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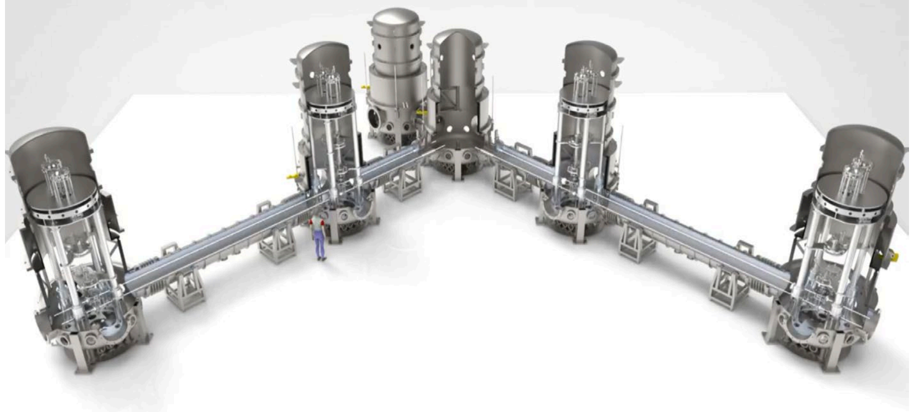
ETpathfinder

Prof Stefan Hild, University of Maastricht & Nikhef

www.einsteintelescope.nl / www.etpathfinder.eu

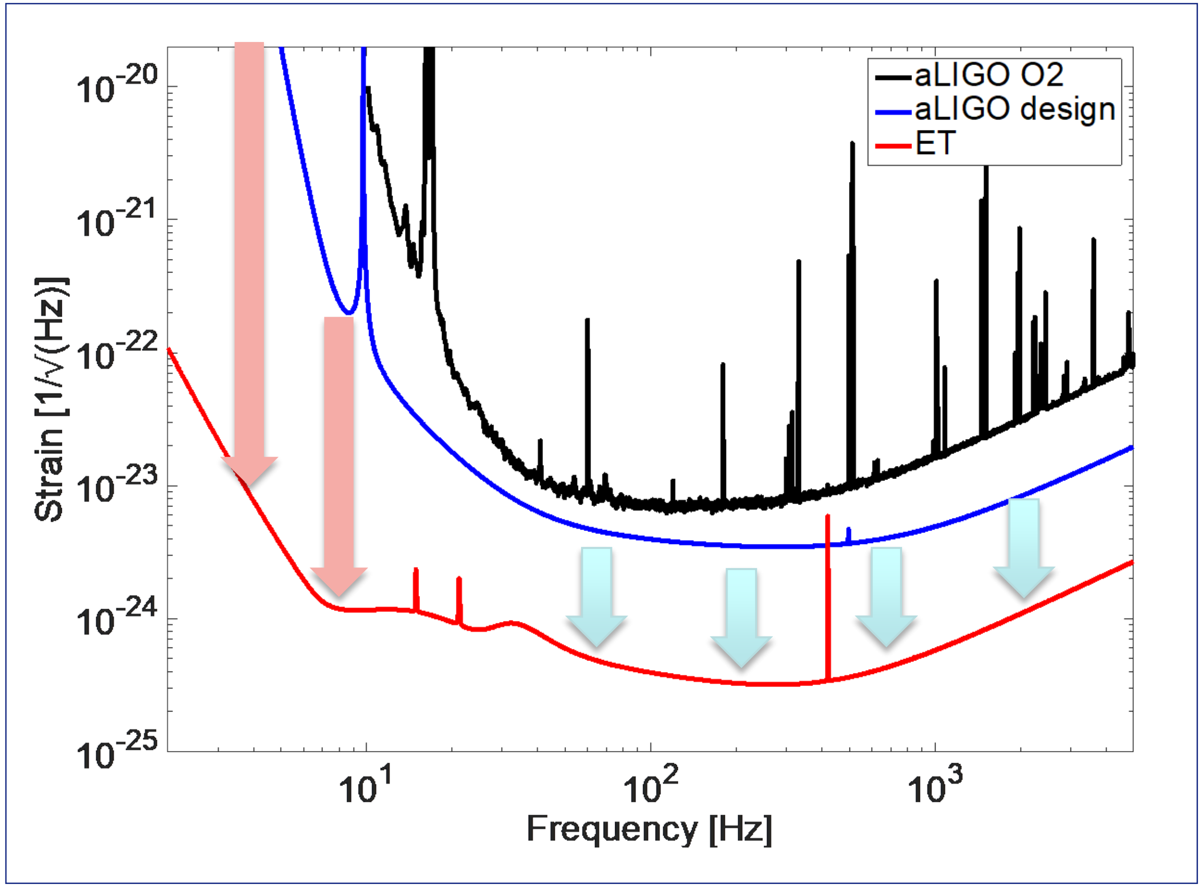


ETpathfinder

Why ETpathfinder needed?

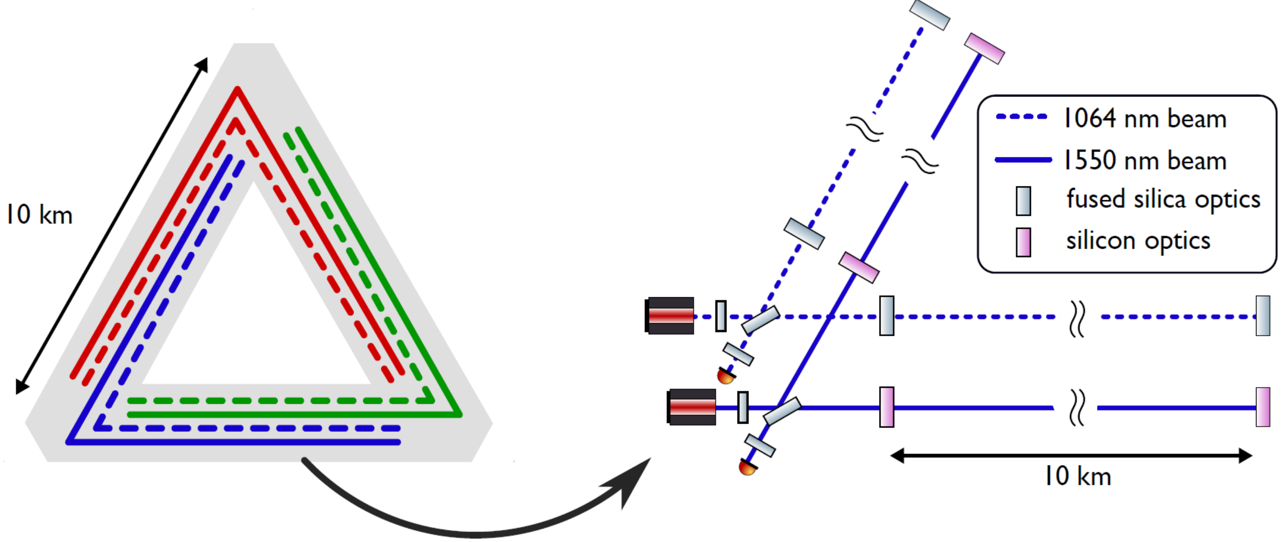
The Low-Frequency Challenge:

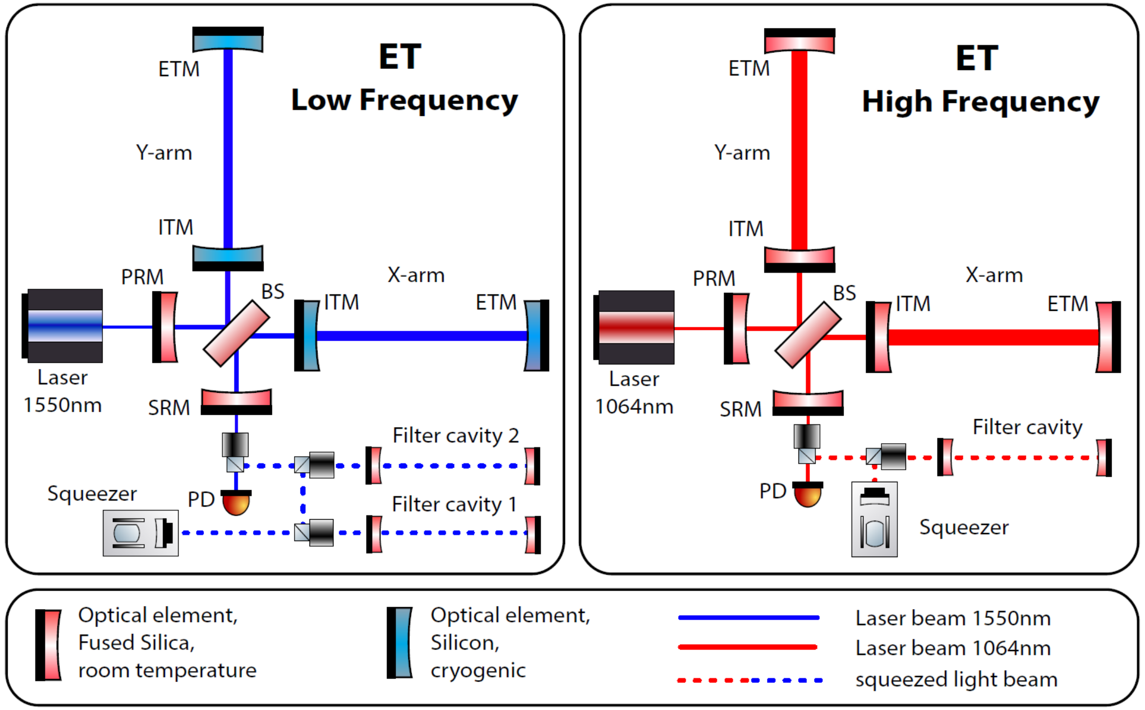
- At mid and high frequency we aim for factor ~10 improvement.
- At low frequency we are aiming for factors 100, 1000 and more improvement.
- **Needs fundamental changes in technology and concepts, that need testing and prototyping.**



Einstein Telescope design

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for f > 1 Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few





New Technologies

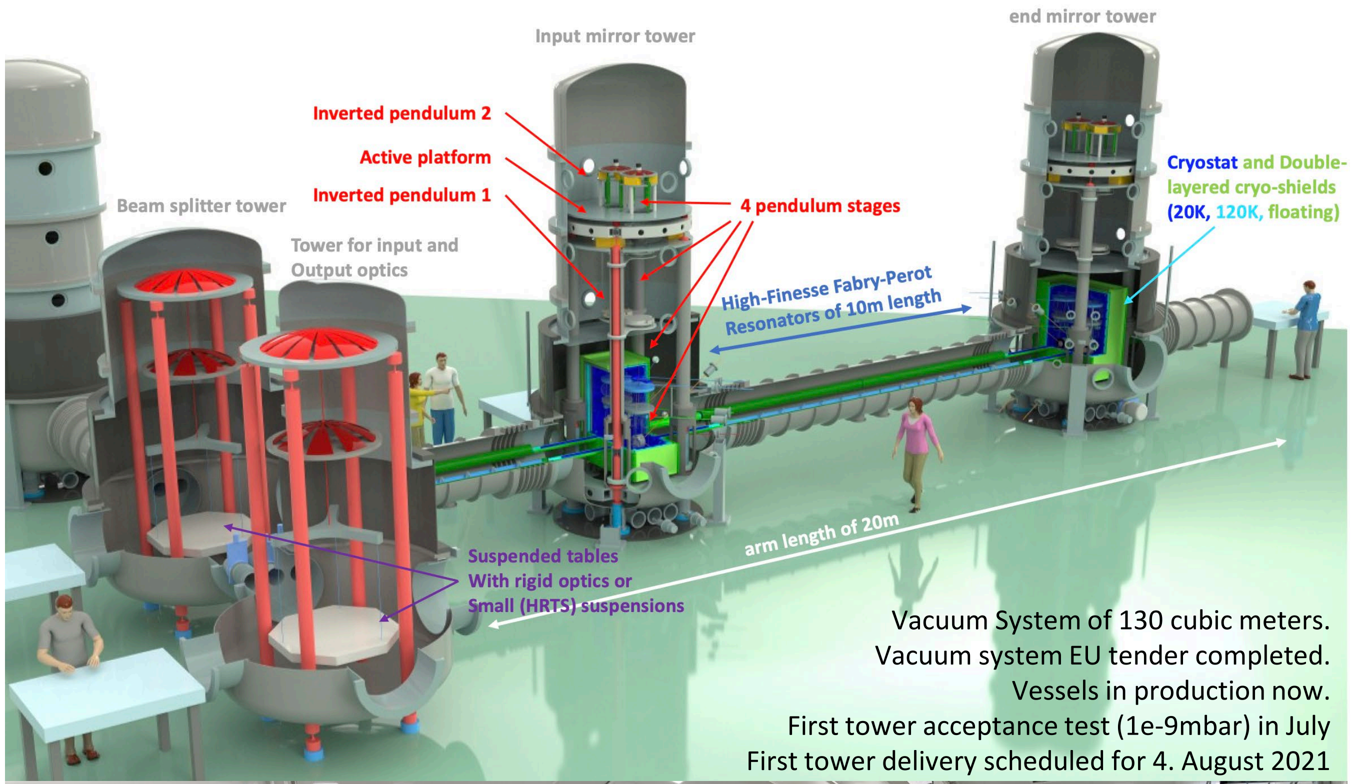
Nikhef

ET requires technological advances on all fronts:

- New mirror material => Silicon
- New temperature => 10-20K
- New laser wavelength => 1.5-2.1 microns
- Advanced quantum-noise-reduction schemes

ETpathfinder Overview

- New facility for testing ET technology in a low-noise, full-interferometer setup.
- Key aspects: Silicon mirrors (3 to 100+kg), cryogenics   cryogenic liquids and sorption coolers, water/ice management), “new” wavelengths (1550 and 2090nm), coatings …
- Start with 2 FPMI, one initially at 120K and one 15K
- 20+ partners from NL/B/G/FR/SP/UK/PL
- Initial capital funding of 14.5 MEuro.
- Detailed Design Report available at apps.et-gw.eu/tds/?content=3&r=17177
- Open for everyone interested to join.
- www.etpathfinder.eu



ETpathfinder Partners

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provincie limburg

Ministerie van Onderwijs, Cultuur en Wetenschap

Provincie Noord-Brabant

SMART HUB
VLAAMS-BRABANT
Met de steun van de provincie Vlaams-Brabant

Vlaamse Regering

Provincie Antwerpen

Ministerie van Economische Zaken

GHENT UNIVERSITY

Universiteit Antwerpen

VUB VRIJE UNIVERSITEIT BRUSSEL

IFAE Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA

LAPP Laboratoire d'Annecy de Physique des Particules

Nikhef

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UNIVERSITY OF BIRMINGHAM

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Nicolaus Copernicus Astronomical Center
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im Forschungsverbund Berlin e.V.

LIÈGE université

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University of Glasgow
VIA VERITAS VITA

TNO

Fraunhofer ILT

UNIVERSITY OF TWENTE.

KIT Karlsruher Institut für Technologie

UHASSELT

UCLouvain

arXiv:2206.04905v1 [astro-ph.IM] 10 Jun 2022

ETpathfinder: a cryogenic testbed for interferometric gravitational-wave detectors

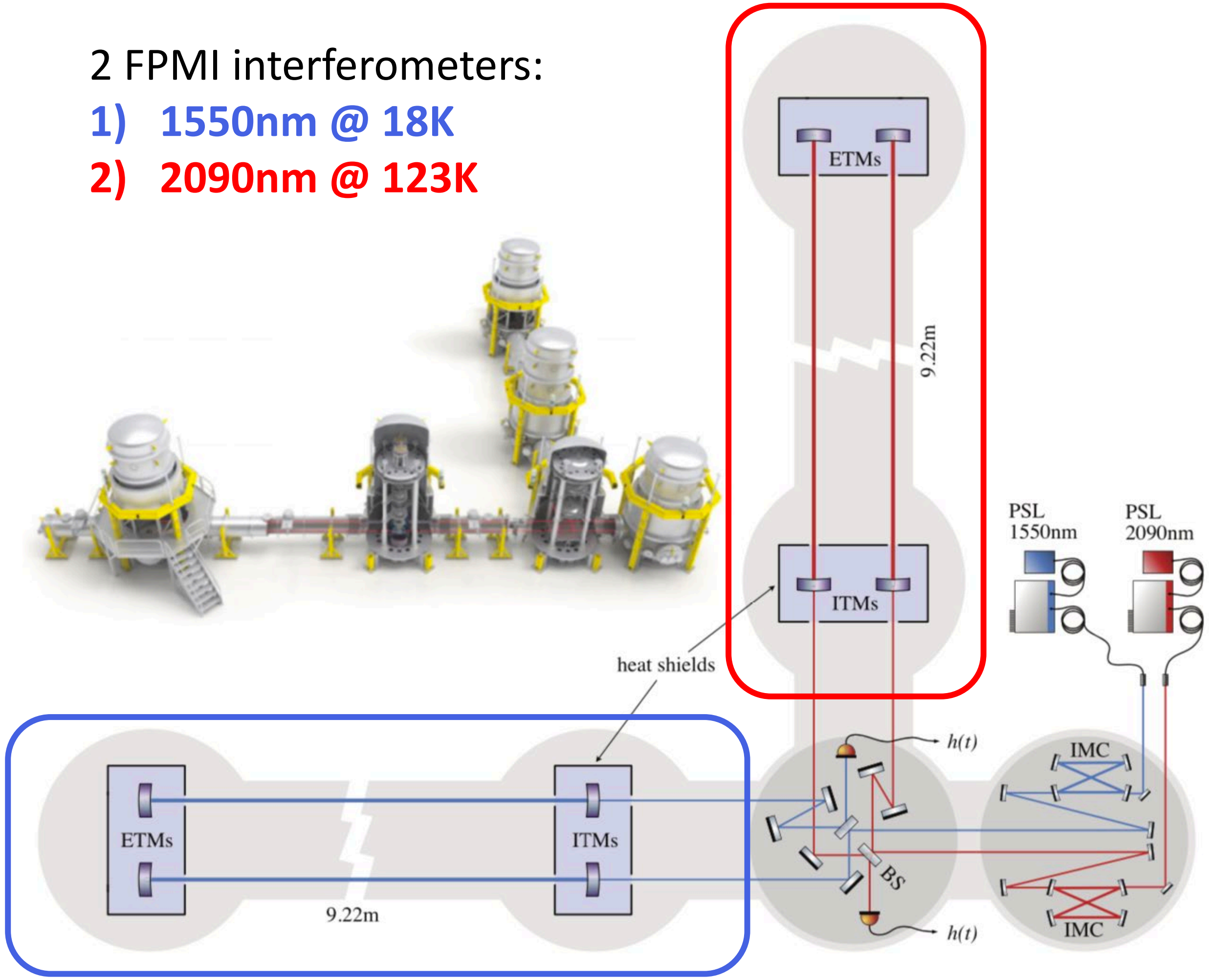
A. Utina[1,2], A. Amato[1,2], J. Arends[3], C. Arina[4], M. de Baar[5], M. Baars[2], P. Baer[6], N. van Bakel[2], W. Beaumont[7], A. Bertolini[2], M. van Beuzekom[2], S. Biersteker[3], A. Binetti[8], H. J. M. ter Brake[9], G. Bruno[4], J. Bryant[10], H. J. Bulten[2], L. Busch[11], P. Cebeci[6], C. Collette[12], S. Cooper[10], R. Cornelissen[2], P. Cuijpers[1], M. van Dael[5], S. Danilishin[1,2], D. Dixit [1,2], S. van Doesburg[2], M. Doets[2], R. Elsinga[2,3], V. Erends[2], J. van Erps[20], A. Freise[2,3], H. Frenaij[2], R. Garcia[13], M. Giesberts[6], S. Grohmann[11], H. Van Haevermaet[7], S. Heijnen[2], J. V. van Heijningen[4], E. Hennes[2], J.-S. Hennig[1,2], M. Hennig[1,2], T. Hertog[8], S. Hild[1,2], H.-D. Hoffmann[6], G. Hoft[2], M. Hopman[2], D. Hoyland[10], G. A. Iandolo[1,2], C. Ietswaard[2], R. Jamshidi[12], P. Jansweijer [2], A. Jones[14], P. Jones[10], N. Knust[15], G. Koekoek[1,2], X. Koroveshi[11], T. Kortekaas[3], A. N. Koushik[7], M. Kraan[2], M. van de Kraats[2], S. L. Kranzhoff[1,2], P. Kuijer[2], K. A. Kukkadapu[7], K. Lam[2], N. Letendre[16], P. Li[7], R. Limburg[3], F. Linde[2], J.-P. Locquet[8], P. Loosen[6], H. Lueck[15], M. Martínez[13], A. Masserot[16], F. Meylahn[15], M. Molenaar[3], C. Mow-Lowry[2,3], J. Mundet[13], B. Munneke[2], L. van Nieuwland[2], E. Pacaud[16], D. Pascucci[17], S. Petit[16], Z. Van Ranst[1,2], G. Raskin[8], P. M. Recaman[8], N. van Remortel[7], L. Rolland[16], L. de Roo[2], E. Roose[7], J. C. Rosier[3], D. Ryckbosch[17], K. Schouteden[8], A. Sevrin[18], A. Sider[12], A. Singha[1,2], V. Spagnuolo[1,2], A. Stahl[19], J. Steinlechner[1,2], S. Steinlechner[1,2], B. Swinkels[2], N. Szilasi[4], M. Tacca[2], H. Thienpont[20], A. Vecchio[10], H. Verkooijen[2], C. H. Vermeer[9], M. Vervaeke[20], G. Visser[2], R. Walet[2,3], P. Werneke[2], C. Westhofen[19], B. Willke[15], A. Xhahi[9], T. Zhang[10]

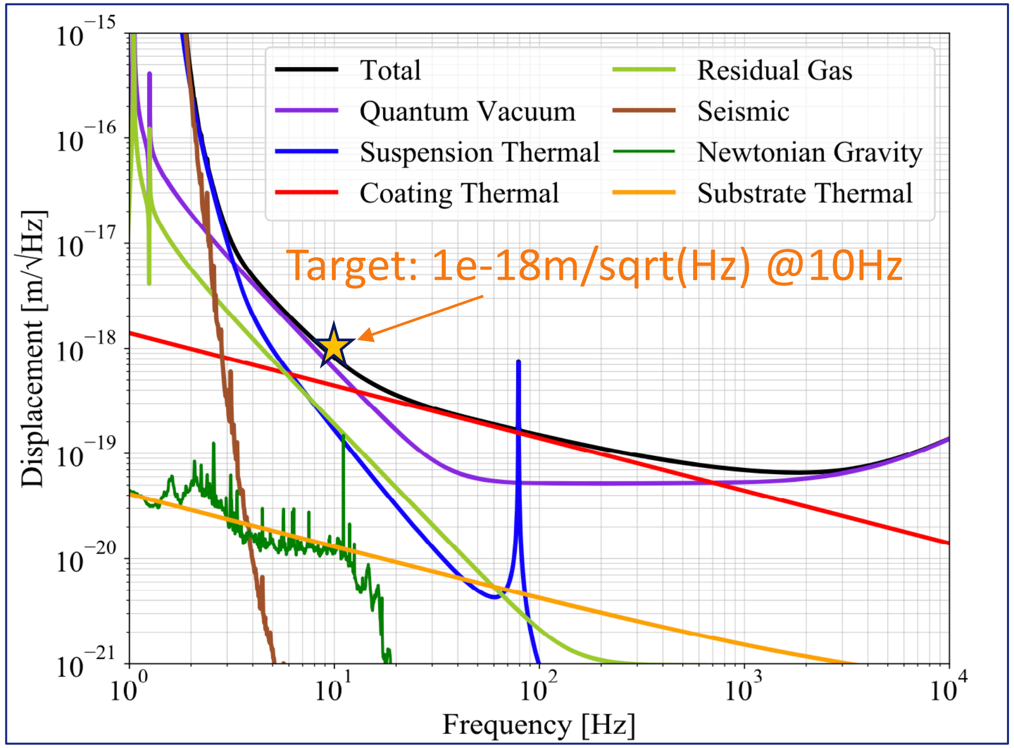
[1] Maastricht University, Department of Gravitational Waves and Fundamental Physics, 6200 MD Maastricht, Netherlands
[2] Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands
[3] VU Amsterdam, Department of Physics and Astronomy, Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, Netherlands
[4] UC Louvain (Center for Cosmology, Particle Physics and Phenomenology, 2 Chemin de Cyclotron, 1348 Louvain-la-Neuve, Belgium)
[5] Eindhoven University of Technology, 5612 AZ Eindhoven, Netherlands
[6] Fraunhofer ILT - Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany
[7] Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium
[8] KU Leuven (Department of Physics and Astronomy, Celestijnenlaan 200D, 3001 Leuven, Belgium
[9] University of Twente, Drienerlolaan 5, 7522 NB Enschede, Netherlands
[10] The University of Birmingham, School of Physics and Astronomy, and Institute of Gravitational Wave Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom
[11] Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
[12] ULiege - Precision Mechatronics Laboratory, 9, allée de la découverte, 4000 Liège, Belgium
[13] The Institute for High Energy Physics of Barcelona (IFAE), Campus UAB, Facultat Ciencies Nord, 08193 Bellaterra, Barcelona, Spain
[14] OzGrav, University of Western Australia, Crawley, WA 6009, Australia
[15] Max Planck Institute for Gravitational Physics (AEI), Callinstraße 38, 30167 Hannover, Germany
[16] Lapp Annecy, Laboratory of Particle Physics, 9 Chem. de Bellevue, 74940 Annecy, France
[17] Ghent: Universiteit Gent, Department of Physics and Astronomy, Proeftuinstraat 86, 9000 Gent, Belgium
[18] Theoretische Natuurkunde, Vrije Universiteit Brussel & The International Solvay Institutes Pleinlaan 2, B-1050 Brussels, Belgium
[19] RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany
[20] Vrije Universiteit Brussel and FlandersMake, Faculty of Engineering, Dept. of Applied Physics and Photonics (TONA), Brussels Photonics (B-PHOT), Pleinlaan 2, B-1050 Brussels, Belgium

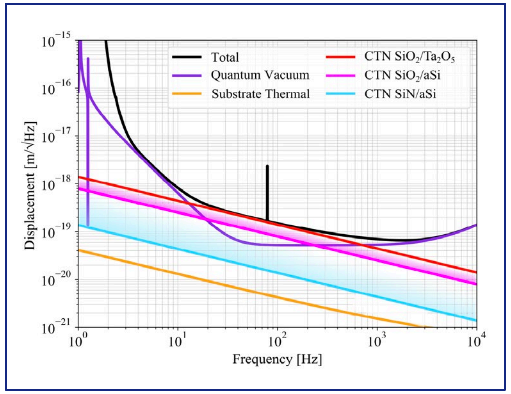
Top-Level layout

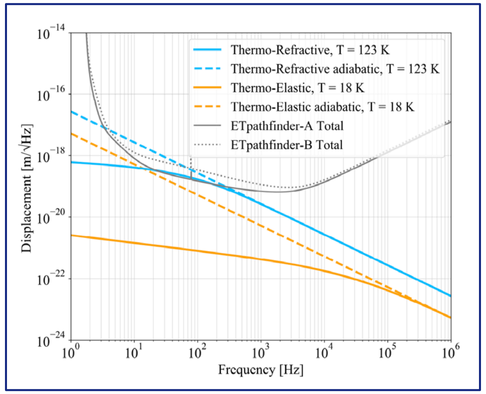
2 FPMI interferometers:

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










January 2020


SCHMITZ
SCHMITZ
April 2020


Summer 2020

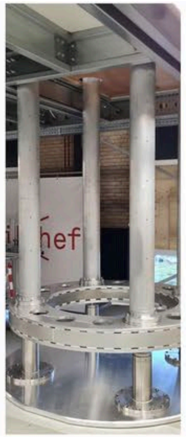
LOXAM
workx
MANITOU
MANITOU
Autumn 2020

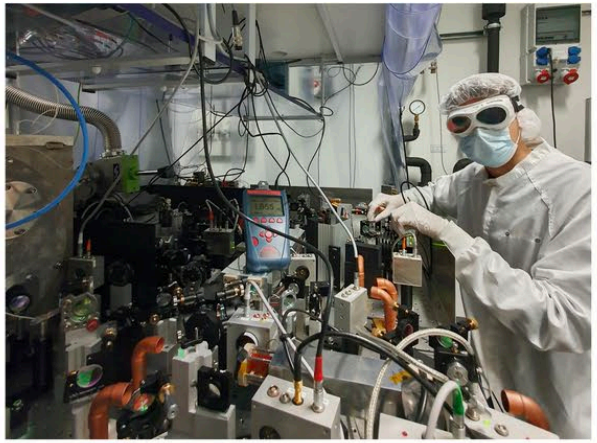
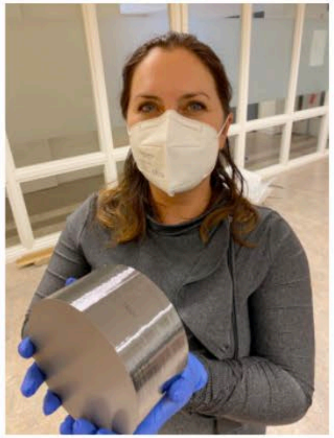
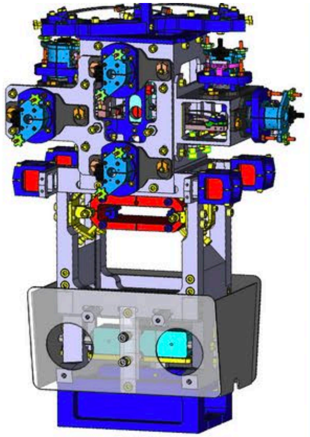
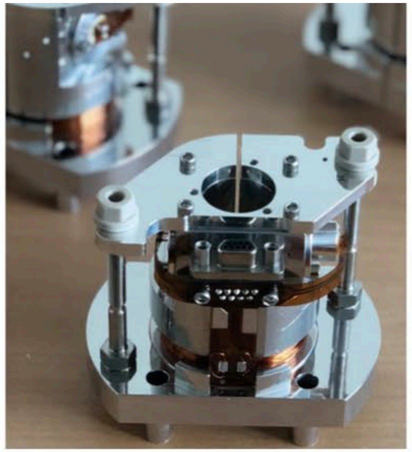
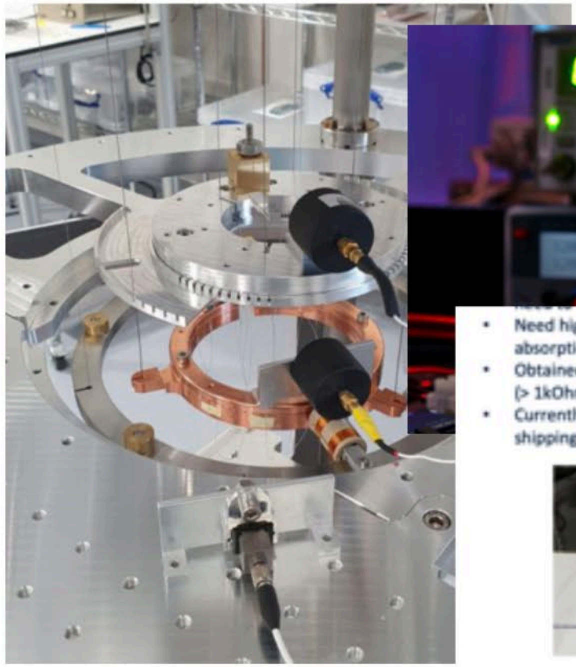
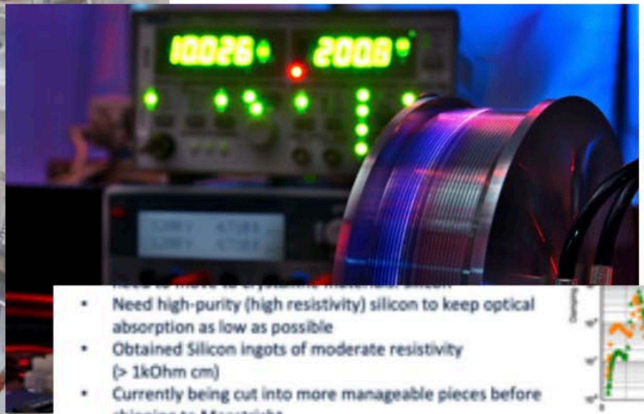

ALTMANN - 2 x 2 to
Summer 2021

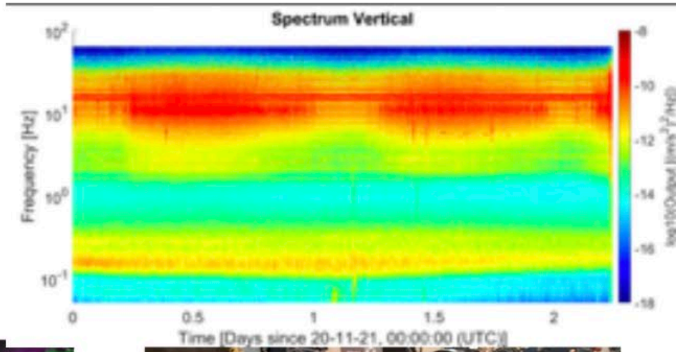
Autumn 2021

Summer 2022

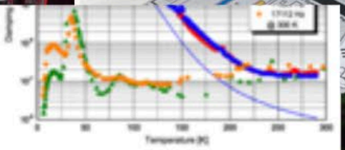
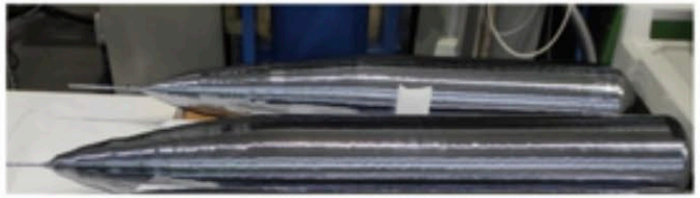
Some Impressions ETpathfinder Activities



- Need high-purity (high resistivity) silicon to keep optical absorption as low as possible
- Obtained Silicon ingots of moderate resistivity (> 1kOhm cm)
- Currently being cut into more manageable pieces before shipping to Maastricht

From ETpathfinder Advisory Board (STAC) report

- […] Overall, the ETPF-STAC was very impressed with the vision for the facility, the technical capability of the leader and team, and the scope of the effort. It will be transformative for the field to have a facility and a research program covering the foreseen capabilities of the installation, and it can become a very natural center for technical innovation and scientific breakthroughs in precision measurement, interferometry, cryogeny for gravitational-wave detectors, and for the formation of a next generation of gravitational-wave scientists (to handle the next generation of gravitational-wave detectors). The growth of the team (and of the institutions interested in participating) is an exciting development and speaks to the timeliness and centrality of this infrastructure. […]
- The ETPF-STAC is very excited to be part of the establishment and exploitation of this unique facility and this dynamic team.


Start Construction: April 2020


Drilling 170 pillars

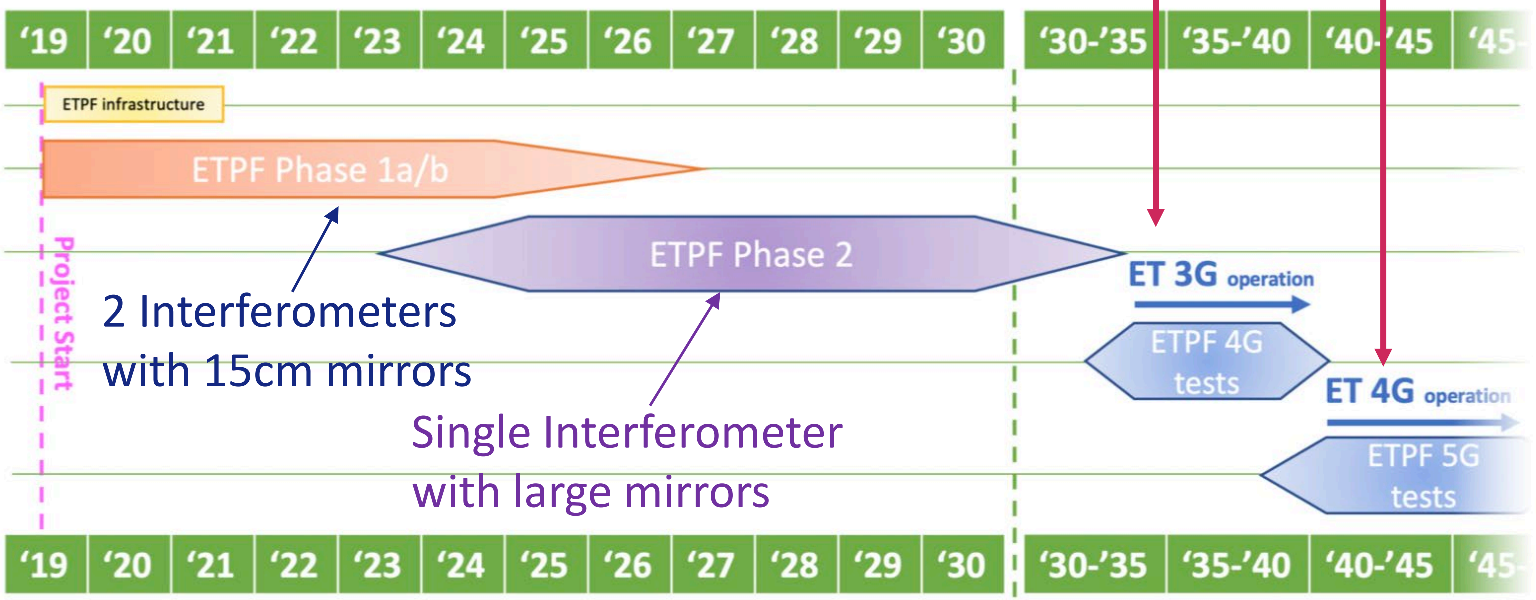

July: ~1000 t of concrete poured


Oct : First cleanroom walls being installed.

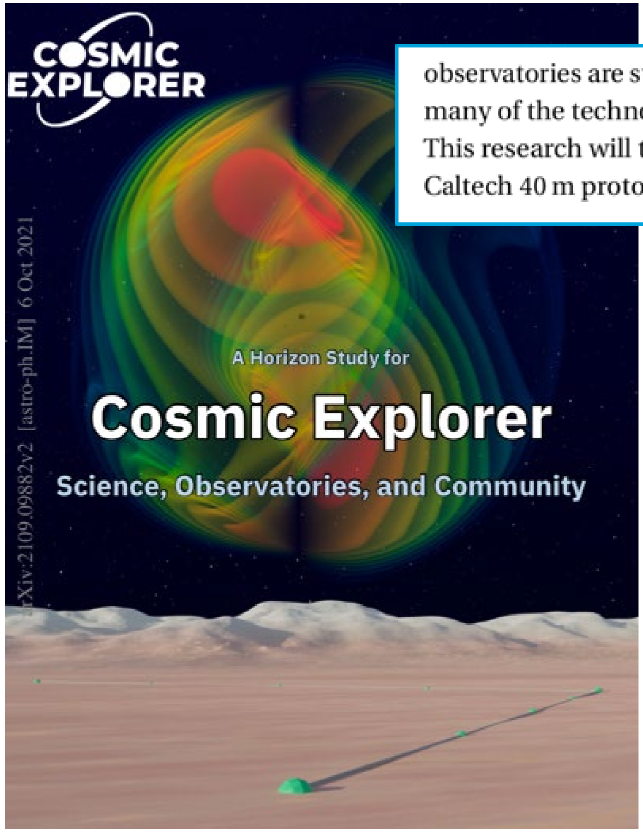
Cleanroom in operation ~ March 2021

ETpathfinder is a longterm acitivity (and independ of ET site decision)

- ESFRI application states ET will be operational from 2035 to 2085.
- Expect many ET detector upgrades over the 50 years.
- While ET operates and observes in “generation X technology” ETpathfinder can do R&D for “generation X+1 technology”



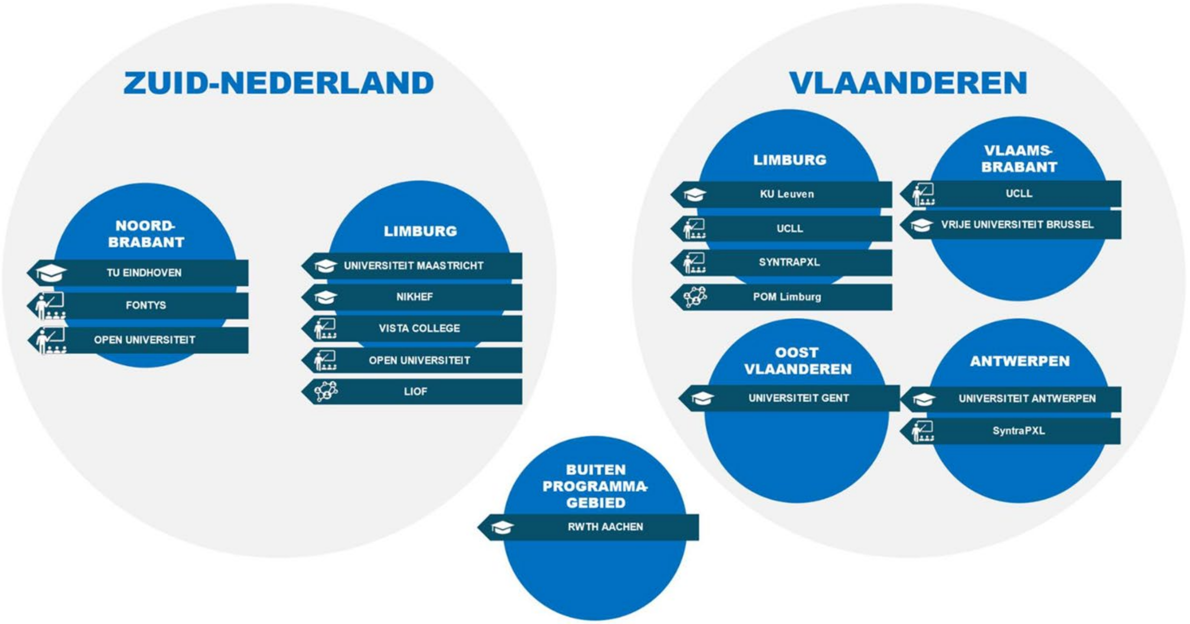
ETpathfinder beyond ET



observatories are still operational. In addition to ensuring that CE will achieve its full potential, many of the technologies required for CE may also be used to enhance existing observatories. This research will take place in collaboration with other projects like ETpathfinder[38] and the Caltech 40 m prototype.[37]

Application submitted: ETpathfinder Skills Lab

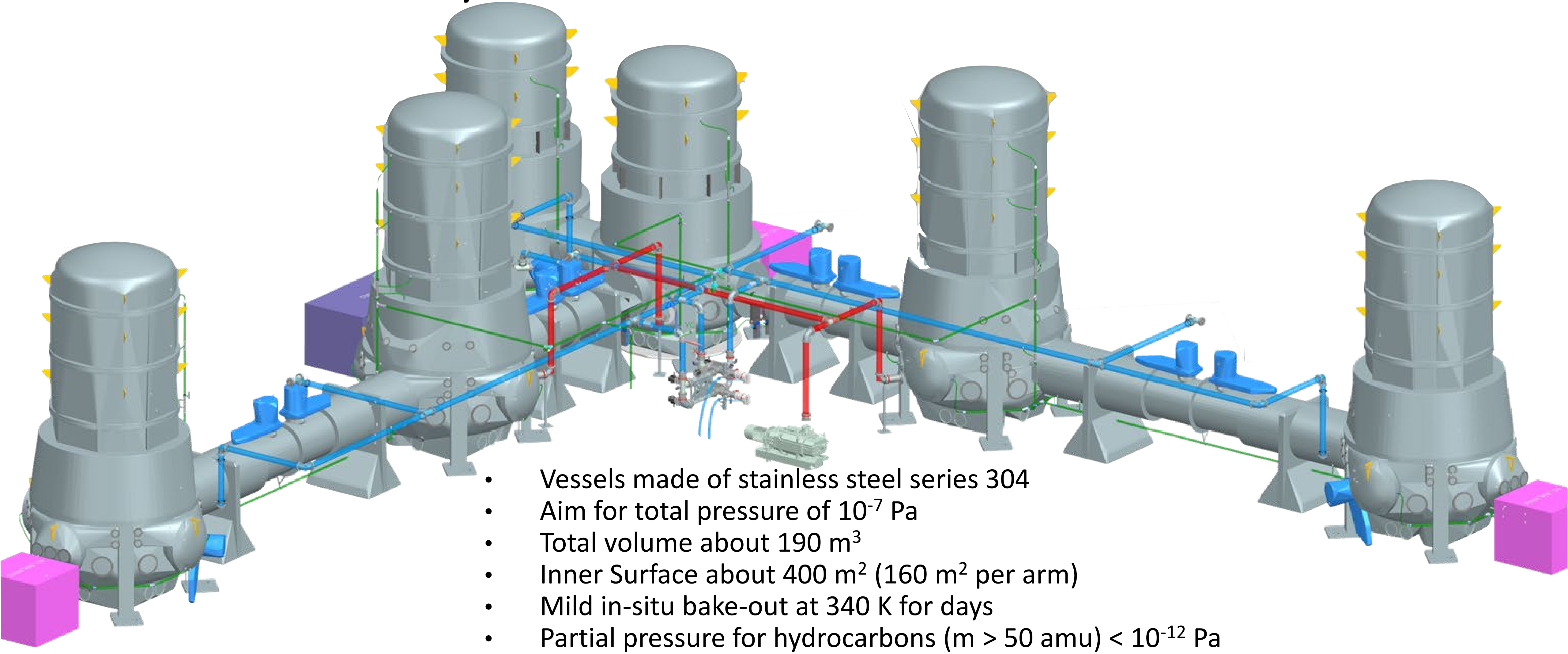
- Proposal centered around a cohort of 15 postdocs (2Y) stationed at ETpathfinder partners, but working in Maastricht more than 50% of time.
- Postdocs are expected to contribute to ETpathfinder, learning skills and then developing training materials and delivering trainings to SMEs.
- Includes not only Universities and research institutes, but also more technical high schools and professional training centers.
- Total volume ~4.4MEuro.
- If successful, then it would start in spring 2025.



Detailed Topics

- Vacuum
- Cryogenics
- Seismic isolation
- Optics

The Vacuum System - Overview

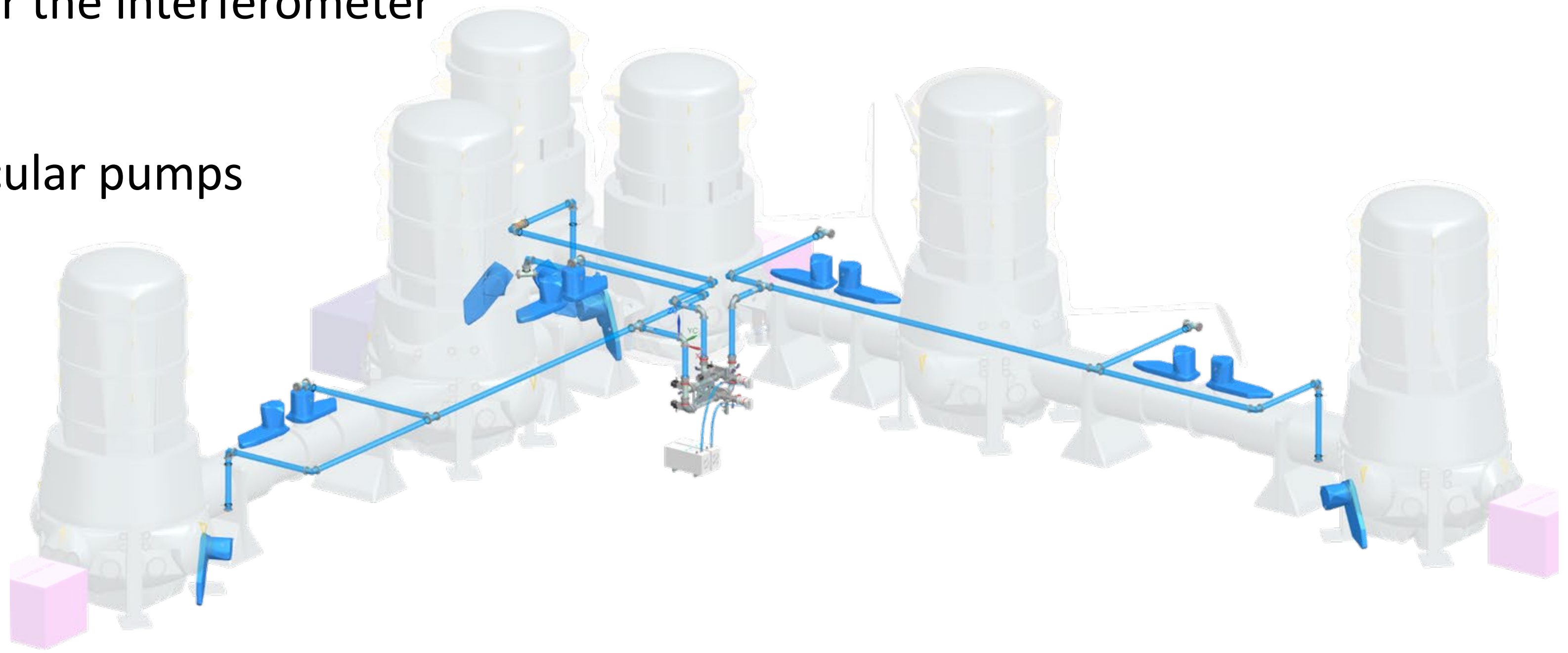


- Vessels made of stainless steel series 304
- Aim for total pressure of 10^{-7} Pa
- Total volume about 190 m^3
- Inner Surface about 400 m^2 (160 m^2 per arm)
- Mild in-situ bake-out at 340 K for days
- Partial pressure for hydrocarbons (m > 50 amu) < 10^{-12} Pa
- 3 vacuum systems: UHV (blue), roughing (red), differential (green)

The Vacuum System - Overview

The UHV system:

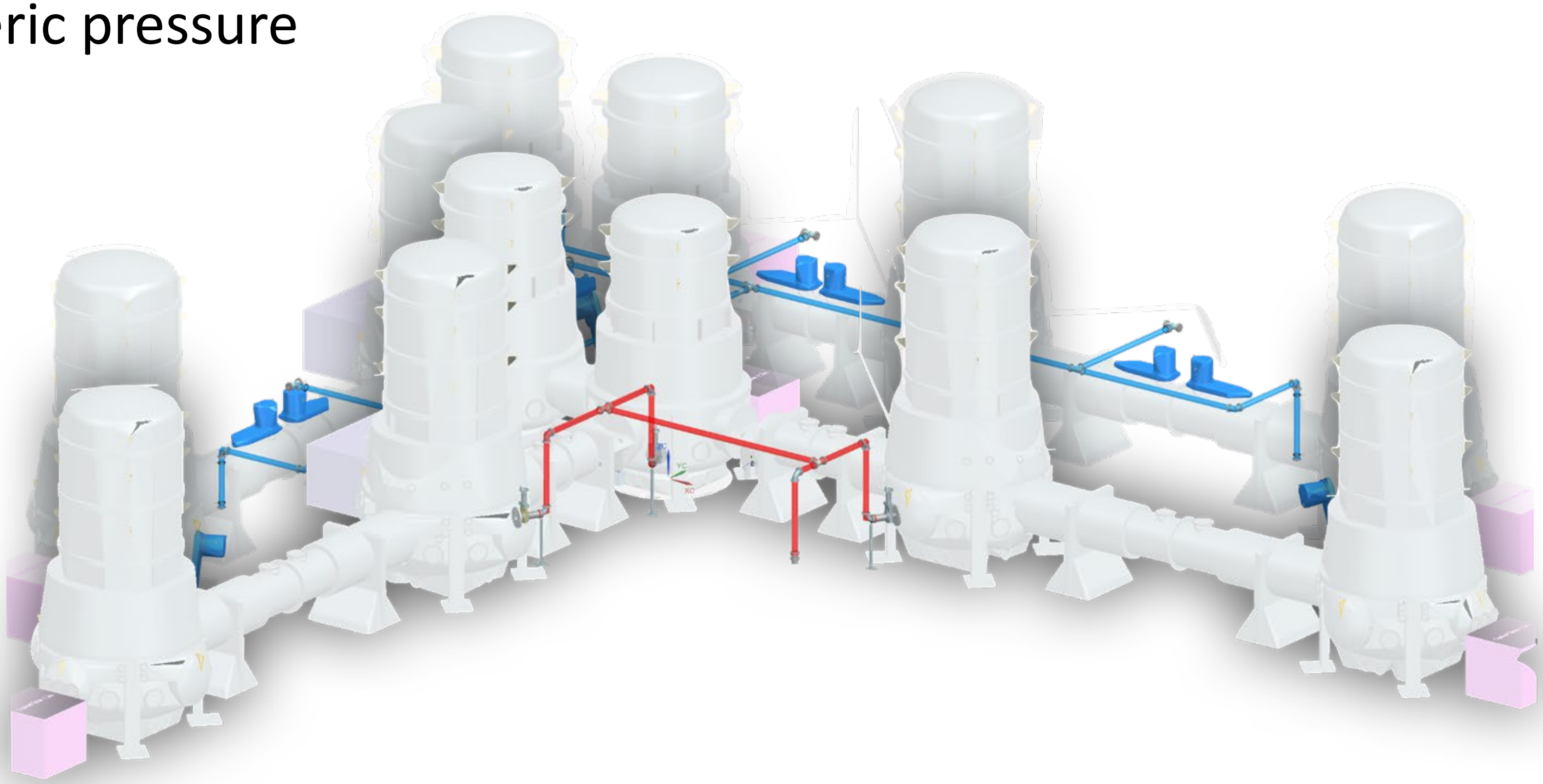
- Provides the vacuum environment for the interferometer
- 3 sections = 2 arms + central section (separated by 3 DN200 valves each)
- 14 magnetically-levered turbo-molecular pumps (3200 l/s for N_2 per TMP)
- Cascaded pumping system with small (380 l/s) TMPs
- Fore-vacuum behind TMPs provided by 2 multi-roots pumps.
- Ultimate pressure below 10^{-7} Pa



The Vacuum System - Overview

The roughing system:

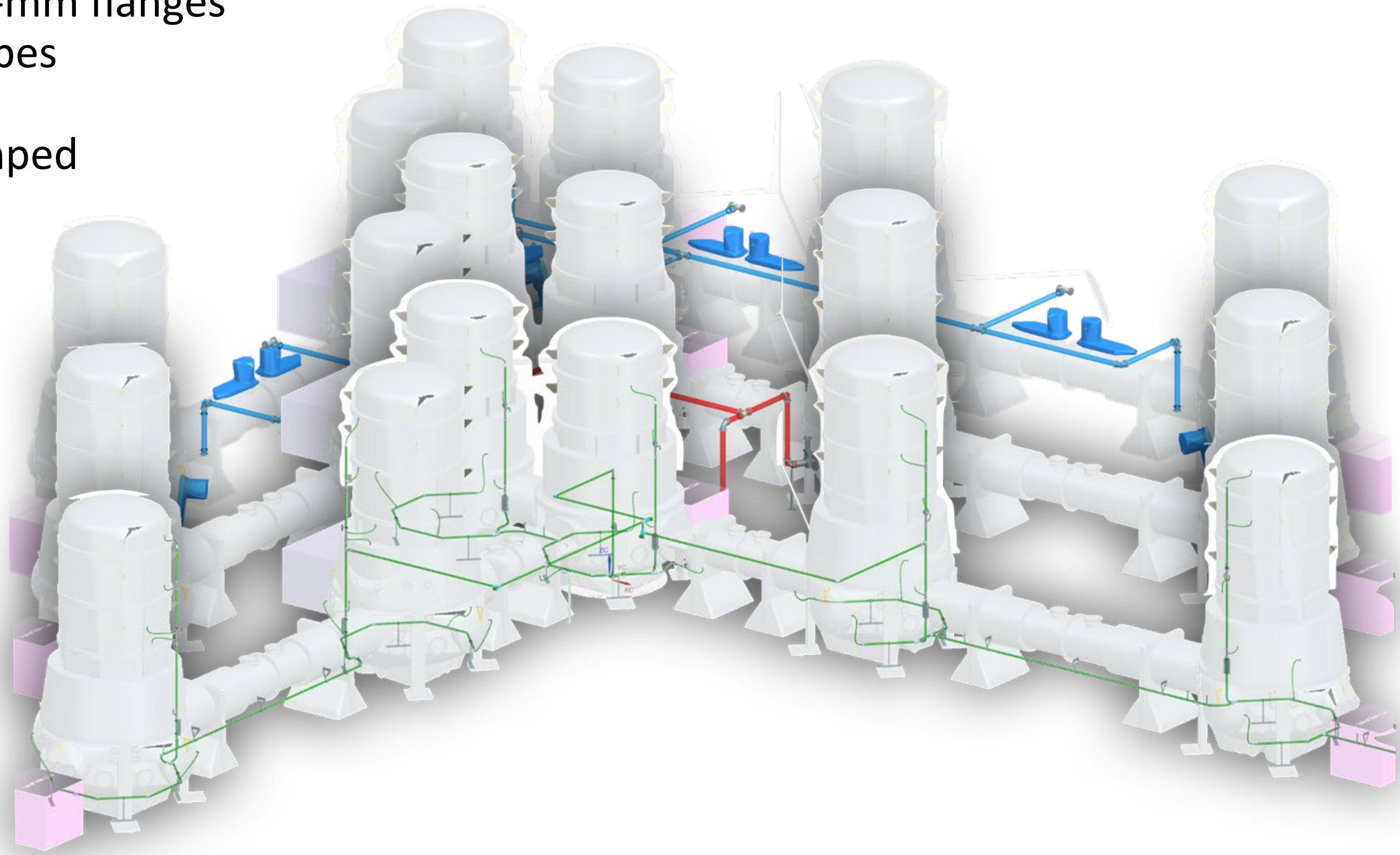
- Pumping down from atmospheric pressure
- Venting with dry nitrogen



The Vacuum System - Overview

The differential system:

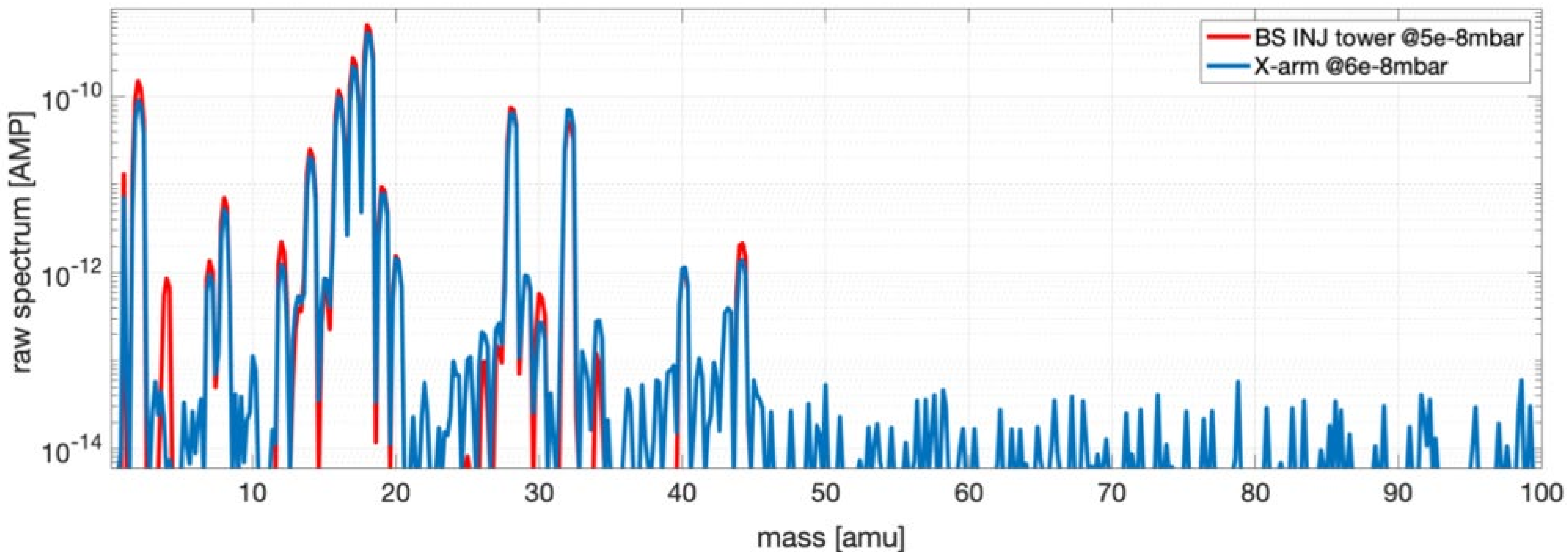
- Segments of the towers and the 800-mm flanges on the towers, bellows, and beam pipes contain double viton O-rings.
- Volume between O-rings can be pumped by 3rd multi-roots pump.
- Pressure between O-rings to be in the 0.1 Pa range.

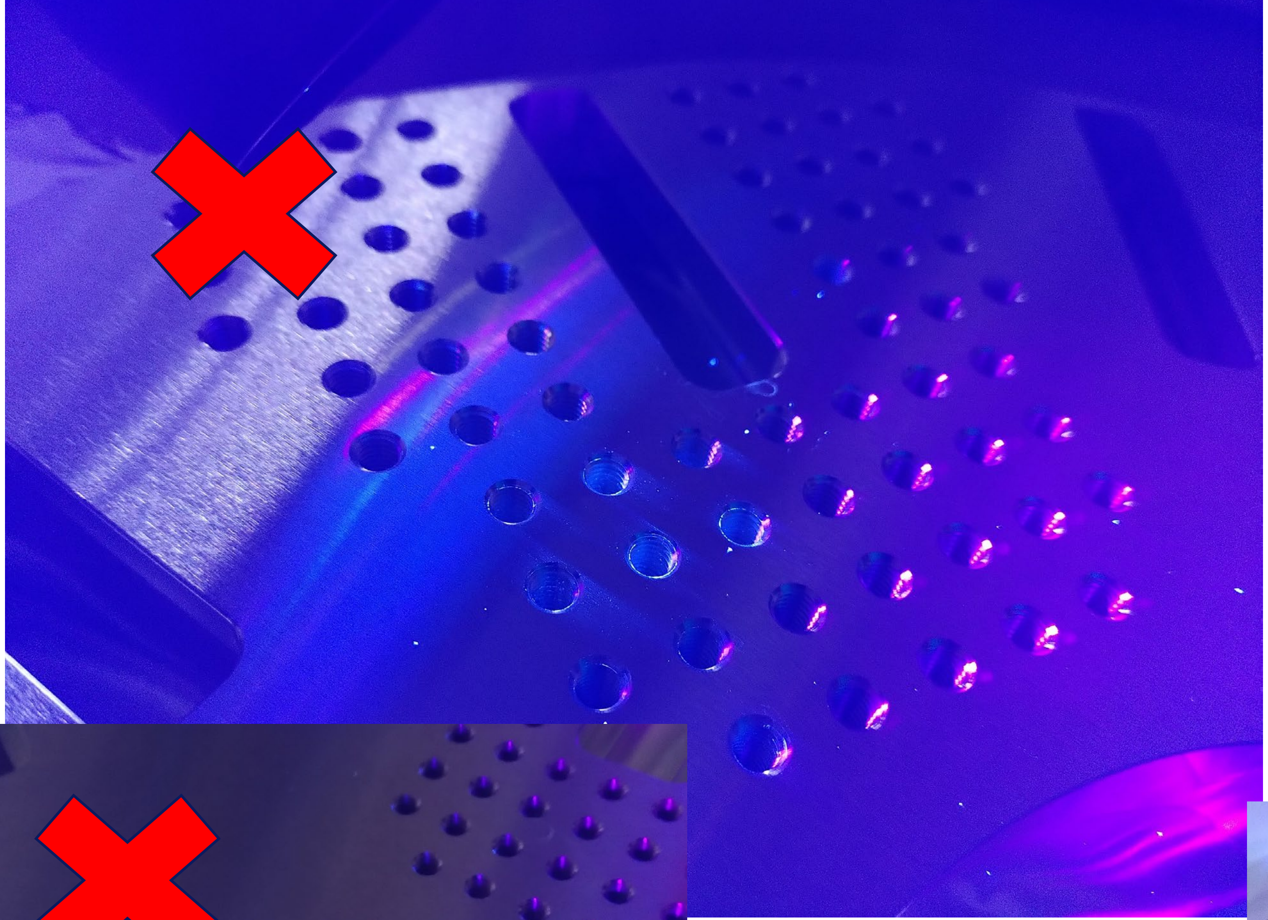


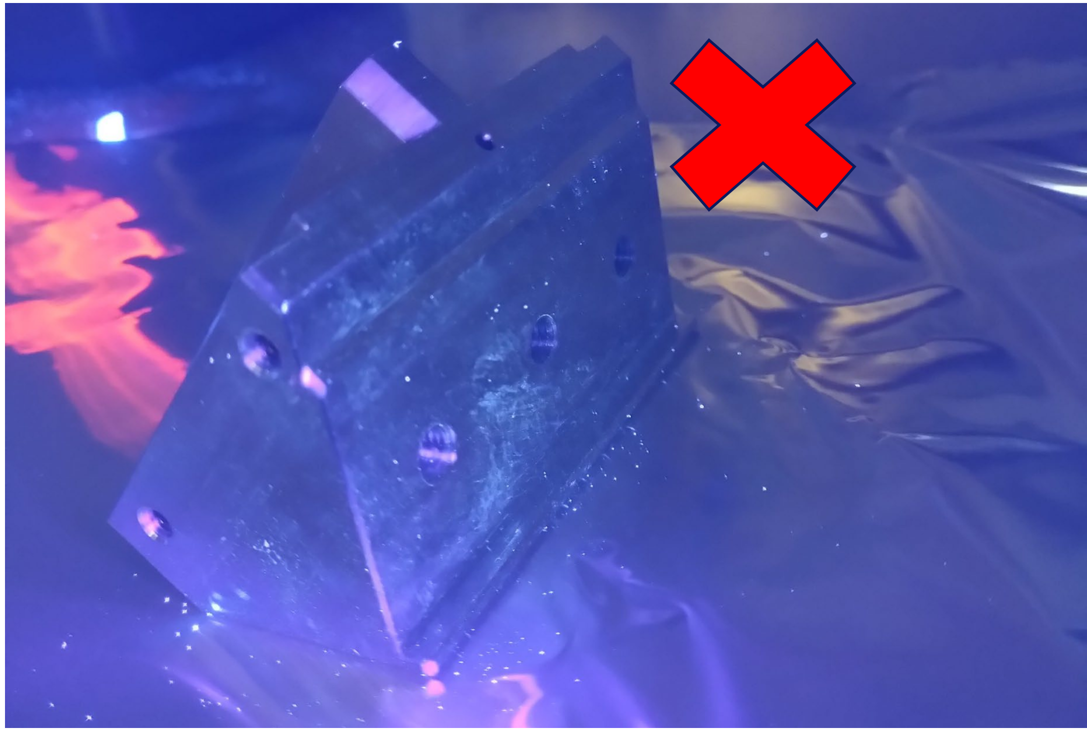
Vacuum Quality

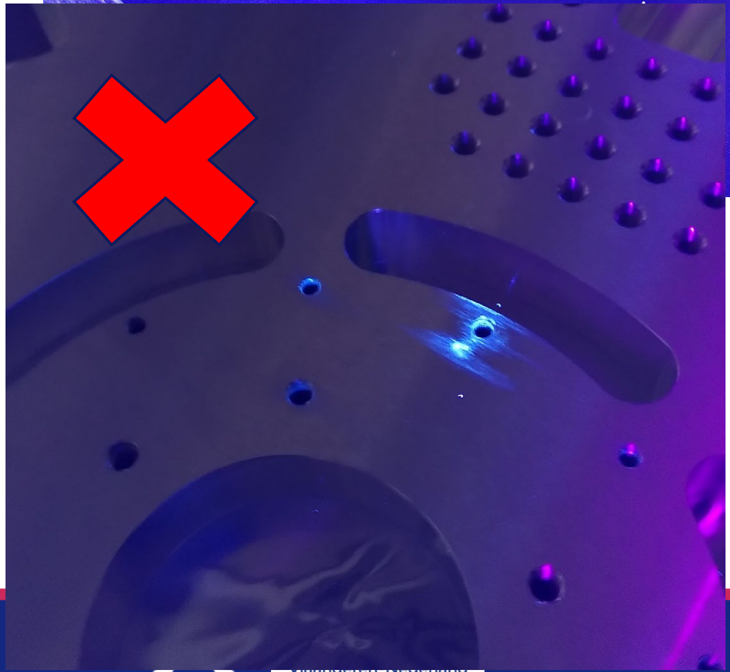
Recap from STAC Nov. 2022:

- RGA measured at 5 x 10^{-6} Pa in the x-arm and injection section.
- Dominant contribution from H_2O.
- Sizable contribution of H2, CO2 (mass 44), CO/N2 (mass 28), O2 (mass 32).
- All hydrocarbons (mass > 45) are negligible.







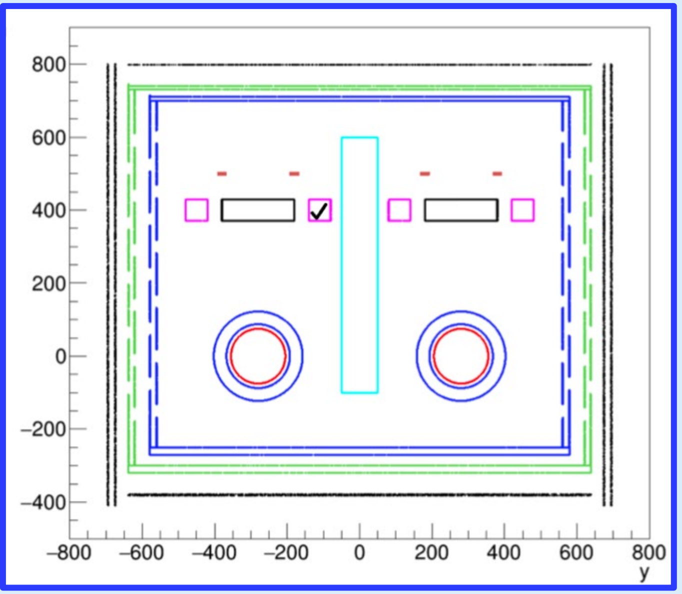


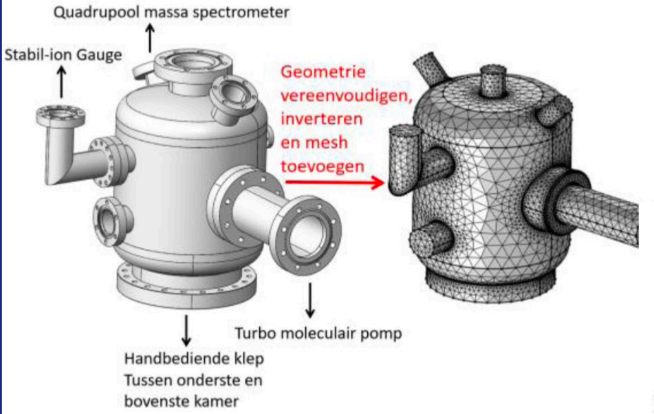
Detailed Topics

- Vacuum
- Cryogenics
- Seismic isolation
- Optics

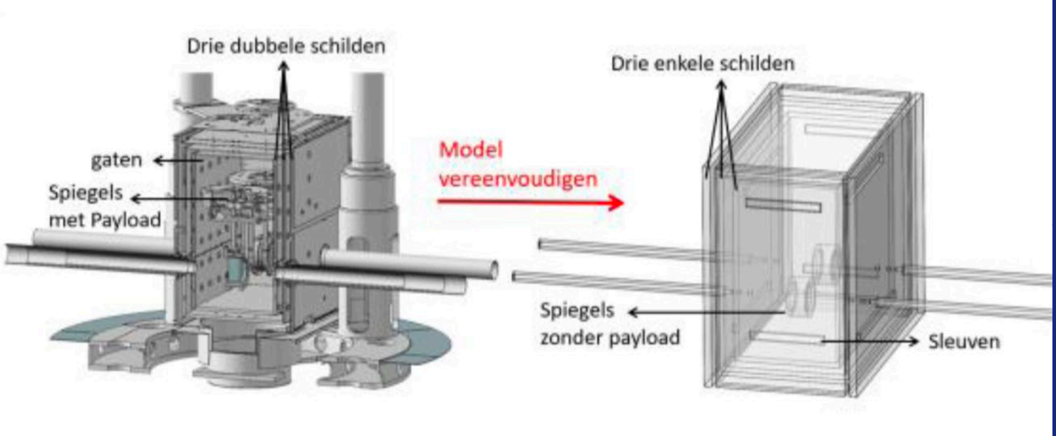
Vacuum / cryogenic simulations

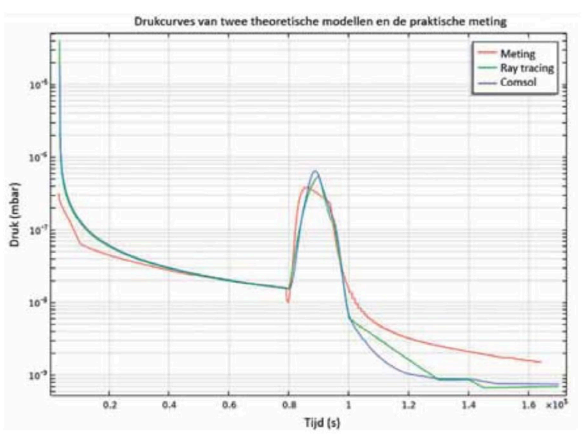
- Modeling:
  - ETpathfinder is a test facility: pump-down should be quick and part of the system will be vented quite often. Largest challenge: water (monolayer of water that will bind to the surface after each venting).
  - In CDR: we developed a simulation package that tracks water molecules : adsorption and desorption on the walls, permeation through Viton O-rings, molecular flow, compression factor of turbo pumps etc.
  - Molfow and Comsol were not capable of doing these calculations (no pressure-dependent, time-dependent and coverage-dependent parameters for the surfaces, and the ETpathfinder geometry was too detailed).
  - Calibrated the calculations against Molflow and Comso using a outgassing set-up at Nikhef (Vera Erends, Berend Munneke, HJB)





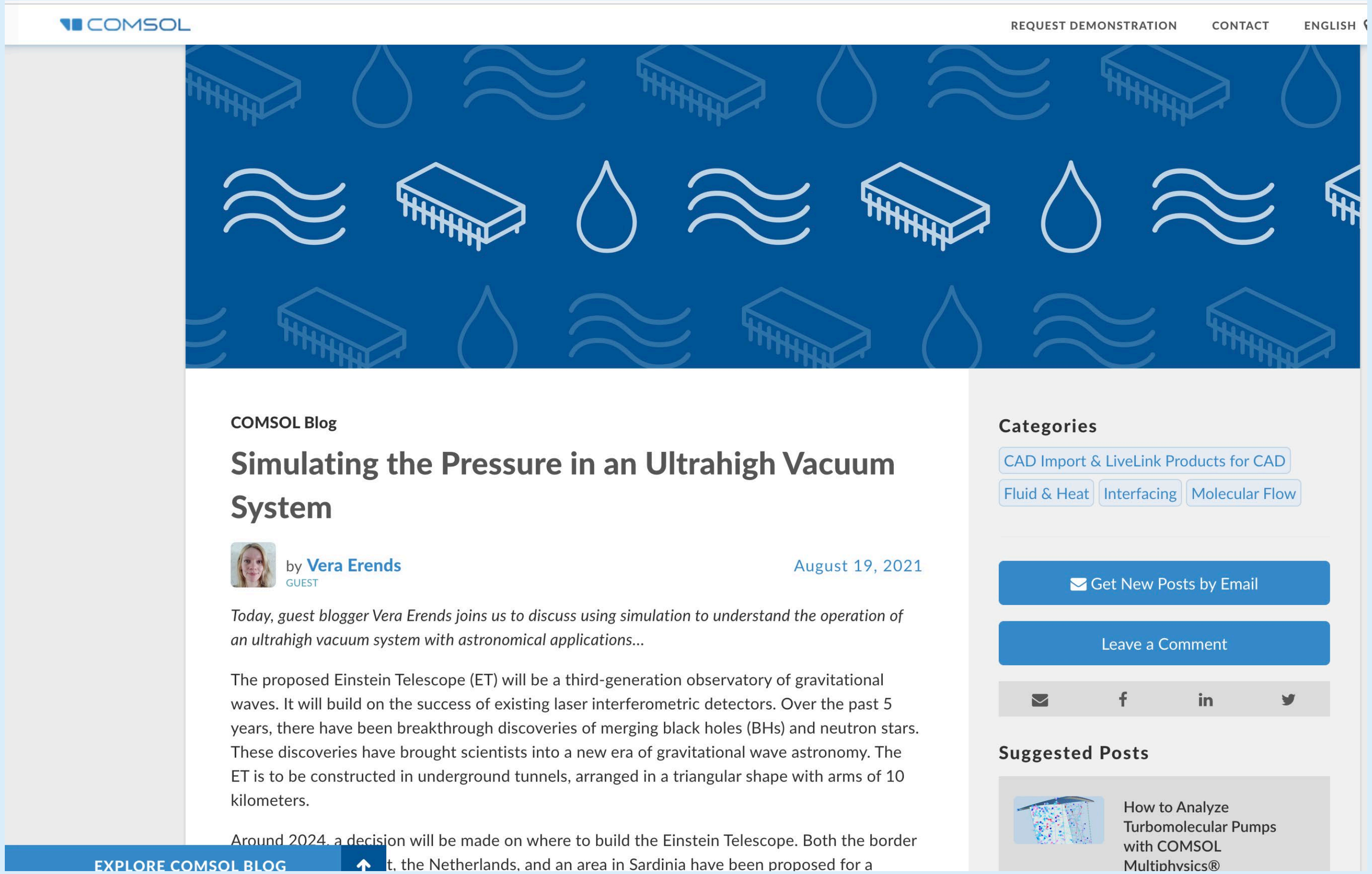
Figures from Publication:
Vera Erends, NEVAC, Oct 2020.





Pics from Article by Vera:
https://nevac.nl/archief_pdf/pdf_208.pdf

Maastricht University



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COMSOL Blog

Simulating the Pressure in an Ultrahigh Vacuum System

by Vera Erends
GUEST
August 19, 2021

Today, guest blogger Vera Erends joins us to discuss using simulation to understand the operation of an ultrahigh vacuum system with astronomical applications…

The proposed Einstein Telescope (ET) will be a third-generation observatory of gravitational waves. It will build on the success of existing laser interferometric detectors. Over the past 5 years, there have been breakthrough discoveries of merging black holes (BHs) and neutron stars. These discoveries have brought scientists into a new era of gravitational wave astronomy. The ET is to be constructed in underground tunnels, arranged in a triangular shape with arms of 10 kilometers.

Around 2024, a decision will be made on where to build the Einstein Telescope. Both the border …t, the Netherlands, and an area in Sardinia have been proposed for a

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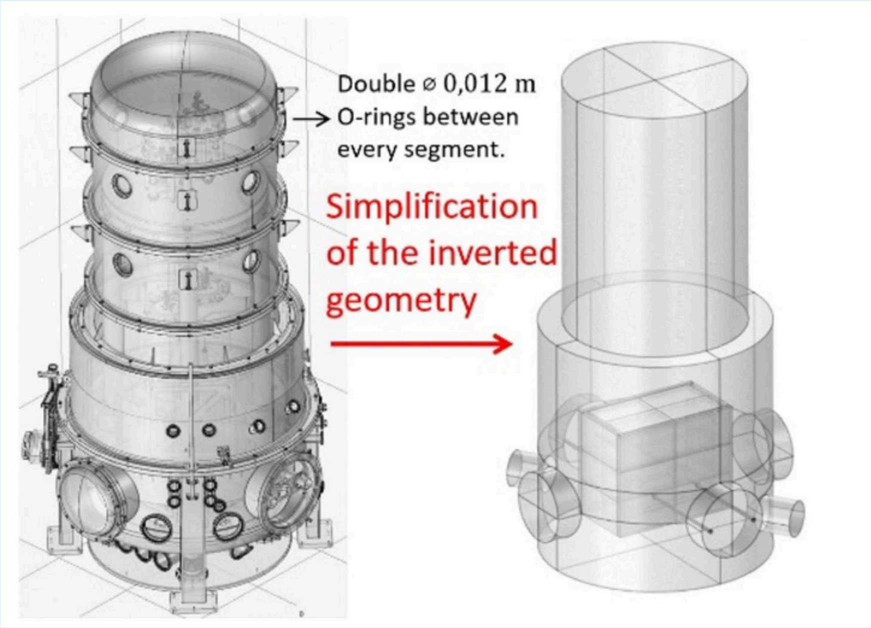
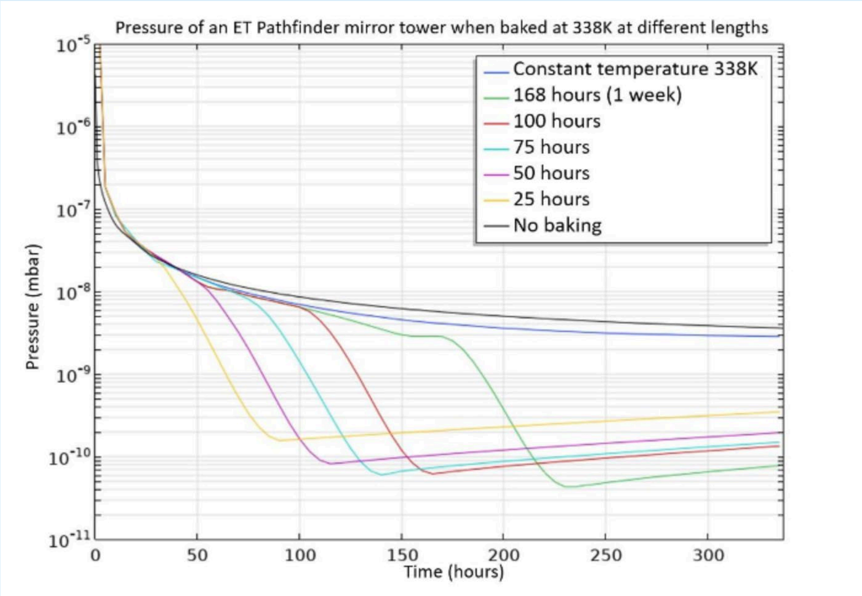


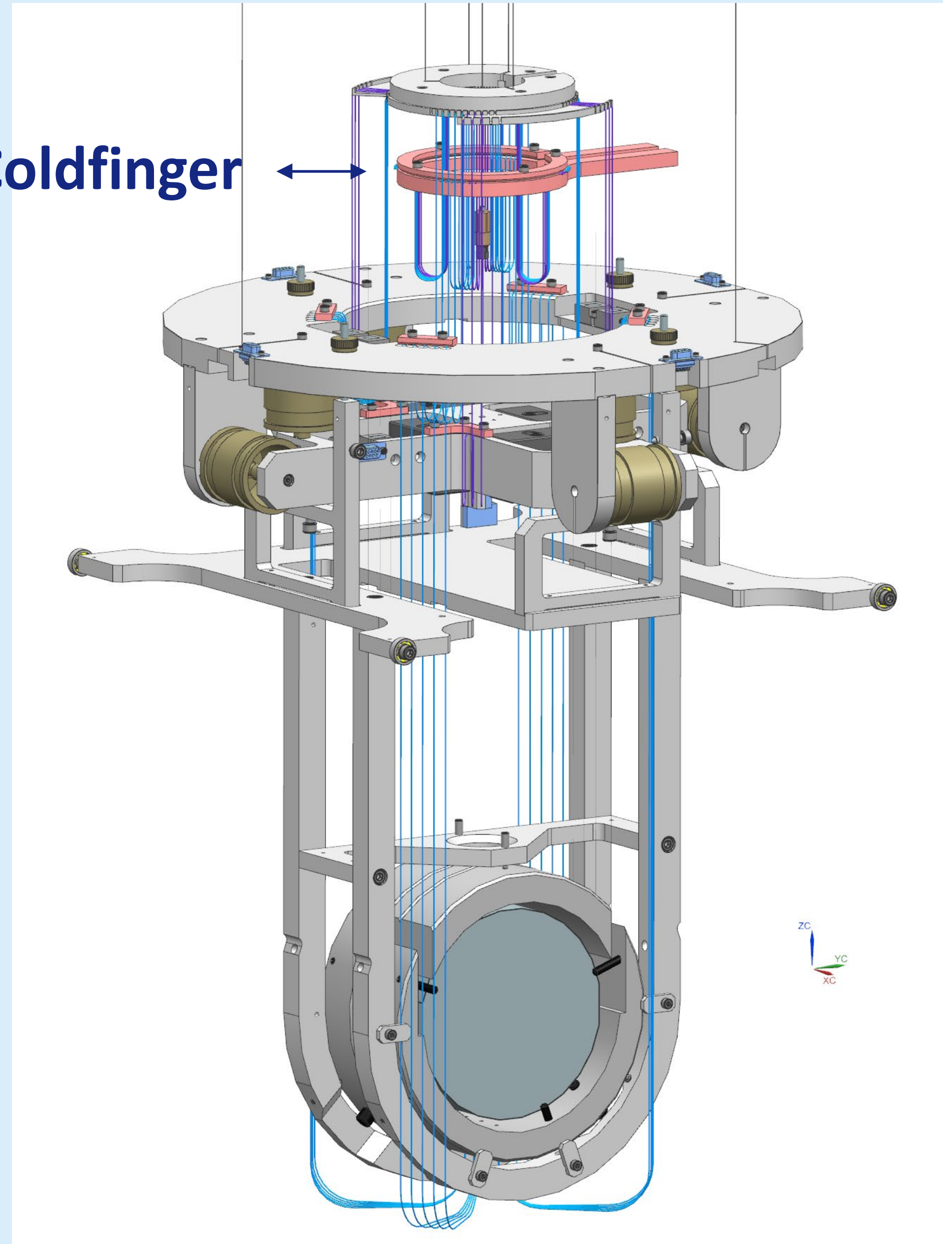


Maastricht University

Cryogenics (I)

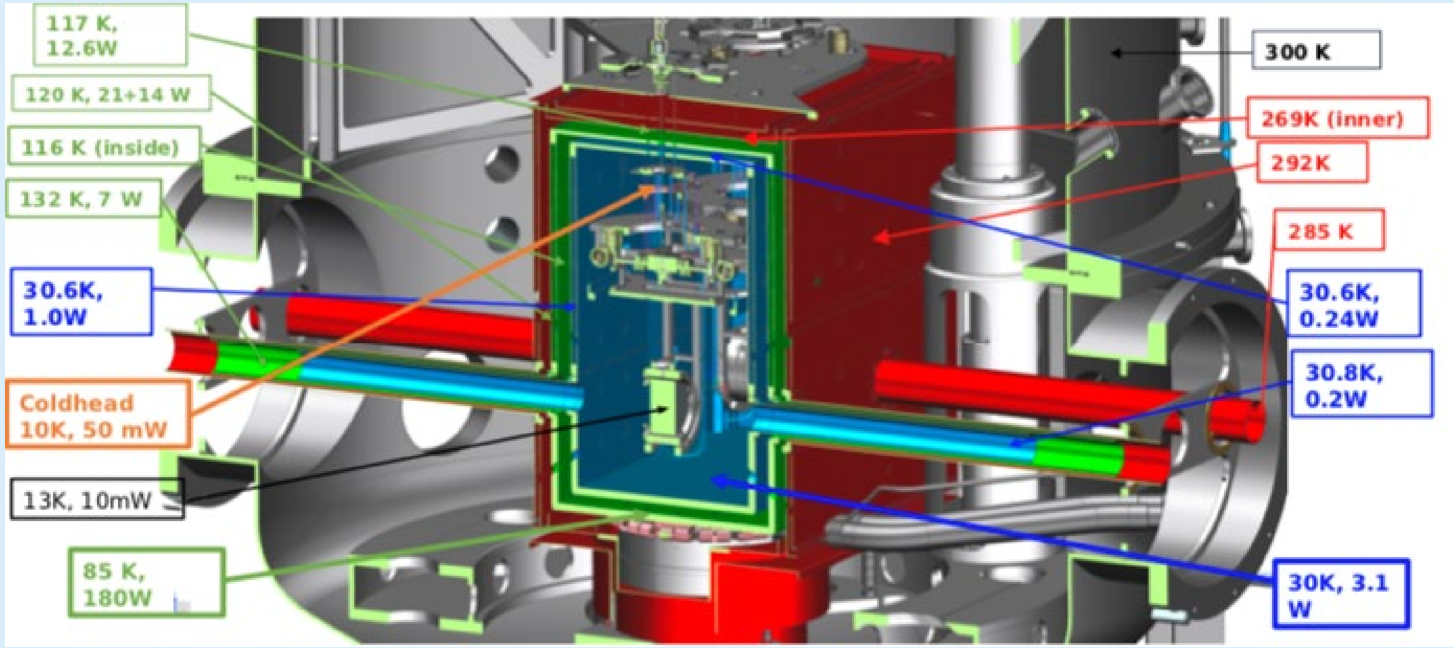
- Mirrors need to be cooled to cryogenic temperatures (~15K, 123K), without introducing noise, i.e. cooling only possible via thin suspension wires.
- General approaches under consideration:
  - Dry system: pulse-tubes. Challenge = reduce and isolate vibrational noise.
  - Sorption coolers (base line in ETpathfinder) = more quite, less cooling power.
  - Cryogenic Liquids: LN2, He, He-II. Challenges = avoid bubbling; transfer liquids from surface 300m above the caverns …

Coldfinger

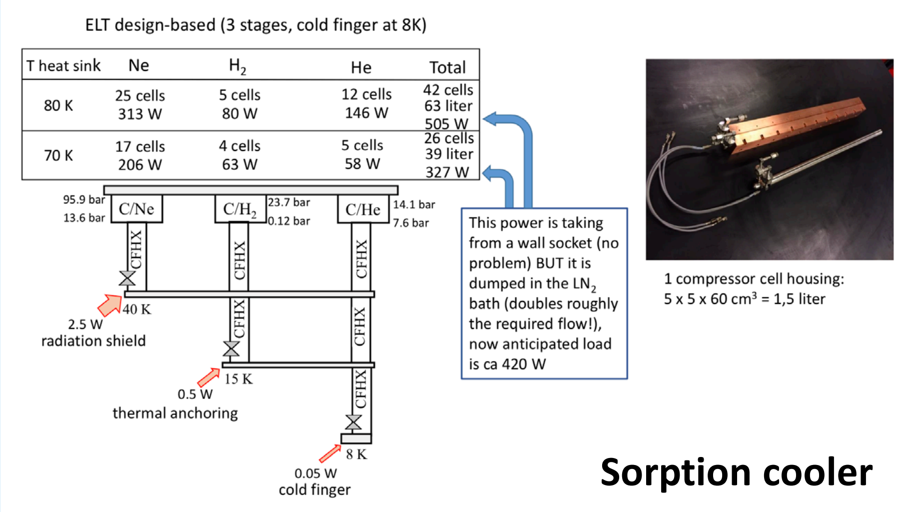


Cryogenics (II)

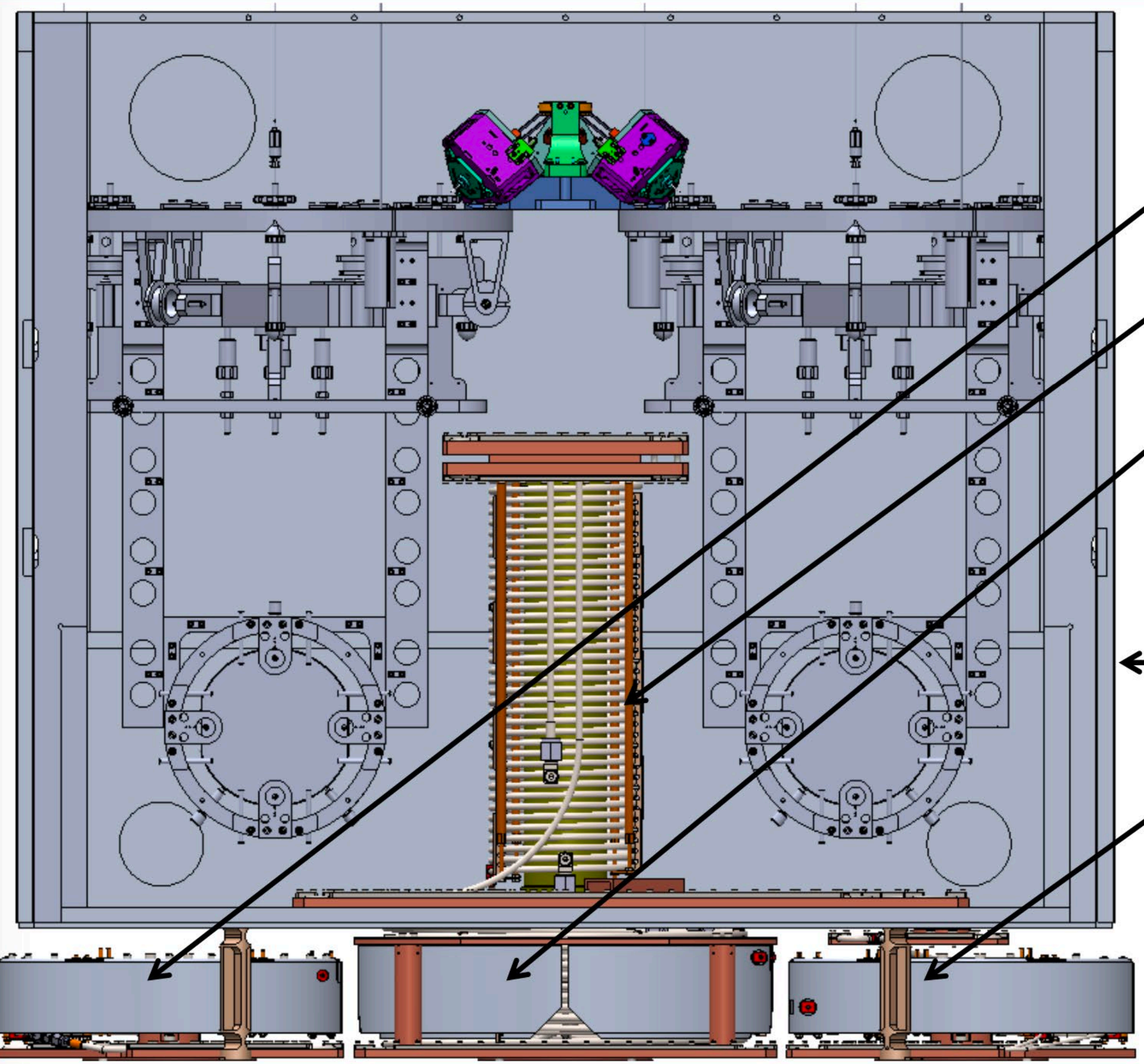
- Need avoid ice on the mirrors and find ways to deal with ice if it builds up (reduce its thermal noise and optical influence)? – Will use 3 pairs of metal-cryo-shields.



- Complex heat extraction matrix (vastly different powers, at different temperatures and with different noise requirements).
- Not only steady state operation sets requirements, but many come from cool-down requirements.
- No off-the-shelf simulation tools available that cover essential functionality. ☹



3. Cryolines



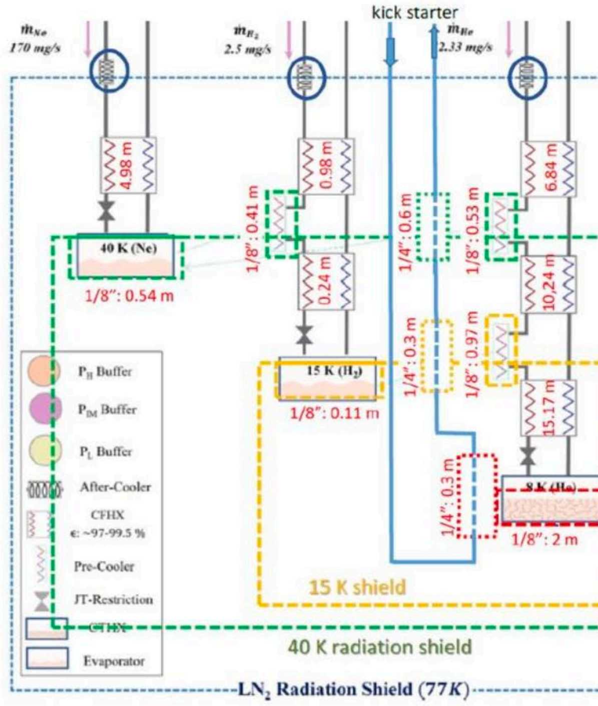
Ne stage

He stage + KS above 15K Shield

He stage + KS beneath 15K Shield

15K Cryoshield

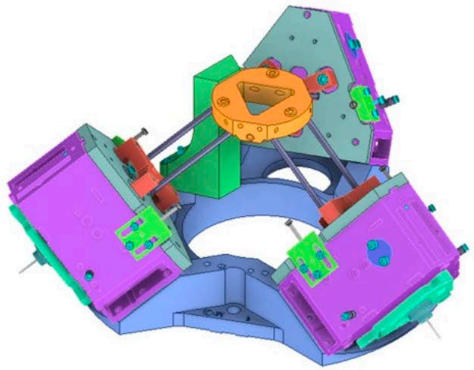
H_2 stage

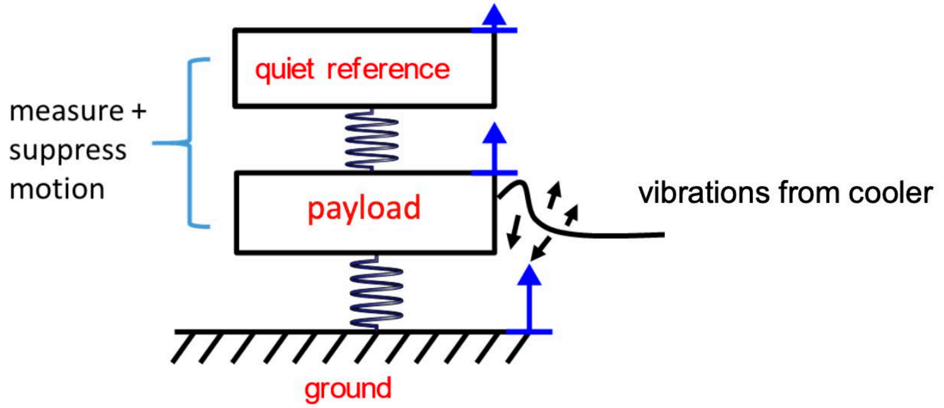


3D Cryogenic Active Vibration Isolator (CAVI)

~ 264mm diameter, 111mm height, mass 2.3kg
3x 1DoF units tilted by 36.24deg, gravity compensation

Was finally delivered in
mid December 2023





Sensing

Attocube sensor heads

Displacement Measuring Interferometer

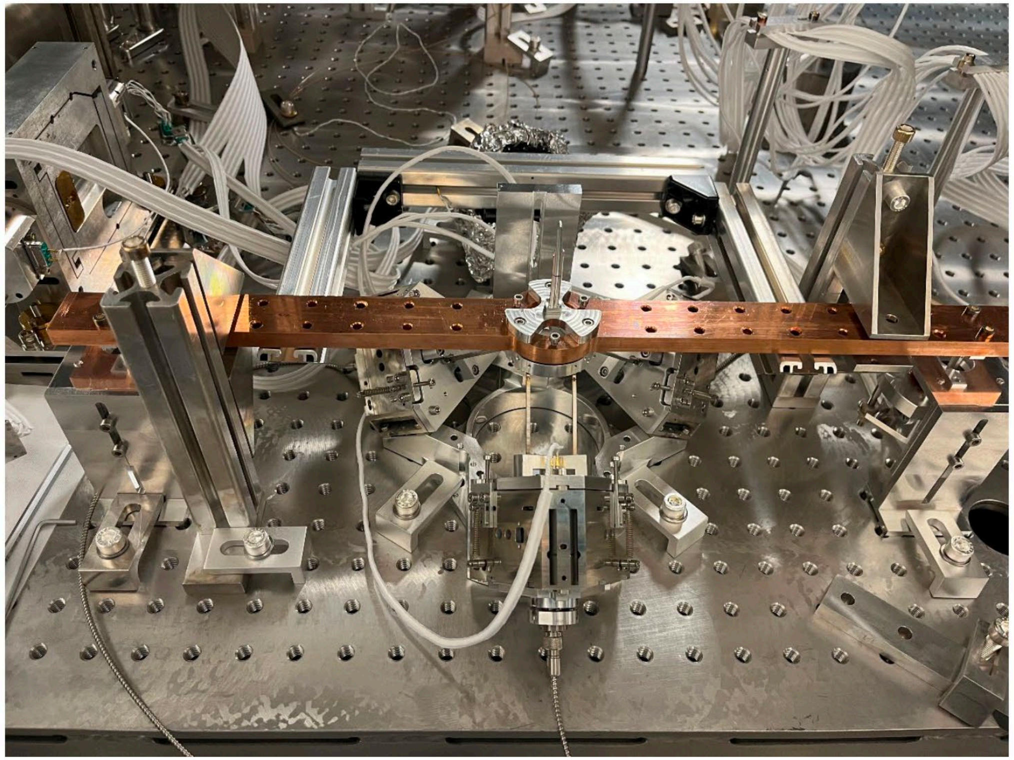
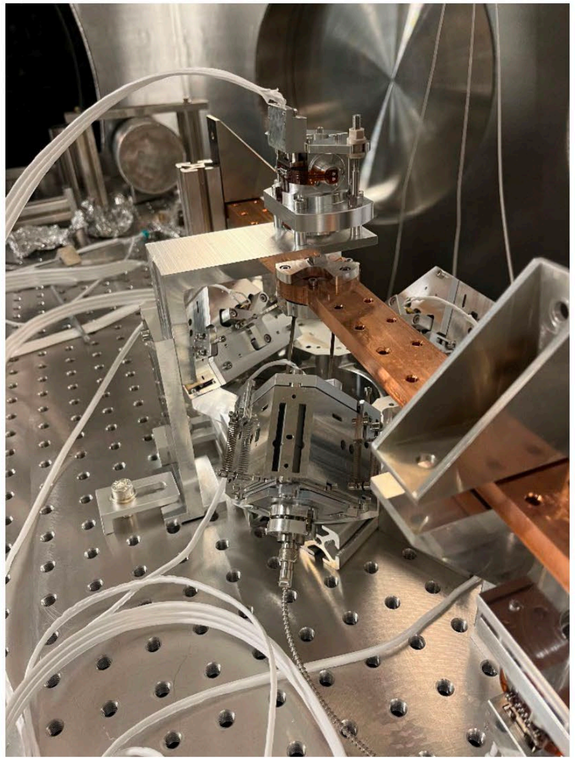
optical fibres

digital and analog signal outputs

Actuating

JPE Cryo Voice Coil Actuator

Loading the 3D CAVI platform

Maastricht University

Luise Kranzhoff
01-02-2024

Nikhef

6

Dutch NGF Valorisation

https://einsteintelescopeforbusiness.nl

Einstein Telescope for business

Apply →

FOR WHOM

Wanted: high-tech entrepreneurs to help build the Einstein Telescope

READ MORE →

PARTICIPATE

The technology domains

The construction and operation of ET will require many advances in research and development and new technological developments. Many of the innovations needed will build on research already conducted at LIGO (United States), VIRGO (Italy), KAGRA (Japan) and other similar facilities.

For the actual construction of the Einstein Telescope (in particular the instrumentation), five technology domains have been defined that will be further developed through research and innovation. The technology domains are:

1. **Vibration-Free Cooling**: development of vibration-free cooling of mirrors to a temperature of 10-20 K.
2. **Vacuum technology**: vacuum system cost savings and design of production facility and installation scenario.
3. **Vibration damping**: development of optimal combination of passive and active vibration damping.
4. **Optics**: development of large Si mirrors and coating for application at 10-20 K temperature.
5. **Thermal deformations**: development of technology to monitor and compensate for thermally induced deformations.

STAATSCOURANT

Officiële uitgave van het Koninkrijk der Nederlanden sinds 1814.

Nr. 28781

23 oktober 2023

Regeling van de Minister van Onderwijs, Cultuur en Wetenschap van 10 oktober 2023, nr. 41107325, houdende regels voor de subsidieverstrekking voor technologiedomeinen voor de Einstein Telescope (R&D regeling technologiedomeinen Einstein Telescope)

Gelet op artikel 1.2. van de Kaderregeling subsidies OCW, SZW en VWS;

Besluit:

Artikel 1. Begripsbepalingen

4. Specifieke doelstelling voor deze openstelling
   In deze openstelling kunnen partijen een aanvraag indienen voor R&D-projecten die bijdragen aan de oplossing voor deze bovenstaande uitdaging. Het beoogde project moet in ieder geval het volgende bevatten:
   - Het ontwerp en productie van drie prototypes van koelunits op een niveau dat compatibel is met cryogene spiegel ruisverplaatsingen van gelijk of lager dan 10-18m/sqrt(Hz) bij Hz.
   - Elke koeleenheid moet in drie fasen koelvermogen kunnen leveren, waarbij in minder dan vier weken 10K, 20K en 50K (of lager) worden bereikt, waarna stabiele bedrijfsomstandigheden worden bereikt met de volgende koelvermogens:
     - Minimaal 50 mW bij een temperatuur onder 10K
     - Minimaal 0,5 W bij een temperatuur onder 20K
     - Minimaal 2,5 W bij een temperatuur onder 50K
   - De thermische massa van de drie bovengenoemde fasen is respectievelijk:
     - 8 kg silicium, 20 kg koper en 40 kg aluminium
     - 40 kg aluminium
     - 130 kg aluminium
   - Onder bedrijfsomstandigheden moeten de trillingen op het niveau van de cold finger (contact-punt met spiegelophanging) lager zijn dan 2x10-8m/sqrt(Hz) voor alle frequenties boven 1 Hz en onder 5x10-6m rms. Tijdens de afkoelperiode gelden er geen strenge trillingseisen.
   - De te ontwikkelen koeleenheid moet compatibel zijn met vloeibare stikstof als backend-koelbron.
   - De koelunits dienen te kunnen functioneren in een geïntegreerd systeem. Als onderdeel van deze aanvraag dient de aanvrager deze geïntegreerde werking te kwalificeren en valideren.
5. Context van het technologiedomein trillingsvrij koelen
   Hieronder is de context weergegeven waarin de trillingsvrije koeleenheid gaat opereren.

Example: Cryocooling for ET/ETpathfinder

Test facilities

Maastricht University

System Architect

Nikhef

Cryogenic precooler

STIRLING CRYOGENICS

LN_2 infrastructure

DEMACO

Cryogenic vibration suppression

JPE Driven by innovation

Universiteit Leiden

Zero-vibration Sorption Cryocooler

DEMCON

KRYOZ

UNIVERSITY OF TWENTE.

COOLL

Cryogenic transfer lines

cryoworld advanced cryogenics

Example:Cryocooling for ET/ETpathfinder

Einstein Telescoop - 10 Kelvin trillingsvrije cryokoeling

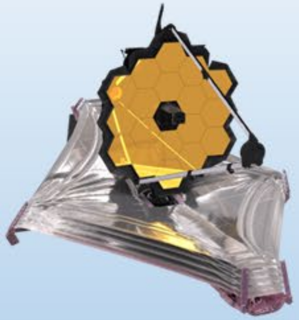
Life-sciences & materiaal onderzoek

(bio)sample onderzoek bij extreem lage temperaturen

Halfgeleider industrie

supergeleidende lineaire motoren voor wafer steppers

Ruimtevaart



cryogeen gekoelde optische sensoren in ruimtevaart satellieten

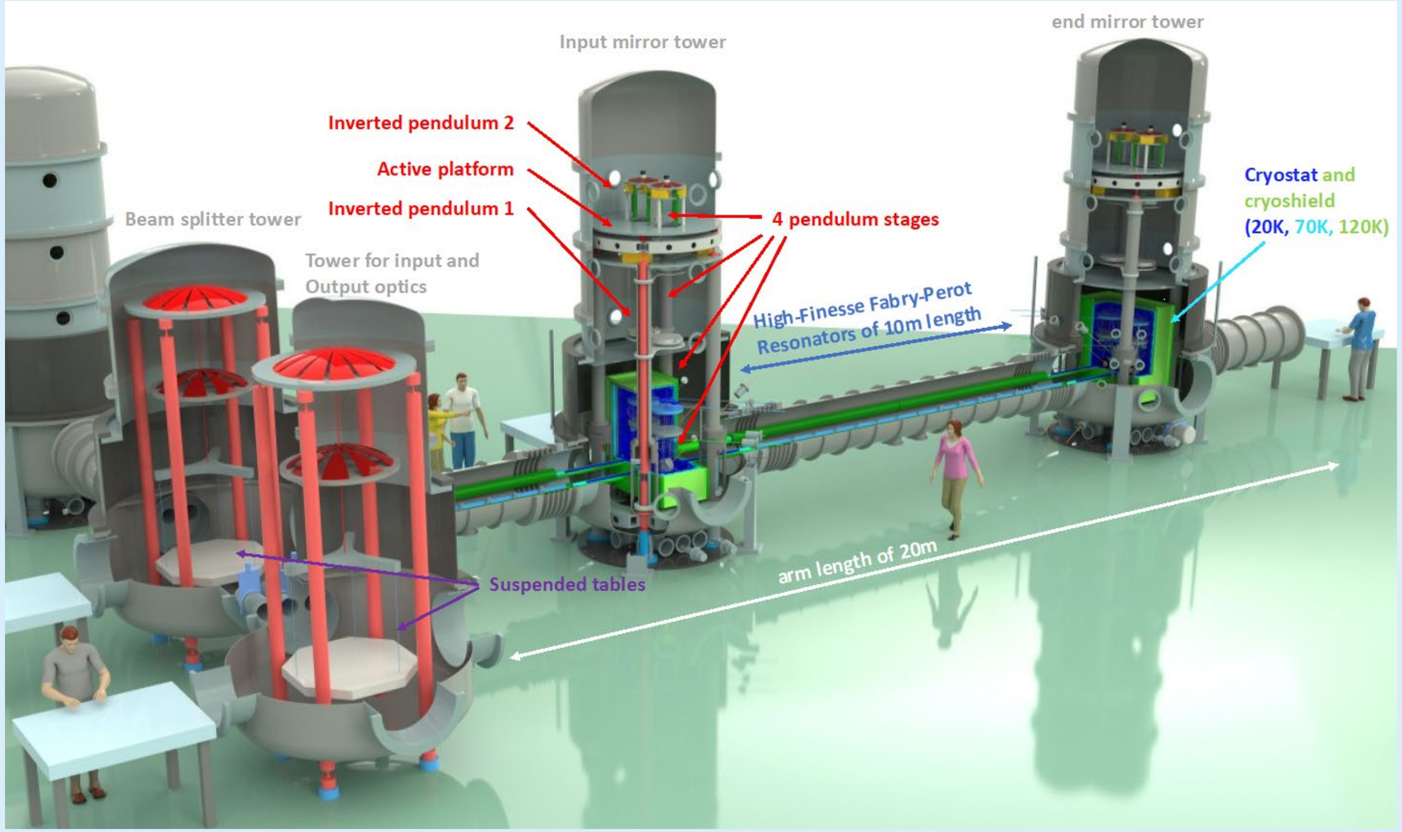
Quantum computing

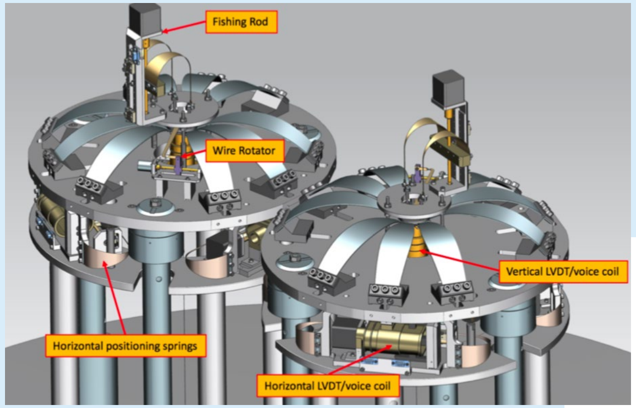
(kosten) efficiënte Qubit cryokoeling voor quantum computers

Detailed Topics

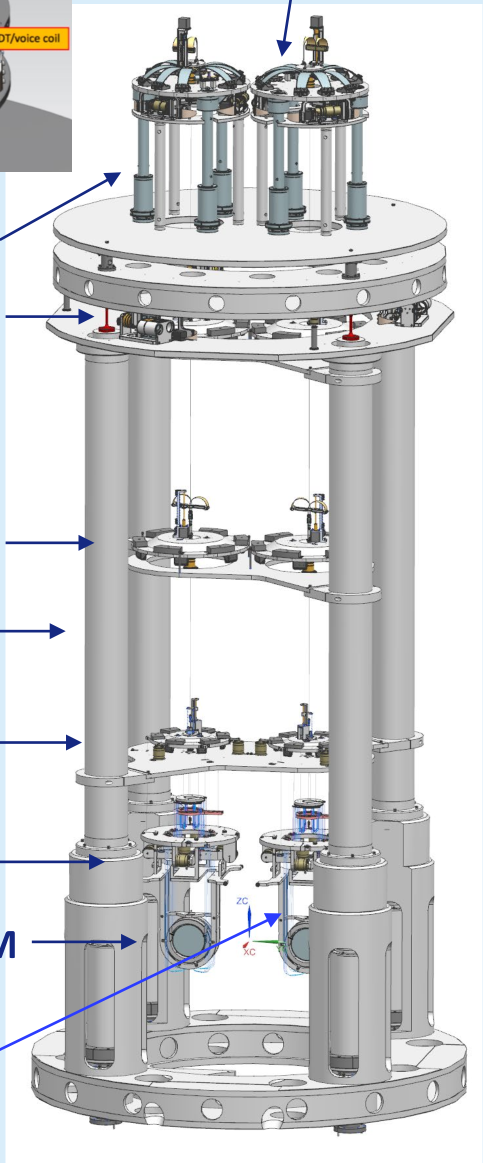
- Vacuum
- Cryogenics
- Seismic isolation
- Optics

Seismic Isolation





F0 platform



Short IP

Filter 1

Filter 2

Long IP (~3m)

Steering Filter

Marionetta + RM

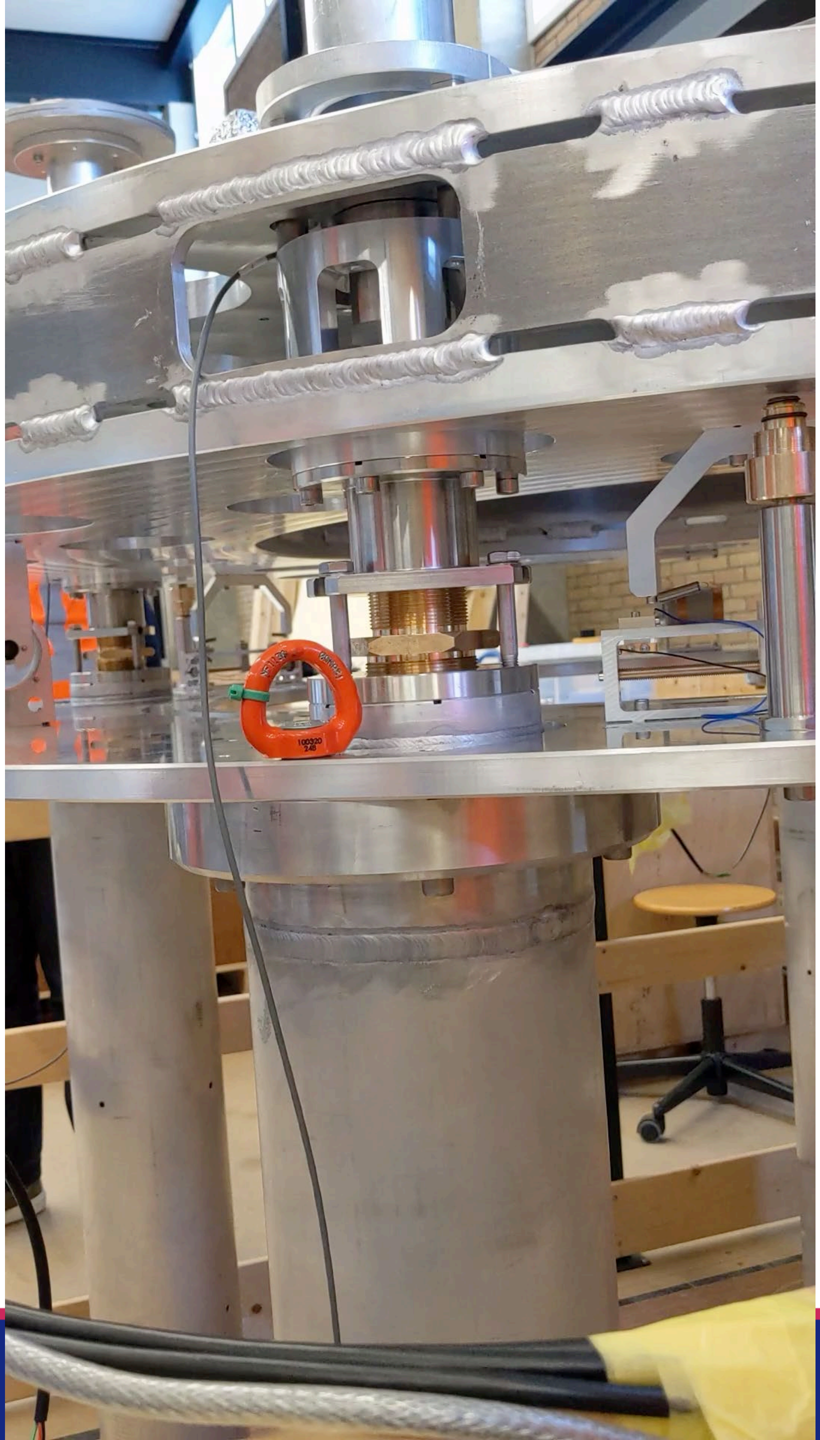
Mirror + RM

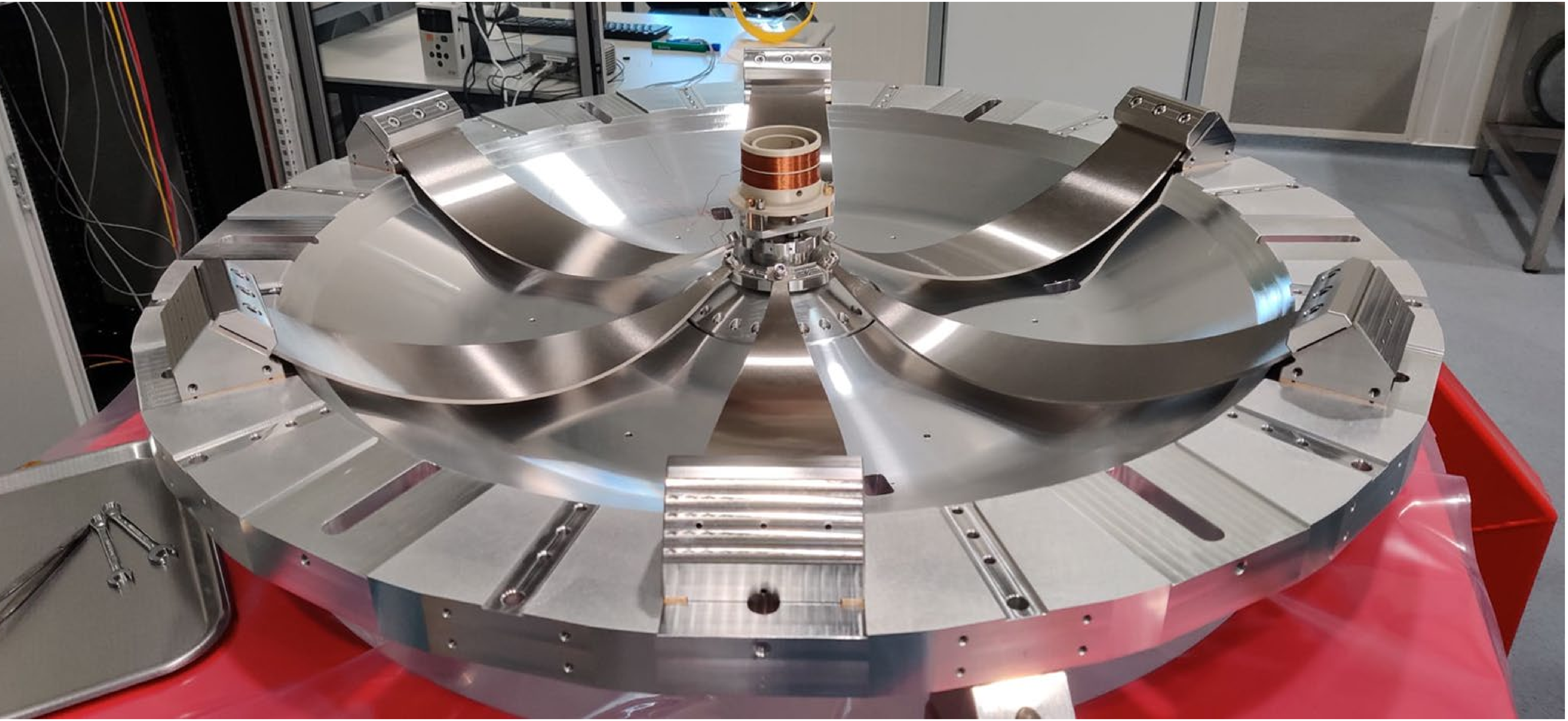
Final stage = 0.7mm Silicon fibres of 40cm length and

2 different designs: Mirror towers and table towers

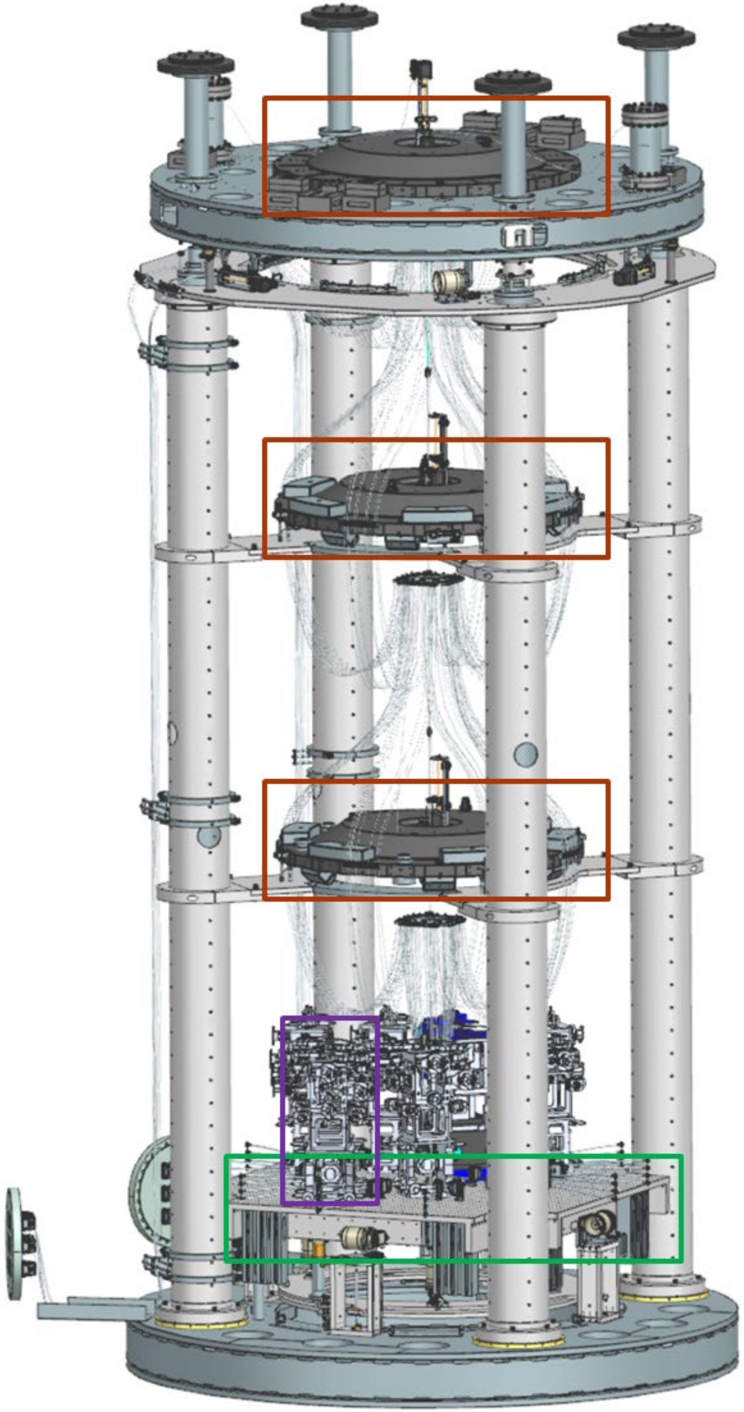
IP leg prototype in action

Timelapse video at 10x speed





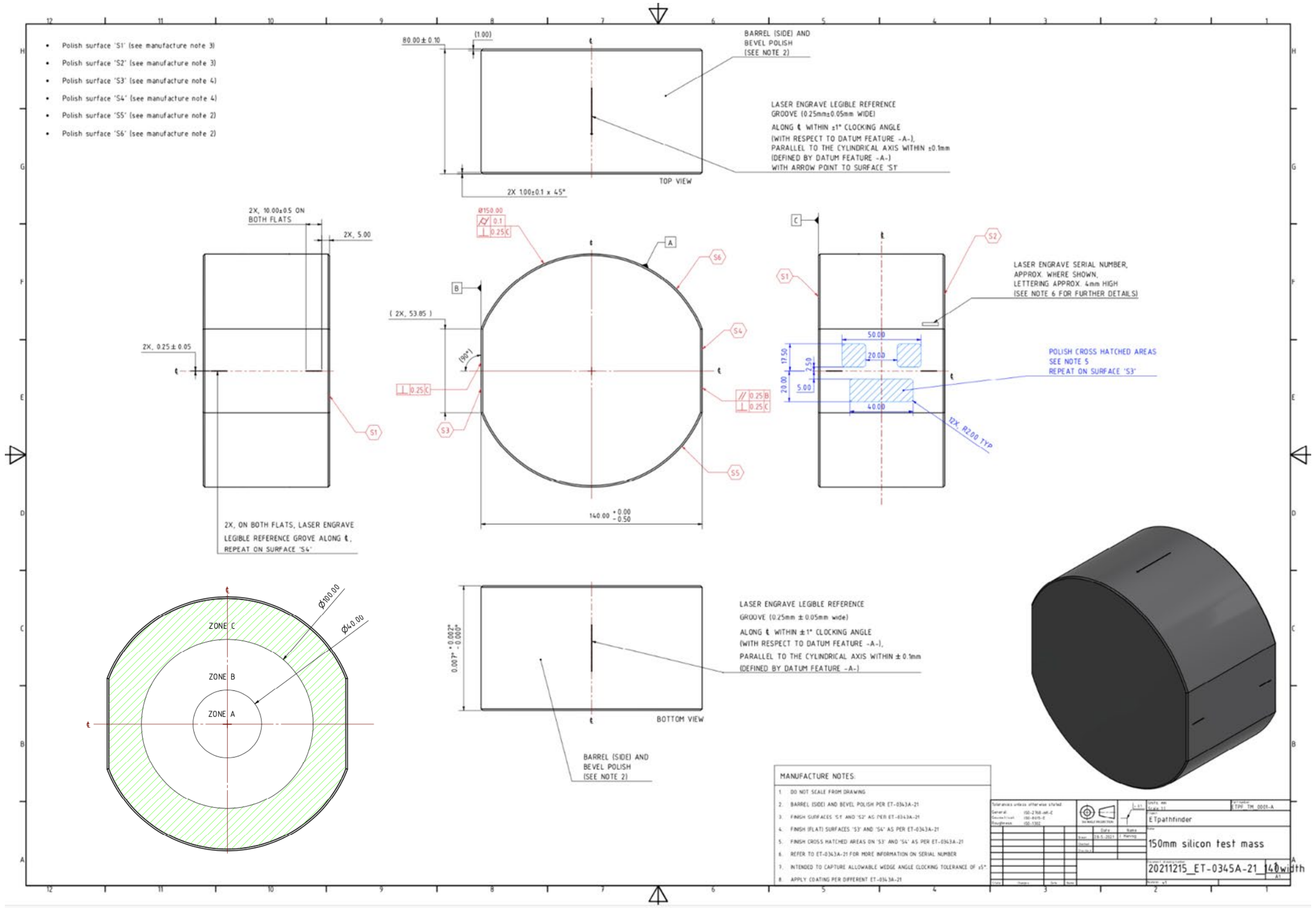
[S.Hild, Maastricht &Nikhef]



Detailed Topics

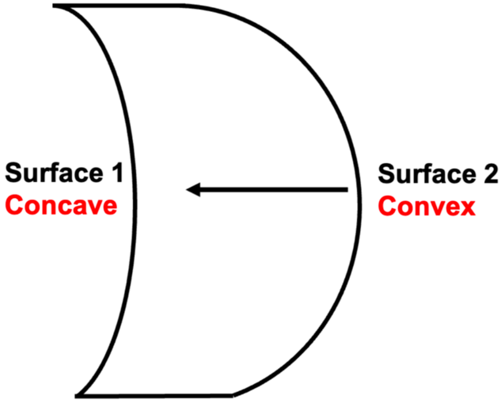
- Vacuum
- Cryogenics
- Seismic isolation
- Optics

Main mirror requirements



12 Radius of curvature

Refer to the sketch in Figure 1 below for an exaggerated visual representation of S1 and S2 ROC.
Surface 1: The ROC of S1 shall be spherical, concave. ROC: 14.5 m ±0.1 m.
Surface 2: The ROC of S2 shall be spherical, convex. ROC: 9 m ± 0.1 m.



13 Surface figure

Surface 1:

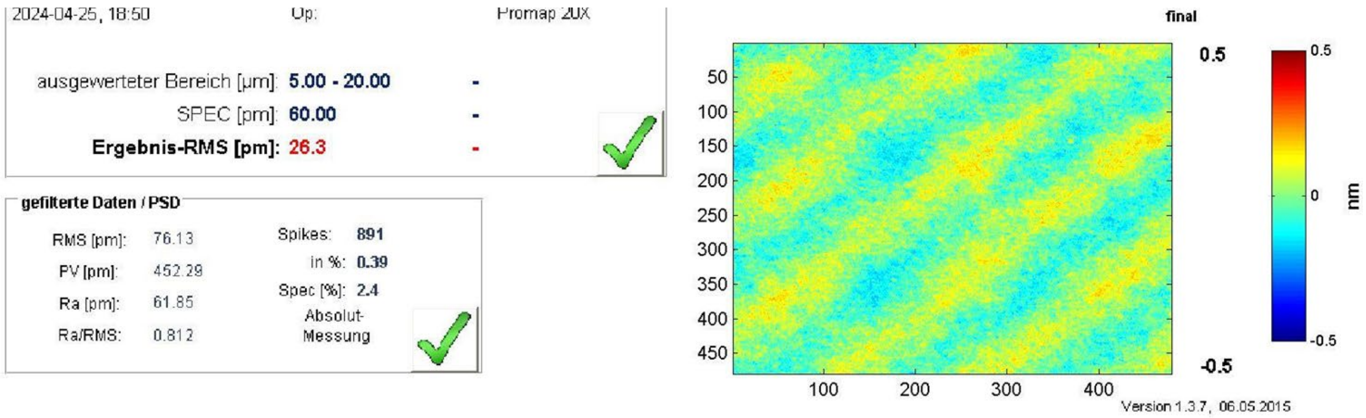
- Zone A: Surface error shall be < 1 nm RMS measured over the totality of Zone A; Micro-roughness shall be < 0.1 nm over the same area (super polish).
- Zone B: Micro-roughness shall be < 5 nm over Zone B, no surface error requirement.
- Zone C: No surface error or microroughness requirement.

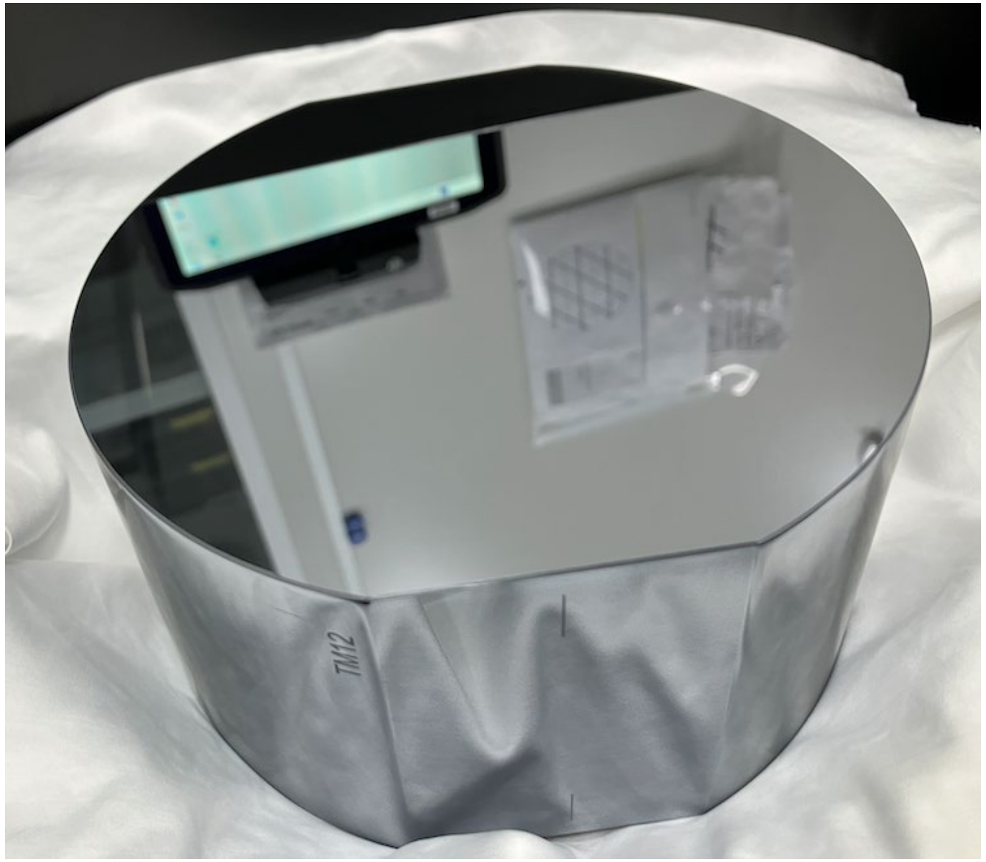
Surface 2:

- Zone A: Surface error shall be < 2 nm RMS measured over the totality of Zone A; Micro-roughness shall be < 0.1 nm over the same area (super polish).
- Zone B: Micro-roughness shall be < 5 nm over Zone B, no surface error requirement.
- Zone C: No surface error or microroughness requirement.

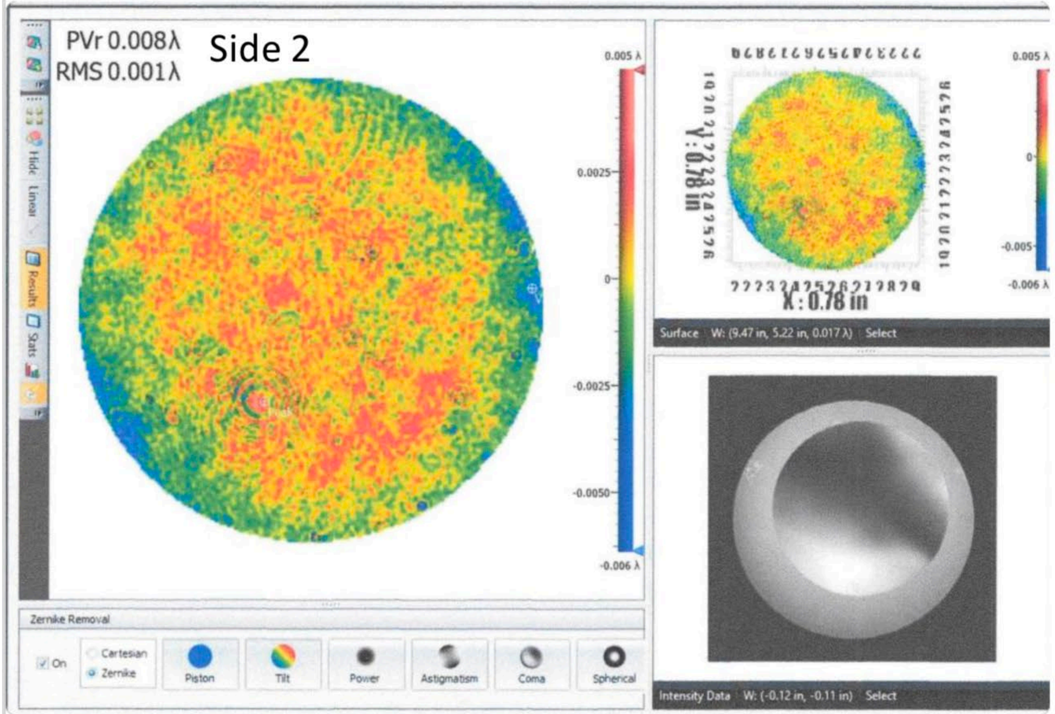
Mirror polishing

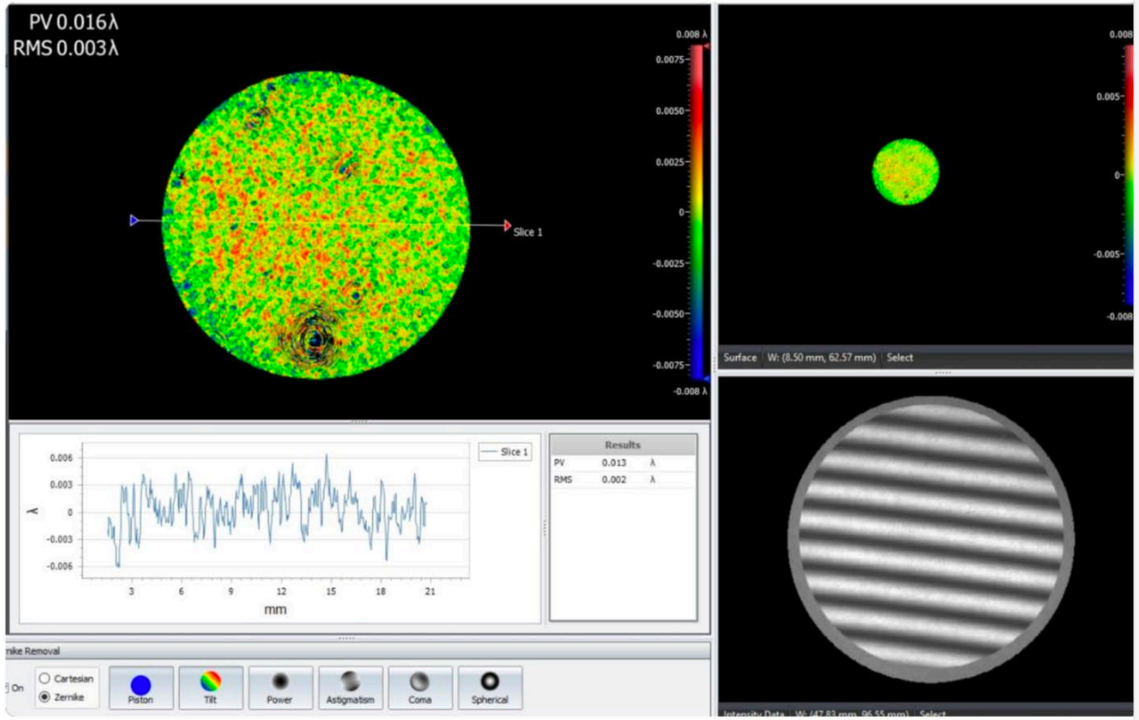
- long procedure with some learning curve and several delays, but hopefully leading to an established procedure.
- information shared by manufacturer so far sounds promising, but hard to estimate the full picture





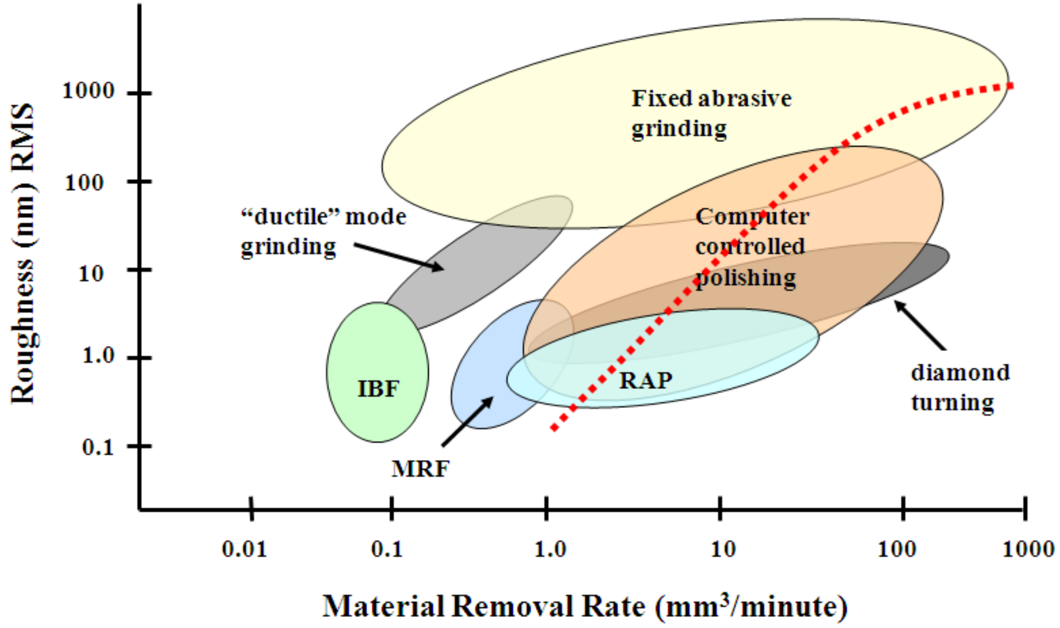
HTRS mirror metrology (Coastline vs B-PHOT)





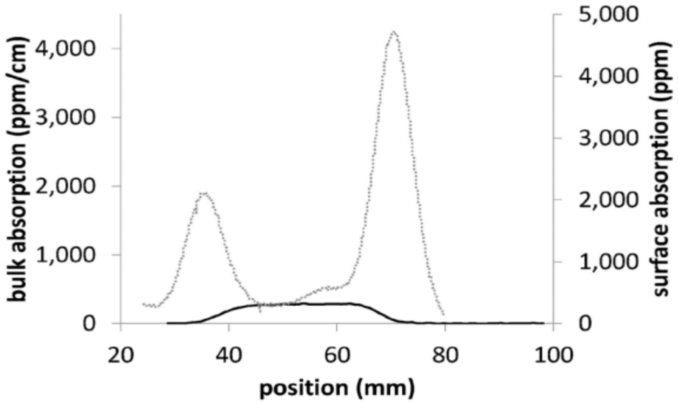
Investigating other (and more local) avenues

- ETpathfinder optics specifications were intentionally demanding (but not unrealistic), to test how suppliers would react
  - there is scope for downgrading the specifications and still make ETpathfinder work, e.g., with respect to surface roughness, alignment of front and back radii, wedge
  - but at which point do we no longer learn anything?
- at the same time, need to build up metrology for silicon mirrors (e.g., transmitted wavefronts)

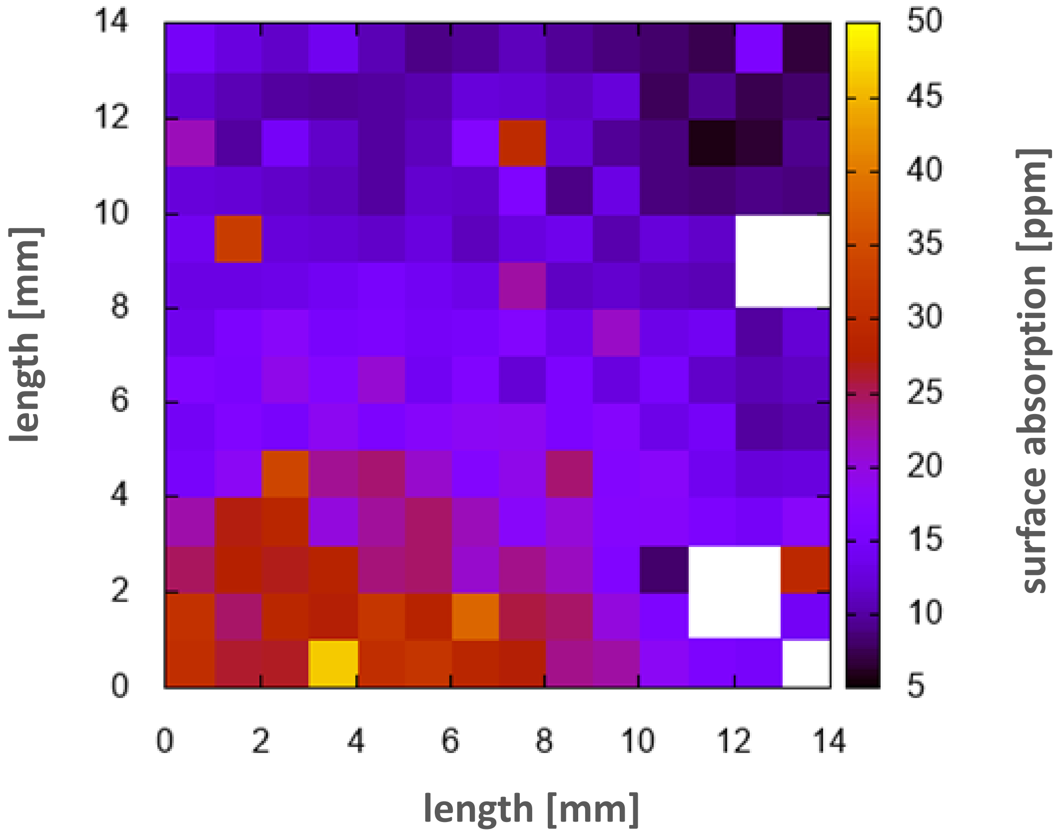


Silicon absorption measurements at UM

- initial tests with the PCI setup at UM
- known issue: measuring low absorption needs high power densities, which in silicon produces two-photon absorption
- main focus right now (also with view to measure polishing test samples) is on measuring surface absorption (Bell et al, 2017) - induced during polishing, but exact cause still unknown at least to us



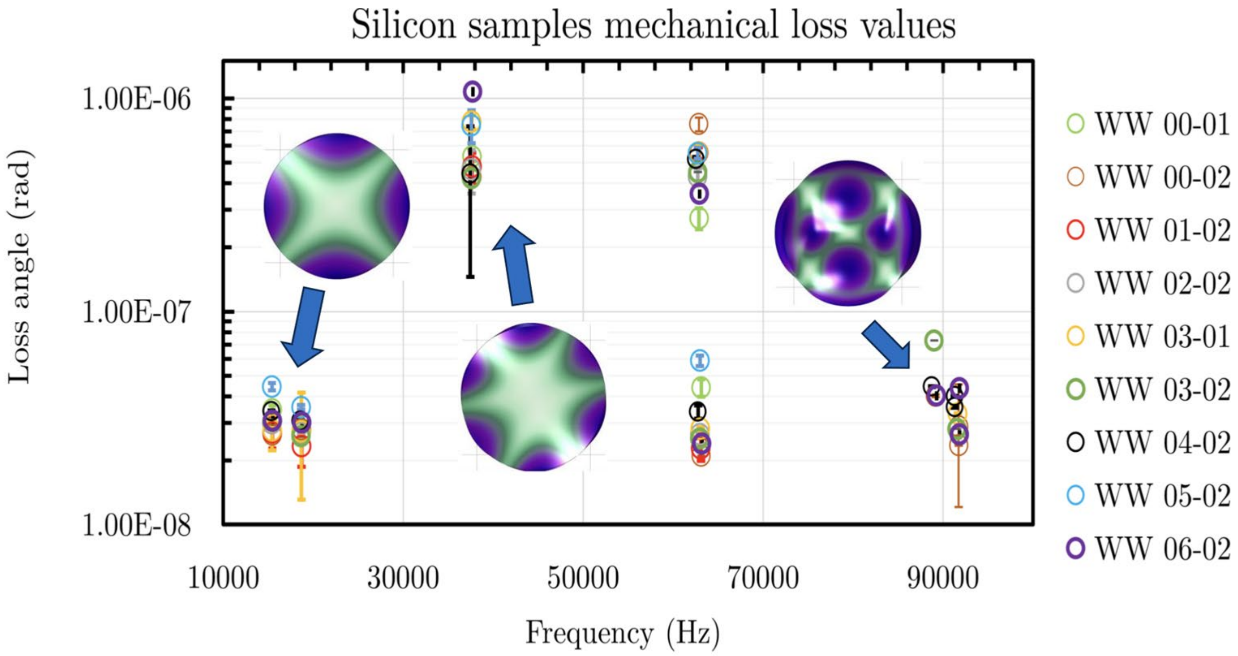
particularly bad example of contamination with Ge during polishing (from Bell et al.)

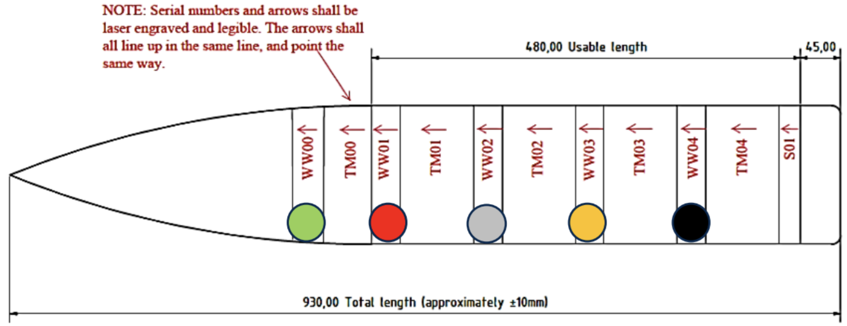


measurement of a 14mm x 14mm square on the end surface of a 1” diameter sample, polished by Pilz Optics

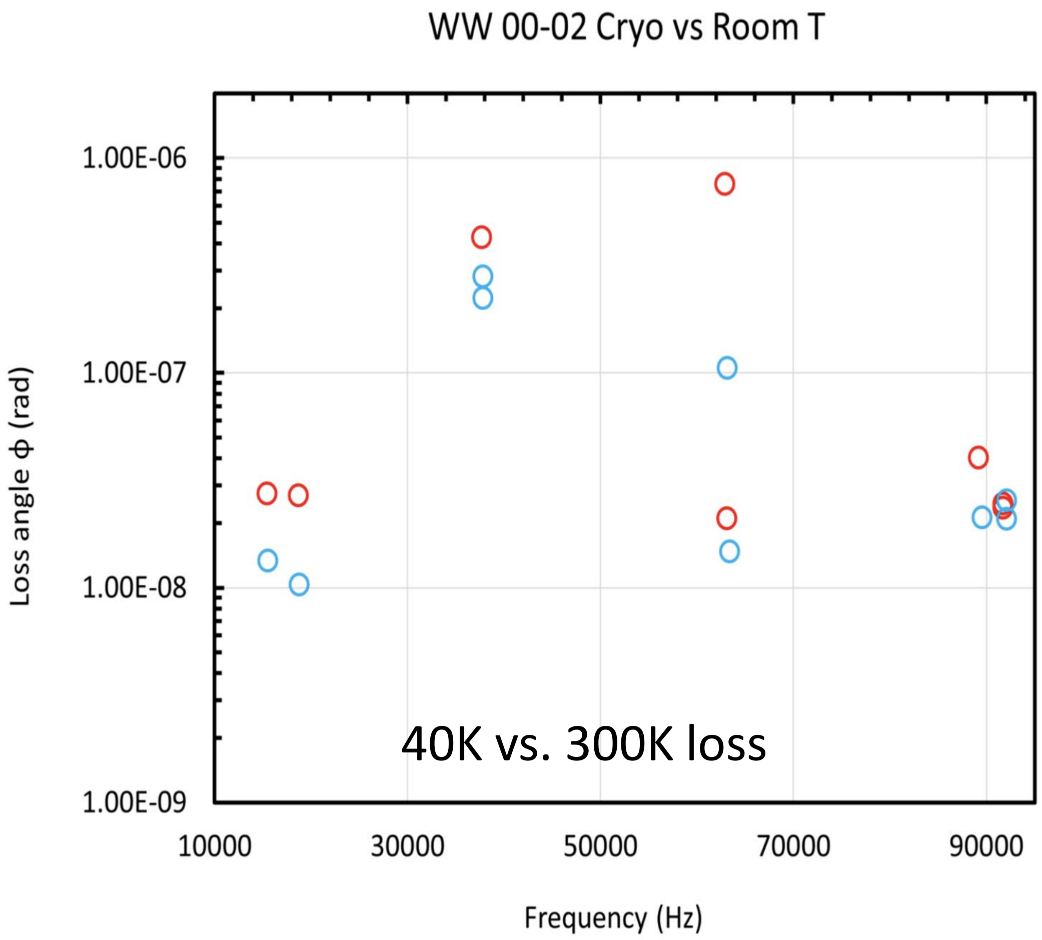
Silicon mechanical loss measurements at UM

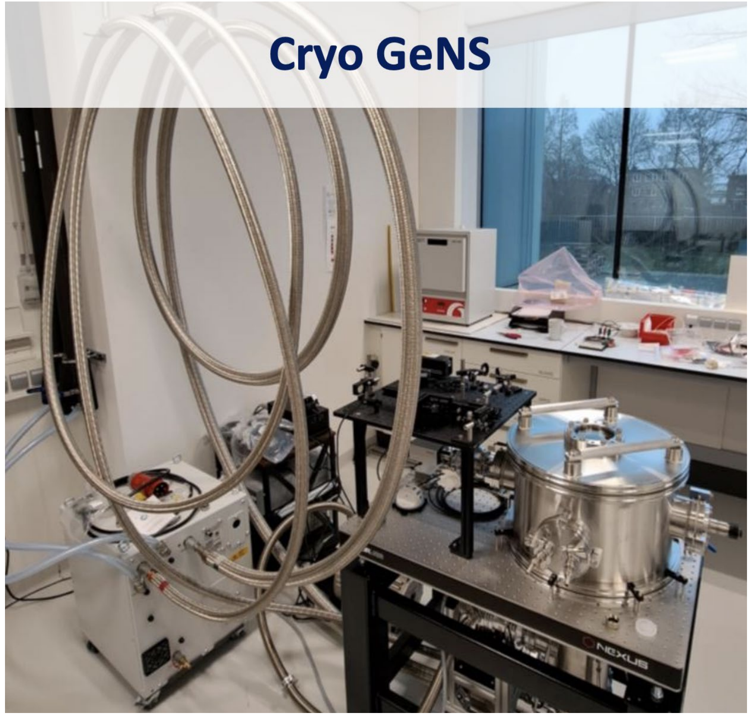
- cryogenic GeNS setup now operational
- measured several silicon disks (50mm x 5mm) obtained from witness wafers along the axis of the silicon ingots (FZ, grown by IKZ)
- very nice loss levels in the few 10^{-8} region obtained





Silicon loss cont'd

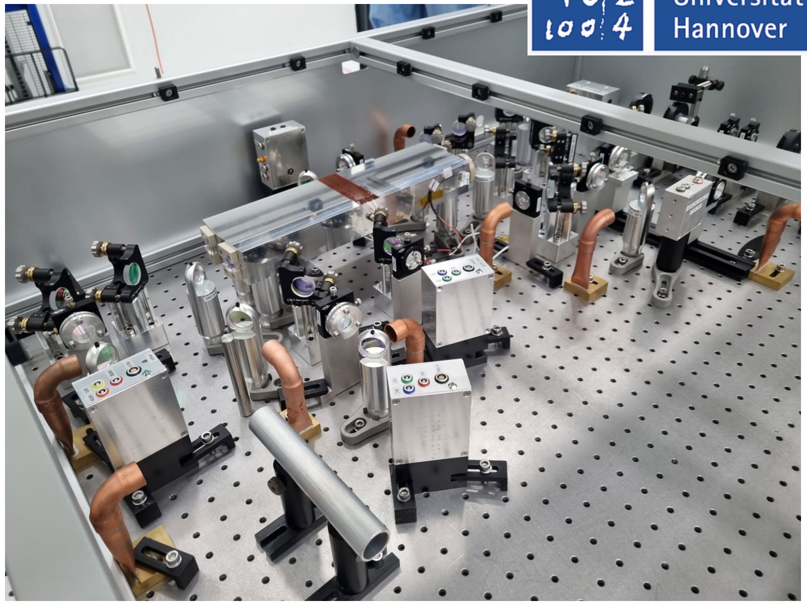


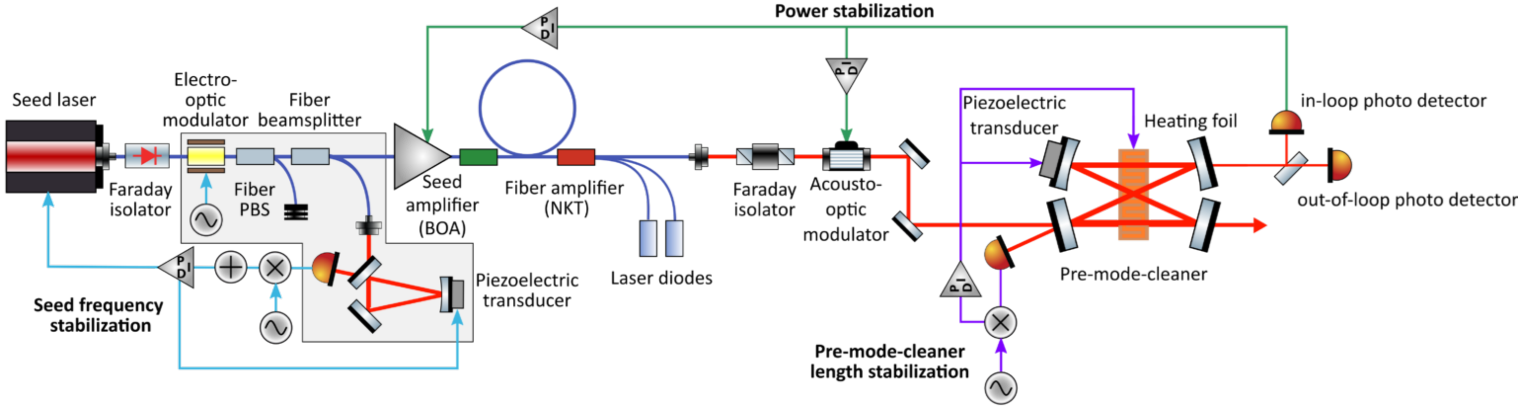


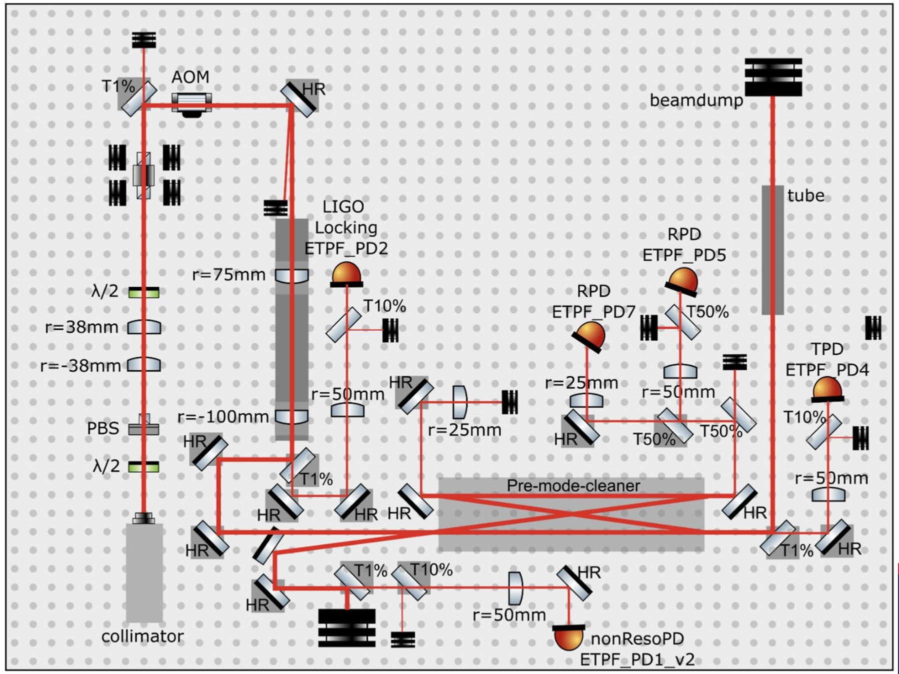
AEI 1550nm Laser Development

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

- diode seed laser (Orion) with frequency pre-stabilisation
- fibre pre-amplifier (booster optical amplifier) followed by NKT Photonics fibre amplifier
- pre-mode cleaner for additional filtering and pointing stability, followed by power stabilisation loop

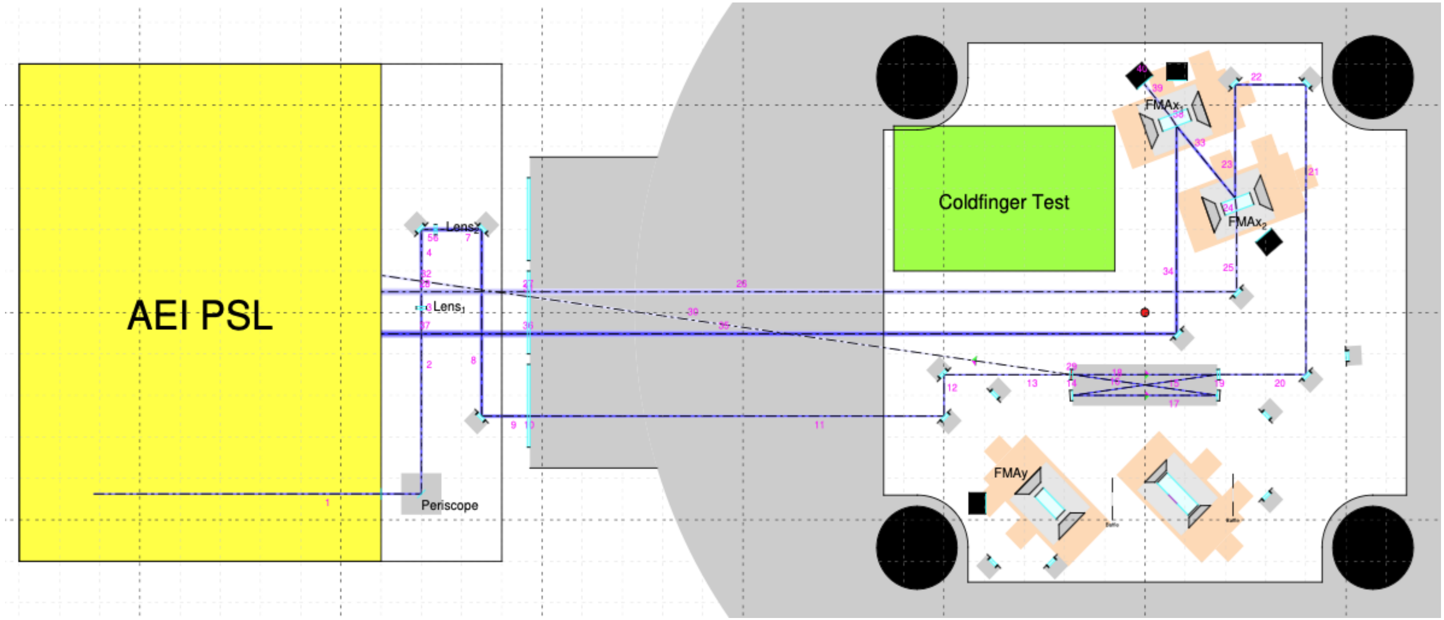






Plans for the 1550nm laser

- stabilisation of laser to PMC-style mode cleaner on first suspended bench should deliver interesting results, potentially improving low-frequency stability of the laser significantly



NPRO laser development within E-TEST

Fraunhofer ILT

Two different NPRO coatings were tested

- First coating: Operation at 2120nm
- Second coating: Operation at 2090nm

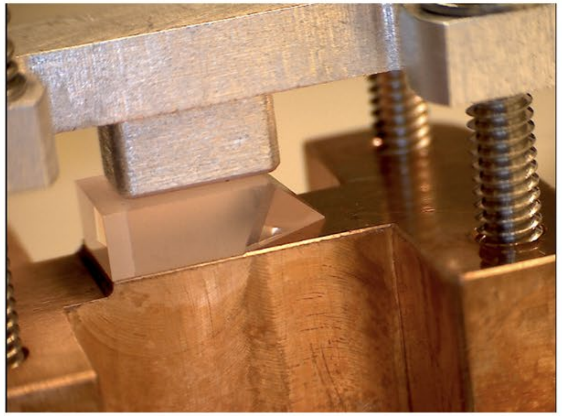
2120nm laser:

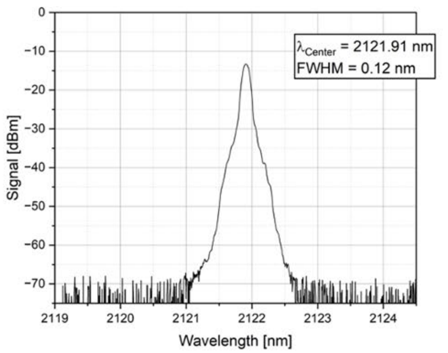
- Low linewidth operation at 2122nm
- Up to 480 mW output power
- Long term power stability
- Single mode beam quality

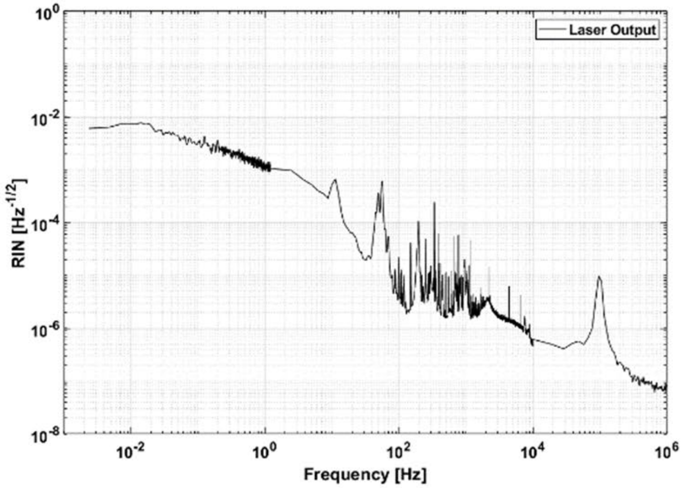
2090nm laser:

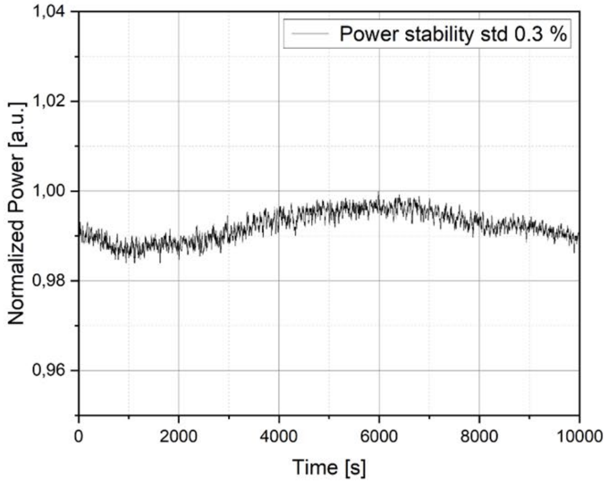
- Low linewidth operation at 2090nm
- Up to 50 mW output power

  At higher power levels emission at 2120nm can be observed









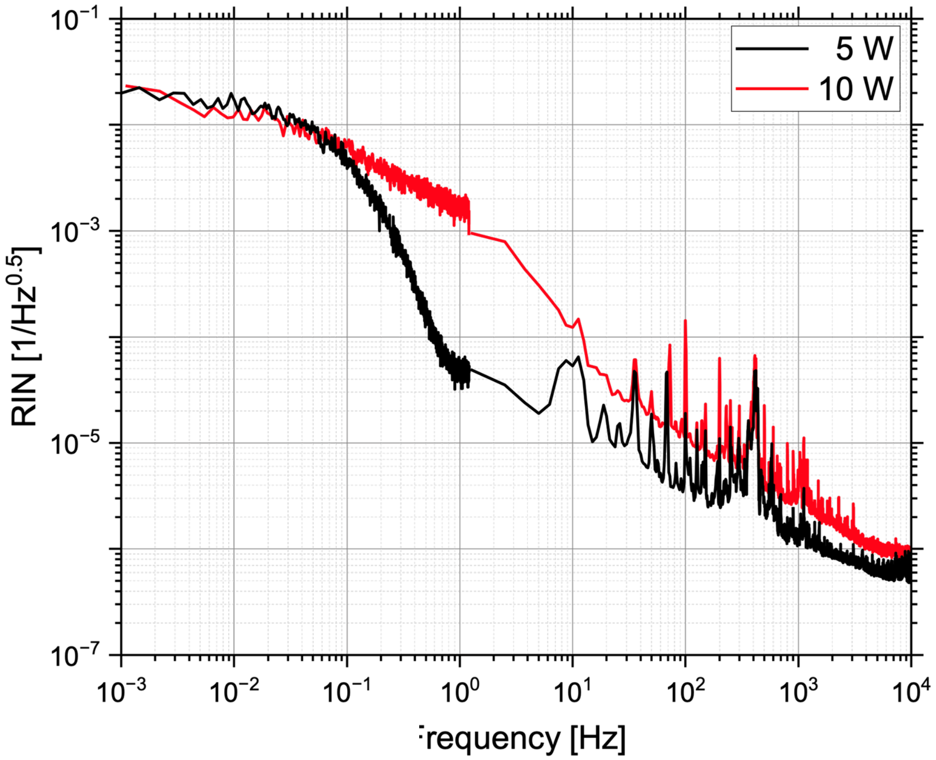
High-power (E-TEST) amplifier

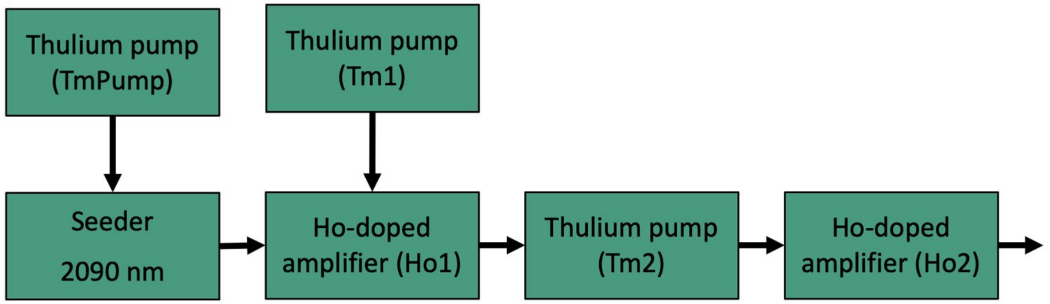
Final Holmium-doped Fiber Amplifier (Ho2)
Main results:

- Output power >10 W
- PER: 26 dB
- Center wavelength: 2095 nm
- ASE level approx. 50 dB
- Beam quality $M^2 = 1.18$

RIN:

- 100 Hz: $<10^{-5}$ $Hz^{-0.5}$
- Power dependent RIN
  - currently under investigation



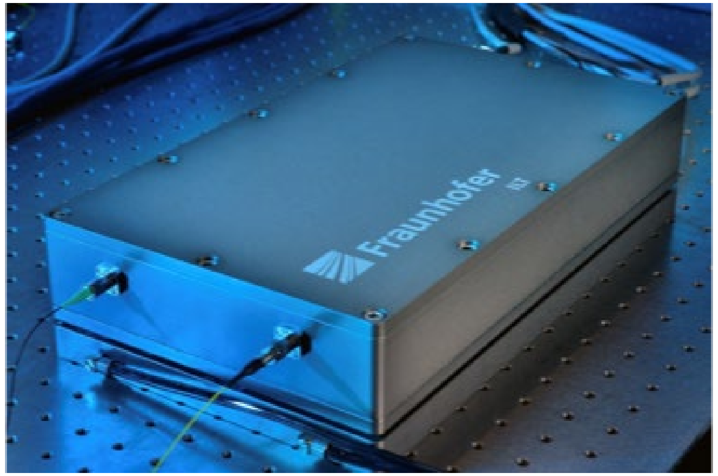


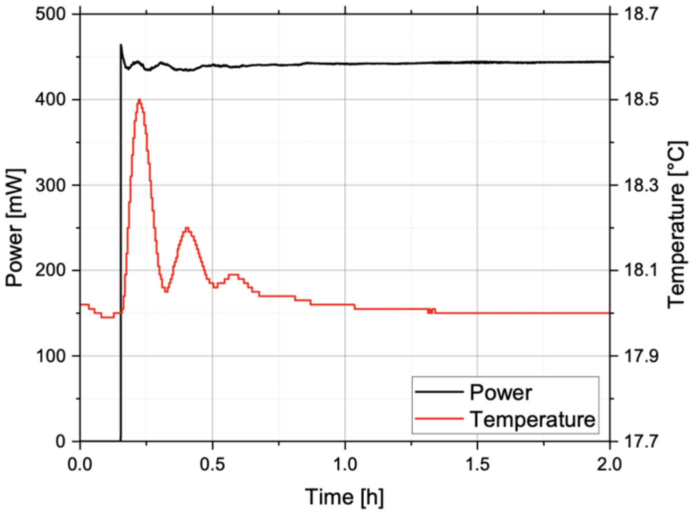
Fiber amplifier development

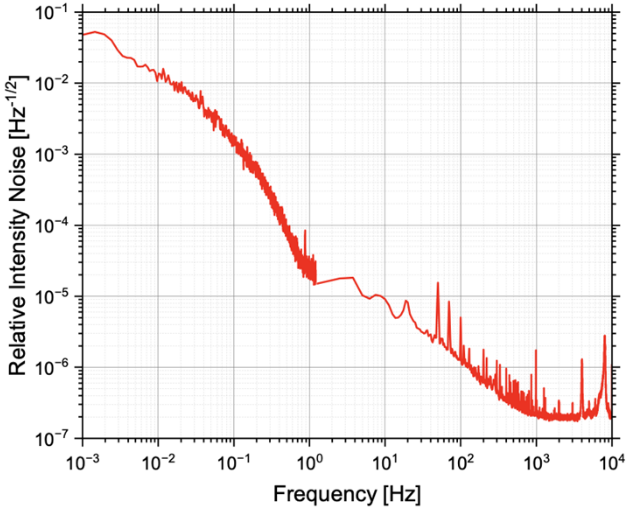
Fraunhofer ILT

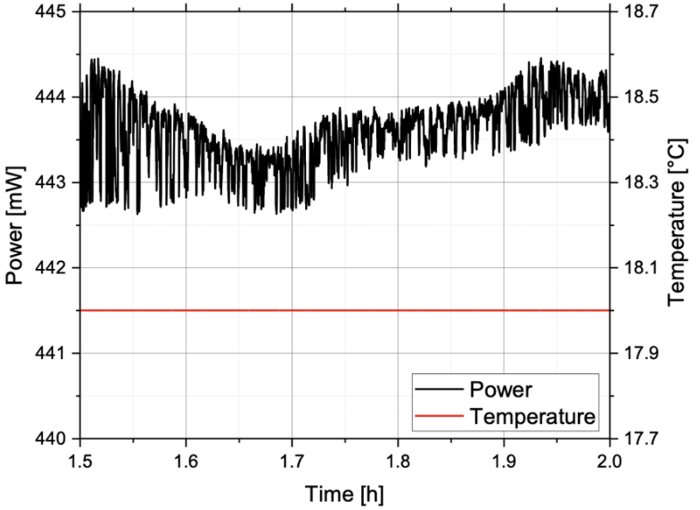
Laser System Specifications / Goals

- Wavelength: 2090 nm (dependent on used seed laser)
- Linewidth: 2 MHz (dependent on used seed laser)
- Continuous wave operation
- Output power: > 100 mW
- Linear Polarization (PER > 20 dB)
- Robust lab demonstrator packaging
- Active actuators (Pump current, Seed diode current, Seed diode temperature)
- Exchangable seed diode via fiber connectors



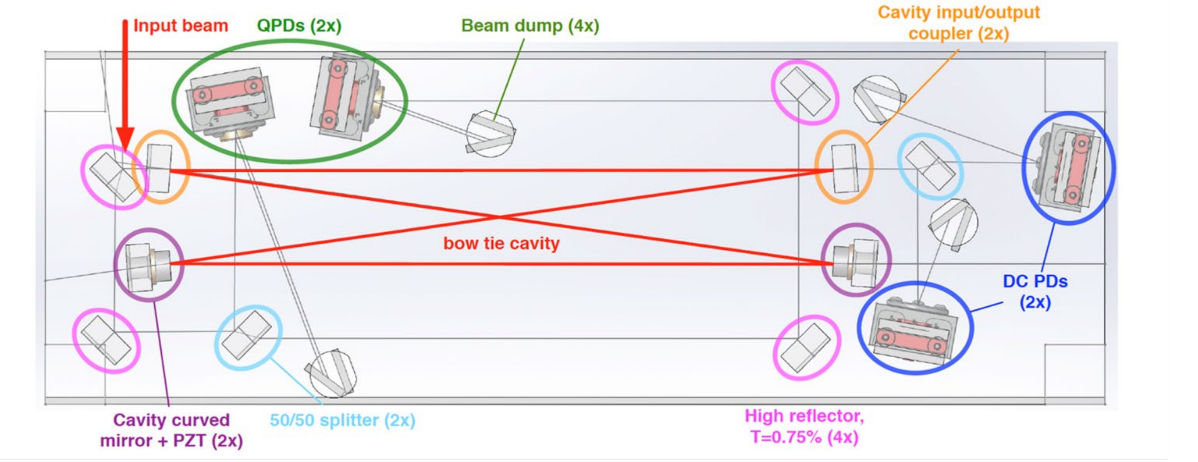






Other R&D activities

- design of an output mode cleaner for ETpathfinder, taking into account new optics manufacturing techniques
- investigating possibilities and advantages of “new” simulation tools (VirtualLab, RP Resonator, etc.)
- simulating suppression of higher-order modes, sidebands, and HOMs of sidebands



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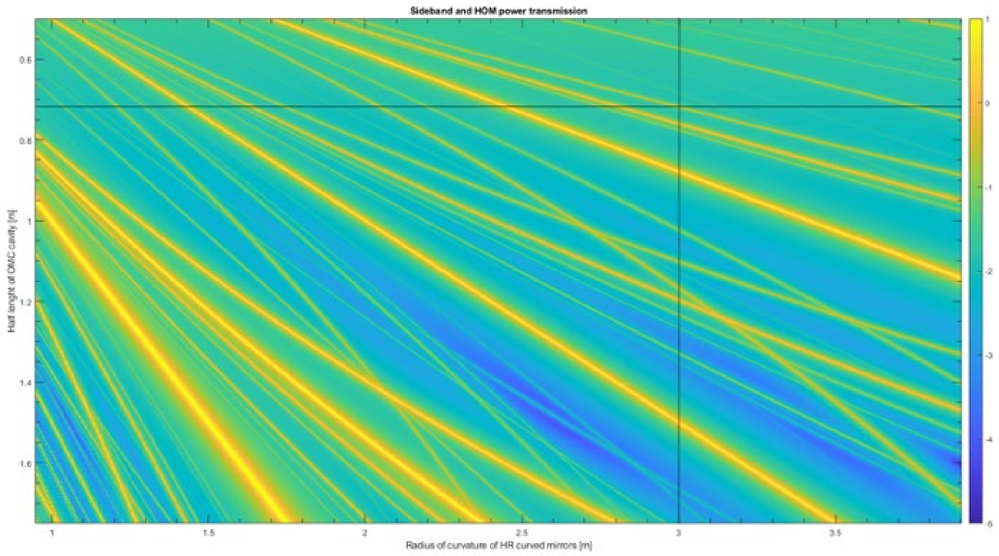

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B-PHOT BRUSSELS PHOTONICS

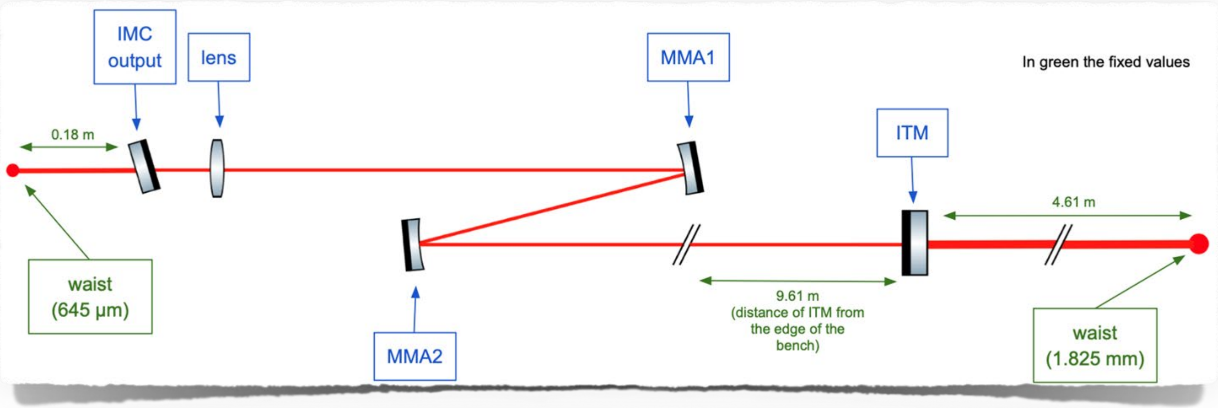
VUB VRIJE UNIVERSITEIT BRUSSEL

Interreg Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

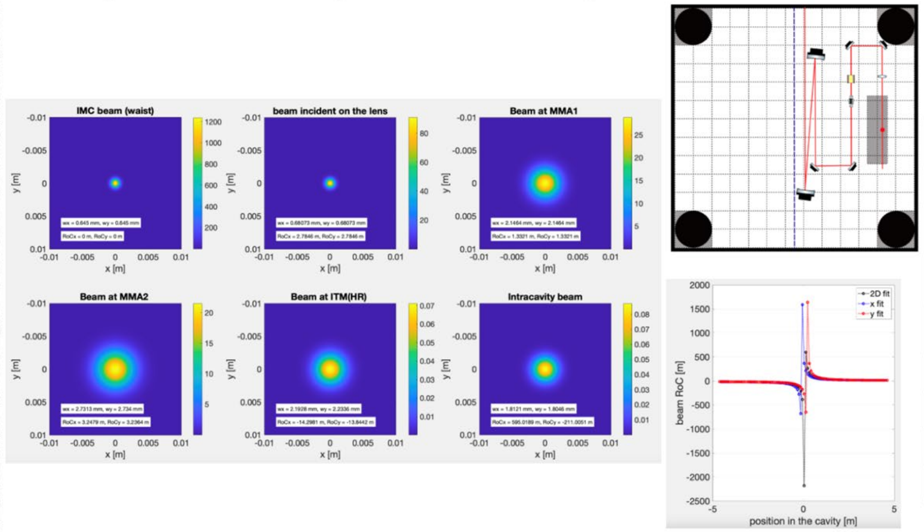
[S.Hild, Maastricht &Nikhef]

Other R&D activities cont'd

- design of mode-matching telescopes for ETpathfinder
- getting acquainted with capabilities of Zemax, VirtualLab, OSCAR, …
- multiple possible solutions, decision still tbd with regard to implementation strategy (e.g., non-FP Michelson needs different mode-matching)



V4 layout: beam profile and layout



Distance IMC-lens	0.10 m
Distance lens-MMA1	1.68 m
Distance MMA1-MMA2	0.70 m
Distance MMA2-ITM(AR)	10.61 m
Distance IMC-ITM(AR)	13.09 m
AoI on MMA*	4°
Lens focal length	0.4 m
RoC MMA1	5.5 m
RoC MMA2	5.5 m

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Other R&D activities cont'd

- new 2μm R&D lab now available at UGhent
- planned location for OMC tests
- planned characterisation of photo detectors

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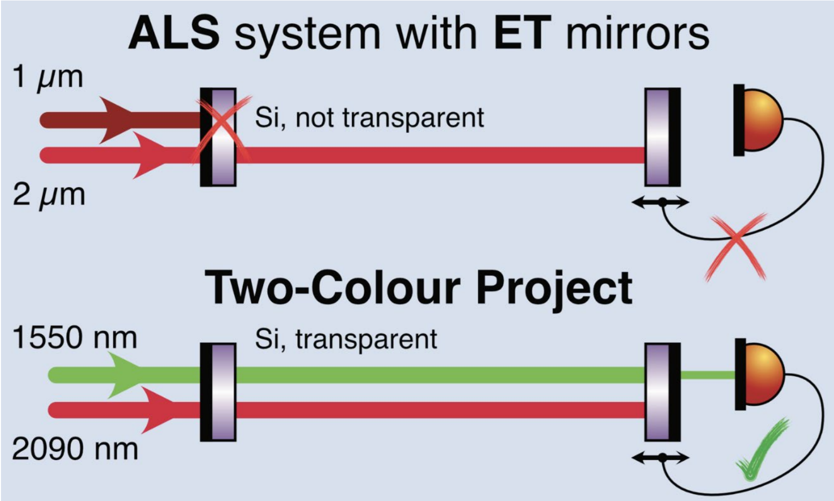
- two-colour experiment (2090nm + 1550nm) being set up in Maastricht; possible solution to ALS-style locking scheme for silicon mirrors (NWO Vidi S. Steinlechner)
- squeezed light source at 1550nm being built up for tests of QND readout schemes (ERC AdV S. Hild)

Maastricht University



Thanks for your attention!
Questions?

ETpf design report

[Research – ETpathfinder](#)

ETpf sensitivity paper

[ETpathfinder: a cryogenic testbed for interferometric gravitational-wave detectors - IOPscience](#)