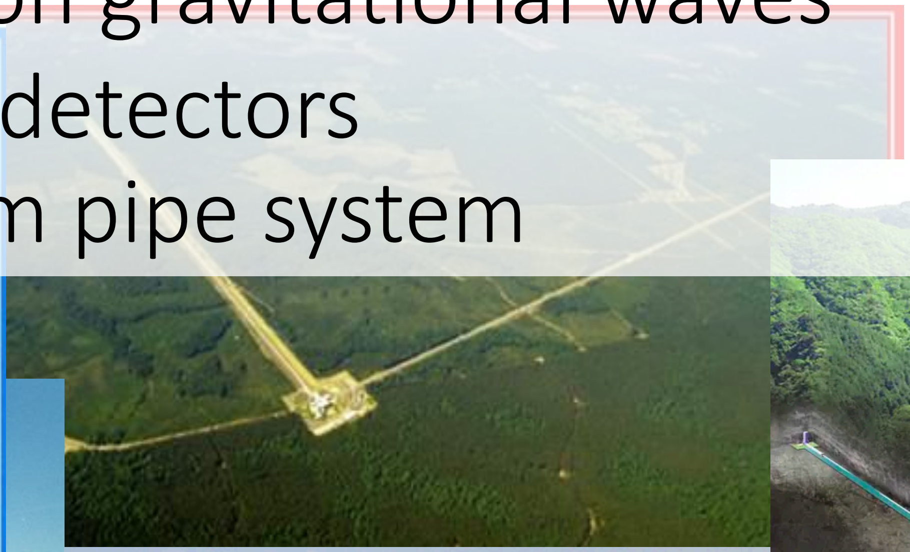
2° generation gravitational waves detectors
beam pipe system



Aniello Grado

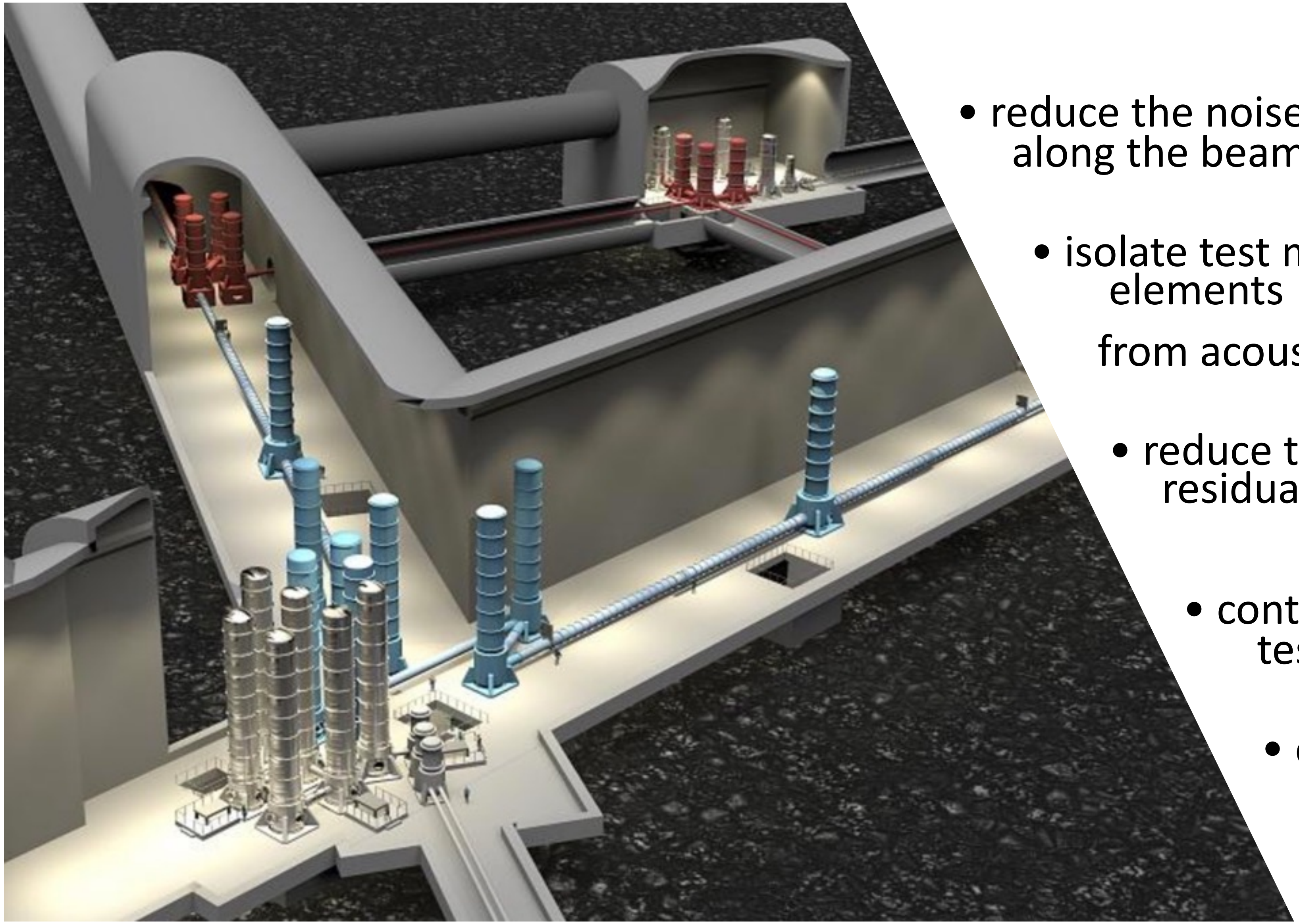
March 27th 2023, CERN

Credits:
A. Pasqualetti, C. Bradaschia, H. Lueck, R. Weiss,
M. Zucker, F. Ricci, Y. Saito,

SUMMARY

- Why UHV needed
- Recall UHV requirements for ET
- Vacuum pipe experience on 2G detectors
  - LIGO
  - Virgo
  - GEO600
  - KAGRA
- Some thought/considerations

Why GW detectors under vacuum?



- reduce the noise due to residual gas 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 residual gas fluctuations,
- contribute to thermal isolation of test masses and of their support structures;
- contribute to preserve the cleanliness of optical elements.

Effect of gas pressure on detector sensitivity

Fluctuations of residual gas density induces a fluctuations of refractive index and then of the laser beam optical path

$$S_L\left(f\right) = \frac{\left(4\pi\alpha\right)^2}{v_0} \int_0^L \frac{\rho\left(z\right)\ \exp\left[-2\pi f\ w\left(z\right)/v_0\right]}{w\left(z\right)}\, dz$$

- Power spectral density fluctuations of optical path ($S_L(f)$)
- Gas optical polarizability (α)
- Interferometer arm lenght (L)
- Molecules number density ($\rho(z)$)
- Average molecules speed (v_0)
- Laser beam gaussian radius ($w(z)$)

S. E. Whitcomb, Optical Pathlength Fluctuations in an Interferometer Due to Residual Gas (California Institute of Technology, Pasadena, 1984)

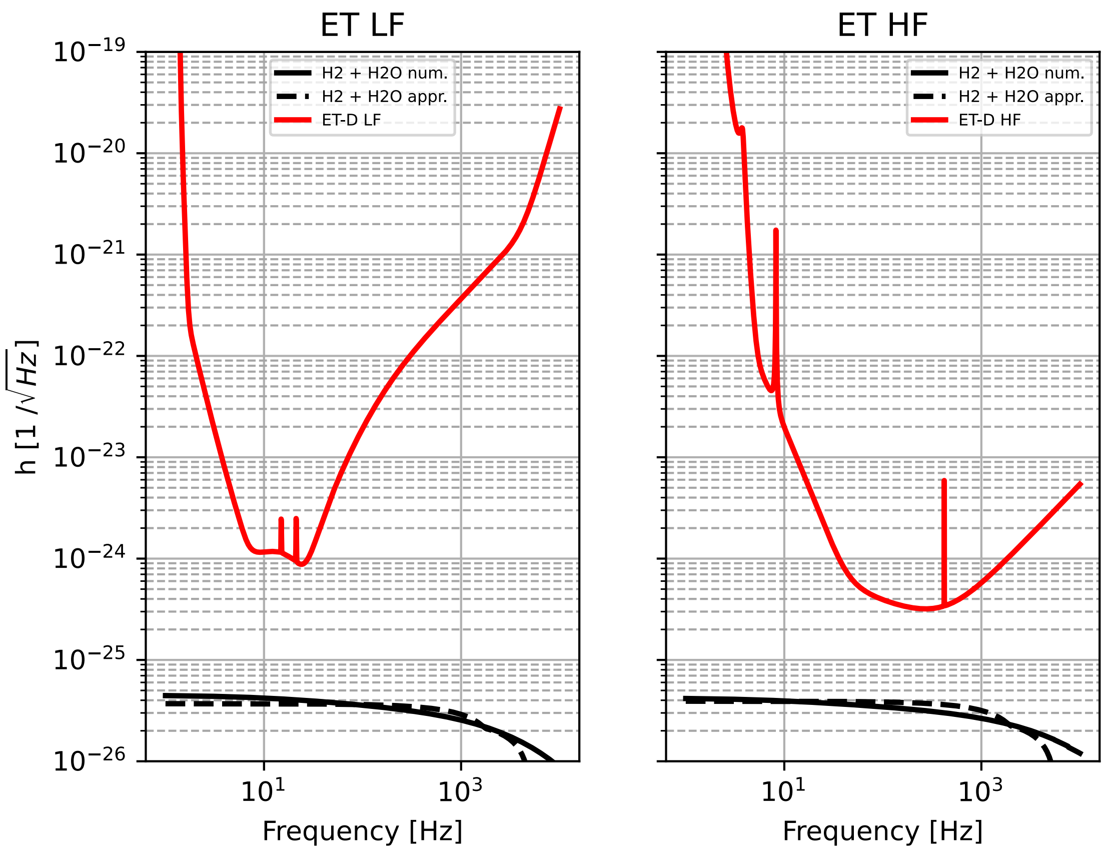
ET beam tubes vacuum requirements

- Tube diameter ~ 1m
- Total lenght 120 km

Surface: 3.8×10^5 m^2
Volume: 9.4×10^4 m^3

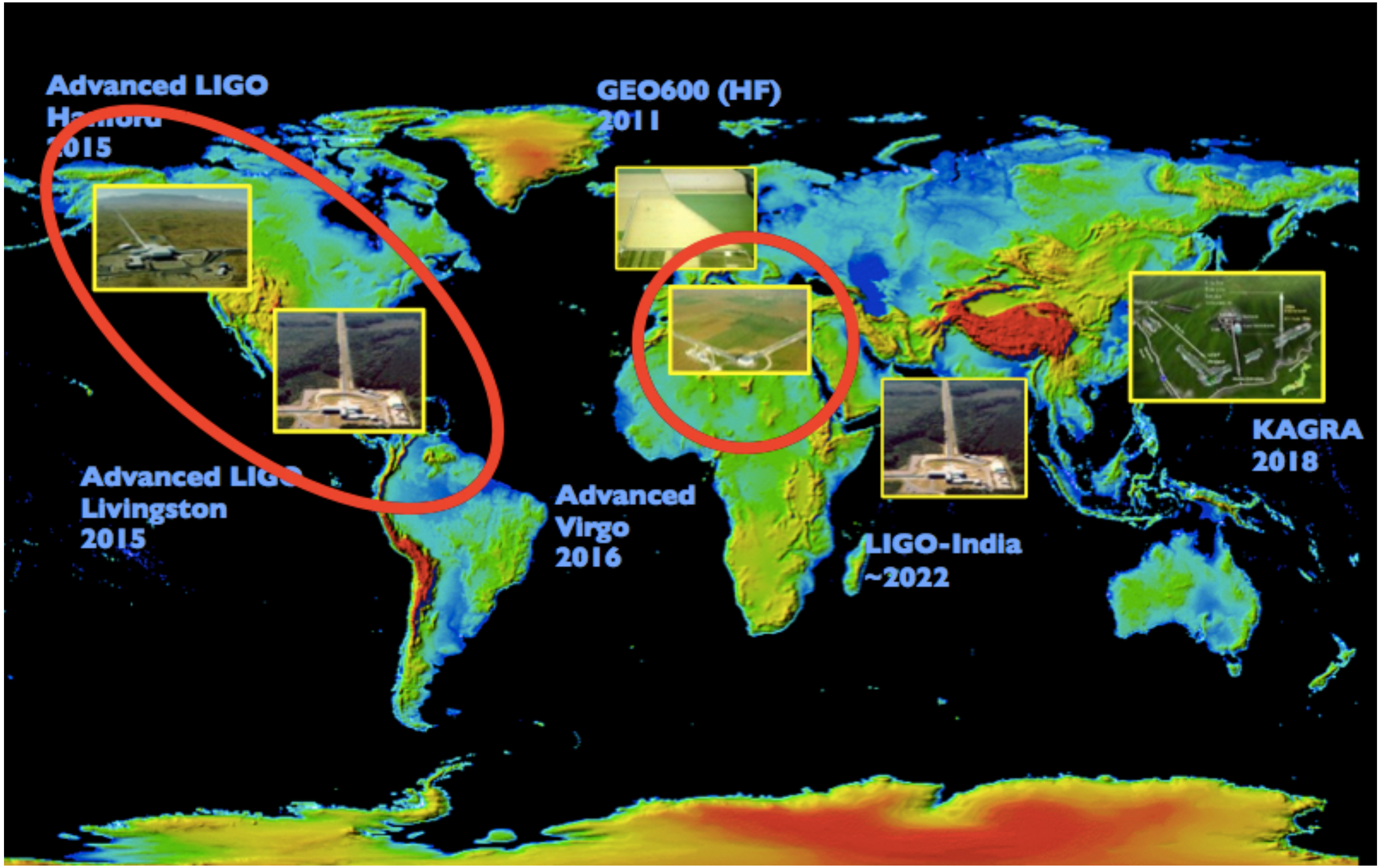
Gas species	Outgassing rate $mbar\, l/s\, cm^2$	Pressure max mbar	Noise LF $1/\sqrt{Hz}$	Noise HF $1/\sqrt{Hz}$
H_2	1.9×10^{-14}	1×10^{-10}	2.9×10^{-26}	2.4×10^{-26}
H_2O	2×10^{-15}	2×10^{-11}	2.9×10^{-26}	2.3×10^{-26}
N_2	2×10^{-17}	2×10^{-13}	3.7×10^{-27}	2.8×10^{-27}
CO_2	1.5×10^{-16}	2×10^{-12}	1.6×10^{-26}	1.2×10^{-26}
C_2H_4	1×10^{-17}	1×10^{-13}	6.3×10^{-27}	5×10^{-27}

Assuming a margin of 9 for ET-HF and 20 for ET-LF



Grado et al. JVST B, vol. 41, issue 2, p. 024201, 2023

GW DETECTORS IN THE WORLD

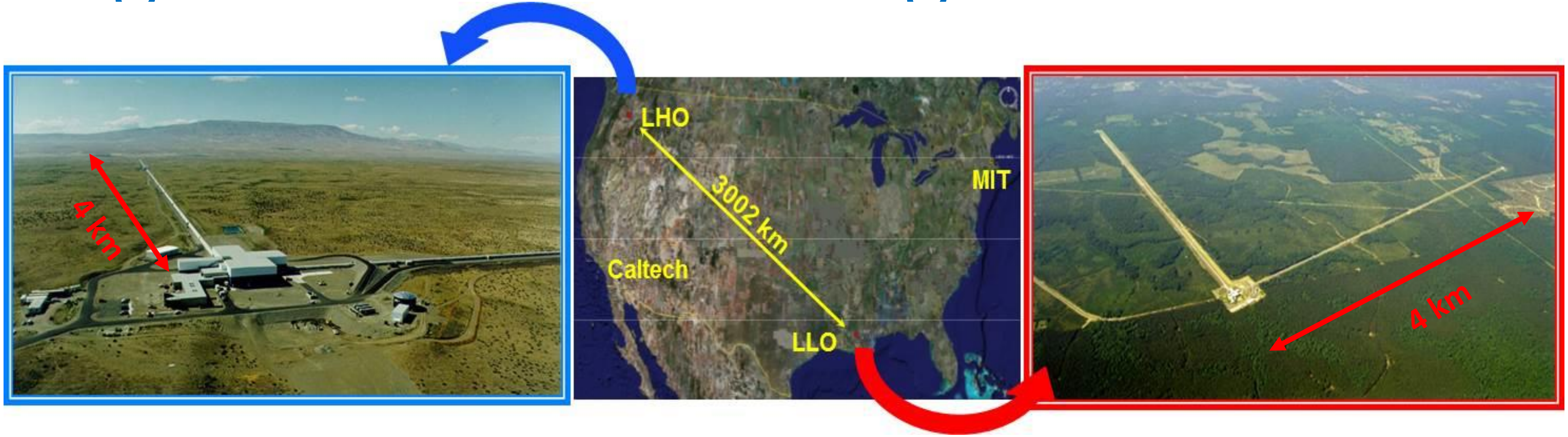


Beampipe realization

- Pipe modules manufacturing
- Cleaning
  - Careful cleaning to remove dusts and non-volatile hydrocarbon contamination (ultrasound, hydrokinetic ….)
- Air-firing
  - High temperature (400 - 450 ^oC) in oven with dry air flux in order to remove the H from bulk material. Factor ~100 depletion of H_2 content. Permanent
- Installation
- Bake-out
  - Treatment at ~150 -200 ^oC in-situ under vacuum to remove the tightly bonded H_2O from the surfaces. If vented to air needs to be repeated

QA

Ligo HANFORD and Ligo LIVINGSTON



For each detector

- 2 x 4 km beam pipe
- 1.2 m diameter
- 9047 m^3 volume
- $3x10^4$ m^2 inner surface
- ~ 10^{-9} mbar

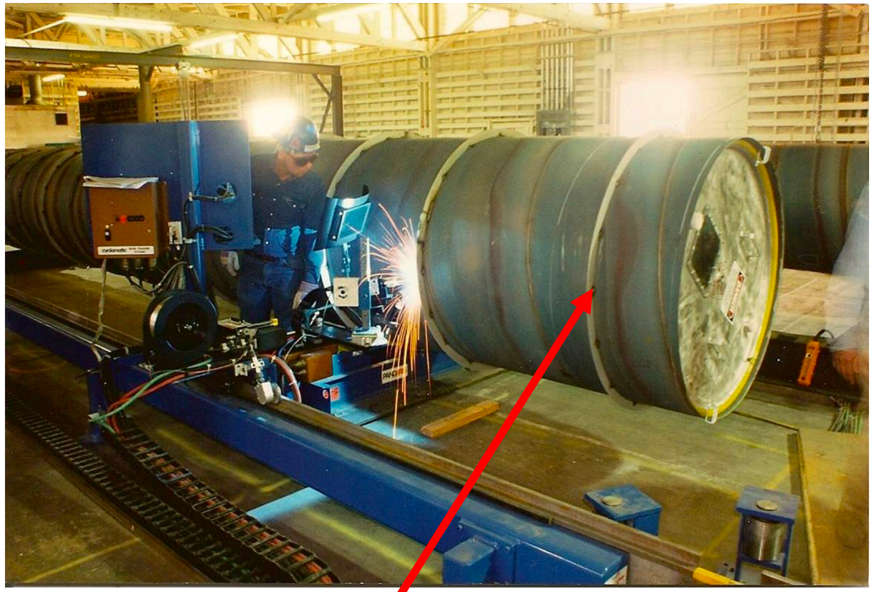
Credit LIGO Collaboration

LIGO beam pipe production

Coupon tests were performed to establish the low hydrogen outgassing of each coil of steel used in fabricating the tube.

- 304L Stainless Steel
- 3.2 mm thick with stiffener rings each 76 cm
- Air fired coil at 455 °C for 36 hours
- Spiral welding to produce 1.2 m diameter 16 m tube module

Every 250 m a DN250 port with UHV valve for pumping and diagnostic

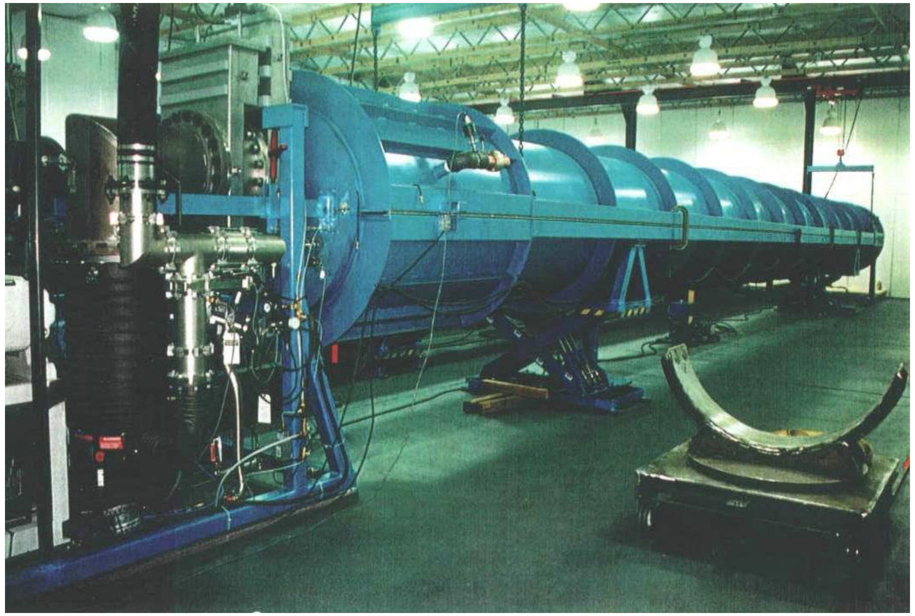


Stiffener ring welding

L. Buboltz, K. Drake, V. Gervais, R. Johnson, L. Jones, S. Peters, M. Tellalian, and R. Weiss, "LIGO beam tube module design, fabrication & installation," in 9th International Conference of Pressure Vessel Technology (2000), p. 797.

Cleaning and checks

Helium leak test of module



Each module leak tested to better that $1x10^{-10}$ mbar l /s. Around 8 hours needed for each test!!

Sections butt welded in travelling clean room

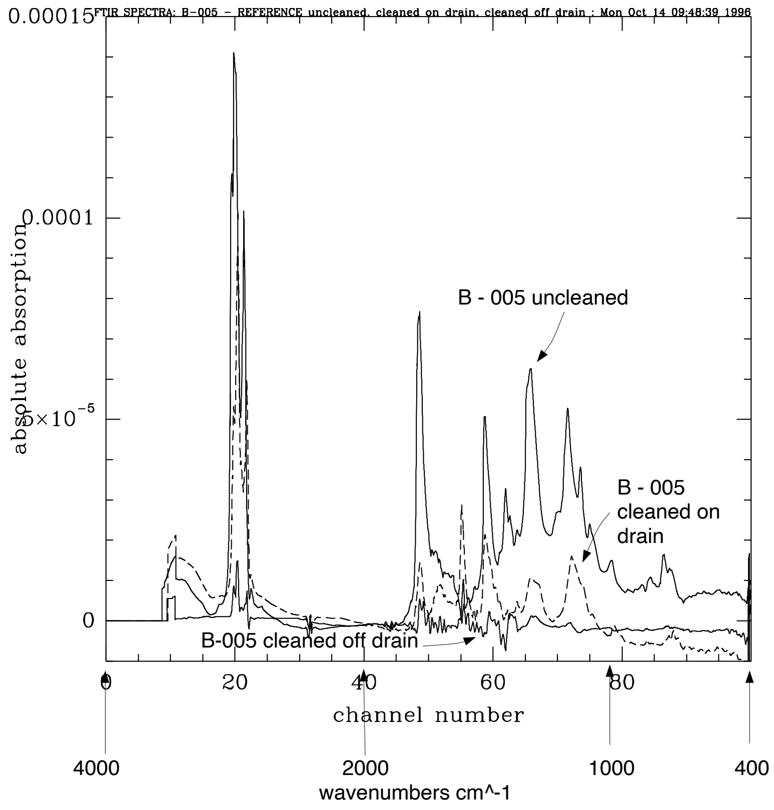
leak test

Section cleaning: steam + water + detergent followed by FTIR check to assess hydrocarbon contamination level

Adopted Standard: **IEST-STD-CC1246D**, *Product Cleanliness Levels and Contamination Control Program*

Beam Tube Cleaning

- Cleaning steps
  - ›› Hot water and detergent - Mirachem 500 spray wash
    - – 30/1 water/Mirachem - 500
    - – 1 cc/ cm^2
  - ›› Steam rinse
    - – 2 cc/ cm^2
    - – 7 - 8.5 atmospheres pressure
    - – 58 - 65 C surface temperature of steel
  - ›› Applied by rotating wand that traverses the tube longitudinally at 20 cm / minute
- Surface analysis
  - ›› Fourier Transform Infrared Spectroscopy FTIR
    - – Sample taken by pouring 2 - isopropanol in strip down tube
    - – Analysis made in professional testing laboratory

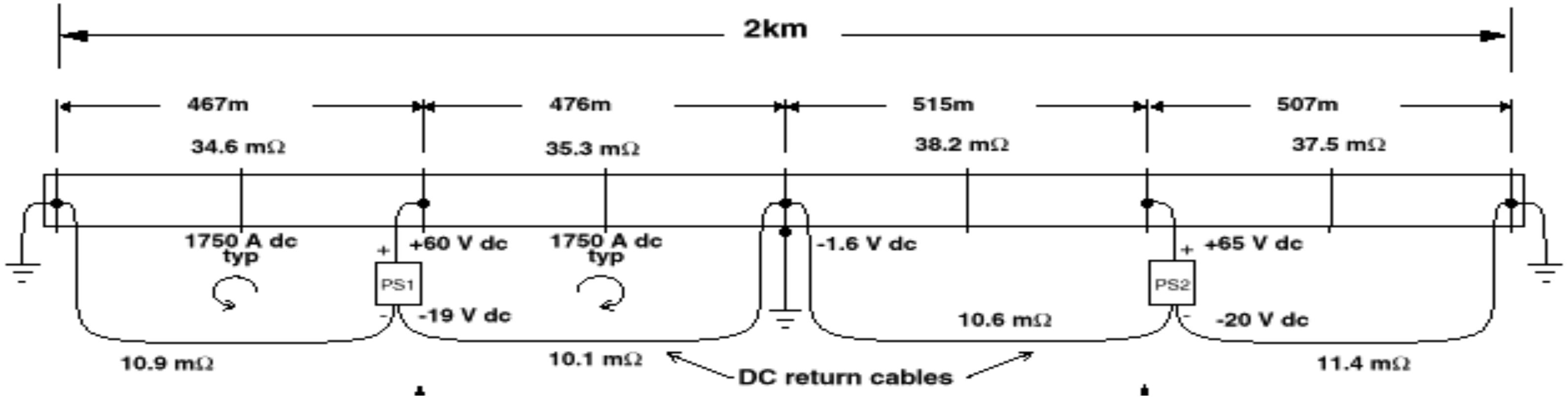


Spectra of tube B-005 uncleaned, and cleaned with sample taken along and off the drain line. The off drain sample is more characteristic of the average wall condition. The spectra have had the reference spectrum of the isopropanol subtracted, hence the negative values of the absorption.

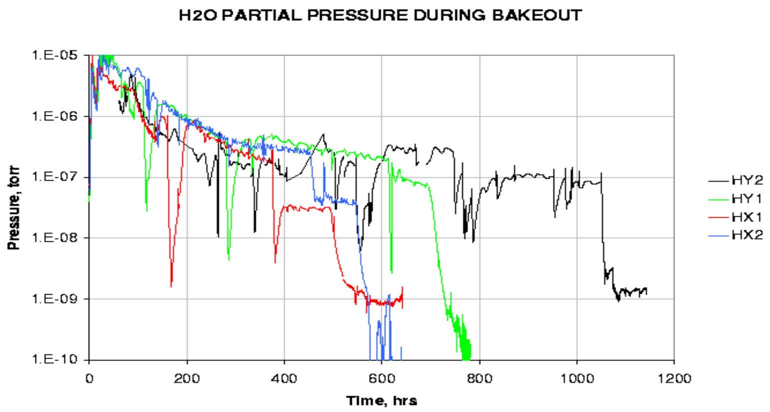
R. Weiss 2003

Joule effect beampipe bakeout to desorb water

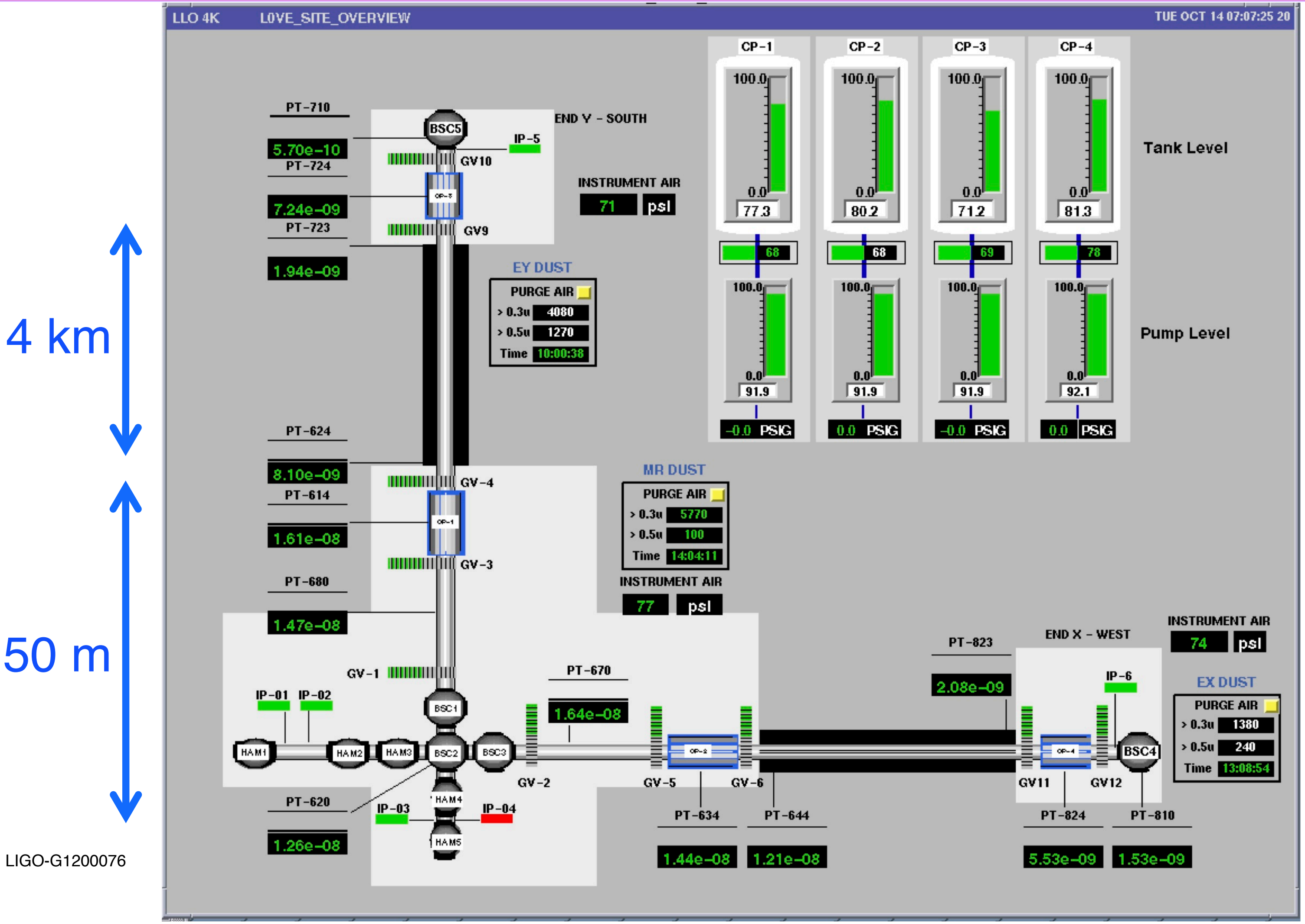
- Glass wool insulation
- I_{DC} = 2,000 A
- ~ 3 weeks @ 160ºC
- Final J_{H_2O} < 2e-17 Tl/s/cm²
- Tubes never to be vented



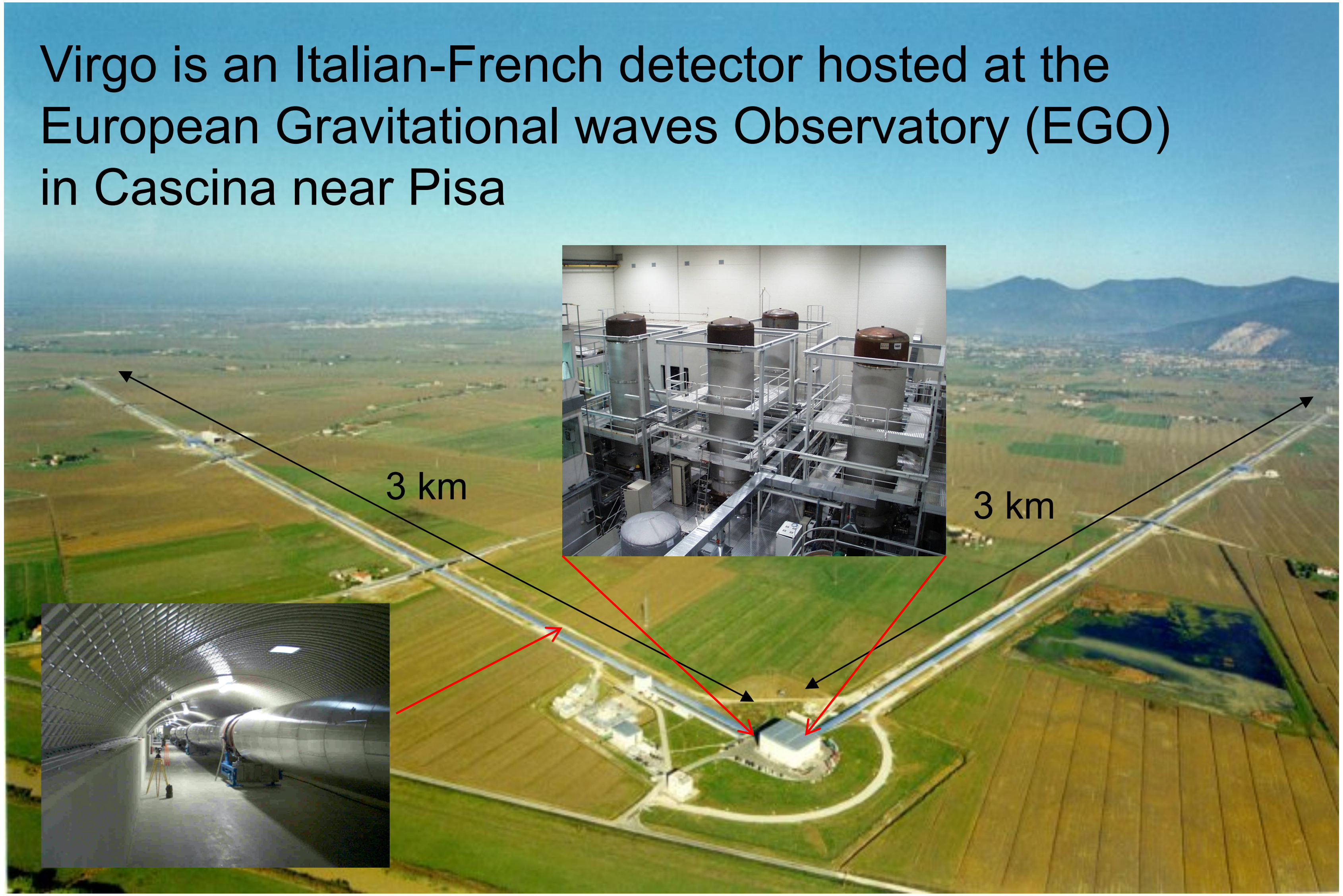
Temporary cryopumps were used during bakeout 17, places, removed after bake



Vacuum System Schematic



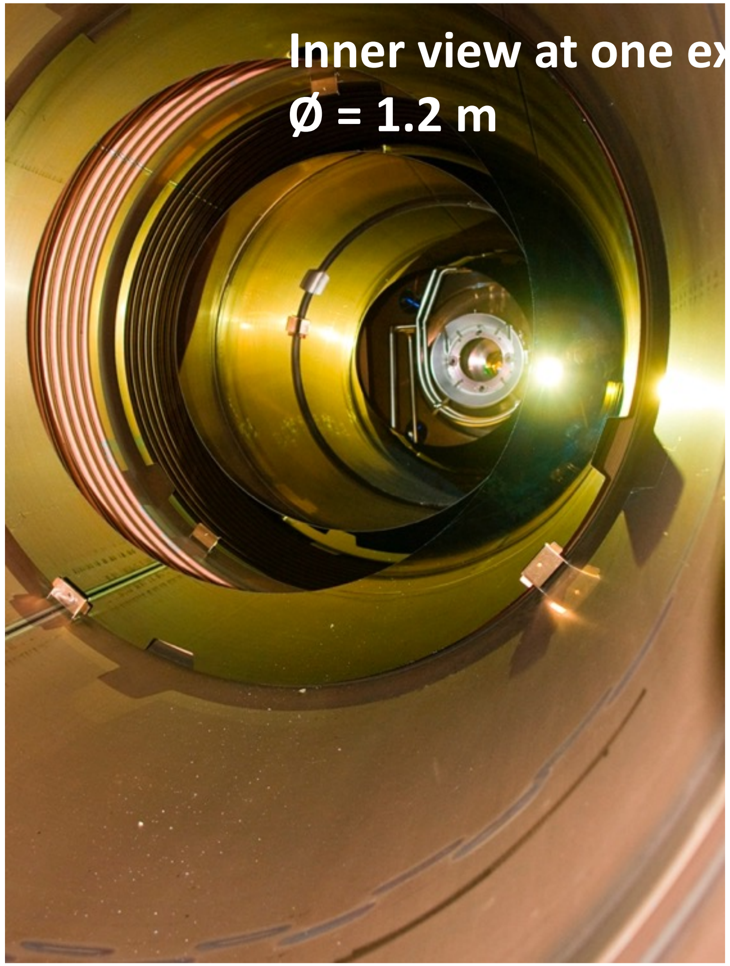
Virgo is an Italian-French detector hosted at the European Gravitational waves Observatory (EGO) in Cascina near Pisa



Thanks to **A. Pasqualetti** and his team for providing slides and info

Virgo 3 km UHV TUBES

- 24000 m^2 walls!
- They contain "only" optical baffles and the laser beam



Courtesy: A. Pasqualetti

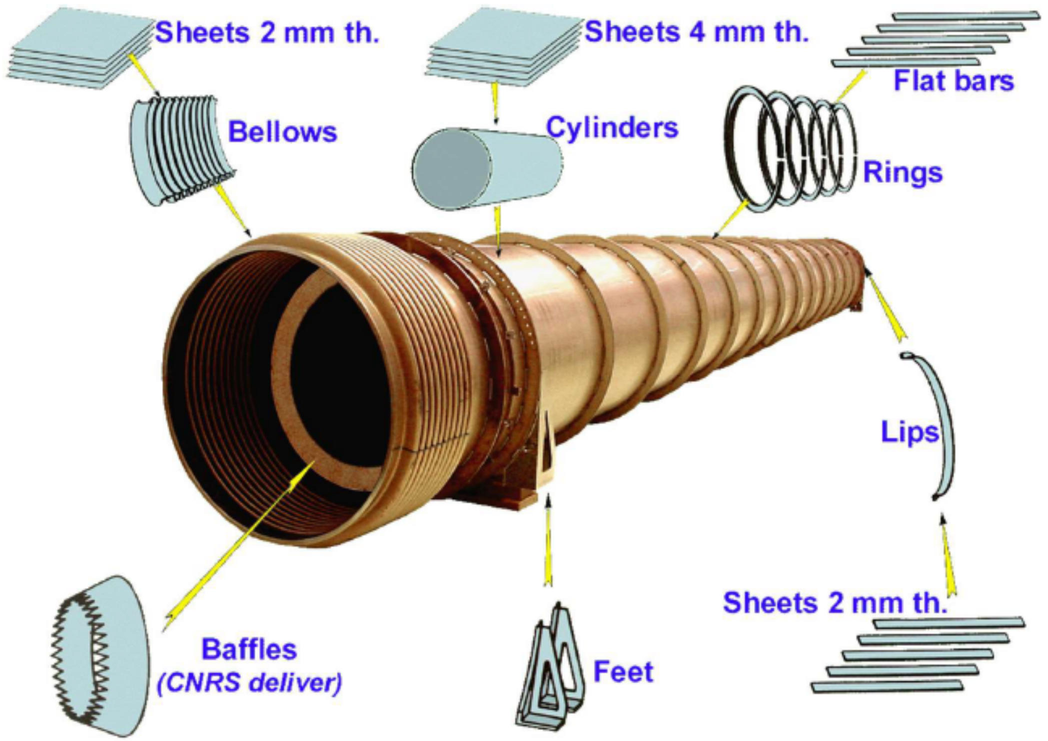
Virgo Sections manufactoring

Technical requirement:

- 404 modules (2 x 3 km)
- Leak rate: 3.10^{-10} mbar.l.s^{-1}
- Dimensions: L 15 m x Ø 1.2 m
- Thickness: 4 mm
- Material: 1.4307 (SS304L)

Schedule requirement:

- Workshop ready: 10 months
- First-of-a-kind: 2 months
- Serial units: 1 section/day



Courtesy CNIM

V. Brisson, J. Hoang, G. Lissilour, P. Marin, A. Reboux, M. Bernardini, and A. Pasqualetti, Vacuum 60, 9 (2001).

The Virgo experience
TUBE manufacturing

-304L cold rolled sheets / solution annealed - surface finish 2B (EN1.4307 by Avesta S.)

'Conventional' industrial tools, rate = 1 section / day (it took about 2 years).
- section realized in 3 consecutive cylinders plus the hydroformed bellows.
- UHV recipes (specific machining oil, dirt free rolling, separated halls and tools, ...)

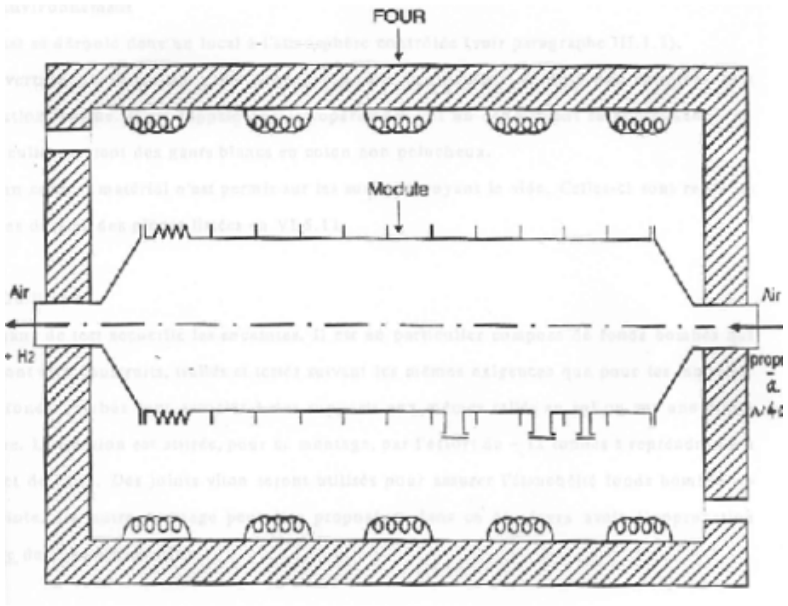
DUST CONTROLLED WORKSHOP

Virgo experience: AIR-FIRING

Base material conditioning was required to meet vacuum goals (24000 m^2 walls).

heating at ~ **400°C in air** involved a ''simple'' oven and reduced the hydrogen outgassing by a factor ~ 100; our result: **$q(H_2) \leq$ 3E-14 $mbar.l.s^{-1}cm^{-2}$ @ 20°C**

The industrial specification was: $q(H_2)$ = 5E-14 - NOT CONTRACTUAL -



- <u>Applied to finished modules</u>
- Electrical oven, 'sealed' section
- 410°C +20/-10 , plateau 72h
- Hot air purge 8 m^3h^{-1}
- 5 days long cycle
- H content raw mat. ≤ 2 ppm wt - CONTRACTUAL -

Courtesy: A. Pasqualetti

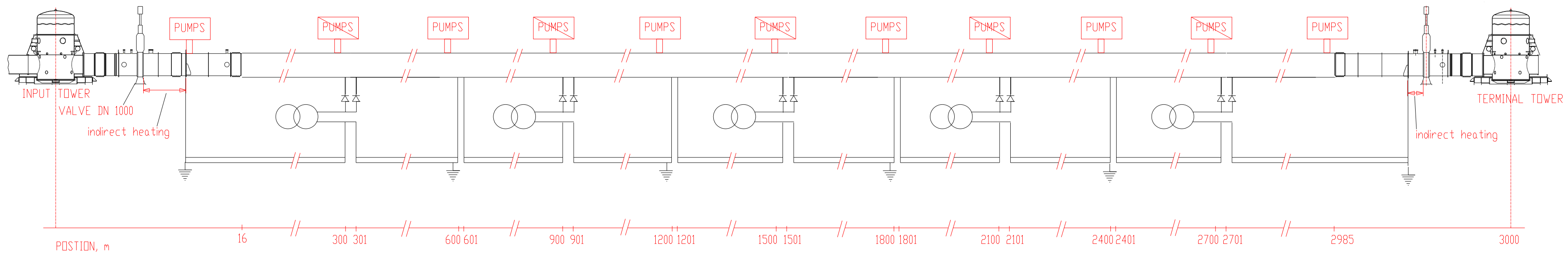
TUBE LOGISTIC

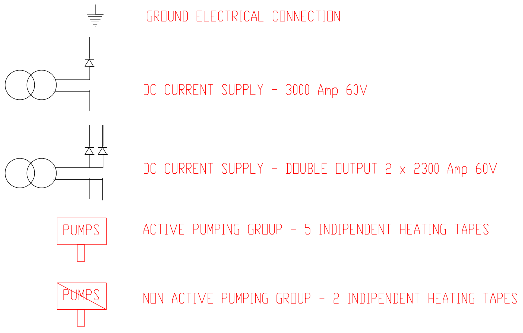
Transportation (resp. transfer), sealed packaging and modules respiration along the trip, storage needs, thermal insulation installation. Rate up to 30 m / day (2 modules)

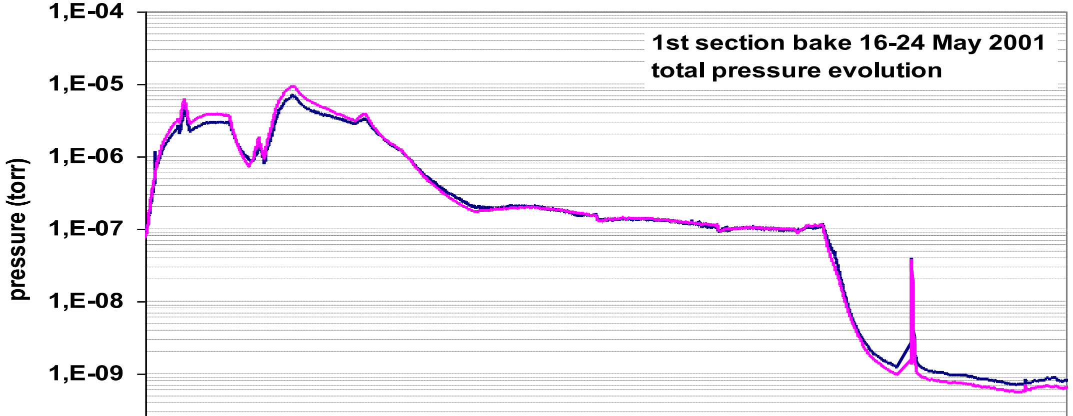
Virgo TUBES: BAKE-OUT in situ

- Chamber at 150°C uniform and at a controlled rate (~1 week for SAT stage)
- 1 Mwatt to heat one tube (15 cm thick thermal insulation)
- Joule effect: 2000 A flowing through tube walls
- diesel generators: ~ 10^5 litres of fuel to bake one tube

Normally to be performed just one time.

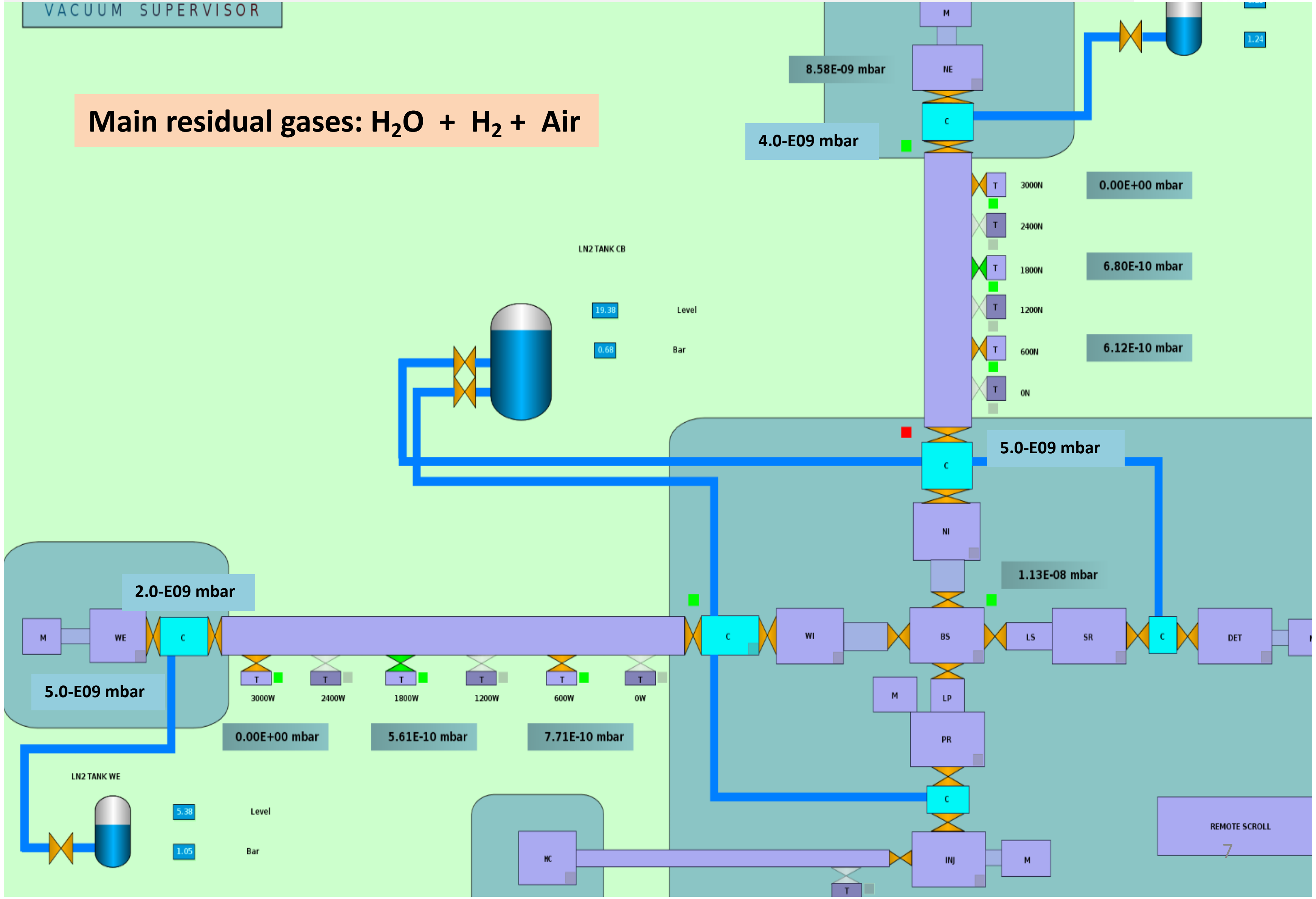






SNAPSHOT of the vacuum level

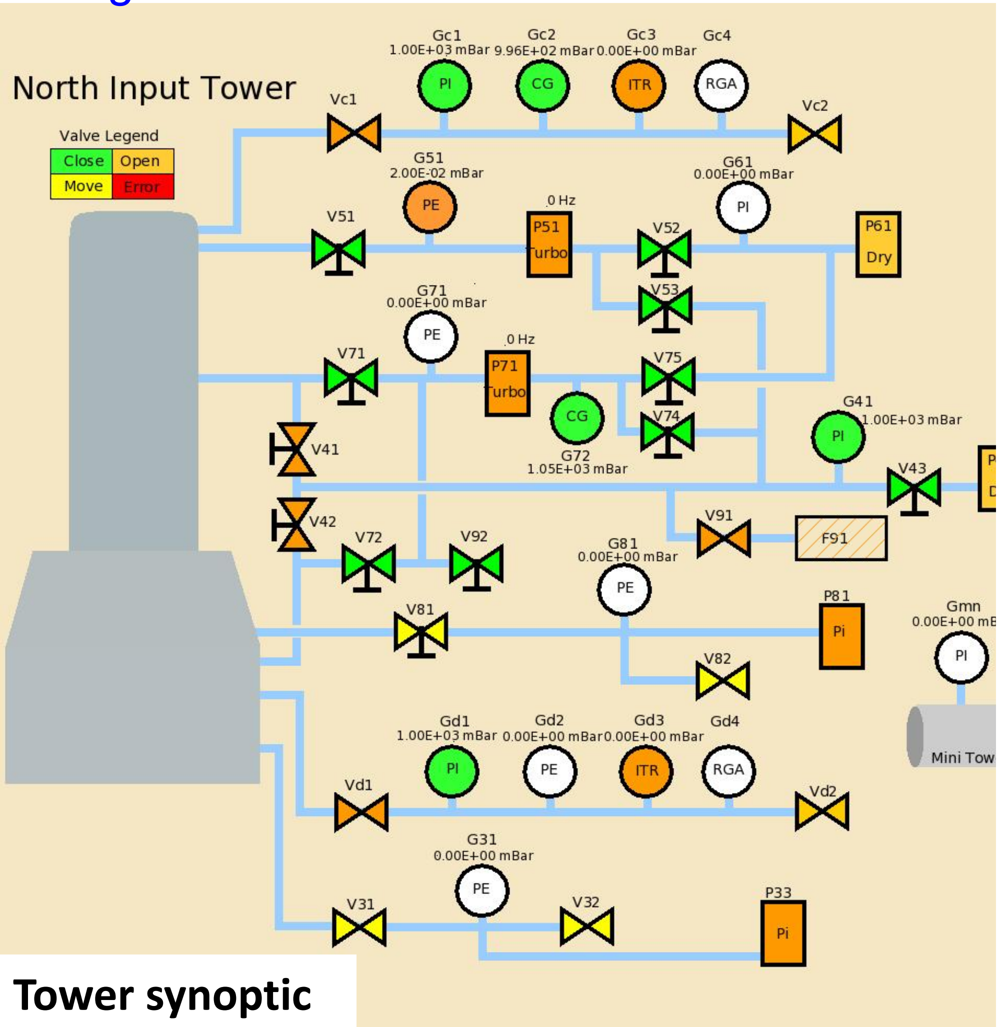
Main residual gases: H_2O + H_2 + Air



PUMPING SYSTEM

Main requirements: oil free pumps against contamination risk, low acoustic / seismic / magnetic emissions , long maintenance intervals to care for duty cycle.

Gauges .



Tower synoptic

Statistic (not updated)

22	Roughing/backing dry pumps
21	Turbo-molecular pumps
28	Ion pumps
38	Titanium sublimation pumps
20	Residual gas analyzers
221	Angle valves
111	Gate valves
4	Large valve ø=1000 mm
153	Gauges

GEO 600

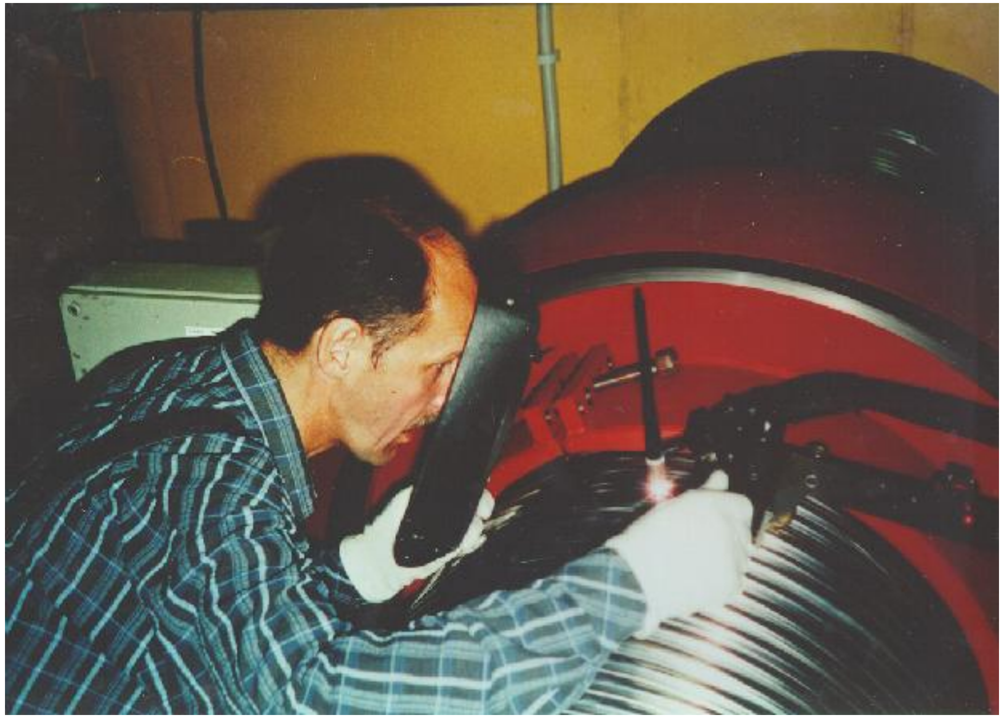
Technology development center for GW detectors

Beam Tubes

- Stainless Steel
  1.4429 (316LN), cold rolled
- 60 cm ID
- 0,8 mm wall thickness
- 2* 133* 4,5m modules (~85kg each)
- 30 mm wave period; semi-circular
- total weight 2* 12 t

H. Lück and GEO600-Team, “The vacuum system of GEO600,” in Second Edoardo Amaldi Conference held in CERN, Switzerland, 1–4 July 1997. edited by E. Coccia, G. Veneziano, and G. Pizzella (World Scientific, River Edge, NJ, 1998), p. 356.

Orbital welding machine
Welding tool fixed
Tube rotating



Only 85 kg
per module

Trolleys on an aluminum rail to allow pushing outwards the tube after section welding

First segment of
tube being
pushed into the trench

Installation of the tubes

June 1996

600m rail

(later used as current return path during bake out)

Post production

Isolation: 20cm rockwool Heating: 300V/600A DC
0.5 Ohm/ 600m → 800 mΩ/km

= 180kW → 300W/m

- Passivation in air
  (dried with silica gel):

  2 days @ 200°C

- Vacuum bake:

  5 days @ 250°C

- Leak tests:

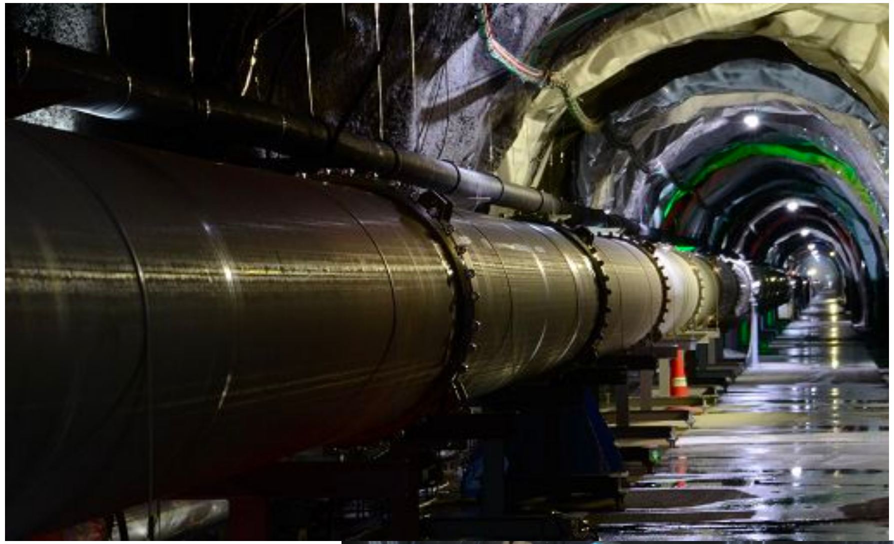
Wrap 3m section of plastic foil around the tube and flush with He.
Observe with RGA @ tube ends.
Reaction time < few seconds. Very sensitive…
5 leaks in total.
Fixed with Ceramabond. Some welded

KAGRA

3 Km arms, underground, criogenic GW detector in Japan

Artist's impression of the KAGRA gravitational-wave detector inside the Ikenoyama mountain in Kamioka, Japan. © KAGRA

Location put sever constraints to the detector realization



Location put sever constraints to the detector realization

- Water in the tunnel
- Limitation on power stations and ventilation

No possibility to weld underground and bake-out !!

This forced to use expensive solution:

flanged modules
electropolishing

- 500 x modules 800 mm diameter, 12 m long, 8 mm tick with flanges and bellows
- To reduce outgassing: "*surface passivation process*" of stainless steel prior to installation was done by applying ***electro-polishing***, and then followed by ***pre-baking treatment***

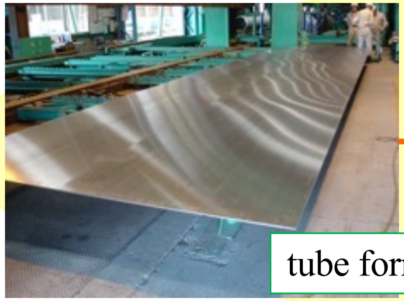
KAGRA

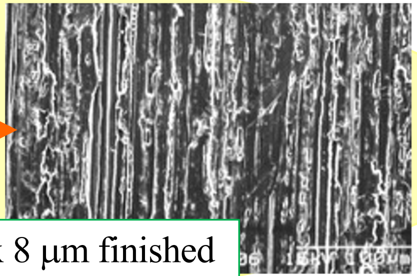
4. Production Process and Installation

** surface finish of tubes and chambers*

** flange and gasket*

unit tube of 12-m long and 0.8-m in diameter

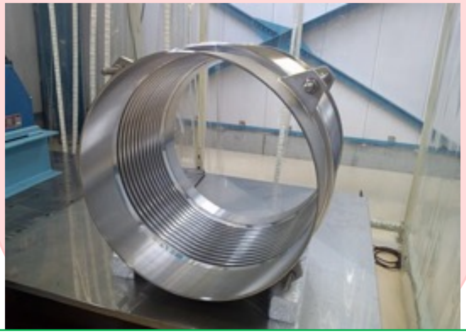




tube forming; SS304L, 8 mm thick, Rmax 8 µm finished

Yoshi Saito et al., JVSJ, Vol.54, No.12, pp.621-626 (2011)

flange; SS F304, Rotary forging

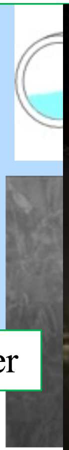


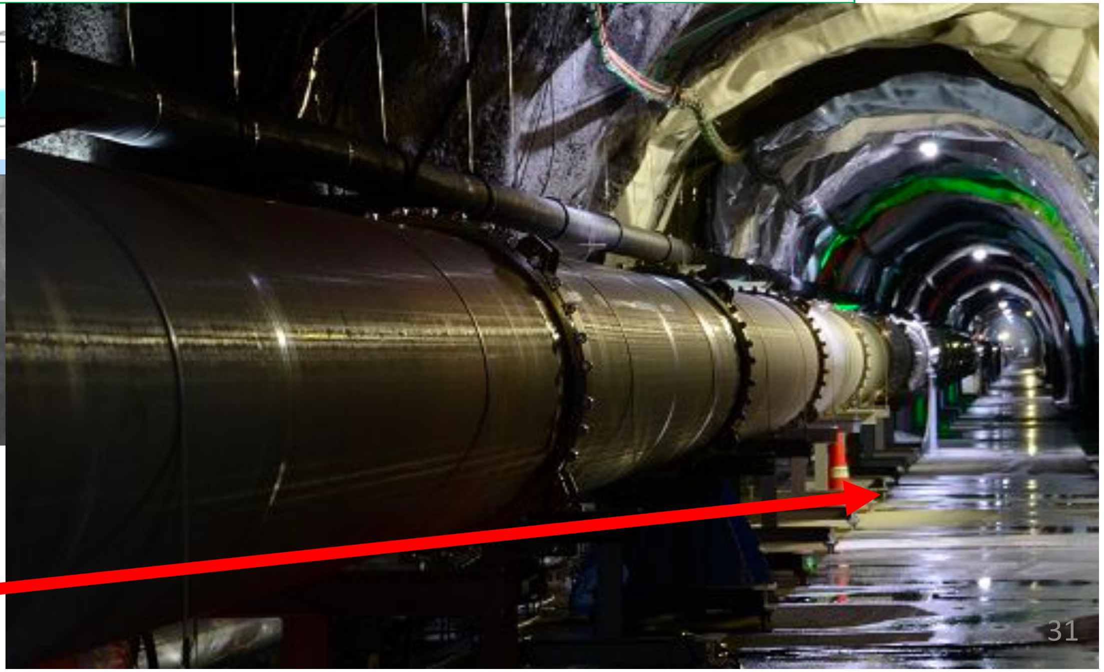
hydro-formed bellows;
SS316L, 0.6 mm thick, chemical polished

TIG-weld Assy

removing 25 µm of outermost layer

electrolytic polishing (EP) and rinsing with ultra pure water;
Rmax 2.5 µm





Credits: Yoshi Saito

Very harsh conditions: 95-99 % humidity !

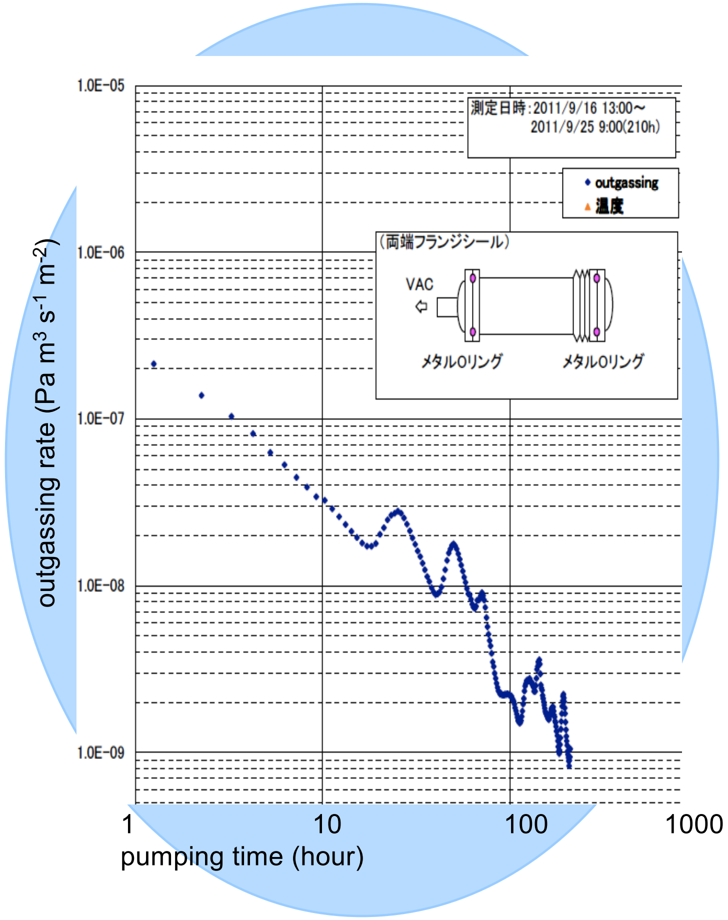
Thermal treatments

unit tube of 12-m long and 0.8-m in diameter

vacuum baking at 200°C for 20 hrs;
*dry air venting (-40°C dew point)
*sealed with blank flange (EPDM gasket)

outgassing rate measured for a unit tube;
the surface passivated tube shows
the rate of the order of ***10^{-9} Pa m^3 s^{-1} m^{-2}***
for pumping time of 100 hours.

storage in the tunnel of Kamioka mine railway



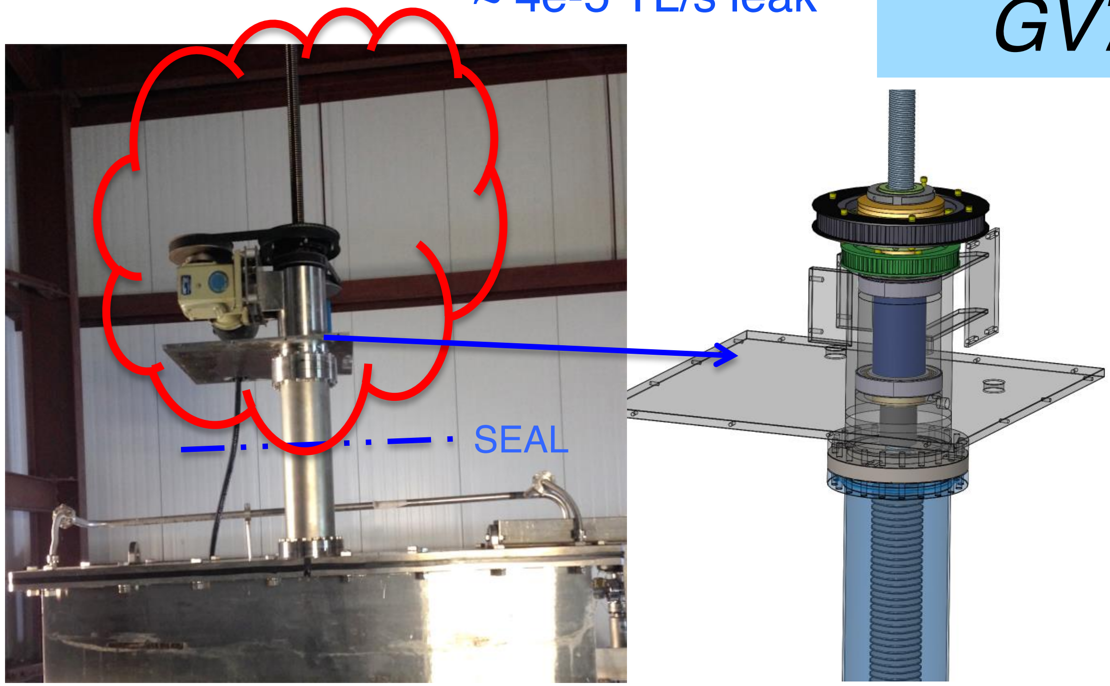
GW beam tubes comparison

	Virgo	LIGO	KAGRA	GEO600
Material (AISI)	304L	304L	304L	316L
Length (Km)	6	2x8	6	1.2
Diameter (m)	1.2	1.24	.81	0.6
Section length (m)	15	20	12	4.5
Thickness (mm)	4	3.23	8	0.8
Tube type	Sheet welded	Spiral weld	Sheet welded	Sheet weld +cold formed deep corrugated
Pipe cost (euro/m)	2400	2200	4745[a]	440
Vacuum (H_2O) mbar	5.6×10^{-10}	1.3×10^{-10}	1.5×10^{-8} [b]	1.5×10^{-7}
Distance among pumps (m)	600	2000	600	600
Firing Temp (^{o}C)	400	455	200	200
Firing duration	5 days	36 h	20 h	48 h
Bakeout Temp	150	160	Electro-polishing + ex-situ vacuum baking @200 deg 20 h	250
Bakeout duration	1 week	3 weeks		5 days
pumps	Turbo, Ti Sub. pumps	Turbo, Ion +NEGs	Turbo, Ion	Turbo

[a]bellowsSS316L, flanges, crow clamp, EP-finished, baked   [b]upgrade vacuum system in 2021

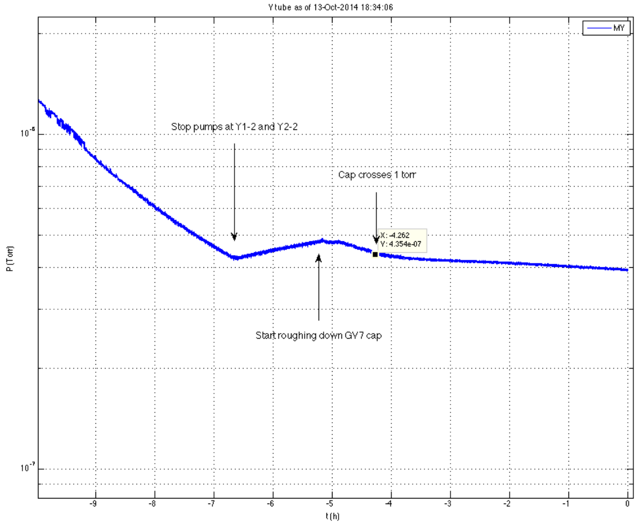
Experiences and learned lessons

Challenges: Valve bonnet leak



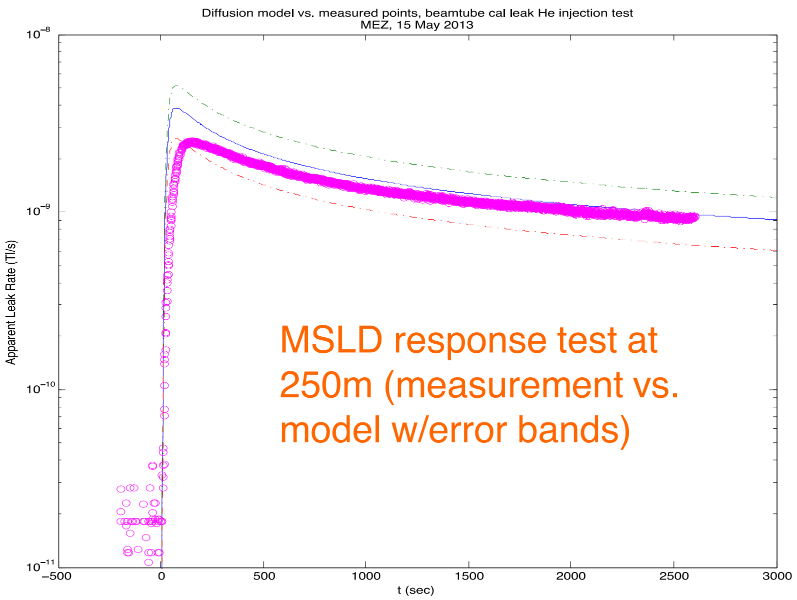
Odd time constant…. leaking through grease?

GV7 sarcophagus concept



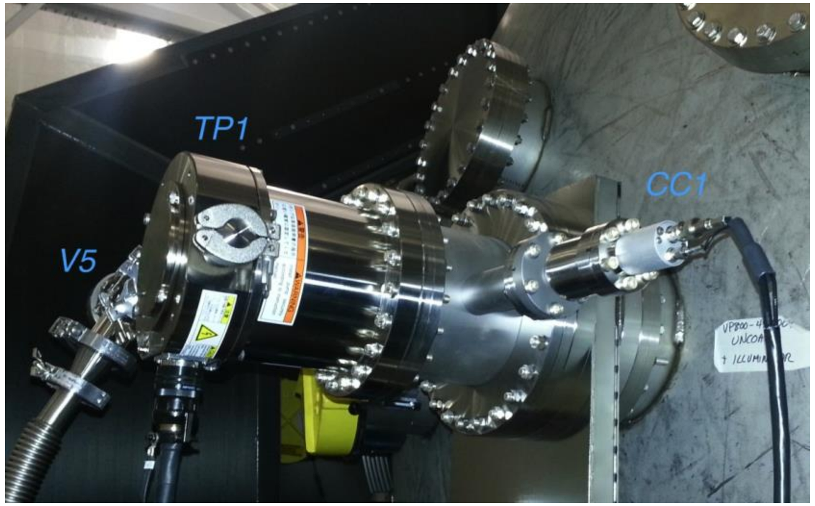
There is no mechanism to vent a beam tube, repair a valve and rebake, so what to do? Answer….design and install an enclosure to evacuate the volume *outside* the valve screw drive mechanism. Leak reduced, but valve now permanently inoperable (located at 2 km "mid-station") in open position. Luckily…. this valve could be abandoned w/o compromising operations

Challenges: Leaks and Detection



MSLD response test at 250m (measurement vs. model w/error bands)

Figure 2: Leak detector response to 30 second calibrated injection of helium test gas at $z = 250$ meters (pink circles). Also plotted is predicted response from diffusion model (solid blue) and approximate standard error margins (dash-dot red and green).



500 l/s turbo for MSLD compression boost (K. Ryan)

MSLD response degradation with distance

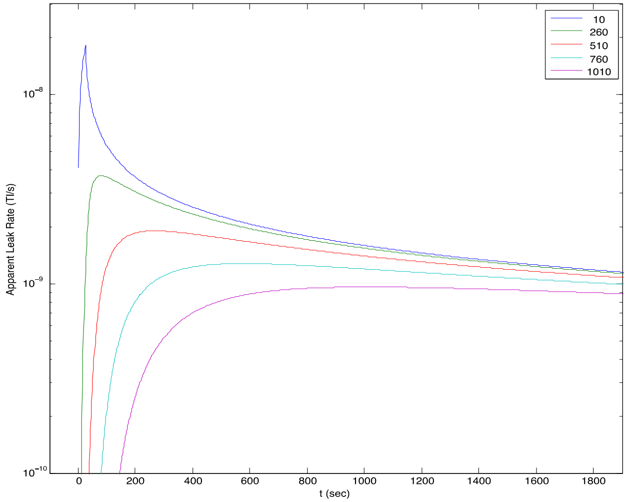
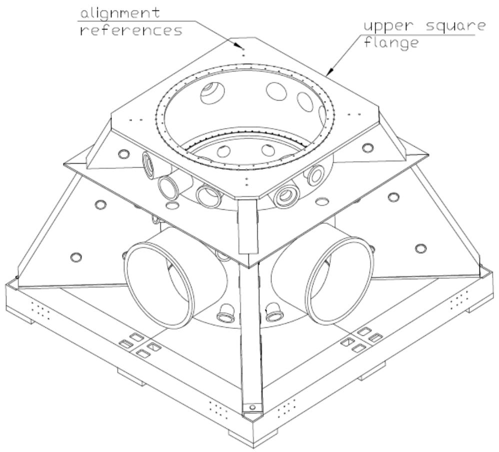


Figure 1: Model leak detector response for He test injections as described in text, assuming different injection positions z ranging from 10m (blue) to 1.01 km (purple). The actual test (Fig. 2) was performed at $z = 250$m (green).

Time constant of system makes Helium MSLD difficult, locating a leak extremely challenging, plus “where to start”?

Virgo view port failure



The North End tower accident - May 9, 2008

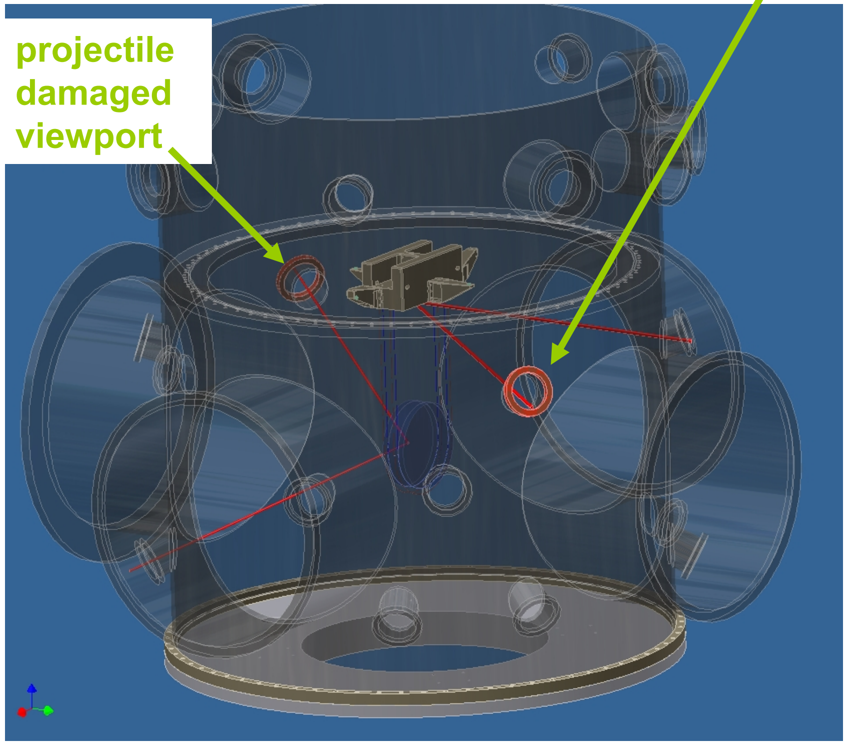
This viewport imploded at 0.12 bar (ΔP = 0.88 bar), about 90’ after evacuation start (the valve to the 3 km tube was closed)

- One fragment hit another (facing) viewport
- CF150 standard viewports off the catalog
- In Virgo >100 such viewports

These viewports are crossed by 1 mW red laser beams for payload position control

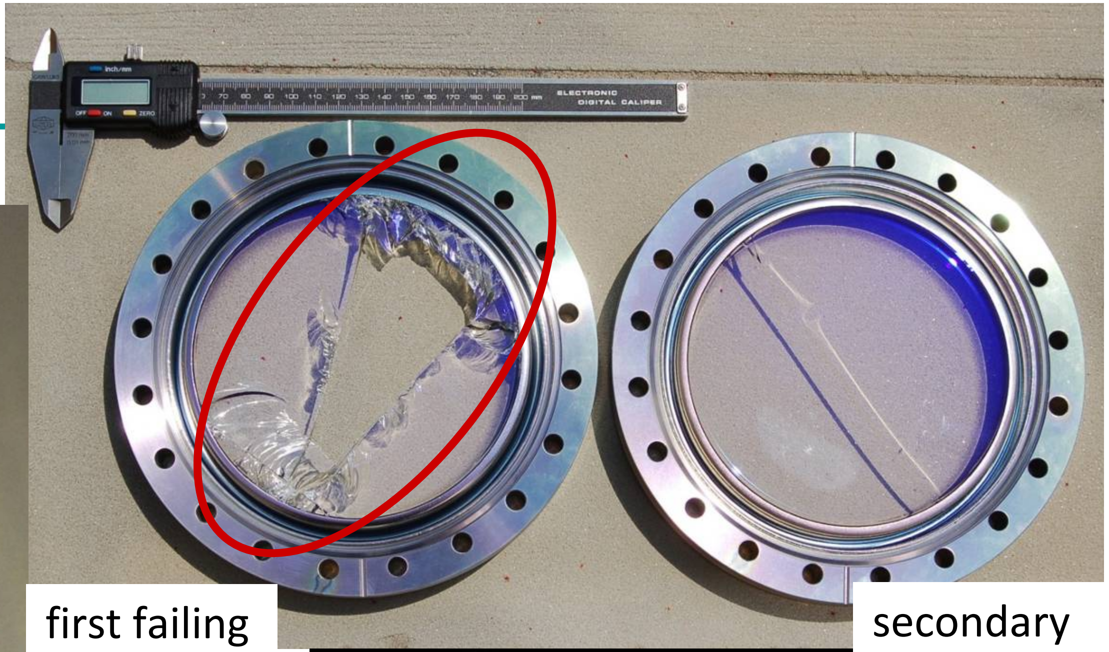
Accelerometers and microphones detected “precursor” cracks about 10’ before the failure

Slow air re-enter:
back to 0.5 bar in 20 sec
back to 1.0 bar in 100 sec



Broken Viewports

From inside



first failing

secondary

Problem due to initial defect + weak design

Since ET is underground a careful design is needed to avoid catastrophic failures

GEO 600 experience

Despite of the harsh condition one leak after 20 years due to MIC, a second leak after 25 years at an attached valve in trench
(lower quality stainless steel)

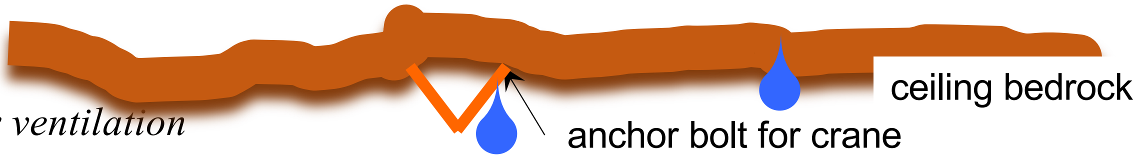
Very successful !!!!

in 2019, a MIC induced leak was fixed by welding a patch.

2. Constraint due to location

** waters in the tunnel*

** power station and air ventilation*



water proof spec is necessary for vacuum component procurement

** A mountain involves water inside:

1) mountain of 300-meters in height indicates a water pressure of 30 atm, when the tunnel is penetrated.

2) 98% (humidity), 19C (temp) inside tunnel through a year.

** A water of 1200 m^3h is being drained after the tunnel was completed: optical-plane of interferometer was tilted as 1/300 for draining water.

** durability test for Turbo-Molecular-Pump, Sputter-Ion-Pump, Roots-Pump, Cold-Cathode-Gauge, ...

humidity: 49C, 95%up, 7 cycles of (8hrs operation+16hrs off-power)

** durability test for metal gasket

* helical spring with aluminum lining >> failed

* Ag-coated stainless steel tube >> OK

humidity: 50C, 95%up, 240hrs

neutral salt spray: 180hrs

THANKS