Virgo GW - BelGrav
DEDICATED TO DETECTING GRAVITATIONAL WAVES

University of Antwerp

LSC
VIRGO
KAGRA

The ET beampipe vacuum system

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IRI Workshop
November 27, 2023

fwo Research Foundation Flanders
Opening new horizons

Residual gas noise contribution for ET:

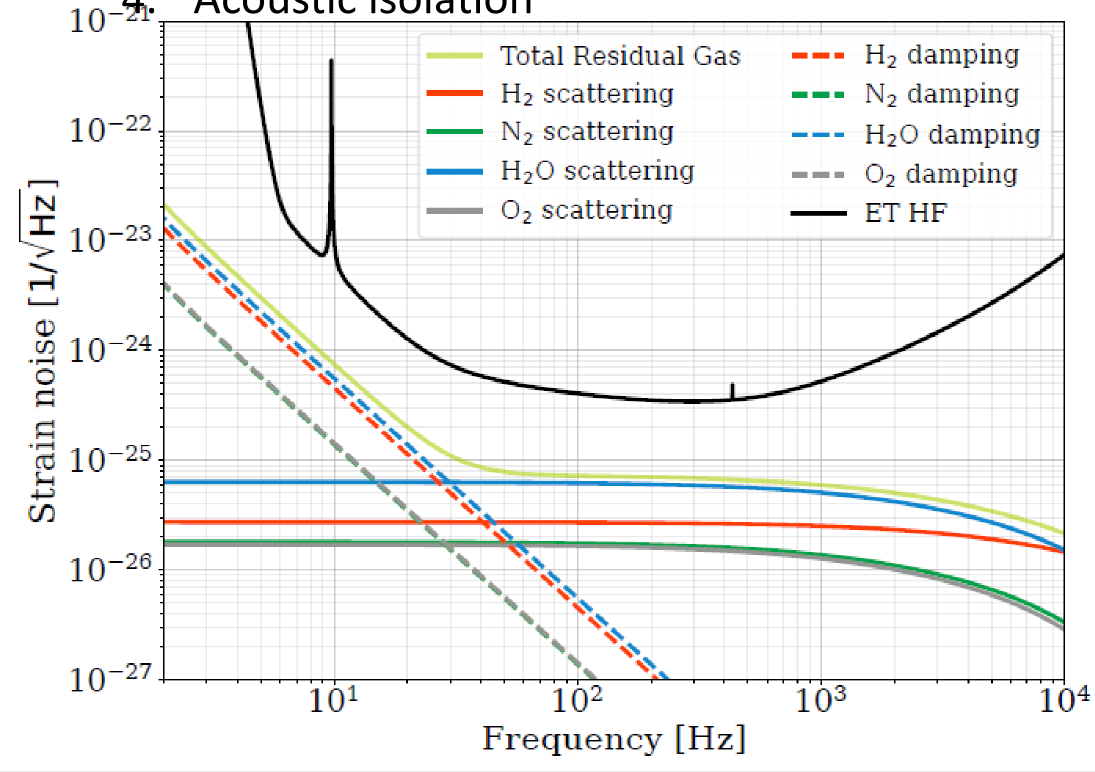
Impact of residual gas in ET's optical beam:

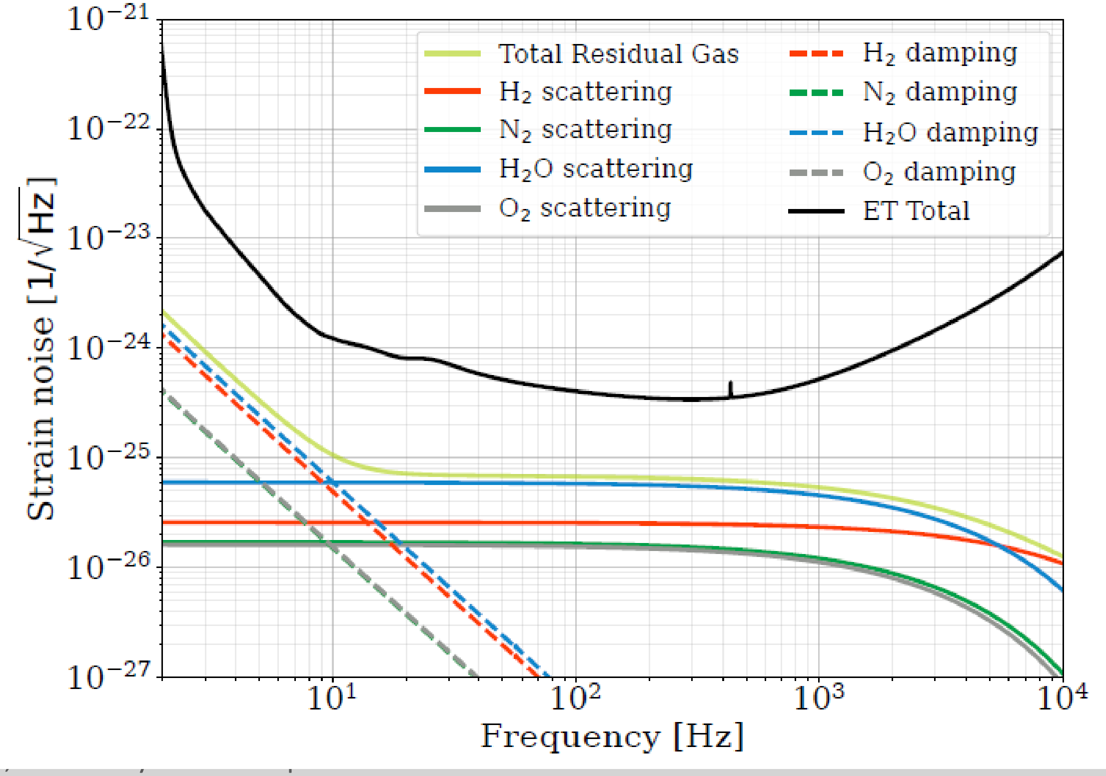
1. Affect phase of laser field as gas molecules transverse the beam, proportional to:
   - mass,
   - square of polarizability
   - Partial pressures
2. Noise on mirrors as gas particles collide with mirror surface: gas damping at low f
3. Mirror cleanliness
4. Acoustic isolation

$$G(f) = \int_0^L \frac{2\eta_0 \alpha^2}{v_0 w(z)} \exp\left[-\frac{2\pi f w(z)}{v_0}\right] dz$$

$$\frac{\Delta l}{l} = \frac{[2G(f)]^{1/2}}{L}$$

Source: S.E. Whitecomb, LIGO-T840003





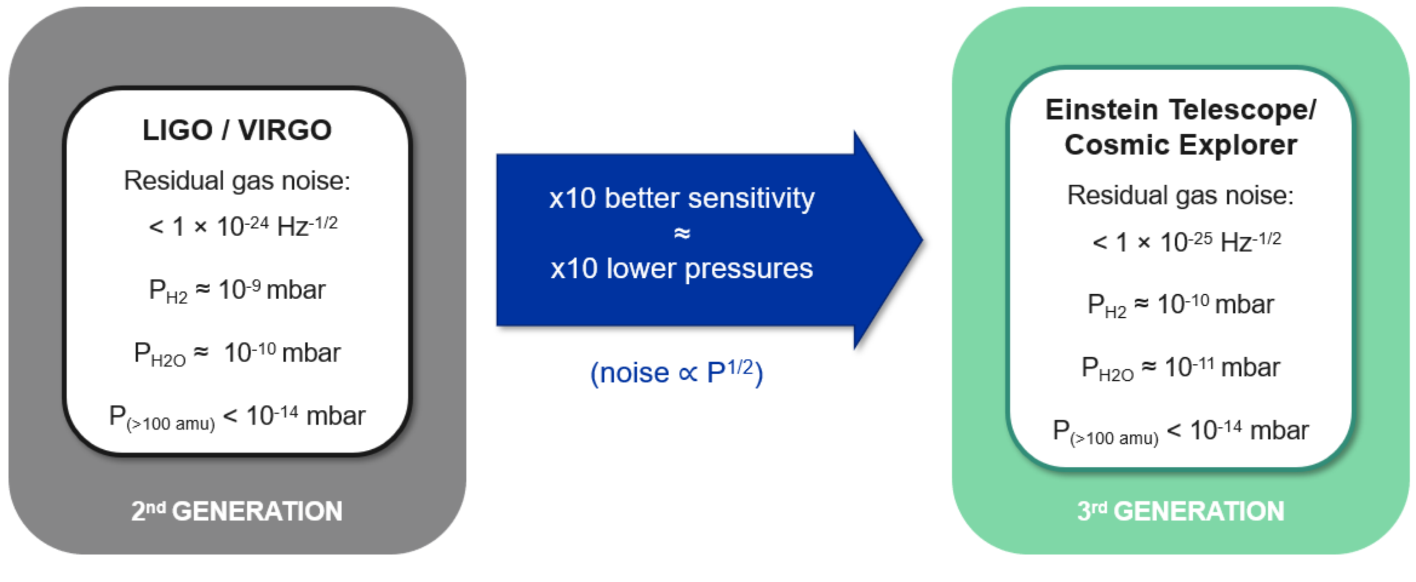
Source: ET design report update 2020

Pressure impact on power spectral density noise curve

- Simple calculation assumes constant pressure profile
- Pressure profile depends on:
  - Outgassing rate, Q
  - Pump distance, L
  - Pumping speed, S
  - Pipe conductance, C

$$P(x) = P_{\mathrm{min}} + \frac{2Q}{C}\left(\frac{x}{L} - \frac{x^2}{L^2}\right).$$

$$P_{min} = 2Q/S$$



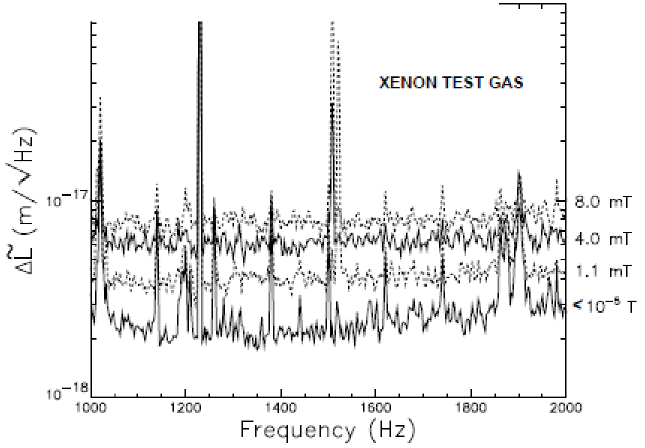


Figure 1. Amplitude spectral density of apparent differential arm lengths in the 40 meter interferometer as a function of xenon test gas pressure. The peak at 1230 Hz is for calibration; other peaks arise from mechanical resonances and interference.

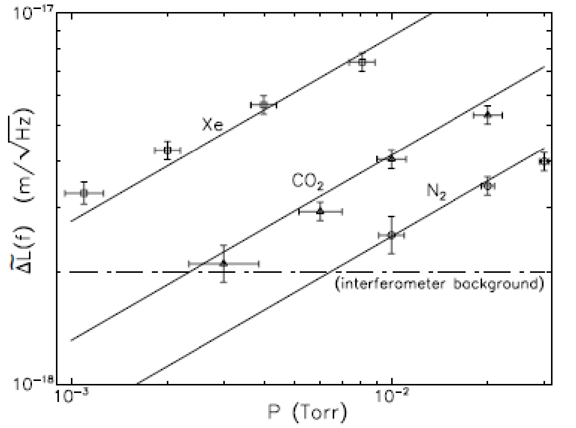


Figure 2. Amplitude spectral density near 1500 Hz for three gases as a function of pressure (points). The background noise (dot-dashed line) was subtracted in quadrature from each raw measurement. Solid lines are model predictions of Eq. (1) for each gas.

Impact on power spectral density:

Density ~partial pressure

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\, dz$$

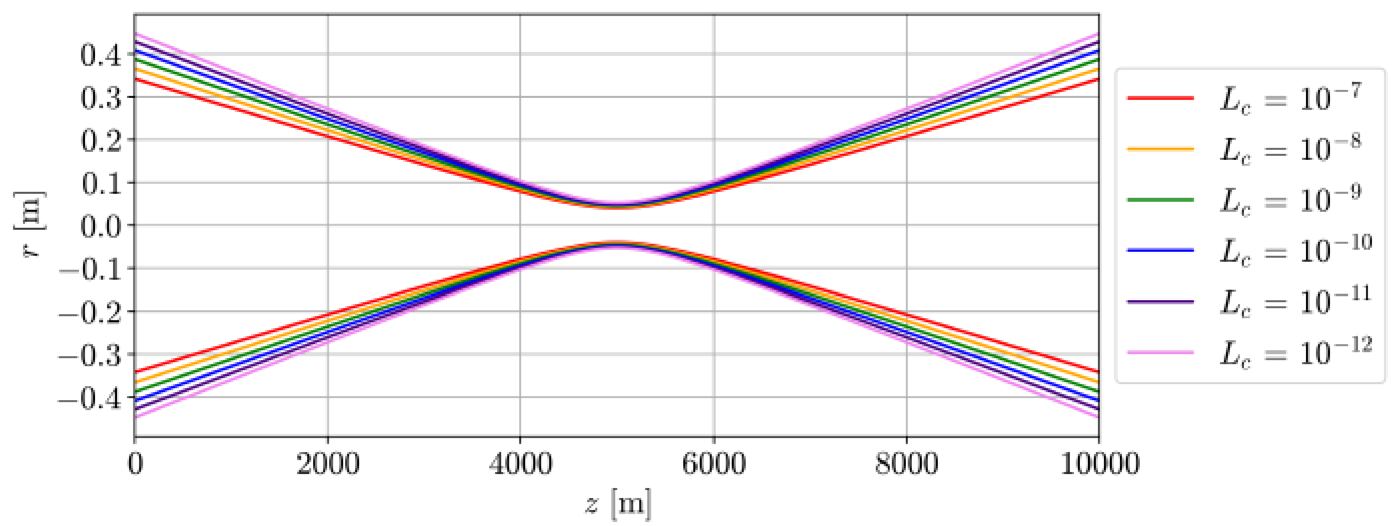
Source: M. Zucker and S. E. Whitcomb, LIGO DCC P940008

Scattered light

source: [M. Andrés-Carcasona et al. arXiv:2307.14104 [gr-qc]]

- Optical aperture of ET's laser beam
- Minimal aperture of vacuum tube design with constant radius determined by the losses close to the mirrors
- Aim to maintain losses below $L_c<10^{-8}$ implies r_{pipe}=0.42m (HF)
  r_{pipe}=0.31m (HF)

$$r(z, L_c) = \frac{w(z)}{\sqrt{2}}\sqrt{\ln\left(\frac{1}{L_c}\right)} + r_{\mathrm{offset}},$$

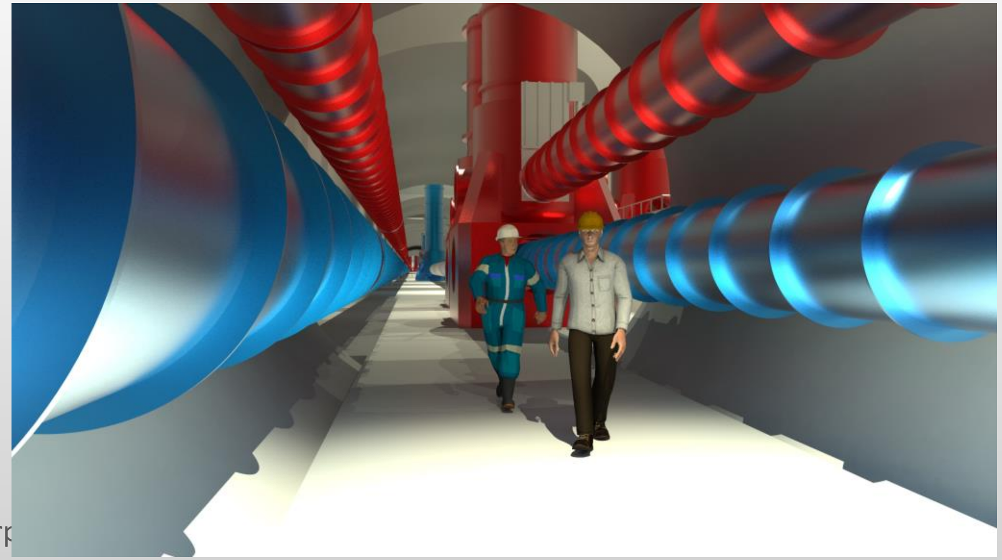


(a) ET-HF

- Optical baffles shield mirrors from stray light
- Typical baffle size is 0.1 m
- Implies minimal beam pipe diameter of 1m
- If pipe needs bakeout: thickness of insulation
- Welding/repair and safety margins

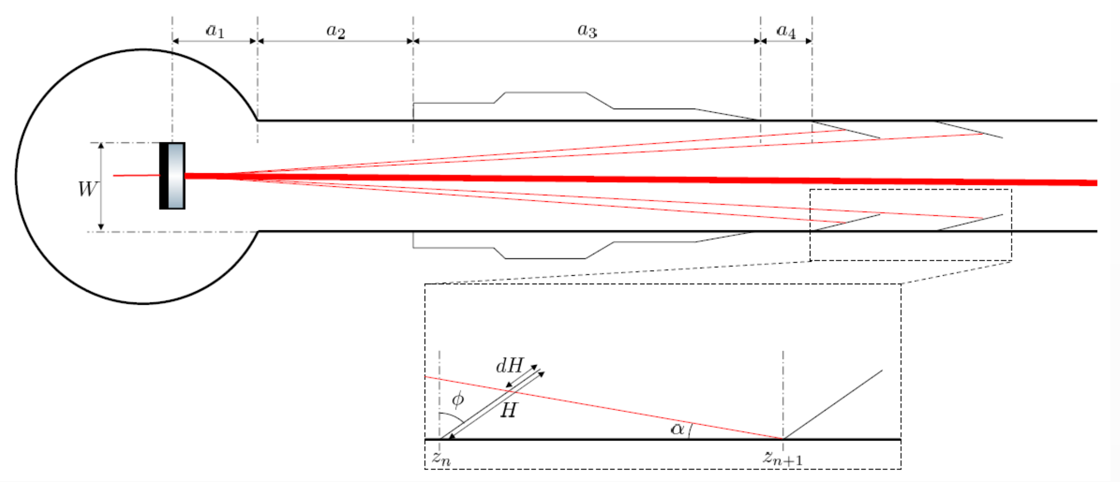
Notes on pipe diameter:

- Has impact on tunnel diameter
- Tunnel excavation price scales with diameter
- Current tunnel diameter: 6.5m



Baffles

source: [M. Andrés-Carcasona et al. arXiv:2307.14104 [gr-qc]]



- Analogous to aLIGO and adV the vacuum system will be equipped with conical baffles shielding the aperture from stray light due to mirror finite aperture and aberrations
- Baffles in ET will start at end of the cryotraps connected to the mirror vacuum towers
- Position of first baffle: 32m (HF), 72m (LF)
- Recursive formula for distances of other baffles

$$z_{n+1} = \frac{W\left[z_n + \sin(\phi)(H - dH)\right]}{W - \cos(\phi)(H - dH)} .$$

- W= farthest point form which photons should be shielded

$$W = R + R_m/2.$$

Beampipe radius   Mirror radius

- Distance between baffles increases rapidly with distance from the main mirrors

Nr of baffles needed for various pipe diameters,
Assuming unequal (minimum) or equal spacing

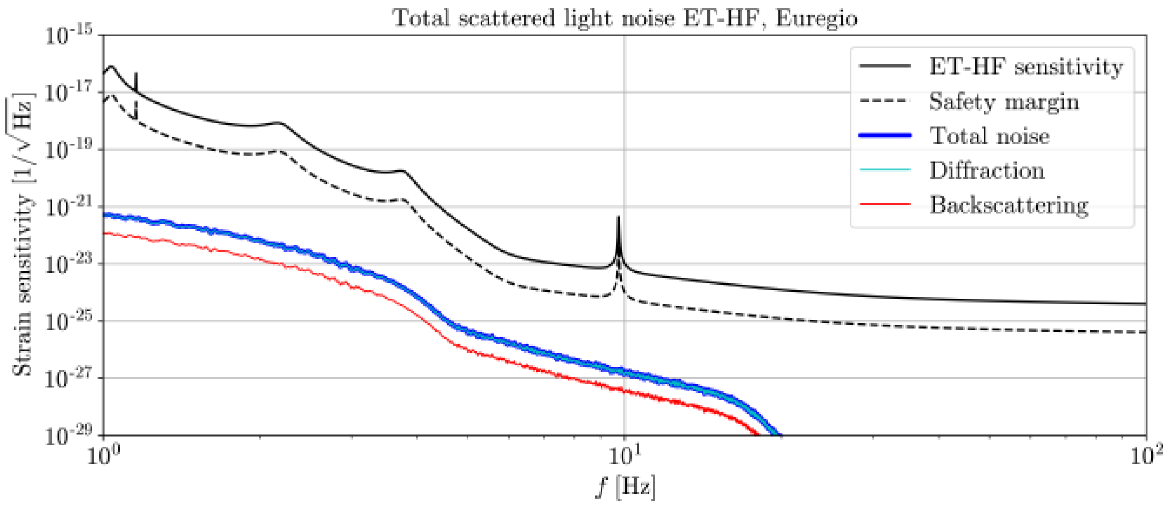
ITF	Minimum	$l_{sec} = 50$ m	$l_{sec} = 100$ m
ET-HF (0.5m)	118	244	162
ET-HF (0.6m)	134	254	172
ET-LF	90	222	136

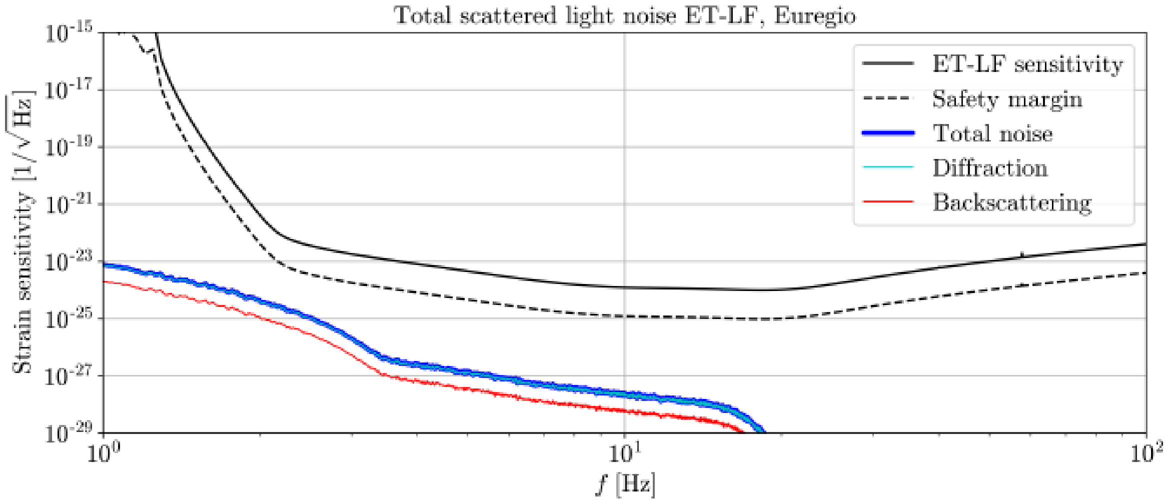
Default configuration for simulations

Scattered light simulation

Contains many ingredients:

- Mirror surface quality impacts BRDF
- Longitudinal vibration of baffles induce phase shifts
- Various sources of noise & mitigation:
  - **Diffraction**: serrate edges of baffles
  - **Backscattering**
  - Reflection on edges: serrating
  - Shining surfaces: do not expose beam pipe to photons





Effect of dust

Goal: set cleanliness requirements for the installation of ET pipes

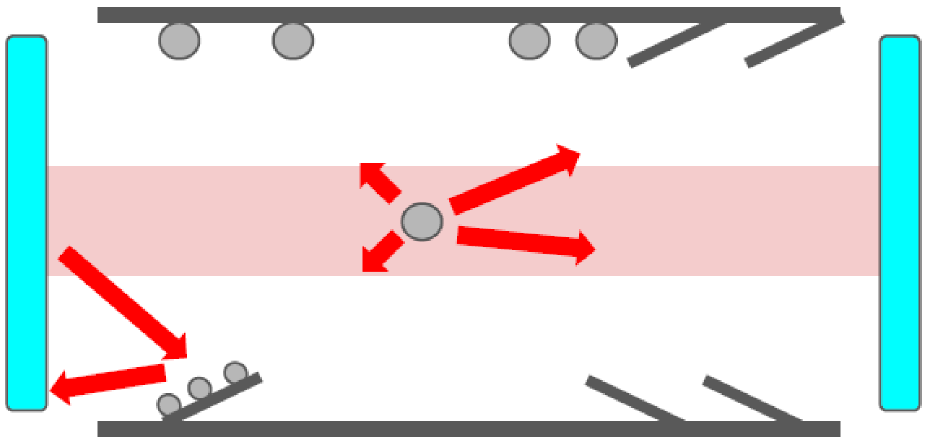
Focus on straylight caused by dust (D≳0.1µm) contamination in the arms (assessment of dust impact on TM towers and baffles requires dedicated study)

Dust can **enter inside the arms**:

- during installation: construction of the pipe with installation of baffles
- during storage of the installed tube sections, before the full pipe is built
- when in vacuum due to the pumps and gate valves

Dust produce **different effects**:

- dust deposited on baffles contribute to scatter light reaching the baffles
- deposited particles can detach, cross the light beam circulating in the arm and scatter light



Source: A. Moscatello at 2nd ET annual meeting, Orsay, 13-16 November 2023

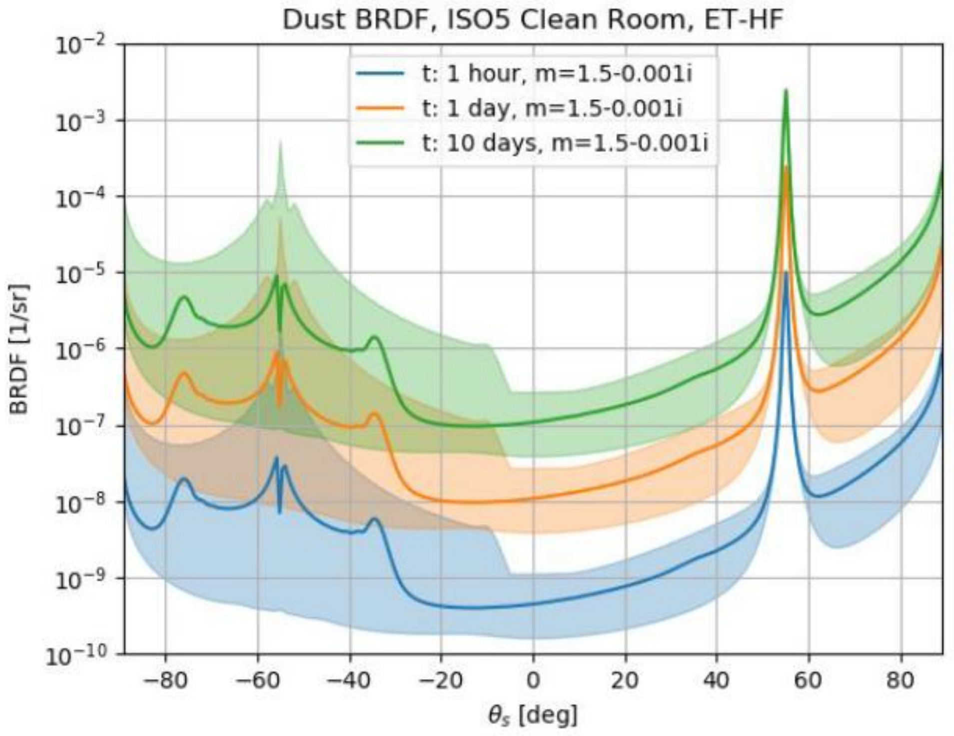
Dust on Baffles

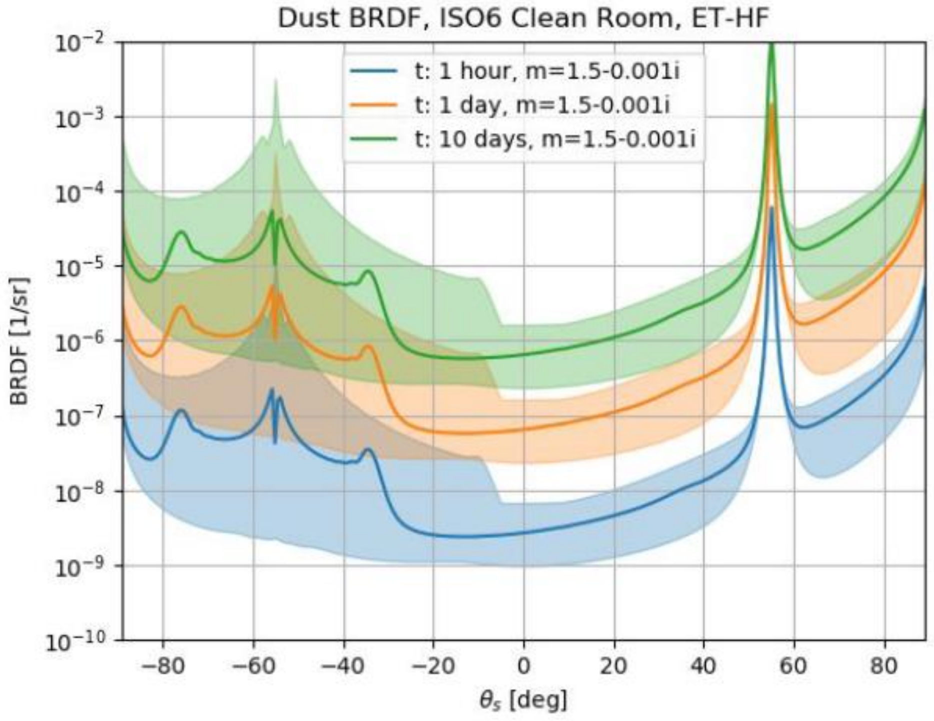
Different cleanliness scenarios are tested: from the deposited dust distribution the BRDF of the dust is computed with Mie Theory.

E.g. assuming each baffle is exposed **1 day** inside an **ISO6** clean room:

$$BRDF_{baffle} + BRDF_{dust} \approx 2*BRDF_{baffle}$$

In mobile cleanroom tents in accelerator tunnels local environments of class ISO 5 can be established





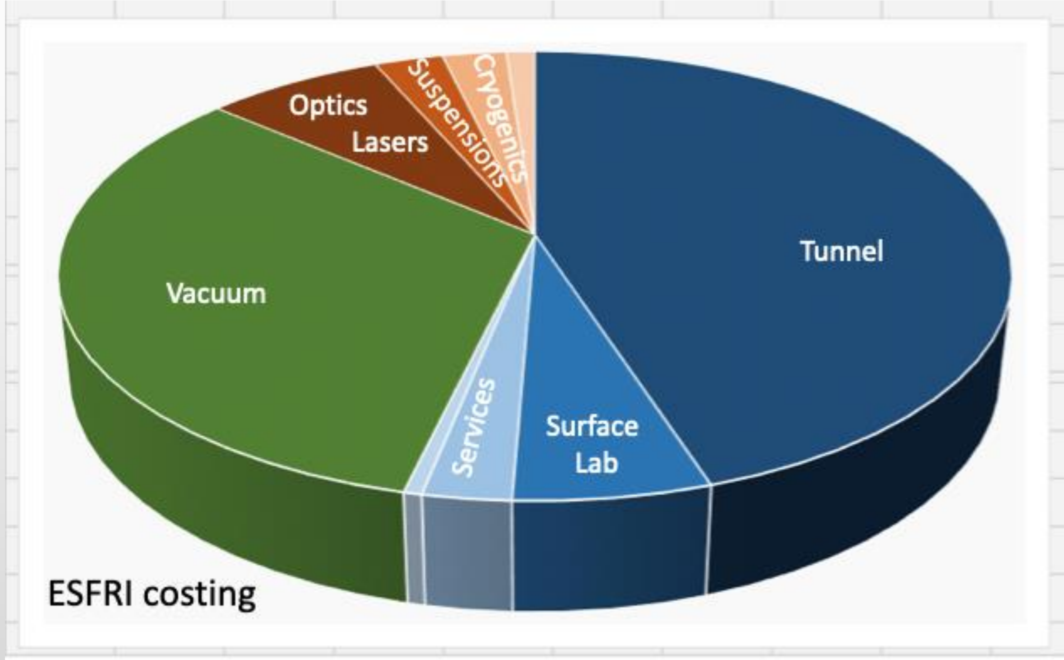
- baffles BRDF=10^{-4}/sr
- baffles reflectivity: 10^{-2}
- shaded area covers different dust's index of refractions

6

Source: A. Moscatello at 2nd ET annual meeting, Orsay, 13-16 November 2023

Contribution to ET's cost and logistics:

- Largest UHV system in the world:
  - 1m diameter pipes, length 120 km
  - Volume: 9.4×10^4 m3
  - Surface area: 3.8×10^5 m2
- Total cost assuming scaling from Virgo:
  - 560 M€ (1/3rd of construction cost)



Assuming Virgo approach:

- 13000 tons of raw steel
- 8000 modules 15 m long
- 8 modules/day production (includes leak and extensive quality control checks)
- 240 pumping stations every 500m (5000 l/s effective, ionic, getter, auxiliary turbo molecular)
- 720 gate valves (250 mm)
- 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)

Lots of time and cost saving possible on several of these items:

- Material type: various steel species with varying price
- Amount of material: thickness & weight
- Length of sections: produced off or on site?
- Types of pumps: varying capacity
- Less valves: but high risk for leaks
- Avoid heat treatment and bakeout: ferritic steel vs stainless

Different designs in 2nd gen interferometers:

From: A. Grado *et al* *J. Vac. Sci. Technol. B* 41, 024201 (2023)

	Virgo	LIGO	KAGRA	GEO600
Material (AISI)	304L	304L	304L	316L
Length (km)	6	2×8	6	1.2
Diameter (m)	1.2	1.24	0.81	0.6
Section length (m)	15	16	12	4.5
Thickness (mm)	4	3.23	8	0.8
Tube type	Sheet welded	Spiral welded	Sheet welded	Deep corrug.
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}	1.5×10^{-7}[b]
Pumps distance (m)	600	2000	600	600
Firing temp (^oC)	400	455	200	200
Firing duration	5 days	36 h	20 h	48 h
Bakeout temp (^oC)	150	160	No (electro-polishing)	250
Bakeout duration	1 week	3 weeks		5 days
Pumps types	TMP, Ion+Ti Sub.	TMP, Ion+Cryo	TMP, Ion	TMP

All stainless steel

Thick walls require no stiffeners

Thin walls require corrugation

Very low cost

Large Energy cost & Logistics!

Concerted effort between ET and CERN

Studies

- **DESIGN** (Mechanical stability, supports, etc.)
- **MATERIAL** (Welding, manufacturing, cleaning, etc.)
- **VACUUM** (Layout, pumps, gauges, bake-out, etc.)

↓

Pre-prototyping

- **PRODUCTION**
- **MEASUREMENT**

↓

Pilot sector

- **FABRICATION & TEST** Solution 1
- **FABRICATION & TEST** Solution 2
- **FABRICATION & TEST** Solution n

Source: C. Scarcia at 2nd ET annual meeting, Orsay, 13-16 November 2023

Beampipe structural materials

Einstein Telescope

Austenitic stainless steel (304L)

- Mechanical properties
- Formability and weldability
- Corrosion resistance (native)
- Vacuum performance (requires HT heat treatment)
- Cost (raw material)
- Non ferromagnetic ($\mu_R \approx 1$)

Ferritic stainless steel

- Mechanical properties
- Formability and weldability
- Corrosion resistance (native)
- Vacuum performance (native)
- Cost (raw material, 30-50% less than austenitic)
- Ferromagnetic ($\mu_R > 200$)

Mild steel

- Mechanical properties
- Formability and weldability
- Corrosion resistance (requires treatment)
- Vacuum performance (native)
- Cost (raw material, 80-85% less than austenitic)
- Ferromagnetic ($\mu_R \approx 100\text{-}200$)

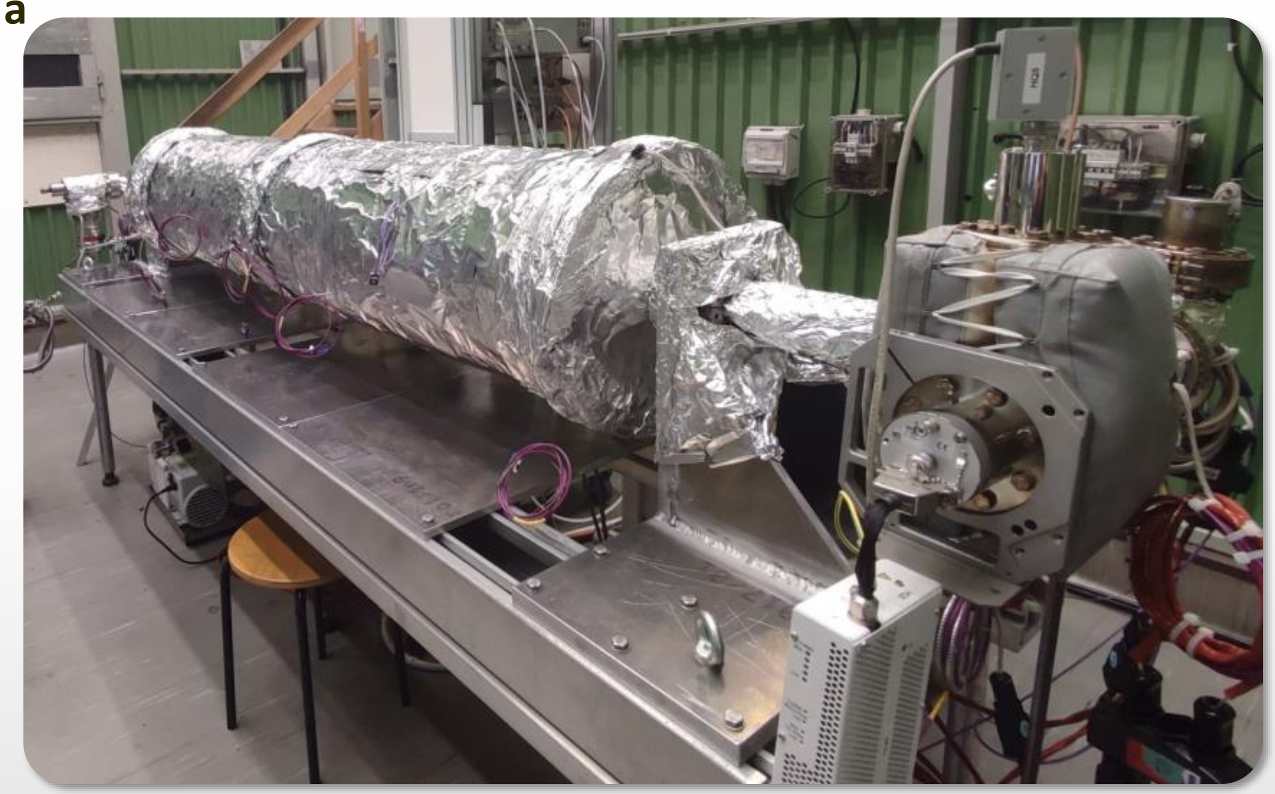
Cosmic Explorer

Source: C. Scarcia at XIII ET Symposium, Cagliari, 8-12 May 2023

Material/vacuum

Reliable and **predictable outgassing rate measured with a dedicated test bench**.

- Ø 400 mm x 2100 mm.
- Thickness < 2 mm.
- Corrugated solution.
- Pumping speeds scaled to ET dimensions.
- Materials:
    - AISI 304L vacuum-fired [austenitic SS]
    - S315MC [mild steel]
    - AISI 441 [ferritic SS]

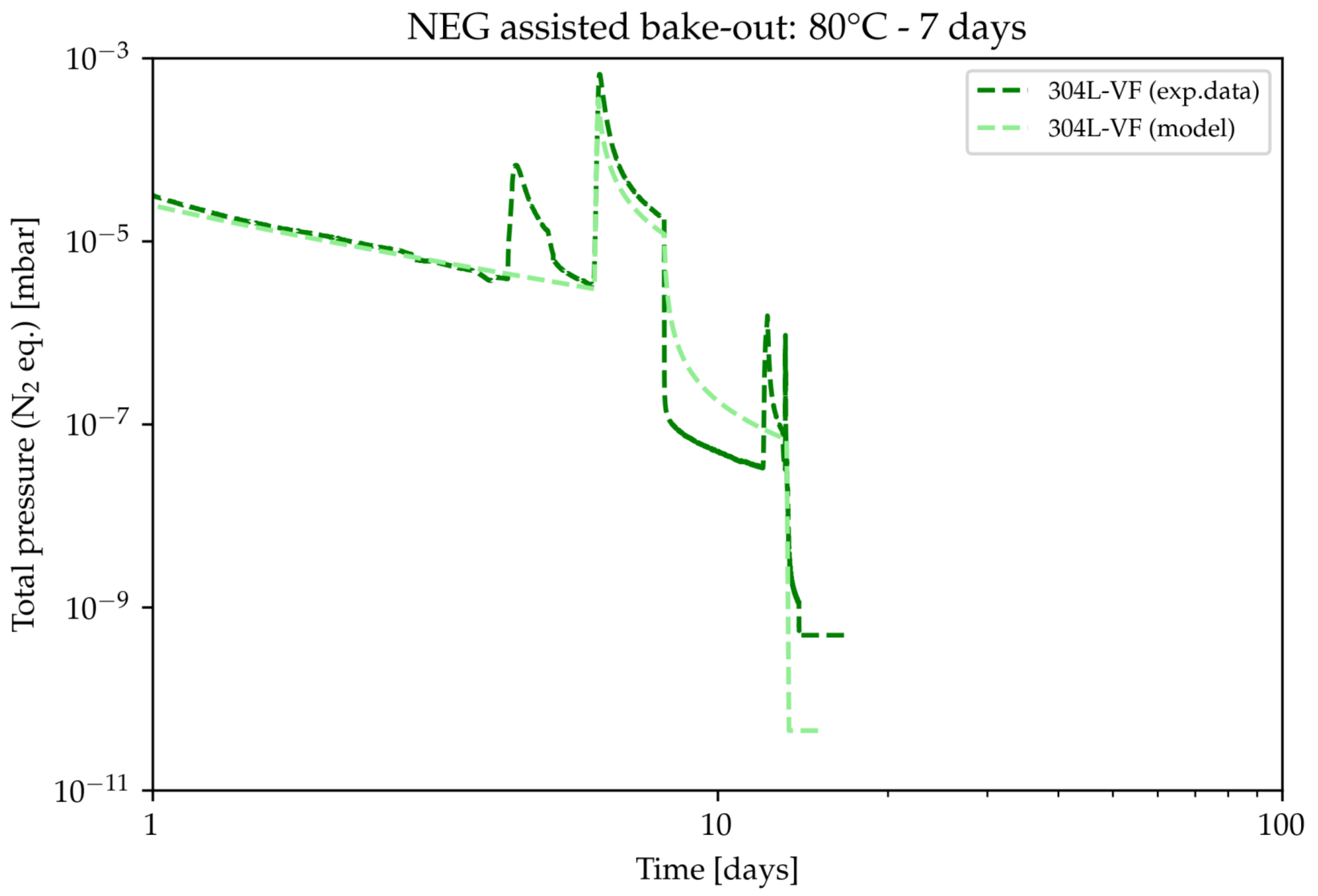


Objectives:

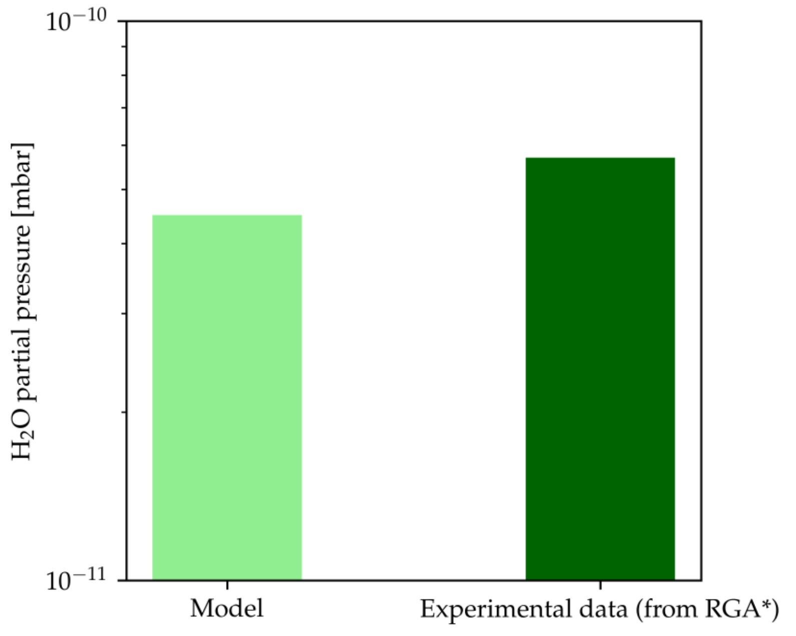
- Verify water outgassing modelling.
- Ultimate pressure after 80°C and 150°C bake-out.
- Estimate outgassing rate of materials.

Source: C. Scarcia at 2nd ET annual meeting, Orsay, 13-16 November 2023

Material/vacuum



Water pressure calculated from mass 18 signal



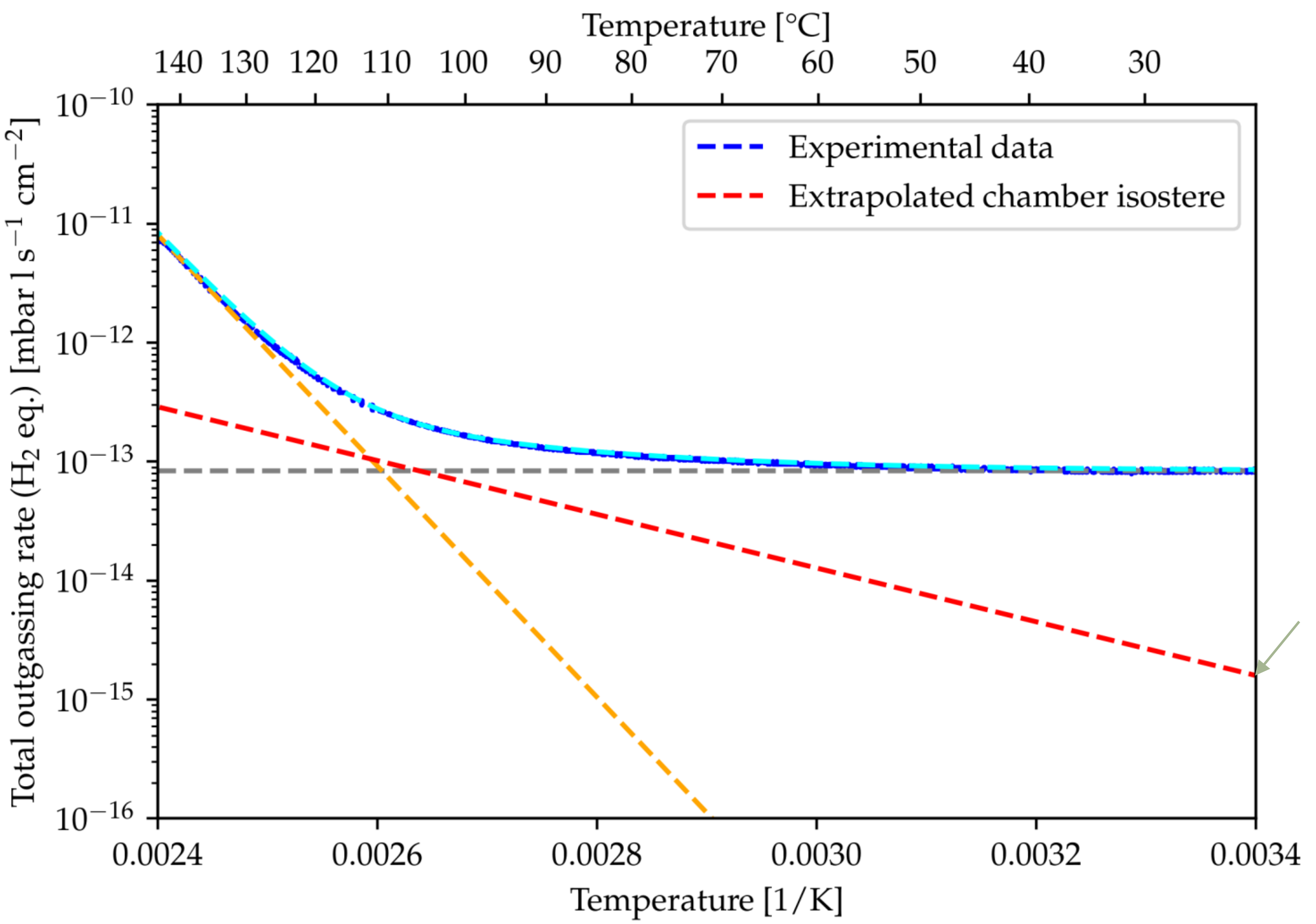
The difference between the model and the experimental data is of 20%

Source: C. Scarcia at 2nd ET annual meeting, Orsay, 13-16 November 2023

Outgassing rate vs temperature

Example:
304L-VF chamber

Hydrogen
Water-like
Instruments & gauges



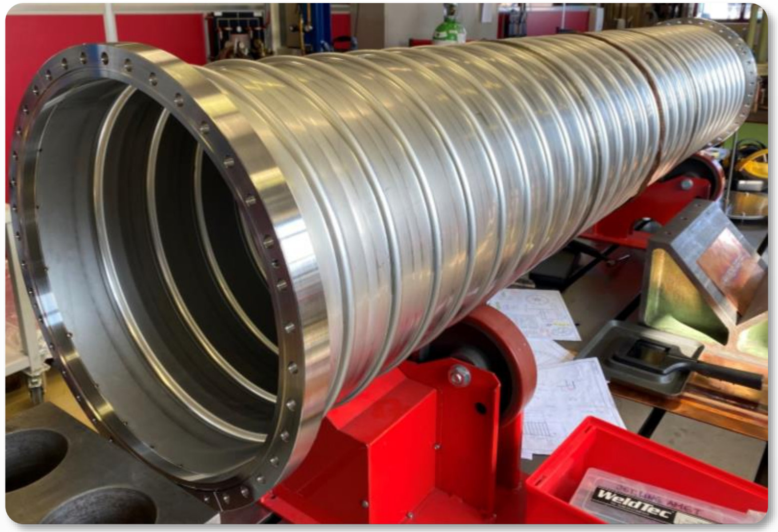
$q_{H2} \approx 1.5\times10^{-15}$ mbar l s^{-1} cm^{-2}

Source: C. Scarcia at 2nd ET annual meeting, Orsay, 13-16 November 2023

Design

Proved mechanical stability of a **corrugated pipe**.

- **For the pilot sector**: Preparation of the technical specifications for a price inquiry following CERN's purchasing rules.
  - Corrugated pipe: Ø 1000 x 1.5 - 2 mm
  - Smooth pipe: Ø 1000 x 3 - 4 mm
- **Contact** with **industry** to evaluate the **feasibility** of a **large-scale production** of the **corrugated** solution.



Source: C. Scarcia at 2nd ET annual meeting, Orsay, 13-16 November 2023

Welding

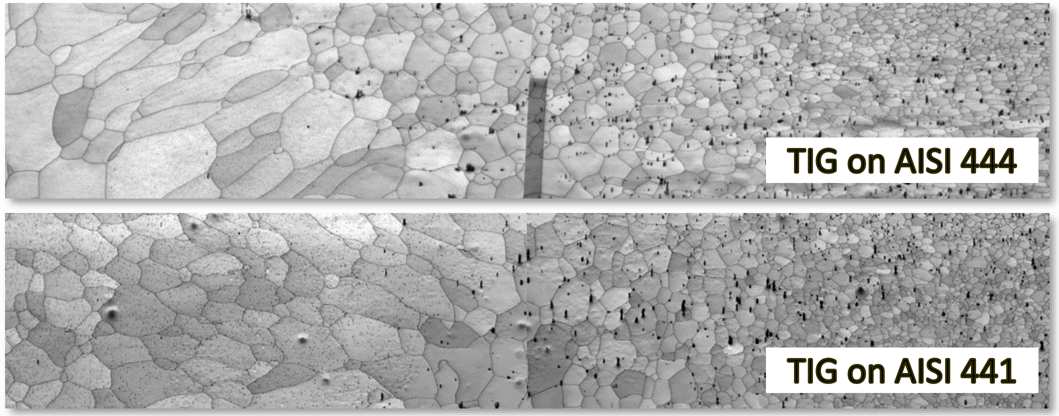
See also Alexey's talk

Welding of **ferritic stainless steels:**
conclusive and **positive tests**

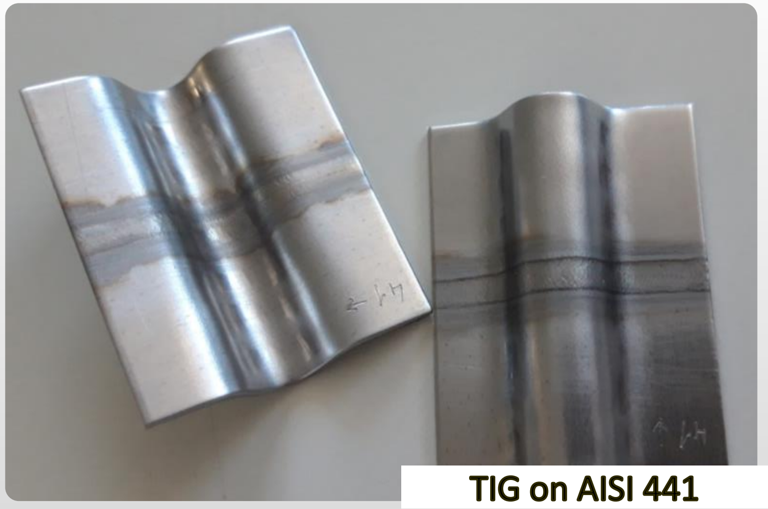
- **Identification** of the **source** of **welding problem** (grain coarsening, martensite precipitation, etc.)
  - ✓ **Selection** of a **ferritic SS** with **better weldability** (AISI 441, industrial partner).
  - ✓ **Improved welding parameters** (characterization w/ Univ. of Ghent).
  - ✓ **Improved manufacturing steps** (cracking during corrugation solved).
  - ✓ **Test welding techniques other than TIG** (**laser** CW v. Pulsed).

In preparation for the pilot sector:

- **Price inquiry for raw material** (coils).
  (preliminary contacts w/ APERAM, Arvedi, AST)



Credit: UGhent



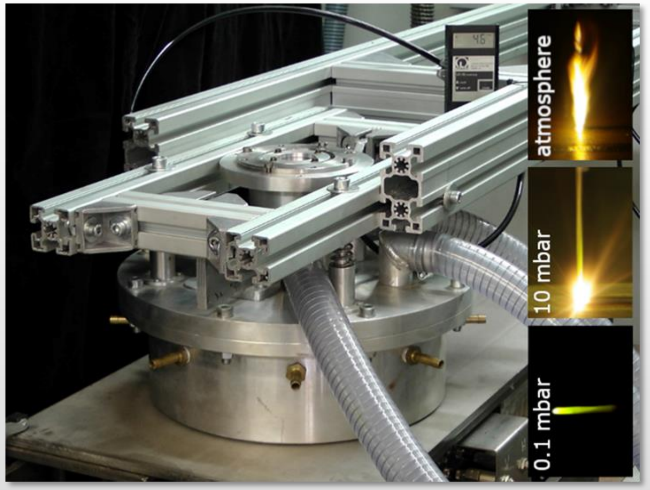
Credit: CERN

Automated Welding under vacuum

New ways to tackle productivity rate and welding quality.

FEF GmbH, RWTH Aachen, Werkhuizen Hengelhoef and APERAM collaborated for the preliminary design of a forming-welding machine:

- Laser beam welding under movable vacuum (30 mbar)
- Possibility to weld realistically up to 500 m long sections
- Possibility to integrate continuous QC monitoring (ultrasonic or X-ray imaging)



Source: U. Reisgen, S. Olschok, N. Holtum, S. Jakobs: "Laser beam in mobile vacuum". Proceedings: Lasers in Manufacturing - LIM 2017, Munich, Germany

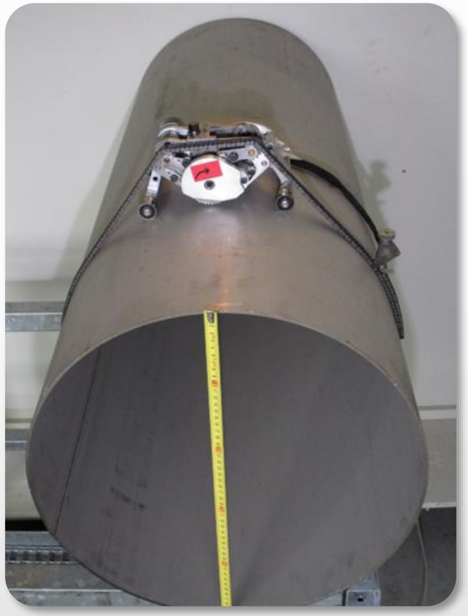
New Interreg proposal submitted with UAntwerpen RWTH Aachen, FEF, Werkhuizen Hengelhoef

Credit: Arc Machines Inc.

Space between ET beampipes very limited.

- New compact and customizable orbital welding tools integrating laser seam tracker and endoscopes.
- In case of a repair during operation, use of light and compact orbital milling machine.

→ **Minimum space required 40/50 cm between two stacked tubes** (insulation included)



Example of light and compact orbital milling machine developed at CERN for pipe cutting. *Credits: CERN*

Outlook: CERN pilot sectors

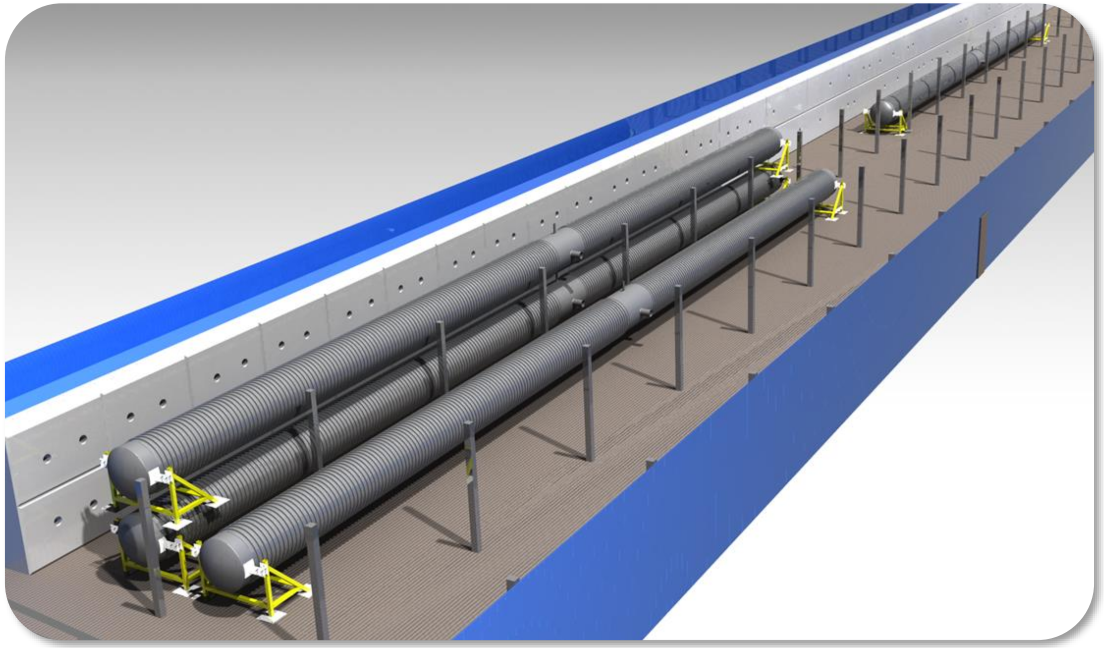
- **Up to 4 tubes**
  Ø 1 m x 50 m
- **Corrugated or VIRGO-like** solution (stacked or adjacent)
- Possibility to test **different materials**
- **Pumping speeds** scaled to **ET** dimensions

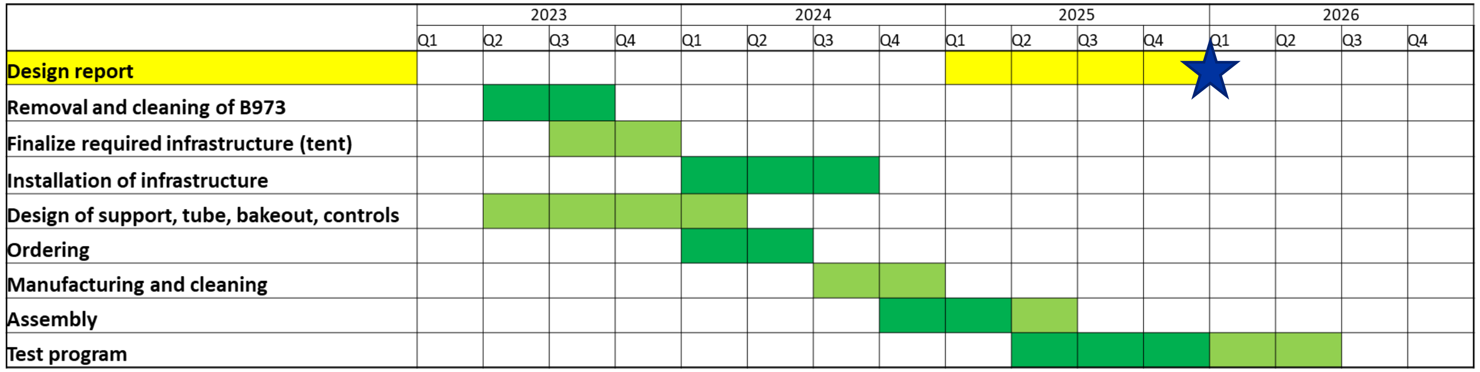
The installation will serve to **test**:

- Installation and alignment of supports and tubes.
- **Welding and assembly tools** and methods.
- **Leak detection** scenarios
- **Ultimate pressure** and **outgassing measurement after bake-out.**

We are **open for** other **experimental measurements:**

- **Dust concentration** and **displacement inside the tube**.
- **Installation** and **alignment** of **baffles inside the tube**.
- **Vibration transfer function studies**.

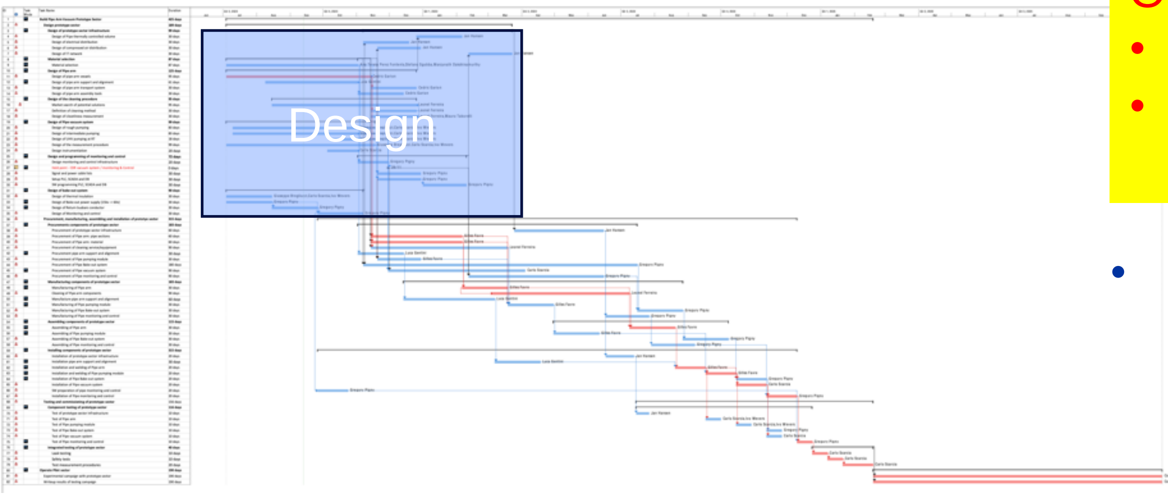


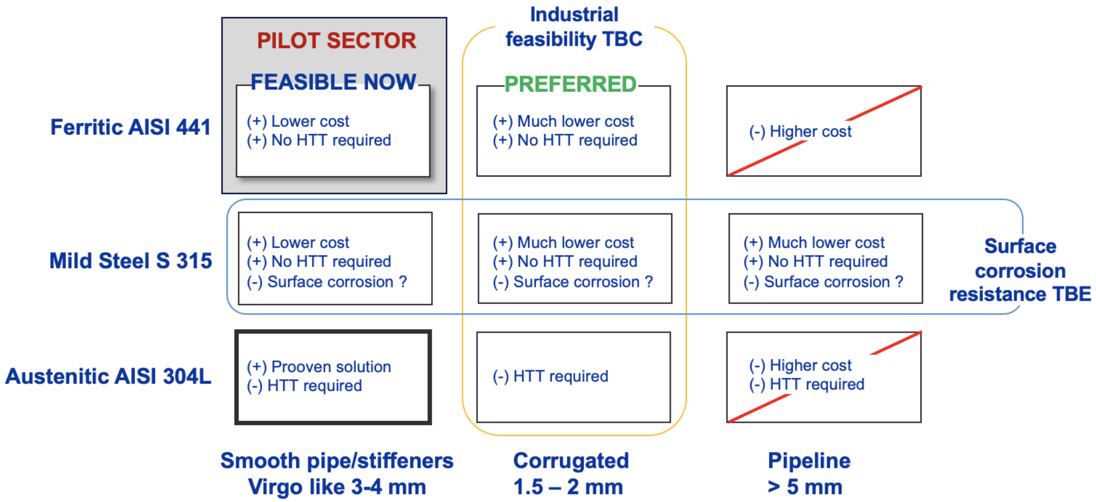


Preliminary schedule

★ Main deliverable: provide design report by end 2025

General Planning





HTT - High Temperature Treatment
Costs - relative to the Virgo like baseline.

Observations:

- Design of pipe arm in the critical path.
- Hold point to line up choices for the vacuum system and bakeout equipment.

- As the corrugated beampipe cannot be fabricated in due time with the required UHV characteristics, it is kept only for design studies while seeking a valid industrial partner.
- The VIRGO geometry beampipe made of 4-mm thick AISI 441 is now prioritized for the first test with the pilot sector.
- The support system of the pilot sector will be compatible with beampipes of different geometries.
- NEXT: A **review on material and design of the beampipe for the pilot sector** will be organized in the coming months with an international panel.

Conclusions & Outlook

- Lots of simulations on various effects:
  - Residual gas and pumping scheme
  - Light scattering and baffles
  - Dust on baffles and free falling dust
  - Many other: alignment, cleaning, installation, safety
  - Completing requirements document

- CERN activities currently focus on
  - Material choices
  - Pipe and support structure design
  - Acquisition of materials and services
  - Planning the production of first pilot sector
  - Production of preliminary TDR by end 2024
  - Pilot sectors ready for testing by end 2025

- Input from Flanders
  - UGent: Materials, procurement, manufacturing (see Alexey's talk)
  - UAntwerpen: Support on pilot sector design and installation
    New hiring completed: P. Revathi will join CERN team as of Jan 2024