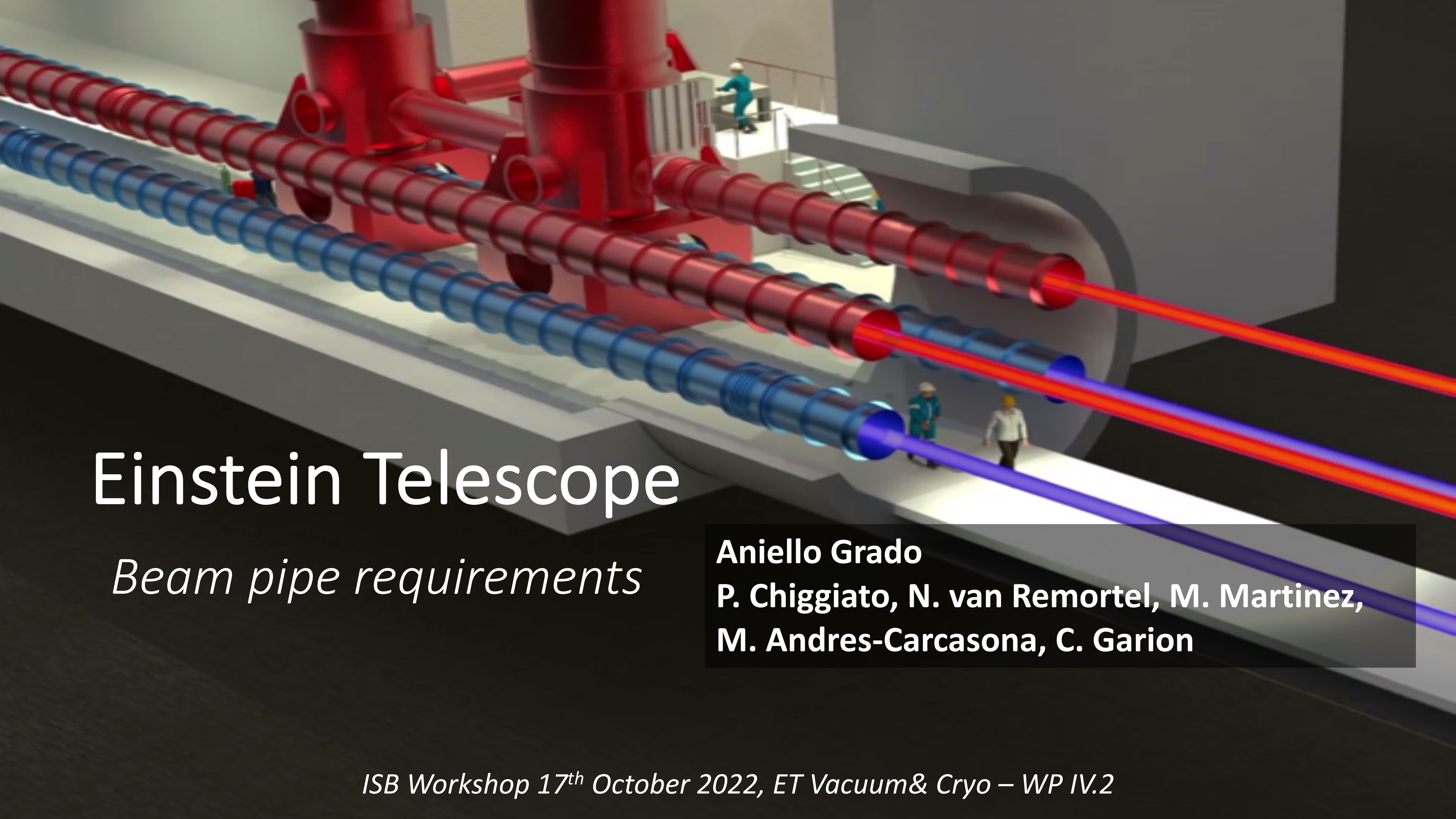


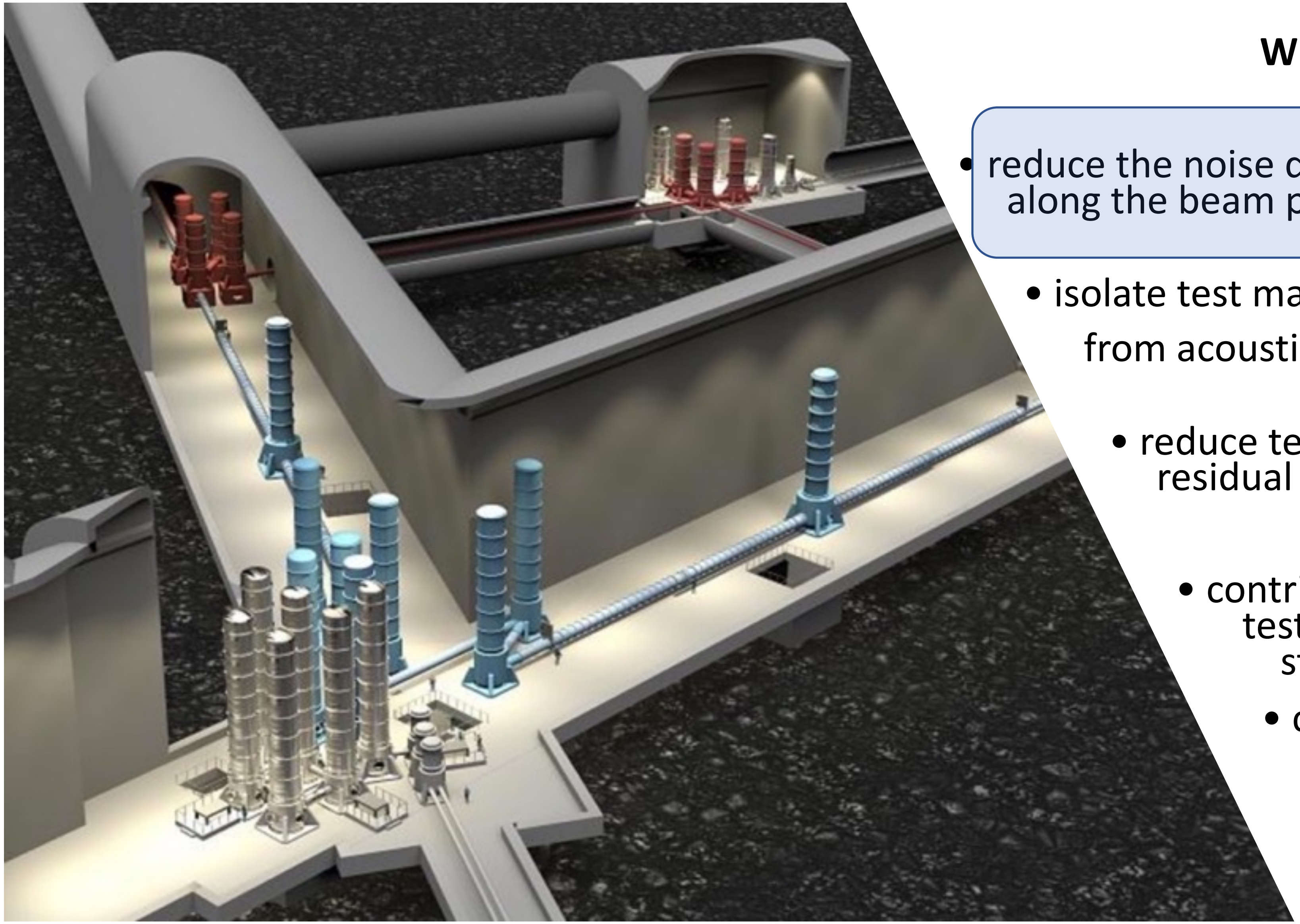
Einstein Telescope

Beam pipe requirements

Aniello Grado
P. Chiggiato, N. van Remortel, M. Martinez,
M. Andres-Carcasona, C. Garion

ISB Workshop 17th October 2022, ET Vacuum& Cryo – WP IV.2

ET vacuum



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

Agreement with CERN

The beam pipe vacuum system is under direct responsibility of the ET Directorate.

In 2022 an agreement among INFN Nikhef and CERN has been signed. Main goals are:

- **Coordinate the effort of ET collaborators** interested in the same technical objectives.
- Coordinate the contact and sharing of information with **Cosmic Explorer in the field of vacuum technology**.
- Re-evaluate **the baseline solution** (Virgo/LIGO) with minor modifications imposed by the new requirements.
- Design and test **technical solutions** that fulfil the ET requirements and are **less expensive** than the baseline. The required **technical infrastructure** will be evaluated and optimized as well.
- Manufacturing, assembly and commissioning of a **pilot sector**.
- Write the **technical design report**, including **cost estimations**.

The requirements of the beam pipe vacuum system is under the ISB responsibility

Global planning

	First year				Second year				Third year			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Functional specifications												
Roles and agreement with Institutes												
Optimisation of baseline, including cost analysis												
Definition of alternative solutions												
Cost & performance of alternative solutions												
Optimisation of interfaces with services/infrastructures												
Decision about vacuum design for pilot sector at CERN.												
Prototyping of the selected solutions.												
Technical design report (ET vacuum system).												

Functional Requirements

Req. ID	Req. name	Responsible	Description/note	Link to other requirements
4.2.F.1	Scattered light	M. Martinez		
4.2.F.2	Beam pipe pressures	A. Grado		
4.2.F.3	…….			
4.2.F.4	Surface contamination	?		
4.2.F.5	Alignment and tolerances	?		
4.2.F.6	Lifetime			
4.2.F.7	Limitation on magnetic properties of the tube			

Division

WP

See Michele's talk on system/subsystem …

Sub. Requirements of 4.2.3 scattered light

Req. ID	Req. name	Responsible	Description/note	Link to other requirements
4.2.F.1.1	Tube diameter			
4.2.F.1.2	Roughness on the inner tube surfaces	M. Martinez		
4.2.F.1.3	allowed tube amplitude vibration (in particular for corrugated tube)			
4.2.F.1.4	any threshold for light-dust interaction			

Sub. Requirements of 4.2.2: beam pipe pressures

Req. ID	Req. name	Responsible	Description/note	Link to other requirements
4.2.F.2.1	Margin factor LF		Depends on the other noises of the noise budget and margin for future upgrade	
4.2.F.2.2	Margin factor HF			
4.2.F.2.3	Partial pressure H_2			Pumps speed, outgassing rate, steel thermal treatments
4.2.F.2.4	Partial pressure H_2O			pumps speed, Bake-out temperature, max temp in the tunnel
4.2.F.2.5	Partial pressure N_2			
4.2.F.2.6	Partial pressure CO			
4.2.F.2.7	Partial …..			
4.2.F.2.8	Pressure uniformity			Space between pumps, number of recesses

Interface requirements

Req. ID	Req. name	Responsible	Description/note	Link to other requirements
4.2.I.1	Vacuum chamber limitation in size and weight			Tunnel diameter
4.2.I.2	Maximum heating power allowed in the tunnels			ventilation
4.2.I.3	Maximum available electrical power available in the tunnel for bakeout			
4.2.I.4	Maximum footprint available for vacuum pipe supports			Tunnel diameter
4.2.I.5	Expected moisture level in the tunnel.			ventilation
4.2.I.6	Maximum allocated pumpdown time.			
4.2.I.7	Building size for thermal treatment and cleaning			
4.2.I.8	Electrical charges on optics coming from ion pumps			

ET beam tubes requirements

LARGEST UHV VOLUME

- Tube diameter ~ 1m
- Total lenght 120 km

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

- Total residual pressure: H_2 10^{-10} mbar, H_2O 5×10^{-11} mbar, N_2 10^{-11} mbar (more stringent reqs comes from ET-HF)
- Hydrocarbon partial pressure < 10^{-14} mbar
- Material ?(2G detectors: SS 304L or 316L)
- Life time: 50 years

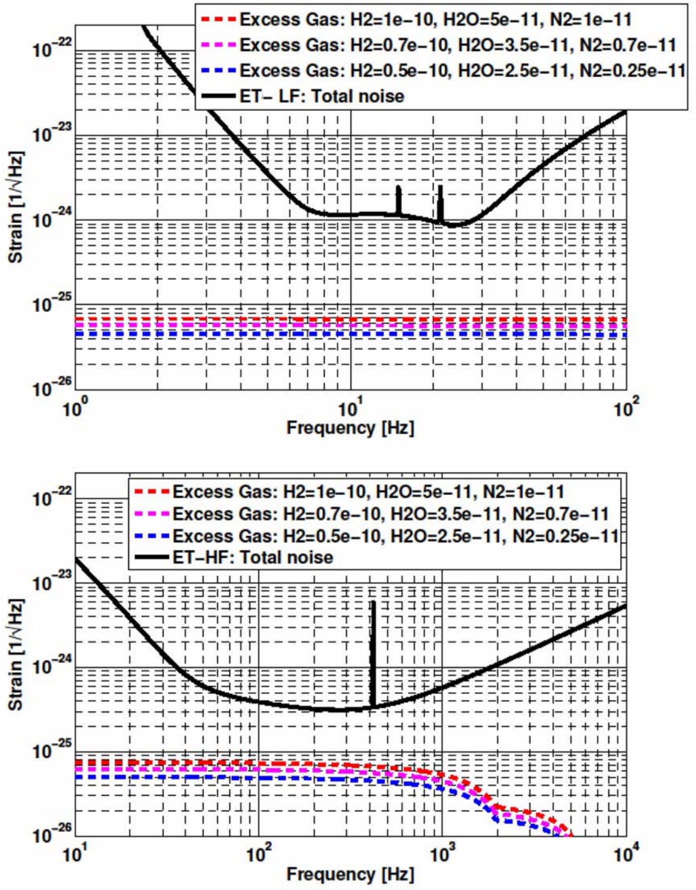
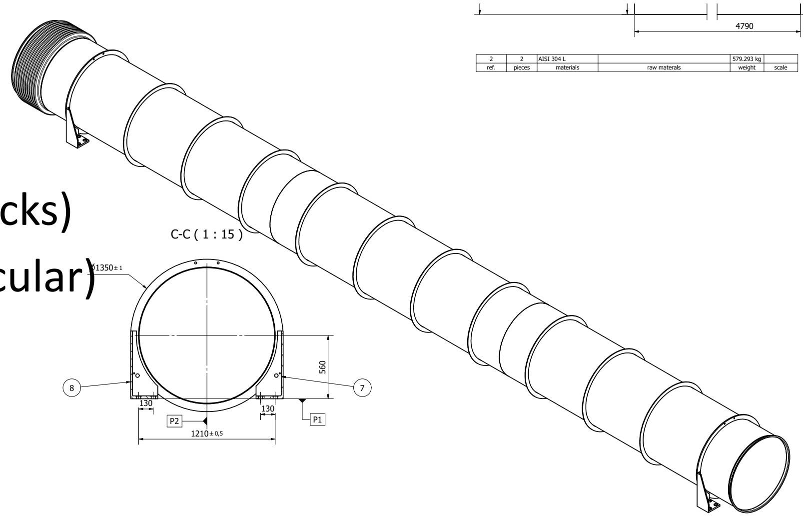


Figure 6.16: Phase noise given by the residual gases compared to the expected sensitivity, computed for the appropriate beam profile for different gas compositions. (Goal gas composition: Hydrogen [1 10^{-10} mbar], Water [5 · 10^{-11} mbar], Nitrogen [1 10^{-11} mbar])

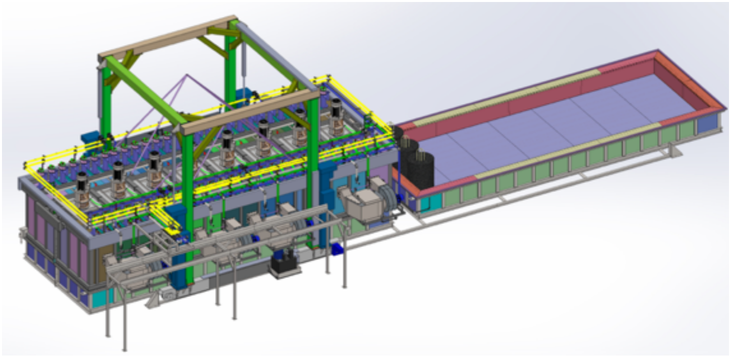
ET technical report 2020

ET beampipe vacuum system

Assuming a Virgo approach and ~ 3 years for the production



- 13000 t of raw steel
- 8000 modules 15 m long (including the bellow for thermal expansion)
- 8 modules/day production (includes leak and extensive quality control checks)
- 240 pumping stations (5000 l/s effective, ionic, getter, ausiliary turbo molecular)
- 720 gate valves (250 mm)
- add flanges every 250 m?
- 48/72 gate valves (1 m diameter)
- 10 ovens (each 4 modules at times) operating ~3 years 24/7 for air-firing
- 4 cleaning systems
- Bakeout (2G heat dissipation is ≈ 250 W/m @ 150°C)



Just scaling the Virgo vacuum costs to ET it would requires

> 560 Meuro !! ***Needed new materials, process production, treatments to reduce the cost***

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

Power spectral density fluctuations of optical path

Gas optical polarizability

Interferometer arm lenght

Molecules number density

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

Average molecules speed

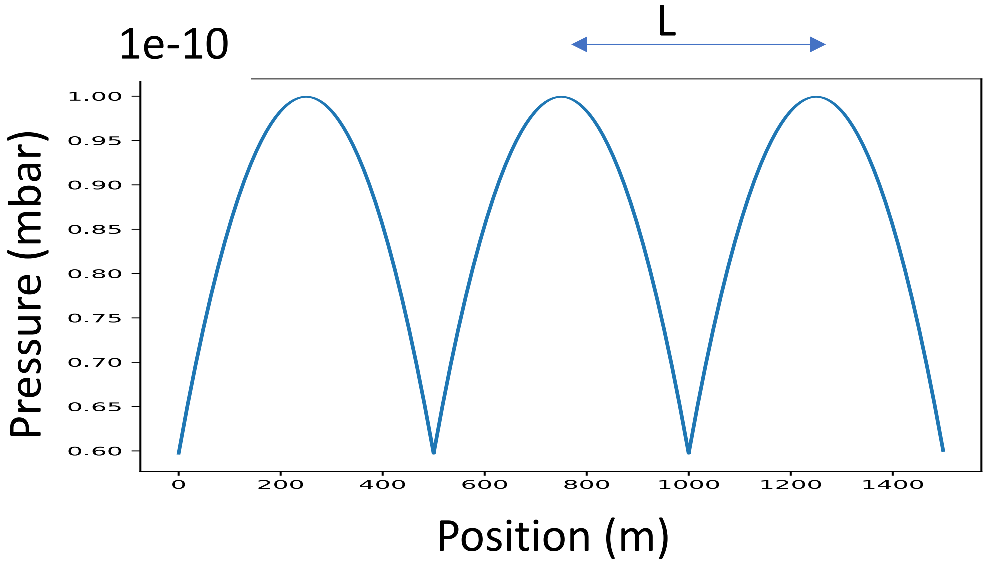
Laser beam gaussian radius

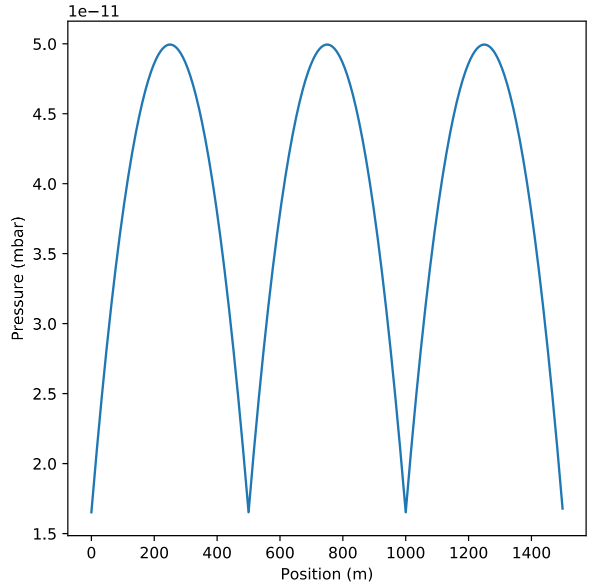
S. E. Whitcomb. Optical pathlength fluctuations in an interferometer due to residual gas. Technical report, California Institute of Technology, October 1984.

Pressure profile along the tube due to tube conductance

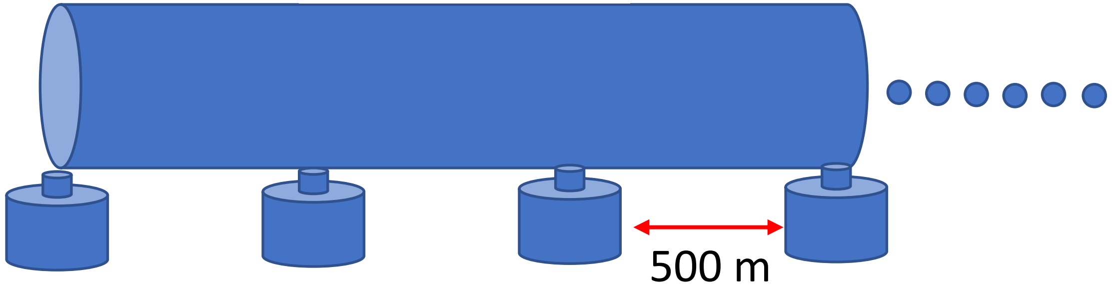
$q = 1.9\ e^{-14}$ mbar l/(s cm^2)
S = 5000 l/s
H_2 partial pressure variation: factor 1.6

$P(z)= Pmin+Q*(z/(C*L)-z^2/(2*C*L^2)$





H_2O partial pressure variation factor: ~3 (assuming specific outgassing rate 5.3e-15 mbar l s^{-1} cm^{-2})



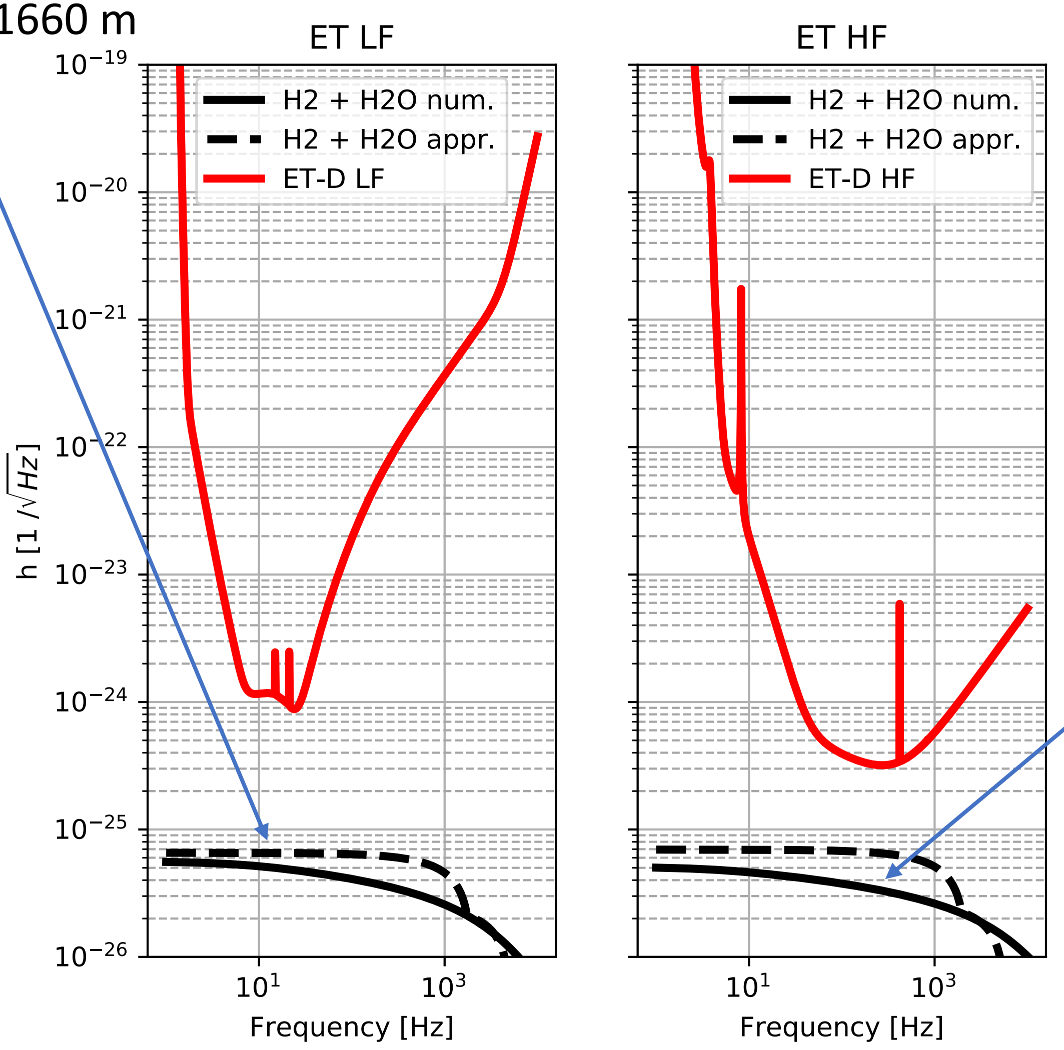
$qH_2 = 1.9\ 10^{-14}$ mbar*l/(s*cm^2) — 1 10^{-10} mbar

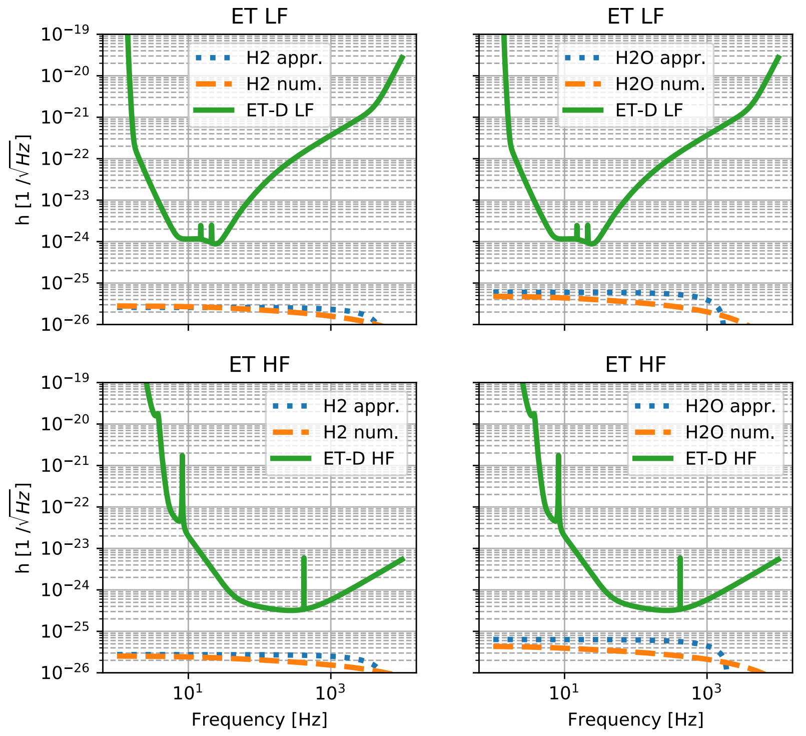
$qH_2O = 5.2\ 10^{-15}$ mbar*l/(s*cm^2) — 5 10^{-11} mbar

K.M Welch Volume 23, Issue 8, 1973, 271

ET beam pipe vacuum requirements

A margin of 10 at low frequency can be achieved with pumps spacing of 1660 m





A factor 2 improvement with a refined calculation considering the proper pressure profile in the tube

A. Grado et al. AIV conference on vacuum, 2022.

Margins due to gas fluctuations

Pumping 5000 l/s every 500 m

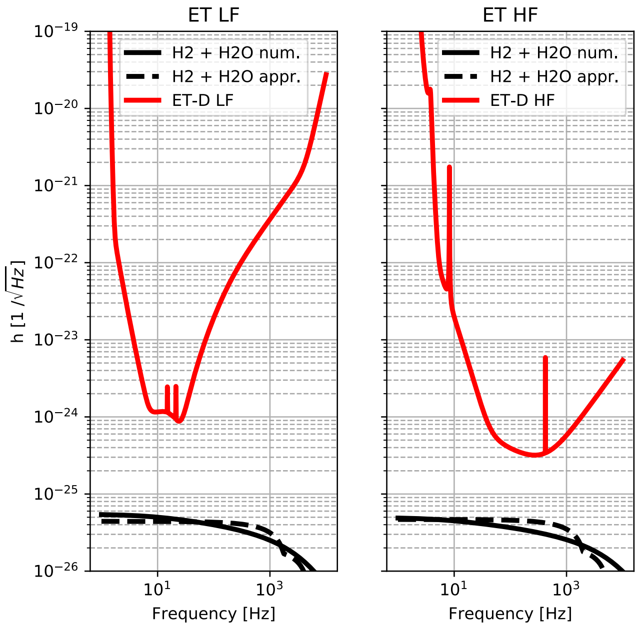
	ET-LF (@ 24 Hz)	ET-HF (@ 272 Hz)
Ratio ET-D/numerical for H2O	22	12
Ratio ET-D/numerical for H2	34	17
Total margin (H2 +H2O)	19	~10

Pumping 2100 l/s every 200 m (getter ?)

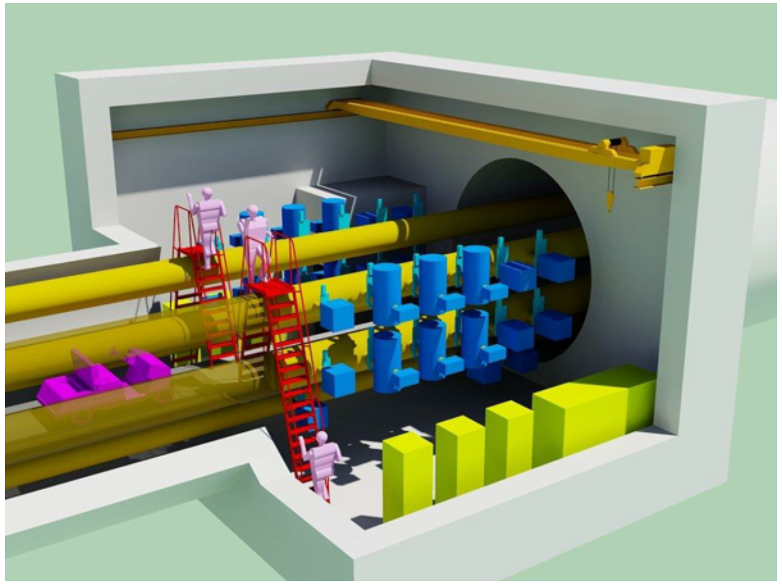
	ET-LF (@ 24 Hz)	ET-HF (@ 272 Hz)
Ratio ET-D/numerical for H2O	22	11
Ratio ET-D/numerical for H2	35	18
Total margin (H2 +H2O)	19	~10

qH_2 = 1.9 10^{-14} mbar*l/(s*cm^2)

qH_2O = 5.2 10^{-15} mbar*l/(s*cm^2)



Pumping system and recesses



We need to minimize the overall cost.

To accommodate pumping stations we need to create recesses (alcove) along the tunnels

How much it costs a recess?

Minimizing the number of recesses increase the pumping size and reduce the pressure uniformity in the pipe.

→ usage of getter pumps with reduced pumps spacing integrated in the tube

pros: no mechanical noise, no electrical power (only during activation and regeneration), very small

cons: increase cost, lower reliability***, to be evaluated scattering issues***

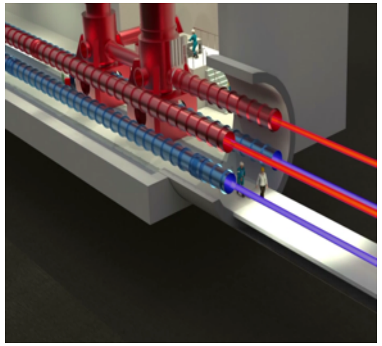
Large valves and recesses

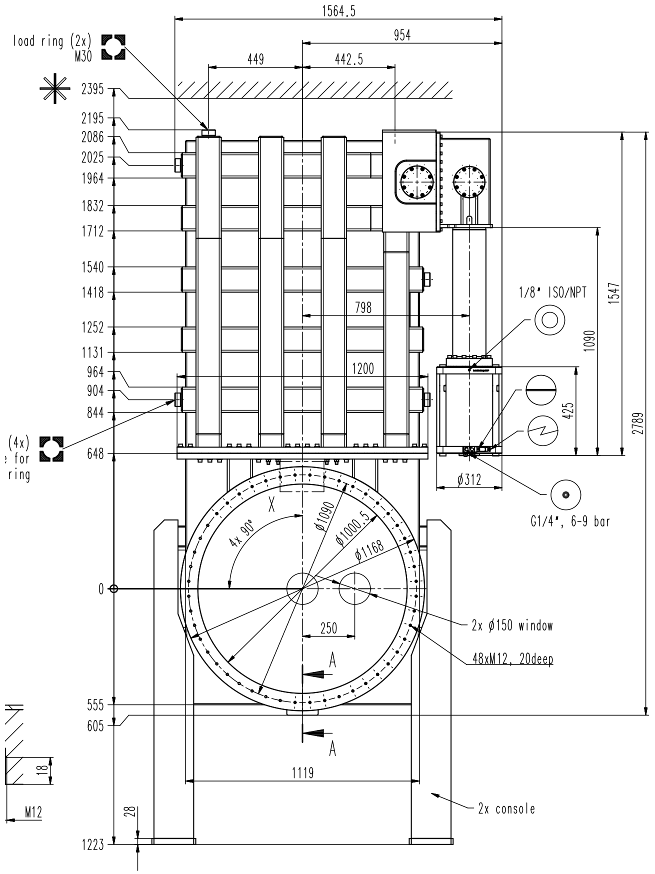
1564 mm

48 large valves to isolate cryotraps

+ ?

24 large valves to section the tube every ~ 3 km
To
- simplify the bakeout
- Leak detection
- speed up the AIV





2789 mm

These valves (from VAT) on request can work horizontally

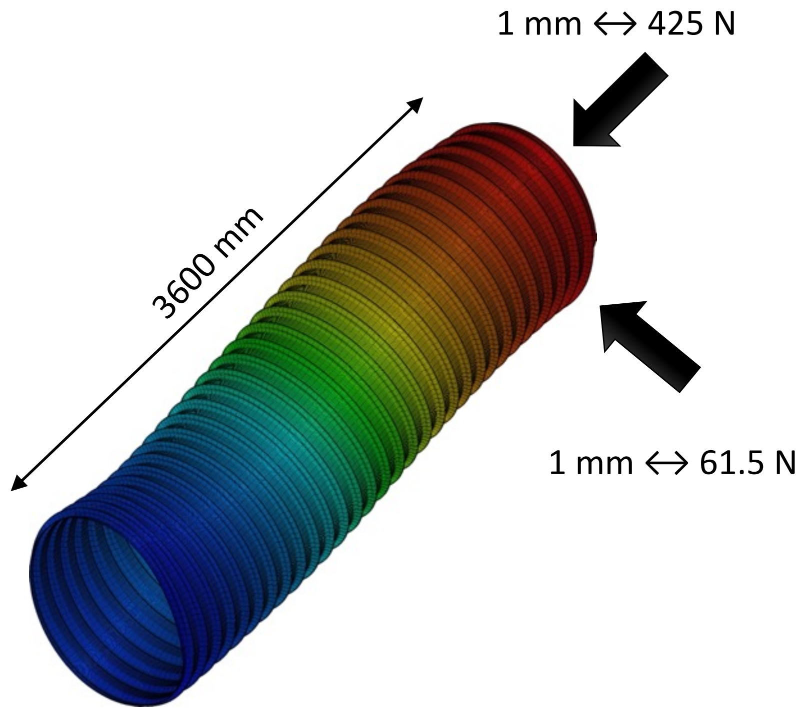
Corrugated tubes

Pro

- less material
- Easier to handle
- Easier to dehydrogenize
- Less expensive backout

Con

- Corrosion issue
- ***To be evaluated the effect of large amplitude tube/baffles oscillations on scattering***



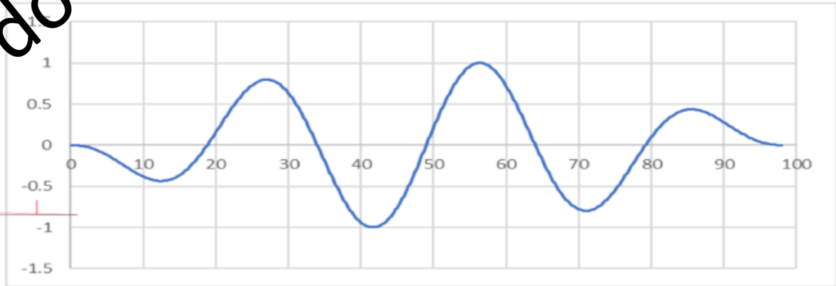
Mechanical aspects

Column Stability for hanging structure

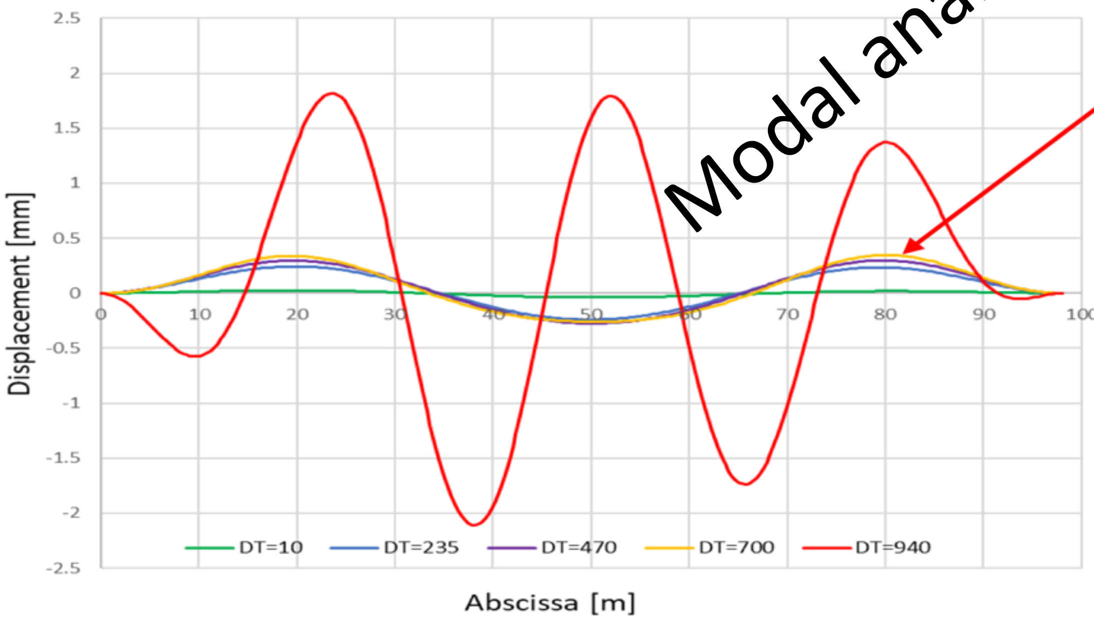
Modal analysis is on the “to do” list

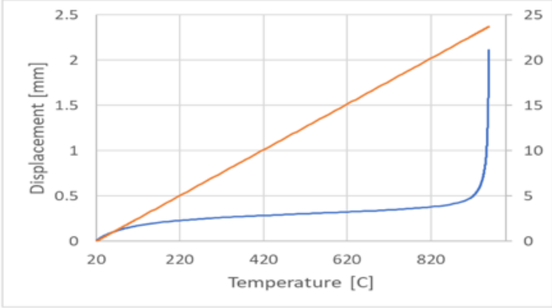
100 m model:

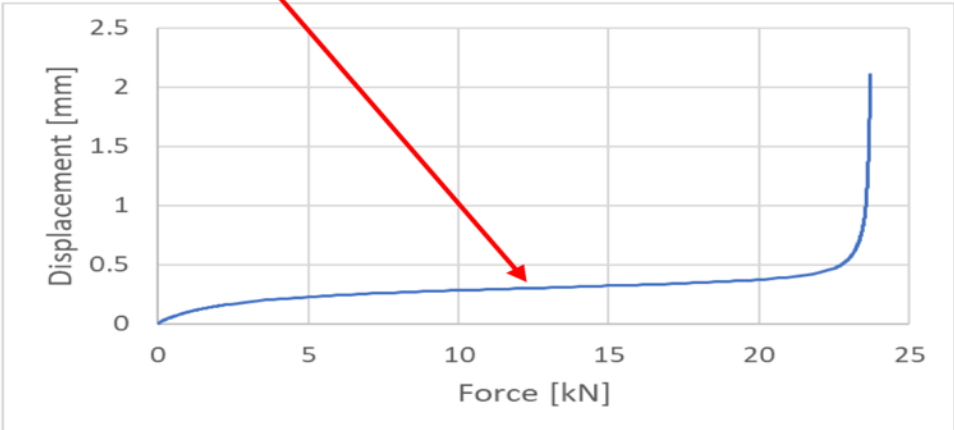
- 2D eigen value model: buckling force: 22.15 kN



- 3D non linear model:
  - Instability at ~ 23 kN (930 C)
  - Plateau with stable deformation related to initial imperfection







Thermal effects due to bake-out

What is the increase in temperature we can accept in the tunnels due to in-situ bake-out?

What is the cost impact on the ventilation system?

(by the way where is placed the ventilation system?)

For corrugated tube

- Heating by Joule effect
- Internal wall resistance (ρ(150 °C) ~ 8.3E-7 Ω.m): R ~ 0.25 Ω/km
- Dissipated power: 55 kW/km (20 cm insulation)
  - Intensity ~ 470 A
  - Voltage drop ~ 120 V/km
- Return:
  - By copper cable, radius ~ 15 mm to get factor 10 lower electrical resistance
  - Other structural conductive material (rail?)
  - By another vacuum line

Calculation by Cedric Garion CERN

For tick tube 10 days, 150 deg bakeout, 20 cm tick insulation

….In this configuration, delivering 300 W per meter of tunnel, in absence of ventilation, a very crude estimate considering a 6 m aperture tunnel, drilled in isotropic rocks – assumed ρ = 2500 kg/m , *k* = 2.0 watt/(m K), *C* = 800 joule/(kg K) – gives an increase of room and wall temperature by about **+13◦C** after a 10 days bake-out.

Design Report Update 2020

Study of the scattered light in the main arms of the Einstein Telescope gravitational wave detector

Marc Andrés-Carcasona on behalf of IFAE

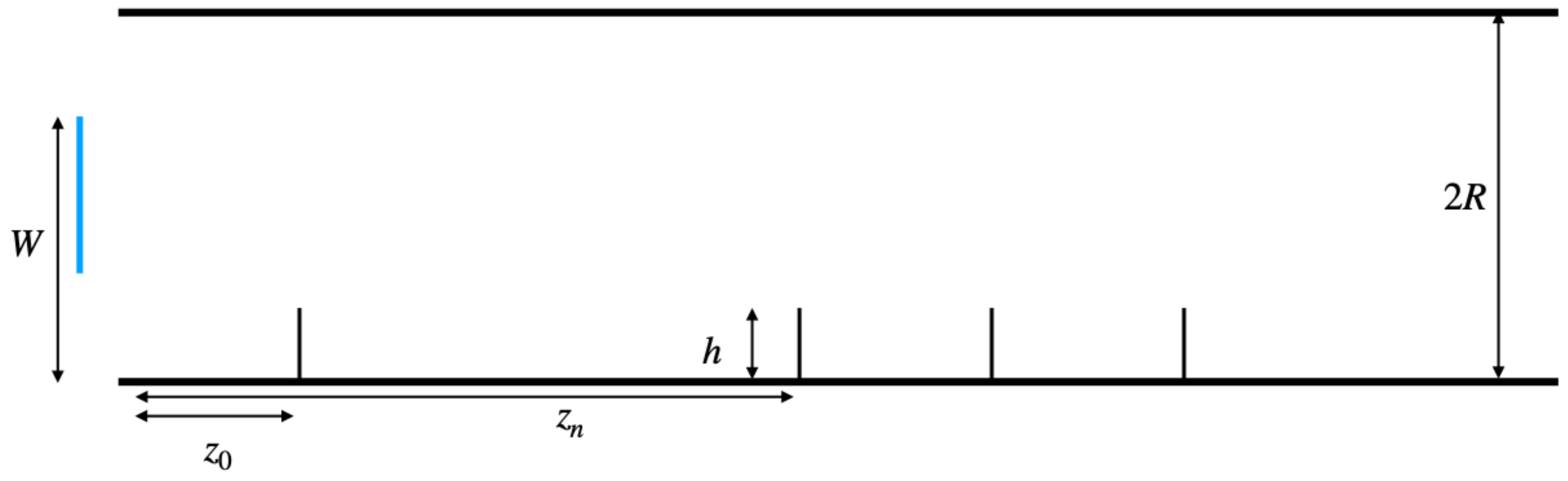
13/10/2022

Mail to: mandres@ifae.es

On ET-TDS: ET-0240A-22

Number of baffles

The classic hypothesis is to geometrically shield any part of the tube with baffles. There are two approaches for this. Brisson and Vinet (VIR-NOT-LAL-1390-123) hide the tube from the photons that are scattered from the center of the mirror while Thorne and Flanagan (LIGO-T950033-00) hide the tube from any position that is left to decide (as enters in the parameter W, see below, and that we chose as the edge of the mirror).



As stated in VIR-NOT-LAL-1390-123:

$$z_n = z_0 \left(a \frac{R}{R-h} \right)^n$$

As stated in LIGO-T950033-00 (changing the notation to match the same one presented here):

$$z_n = z_0 \left(\frac{W}{W-h+dh} \right)^n = z_0 \left(\frac{R+R_m}{R+R_m-h+dh} \right)^n$$

Where $\boldsymbol{a}$ represents a safety factor set to 0.95 for now, $\boldsymbol{h}$ the height of the baffle that will be discussed later, $\boldsymbol{R}$ the radius o the tube, $\boldsymbol{R_m}$ the radius of the mirror (assumed to be 31 cm for ET-HF as stated in ET-0007B-20) and $\boldsymbol{dh}$ a safety factor set to 1cm.

In practice, LIGO decided to place a baffle at each tube joint once the distance predicted by these formulae is greater than the section's length.

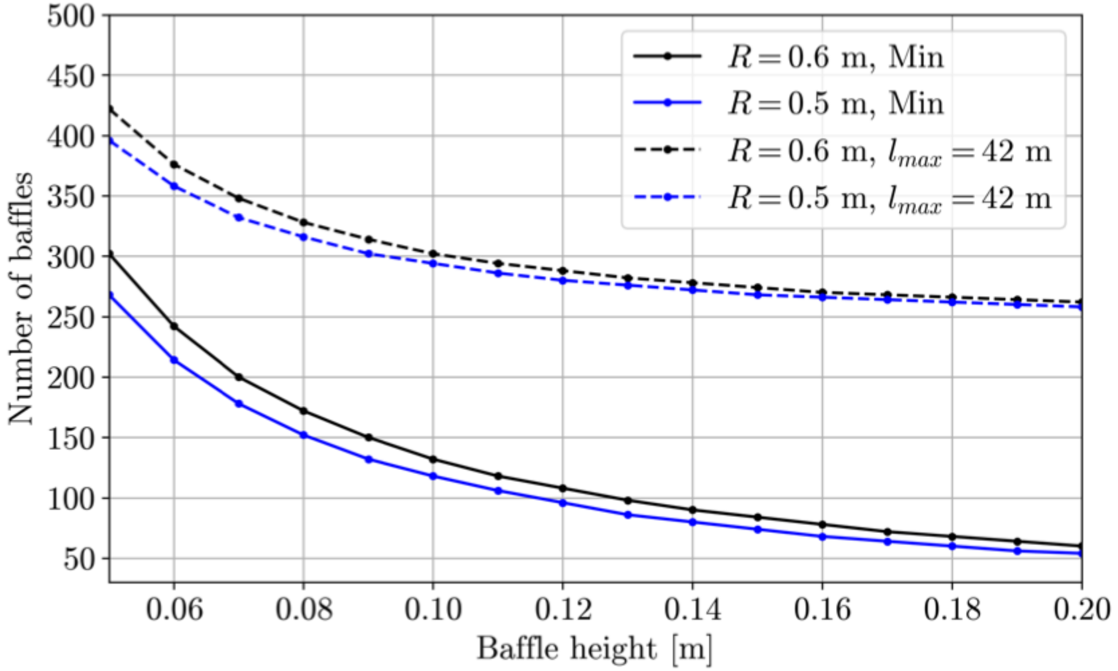
Number of Baffles

The total number of baffles will strongly depend on the choice of whether to place one at the tube joints for the central section. If these are added:

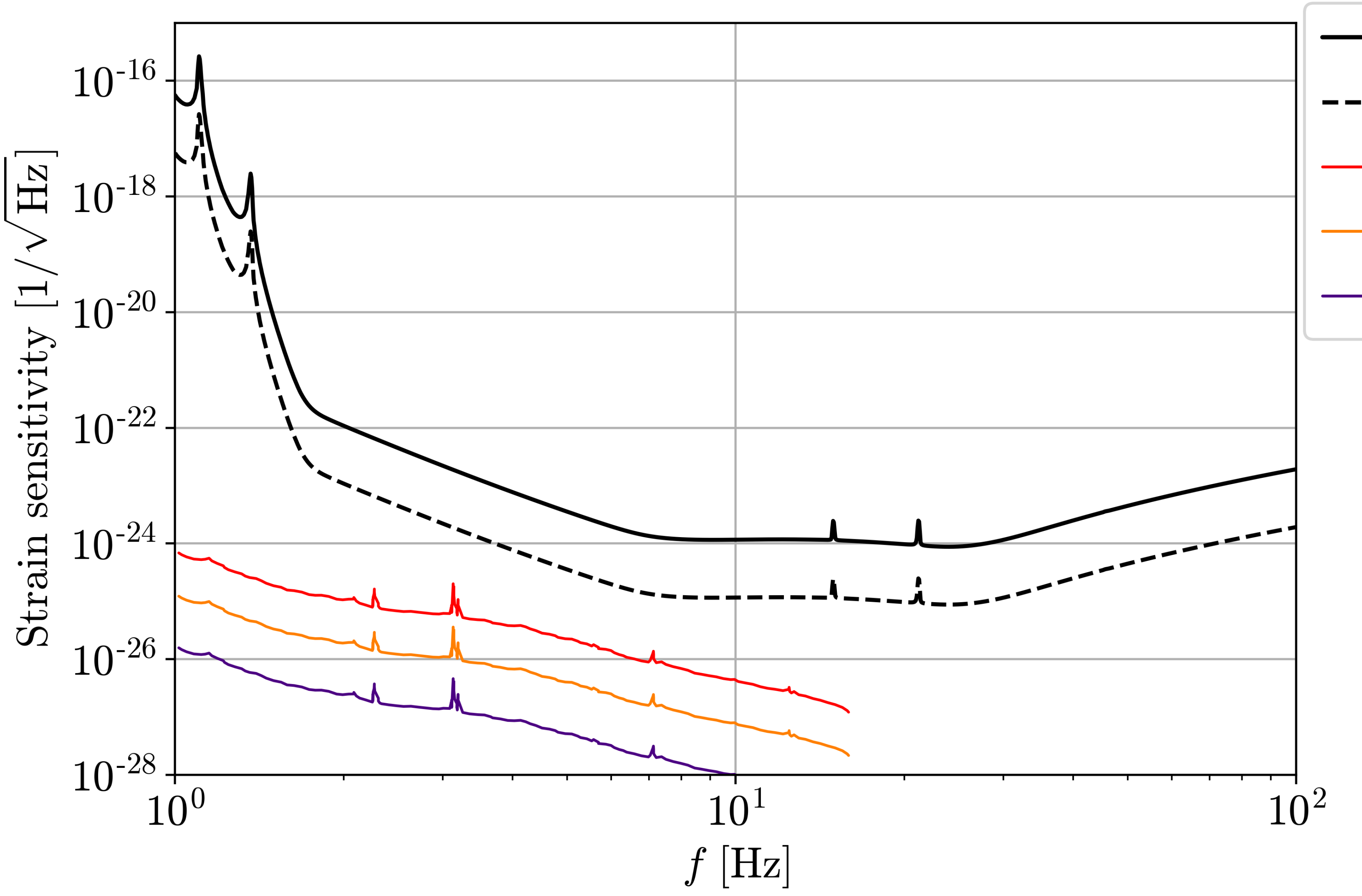
- **Advantages**:
  - Easier to install baffles near each section's end than in the middle.
  - A great number of sections could be fabricated in the same way.
  - There are more baffles to hide other necessary parts of the tube, such as vacuum pumps, sensors, etc.
  - It is a conservative approach, because it adds more baffles than strictly needed.
- **Disadvantages**:
  - Greater economic cost.
  - Higher diffraction noise. This is discussed in later sections and can be compensated serrating the baffle edges.

Assuming a baffle height of 8 cm and a beam tube of 60 cm radius, the minimum number of baffles is about 170 while if one is placed at every joint (assuming a length of the section of 42m), this number increases to around 320 baffles.

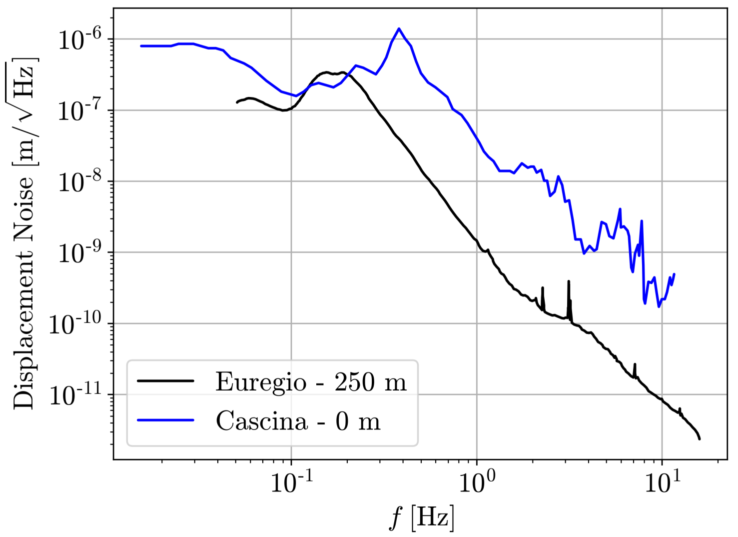
We expect to optimize the number of necessary baffles in the following months to obtain a value that is inbetween but does not compromise the sensitivity.



Number of baffles as a function of the baffle height following Thorne and Flanagan for different tube radii. We include the minimum number of baffles and also the case where a baffle is placed each $l_{max} = 42$ m, as was done in LIGO. The first baffle is placed at 6 m from the mirror.

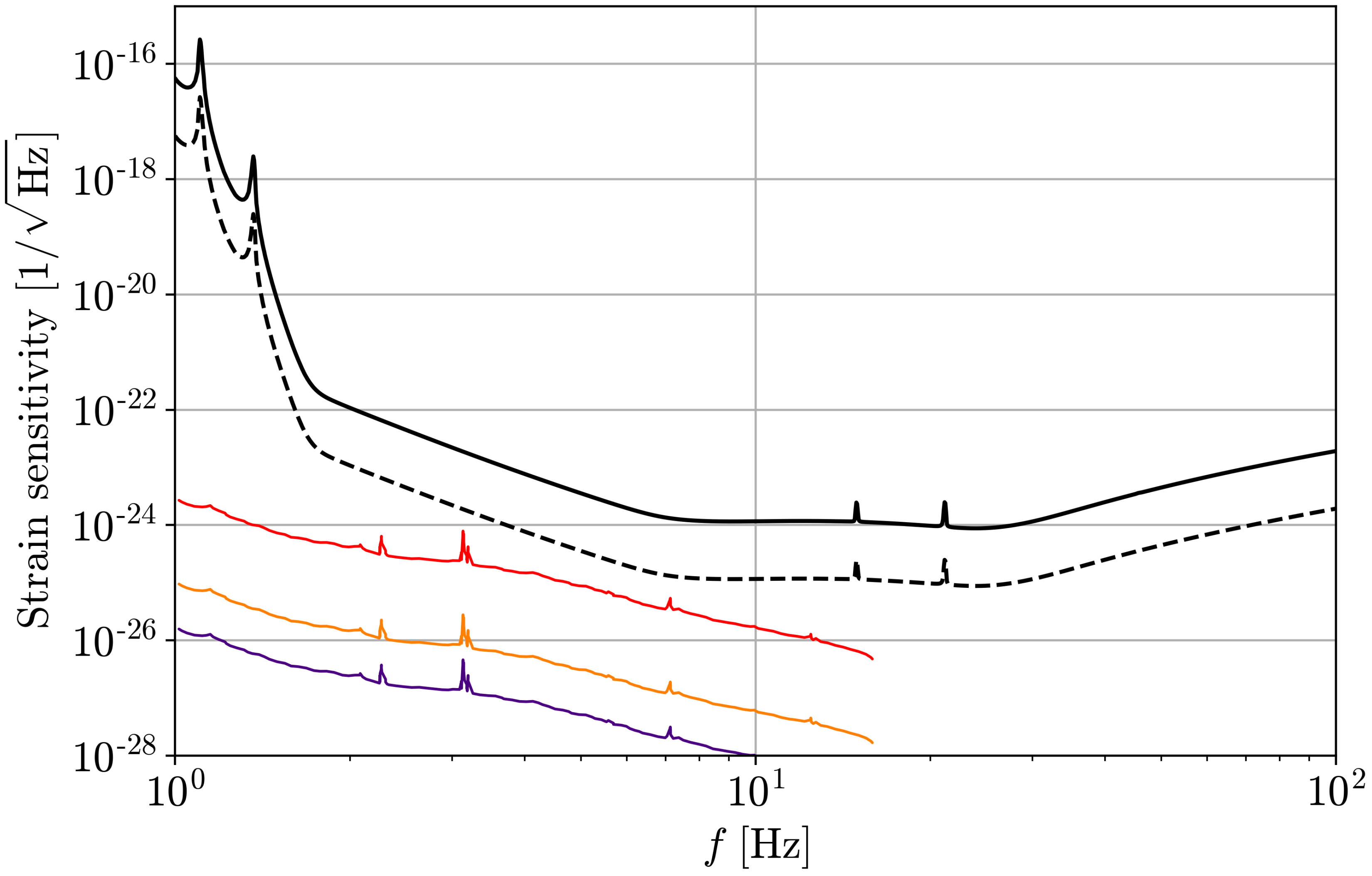


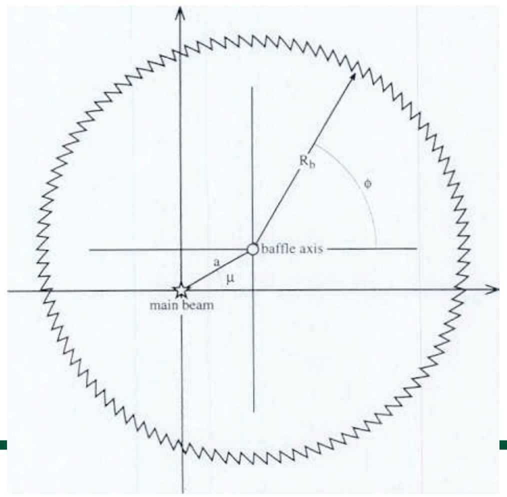
ET projected sensitivity
Safety margin
Bare tube - reflection
Baffle Backscattering
Diffraction - random teeth
Strain sensitivity [1/√Hz]
f [Hz]



Displacement Noise [m/√Hz]
f [Hz]
Euregio - 250 m
Cascina - 0 m

Diffraction noises for different serrations





Parallel sections on 18/10 15.30 to 19.00 and 19/10 09.00 to 12.30

Main goal of the parallel sections is:

- discuss about beam pipe functional and interface requirements.
- update the preliminary list of requirements
- Define a responsible for each requirement

Prioritize requirements:

- Beam pipe diameter
- Pressure level
- Tunnel diameter

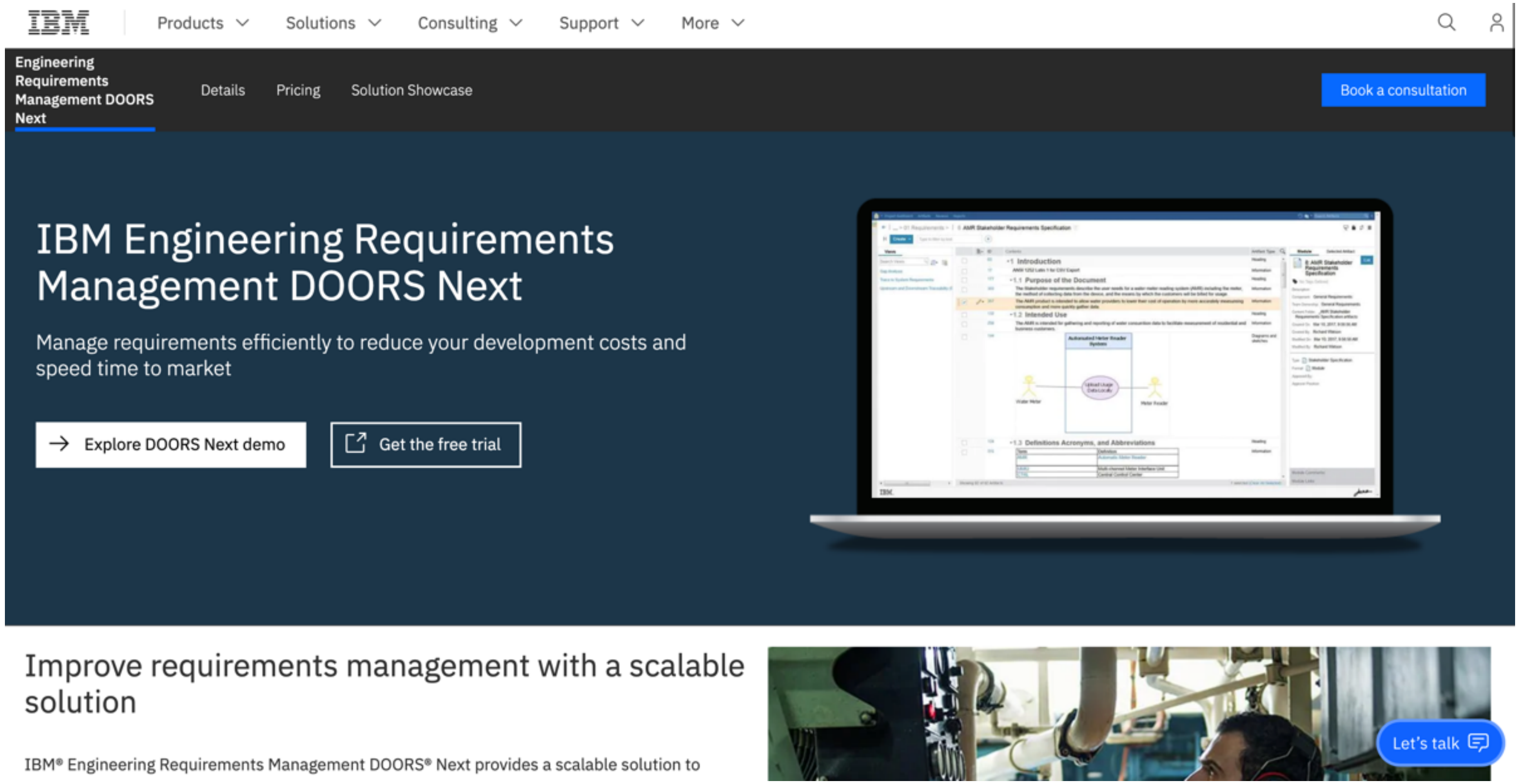
During the parallel sections would be very useful to have people from:

- Optic division
    - Scattered light
    - Optical design ?
- Vacuum&Cryogenics
    - Towers
- Infrastructures
    - Underground works
    - Surface infrastructures
- Sensitivity curve

Requirements control

- For a such big project keep under full control the requirements may be not easy. Should we adopt since the beginning some specific tool to do that?

Example:



Thank you for the attention