Preparatory Program for the Einstein Telescope

German Einstein Telescope Research and Development

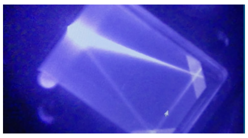
EINSTEIN TELESCOPE

EINSTEIN TELESCOPE
GERMAN R&D PROJECTS

Joint Project D: Mirror Technologies for ET-LF

Vorbereitungsprogramm Projektförderung Einstein-Teleskop (ET-VorPro)
Vorhabenbeschreibung für einen nationalen Forschungsverbund

March 2026



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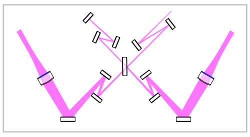

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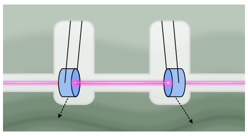

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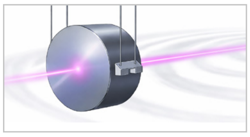
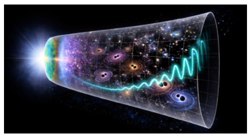


D Mirror Technologies for ET-LF



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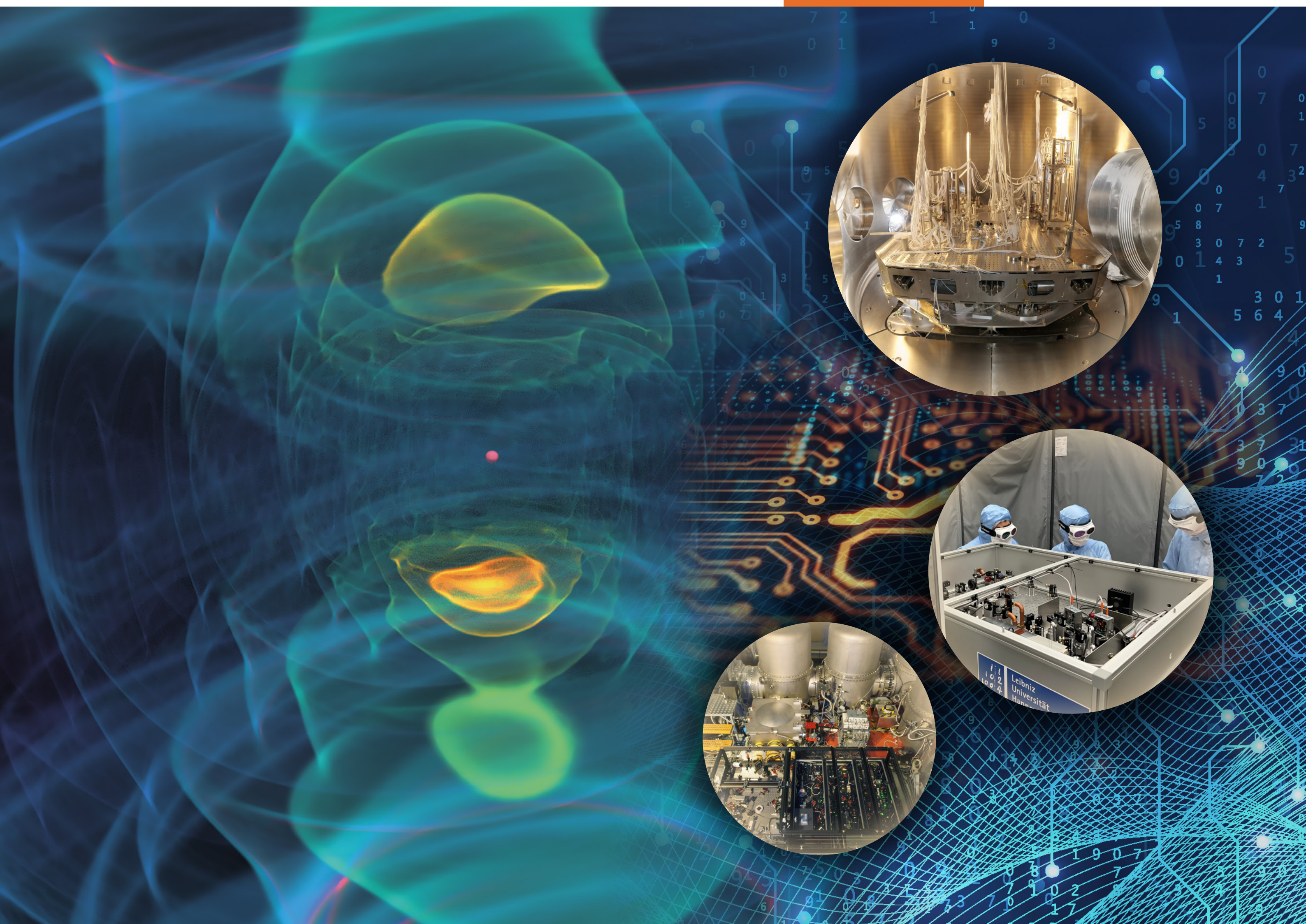


Joint Project D:
Mirror Technologies for ET-LF

ET-RD-D-MiTEL

Abstract

This is one of five topical joint projects coordinated by the German community to prepare for the Einstein Telescope and to enhance the relevant capabilities in Germany for realising the observatory. The topics of the five projects were selected on the basis of three criteria: 1) the leading expertise and scientific excellence of German groups, particularly in key scientific areas and core technologies; 2) the importance and timeliness of the underlying scientific questions; and 3) their expected impact on the international development of the Einstein Telescope.

Joint Project D focuses on the mirror technologies of the low-frequency interferometer (ET-LF), which are central to achieving the targeted sensitivity and represent one of the most demanding technological challenges of the observatory. The ET-LF mirrors require large silicon substrates that combine extremely low optical absorption and excellent mechanical properties with dimensions far beyond those currently achievable using established production methods for ultra-high-purity silicon. Their operation further requires advanced cryogenic suspension systems with low mechanical dissipation, as well as reliable ultra-high-vacuum conditions to ensure stable long-term operation. By combining expertise in crystal growth, materials science and cryogenic engineering, the members will address the key elements of the ET-LF mirror system, including scalable routes for large silicon substrates, suspensions and the operation of cryogenic mirrors in vacuum. The research will be carried out in close interaction with the international ET collaboration and will provide experimentally validated input for the ongoing ET design activities. The results will contribute to strengthening strategic technological capabilities in Germany and support key areas of the High-Tech Agenda Germany, particularly in microelectronics and quantum technologies.

Speakers: Dr. Robert Menzel, Leibniz-Institut für Kristallzüchtung
Dr. Joachim Wolf, Institute of Experimental Particle Physics

Partners:

1. **Deutsches Zentrum für Astrophysik** (DZA)
   - Prof. Dr. Günther Hasinger, Prof. Dr. Michèle Heurs
2. **Leibniz-Institut für Kristallzüchtung** (IKZ)
   - Prof. Dr. Thomas Schröder
3. **Karlsruhe Institute of Technology** (KIT-ETP)
   - Institute of Experimental Particle Physics (ETP), Prof. Dr. Ralph Engel
4. **Karlsruhe Institute of Technology** (KIT-IBPT)
   - Institute for Beam Physics and Technology (IBPT), Prof. Dr. Steffen Grohmann
5. **Ostbayerische Technische Hochschule Regensburg** (OTH)
   - Prof. Dr. Rupert Schreiner

Associated Partners:

7. **Leibniz Universität Hannover** (LUH)
8. **Maastricht University** (UM)
9. **Laboratori Nazionali di Frascati (INFN-LFN)**
10. **Dutch Organisation for Applied Scientific Research (TNO)**

Contents

Title image: Visualization showing the merger of two massive black holes, illustrating the gravitational wave observation named GW-231123. The merging black holes are about 132 and 106 times as massive as our Sun. © I. Markin (Universität Potsdam), H. Pfeiffer (Max Planck Institut für Gravitationsphysik), T. Dietrich (Universität Potsdam und Max Planck Institut für Gravitationsphysik) **Top inset:** View into the 10 meter prototype's central vacuum tank. Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut Hannover) **Middle inset:** Researchers set up the laser source from Hannover at its new location at ETpathfinder. S. Hild/ETpathfinder **Bottom inset:** Unique squeezed-light source at GEO600. H. Grote/Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut Hannover) **Title layout:** Milde Science Comms/formgeber/K. Beil

1 German Einstein Telescope R&D

The Einstein Telescope (ET), Europe's planned next, i.e. third, generation gravitational wave observatory, has reached a critical stage on its path to realization. Its scientific case and conceptual design have been evaluated as outstanding in various international studies and reviews, including the roadmap of the European Strategy Forum on Research Infrastructures (ESFRI). This makes ET a high priority project for the European scientific community.

Within the next three years major milestones will be achieved. These include the selection of the site(s) in a science-driven European process, the preparation of a full Technical Design Report (TDR), the development and implementation of a coordinated research and development (R&D) roadmap, and the preparation of the decision on the realization of the observatory. Germany has selected a Pre-phase (Vorphase) for ET in its national prioritization process for large-scale research infrastructures in 2025, identifying ET as a European lighthouse project and preparing for its realization.

This document presents a proposal submitted in response to the Preparatory Program (Vorbereitungsprogramm), which accompanies the Pre-phase and aims to advance the technologies and scientific methods essential for the construction of the ET within the next three years. The proposal is the result of a coordinated effort across the core of the German ET community and reflects the common strategic priorities developed through a structured national coordination process. Five topical joint projects have been defined that combine and strengthen German expertise in key areas of ET R&D (see Appendix A.2 and A.3). The projects focus on areas in which Germany has strong and emerging world-leading capabilities and in these areas coordinated contributions will have a significant impact on the design and realization of the ET. By bundling expertise across institutions, they establish a coherent national framework through which German contributions can most effectively and credibly interface with the ET Collaboration (ETC) and ET Organisation (ETO), while laying the foundation for the next decade of R&D for the ET. Through the funding of doctoral and postdoctoral researchers, we will train a new generation of experts who will contribute to the long-term development, operation, and scientific exploitation of the ET.

The proposed R&D will further drive innovation in key technologies such as quantum metrology, contributing to Germany's technological sovereignty and competitiveness. The significant scientific and technological challenges of the ET require a coordinated European and global effort. While a centralized R&D roadmap is still evolving, the here presented proposals build on the strong expertise of German researchers and their close embedding within the collaboration to ensure that the five joint projects effectively strengthen the international effort.

1.1 Coordination and structure

The structure and coordination of the joint projects are illustrated in Figure 1.1. Each joint project is coordinated by a team of speakers and co-speakers elected by the respective PIs. A central element is the close coordination with the ETC. Researchers involved in the projects contribute to ETC activities, including leadership roles in divisions and working groups, and provide personnel to key tasks, thereby significantly strengthening the available workforce. This ensures that the projects are closely aligned with the scientific and technical priorities of the collaboration, as e.g. outlined in the Preliminary Technical Design Report (Pre-TDR) (ET-0171A-26) and the ET Blue Book [1].

The projects also coordinate with the Einstein Telescope Organization (ETO), both through direct involvement of project members in ETO activities, such as detector task forces, and through interaction with the German Pre-phase, which implements and extends dedicated German contributions to the ETO. The Pre-phase further establishes national structures that support the projects of the Preparatory Program. Within Germany, the projects of the Preparatory Program and the Pre-phase are coordinated by the German ET coordination team. This team consists of the ETC research unit

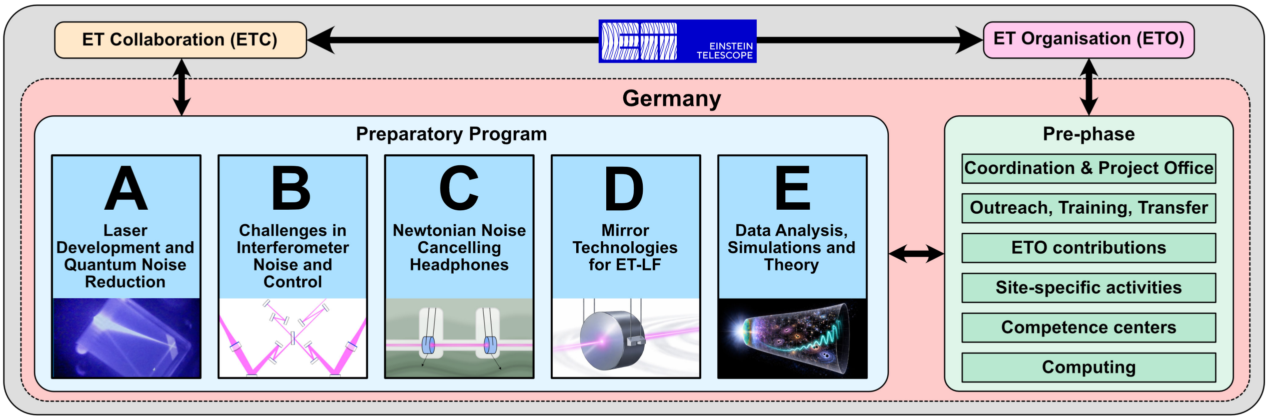


Figure 1.1: Overview of the five joint projects proposed for the Preparatory Program.

leaders in Germany and additional ex-officio members and is chaired by the national representative to the Forum of National Representatives (FNR) of the ETC.

1.2 Support structures and Training

The five joint proposals make use of complementary support structures for **training**, **outreach**, **transfer**, **research data management** and **sustainability**. These structures operate on three levels: (1) existing local structures at participating institutions, such as graduate schools, transfer agencies, and data management frameworks, (2) German-wide structures established and maintained through the Pre-phase, and (3) international structures of the ETC and partner organizations. Together, these levels integrate research, training, and collaboration across institutions, ensure that national activities are aligned with international developments and consolidate distributed expertise into a coordinated German contribution. Within this framework the joint projects will develop and implement coordinated outreach strategies and activities. A research data management plan is available for the joint projects and will be further refined in coordination with the Pre-phase. Doctoral and postdoctoral researchers will receive interdisciplinary training spanning fundamental physics, data science, and engineering. This includes project-specific training, annual lecture weeks, workshops, mentoring, and soft-skill development. The ET community is strongly committed to Diversity, Equity, Inclusion and Accessibility and these principles are implemented across all levels of the program.

1.3 Exploitation of results, Transfer and the High-Tech Agenda Germany

The scientific results will be published (open access) and presented at international conferences. Results relevant to the design, development, and scientific use of the Einstein Telescope will be shared within the ETC and the ETO, ensuring direct integration into the international project.

The methods, technologies, and algorithms developed in the joint projects (see Section 3.2) are highly relevant for the **High-Tech Agenda Germany** (HTAG), in particular for key areas such as **Artificial intelligence** and **Quantum technologies**, as well as strategic research fields such as aerospace. To maximize impact, innovations will be transferred to industry, other scientific domains, and society through structures developed jointly with the Pre-phase.

1.4 Necessity and Urgency of the Grants

The funding is necessary and urgent to (1) position Germany for a leading role in scientific and technological development of the ET by securing the necessary expertise and personnel at this critical stage, (2) ensure that Germany is fully prepared for the forthcoming approval and realization phase of the observatory, and (3) reinforce the international ET project through coordinated, high-impact and strategically aligned contributions. No alternative funding opportunities are available for the proposed projects.

2 Status and preliminary work

2.1 Introduction and Status

As a next-generation gravitational-wave observatory, the ET will comprise dedicated interferometers optimized for high-frequency (ET-HF) and low-frequency (ET-LF) operation. In the low-frequency interferometer, thermal noise is expected to dominate the sensitivity in the astrophysically highly relevant frequency range below several tens of hertz. To reduce thermal noise contributions, ET-LF foresees cryogenic operation at 10–20 K.

At cryogenic temperatures, the mechanical loss, thermal conductivity and optical absorption of the substrate material determine the achievable thermal noise level. Crystalline silicon has therefore been selected as the baseline substrate material for ET-LF due to its favorable mechanical and thermal properties at low temperatures [2]. At 1550 nm, ultra-high-purity silicon exhibits low bulk optical absorption, enabling high circulating laser power. At the same time, silicon is the most important semiconductor material and is produced by a highly developed industry, including a world-leading manufacturer in Germany. While ET can build upon this established technological base, the extreme specifications for ET-LF test masses (mirror diameter larger 450 mm and bulk absorption smaller than 20 ppm/cm) cannot be achieved using currently available industrial production processes.

The implementation of cryogenic interferometry introduces additional technical requirements beyond silicon substrate bulk properties. Residual optical absorption leads to heat deposition that must be extracted at temperatures of 10–20 K. This requires optimized thermal links and stable cryogenic interfaces. In addition, cryogenic operation under ultra-high vacuum (UHV) conditions requires control of ice formation on cold optical surfaces, electrostatic charging and field emission effects, which influence the optical performance.

Joint project D addresses the coupled technological challenges in the production and stable operation of ET-LF mirrors and their suspension. The research activities include silicon substrate development and characterization, investigations of optical absorption and development of monolithic fibres for mirror suspensions, control of ice accumulation in cryogenic environments and mitigation of electrostatic and field-emission-related effects. The partners closely collaborate with leading European groups: the Material and Surface Science Laboratory (INFN-LNF) in Italy, TNO (Department of Semiconductor Equipment), and the University of Maastricht (ET Pathfinder) in the Netherlands. In particular, the joint work with ET Pathfinder spans all key activities, ranging from silicon substrate development and superpolishing of mirrors to cryogenic sensing and in-situ cleaning.

2.2 State of the Art

2.2.1 Silicon Substrates

Two established technologies are currently available for the production of large-diamter, high-purity silicon crystals: the Float Zone (FZ) and the Czochralski (Cz) method. Both offer distinct advantages, but neither fulfills all requirements for ET mirror substrates.

FZ silicon is grown from the melt using induction heating without contact to a crucible or other foreign material. The absence of a container avoids contamination, e.g. with oxygen and carbon $(O,C) < 10^{16}\,\mathrm{cm}^{-3}$ and transition metals. This allows for specific resistivity $> 10\,\mathrm{k\Omega \cdot cm}$. FZ silicon therefore represents the reference material for lowest optical absorption. Bulk optical absorption values below 5 ppm/cm at 1550 nm have been demonstrated for FZ-Si, which is within the range of the ET-LF absorption target [3]. However, inherent FZ process instabilities limit diameter scalability. Despite sustained efforts and demand in the semiconductor industry for 300 mm FZ-Si [4], the maximum achievable diameter has remained at 200 mm for decades, which is significantly below the ET test-mass requirement.

The Cz process for silicon provides substantially better diameter scalability, with crystal diameters up to 450 mm already demonstrated [5,6]. The process is based on growth from a melt contained in a quartz crucible. Heaters and crucible support are made from graphite. As a consequence, oxygen concentrations up to $\sim 10^{19}\,\mathrm{cm}^{-3}$ and carbon concentrations around $\sim 10^{18}\,\mathrm{cm}^{-3}$ are incorporated into the crystal. These impurities are considered a primary source of the optical absorption [7, 8], which is approximately two orders of magnitude higher in Cz-Si compared to FZ-Si and drastically exceeds the ET design specification. The Magnetic Czochralski (MCz) method is an improvement of the Cz process, in which magnetic fields are applied to control melt convection. Time-dependent traveling magnetic fields (TMF) allow for active control of the melt flow pattern, which allows to reduce impurity incorporation and also improve the radial homogeneity of the impurity distribution in the crystal. Complementary to growth approaches, bonding concepts are being explored to realize large monolithic test masses from smaller FZ-Si components. However, a demonstrated route toward simultaneously achieving FZ-like absorption and full ET-scale mirror diameters has not yet been established.

2.2.2 Mirror Suspensions

Suspensions based on silicon or sapphire fibres are foreseen for the ET-LF mirrors with a mass of $> 200\,\mathrm{kg}$ [2]. At 10–20 K, suspension thermal noise is governed by the mechanical loss angle and elastic properties of the fibre material. Both silicon and sapphire exhibit low internal dissipation and high thermal conductivity at cryogenic temperatures. Mechanical feasibility requires breaking strengths of 3–5 GPa and working stresses up to $\sim 1.6\,\mathrm{GPa}$ with safety factors ≥ 4. The fibre geometry must balance dilution factor, violin-mode placement and heat extraction from the mirrors. Interface losses at welds and bonded joints are known to exceed bulk losses and remain a critical problem. The experimental validation of cryogenic suspension concepts for ET-scale mirrors is currently carried out in partner test facilities, including cryogenic Q-measurement setups and investigations of integrated cooling concepts for cryogenic payloads.

2.2.3 Cryogenic/Vacuum Operation

Cryogenic operation of suspended test masses in UHV has been demonstrated at prototype level. Large cryostats integrating multi-stage suspensions, thermal shielding and vacuum infrastructure are conceptually defined for operation of silicon mirrors at 10–20 K. Vacuum technology for large detector towers is well established and derived from second-generation gravitational-wave detectors.

At cryogenic temperatures, cold optical surfaces act as efficient cryopumps, leading to adsorption of residual gases and formation of molecular layers on the mirror surface. For ET-LF mirrors, the rate of cryosorption must remain below approximately one monolayer per year to avoid absorption of laser light in water ice. Techniques such as electron-stimulated desorption (ESD) is an established technology in accelerators (beam scrubbing) and UHV applications. Hot filaments used as an electron source produce light, heat, and increased desorption. Field-emission-based electron sources can avoid these effects, but need further improvement to increase their homogeneity and emission current, and their integration into ET is subject of ongoing research.

2.3 Preliminary work

The members of the joint project D have contributed to several technologies relevant for the cryogenic mirror system of the Einstein Telescope (ET-LF) in recent years.

Previous work addressed ultra-pure silicon materials and suspension technologies for cryogenic mirrors. Quasi-monocrystalline silicon was investigated as a candidate material for cryogenic mirrors [9]. Ultra-pure FZ-Si crystals with resistivity exceeding $10\,\mathrm{k}\Omega\cdot\mathrm{cm}$ were produced for mechanical loss measurements at ET Pathfinder, enabling the qualification of silicon for ET-LF mirrors [10]. Silicon fibre growth and mirror–fibre attachment techniques were developed, supported by numerical modelling of the growth process [11].

Further work focussed on technological challenges associated with scaling silicon mirror substrates. Silicon bonding techniques were developed for assembling larger mirror substrates from high-purity FZ-Si segments, which may enable mirror dimensions beyond the limits of single-crystal growth.

Members of the joint project also contributed to the conceptual design of the ET-LF cryogenic infrastructure and to the definition of the baseline cryogenic payload design [12]. This includes system-level integration studies, vacuum interface concepts and cryogenic suspension approaches based on He-II cooling concepts [13]. Simulations of cryogenic test-mass towers equipped with cryopumps were performed, addressing heat loads in the cryogenic supply as well as the separation of cryostat and suspension-tower vacuum volumes. Experimental studies of cryogenic vacuum conditions have been initiated in dedicated ultra-high-vacuum facilities. This work is further strengthened by the ERC Advanced Grant “GRAVITHELIUM” (2024), which investigates the integration of superfluid He-II cooling into cryogenic payloads [14]. Additional developments addressed vacuum diagnostics and contamination control for cryogenic operation. Field-emission electron sources and diagnostic concepts for ultra-high-vacuum systems were developed, forming the basis for low-heat vacuum gauges and electron-stimulated desorption techniques in cryogenic ET environments.

2.3.1 Challenges

The realization of ET-LF mirrors requires overcoming several interconnected technological challenges. Ultra-high-purity silicon substrates must combine optical absorption levels comparable to FZ material with diameters compatible with ET-scale test masses, which cannot currently be achieved with existing crystal-growth technologies. Cryogenic mirror suspensions must provide low mechanical dissipation while supporting mirror masses exceeding 200 kg and enable efficient heat extraction at 10–20 K. Finally, the operation of cryogenic mirrors in ultra-high vacuum introduces challenges related to cryosorption and ice-layer formation on cold optical surfaces, which requires new approaches for monitoring and mitigation under realistic interferometer conditions.

2.3.2 Infrastructures

The joint project D members provide complementary infrastructure for crystal growth, material characterization, cryogenic suspension testing and cryogenic vacuum facilities.

- Crystal growth infrastructure at IKZ comprising industrial-scale furnaces for FZ and Cz silicon crystal growth, raw-material processing facilities, and laboratories for chemical and electrical material characterization
- Cryogenic UHV infrastructure derived from the KATRIN experiment, including the VINCENT chamber for mirror cooling and surface studies at cryogenic temperatures.
- Nanofabrication facility for the production of field-emission tip arrays for electron sources and vacuum diagnostics.

3 Objectives

3.1 General Objectives

The joint project D adresses the key enabling technologies for ET-LF mirrors, covering the full chain from defining impurity targets and developing crystal-growth processes for ultra-high-purity silicon substrates to superpolishing. The research includes the development and characterization of mirror suspensions, as well as strategies for stable long-term operation of the mirrors and validation under UHV/cryogenic conditions.

- Define material requirements for ET-LF silicon mirrors, including impurity limits, defect-related optical absorption and key material parameters relevant for cryogenic operation and a potential wavelength shift
- Develop scalable technologies for large ultra-high-purity silicon mirror substrates, combining crystal-growth optimization, modelling and alternative approaches such as bonding concepts.
- Establish fabrication and verification of silicon optics, including superpolishing and validation under interferometer-relevant conditions.
- Develop and qualify cryogenic suspension technologies based on silicon fibres capable of supporting ET-scale mirrors while minimizing suspension thermal noise.
- Enable stable operation of cryogenic mirrors in ultra-high vacuum, including monitoring and mitigation of cryosorption processes and development of low-heat vacuum diagnostics.
- Provide validated material parameters, technologies and experimental results as input to the pre-TDR.

3.2 Relevance with respect to the Goals of the Call and the HTAG

A central objective of this proposal is the development of a scalable production process for high-purity silicon. Monocrystalline silicon is the dominant semiconductor material for photovoltaic, microelectronic and power-electronic applications. More than 90% of the world's production is achieved using the Cz growth process [15]. While wafer diameter is a major cost driver in manufacturing (dies per wafer and fab throughput) [6], device performance critically depends on purity and the controlled and homogeneous distribution of dopants and residual impurities.

Ultra-high-purity silicon is particularly important for high-voltage power devices (e.g., IGBTs and MOSFETs) that enable efficient power conversion in renewable-energy systems such as solar and wind power plants [16]. The improvement of MCz-Si purity and oxygen control is needed because ultrapure FZ-Si wafers are not available at diameters > 200 mm. Hence, the planned advances in this proposal also address the material basis for the **HTAG key technologies for microelectronics and climate-neutral energy generation**.

Germany is well positioned to transfer ET-driven developments into industrial application. The Siltronic AG is one of the world's leading producers of ultrapure silicon wafers and represents a key industrial anchor for the materials supply chain. PVA TePla is a major German equipment supplier for crystal growth systems and a potential partner for scaling and industrialization of the developed growth concepts. This German ecosystem supports the call's goals of strengthening technological sovereignty, building long-term expertise and accelerating transfer from research to application.

In silicon-based **quantum technologies**, dielectric losses in the silicon substrate arising from defects and impurities limit superconducting qubit coherence times [17]. The availability of silicon wafers with higher purity than currently commercially available could help reduce these losses and enable improved qubit lifetimes. In addition, low-noise cryogenic technologies developed in this project are directly relevant for emerging quantum-technology platforms. Superconducting quantum circuits and quantum sensors require operation at millikelvin temperatures and ultra-stable cryogenic cooling systems are therefore essential.

Numerical simulations for crystal growth process upscaling will employ and further develop machine-learning techniques, linking this work to the HTAG key technology of **artificial intelligence**.

3.3 Overview of sub-projects

The activities of joint project D are organized around interconnected research programs addressing the key technological challenges of silicon mirror technologies for ET-LF. All partners contribute to common scientific objectives aimed at the development of ET-LF mirrors and their stable operation.

DR1: Silicon qualification and material properties for ET-LF (Projects: D1, D2, D3, D4, D7)
Silicon samples produced in the crystal growth activities are systematically characterized through optical absorption measurements and other material studies, while polished substrates enable precise bulk property measurements at two different operating wavelengths. Together, these activities establish the correlations between impurities, crystal defects and optical performance required to define material targets for ET-LF.

DR2: Large-diameter silicon substrates for ET-LF (Projects: D2, D4)
Different crystal growth methods and a bonding concept for achieving full-scale ET mirror dimensions are investigated, while particular focus is placed on the MCz method as a demonstrated scalable route for large-diameter silicon crystals. Together, these activities aim to identify and develop a viable production path for ultra-pure silicon substrates at ET scale.

DR3: Cryogenic Suspensions (Projects D3, D6)
Growth processes for monocrystalline silicon fibres are developed, while the fibres are subsequently characterized and tested at system level to assess their suitability for ET-LF cryogenic suspensions.

DR4: Stable Operation of Mirrors (Projects: D5, D7)
Mitigation of cryogenic mirror performance limitations through control and removal of ice layers and reduction of residual surface gas.

Project	Partner	PI	research program
D1	DZA	Günther Hasinger	DR1
D2	DZA	Michèle Heurs	DR1, DR2
D3	IKZ	Iryna Buchovska	DR1, DR3
D4	IKZ	Radhakrishnan Sumathi	DR1, DR2
D5	KIT-ETP	Ralph Engel	DR4
D6	KIT-IBPT	Steffen Grohmann	DR3
D7	OTH	Rupert Schreiner	DR1, DR4

Table 3.1: Partner projects and connections to research programs.

3.3.1 Budget

Joint project D requests a total budget of 4287 k€ (including overheads). This includes budget for personnel, consumables, as well as travel funds and other expenses. A detailed table can be found in Appendix A.1.

4 Deutsches Zentrum für Astrophysik (DZA)

PIs: Prof. Dr. Günther Hasinger (Project D1)
Prof. Dr. Michèle Heurs (Project D2)
Dr. Robert Menzel, IKZ (Project D2, D3)
Contacts: Prof. Dr. Günther Hasinger

4.1 The Partner

The German Centre for Astrophysics (DZA) is a major research centre with international visibility that is currently in the build-up phase. Having emerged as the winner of the competition for ideas "Knowledge Creates Perspectives for the Region!" initiated by the Federal Ministry of Education and Research in 2021, the DZA is dedicated to astrophysical research, the development of related technologies and the development of large data science applications. The DZA will be able to operate independently and, as a centre for astrophysics, data science, and technology development, perform cutting-edge research and become a driver of innovation in Lusatia, helping the region in the border triangle of Germany, Poland, and the Czech Republic to make the transition following the lignite phase-out. Research will focus, among other things, on precise measurement techniques for gravitational wave detection. For this purpose, a Low Seismic Lab will be built about 200 meters underground in the Lusatian granodiorite, particularly well-suited due to the low seismic noise in the region.

In the context of the Einstein Telescope, DZA has committed itself to work on the development of the silicon mirror technology. To this end, DZA is collaborating closely with the Leibniz University Hannover (Prof. M. Heurs), the Institute für Kristallzüchtung in Berlin (Prof. Thomas Schröder), and the Institute for Gravitational Research of the University of Glasgow (Dr. M. Henning).

4.2 Project D1: ET Pathfinder Silicon Mirrors

In contrast to currently operating gravitational wave observatories, the baseline design of the Einstein Telescope foresees a so-called ‘xylophone’-concept, with a state-of-the-art interferometer covering the high frequency observation band and a cryogenic low-frequency detector employing new technologies [18]. ETpathfinder [19] has been set been set up as full-interferometer R&D facility for testing, validating and optimising the innovative technologies which will enable the realisation of the ET low frequency interferometers.

Figure 4.1: ETpathfinder facility, Maastricht.

In the first phase of ETpathfinder, the vacuum system hosts two complete Fabry–Perot Michelson interferometers operating simultaneously with different laser wavelengths: 1550 nm and 2090 nm. This is one of the most important experimental features of the facility because it allows to directly compare two candidate technologies for ET.

The Einstein Telescope needs to minimize thermal noise, quantum noise, and optical absorption in their mirrors and coatings. Different wavelengths interact differently with materials such as silicon test masses used in cryogenic detectors. The 1550 nm option has the advantages of mature fiber-laser technology, being compatible with many existing interferometer optics, and lower absorption in some coatings. The challenges are, however, that silicon becomes transparent above 1.1 µm, so that the laser wavelength of 1.5 µm is near the boundary of the good transmission window. The 2090 nm option has the advantages of even better transparency in silicon, potentially lower thermal noise in cryogenic mirrors. However, the laser technology at this wavelength is less mature and harder to stabilize.

By running both wavelengths in parallel, one can directly compare noise behavior, mirror absorption, and interferometer stability in a coupled experiment with different wavelengths and temperature in cryogenic operation. Temperatures of roughly 15 K and 120 K are part of the parameter space being explored. This helps to determine which combination is best for the future Einstein Telescope's low-frequency interferometer.

4.2.1 Preliminary Work

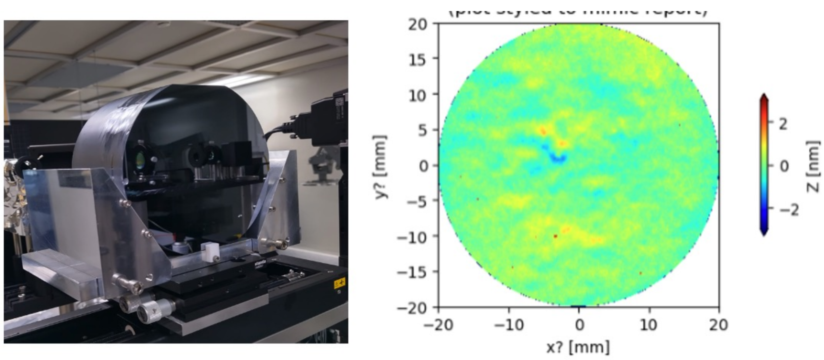


Figure 4.2: ETpathfinder substrate on testbench at LMA (France).

One of the key-aspects (next to seismic-low noise operation, new laser wavelength and advanced quantum noise suppression techniques) of the low frequency interferometers is the cryogenic operation in order to suppress the thermal noise of the mirrors. This requires the use of new materials suitable for cryogenic operation of the main mirrors and silicon is one of the most promising substrates [18]. Recently, the ETpathfinder team has shown that for small mirrors (15cm diameter) silicon substrates of low surface roughness, low absorption, low birefringence and sufficiently low figure errors can be obtained [20]. The key challenge lies here in obtaining a superpolishing of the main surfaces with surface roughness (length scale larger than 1mm) of below 1 nm and a microroughness (sub-millimeter length scales) of below 100 pm, without introducing excess optical absorption at the polished surfaces. To the best of our knowledge right now there is only a single company, Zeiss SMT (Oberkochen) which has been able to demonstrate this capability [20].

Relevant publications

(1) S Hild et al, "Sensitivity studies for third-generation gravitational wave observatories", Class. Quantum Grav. 28 (2011) 094013 [18]
(2) ETpathfinder: Status and Future Plans, presentation at the ET annual meeting, Nov 2025, //apps.et-gw.eu/tds/ql/?c=18228 [20]
(3) ETpathfinder TM Specification; TM drawing, ET-0345A-21, available at //apps.et-gw.eu/tds/ql/?c=16066 [21]

4.2.2 Objectives

While the baseline laser wavelength of ETpathfinder and ET is 1550nm, an interesting case was made within the context of LIGO Voyager to push for an even longer wavelength, i.e. a wavelength around 2 microns. The potential advantages of a wavelength around 2 microns could include access to different coating materials, smaller scattering losses, reduced 2-photon absorption, and related noise terms in case of very high power densities inside silicon substrates. Hence ETpathfinder has set up a parallel research path for an interferometer with 2090nm laser wavelength [19] aiming to develop and validate relevant aspects on optics, laser and squeezing sources as well as photo-detection.

In order to enable this research program and for the German research community to benefit from it, here we ask for the funding of four mirrors to be polished, which are required for the 2090nm ETpathfinder main interferometer.

With this project we would like to help maintain and further develop the technological leadership of the Zeiss SMT company in the field of silicon polishing technology, as well as to enable the German scientific community, specifically the German Center for Astrophysics, to participate in these developments in preparation for the production of the ultimately needed large ET silicon mirrors. The specifications of these mirrors are given in "ETpathfinder TM Specifications" [21].

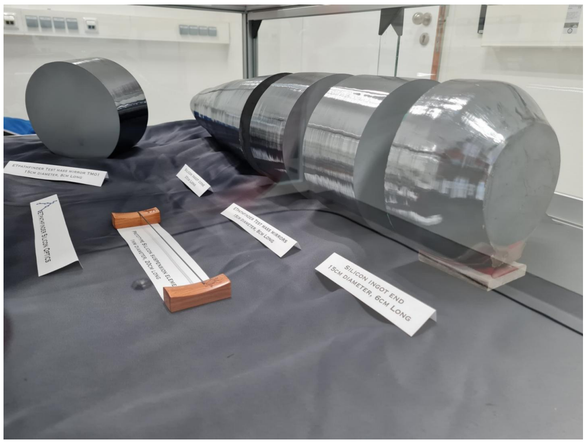


Figure 4.3: Blank and silicon ingots of ET Pathfinder mirrors.

4.2.3 Work Plan

Resources

The costs for these four mirrors are 380,000.00€ + 3,610.00€ taxes for polishing, and 68,000.00€ + 654.31€ taxes for coatings, totaling 453,139.31€.

Schedule and Milestones

- Preparation of the polishing tender (M1-3).
- Execution of the polishing tender (M4-6).
- Production of 4 polished substrates (M7-18).
- Coating of substrates (M19-30).

Collaborators

IKZ, ETpathfinder, TU Dresden

4.3 Project D2: Towards full-scale ET-LF test masses

The success of future cryogenic GWDs such as the Einstein Telescope Low-Frequency (ET-LF) detector relies on the successful development of the main interferometer mirrors and support structures, i.e. the test mass optics and suspensions. The cryogenic test mass mirror substrates and coatings must meet stringent optical absorption and scattering requirements, as well as the requirements for a diameter of ≥45 cm and weight of 211 kg [2]. Currently, the lack of a proven production route that fulfills these challenging specifications is a major risk to reaching the design sensitivity of ET-LF. We thus propose the following pathways to realise full scale ET-LF test mass mirrors.

4.3.1 Preliminary Work

Floatzone silicon grown by IKZ has been shown to have material properties ideal for use in cryogenic GWD optics, providing excellent thermal conductivity, low optical absorption, and low mechanical loss at cryogenic temperatures [10, 19, 22]. Researchers at DZA (in collaboration with the University of Glasgow) have conducted promising preliminary work on direct bonded silicon samples, as seen in figure 4.4.

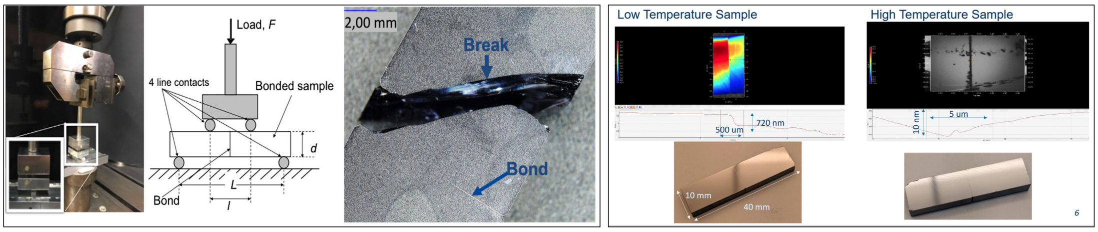


Figure 4.4: Results of initial direct bond testing. Strength testing on left and quality comparison of low and high annealing temperatures on right.

Relevant publications

(1) G Iandolo et al, "Mechanical characterization of silicon for the ETpathfinder test masses", 2025 Phys Rev D 112, 043041 [10]
(2) A Sider et al 2023, "E-TEST: a compact low-frequency isolator for a large cryogenic mirror", Class. Quantum Grav. 40 165002 [22]
(3) A Utina et al, "ETpathfinder: a cryogenic testbed for interferometric gravitational-wave detectors", 2022 Class. Quantum Grav. 39 215008 [19]

4.3.2 Objectives

Bulk silicon of both high optical quality and large diameter satisfying the optical substrate design requirements for ET-LF cannot currently be provided by industry anywhere in the world. The general objective of the project proposed here is to identify the most viable production pathway for the production of ET-LF mirror substrates, based on silicon produced via semiconductor industry-established growth methods such as Float Zone (FZ), Czochralski (CZ), and magnetic Czochralski (mCZ), in combination with bonding techniques to increase substrate size. FZ, CZ and mCZ silicon have been evaluated for the material properties most critical to the operation of cryogenic GWDs, i.e. thermal conductivity, optical absorption at 1550 nm, and mechanical loss at cryogenic temperatures. The diameter of industry standard CZ/mCZ silicon ingots is currently 300 mm; technically, diameters of ≥450 mm are possible, have been demonstrated, and offer economic advantages, but were not adopted by the semiconductor industry due to market dynamics [6].

Additionally, Cz/mCz silicon has been shown to exhibit absorption levels of >1000 ppm/cm due to oxygen, carbon, and other impurities introduced from the crucible and graphite heaters during growth [3]. Therefore, these materials with their currently achievable parameters require active development before they can be considered for use as the ET-LF test mass substrates. Currently, the maximum diameter of FZ silicon ingots is 200 mm – and while there is no *physical* limit to the FZ silicon ingot diameter, scaling the FZ growth process to diameters beyond this remains technologically extremely challenging. However, industry partners have recently started re-investigating the technological expansion of FZ-grown silicon for the high-power electronics sector.

No current method combines both the required large diameter and optical purity that is necessary to produce a silicon test mass suitable for the ET-LF detector. We hence propose conducting essential research and development required to make silicon test mass optics for future cryogenic GW detectors a reality. The work plan below describes a larger research effort to this end, with individual sub-projects pursued by DZA/IKZ from separate funding sources. We will, however, describe our entire research programme here, highlighting the titles of the (interrelated) sub-projects

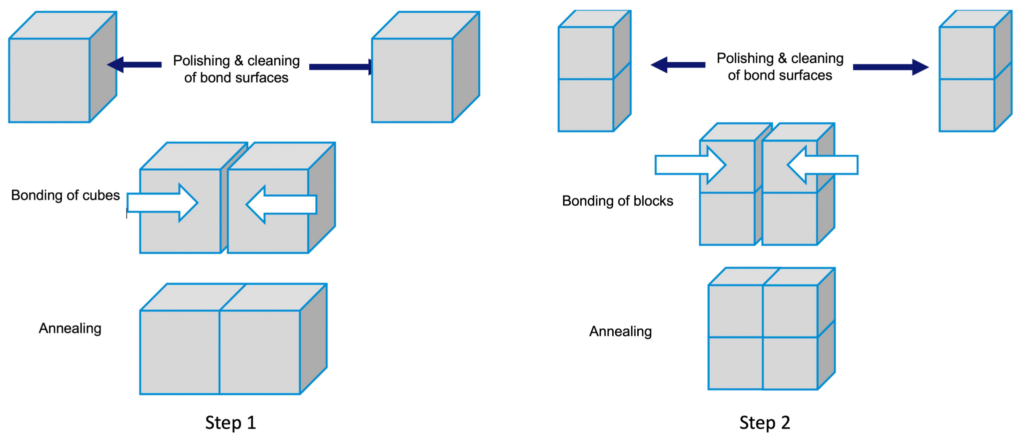


Figure 4.5: Schematic of a 2 x 2 compound test mass produced by consecutively bonding FZ silicon samples of (50 x 50 x 50) mm^3 together.

to be funded within the Vorbereitungsprogramm in **bold** and denoting those primarily outside of the Vorbereitungsprogramm in *italics*.

4.3.3 Work Plan

Development and investigation of composite silicon test masses: Bonding techniques offer a promising path towards larger substrates. We will work towards developing a composite test mass by bonding high-quality FZ silicon samples, polishing, and eventually optically coating the resulting composite to realise a large-diameter composite optic for installation in a future ET-LF detector. In an iterative approach, using first small samples of FZ silicon of (5 x 10 x 20) mm^3, we will identify the best approach to a bonded mass, exploring the parameters needed to create a strong, low-loss bond. The to-be-investigated process steps that influence these parameters include the quality of the polished surface (that is to be bonded), the preparatory bond surface cleaning and etching, the role of the silicon oxide layer, and the bond anneal temperature. The effects of surface quality and polishing compounds on the surface optical absorption of polished silicon [23] will also be studied, as will their impact on bond quality. New collaboration partners (from research and industry) within Germany are actively being recruited for these aspects. The results will allow us to down-select and optimise crucial bond parameters. We will then apply the identified optimal bonding approach to increasingly larger FZ silicon samples (predominantly produced by IKZ, compare also Project D3). We will upscale the composite test masses by first using (30 x 30 x 30) mm^3 cubes and later (50 x 50 x 50) mm^3 cubes, eventually resulting in a composite optical substrate of (100 x 100 x 50) mm^3, see figure 4.5.

Surface and bulk silicon characterisation: We will characterise the surface and bulk optical absorption of small polished and bonded silicon samples in our labs at DZA by photo-thermal common path interferometry (PCI) and photo-thermal deflection (PD) measurements, and investigate the mechanical properties of the bonded samples using a strength testing setup (the experimental setups will be procured and provided by DZA from funding outside of this proposal). We have already identified potential collaborators with crystallographic measurement capabilities that exceed our means (such as Transmission Electron Microscopy) and nano-fabrication laboratories offering advanced chemical treatment processes (at Technische Universität Dresden). We will expand our evaluation of optical and mechanical properties to include samples produced by alternative crucible-free growth concepts (e.g., large-area seeding, cf. Nathan Stoddard) and compare them with conventionally grown mCz and FZ silicon (from IKZ, compare also Project D4, and potentially also from other sources).

Modelling: In parallel to the above research directions, we will conduct machine-learning driven scalability analyses together with IKZ, using process simulations and finite element modelling (FEM) of critical material properties for test mass geometry and integrity, including loss and thermal noise investigations.

Metrology for large-diameter silicon optics for ET-LF: The metrology (and handling) of large-diameter silicon substrates remains an underdeveloped research area, which is nonetheless essential for ET. We plan optical metrology to characterise surface, bulk, and total absorption, scatter, reflectance, and transmission of large-diameter silicon optics for the ET-LF detector, regardless of where the optics will be produced.

Enhancing the capabilities of the magnetic Czochralski growth approach: While the upscaling of FZ silicon by bonding is a promising approach, its success is not guaranteed. It is therefore crucial to further research the possibilities of using magnetic Czochralski-grown silicon, by ascertaining its suitability as a substrate for the end test masses (these are not subject to high transmitted optical powers, so the requirements regarding optical absorption and scattering are less stringent), and/or by improving the mCZ process enough to make mCZ-grown silicon sufficiently pure to be suitable as an input test mass. We will evaluate mCZ silicon samples produced within Project D4 via optical absorption measurements at DZA to determine the radial uniformity of material properties across large-diameter ingots. Asymmetric arm cavity topologies using a combination of FZ and mCZ silicon test masses will be investigated by simulations, as well as scalability modelling (simulations on diameter upscaling of (m)Cz and FZ silicon) using machine learning methods (see also "Modelling" above).

Development of larger-diameter FZ silicon: We will continue our collaboration with silicon growth partners, helping to drive the development of FZ silicon to larger diameters (> 200 mm) by offering collaboration and feedback on their silicon growth processes in the form of measurement and characterisation of the optical and material properties of the grown silicon, and sustaining industrial/scientific interest in the development of larger-diameter FZ silicon.

Resources

- 75% x FTE (3 years) doctoral researcher for simulations on diameter-upscaling of (m)Cz and FZ silicon using machine learning methods (WP4):
  This is intended to be a shared position between IKZ and DZA, making use of existing expertise at both institutions and fostering deeper cooperation on this topic.
- 2 x 100% x FTE (3 years) postdoctoral researchers:
  PD1 will be focusing on bonding technologies (WP3); PD2 will be responsible for optical metrology (WP1 and WP2). Both positions will be located primarily at DZA and collaborate intensively. They will individually also work closely together with the collaboration partners at IKZ and IGR Glasgow (on bulk material properties and bonding technologies) and at LUH (on optical metrology).
- invest & software 313 k€:
  200 k€ for the outsourcing of specialised polishing services to research and industry
  113 k€ for simulation software licenses (Comsol Multiphysics)

Schedule and Milestones

Project Work Packages	2026		2027				2028				2029	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
WP1 Comparison of silicon growth approaches for suitability in GWDs												
WP1.1 Optical metrology of FZ silicon (from D3), incl. absorption				M1								
WP1.2 Optical metrology of mCz silicon (from D4), incl. absorption								M2				
WP1.3 Optical absorption measurements of Cz silicon & other methods												
WP2 Surface and bulk characterisation of silicon optical parameters												
WP2.1 Measure effect of polishing compounds on surface optical absorption						M3						
WP2.2 Measure and compare bulk optical absorption of silicon (FZ/(m)Cz/?)								M4				
WP3 Composite silicon test mass optics												
WP3.1 Small-scale bonded silicon test mass prototypes					M5							
WP3.2 Small-scale prototype testing (strength/optical absorption)												
WP3.3 Large-scale bonded silicon test mass prototype									M6			
WP3.4 Large-scale prototype testing (strength/optical absorption)												
WP4 Modelling												
WP4.1 Machine-learning-driven scalability modelling for mCz and FZ upscale									M7			
WP4.2 FE modelling (COMSOL) of material properties of composite optics												
WP5 Large diameter silicon optics metrology lab												
WP5.1 Optical absorption setup for ET-LF scale optics												
WP5.2 Scatter/Reflectance/Transmission setup for ET-LF scale optics												

Funded through this project — Funded elsewhere

Milestones

- M1: Baseline optical absorption measurements for Project D3
- M2: Baseline optical absorption measurements for Project D4
- M3: Downselection of viable polishing compounds, based on surface optical absorption
- M4: Define viability of different silicon growth methods, based on bulk optical absorption
- M5: Successful small-scale composite test mass prototype
- M6: Successful large-scale composite test mass prototype
- M7: Initial mCz and FZ scalability models created

Collaborators

Institut für Kristallzüchtung (IKZ)
Dr. Margot Hensler Hennig, external scientific consultant
Institute for Gravitational Research of the University of Glasgow, UK
Technische Universität Dresden (TUD)

5 Leibniz-Institut für Kristallzüchtung (IKZ)

PI: Prof. Dr. Thomas Schröder (Project D3-D4)
Priv.-Doz. Dr. habil. Radhakrishnan Sumathi (Project D4)
Dr. Iryna Buchovska (Project D3)
Contact: Dr. Robert Menzel (Project D2, D3)

5.1 The Partner

The Leibniz-Institut für Kristallzüchtung (IKZ) is an internationally recognised competence center for a wide range of crystalline materials. It has a strong expertise in high-purity silicon crystal growth for advanced scientific and technological applications, particularly in the semiconductor industry. IKZ develops and optimizes scalable silicon growth techniques, including Float Zone (FZ) and Czochralski (Cz), with a focus on crystal quality, impurity incorporation, defect formation and material homogeneity. A key strength of IKZ is the tight integration of crystal growth process development with numerical simulation, growth equipment engineering, and systematic material characterization. The available infrastructure includes specialized FZ and Cz crystal pullers. Within the ET collaboration, IKZ participates as Research Unit Berlin and has been actively contributing to ET-related material R&D, addressing silicon crystals for mirror substrates and suspensions.

5.2 Project D3: High-performance crystalline silicon for ET application

5.2.1 Preliminary Work

For several years, members of the ET working group at IKZ have been developing and investigating silicon materials for gravitational wave detectors, including the Einstein Telescope and its prototypes. In recent years, IKZ has fabricated multiple bulk silicon crystals using various growth methods to evaluate their quality and suitability as mirror substrates. This includes studies of optical and mechanical properties of quasi-monocrystalline crystals produced by directional solidification, a method capable of yielding exceptionally large crystals and offering a promising alternative to conventional high-purity, smaller-scale growth technologies [9]. In addition, IKZ has grown several large, high-purity crystals using the Float-Zone technique for mirror applications in ET prototypes at Glasgow University and ET pathfinder (Fig. 5.1). These materials subjected to rigorous testing for mechanical losses at both room and cryogenic temperatures, confirming their high homogeneity, quality, and suitability for reliable mirror performance [10].

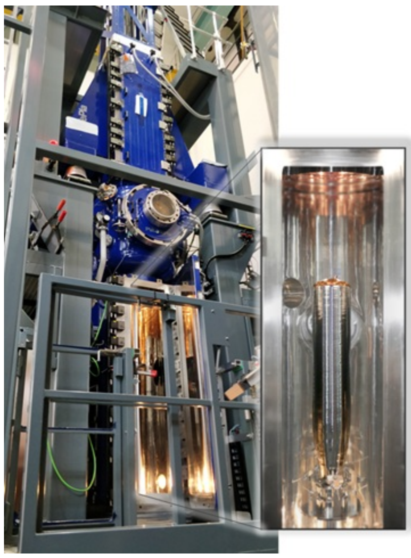


Figure 5.1: IKZ FZ-30 puller with high-purity crystal.

Since 2020, IKZ has also conducted extensive research on the growth of monocrystalline silicon fibres for mirror suspensions in ET [11]. The developed fibres demonstrate excellent quality, high uniformity, and strong process reproducibility.

The PI has extensive experience in developing high-quality silicon crystals for advanced applications [24]. She is a member of Research Unit Berlin and has been directly involved in the above research, including its scientific coordination. In addition, she serves as Co-Chair of the Low-Frequency Core Optics Work Package within the ET Collaboration.

Relevant publications

- Quasi-monocrystalline silicon for mirrors in cryogenic gravitational-wave detectors [9].
- Monocrystalline silicon fibres for mirror suspension in gravitational-wave detectors [11].
- High-performance multicrystalline silicon material for PV [24].

5.2.2 Objectives

Crystalline silicon for application in the ET must meet exceptionally stringent material requirements, with particular emphasis on low optical absorption under operating conditions. Previous studies indicate that bulk absorption correlates with impurity concentration [3]. However, it is still unclear whether specific impurities have a disproportionate effect, and which species and concentration levels are critical for optical performance under ET operating conditions. Similar gaps exist for other key optical parameters, such as birefringence and the thermo-refractive coefficient, for which available data are limited and partly inconsistent. In addition, impurity-related mechanical losses have been indicated but not systematically studied under ET-relevant conditions [10]. These uncertainties hinder predictive optimization and scalable production of compliant mirror substrates.

Requirements for suspension materials are governed by thermal and mechanical properties, as well as compatibility with mirror substrates. As the central elements are thin fibres, their performance (e.g., safety factor, breaking strength, bending stress, thermal noise) depends on both intrinsic material properties and fibre geometry. While previous studies demonstrate promising average properties, their statistical distribution requires improvement, likely through process optimization. Another key challenge is the mirror-to-fibre attachment, expected to rely on fibres with tailored shape profiles. The optimal profile for achieving the required suspension performance remains unknown, and the corresponding reproducible fabrication processes have yet to be established.

The project addresses these challenges through the following approaches:

- Quantify the effects of process parameters and contamination on silicon under ET conditions.
- Define fabrication conditions for silicon fibres with optimized geometry and performance.
- Establish a quality baseline for ET-relevant silicon substrates and suspensions.
- Provide ultra-pure FZ silicon as reference material for benchmarking and further development.

5.2.3 Work Plan

WP1: Development of an experimental basis for impurity- and process-controlled silicon.

This work package establishes a comprehensive experimental dataset for silicon with predefined impurity profiles and controlled process conditions. FZ and Cz techniques will be used to grow bulk crystals with systematically varied impurity contents and growth parameters. Particular focus will be placed on impurities relevant for ET operation, including oxygen, carbon, electrically active donors and acceptors, and metallic contaminants. Some impurities will be intentionally introduced, while others will be process-related. The work will comprise at least eight series of growth experiments, each varying a single key parameter. Impurity distributions will be quantified using direct analytical techniques (e.g., ICP-MS, FTIR) and also using indirect characterization (e.g., charge carrier lifetime, photoluminescence imaging, resistivity profiling). Measurements will be conducted both in-house and with external partners. A similar approach will be applied to silicon fibre growth using FZ and pedestal techniques. At least 80 experiments are planned, organized into series varying fibre dimensions, shape profiles, and process conditions affecting homogeneity. Particular attention will be given to terminal sections (heads) for mirror-to-fibre attachment. fibre uniformity and profile will be systematically monitored and documented. This work package will result in a comprehensive, structured database enabling detailed analysis.

WP2: Systematic study of impurity and process effects on key material properties.

This work package investigates how impurities and process conditions affect the optical, thermal, and mechanical properties of crystalline silicon. Materials from WP1 will be characterized under ET-relevant conditions. For bulk silicon, focus will be on optical absorption, birefringence, thermo-refractive coefficient, and mechanical losses. For fibres, key parameters include Q-factor, breaking strength, bending stress, thermal noise, and their statistical distributions. Part of the characterization will be performed at partner facilities and within related association projects (e.g., D2 project at DZA and D7 project at KIT-IBPT), with additional measurements by external collaborators. The data will be analysed and correlated with WP1 results to establish relationships between material properties, impurity content, and processing conditions. The goal is to identify and quantitatively describe the mechanisms governing silicon performance in ET applications.

WP3: Fabrication of ultra-pure 6-inch FZ-Si reference substrates.

This work package complements the previous activities by providing high-performance benchmark material to serve as a reference for large-scale mirror substrate development and downstream association activities. Ultra-pure 6-inch FZ silicon crystals will be grown and processed into substrates. These materials will serve as a reference for comparison with MCz silicon developed within the D4 project and will support bonding studies conducted within the D2 project.

Resources

- 75% x FTE (3 years) doctoral researcher for WP1 - WP3.
- 50% x FTE (3 years) engineer for crystal growth support, process preparation, and post-treatment.

The project builds on established silicon growth infrastructure at IKZ, including crystal pullers (Fig. 5.1) and fully equipped laboratories for material preparation and characterization. We request 142 k€ for consumables (high-purity feedstock, slim rods, seeds) and advanced characterization.

Schedule and Milestones

	2026		2027				2028				2029	
	III	IV	I	II	III	IV	I	II	III	IV	I	II
WP1. Development of an experimental basis for impurity- and process-controlled silicon.												
WP1.1. Growth of bulk silicon crystal series with controlled impurities and process conditions												
WP1.2. Growth of crystalline silicon fibre series with controlled profile and process conditions												
WP1.3. Quantification of impurity and dimensional profiles in series WP1.1 and WP1.2						M1						
WP2. Systematic study of impurity and process effects on key material properties												
WP2.1. Measurement of key bulk material properties in the silicon crystal series WP1.1												
WP2.2. Measurement of key fibre properties in the crystal series WP1.2												
WP2.3. Analysis of data WP1.3, WP2.1 and WP2.2 and interpretation of impact mechanisms										M2		
WP3. Fabrication of ultra-pure 6-inch FZ-Si reference substrates												
WP3.1. Growth of ultra-pure 6-inch FZ-Si crystals												
WP3.2. Comparative characterization of FZ-Si and Cz-Si substrates WP1.1. and WP3.1												M3
WP3.3. Provision of FZ-Si substrates for bonding development						M4						

Milestones:

- M1: Defined impurity- and process-controlled silicon material basis available.
- M2: Quantitative impact relationships established.
- M3: Quantitative FZ-Si / Cz-Si benchmark established.
- M4: FZ-Si substrates supplied for bonding-based scaling approaches.

Collaborators

DZA, KIT-IBPT, Maastricht University, University of Glasgow, University of Ferrara, Perugia University. Collaboration partners will be provided with silicon substrates and fibres for relevant parameter measurements and research on silicon bonding.

5.3 Project D4: Magnetic Czochralski (MCz) Silicon crystals for ET-LF Mirror Substrates

5.3.1 Preliminary Work

Over the past years, IKZ has investigated the production of crystalline silicon (Si) using different growth methods: i) Directional solidification (quasi-mono) [9], ii) Float-Zone (FZ) [10], iii) Czochralski (Cz), for application as a substrate material for the Einstein Telescope (ET)-Low frequency (LF). Combined with systematic defect and impurity analyses, this work has provided the material basis for mechanical characterization and optical absorption studies within ET-Pathfinder. Currently, ultra high pure FZ-Si is validated as the current benchmark substrate material for cryogenic ET test masses. In the area of Cz growth, magnetic-field-assisted Si (MCz-Si) has been investigated at IKZ to control melt convection and impurity transport. Preliminary 3D simulations were performed to study the application of travelling magnetic fields (TMF) in the Cz process [25]. Experimental validation was successful across multiple scales. IKZ has also patented and developed a self-crucible growth method for avoiding crucible contact and the associated contamination, while overcoming the diameter limitations in FZ growth [26, 27]. 4-inch diameter crystals were demonstrated. These research activities are directly relevant to achieve ultra-high-purity Si for ET-LF substrate material.

The project PI Dr. habil. R. R. Sumathi has several years of experience and strong expertise in crystal growth, materials research, and technology development [28–30]. In her current research work on ultra-high purity germanium (uHPGe), within the framework of LEGEND project, Ge single crystals with net carrier concentrations in the range of 10^{10}-10^{11} cm^{-3} and low dislocation densities were achieved [31–33].This demonstrates process-chain control at ppt-level impurity concentrations, which is transferable to MCz-Si growth. She has recently joined the ET Research Unit Berlin.

Three relevant publications

[1] R. R. Sumathi et al. (2023), "Development of large-Diameter and very high purity Ge crystal growth technology for devices", Cryst. Res. Technol. 58, https://doi.org/10.1002/crat.202200286.
[2] P. C. Palleti, et al. (2024), "Properties of a highly compensated high-purity germanium", J Mater Sci: Mater Electron, 35:57, https://doi.org/10.1007/s10854-023-11814-8.
[3] P.C. Palleti, et al. (2026) "Impact of crystal defects on carrier transport properties in high-purity germanium Crystals", Mat. Sci. & Eng. B 324:119048, https://doi.org/10.1016/j.mseb.2025.119048.

5.3.2 Objectives

The test mass mirrors are the key components enabling the performance of the ET-interferometer. The choice and quality of mirror materials under cryogenic conditions are crucial, as they determine both the reduction of thermal noise and the long-term stability of the test masses. Silicon is considered as the best baseline material for ET-LF test masses due to its outstanding mechanical and thermal properties at low temperatures [2] . The Cz and FZ crystal growth techniques are the two main industrially established methods for producing bulk Si crystals. However, no single method has yet achieved both the size(mass) and crystalline(optical) quality requirements of Si mirror substrates simultaneously, representing a critical technological and scientific gap for realizing the ET infrastructure. Given that the Cz method offers better scalability, focusing on enhancing crystal quality and purity may render the production of suitable mirror substrates feasible. In this project, we aim to establish the TMF assisted Czochralski (MCz) as a viable technique to attain both the size and quality at the same time. More advanced and targeted processing approaches will also be investigated, including the combined MCz-self-crucible method.

The main objectives of the project are as follows:-

- Reducing impurity concentrations in the Cz growth of 6-inch diameter Si crystals, using (i) travelling magnetic fields, (ii) self-crucible technique, (iii) combining TMF and self-crucible, (iv) tailored coating process for crucibles.
- Quantifying impurity concentrations using advanced measurement techniques (e.g. Photothermal ionisation spectroscopy (PTIS), Accelerator mass spectroscopy (AMS).
- Correlating the quality of the MCz-Si with the FZ Si crystals.
- Achieving ultra-low absorption levels in the MCz-Si as required for ET mirror substrates.
- Establishing scientific and technological basis for scaling-up this process to large-diameter Si substrates suitable for ET mirrors.

5.3.3 Work Plan

The project consists of the following four work packages:

WP1: Technological modification of the existing 6-inch Cz-equipment and MCz-Si crystal growth. The Cz growth equipment (model-EKZ2000) at IKZ will be upgraded and extended for controlled 6-inch (15 cm) diameter crystal growth. This includes the implementation of an automatic diameter measurement and control system and the integration of advanced magnetic field capabilities (WP1.1). Initial crystal growth experiments will be performed to optimize the magnetic field parameters (WP1.2). Then the crystals will be continously grown. Within this technology development, systematic study of the growth process and improvement of purity, with a focus on minimizing contamination from the crucible–melt interface, will be carried out as a scientific part (WP1.3) and will form part of the PhD thesis. The development of MCz equipment and processes is supported by numerical simulations (WP1.4), which are used to guide parameter selection and reduce the experimental parameter space. Material characterization accompanies all growth campaigns to provide direct feedback on achieved purity and optical performance.

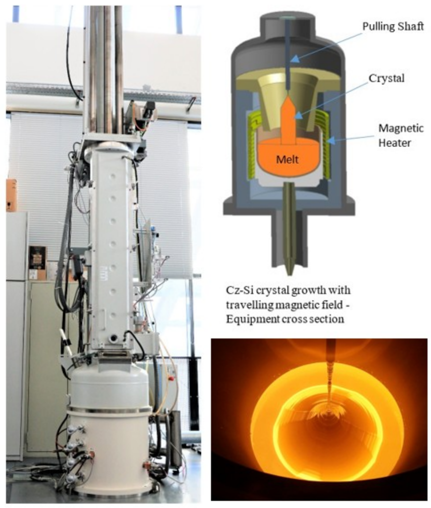


Figure 5.2: Cz-equipment (6-inch dia.) at IKZ with a sketch of the planned TMF-MCz-set-up and a photo during crystal growth.

WP2: Implementation of the novel self-crucible method. A self-crucible concept [26] minimizes the incorporation of impurities from the crucible material (WP2.1). Furthermore, combining TMF and self-crucible concept will be a good approach to further eliminate direct contact between the Si melt and the quartz crucible (WP2.2). In addition, crucible coatings (e.g. Si_3N_4), and graphite heater coatings, for e.g., SiC, will be investigated to limit contamination originating from these foreign materials (WP2.3). Possibilities for scaling up the process to the required diameter will be explored in collaboration with industry partners.

WP3: Quantifying the concentrations of oxygen, carbon and other trace impurities in MCz-Si – Correlating the results with ultra-pure FZ-Si. Conventional Cz growth involves contamination of the crystal from the quartz crucible and graphite heaters. This leads to the incorporation of oxygen (up to 10^{19} cm^{-3}) and carbon (around 10^{18} cm^{-3}) into the crystal [34, 35]. These impurities are widely regarded as the dominant contributors to optical absorption at 1550 nm [3]. Hence, individual measures are essential in systematic crystal growth experiments. Within WP3.1, a targeted reduction towards oxygen concentrations of $4-8\times10^{16}$ cm^{-3} will be pursued. Growth parameters such as TMF frequency, crystal/crucible rotation, and chamber pressure will be adjusted iteratively. In WP3.2, the quality and purity of MCz-Si will be directly correlated with the ultra-high-purity FZ-Si standard reference, and this research activitiy is interrelated with WP3.2 in D3 Project.

WP4: Evaluation of the effects of impurities and point defects on key material parameters of MCz-Si for ET-LF application. In the work package WP4.1, particular emphasis will be placed on specific characterisation of material properties (optical absorption, mechanical losses, temperature dependent refractive index, etc.) required for the ET mirror substrates, and interrelated with the measurements in the D2 project. In addition, the focus will lie on the control and analysis of the point-defect balance and its radial distribution across the crystal (WP4.2). Vacancy- or interstitial defects, in the presence of oxygen can affect the optical absorption homogeneity. A systematic investigation on the effect of impurities and point defects on the Si mirror properties will be carried out (4.3), and this study will be part of the PhD thesis.

Resources

- 75% x FTE (3 years) doctoral researcher for scientific study: WP1 – WP4.
- 100% x FTE (3 years) engineer for the development of TMF-MCz equipment and continuous crystal growth support, raw material preparation, and crystal machining: WP1 – WP2.
- 20% x FTE (3 years) post-doc for simulation of the equipment / growth process: WP1 – WP2. The Czochralski equipment infrastructure available at IKZ must be upgraded to enable the growth of ultra-high-purity silicon crystals for use as ET-LF mirror substrates. We therefore request 181 k€ for the investment, along with an additional 95 k€ for implementing diameter control. Furthermore, we request 163 k€ for consumables (silicon raw materials, graphite heater elements, and quartz crucibles (both coated and uncoated)).

Schedule and Milestones

Project Work Packages	2026		2027				2028				2029	
	Q1	Q2	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
WP1: MCz-Si crystal growth												
WP1.1. TMF integration and diameter control	■	■	■	M1	■	■						
WP1.2. Magnetic field parameter optimisation		■	■	■								
WP1.3. Improving the purity in MCz-Si growth					■	■	■	■	■	M2	■	■
WP1.4. Numerical Simulation	■		■	■			■			■		
WP2: TMF + self-crucible, and crucible coating												
WP2.1. Self-crucible approach		■	■	■	■	■						
WP2.2. Combined TMF – self-crucible approach					■	■	■	M3	■	■		
WP2.3. Tailored coatings on crucibles/heaters				■	■	■	■	■				
WP3: Quantification & correlation of impurities												
WP3.1. Targeted oxygen reduction (~10^{16} cm^{-3})						■	■	■	■	M2		
WP3.2. Correlating MCz-Si and FZ-Si properties										■	M4	
WP4: Evaluation of material properties for ET												
WP4.1. Optical absorption and mechanical-loss					■	■	■	■	■	■	■	■
WP4.2. Point defect distribution analyses								■	■	■		
WP4.3. Impurities/defects on mirror properties							■	■	■	■	■	

Milestones:

- **Jun 2027:** M1: Cz-equipment modified with TMF for MCz crystal growth
- **Nov 2028:** M2: Improved purity in MCz-Si and targeted oxygen concentration achieved.
- **Jun 2028:** M3: Combined "MCz + self-crucible" growth approach attained
- **Mar 2029:** M4: Trace-level impurities quantified and MCz-Si correlated with FZ-Si.

Collaborators

1) Deutsche Zentrum für Astrophysik (DZA): for ET-relevant material property measurements; 2) Helmholtz Zentrum Dresden-Rossendorf(HZDR): for quantification of trace impurities in Si; 3) University of Maastricht: for testing Si Mirrors for ETpathfinder; 4) Siltronic AG: for future scaling-up of the MCz-Si growth process.

6 Institut für Experimentelle Teilchenphysik (ETP) des Karlsruher Instituts für Technologie (KIT)

PI: Prof. Dr. Ralph Engel (Project D5)
Contacts: Dr. Joachim Wolf (Project D5)

6.1 The Partner

The Karlsruhe Institute of Technology (KIT) is "The Research University in the Helmholtz Association", combining both a large variety of university-level research projects and large-scale projects that require a strong national research facility in the framework of the Helmholtz Association. With more than 10 000 employees and about 23 000 students, KIT offers a wide range of expertise and a research-based study programme for our students.

The Institute for Experimental Particle Physics (ETP) is part of the KIT centre KCETA that accommodates experimental and theoretical research, and education at the interface of astrophysics, particle physics, and cosmology. Apart from the participation in other large-scale experiments, the KATRIN neutrino mass experiment at KIT offers 25 years of expertise in designing, manufacturing, and operating large-scale UHV and cryogenic equipment [36–38].

6.2 Project D5: Controlling of ice layers on cryogenic mirrors

The 10 K cryogenic mirrors of the ET-LF interferometers will accumulate water ice and other gases over time. The rate of condensation has to stay below 1 mono-layer per year. This project aims at monitoring, controlling, mitigation, and removal of ice layers on the cryogenic mirrors of the ET-LF interferometers. This project is interconnected in part with project D7.

6.2.1 Preliminary Work

Based on available equipment from the KATRIN R&D phase, the "VINCENT" vacuum chamber (Fig. 6.1) has been set up at KIT as a test environment for the investigation of ice layers on cold

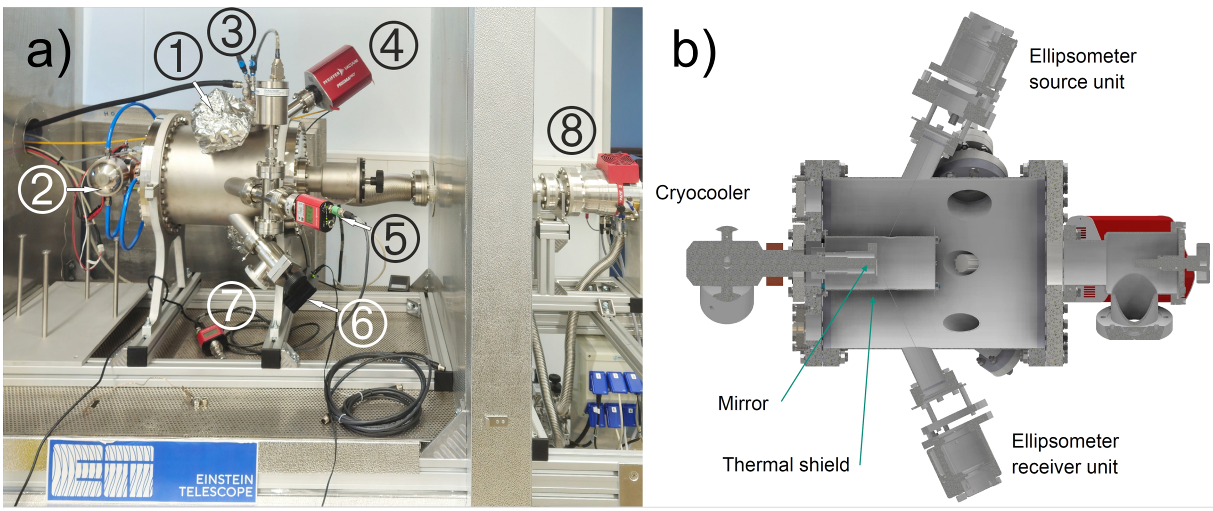


Figure 6.1: The "VINCENT" cryogenic vacuum test chamber at KIT. **a)** existing vacuum chamber: (1) window for ellipsometer, (2) cryo-cooler 40 K, (3) microwave plasma source, (4) RGA, (5) wide-range vacuum gauge, (6) UV light source, (7) valve for gas inlet, (8) TMP. **b)** CAD drawing of the internal holder for sample mirrors with cryo-shield.

silicon mirror surfaces. First commissioning tests involve moderate thermal baking (100 °C). Ellipsometry is available to start first test measurements of growing ice layers on the mirror. The Si-mirror and the surrounding cryo-shield can be cooled down to 40 K by a cryo-cooler (*LIHAN TC4188*). A gas inlet system controls the gas flow into the UHV chamber, defining the pressure at the mirror.

In addition, a vacuum setup initially developed to measure outgassing rates from different materials for the KATRIN experiment, can be used for material screening and selection.

Relevant publications

- Commissioning of the vacuum system of the KATRIN Main Spectrometer [36].
- The design, construction, and commissioning of the KATRIN experiment [37].
- Characterization of the KATRIN cryogenic pumping section [38].

6.2.2 Objectives

This project will operate the UHV chamber in Fig. 6.1 to investigate cryosorption of water vapour and other gases on cryogenic mirrors. The first objective is the measurement of the rate of growth of the ice layers. Initially this will be done with the available ellipsometer setup.

In the final ET cryostats with diameters of up to 4.5 m, ellipsometry might not be as easily applicable as in the small test setup. In addition, stray light from ellipsometry can disturb the highly sensitive signal of the interferometer. Therefore, our second objective is the adoption of a well established technology in vacuum coating applications, a quartz micro balance (QMB), for monitoring the thickness of layers at cryogenic temperatures. QMBs are generally used well above room temperature. The resonance frequency of the Quartz oscillator changes with temperature and the mass of the adsorbed material. Currently no systems are available for cryogenic temperatures at 10 K. Starting with existing QMB systems, a QMB sensor and operation method have to be developed that provides reliable data at low cryogenic temperatures. The small sensor would be attached close to the mirror and kept at the same temperature. This would allow the continuos long-term monitoring of the accumulation of ice without disturbing the delicate balance of the mirror suspension. We will also look into the integration of an ellipsometry system in ET for regular cross calibration.

The stringent vacuum requirements demand careful material selection and cleaning procedures, as well as conditioning of the vacuum chamber after pump-down, mainly removing water and hydrocarbons from the inner surfaces. Since the usual vacuum baking is prohibited by the delicate inner suspensions of the mirrors and the mirrors themselves, we will investigate the efficiency of non-thermal methods, such as argon-plasma cleaning, ozone cleaning, and UV cleaning. For accurate and reproducible measurements with the VINCENT test chamber, a viable conditioning procedure is need after each venting and pump-down, removing water after the contact with humid air.

A further objective is the systematic screening of materials with low outgassing rates that are allowed to be used inside the vacuum chambers of ET. This will be a collaborative effort of the ET collaboration. We will use an improved version of the outgassing setup from the KATRIN experiment to contribute to this task.

An in-situ method to remove ice layers from cold mirrors will be tested, using electron-stimulated desorption (ESD) with electrons from a field emission source (FES) developed in project D7.

A "hot cathode" vacuum gauges with a glowing filament can produce additional outgassing, heat and light. We plan to measure the effect on the cold mirror and compare it to the D7 FES-gauge.

6.2.3 Work Plan

The project is structured into six work packages:

- **WP1** measures the growth rate of ice layers on the cryogenic mirror with the ellipsometer.
- **WP2** develops and tests QMB sensors for cryogenic temperatures down to 10 K.
- **WP3** investigates non-thermal conditioning of UHV vacuum chambers.
- **WP4** contributes to the systematic outgassing tests in the ET collaboration.
- **WP5** tests the in-situ ESD cleaning method developed in project D7.
- **WP6** compares the effect on the cold mirror of a hot-cathode vacuum gauge and the FES gauge.

Resources

We can re-use vacuum equipment from the R&D phase of the KATRIN experiment, including two vacuum labs, one for VINCENT and one for the outgassing measurements. The institute has a mechanical and an electronics workshop, who developed the vacuum control system for ETpathfinder.

We request funds for 1 FTE for 3 years (postdoc). We will also offer work packages to students as topics for Bachelor and Master theses. We further request 36 k€ of travel funds, 62 k€ for the development of the cryogenic QMB technology, 72 k€ for upgrading to a cryo-cooler that can reach a realistic temperature of 10 K, and 20 k€ for consumables and vacuum parts.

Schedule and Milestones

Project D5	Year	2026		2027				2028				2029	
	Quarter	III	IV	I	II	III	IV	I	II	III	IV	I	II
Dr. Joachim Wolf	20%	Coordination, supervising students											
Dr. Adrian Schwenck	10%												
Postdoc (NN) Bachelor and Master theses	100%	WP1		M1		continued application							M4
		WP2				M2					M3		M4
		WP3	M5			continued application after each venting							
			WP4		M6	regular application for material screening							
								WP5		M7			
										WP6		M8	
Hendrick Weingardt	20%	technical support											

funded through the project | other funds / own contribution

Milestones:

- **M1 (Mar. 2027): Finish ellipsometer measurements of growth rate with different gases.**
- **M2 (Dec. 2027): First QMB measurement with cryogenic (40 K) measurements**
- **M3 (Dec. 2028): First measurement with cryogenic (10 K) measurements**
- **M4 (Jun. 2029): Finalize design for QMB and Ellipsometry tests in ETpathfinder.**
- **M5 (Oct. 2026): Find the best non-thermal conditioning technique for UHV chambers.**
- **M6 (Jun. 2027): Start material screening with improved outgassing measurements.**
- **M7 (Sep. 2028): Results of ESD cleaning methods in VINCENT with an FE source**
- **M8 (Dec. 2028): Compare influence of a HC vacuum gage with a hot filament and with FE.**

Collaborators

The outgassing measurements for material screening is a joined effort of several labs in the ET collaboration. A database to collect the data is operated by EGO in Italy. The ESD in-situ cleaning will be developed in close collaboration with project D7 and the ET collaborators from INFN-LFN. Work on monitoring of ice and conditioning of UHV chambers includes additional ET groups from TNO (Delft/NL) and ETpathfinder. New mirror materials and coatings developed in D1-4 can be tested for outgassing and cryo-compatibility. The general work of this project is connected to the ET-ISB vacuum & cryogenics and optics.

7 Institute for Beam Physics and Technology at Karlsruhe Institute of Technology (KIT-IBPT)

PI: Prof. Dr. Steffen Grohmann (Project D6)
Contacts: Prof. Dr. Steffen Grohmann (Project D6)

7.1 The Partner

The Karlsruhe Institute of Technology (KIT) is "The Research University in the Helmholtz Association", combining both a large variety of university-level research and large-scale projects that require a strong national research facility in the framework of the Helmholtz Association. From fundamental research to application, KIT excels in a broad range of disciplines, i.e., in the natural sciences, the engineering sciences, economics as well as in the humanities and the social sciences. With more than 10 000 employees and about 23 000 students, KIT offers a wide range of expertise and a research-based study programme for its students.

The Institute for Beam Physics and Technology (IBPT) is active in the Helmholtz Program MT: Matter and Technology. It operates the accelerator facilities KARA (Karlsruhe Research Accelerator) both as an accelerator test facility and as KIT Light Source, and the short-pulse linear accelerator FLUTE (Far Infrared Linac and Test Experiment) as a source of intense, ultra-short electron and terahertz radiation pulses. The institute's research includes R&D on superconducting systems and cryogenic technologies, the latter being coordinated by the PI.

7.2 Project D6: Cryogenic mirror suspensions

7.2.1 Preliminary Work

The aim of ET-LF is to extend the detection frequency band to lower frequencies, which will allow for observing the entire Universe. This requires the reduction of the limiting Newtonian noise (NN) by installing the laser interferometer several hundred meters underground. Concurrently, the suspensions of the mirrors forming the main Fabry-Perot cavities must be cooled to 10 K to 20 K to suppress the equally limiting suspension thermal noise (STN) to the underground NN level. Both NN and STN are fundamental noises that form major constraints and requirements on ET-LF.

The PI is a founding member of ET's Instrument Science Board (ISB), in which he has been co-chairing the Vacuum and Cryogenics Division since 2020. In close collaboration with the division members and his co-chair, he has been coordinating the division's R&D activities, including a baseline design of the ET-LF cryogenic payload [12], a baseline design concept of the cryostat hosting the cryogenic payload [39], a conceptual design of the cryopumps connected to the cryostats [40], and the development of a helium-based cryogenic infrastructure and payload cooling concept [41].

In 2024, the PI was awarded with the ERC Advanced Grant “GRAVITHELIUM: Gravitational-wave detectors cooled with superfluid helium” [14]. The 5-year project started in October 2024 with a total funding of 3.6 M€. It is hosted at KIT-IBPT in the Helmholtz Program MT: Matter and Technology, and supported by the Refrigeration and Cryogenics Unit at KIT's Institute of Technical Thermodynamics and Refrigeration (KIT-ITTK). The project is a central contribution to the “Joint Project D on Mirror Technologies for ET-LF”, although no additional funding is requested.

Three relevant publications

7.2.2 Objectives

The objective of GRAVITHELIUM is the experimental investigation and validation of full-scale cryogenic mirror suspensions for ET-LF. The construction of a dedicated test facility for cryogenic Q-measurements is part of the project. Its commissioning is shown in Fig. 7.1.

The measurements in GRAVITHELIUM will provide essential physical data on monocrystalline payload suspensions at low temperature, including marionette and mirror suspensions made of silicon and sapphire as described in [12]. In a further step, the concept of integrating a static superfluid helium (He-II) column within the marionette suspension is being investigated, cf. [12]. This comprises the developments of a lab-scale superfluid helium liquefier, and a vibration isolation system (He-II-VIS) for an attenuated and force-free helium supply to the suspension. The experimental He-II campaign addresses open questions related to the two-fluid behaviour of He-II in a suspension tube. It will further answer the question of how closely a He-II-based cooling interface can be integrated within a cryogenic payload. GRAVITHELIUM will hence provide comprehensive data on all relevant technologies for the cooling system integration in cryogenic payloads of next-generation gravitational-wave detectors.

Figure 7.1: Commissioning of the GRAVITHELIUM test cryostat.

7.2.3 Work Plan

Resources

The resources provided by the ERC project GRAVITHELIUM are sufficient to carry out the project; no additional funding is being applied for.

Schedule and Milestones

The Gantt diagram of the ERC project GRAVITHELIUM is shown in Fig. 7.2, overlapping with the funding period of this call and thus illustrating why funding is not required.

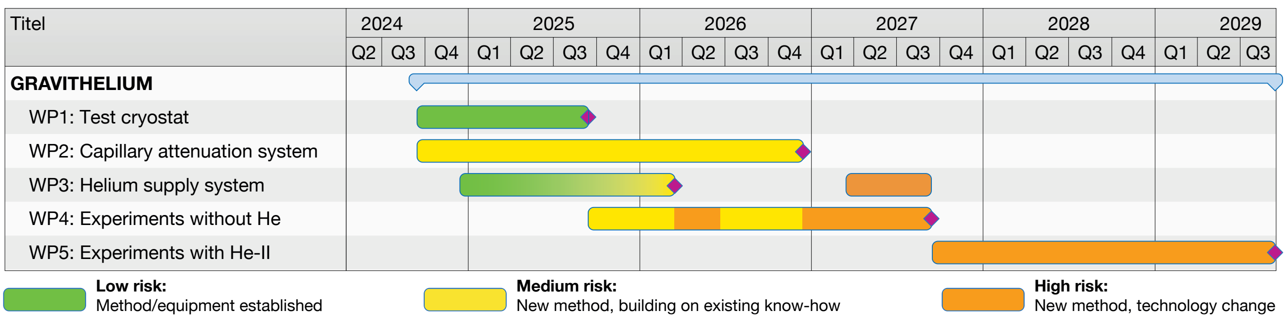


Figure 7.2: Gantt diagram of the ERC project GRAVITHELIUM.

8 Ostbayerische Technische Hochschule Regensburg (OTH-Regensburg)

PI: Prof. Dr. Rupert Schreiner (Project D7)
Contacts: Prof. Dr. Rupert Schreiner (Project D7)

8.1 The Partner

OTH Regensburg is one of the largest and most research-intensive universities of applied sciences in Bavaria. In the LEOS research cluster, we focus on the realization, characterization, and application of Silicon-based sensor and actuator elements in cooperation with research institutes and industry partners. In addition to a fully equipped clean room laboratory, innovative methods for laser micro structuring and microprinting techniques are available for this purpose.

8.2 Project D7: Development of field emission electron sources for the ET-LF cryostats

8.2.1 Preliminary Work

We have been successfully developing field emission electron sources (FES) for various applications for over a decade [42–44]. FES consists of a FE cathode, a high-voltage-resistant insulation, and an extraction electrode. To keep the required voltages for electron emission and the ohmic losses in the cathode as low as possible, high field enhancement is necessary. It can be approximated by the ratio of emitter height to tip radius. The tip radii should not be too small, as even small deviations in the radius can lead to significant inhomogeneities in the current distribution. The optimized design has tips with heights of 100 μm and radii of 100 nm. Micro structuring with short-pulse lasers has proven to be the method of choice [43]. It allowed us to produce FES with emission currents up to several mA, with only a few hundred emission tips (Fig. 8.1.a).

Relevant publications

- Development of FE-based electron sources for XHVion gauges in cryogenic vacuum environments [42].
- Integrated multichip field emission electron source fabricated by laser-micro-machining and MEMS technology [43].
- Investigation of Influencing Factors on the Measurement Signal of a CMOS Image Sensor for Measuring Field Emission Currents [44].

8.2.2 Objectives

The allowed growth rate of ice on the cryogenic mirrors is limited to less than one monolayer per year. In order to achieve this challenging goal, it is planned to develop an electron source (200 eV) that allows the in-situ removal of ice layers off the cold mirrors, using electron stimulated desorption (ESD), in particular after the critical cool-down procedure, but also during the long-term operation of the interferometers. The FES will also help to control electrical charging of the mirrors. The commonly used hot filaments for thermionic electron emission is not suitable for cryogenic applications,

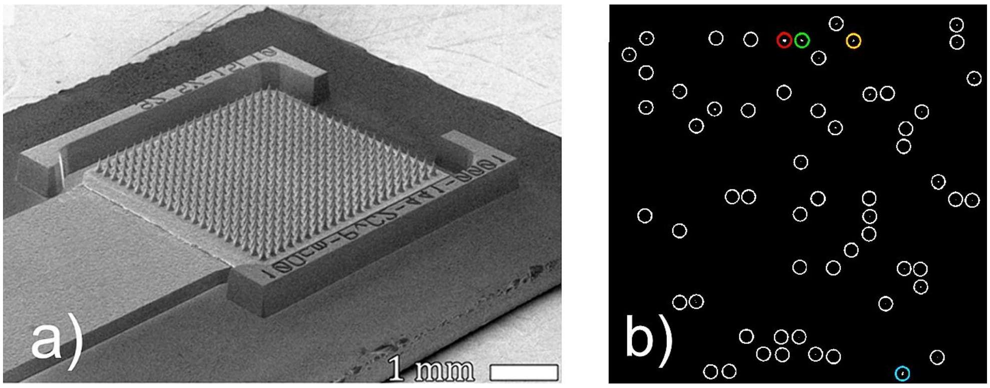


Figure 8.1: **a)** Si-FE array with 441 individual tips realized by ns-laser micro-fabrication. **b)** At a set current of 100 μA, a modified CMOS sensor measured 59 tips contributing to the emission (marked by rings), with 4 tips (coloured rings) accounting for more than 35% of the total current.

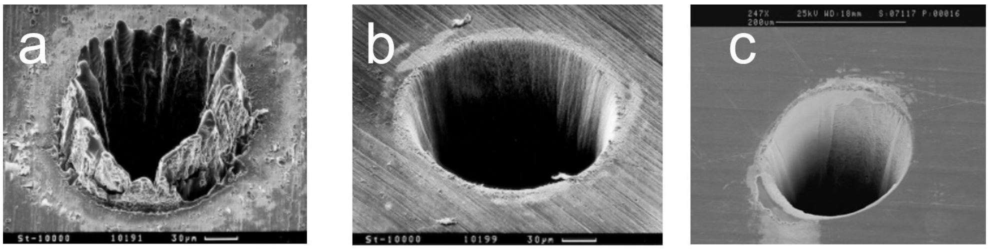


Figure 8.2: SEM Images: Comparison of micro holes drilled in a 100 μm-thick stainless-steel foil using 3.3 ns (a) and 200 fs pulses (b). Micro hole in 0.5 μm thick copper foil with 0.8 ps pulses at a repetition rate of 975 kHz and 50 μJ pulse energy (c). Images adapted from [45].

due to the emission of heat, light and increased desorption rates of gas. FES are a viable alternative that avoid these issues and work in cryogenic environments [42].

For systematic investigations of the homogeneity of the emission current distribution, we use our new measurement method based on modified CMOS sensors (Fig. 8.1.b) [44]. Recent measurements of FES have shown that despite the high total emission currents, electron emissions do not occur uniformly across the entire array of tips, but rather emanate from individual emission centers ("hot spots"). These are the highest and sharpest tips. Even slight deviations in geometry or surface texture of tips can result in an emission dominated by only a few emitters (Fig. 8.1.b). This limits the total achievable emission current and leads to unwanted local current loads and heating effects.

This project aims to achieve a highly uniform, homogeneous electron emission (deviations below 25%) from larger surfaces at an emission current of at least 1 mA per mm^2 without local hot spots. Therefore, the structural accuracy of the existing laser structuring system must be significantly improved. This can be achieved by replacing the existing ns-pulse laser with a laser with pulses in the ps-range. The ns-pulses heat the material, which melts and vaporizes. This leads to the formation of melted rims, burs, and changes in the material structure (8.2.a). Shorter laser pulses in the ps-range vaporized the material more locally, before the surrounding material can melt (8.2.b,c). Such lasers offer the highest precision for micro- and nano structuring at the cost of a lower ablation rate. Therefore, we plan to implement a ps-laser in our laser structuring system for FES that represents a good compromise between processing speed and strongly improved structural quality.

Another challenge is finding the right material combinations for the FES assembly for stable long-term operation under cryogenic conditions. Apart from outgassing rates and formation of oxides in air, properties such as electrical conductivity and thermal expansion coefficients at cryogenic temperatures have to be considered. We will start with silicon and BF-33 glass, our present material of choice, extending our tests to various metals and and glass-ceramics substrates as insulators. With our available lab equipment for precise alignment and substrate bonding, a suitable process for the fabrication of large-area metal-glass-metal connections will be developed.

Hot cathode ionization gauges are used for pressure measurements in UHV. The hot filaments produce light, heat and additional outgassing. We are working on replacing the hot filament of a Bayart-Alpert gauge with a FES, thus avoiding the undesirable effects. We also plan to extend this technology to RGA mass spectroscopy. Together with our partners at KIT, the new vacuum gauges will be tested in the VINCENT chamber (D5) under cryogenic conditions for long-term stability.

8.2.3 Work Plan

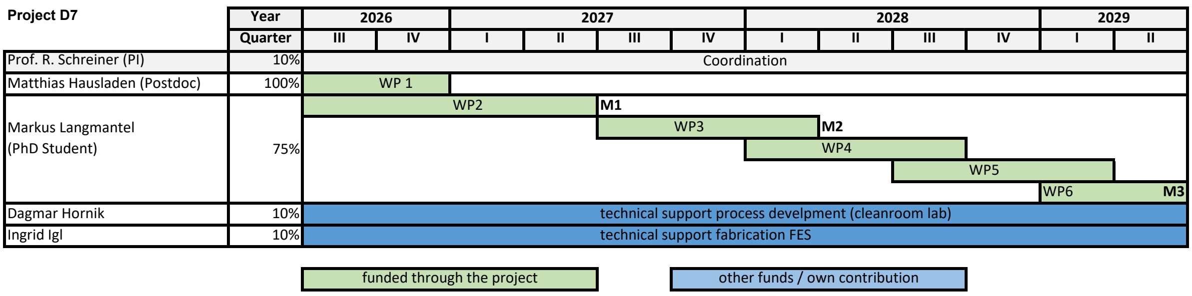
The project is structured into six work packages:

- **WP1:** implementation of the experimental setup for ps-laser structuring.
- **WP2:** developing the process for FES production (cathodes, isolation and extraction electrode).
- **WP3:** production of FES and initial characterization of emission and homogeneity.
- **WP4:** integration of a FES in the INFN-LNF ESD setup and test in the KIT VINCENT chamber.
- **WP5:** implementation of a FES in Bayart-Alpert vacuum gauge and test in cryogenic conditions.
- **WP6:** extension of the FES technology for RGA mass spectrometry.

Resources

We will use the existing fabrication and characterization capabilities for FES at OTH. We request funds for a PhD student for 3 years and a postdoc for 1/2 year for research into FES for the ET-LF cryostats; a total of 36 k€ for travel expenses and 25 k€ per year for consumables (wafers, chemicals, mechanical and electronic components, vacuum components, photomasks, and photoresists). Investment: picosecond laser (100 k€) + scanning device for beam deflection (20 k€), mechanical structure and control cabinet (26 k€).

Schedule and Milestones



Milestones:

- **M1:** The ps-laser mikro-structuring system is operational, first FES produced.
- **M2:** FES implemented and tested in vacuum for homogeneity, total current and heat emission.
- **M3:** ESD cleaning and FES UHV-gauge are successfully tested for ET-LF cryostat operation.

Collaborators

The in-situ cleaning with ESD is developed in cooperation with groups of R. Cimino at INFN-LFN (Frascati) and project D5 (KIT). After initial tests, the FE ionization vacuum gauge will be implemented in the test setup at KIT.

9 Associated Partners

9.1 Leibniz Universität Hannover (LUH)

Coordinator: Prof. Dr. Michèle Heurs, Institute for Gravitational Physics

9.1.1 Background

The research at the Institute for Gravitational Physics (IGP) of Leibniz University Hannover (LUH), in close collaboration with the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI) in Hannover, focusses on experimental laser-interferometric gravitational wave detection. Together, these institutions have operated the gravitational wave detector (GWD) GEO 600 for decades, and high tech produced within this British-German collaboration remains essential for all current GWDs worldwide. Michèle Heurs is a council member of the LIGO Scientific Collaboration (LSC) and heavily involved in the Einstein Telescope collaboration (currently as the German Forum of National Representatives member).

9.1.2 Involvement

One of the research foci of the IGP is laser stabilisation and non-classical light sources (see Joint Project A), another is back-action evading techniques, one of the research areas of Michèle Heurs (Professor at LUH). Heurs holds a dual appointment at LUH and DZA and is a lead scientist at DESY. Her research at DZA is focussed on silicon technologies, combining expertise in optical metrology with that of the other collaboration partners IKZ (crystal growth) and IGR (bonding technologies).

9.2 University of Maastricht (UM)

Coordinator: Prof. Dr. Stefan Hild, Experimental Physics

9.2.1 Background

The Department of Gravitational Wave Research and Fundamental Physics at the University of Maastricht is one of the key players in the international gravitational wave community and its members hold various key positions in the Einstein Telescope collaboration, including for instance the co-chair of the ET instrument science board (S.Hild) and the co-chair of the work package Modelling and Design Tools (S. Steinlechner).

9.2.2 Involvement

Maastricht and Nikhef lead a consortium, consisting of more than 20 research institutes and universities from the 6 European countries, that are developing and operating an R&D test facility for the Einstein Telescope located in Maastricht, named ETpathfinder [19]. Joint project D includes two projects (D5 and D7) that will develop cryogenic sensing and in-situ cleaning technology that are intended for ultimate tests in ETpathfinder. UM supports the projects (J. Steinlechner) as part of the ET working group with KIT, TNO, and INFN-LFN. ET-Pathfinder further offers the opportunity to test silicon mirror substrates produced in projects D3 and D4 and superpolished mirrors within project D1.

9.3 Laboratori Nazionali di Frascati (INFN-LFN, Frascati)

Coordinator: Prof. Dr. Roberto Cimino, Laboratori Nazionali di Frascati - INFN

9.3.1 Background

The "Material and Surface Science Laboratory" (MASSLab) at LNF has been built and devoted over the past years to the study of materials of interest for the high energy particle accelerators and astrochemistry. Over the years, the group has conducted detailed studies on the interaction mechanisms between low-energy electrons and cryogenic surfaces, with particular attention to electron-induced desorption processes involving cryosorbed molecules. The experimental work has been carried out using state-of-the-art instrumentation, including ultra-high-vacuum (UHV) systems equipped with dedicated gas lines and a high-resolution mass spectrometer. The knowledge gained through these studies has enabled the group to propose an innovative active-mitigation technique based on low-energy electrons [46]. The group is part if the ET-ISB vacuum & cryogenics section.

9.3.2 Involvement

The primary objective of the LNF activity is the testing and development of an electron gun intended for frost-mitigation on the new ET mirrors. The device must be based on a design fully compatible with the cryogenic operating conditions of the LT-ET tower. An electron-gun based on FES will be devoloped in cooperation with project D7 and will be tested at LNF and together with continuous ice monitoring at KIT (D5).

9.4 Dutch Organisation for Applied Scientific Research (TNO, Delft)

Coordinator: Ing. Freek Molkenboer, TNO

9.4.1 Background

TNO – Unit High Tech Industry has a long-standing track record with respect to optics lifetime to the table. In collaboration with ASML, Carl Zeiss SMT and EUV mask suppliers, TNO has developed the essential knowledge and expertise to achieve a sufficiently long lifetime of the optical elements that are at the heart of ASML's EUV lithography tools [47]. TNO has equally relevant expertise in the field of nuclear fusion, using a radio-frequency plasma to clean ITER's front-end diagnostic mirrors. Similar to Einstein Telescope, the very advanced optical elements in these systems need to remain damage-free and clean. As such, TNO has a strong background in surface characterization, surface cleaning, and UHV, along with many set-ups to perform life-time tests. TNO also brings the knowledge on how to bring low TRL research to industrial companies, vital for the adoption of the conducted research towards the Einstein Telescope.

9.4.2 Involvement

TNO is a member of the ET working group that includes activities in projects D5 and D7. The electron-gun, in-situ removal of ice from mirrors and conditioning techniques developed in D5 and D7 can be tested on a larger scale at TNO, building on the expertise of surface analysis. In particular, the effect on the complex optical coatings of the mirrors can be investigated together with TNO.

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A Appendix

A.1 Overall Budget for Joint Project D

Tab.A.1 summarizes the total budget request for **joint project D**. A detailed justification is given in the description of the corresponding projects. The total requested sum including overheads ("Programmpauschale") is 4287 k€.

Proj.	Partner	PI	Personnel	PM	Pers. Funds	Travel	Inv. + Other	Over-head	Sum
D1	DZA	Günther Hasinger	-	-	-	18	453	0	471
D2.1	DZA	Michèle Heurs	Postdoc 100%	36	250	36	313	0	599
D2.2	DZA	Michèle Heurs	Postdoc 100%	36	250	18	0	0	268
D2.3	DZA	Michèle Heurs	PhD student 75%	36	192	18	0	0	210
D3.1	IKZ	Iryna Buchovska	PhD student 75%	36	199	36	153	33	421
D3.2	IKZ	Iryna Buchovska	Engineer 50%	36	126	0	0	0	126
D4.1	IKZ	Radhakrishnan Sumathi	PhD student 75%	36	199	36	440	50	725
D4.2	IKZ	Radhakrishnan Sumathi	Engineer 100%	36	252	0	0	0	252
D4.3	IKZ	Radhakrishnan Sumathi	Postdoc 20%	7	52	18	0	0	70
D5	KIT-ETP	Ralph Engel	Postdoc 100%	36	249	36	154	88	527
D6	KIT-IBPT	Steffen Grohmann	-	-	-	-	-	-	-
D7.1	OTH	Rupert Schreiner	Postdoc 100%	6	48	0	0	10	58
D7.2	OTH	Rupert Schreiner	PhD student 75%	36	210	36	221	93	560

Figure A.1: Budget overview for **joint proposal D** in units and rounded to 1000 € (1 k€). For each requested position the person months (PMs) are provided.

A.2 The five joint projects and involved institutions

- **Joint Project A: Laser Development and Quantum Noise Reduction - ET-RD-A-LASQ**
  - Friedrich-Schiller-Universität Jena (FSU)
  - Fraunhofer Institute for Laser Technology ILT (ILT)
  - Leibniz University Hannover (LUH)
  - Laser Zentrum Hannover e.V. (LZH)
  - Physikalisch Technische Bundesanstalt (PTB)
  - Technische Universität Braunschweig (TUBS)
  - Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute, AEI)
- **Joint Project B: Challenges in Interferometer Noise and Control - ET-RD-B-IFO**
  - Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)
  - Helmut-Schmidt-Universität Hamburg (HSU)
  - Leibniz University Hannover (LUH)
  - University of Hamburg (UHH)
  - Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute, AEI)
  - Maastricht University (UM) - Netherlands
- **Joint Project C: Newtonian Noise Cancelling Headphones - ET-RD-C-PREDICT-NN**
  - FH Münster - University of Applied Sciences (FHM)
  - Helmut-Schmidt-Universität Hamburg (HSU)
  - Karlsruher Institut für Technologie (KIT)
  - University of Hamburg (UHH)
  - University Münster (UM)
- **Joint Project D: Mirror Technologies for ET-LF - ET-RD-D-MiTEL**
  - Deutsches Zentrum für Astrophysik (DZA)
  - Leibniz-Institut für Kristallzüchtung (IKZ)
  - Karlsruhe Institute of Technology (KIT)
  - Ostbayerische Technische Hochschule Regensburg (OTH)
  - Leibniz University Hannover (LUH)
  - Maastricht University (UM) - Netherlands
  - Laboratori Nazionali di Frascati (INFN-LNF) - Italy
  - Dutch Organisation for Applied Scientific Research) (TNO) - Netherlands
- **Joint Project E: Data Analysis, Simulations and Theory - ET-RD-E-DAST**
  - Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute, AEI)
  - Universität Bielefeld (UBI)
  - Ruhr-University Bochum (RUB)
  - Deutsches Elektronen-Synchrotron (DESY)
  - Friedrich-Schiller-Universität Jena (FSU)
  - Universität Hamburg (UHH)
  - Universität Heidelberg (UH)
  - Humboldt-Universität zu Berlin (HU)
  - Karlsruhe Institute of Technology (KIT)
  - Universität zu Köln (UoC)
  - Universität Potsdam (UP)
  - Universität Tübingen (EKUT)
  - ELLIS Institute Tübingen and Max Planck Institute for Intelligent Systems (ELLIS)

A.3 German R&D coordination and proposal preparation

The compilation of the five joint projects is based on a community-wide survey of relevant R&D in Germany that was analysed and curated by a team of experts in a structured national process. The experts, also referred to as R&D coordinators are listed below. These experts were mandated by the ET German coordination team (see Section 1.1).

- Oliver Gerberding, Prof. Dr., University of Hamburg (overall German R&D coordinator, Co-Chair of ETC-ISB IFO Division WP on Modelling and Design Tools)
- Patrick Baer, Dr., Fraunhofer Fraunhofer Institute for Laser Technology Aachen (ETC Research Unit Leader Fraunhofer - Lasers & Optics)
- Benno Willke, Apl.-Prof. Dr., Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute), Leibniz Universität Hannover Co-Chair of ETC-ISB Optics Division on Lasers)
- Harald Lück, Dr., Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute), Leibniz University Hannover (former ETC Co-Spokesperson, from 2023 to 2026)
- Mikhail Korobko, Dr., University of Hamburg (Co-Chair of ETC-ISB IFO Division WP on Observatory Design and Noise Budget)
- Andreas Rietbrock, Prof. Dr., Karlsruher Institut für Technologie, Karlsruhe (Division co-chair of Site Characterization Board)
- Steffen Grohmann, Prof. Dr.-Ing., Karlsruher Institut für Technologie, Karlsruhe (ETC-ISB Division co-chair of Vacuum & Cryogenics)
- Robert Menzel, Dr.-Ing., Leibniz-Institut für Kristallzüchtung, Berlin
  (ETC Research Unit Leader Berlin)
- Alessandra Buonanno, Prof. Dr., Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute), Potsdam (ETC Research Unit Leader Max Planck Institute for Gravitational Physics — Potsdam)
- Michela Mapelli, Prof. Dr., Universität Heidelberg (Co-Chair of ETC-OSB Division 3: Population Studies, ETC Research Unit Leader Heidelberg)
- Sebastiano Bernuzzi, Prof. Dr., Friedrich-Schiller-Universität Jena (ETC Research Unit Leader FSU Jena)
- Samaya Nissanke, Prof. Dr., Deutsches Elektronen-Synchrotron (DESY) Zeuthen, German Centre for Astrophysics (DZA), University of Potsdam (Co-Chair of ETC-OSB Division 5: Synergies with other GW observatories and a member of ETC Bylaws Committee, ETC Research Unit Leader DESY)

The R&D coordination efforts and the proposal preparations were also supported by:

- Michèle Heurs, Prof. Dr., Leibniz Universität Hannover (LUH), German Centre for Astrophysics (DZA)
  (National representative in the FNR and chair of the ET German coordination team)
- Andreas Haungs, Dr., Karlsruher Institut für Technologie, Karlsruhe
  (co-coordinator for the Pre-phase, ETC Research Unit Leader KIT)
- Katharina Henjes-Kunst, German Centre for Astrophysics (DZA)
  (co-coordinator for the Pre-phase)