



ETpathfinder: prototyping low-frequency technologies for the Einstein Telescope

Elise Van den Bossche (Maastricht & VUB)
for the ETpathfinder Team

BE-NL GW, UCLouvain, October 2026

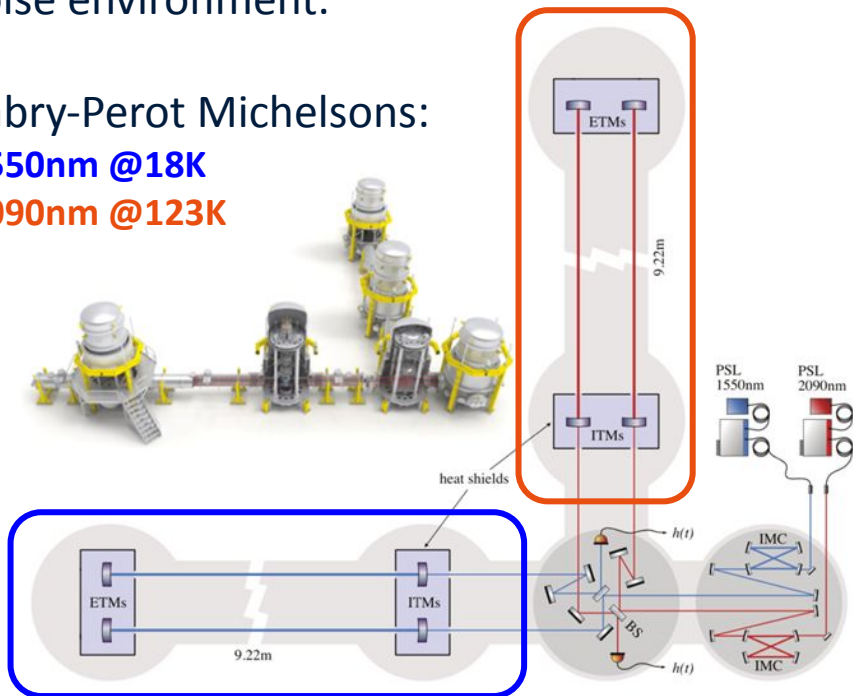


ETpathfinder in a Nutshell

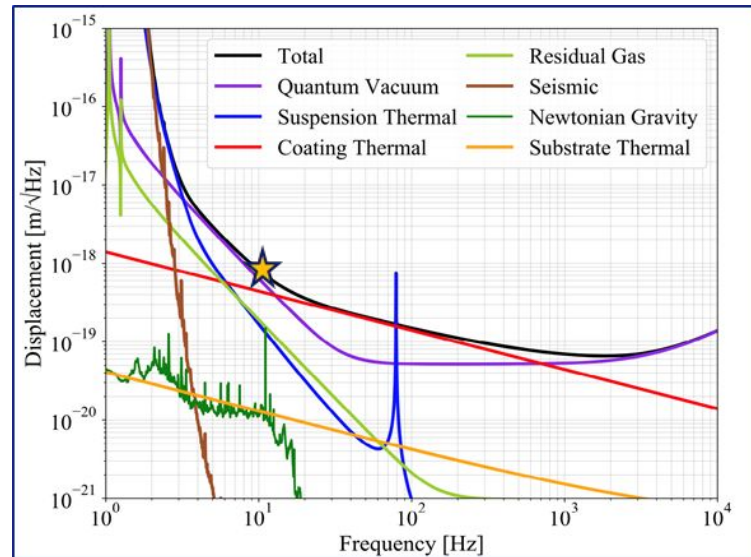
Main target: provide a testbed for ET technologies/concepts and qualify them in a low-noise environment.

Two Fabry-Perot Michelsons:

- 1) 1550nm @18K
- 2) 2090nm @123K



Target: $1e-18m/\sqrt{Hz}$ @10Hz



<https://doi.org/10.48550/arXiv.2206.04905>



The ETpathfinder Team

STAC

Scientific and Technical Advisory Committee

David Shoemaker (Chair) - MIT



Viviane Fafone - Rome



Kazuhiro Yamamoto – KAGRA



Gianluca Gemme – Virgo



Patrice Verdier – CNRS



Andreas Haungs – KIT



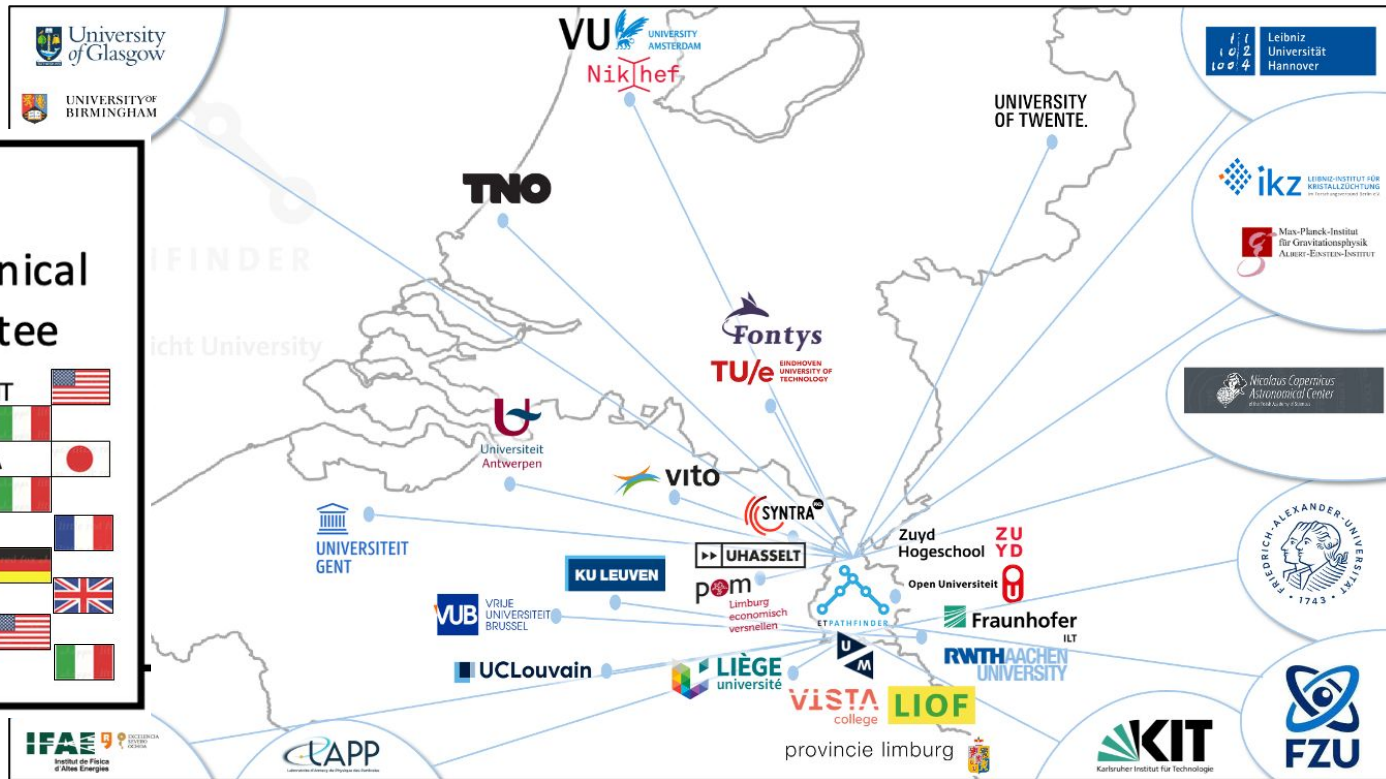
Angus Bell – Glasgow



Anamaria Effler – LIGO



Helios Vocca – INFN/CAOS



Since 2022 ETC spokespersons, ETO directors, ISB co-chairs, heads of ETO-PO/ED are always invited to join the ETPF STAC meetings.



ETpathfinder Timeline



Construction started early 2020



Autumn 2020



Summer 2021



Autumn 2021



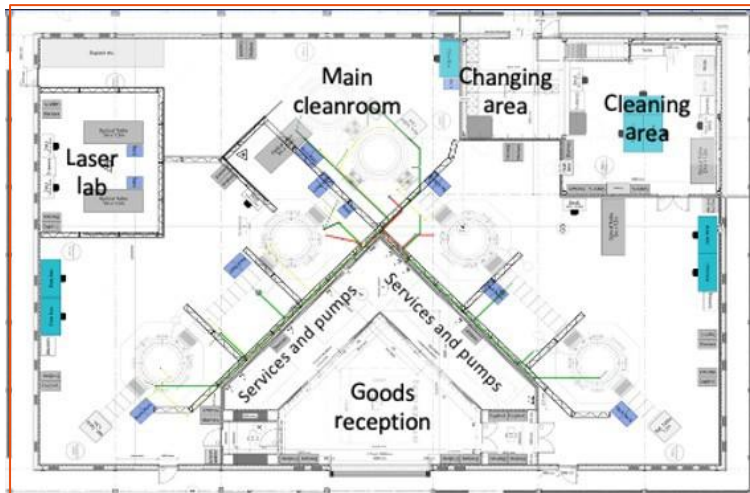
Summer 2022



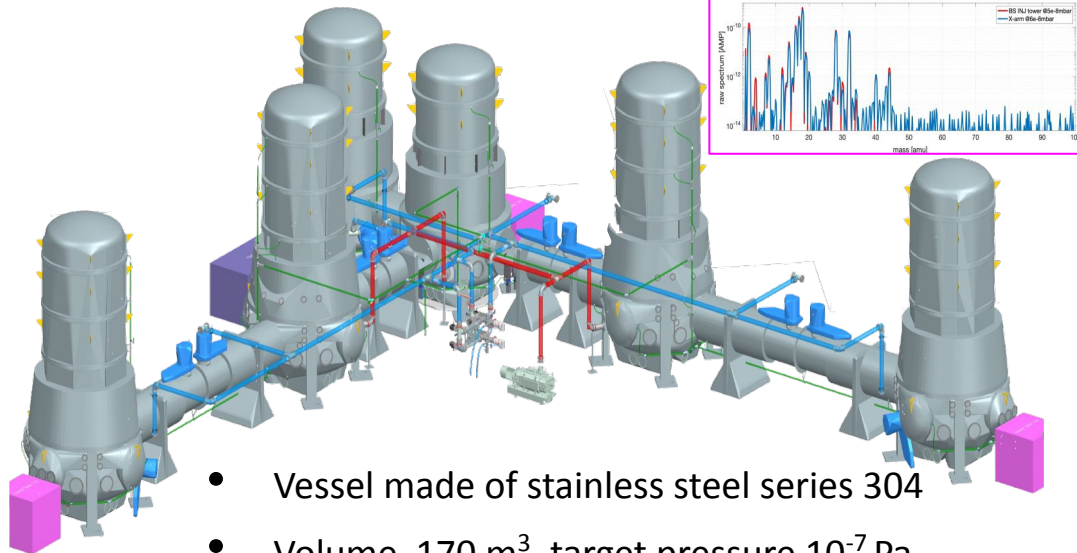
Now ...



Infrastructure



- Cleanroom of 6000m³, nominal ISO 7/8
- In reality ~ISO 5/6 when activity
- No airborne particles measurable at rest
- Infrasound and seismic sensing arrays



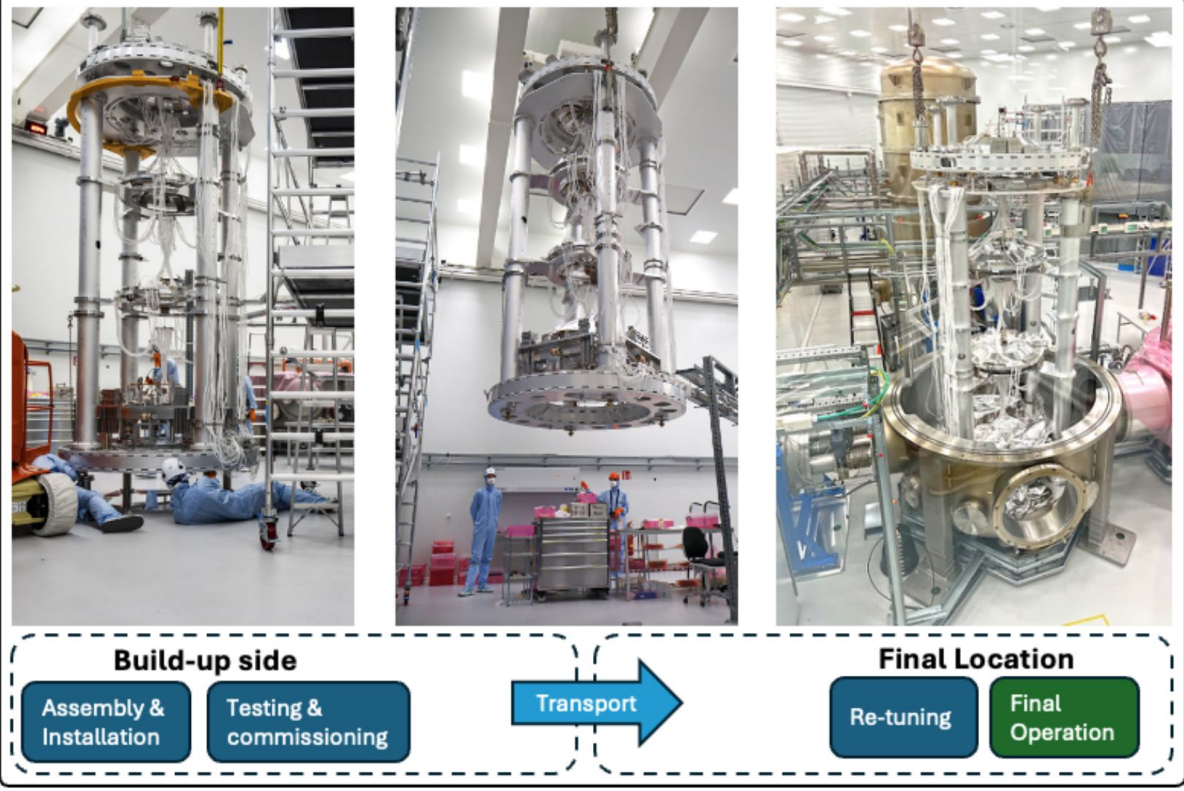
- Vessel made of stainless steel series 304
- Volume 170 m³, target pressure 10⁻⁷ Pa
- Inner surface about 400 m²
- Partial pressure hydrocarbons < 10⁻¹² Pa
- roughing (r), differential (g), UHV (b)
- 14x turbos with magnetic bearing (each 3000l/s) backed up by small turbos
- Siemens PCS7 Vacuum Control System

<https://arxiv.org/pdf/2508.16461>



Off-Location Installation Approach for Inner Mechanics

- ET will require hundreds of seismic isolation systems
- Idea: “factory” above ground that produces fully functional suspension systems
- Only light re-tuning after transport to final location
- Tested procedure for ETPF suspended bench:
 - Assembly ~ 35 days
 - Commissioning ~ 15 days
 - Hoisting ~ 1 day
 - Re-tuning ~ 2 days

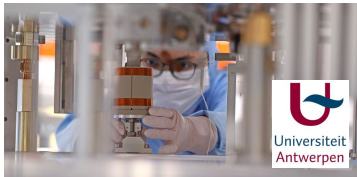




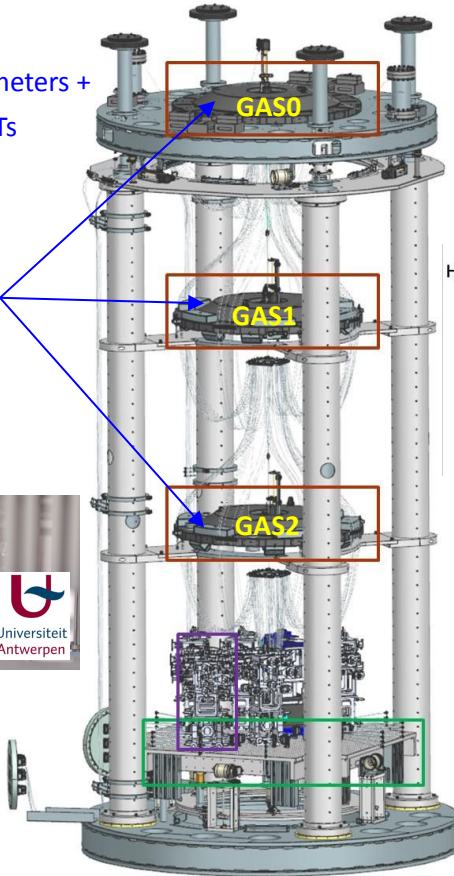
Current: Two Suspended Benches Installed

2 triaxial seismometers +
3 horizontal LVDTs

Vertical LVDTs



4 horizontal +
3 vertical LVDTs



Control scheme:

1. OB angular control
2. IP inertial damping
3. Vert inertial damping on GAS0

Horizontal X, Z

Bench LVDT	IP LVDT	IP Seismometers
DC-15 mHz	15 – 95 mHz	0.095 – 4 Hz

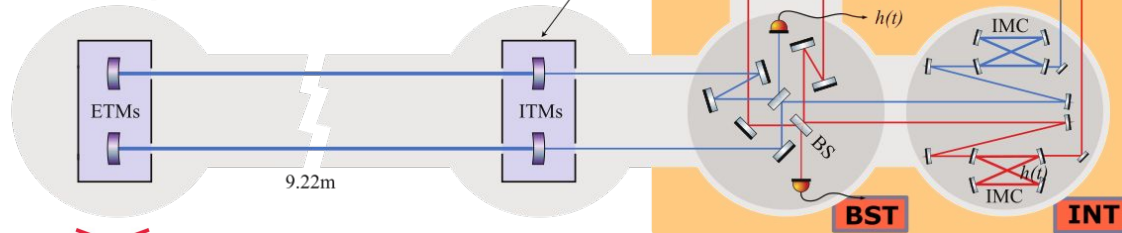
IP-TY

IP LVDT	IP Seismometers
DC – 95 mHz	0.095 – 4 Hz

Vertical Y

Bench LVDT	GAS-0 LVDT
DC-15 mHz	15 mHz – 0.6 Hz

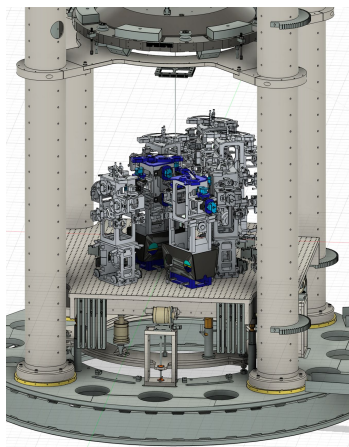
ETpathfinder-A (1550nm, 18K)



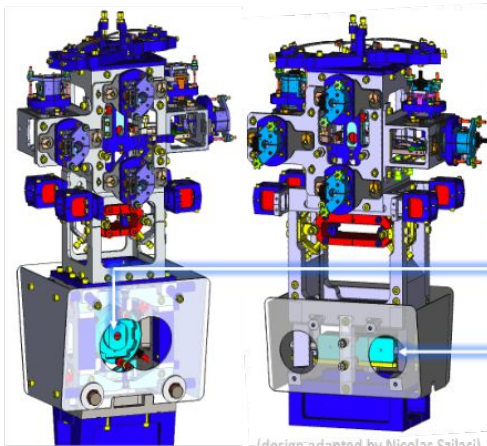


Bench-Top Suspensions: HRTS

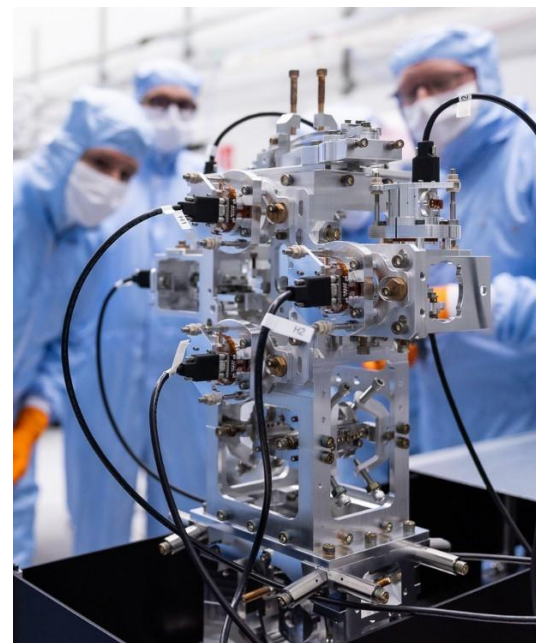
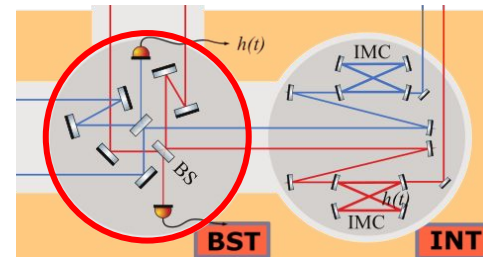
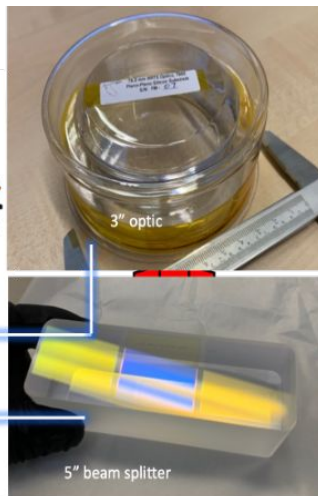
- For the six 3" folding mirrors and the two 5" beamsplitters on the BST, HRTSs (LIGO A+ design) and an adapted version
- Some delay, several manufacturing issues needed fixing
- Now: one fully assembled and commissioned (robustness tests, cross-coupling), more under construction



~ 50 cm



(design adapted by Nicolas Szilasi)





1550nm Pre-Stabilised Laser

Developed at AEI (Nicole Knust, Fabian Meylahn; group of Benno Willke)

- Amplified diode seed laser with frequency pre-stabilisation
- Pre-mode cleaner for additional filtering and pointing stability, followed by power stabilisation
- At BST: first in-vacuum measurements & characterization using IMC on suspended bench
- Next: installation of PSL & IMC at INT

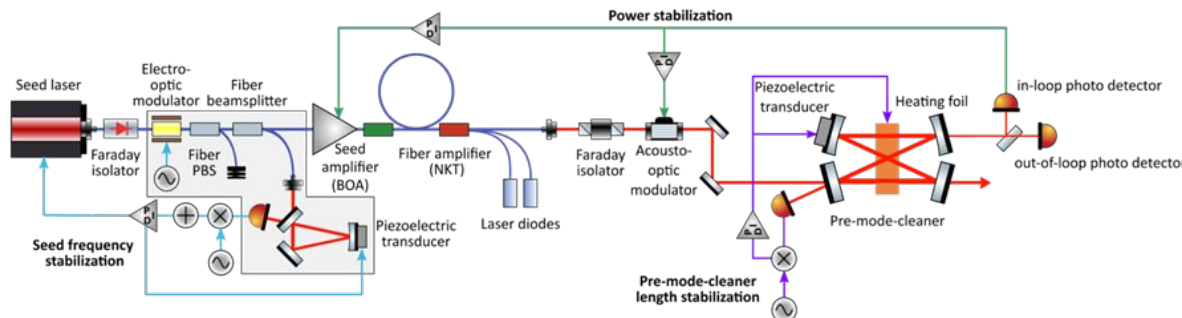
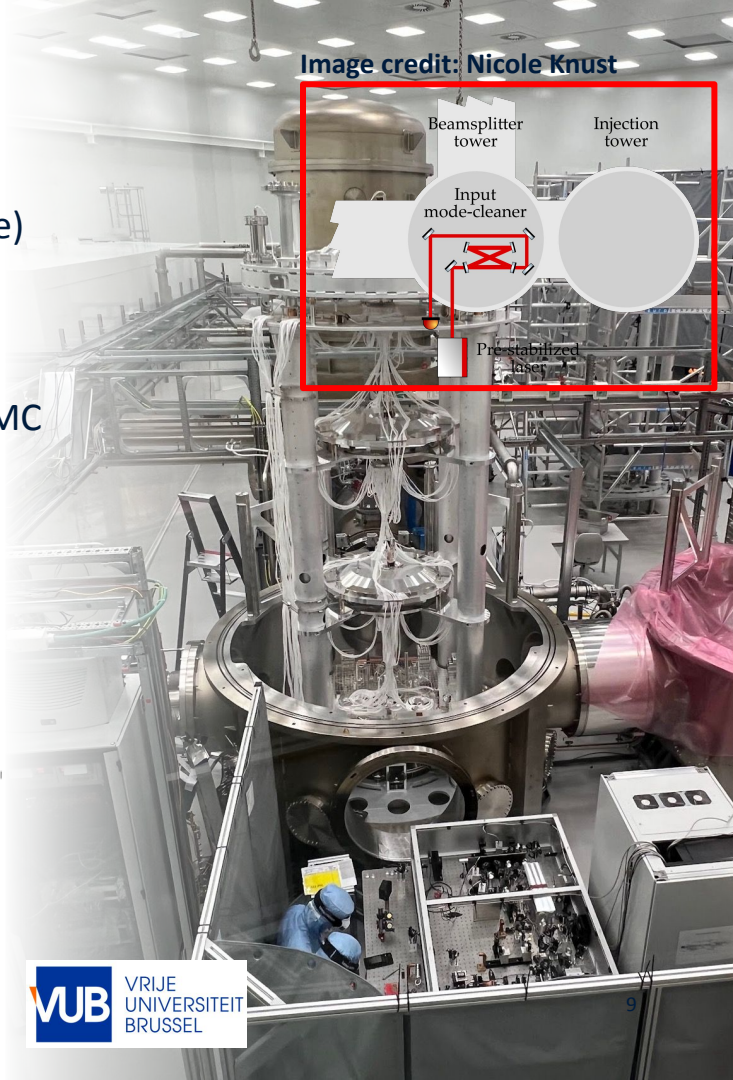
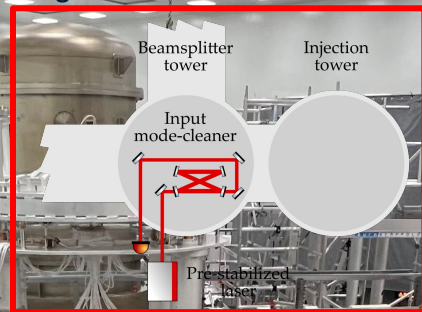


Image credit: Nicole Knust

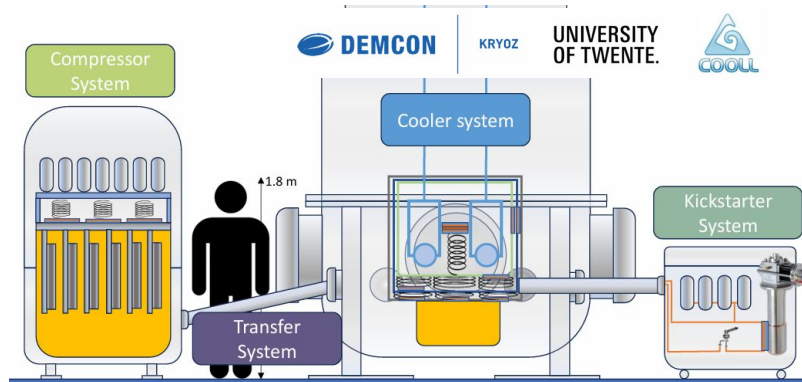




Next Goal: Short Michelson with Silicon Mirrors

Need a cryogenic mirror tower, ingredients:

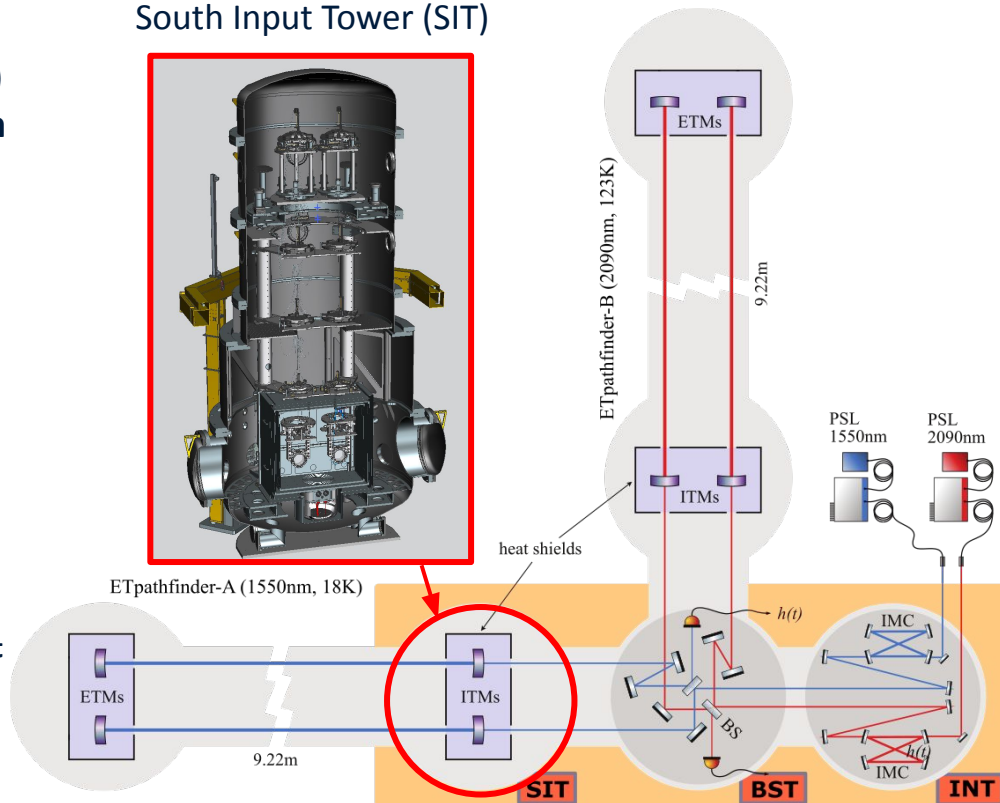
- Polished and coated **silicon mirrors** (2x 3.2kg)
- Last stage in the chain: **crystalline suspension**
- **Cryogenic system** that can cool down to 10K



Partners taking charge of subsystems, managed by Nikhef and Maastricht



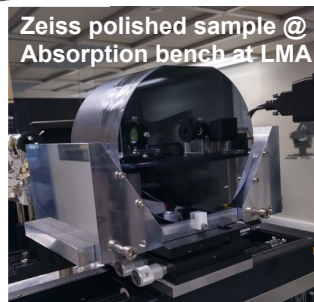
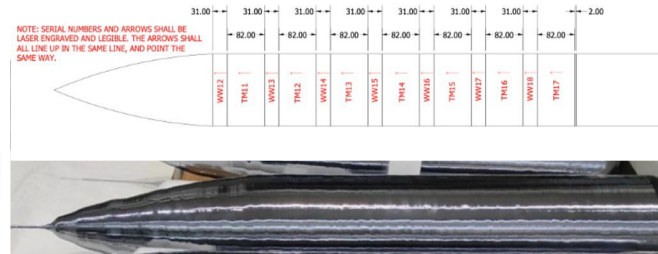
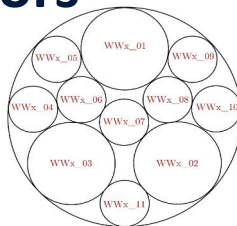
South Input Tower (SIT)



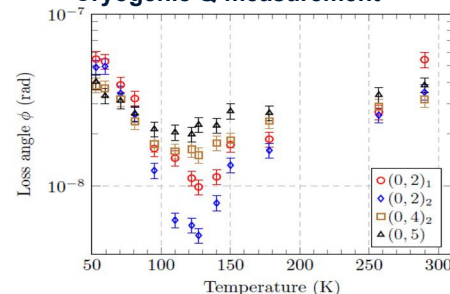


ETpathfinder Silicon Mirrors

- Floatzone ingots procured from IKZ, Berlin
- Several samples from witness wafers:
 - Cryogenic mechanical loss in range $1e-8$
 - Bulk birefringence about $1e-8$ (Ferrara)
- Mirror substrates polished by Zeiss MT:
 - roughness $< 100\text{pm}$, flatness $< 1\text{nm}$
 - No excess surface absorption (LMA)
- Laser-assisted diamond turning and polishing @B-PHOT

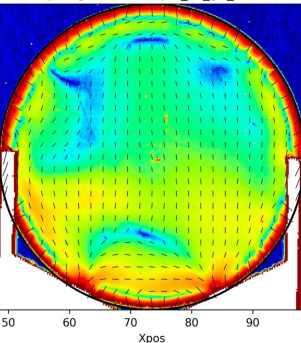


Cryogenic Q-measurement



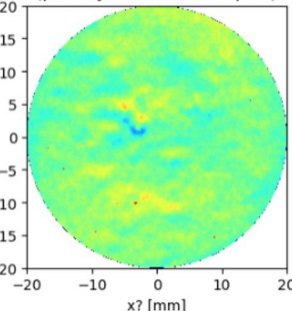
Birefringence map (Ferrara)

Δn map (log scale) sample_1s_gV_VW01-02

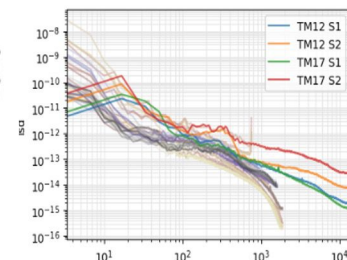


Flatness map of ETPF ITM

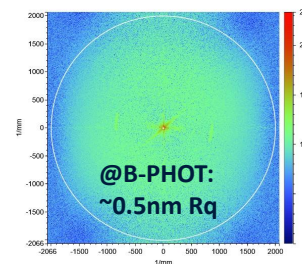
processed (plot styled to mimic report)



ETpathfinder silicon mirrors show flatness comparable to LIGO/Virgo



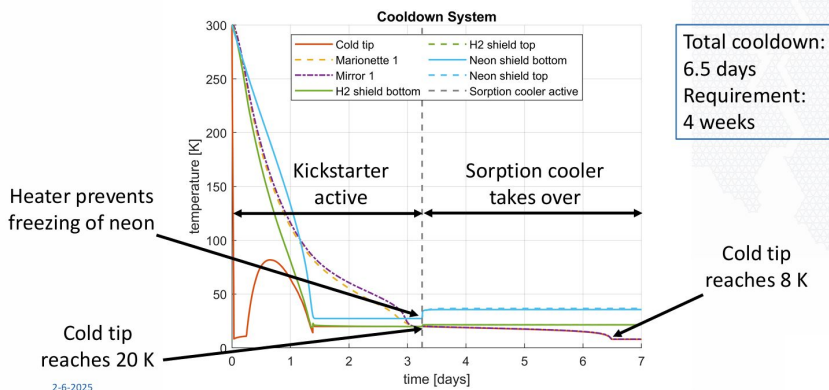
<https://journals.aps.org/prd/abstract/10.1103/xzbl-3snb>



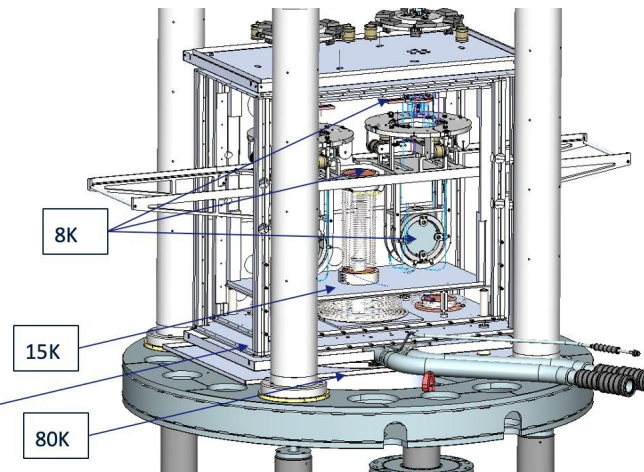
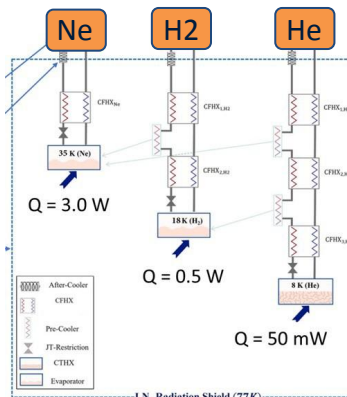


Cryogenic Strategy

<https://www.sciencedirect.com/science/article/pii/S0011227523000917>

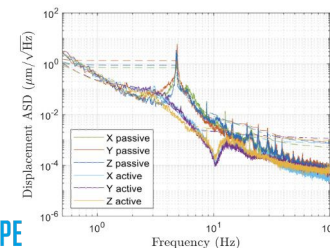
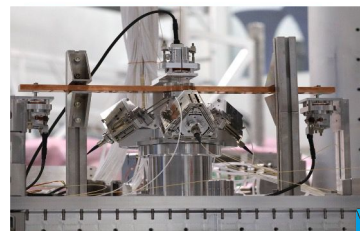


3-stage Joule-Thomson cooler



- Both radiative and conductive cooling approach
- Two floating shields (265K, 223K) and three actively cooled shields (80K, 40K, 15K)
- Subcooled LN2 allows rapid cooling to 80K
- Cooldown via a closed helium loop (mechanical)
- Low-vibration sorption coolers in science mode
- Triaxial active damping of (ground) vibrations coupling via dynamic links

Validation of a triaxial cryogenic active vibration isolator





Cryogenics: Assembly in Progress (Twente)

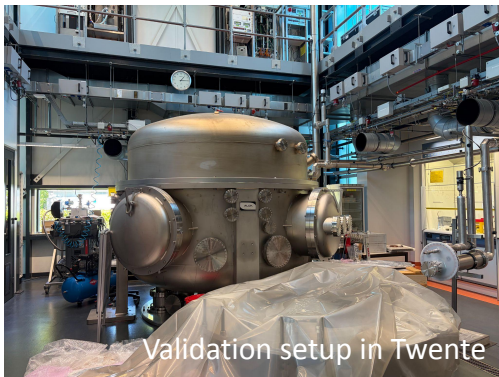


KRYOZ

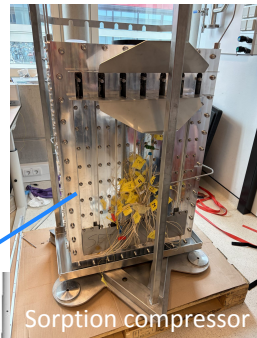
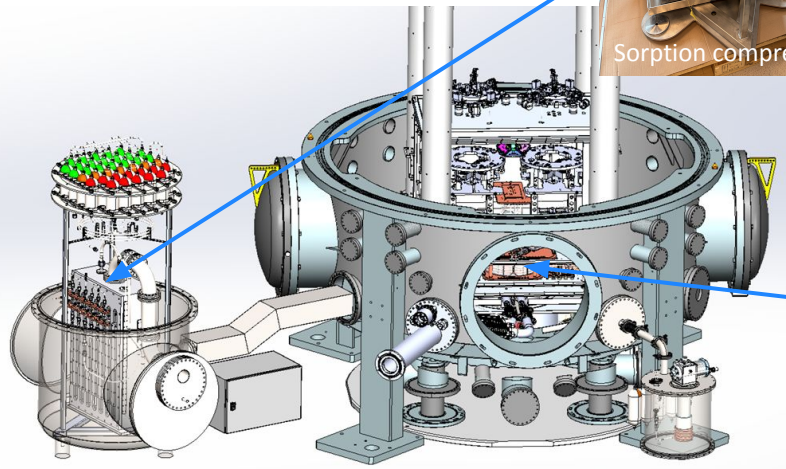
UNIVERSITY
OF TWENTE.



- Assembly of cooler subsystems with good progress
- Full system to be assembled in Twente for characterisation in less stringent environment with additional sensors
- By summer 2027: integration of two coolers in ETpathfinder



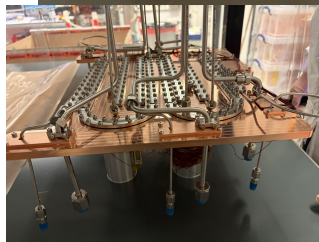
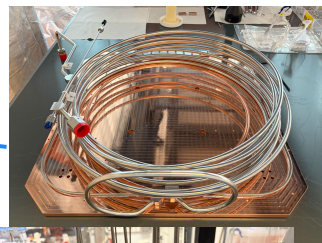
Validation setup in Twente



Sorption compressor



Assembly of heat exchangers



Detailed test plan for validating system against thermal and seismic requirements in November:

Temperature requirements

8K at the cold platform, 15K at the mirror

Vibration level

< 32 nm peak-to-peak

Cooldown time

< 4 weeks



Crystalline Suspension

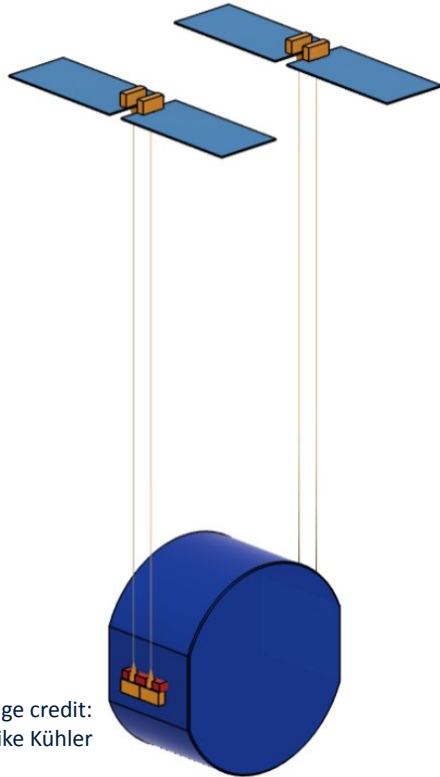
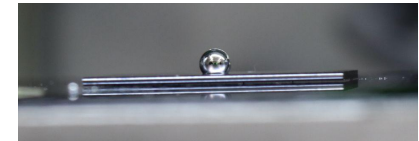
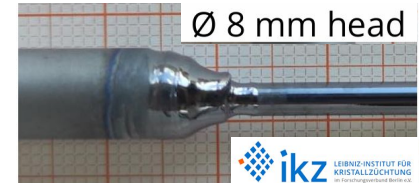
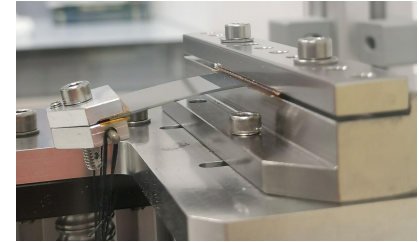


Image credit:
Maïke Kühler

- Silicon blade springs, rectangular accounting for crystal structure
 - Diamond vs. laser cut
 - Median breaking stress 363 MPa
- Crystalline sapphire fibers (1mm diameter) with welded cones from Glasgow
- Longterm: silicon fibres, but currently only one-sided welding possible

Laser welded sapphire cone geometries for anchor assembly prototyping



- Gallium bonding at ear
 - allows for repair
 - application methods

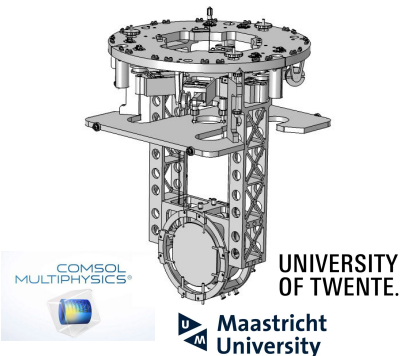


New Simulation Workpackage

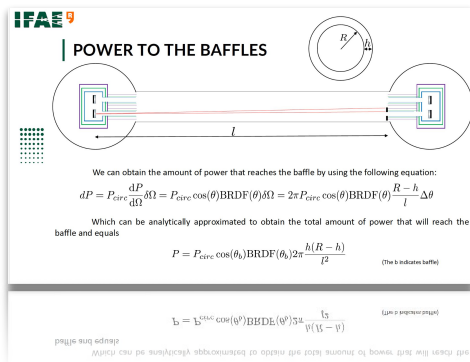
- ETPathfinder is transitioning from installation to commissioning
- Design decisions across multiple subsystems with near-term influence, e.g. control scheme and performance checks during commissioning
- Aim: support ETPathfinder as long-term prototyping facility with framework and tools, best practices for simulation software

First step: bringing together modelling done by different partners, e.g.:

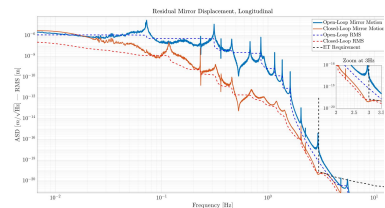
Cooldown of cryogenic payload
[E. Prins, M. van Limbeek]



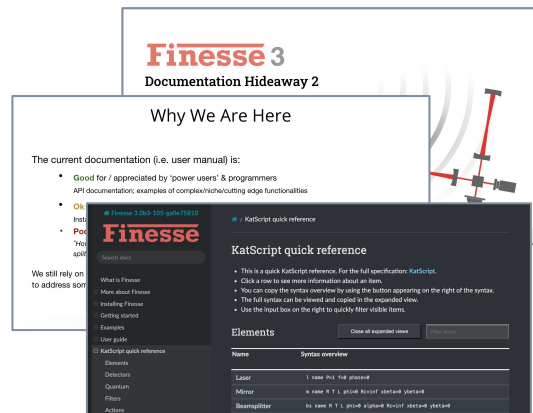
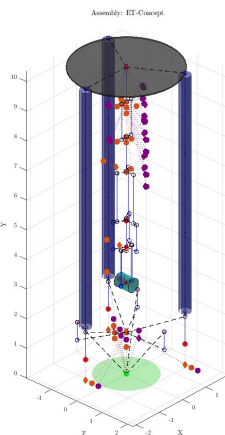
Instrumented baffles in the arms IFAE@BCN
[E. Vallejo, L.-M. Mir, M. Martinez]



Mechanical modelling and control
[R. Cornelissen, S. Sijtsma]



Nikhef



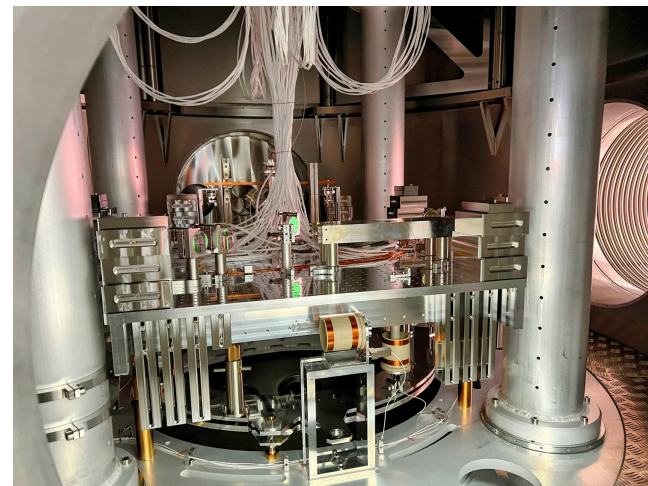
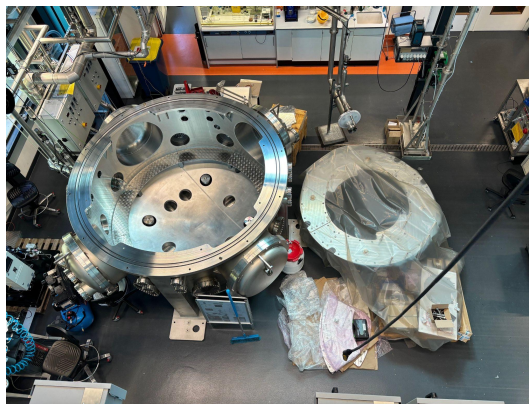


Summary and Outlook

- ETPathfinder: prototype facility to test ET-LF technologies, e.g. cryogenic silicon mirrors and new laser wavelengths
- Initial funding from Interreg, now mixture of individual and consortia grants in various countries; 20+ partners
- Installation is progressing well, two suspended benches at room temperature installed with off-location approach
- Next goal: installation of a cryogenic mirror tower to realise a short Michelson with crystalline suspension
- Full FPMI at 15K planned for 2028

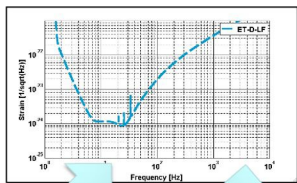


What's next?

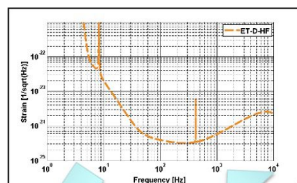




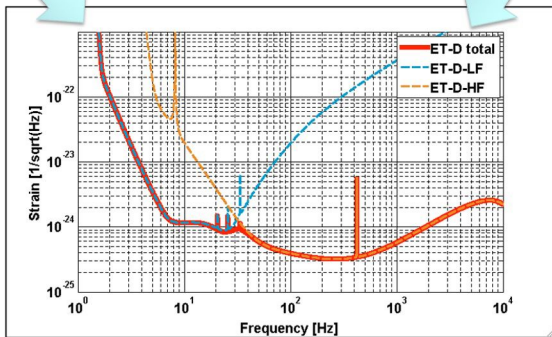
Thinking BIG: ET-LF Integration Center



ET-D-LF



ET-D-HF



Gedanken-Experiment how the ET-LFC could look like.

- Need for ET-LF: quick transition from construction to scientific observation
- Idea: build full-scale ET-LF cryogenic integrated tower before ET installation phase

- With an official ET(O) mandate, this would allow us to:
 - integrate and validate ET-LF technology in realistic conditions and sensitivity close to ET-level
 - Test installation and maintenance procedures for ET-LF towers
 - Develop quality assurance procedures
 - Training of staff and development of skills
- Will need extension of infrastructure and team of engineers
- Exciting news: Dutch government supports these plans!



Thanks for your attention!

Questions?

ETpf visiting scientist program



ETpf design report



ETpf sensitivity paper

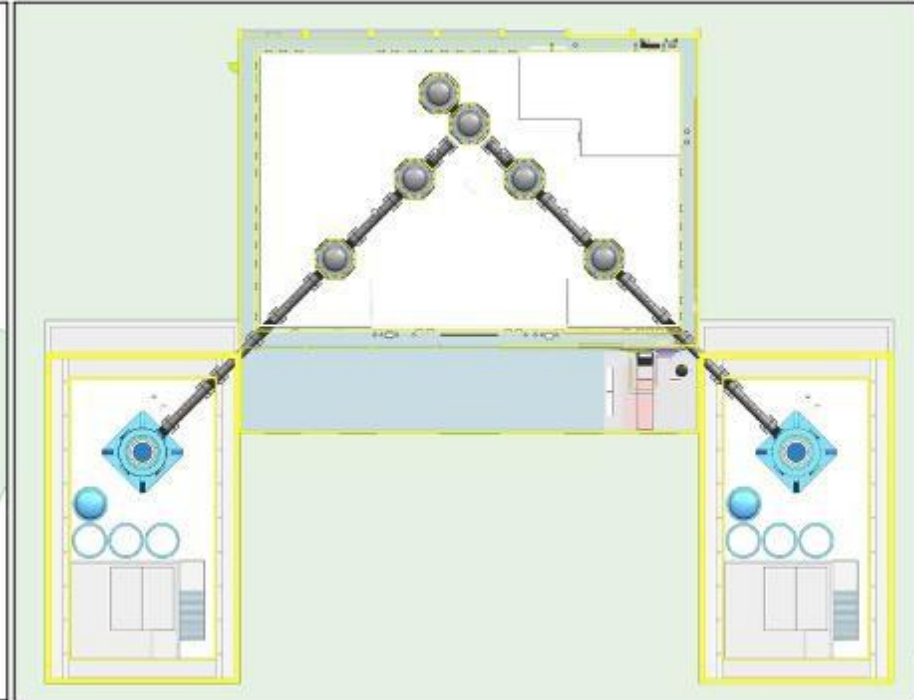
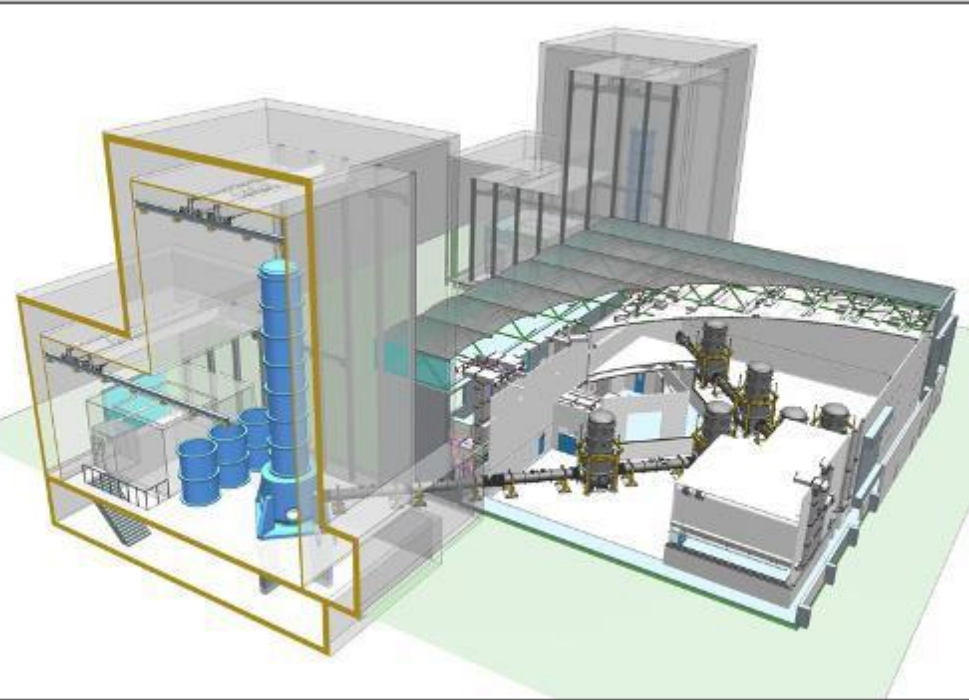


<https://youtu.be/03IMzh5KM98?si=JwYik0bllbcGCca>
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Back-up Slides



How could an ET-LFC look like?



Note: The ET-LF tower design is not frozen. So this is a Gedanken-Experiment to give an idea of what such an ET-LF integration center could look like. Rough costs would = 51MEuro capital + 2 Meuro per year operational cost (mainly for a central team of 15 Engineers/Technicians)
19ME tower buildings, 12ME cleanrooms, 10ME vacuum, 10ME scientific instrumentation.



Idea: ET Low-Frequency Development, Training and Integration Center (ET-LFC)

NEED: In order to transition ET-LF interferometers as quickly and as low risk as possible from construction to scientific observation it is urgently necessary to use the time window until installation of ET will start to construct **the first full-scale ET-LF cryogenic integrated towers** in order to:

- Integrate and validate the performance of ET-LF technology at a **system close to the real ET and a displacement sensitivity close to the targeted ET-level;**
- Develop and validate **installation and maintenance procedures** for ET-LF towers;
- Develop and validate **quality assurance procedures;**
- Critical training **of staff and development of skills;**



Potential Benefits of an ET-LFC coupled to ETpathfinder: We have the opportunity to co-locate the ET-LFC (focussing on integration and training) with the ETpathfinder project (focussing on R&D). This provides several significant additional benefits to the ET project, such as:

- reduced time** between completion of the construction of the civil infrastructure and the first operation of an ET-LF interferometer in observation mode and therefore **savings** in terms of operational costs during the period ET has not reached science mode yet (note: ET operation costs are estimated to be 50M€ per year);
- reduced risk of overlooking unknown unknowns** in the ET-LF technologies and designs;
- training of researchers and technical personnel.**

A key prerequisite for realising the ET-LFC is a clear and strong mandate from the whole ET, including ETO, the ET Collaboration and other key stakeholders.



Limburgs
Parlement

3^e Gewijzigde Motie 3236

Motie Limburg voor de Einstein Telescope

Provinciale Staten van Limburg, in vergadering bijeen op 7 november 2025,
Gelezen het GEWIJZIGD G-25-020 Statenvoorstel inzake Programmabegroting 2026, brief GS van
21-10-2025 (GS DOC-00838353)

Constateerende dat:

- De deelstaat Saksen zich recent formeel kandidaat heeft gesteld voor de locatie van de Einstein Telescope, waarmee voor onze kandidatuur met de Euregio Maas-Rijn nu twee concurrenten officieel in de race zijn;
- Deze twee tegenkandidaten voor de Euregio, Saksen en Sardinië, ook meteen verregaande samenwerking hebben aangekondigd en met het 2L-model hun kandidatuur gezamenlijk maken en versterken;
- Provinciale Staten bij de begroting 2025 bijna unaniem motie 3135 Hanegraaf cs aannam om de kansen van de Einstein Telescope voor Limburg te verzilveren en middelen aan te trekken

Overwegende dat:

- Al in 2018 uit onderzoek bleek dat de komst van de Einstein Telescope zowel de wetenschappelijke positie als de economische ontwikkeling van onze regio versterkt en er sindsdien hard gewerkt en geïnvesteerd is om deze komst naar onze regio te realiseren;
- De ET Pathfinder in Maastricht volledig operationeel is en de komende veertig jaar bijdraagt aan de innovatieve technologieën die nodig zijn voor de Einstein Telescope, ook als die onverhoopt elders wordt gerealiseerd;
- Investerings in R&D-faciliteiten en sleuteltechnologieën aantoonbare economische meerwaarde hebben en houden voor Limburg, ook als de Einstein Telescope onverhoopt niet in onze regio wordt gerealiseerd;

Sprekende uit dat:

- Provinciale Staten van Limburg de komst van de Einstein Telescope naar haar provincie of de Euregio volmondig wil steunen en waar mogelijk bespoedigen;

En roepen het College van Gedeputeerde Staten op om:

1. Voor investeringen in de versterking van de propositie van de Einstein Telescope en R&D faciliteiten en sleuteltechnologieën een fonds uit te werken met een beoogde omvang van (ten minste) €10.000.000;
2. Dit Einsteinfonds nader uit te werken in een Statenvoorstel, hierin op te nemen dat de benodigde middelen gedekt zullen worden uit het begrotingsresultaat 2026 en dit Statenvoorstel ter besluitvorming voor te leggen aan Provinciale Staten vóór de zomer van 2026.

Jenneskens
D66

Bloi
VVD

Smeets
SP

Diessen
Forum voor Democratie

Hanegraaff
CDA

Sol
GroenLinks

Berghorst
PvdA

Fischer
50PLUS

And call on the Provincial Executive to:

1. To develop a fund with a target size of (at least) €10,000,000 for investments in strengthening the Einstein Telescope proposition and R&D facilities and key technologies;
2. To further develop this Einstein Fund in a Provincial Council proposal, to include in it that the necessary resources will be covered by the 2026 budget result, and to submit this Provincial Council proposal for decision-making before the summer of 2026.



Coordination Effort on Funding Agency Level across Europe

- Initiated by INFN and NWO-I (Nikhef).
- Not yet signed ... but allegedly several countries ready to sign ...
- Positioning Virgo as ET-HF integration facility focussing on room temperature, 1064nm, fused silica and ETpathfinder as ET-LF integration facility focusing on cryogenic temperatures, silicon mirrors and 1550/2090nm.

Integration facilities for R&D and validation

Various laboratories and facilities across Europe (existing or under construction) will contribute to the R&D efforts. In addition to R&D efforts on specific GW technologies, the integration challenges into a functional GW interferometer need to be addressed. In Europe, two integration facilities are operational for testing and validating novel technologies: VIRGO as a high-frequency interferometer and ETpathfinder as a low-frequency interferometer. VIRGO is the facility where solutions for the ET-HF interferometer are integrated and where low-frequency control methods are tested. The ETpathfinder facility is where the integration and control methods for the ET-LF interferometer are tested.

DRAFT

Letter of Intent for a joint European R&D effort for the Einstein Telescope

Introduction

The Einstein Telescope (ET) will be the third-generation ground-based Gravitational Waves (GW) detector in Europe. It will observe the GW sky much sharper and deeper than the existing interferometers of LIGO and VIRGO, and in a much broader frequency range.

To achieve such improved sensitivities, ET requires novel technologies that do not yet exist. All aspects of the LIGO/VIRGO technology must be profoundly redesigned and dramatically improved, both to enhance the sensitivity at high frequencies (HF, 20-3000 Hz) and at low frequencies (LF, 2-30 Hz). The former requires, among other aspects, better lasers, larger test masses, better mirrors substrates and coatings, better suspensions, and very effective thermal compensation. The latter requires, among other aspects, cryogenics technologies and materials to cope with fundamental thermal noises, better control systems, an effective Newtonian noise subtraction system and, again, better suspensions that can sustain larger test masses.

The institutions supporting ET are investing in improving technologies, existing facilities and/or building new ones to address these challenges and to sustain a robust R&D program on all aspects. However, it is unrealistic that any single institution can address all challenges or carry out all R&D activities. It is evident that the amount of work, the diversity of efforts and the complexity of the challenge make it desirable to coordinate and share R&D activities at the European level.

R&D activities for the realization of ET have already started at various research institutions in Europe. With this Letter of Intent, the signatory research institutions express their joint ambition to establish a coordinated European R&D effort for the implement of the Einstein Telescope.

Integration facilities for R&D and validation

Various laboratories and facilities across Europe (existing or under construction) will contribute to the R&D efforts. In addition to R&D efforts on specific GW technologies, the integration challenges into a functional GW interferometer need to be addressed. In Europe, two integration facilities are operational for testing and validating novel technologies: VIRGO as a high-frequency interferometer and ETpathfinder as a low-frequency interferometer. VIRGO is the facility where solutions for the ET-HF interferometer are integrated and where low-frequency control methods are tested. The ETpathfinder facility is where the integration and control methods for the ET-LF interferometer are tested.

VIRGO is currently the state of the art in Europe. It will likely be upgraded in the next four years to solve the stability issues of the input and output cavities and will be further upgraded and operated until the start of ET data taking. VIRGO does not have the ambition to become a cryogenic interferometer, but future upgrades will require new developments, several of which are similar to those required for ET, in particular for the HF interferometers, but not uniquely for that.

ETpathfinder in Maastricht, while being of short armlength, offers a full cryogenic interferometer facility for testing and validating LF technologies in an integrated system operated as an interferometer, making this a unique facility in Europe and the world. The ambition is for ETpathfinder, in due time, to have the capacity to serve as a full integration and quality assurance center for hardware to be delivered to ET-LF. The ETpathfinder program will thus focus on technologies required for the LF interferometers of ET, but not exclusively. By providing a fully operational interferometer, it will also create synergies with Virgo and ET HF instrumentation.



Coordination Effort on Funding Agency Level across Europe

Taking into account the considerations formulated in the introduction, in particular the significant resources and the expert knowledge to operate these HF and LF interferometers, the signatory research institutions envisage a concerted European effort with VIRGO and ETpathfinder as the central integration and validation centers in the R&D Roadmap for the realization of ET.

Positioning

Roadmap Task Force to develop a European ET R&D Roadmap

The signatory research institutions envisage the creation of a joint team **R&D** to develop a concerted R&D Roadmap in Europe to be executed during the implementation phase. This R&D Roadmap is to consider the final validation of the technologies through VIRGO and ETpathfinder as **Roadmap** integration and validation centers. Accordingly, the R&D Roadmap is to deliver the key technologies to realize the baseline ET research infrastructure. The delivery of the R&D Roadmap is expected during the preparatory phase of the ET process.

The European R&D Roadmap should identify, embrace and foster opportunities for global collaboration.

Coordination of Resources

Connection to CE and KAGRA

The R&D Roadmap should form the basis for research institutions to commit in due time to its implementation supported by resources formalized in MoUs. The technological R&D efforts considered are largely independent of the final geometry of the ET interferometer, or the final detector location(s).

Independent from side and geometry

The mandate of the Roadmap Task Force should be endorsed by the ET BGR and the Roadmap Task Force responds directly to the ET Coordinators. The Roadmap Task Force will closely collaborate with ETO to align requirements but will operate with a mandate parallel to that of the ETO, and with the ET Collaboration to align with the preparatory R&D that is ongoing in the collaboration.

BGR / ET coordinators / ETO / ETC connection

The Roadmap Task Force will consist of researchers appointed by the participating institutions, and each participating institution will cover the costs of its own researchers, such as travel expenses.

The Roadmap Task Force does not directly manage resources and has no budget.

The Roadmap Task Force will advise the ET Coordinators by making proposals to distribute the R&D effort among research institutions. The aim is to avoid unnecessary duplication and to ensure that all relevant aspects are addressed and covered.

Participation should not impede potential "competition" on the desired geometry and/or location(s) of the final ET infrastructure. Research institutions can therefore join the coordinated efforts towards an R&D Roadmap even before they have formally committed to join and financially support the realization of ET.

The Roadmap Task Force will contemplate activities of all institutions that are initially willing to join the R&D efforts with options to gradually include the efforts of additional institutions joining at a later stage in the overall coordinated effort.

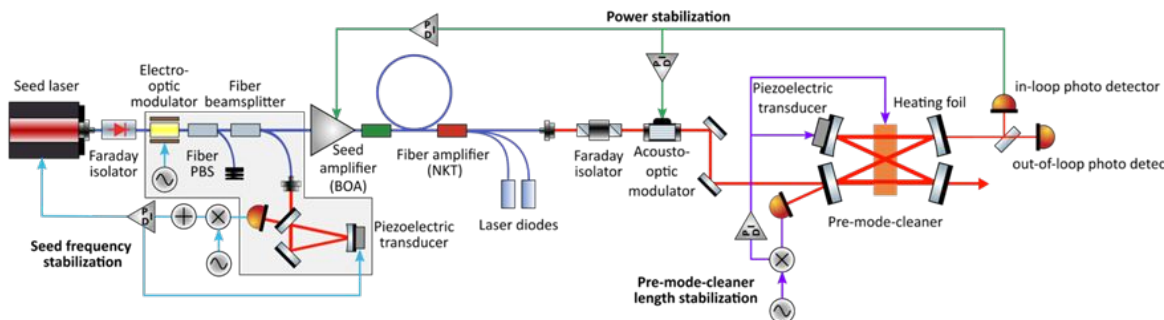
While the leadership of VIRGO and ETpathfinder is under the EGO Council and the ETpathfinder Collaboration Board respectively, the Roadmap Task Force will foster a strong connection between the European R&D Roadmap efforts and these two facilities as HF and LF integration and validation centers. The Roadmap Task Force will consider the R&D efforts for potential upgrades of both research facilities to further strengthen their ability to enhance the ET performance, as well as the performance of VIRGO and ETpathfinder. They will also discuss potential contributions from other facilities that could play a key role in such a concerted R&D effort.



1550nm Pre-Stabilised Laser

1550nm pre-stabilised laser system developed at AEI (Nicole Knust, Fabian Meylahn; group of Benno Willke)

- Diode seed laser (Orion) with frequency pre-stabilisation
- Pre-amplifier (booster optical amplifier) followed by NKT Photonics fibre amplifier
- Pre-mode cleaned for additional filtering and pointing stability followed by power stabilisation

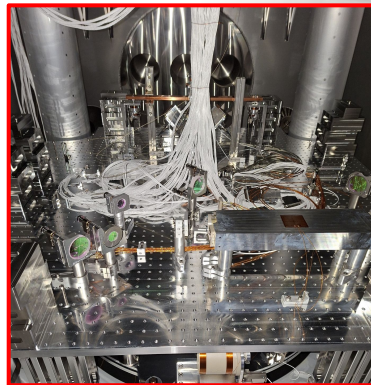
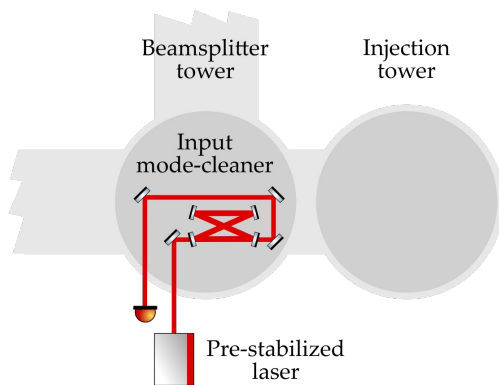




Input Mode Cleaner (IMC)

- Integration of laser into Virgo-like DAQ
- Implementation of outer frequency stabilisation of the laser system to the IMC
- Investigation of relative power noise, frequency noise and beam pointing downstream of IMC

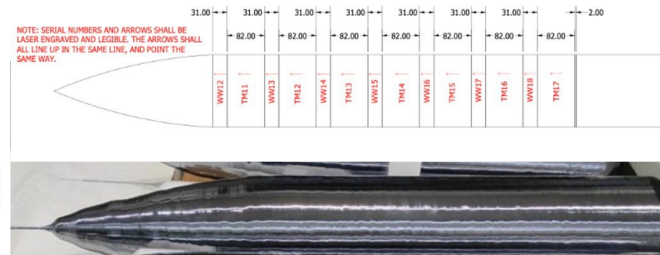
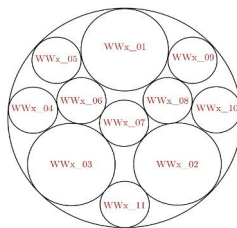
Image credit: Nicole Knust





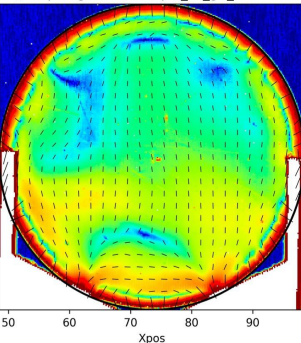
ETpathfinder Silicon Mirrors

- Floatzone ingots procured from IKZ, Berlin
- Several samples from witness wafers:
 - Cryogenic mechanical loss in range $1e-8$
 - Bulk birefringence about $1e-8$ (Ferrara)
- Mirror substrates polished by Zeiss MT:
 - roughness $< 100\text{pm}$, flatness $< 1\text{nm}$
 - No excess surface absorption (LMA)
- BPhot: Polishing with laser-assisted diamond turning



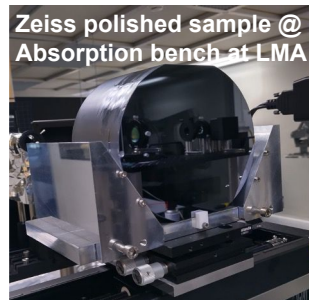
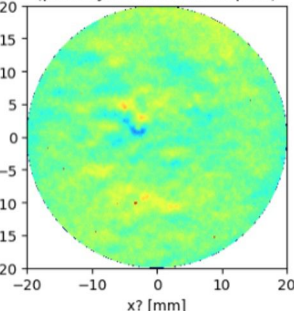
Birefringence map (Ferrara)

Δn map (log scale) sample_1s_gv_VW01-02

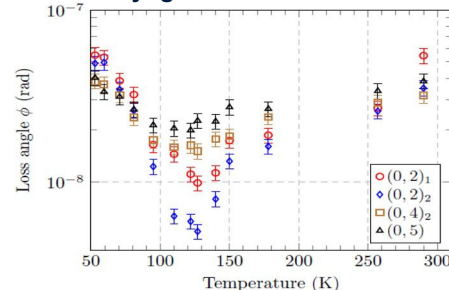


Flatness map of ETPF ITM

processed (plot styled to mimic report)



Cryogenic Q-measurement



<https://journals.aps.org/prd/abstract/10.1103/xzbl-3snb>

ETpathfinder silicon mirrors show flatness comparable to current LIGO/Virgo mirrors

