this stage these benefits are expected rather than realised, with further developments (and funding) required. R&D investments like these UCI-funded projects are fundamental to enable commercial benefits down the line. Many of the activities are expected to lead to future revenue, reduced time to market, and for three of them, to the potential creation of a spin-out organisation to support commercialisation endeavour (should uptake warrant it). The four activities examined had clear industry application identified. All of the research organisations and industry partners consulted reported (materialised) benefits for their reputation, competitiveness, and the visibility of their work, which could be leveraged for commercialisation, securing funding from other sources, and developing new partnerships. From a technology development perspective, UCI funding enabled TRL progression for three activities, helped create new concepts, and even a new product, overall accelerating innovation. Additionally, UCI funding was instrumental in strengthening existing skills and equipment and developing new ones, overall enhancing organisational capabilities, which helped funded teams secure follow-on opportunities. The activities generated limited investment and employment impact due to the relatively limited grant sizes, short projects, and hardware focus of the activities.

While attribution to UCI funding for industry and societal impact is challenging due to the multitude of other factors involved, the four examined activities, especially the hardware and capabilities developed, showed relevance across many higher order themes. At an industry level, all case studies participated (even if marginally) in providing opportunities to enhance:

- Economic growth, through potential revenue and spin-out organisations;
- Knowledge and technology, through better (accuracy and speed performance) hardware, measurements and data;
- German / European competitiveness, through time and cost savings enabled by the capabilities developed which can boost commercial uptake and innovation;
- Sovereignty and resilience, through enhanced capabilities and applications in wide-ranging sectors (e.g. public health, catalysis, space, energy, transports, agriculture);
- Regulation and policy-making, through evidence-based decision-making driven by better and more timely data; and
- Entrepreneurship and innovation, through technology development and supporting research organisations and industry R&D.

Two case studies also contributed to improving investment attractiveness. At a societal level, all case studies helped further scientific knowledge, which is unsurprising given the involvement of leading German research institutes. Depending on their focus, they showed relevance across wide-ranging societal themes, from sustainability, to health and well-being, and resilience and governance.

All projects are small contributions within a wider picture. The four Hi-Acts UCI-funded projects were successful and generated benefits, particularly at organisational level. They showed significant potential for emerging impacts, though their limited budget and scope mean that further support and work will be required to build on what has been achieved to ensure that the full impact potential outlined in the case studies is realised. Other factors (e.g., economic and social environment, geopolitics, policy) may also play a role in enabling or inhibiting the realisation of impact.

Looking ahead, assessing the impact of UCI funding may be facilitated if teams are requested to quantify benefits (whether anticipated or estimated) in proposals and reporting.