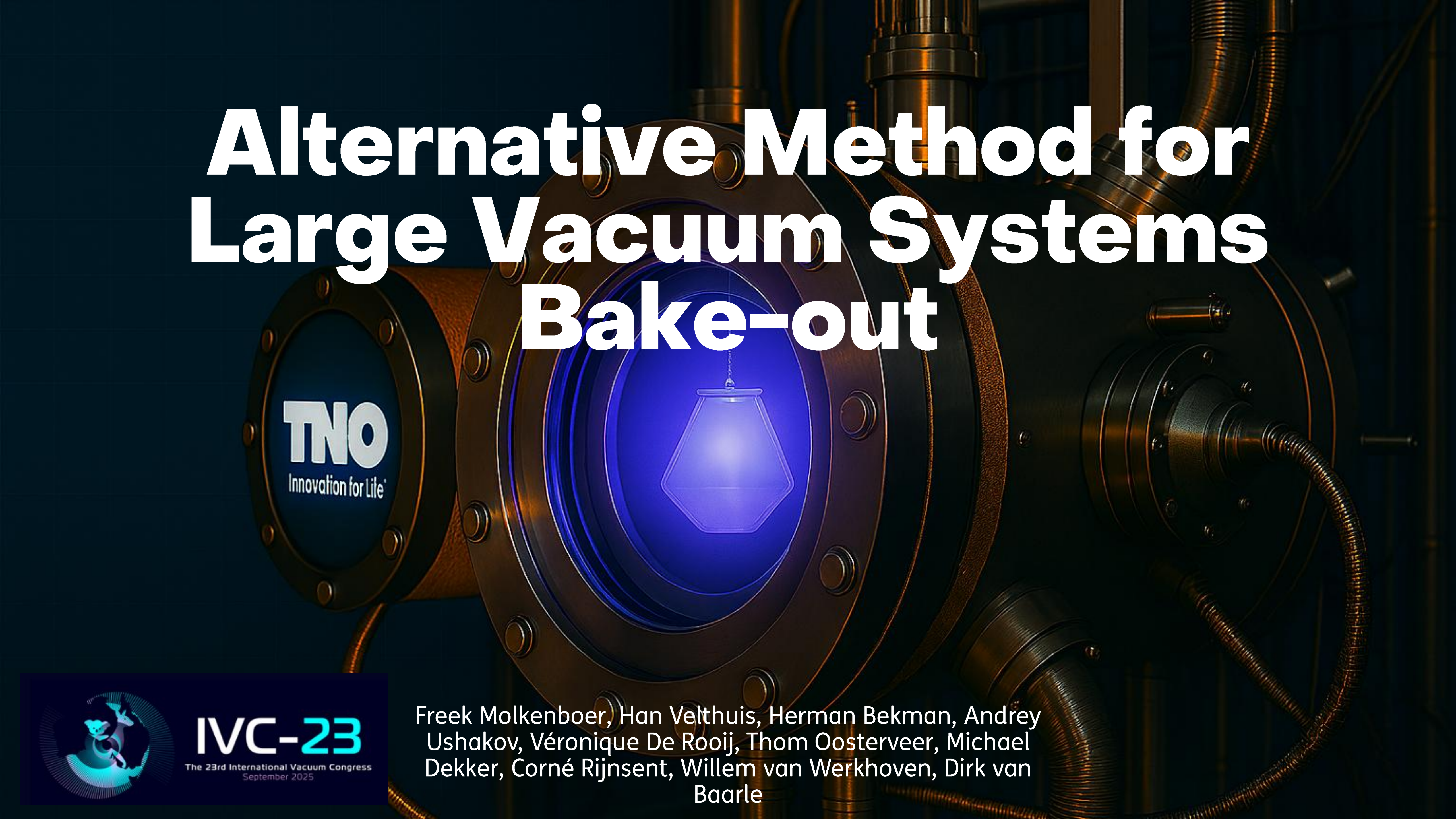


Alternative Method for Large Vacuum Systems Bake-out

IVC-23
The 23rd International Vacuum Congress
September 2025

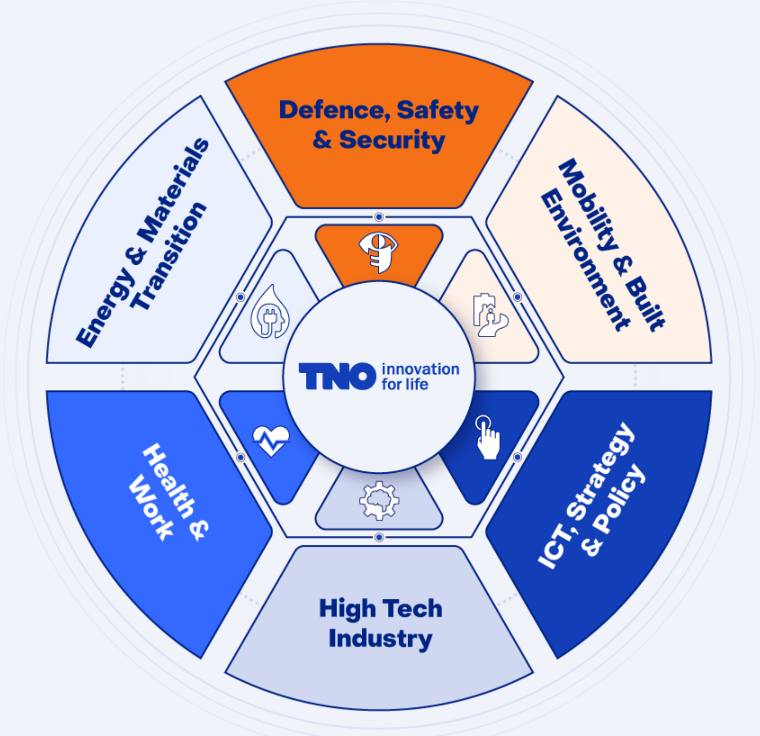
Freek Molkenboer, Han Velthuis, Herman Bekman, Andrey Ushakov, Véronique De Rooij, Thom Oosterveer, Michael Dekker, Corné Rijnsent, Willem van Werkhoven, Dirk van Baarle

Outline

- Intro TNO
- Gravitational waves
- Einstein Telescope and cosmic explorer
- ET MacBeth project
- An alternative method for large vacuum systems bake-out
- Conclusions and outlook

TNO – Semicon Equipment groups

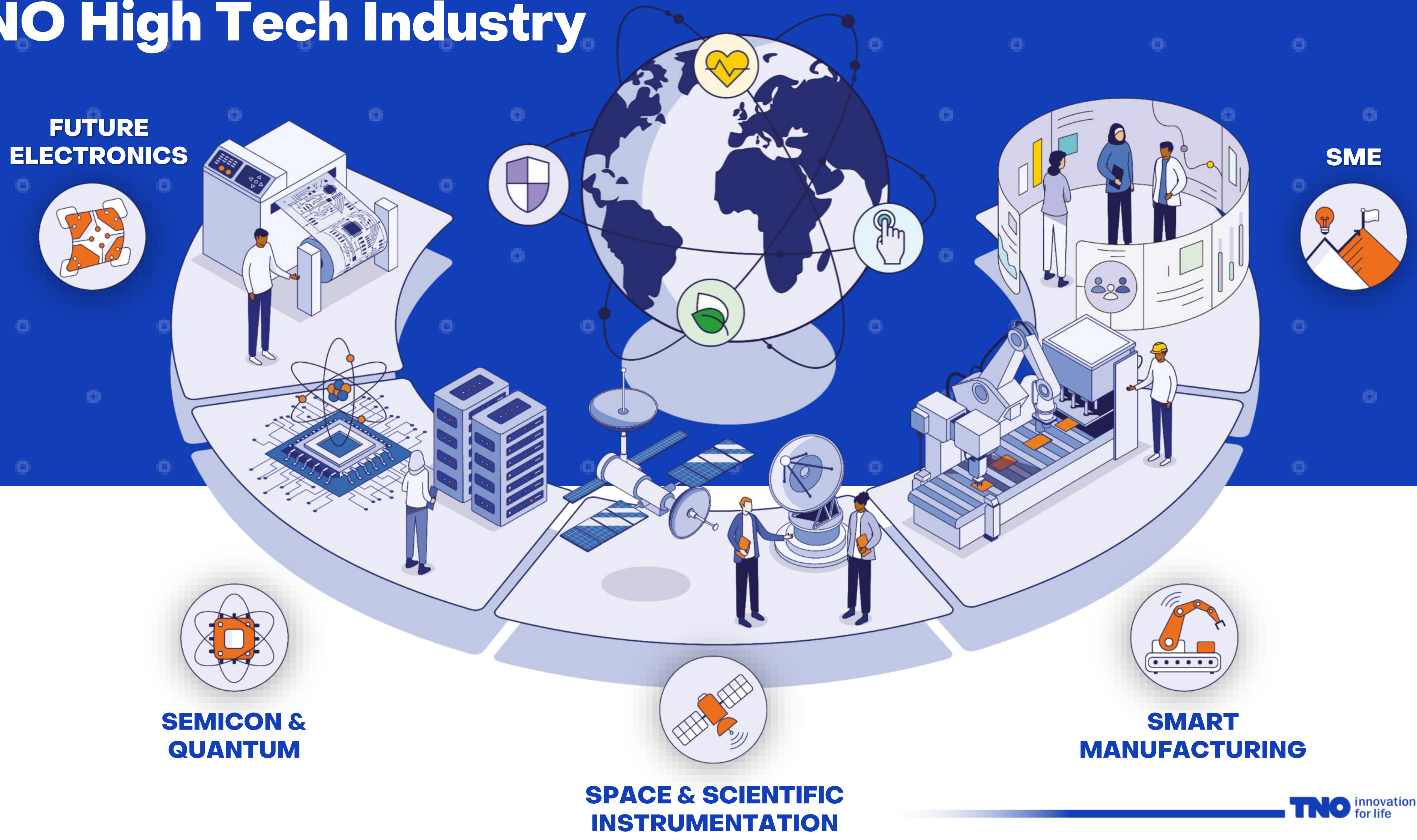
- **TNO: Netherlands Organisation for Applied Scientific Research**
  - Established in 1932, non-profit organisation
  - Independent and confidential partner
  - 2024: ~4500 employees, ~764 MEUR organisation revenue



Campus TU-Delft, Delft

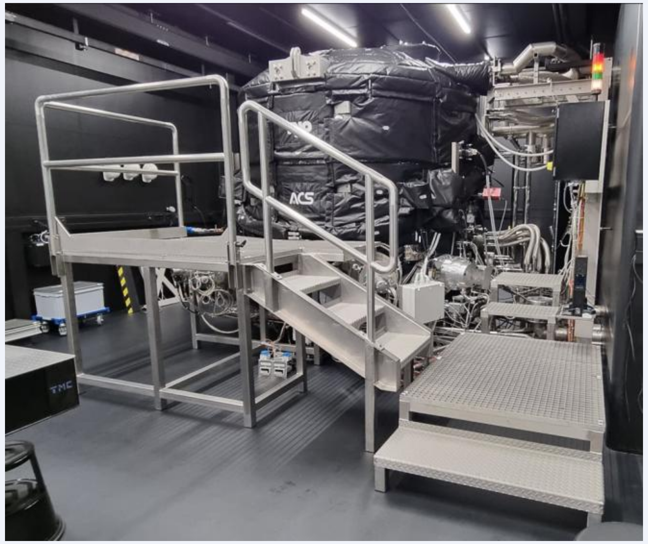
Philips High Tech Campus, Eindhoven

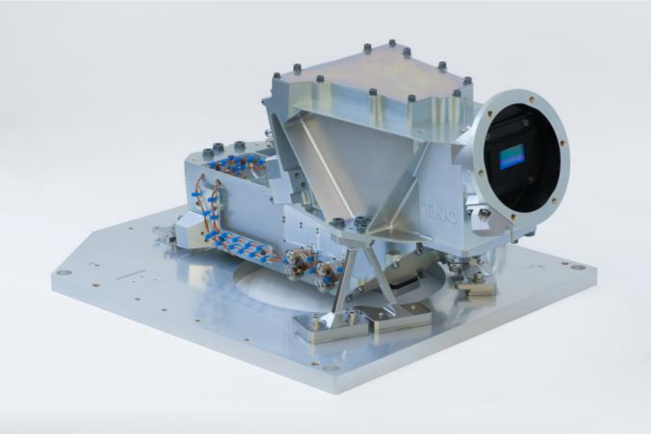
TNO High Tech Industry



TNO innovation for life

TNO High Tech Industry





APPLICATIONS

First MetOp-SG and Sentinel-5 launched

13/08/2025 6688 VIEWS 50 LIKES

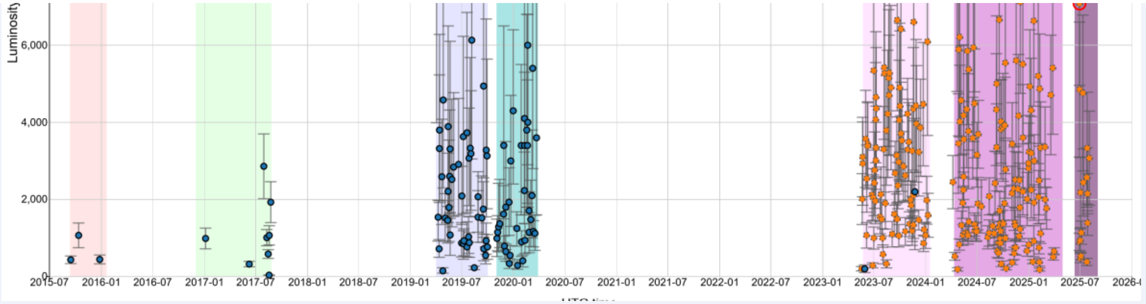
ESA / Applications / Observing the Earth / Meteorological missions / MetOp Second Generation

Ushering in a new era of weather and climate monitoring from polar orbit, the first in a new series of satellites, MetOp Second Generation, has been lofted into orbit aboard an Ariane 6 rocket from the European spaceport in Kourou, French Guiana. As part of this new satellite's sophisticated instrument package is the new Copernicus Sentinel-5 instrument, which is designed to deliver critical data on air pollutants, ozone and climate-related gases.

Lifting off on 13 August at 02:37 CEST (12 August 21:37 local time), the Ariane 6 rocket carried the four-tonne satellite into orbit around Earth. Confirmation that MetOp-SG-A1 was alive and well came at 04:47 CEST, after its solar array had been deployed, ensuring that the satellite could generate power.

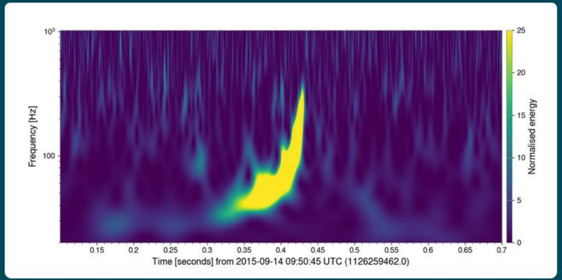
Gravitational waves

"LIGO" - Director's Cut



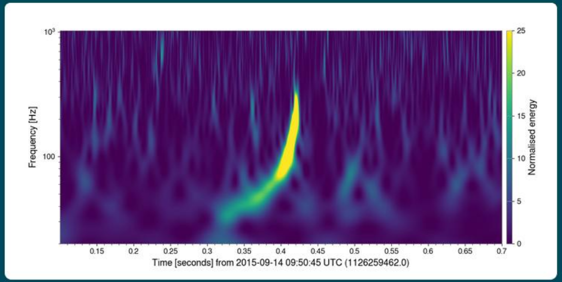
https://catalog.cardiffgravity.org/

H1 strain



32sec · 16KHz: GWF HDF TXT
32sec · 4KHz: GWF HDF TXT
4096sec · 16KHz: GWF HDF TXT
4096sec · 4KHz: GWF HDF TXT

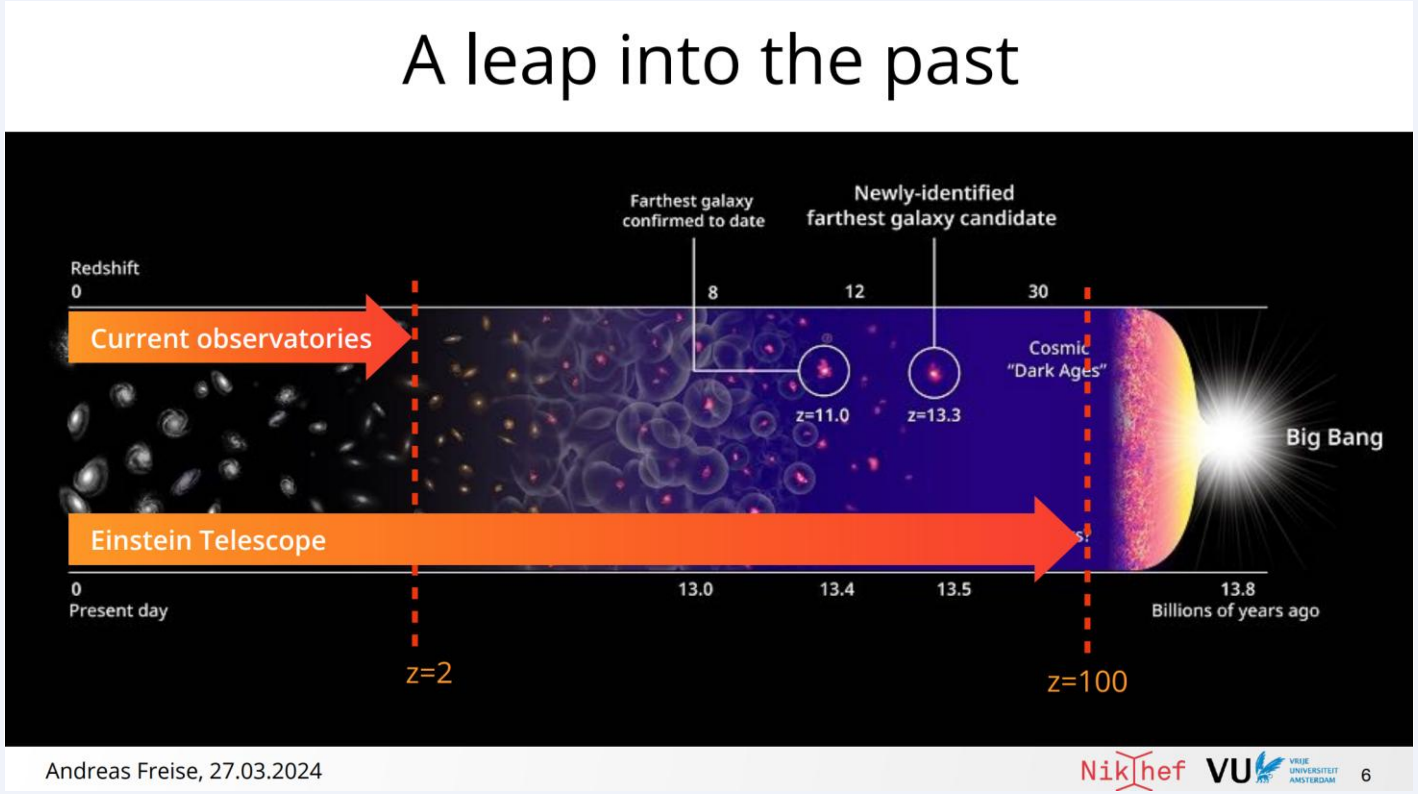
L1 strain

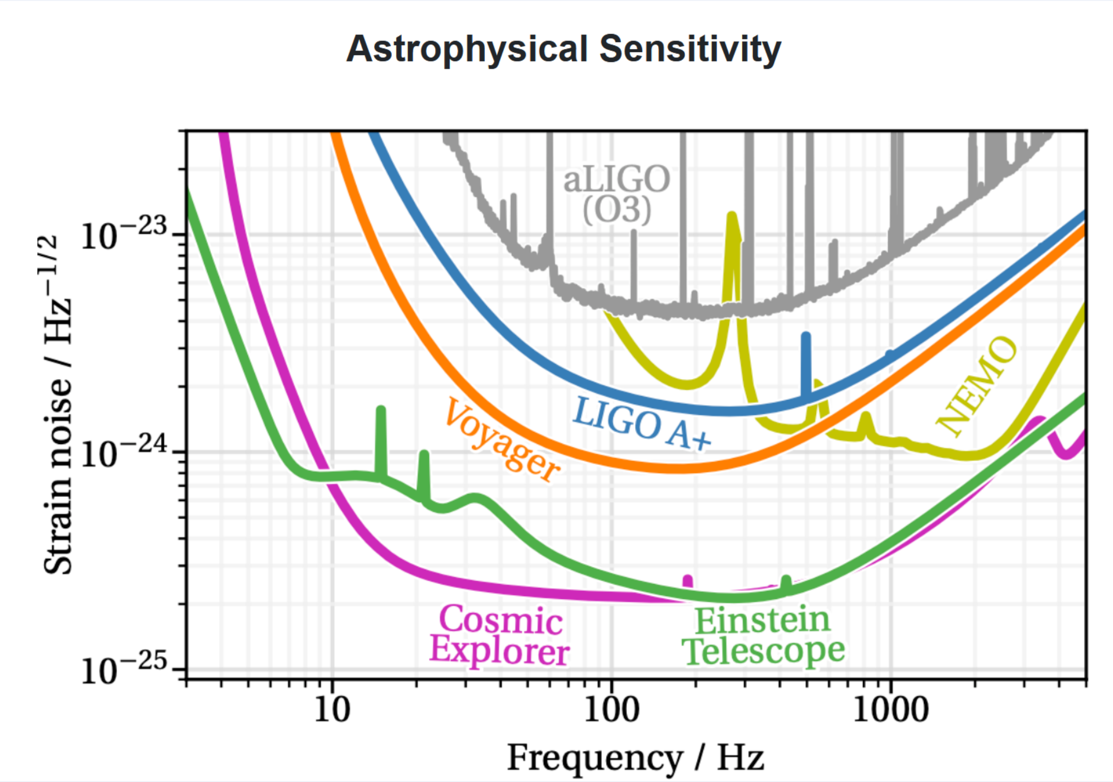


32sec · 16KHz: GWF HDF TXT
32sec · 4KHz: GWF HDF TXT
4096sec · 16KHz: GWF HDF TXT
4096sec · 4KHz: GWF HDF TXT

https://doi.org/10.7935/82H3-HH23

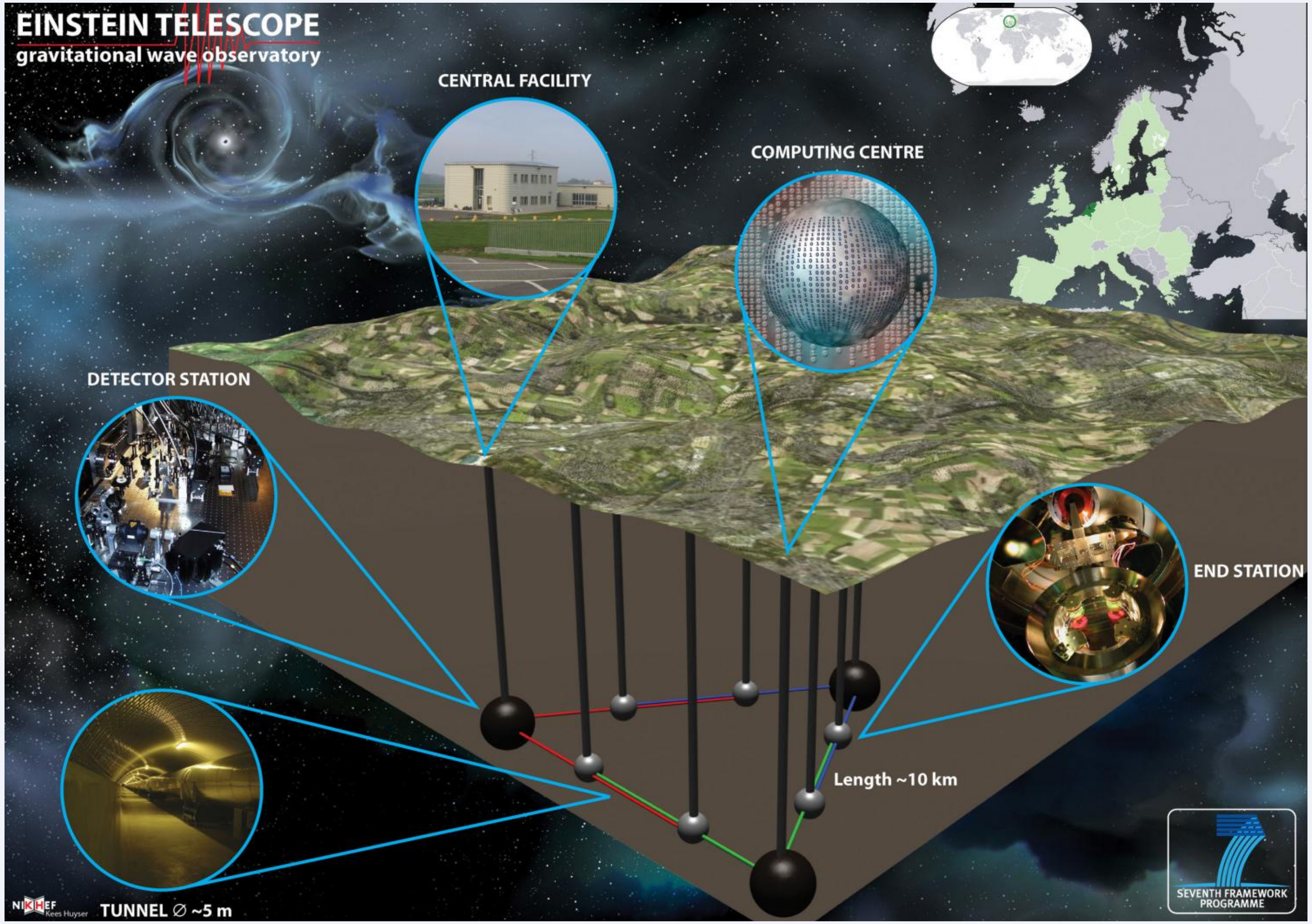
3rd generation gravitational wave detector



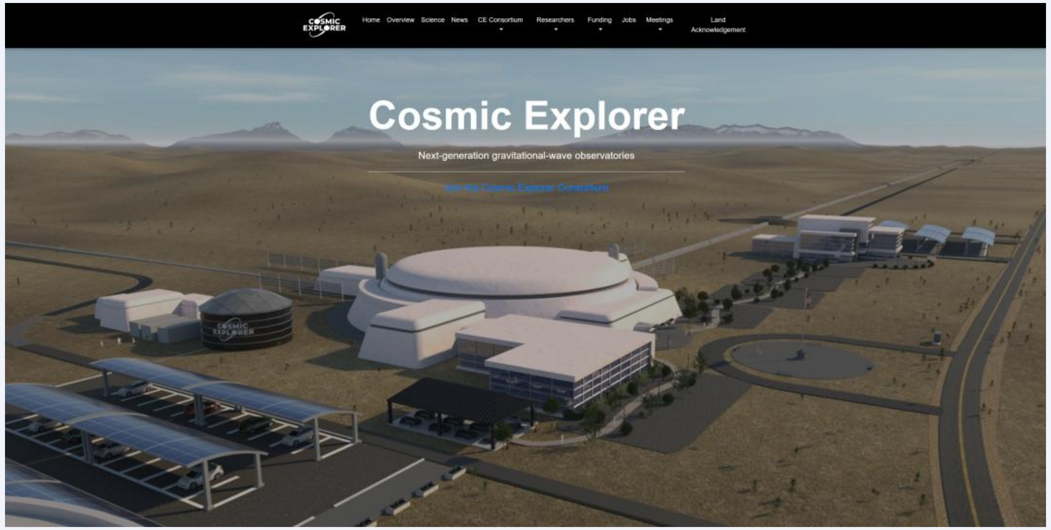


https://cosmicexplorer.org/

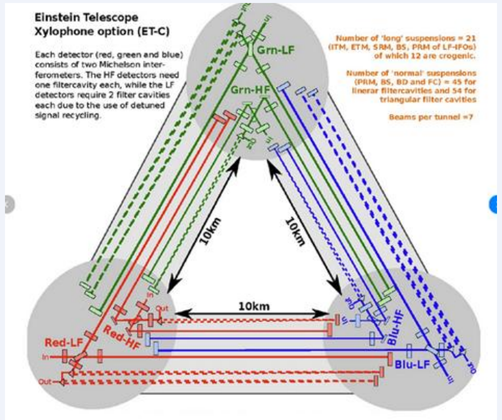
3rd generation gravitational wave detector



https://www.et-gw.eu/index.php/etimages (Kees Huyser)



https://cosmicexplorer.org/



Let’s talk vacuum

- Main information sources:
- The vacuum Pipe of ET
  - ET-PP-Deliverable-6.2 [ET-0005A-25] CERN team 09/01/2025
- Einstein telescope beampipe requirements [ET-0385A-24]
  - Many authors, release date 2/7/2024
- Design report Einstein Telescope update 2020
  - ET steering committee editorial team, released September 2020

- Varies other presentations, talks at ET related symposiums, etc.

Einstein Telescope vacuum

- The Einstein Telescope will be the biggest vacuum system in the world

Why do we need an ultra-high vacuum system?

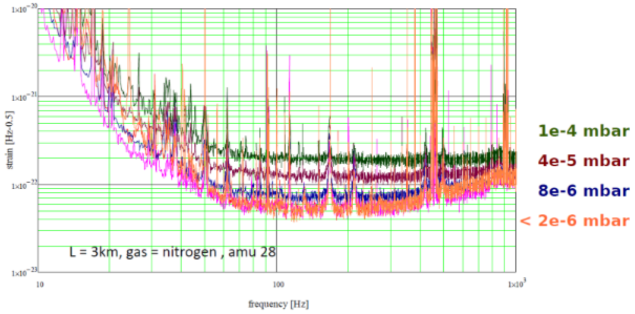
- Reduce the **phase noise due to residual gas density fluctuations** along the beam path to an acceptable level
- Isolate test masses and other optical elements from **acoustic noise**
- Reduce **test mass motion** excitation due to residual gas fluctuations
- Reduce friction losses in the mirror suspensions → **suspension thermal noise**
- Contribute to **thermal isolation of test masses** and of their support structures
- Contribute to preserve the **cleanliness** of optical elements

Virgo design values

Gas species	Pressure [mbar]	Noise [$\sqrt{\text{Hz}}$]
Hydrogen	1×10^{-9}	9.7×10^{-26}
Water	1.5×10^{-10}	2.5×10^{-25}
Air	5×10^{-10}	5.6×10^{-25}
Hydrocarbons	1×10^{-13}	2.9×10^{-26}
Total	1.7×10^{-9}	6.2×10^{-25}

Einstein Telescope aims at an order of magnitude improvement

$$S_L(f) = \frac{4\rho\,(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{1}{w(z)} e^{-2\pi f w(z)/v_0} dz$$



Fluctuations of the refractive index of residual gas limits sensitivity

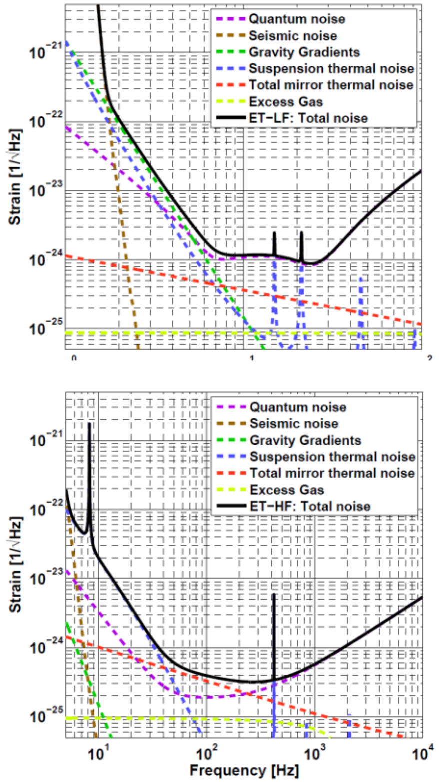


Figure 1.13: Noise budget for the low-frequency (top) and high-frequency (bottom) interferometer for the parameters stated in table 6.1. Shown in black is the amplitude spectral density of a gravitational wave required to produce a signal with the same strength as the total noise of the interferometers. The total noise is decomposed into the individual noise sources, which being statistically independent add up quadratically.

Gas	Max pressure [mbar]
H_2	6.0×10^{-11}
CH_4	2.2×10^{-12}
H_2O	2.6×10^{-13}
CO	2.9×10^{-12}
CO_2	1.3×10^{-12}

Tab. 8; *Maximum ultimate partial pressures in the ET beam pipe after a 7-day bakeout at 150°C, following the layout presented in section 6.3.3. The ultimate pressures reported should be regarded as upper limits.*

Source: Einstein Telescope: vacuum considerations: Jo van den Brand: Webinar Technical Challenges Einstein Telescope, July 15, 2020

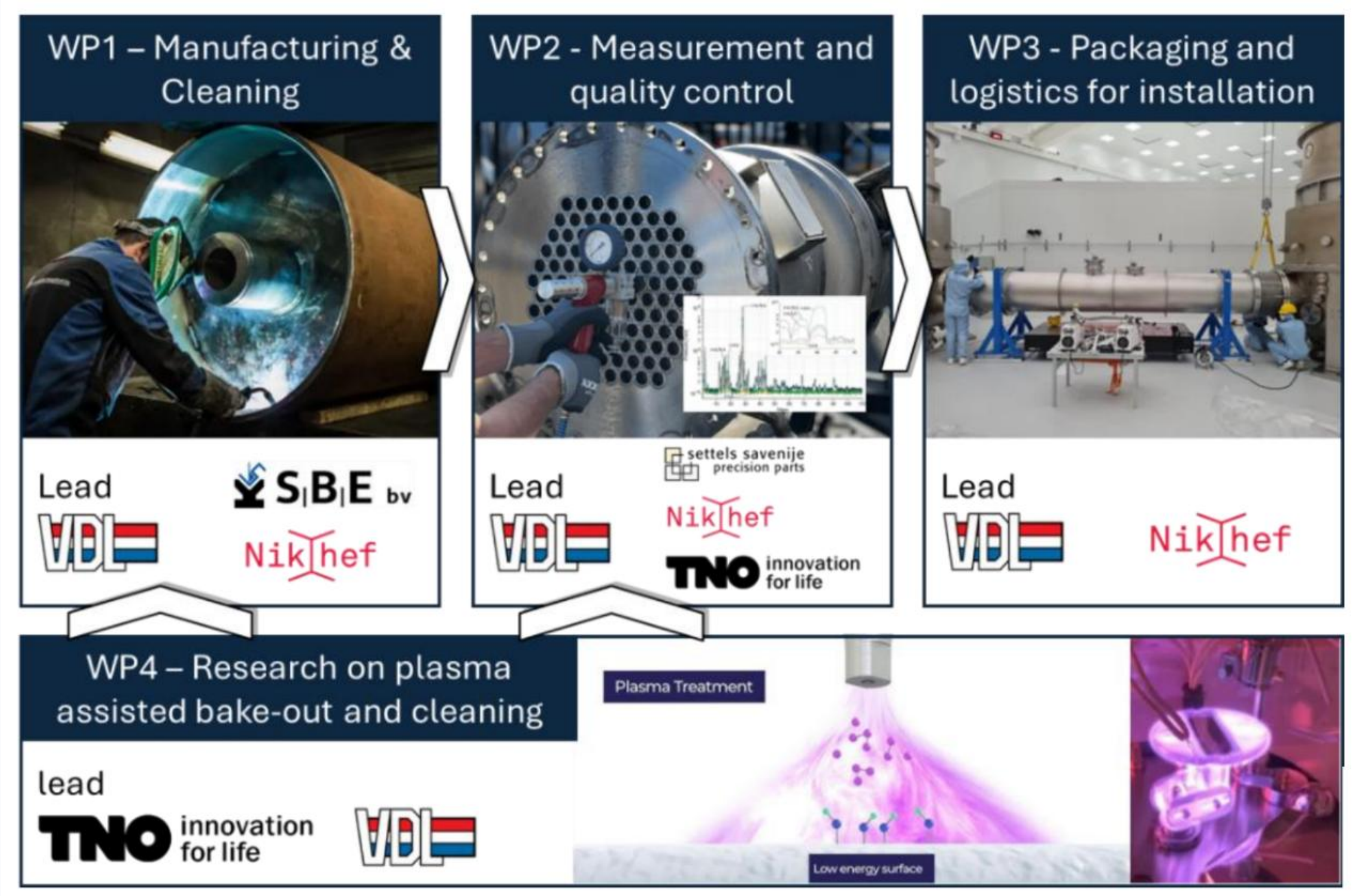
Einstein Telescope vacuum - Cost

- The vacuum system is expected to be ~1/3 of the construction cost of the Einstein Telescope, mainly the beam-pipe

- The Einstein Telescope will have over 120 km of beam-pipe, 1 meter in diameter
  - Material
  - Manufacturing
  - Cleanliness
  - Labour

MacBeth Project

- **Ma**nufacturing and **C**leanliness of **B**eampipe for **E**instein **T**elescope in **H**igh-vacuum



MacBeth Project

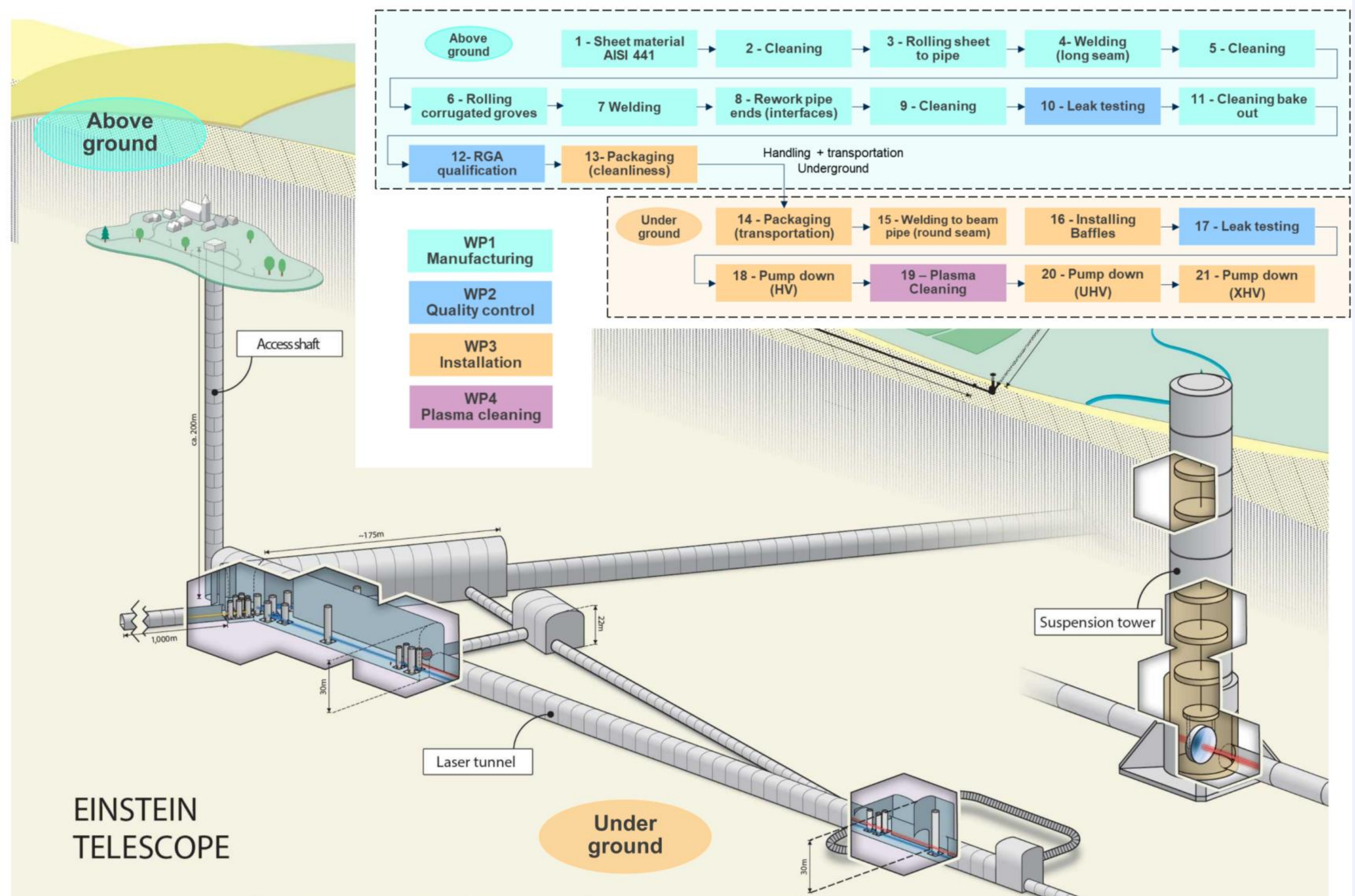


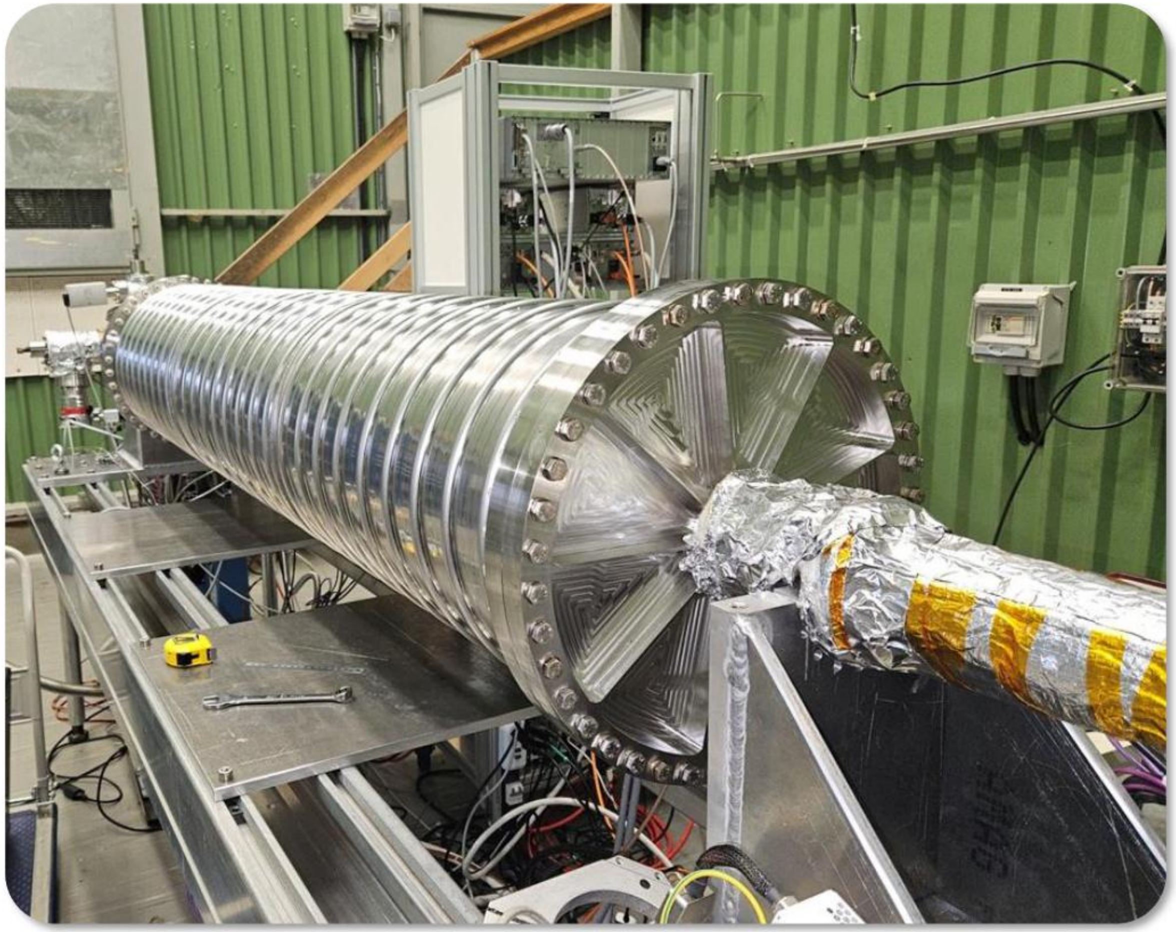
Figure 3: Visualization of the Einstein Telescope and all process steps from manufacturing to installation

- Design and make pilot section of a corrugated beam-pipe (see next slide)
- Study:
  - How to do industrial scale with the required cleanliness levels
  - How to measure the cleanliness levels and the quality also at the industrial scale

Corrugated beam-pipe

- Corrugated beam-pipe will enable the reduction of chamber thickness
  - Less material needed, costs reduction
  - No reinforcements needed?
  - Less energy needed for thermal bake-out
  - No bellows needed?
  - Manufactory will be more complicated

- Best shape currently investigated
- Prototype to be delivered for testing to CERN



AISI 441 corrugated chamber. Credit: CERN

The Einstein Telescope beam pipe vacuum system: Exploring novel techniques and materials for a cost-effective design solution. Carlo Scarcia CERN

Alternative method for large vacuum systems bake-out

- The challenge; <u>surface absorped water</u>
- Current intended method for the Einstein Telescope
  - Joule heating with thermal insulation
  - 5 km at a time, re-use of thermal insulation

2. CONF-881002--14

Proc. 35th National Symposium & Topical Conf. of the American Vac. Soc., Atlanta, GA, 10/3-7/88.

BNL-41181

OUTGASSING AND DESORPTION OF THE STAINLESS STEEL BEAM TUBES AFTER DIFFERENT DEGASSING TREATMENTS*

BNL--41181

DE89 001268

OCT 28 198

H.C. HSEUH & XIUHUA CUI**
Brookhaven National Laboratory
Upton, New York 11973

Abstract

VACUUM-PLASMA PROPERTIES OF STAINLESS STEEL AFTER IMPACT OF COMBINED GLOW-MICROWAVE DISCHARGES IN ARGON ATMOSPHERE

G.P. Glazunov, V.E. Moiseenko, S.M. Maznichenko, M.N. Bondarenko, A.L. Konotopskiy, I.K. Tarasov, A.N. Shapoval

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: glazunov@ipp.kharkov.ua

case it is a copper sheet with dimensions 5×20 cm, then intense copper lines appear in the spectrum (Fig. 15,b). As the working gas pressure increases (the pumping is only with fore pump), intense lines characteristic of water (OH) are detected in the spectra (Fig. 16), which is apparently due to the insufficient speed of the fore vacuum pumping of impurities. Note, the intensity of OH signal in combined discharges is higher than that for GD. It could say about more effective surfaces treatment with combined discharges. Over time, during discharge cleaning, the intensity of the water lines decreases (see Fig. 16,b) which is indication of the wall conditions improvement.

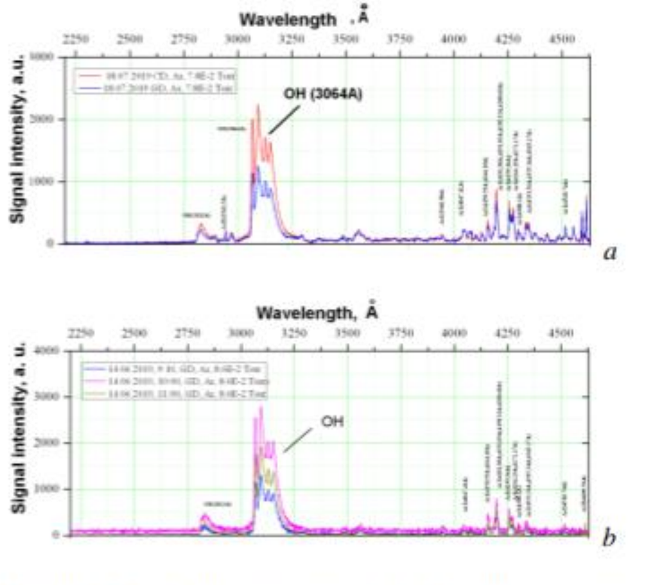


Fig. 16. Emission plasma spectra of glow and combined discharges during evacuation of the chamber by a fore pump (a); spectra of glow discharges vs a cleaning time

Setup design considerations

- *Diameter-to-length ratio*
- *Vacuum levels*
- *Plasma generation*
- *Costs*

Gas	Max pressure [mbar]
H_2	6.0×10^{-11}
CH_4	2.2×10^{-12}
H_2O	2.6×10^{-13}
CO	2.9×10^{-12}
CO_2	1.3×10^{-12}

Tab. 8; *Maximum ultimate partial pressures in the ET beam pipe after a 7-day bakeout at 150°C, following the layout presented in section 6.3.3. The ultimate pressures reported should be regarded as upper limits.*

Vacuum chamber

Plasma

Gas control

RGA

Safety

Pumps

Pressure sensors

Bake-out

Plasma source

Plasma head

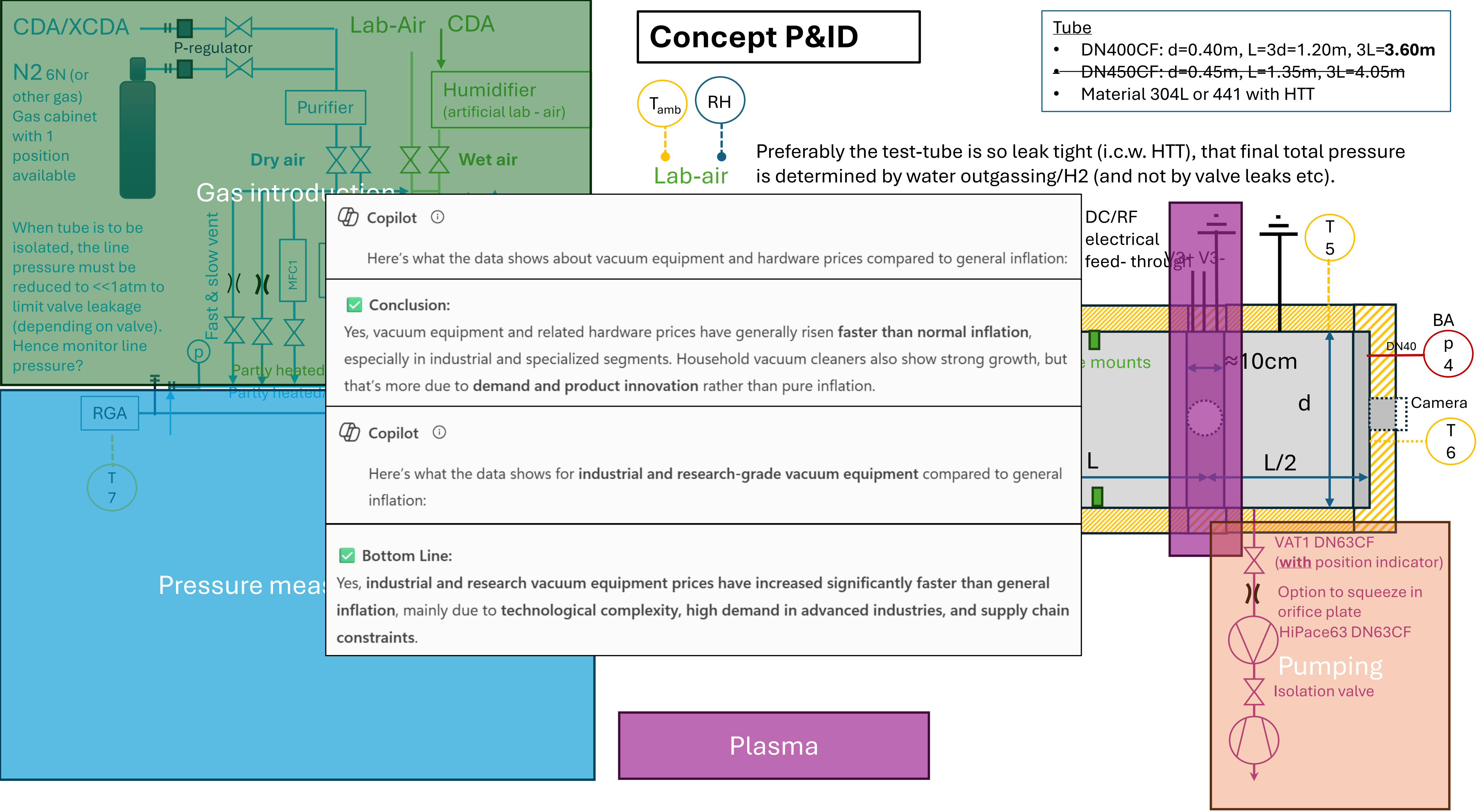
Recondition of wall

Control system

Concept P&ID

Tube
- DN400CF: d=0.40m, L=3d=1.20m, 3L=**3.60m**
- ~~DN450CF: d=0.45m, L=1.35m, 3L=4.05m~~
- Material 304L or 441 with HTT

Preferably the test-tube is so leak tight (i.c.w. HTT), that final total pressure is determined by water outgassing/H2 (and not by valve leaks etc).



Copilot ⓘ

Here's what the data shows about vacuum equipment and hardware prices compared to general inflation:

✅ **Conclusion:**

Yes, vacuum equipment and related hardware prices have generally risen **faster than normal inflation**, especially in industrial and specialized segments. Household vacuum cleaners also show strong growth, but that's more due to **demand and product innovation** rather than pure inflation.

Copilot ⓘ

Here's what the data shows for **industrial and research-grade vacuum equipment** compared to general inflation:

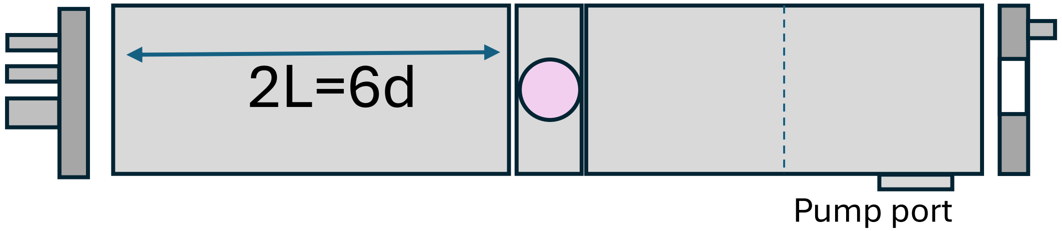
✅ **Bottom Line:**

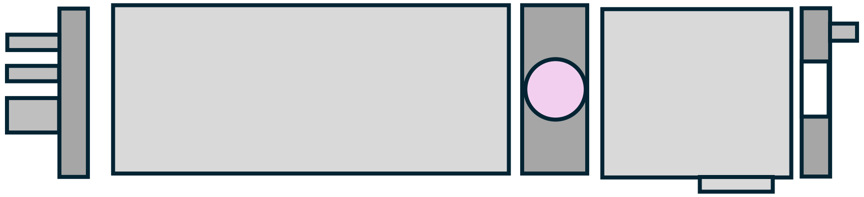
Yes, **industrial and research vacuum equipment prices have increased significantly faster than general inflation**, mainly due to **technological complexity, high demand in advanced industries, and supply chain constraints**.

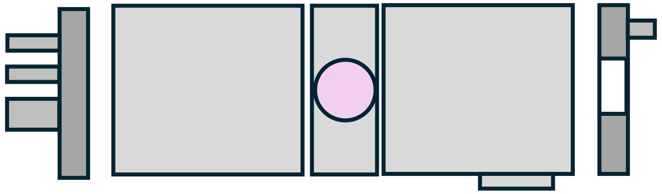
Reduced test tube configuration to drastically cut back on HW costs (02-04-2025)

- Introduce zero length viewports & electrode feedthroughs
- Reduce tube diameter 400mm→300mm
- One electrode section (extent plasma tested by varying the tube length)
- Inner diameter d=0.3m, section length (L=3d=0.9m) 2L=6d=1.8m, 4L=3.6m
- Tube sections separately bakeable
- With preferred option we can realize tube length 2L and 4L with symmetric plasma (thus test extent plasma)

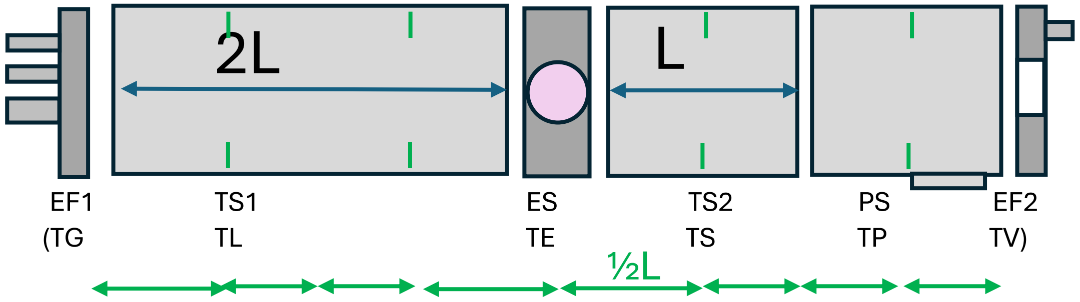
Options







Preferred option

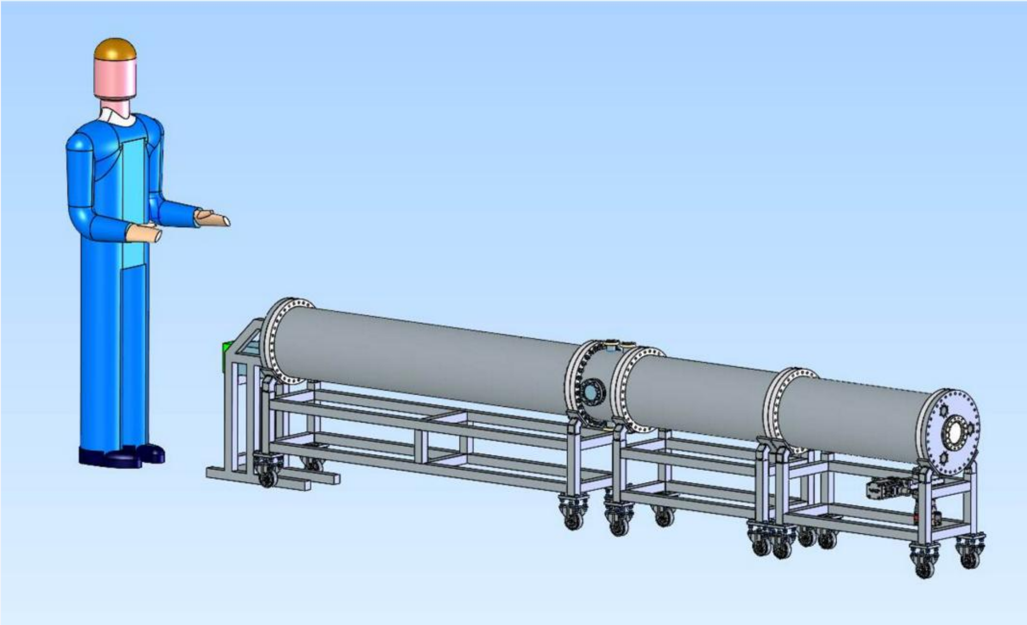


Tube sections/components

EF1	End Flange 1	(TG	Gas flange)
TS1	Tube section 1	(TL	Long tube)
ES	Electrode section	(TE	Electrode section)
TS2	Tube section 2	(TS	Short tube)
PS	Pump section	(TP	Pump tube)
EF2	End Flange 2	(TV	Viewport flange)

Vacuum chamber

- Vacuum fired AISI 304, cold rolled 2H finish
- Total length 3,6 meters (excluding frame)
- 4 configurations possible
  - Need to validate efficiency of plasma at varies distances from plasma source

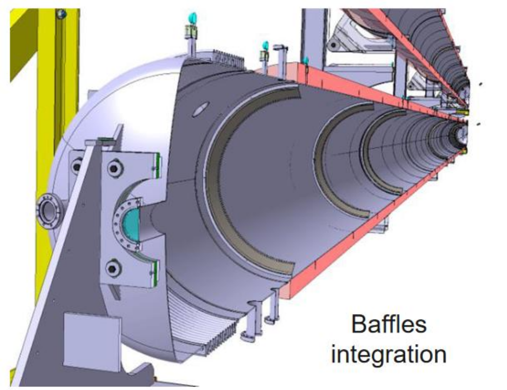


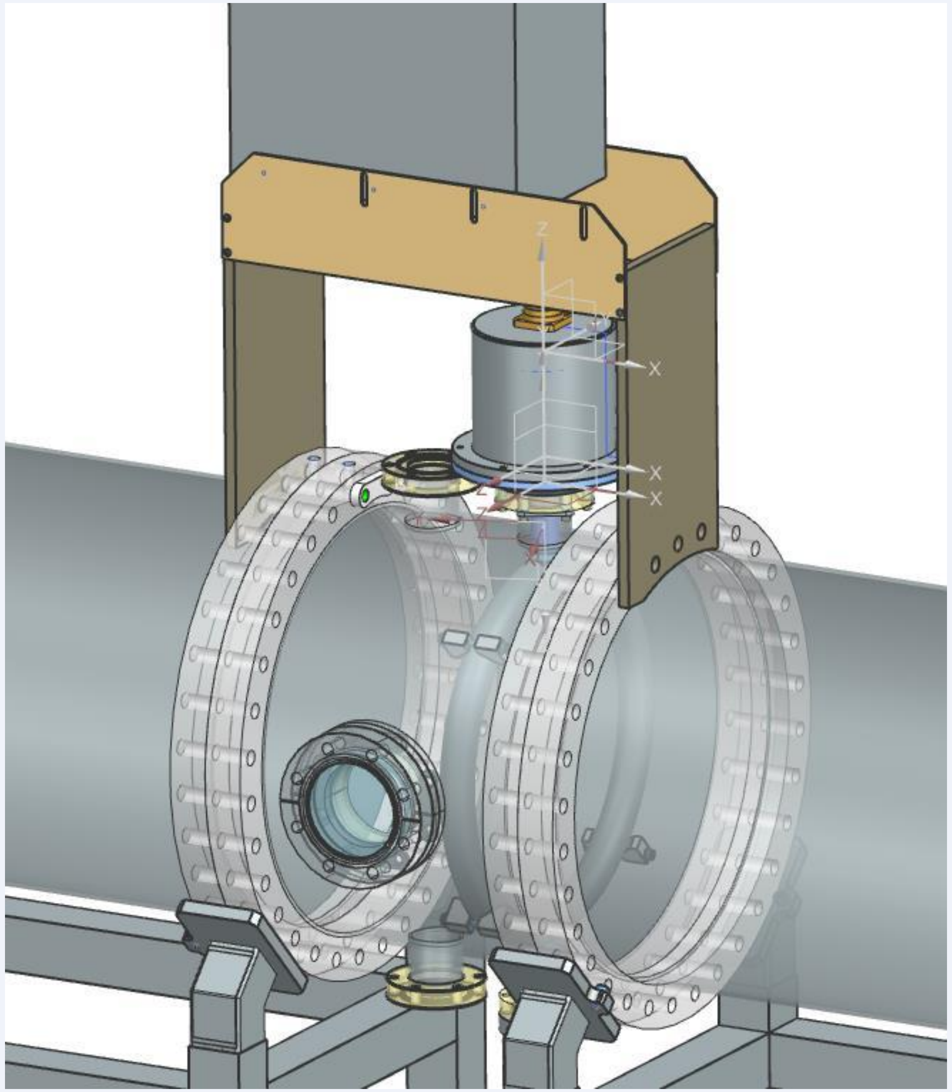
Plasma

- Long list of 10 plasma “types”

- Selected
  - RF 13,56 Mhz
  - DC Plasma
  - Or combined

- Shape of plasma antenna will ensure it will stay out of the beam path

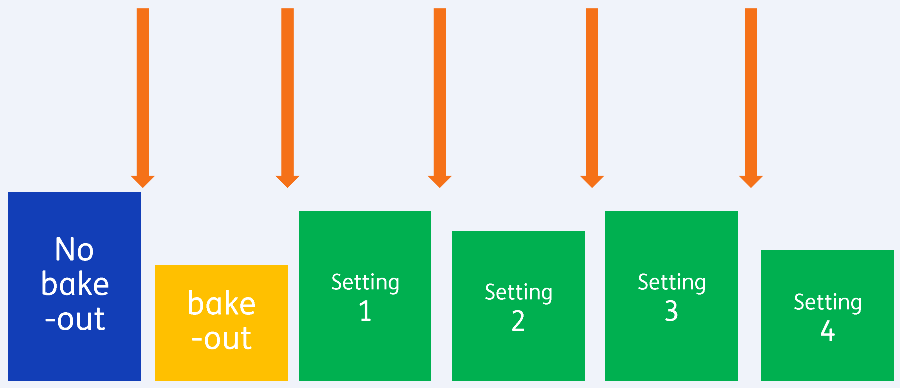




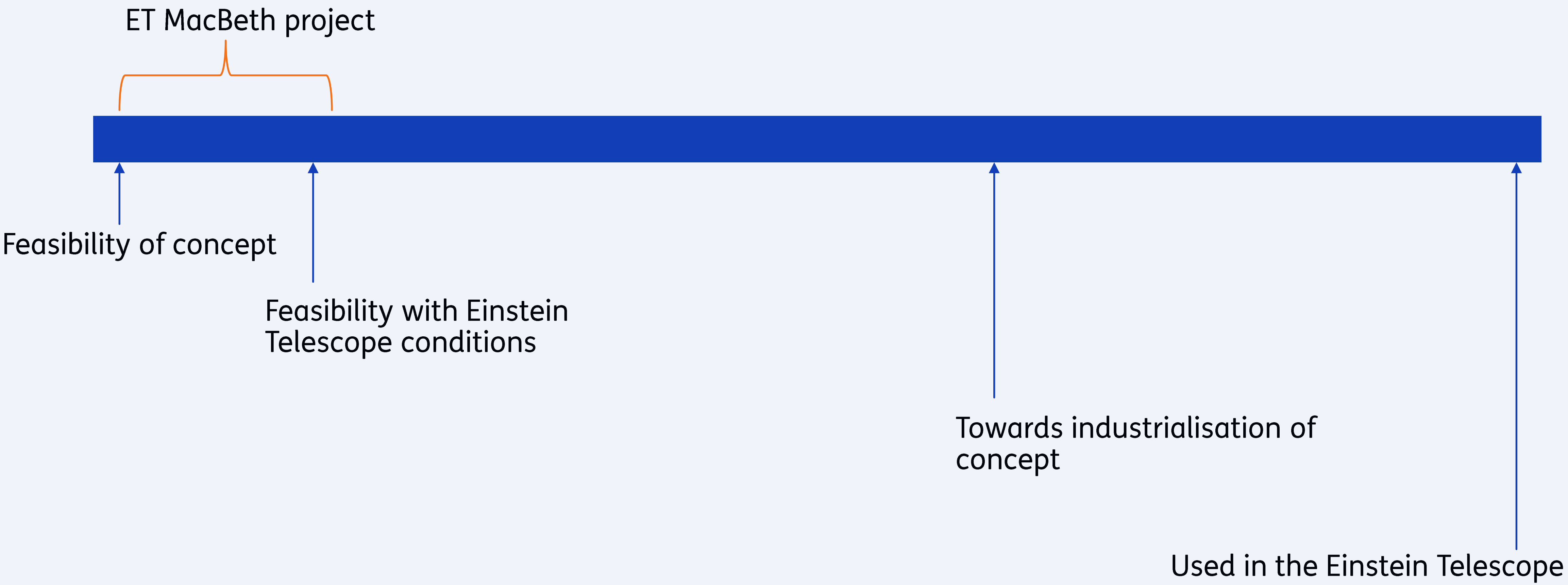
Experimental plan

- Total project has two experimental phases
  - “fundamental”
  - “towards Einstein Telescope”
- During the fundamental phase we look at parameters like
  - Pressure
  - Plasma source
  - Plasma settings per source
  - Process gas? (default is N2)

  “no limits”
- Efficiency of a setting is compared to 1 week bake-out @150°C
- During the “towards Einstein Telescope” phase we start limiting the parameter scope and
  - Increase measurement accuracy



Time-line


ET MacBeth project
Feasibility of concept
Feasibility with Einstein Telescope conditions
Towards industrialisation of concept
Used in the Einstein Telescope

Outlook and conclusion

- Hardware is currently arriving
- Installation is ongoing
- Validation of total setup to start in Oktober 2025

- Experimental risk
  - Cleaning efficiency of surfaces far away from plasma source
- “High risk, high gain” project
  - Fits well with the “yet to be invented technology” statement that is commonly used within the Einstein Telescope community

- A lot of experimental work ahead of us

Thank you for your attention

Acknowledgement

Part of this work is funded by the Dutch R&D technology domain Einstein Telescope initiative

"LIGO" - Director's Cut

TNO innovation for life