Scattered light in the arms for the vacuum pipe design

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(On behalf of IFAE Team)*

ICREA IFAE BIST EXCELENCIA SEVERO OCHOA

ET Symposium, Cagliari, Italy, May 8th - 12th 2023

* In collaboration with Hiroaki Yamamoto and Alena Ananyeva (Caltech)

Outline

- Part I
  - Notes on Stray Light Calculations & Caveats
  - Considerations on tube dimensions
  - Baffle strategy
  - Stray Light contributions
  - SL noise vs ET sensitivity
  - Mechanical transfer factors
  - Baffle Production
- Final notes & Next steps

Stray Light Noise Calculations

VIR-NOT-LAL-1390-123

(Initial considerations)

LIGO-890017-00-R

LIGO-T940063-00-R, LIGO-T950033-00

- Our results are based on detailed analytical calculations made by LIGO (Thorne et al.) and Virgo (Vinet et al.) in the last decades + FFT simulations by H. Yamamoto
- Some of the calculations are limited accuracy/validity
- There is an extensive literature on the subject. LIGO and Virgo were built using those considerations.
- When possible we use simulations to test the validity of the analytical expressions
- **There are unknowns that suggest caution in comparing SL noise with ET sensitivity curves**
  - **You want to be factor 10 below sensitivity**
- **We are using ET CDR based parameters**
  - **using foreseen mirror maps (O5 quality)**
  - **using conservative baffle BRDF (0.01 str-1)**
  - **First using average seismic levels**
  - **using ground-baffle transfer factors = 1**

CNRS
Centre National de la Recherche Scientifique

INFN
Istituto Nazionale di Fisica Nucleare

VIRGO

Summary of scattered light noise calculations and baffle design in the long cavities

Violette Brisson, Jean-Yves Vinet

Groupe Virgo-LAL and Groupe Laser-Optique, Bat 208 Orsay

VIR-NOT-LAL-1390-123
Issue: 1
Date : September 1st, 1998

LIGO-T890017-00-R

\# 36

List of 3/1/89

Light Scattering and Proposed Baffle Configuration for the LIGO

Second Draft, 11 January 1989

*Kip S. Thorne**

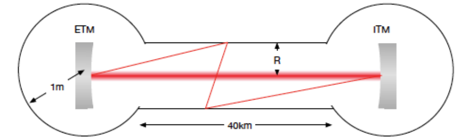
California Institute of Technology, Pasadena, California 91125

ABSTRACT

When light, hitting a mirror, scatters out of the main beam of an interferometric gravitational-wave detector, then makes its way back into the beam via reflection, scattering, and/or diffraction off the LIGO vacuum pipe, baffles, or mirrors, it produces a slight phase shift in the main beam's light. Wiggle of the main beam and vibrations of the vacuum pipe and baffles cause this phase shift to oscillate, simulating a gravitational wave. The dominant contributions to this gravitational-wave noise are here computed; and those computations are used to suggest constraints on the design of the baffles for the LIGO. If these constraints are followed, there is no reason to expect serious problems with light scattering in the LIGO, even in very advanced detectors of the highest currently projected sensitivities. By contrast, without baffles there would be severe and perhaps insurmountable light-scattering noise.

LIGO-T950033-00

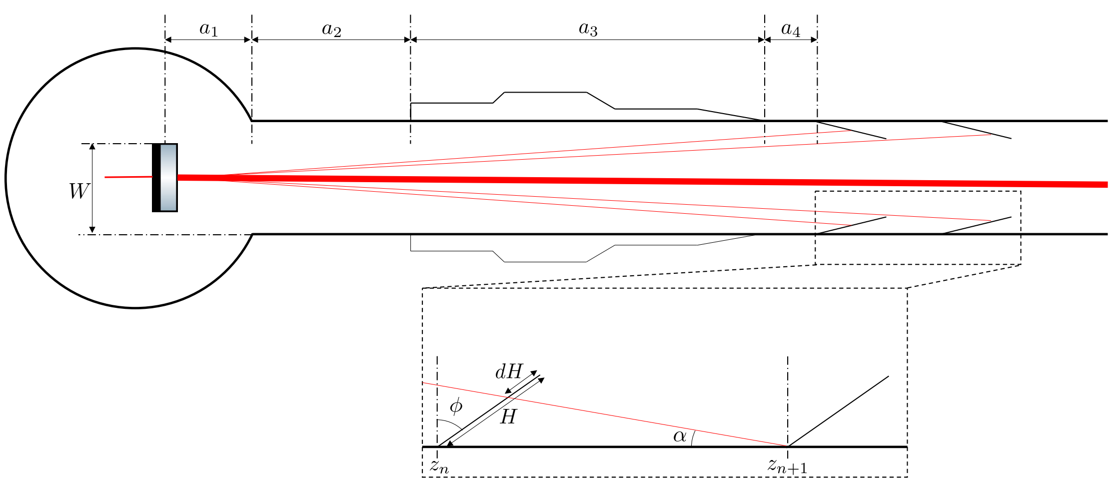
On tube diameter



- Current (LVK) approach is to hide the bare tube from the mirrors using baffles to avoid noise from reflections and scattering on the tube walls and on UHV structures hard to model.

- The baffle aperture talks to many aspects including the cavity optics, mirror maps, the level of scattering and losses, seismic noise levels, and should also include considerations on possible beam offsets

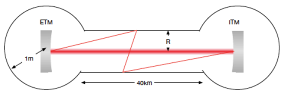
- We established the positions of the arm baffles (defined as after the cryotraps)
  - ET CDR suggests z0 positions for first baffle of about 35 m for ET-HF and 75 m for ET-LF from mirror
  - Baffle are 55 degrees inclination (phi) —> baffle 8 cm vertical height
  - W is defined by the height at the edge of the mirror
  - dH is about 1 cm safety margin
  - Aperture is a function of losses and level of scattering / diffraction in baffle edges
    - Should avoid exposing the baffles to the “core” of the laser beam

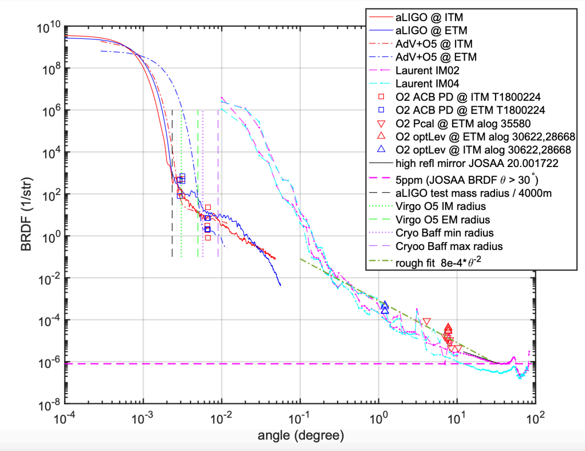


$$z_{n+1} = \frac{W\left[z_n + \sin(\phi)(H - dH)\right]}{W - \cos(\phi)(H - dH)}$$

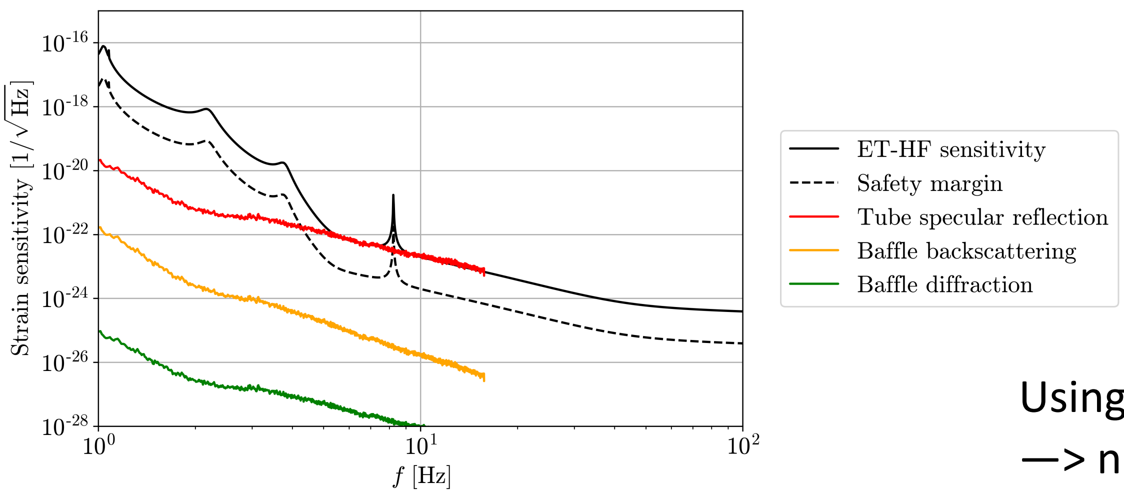
On bare tubes

LIGO-T950101





- The effect on sensitivity from a bare tube is very hard to model and here only the contribution from reflections propagating from mirror to mirror are taken into account (large dependence on mirror, tube reflectivity, # reflections, # surviving photons)
- Here we show results for ET-HF (1.2 M) and seismic noise from EMR



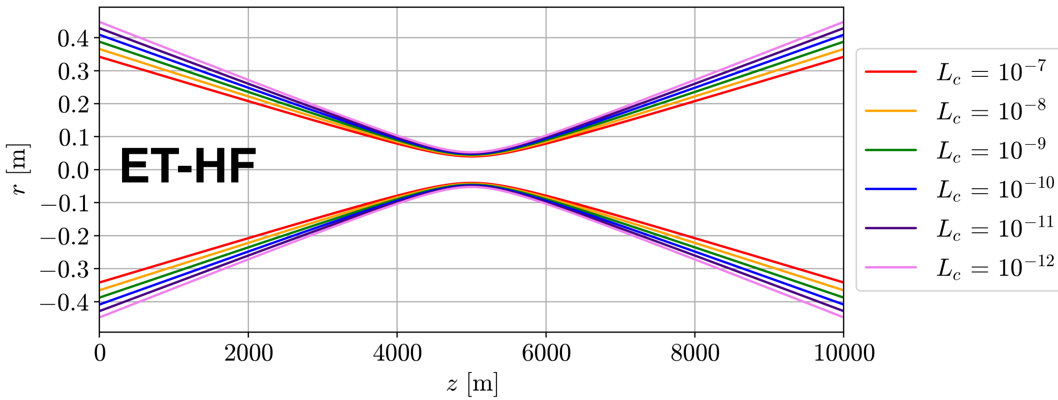
$$\tilde{h}_{\rm refl}(f) = \alpha\sqrt{2\mathcal{A}(\theta)\mathcal{M}(\theta)}\frac{\lambda}{\sqrt{LR}}\frac{\bar{A}(f)\tilde{\xi}_s(f)}{R}\sqrt{\Delta\theta}$$
$$= \frac{2.4\times10^{-24}}{\mathrm{Hz}^{1/2}}\left(\frac{10\mathrm{Hz}}{f}\right)^2\sqrt{\mathcal{A}(\theta)\mathcal{M}(\theta)}\bar{A}(f)$$
$$\times\left(\frac{\Delta\theta}{0.01}\right)^{1/2}\frac{\tilde{\xi}_s(f)}{10^{-7}(f/10\mathrm{Hz})^{-2}}. \quad (3$$

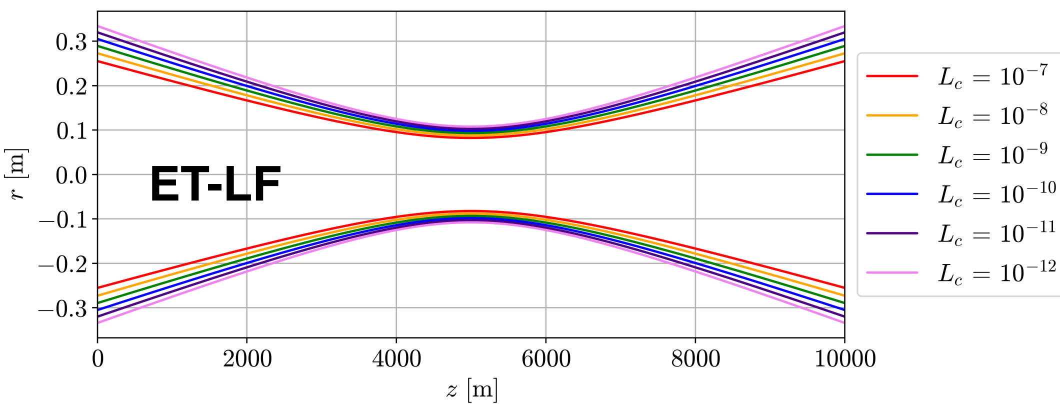
Using no magnification / attenuation effects
—> need to determine those factors

- The effect on ET sensitivity from the scattering out of tube material and structures inside the tube is not included here. The induced noise could be larger.
- —> Conclusions have to be taken with care (depends a lot of assumptions)

Beam losses

This is computed analytically
not including mirror maps
—> defects will increase losses





IFO	λ	mode	mirror ⌀	R_C	w_0	z_0	w	g−factor
ET-HF	1064 nm	TEM_{00}	62 cm	5070 m	1.42 cm	5000 m	12.0 cm	0.95
ET-LF	1550 nm	TEM_{00}	45 cm	5580 m	2.9 cm	5000 m	9.0 cm	0.63

A 2000 nm laser with 16 cm waist —> 1.2 m tube
Adding some margin to the ET-HF —> 1.2 m tube

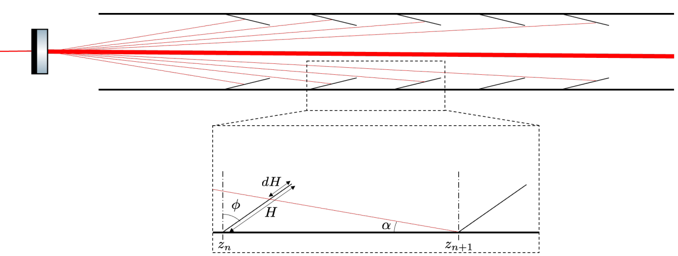
Adopting the approach of

- minimal losses @ level of 10^{-10}
- Aperture is 0.85 m for ET-HF
- Aperture is 0.62 m for ET-LF
- Adding 2x 8 cm baffle height
  —> 1.0 m (0.78 m) tube for ET-HF (ET-LF)

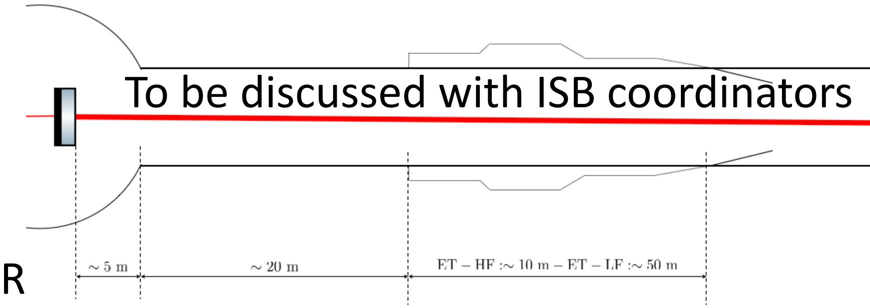
Previous work by CE used a similar argumentation

- clipping losses below 10^{-8}
- @ 3 x beam waist + 5 cm offset/tolerance
- Aperture is 0.82 m for ET-HF
- Aperture is 0.64 m for ET-LF
- Adding 2 x 8 cm baffle height
  —> 1.0 m diameter tube for EF-HF.
  —> 0.8 m diameter tune for EF-LH
- ET CDR :
  - ET-LF 0.8 m —> 1.0 m tube
  - ET-HF 1.0 m —> 1.0 m tube !
- Need to review the 8 cm baffle height

Baffles



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



To be discussed with ISB coordinators

We do not attack the region close to mirrors
—> there will be tower and cryotrap baffles
—> we adopted distances to main tube as in CDR

ET-HF

Variable	Value
Baffle aperture	1.04 (R = 1.2 m) 0.85 (R = 1 m)
Baffle inclination	35
Position of first arm baffle	35 m

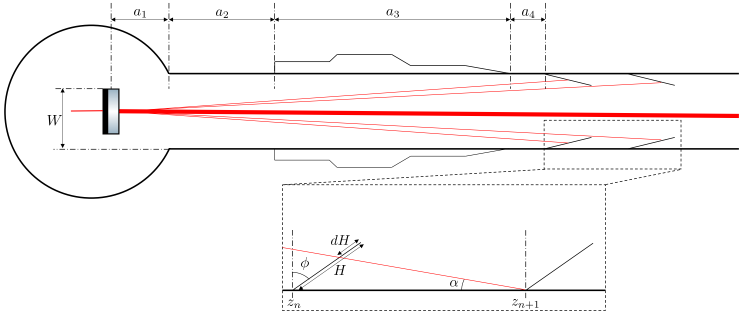
ET-LF

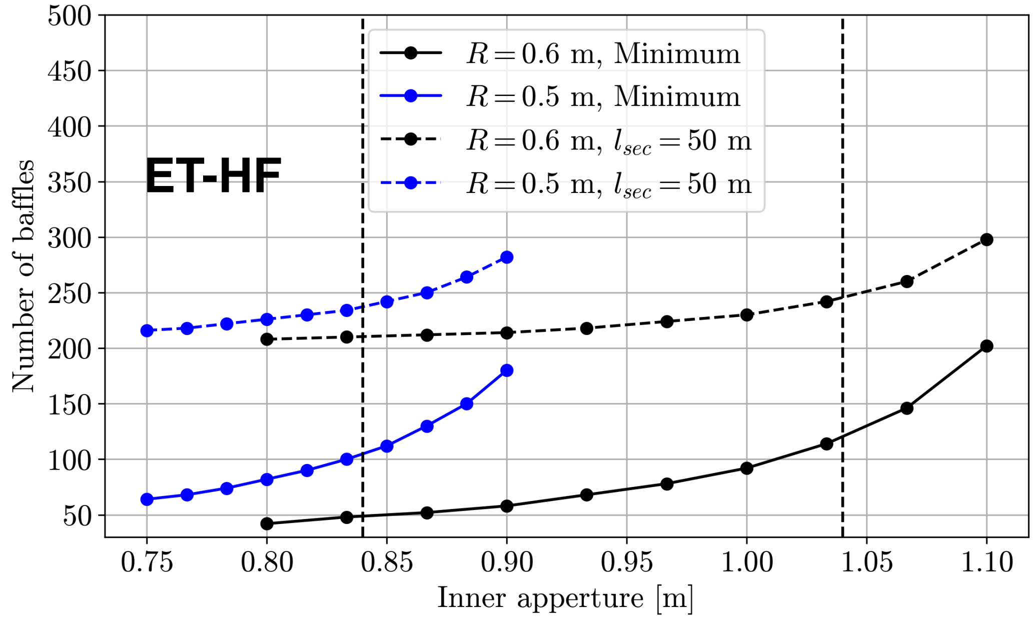
Variable	Value
Baffle aperture	0.84 (R = 1.0 m)
Baffle inclination	35
Position of first arm baffle	75 m

Baffle as needed (geometry) and assuming installation every sector or alternated.

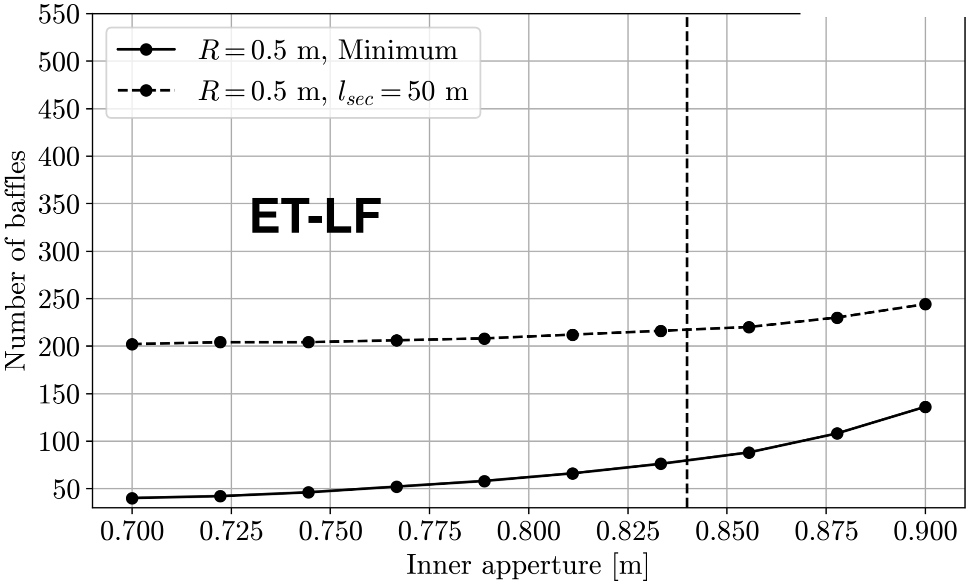
Configuration	Minimum	lsec = 50 m	lsec = 100m	lsec = 150m
ET-HF (R = 1m)	112	240	156	132
ET-HF (R = 1.2m)	116	242	160	136
ET-LF	78	216	128	102

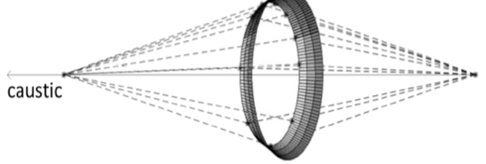
Baffles



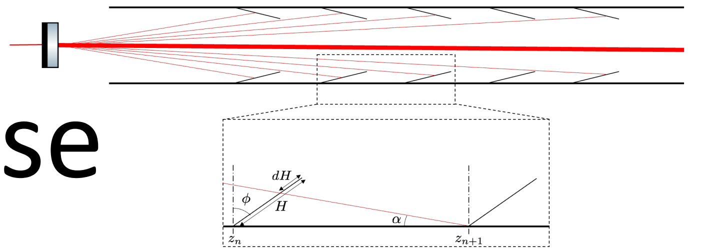


For completeness we provide information on # baffles versus tube radius and appertures and assuming minimal (geometrical) configuration and/or at the end of each 50 m section





Stray light noise

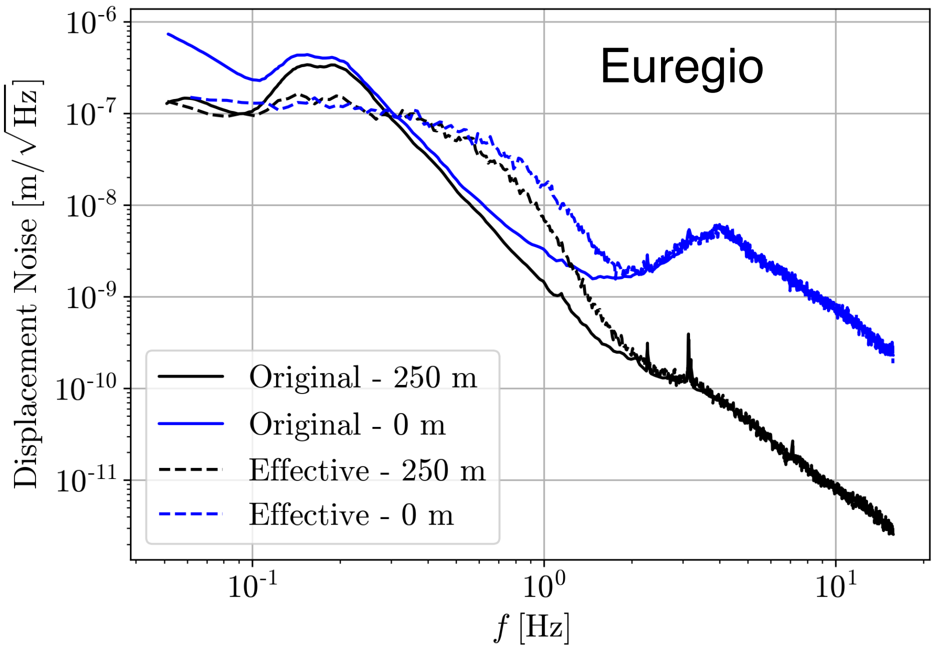


- Once the baffles are installed there are two main sources of noise that might affect the sensitivity of the interferometer
  - Backscattering from baffles to mirrors that couples with cavity
    - Introduces noise in phase and radiation pressure on the mirrors
  - Diffraction due to the inner apertures reaching the other mirror
    - Introduces noise in the phase of the main beam
- Effects related to scattering at the edges of the baffles is suppressed by serrating the baffle apertures (VIR-NOT-LAL-1390-123)

- The presence of shinning areas in the tube viewed by the mirrors now covered by the baffles

- In computing the noise from stray light there is a compromise among factors: optical quality of the baffle (BDRF), amount of light (optical parameters of the cavity & apertures), and baffle movement.
  - We use a conservative BRDF levels in the baffle (0.01 str-1)
  - We use average seismic noise upper band @ ground (and transfer factors = 1)
  - We use maximum possible apertures as dictated by baffle height and beam tube diameters
  - We assume O5 quality for the mirrors (you will see also what happens if this is not achieved)

Seismic Noise



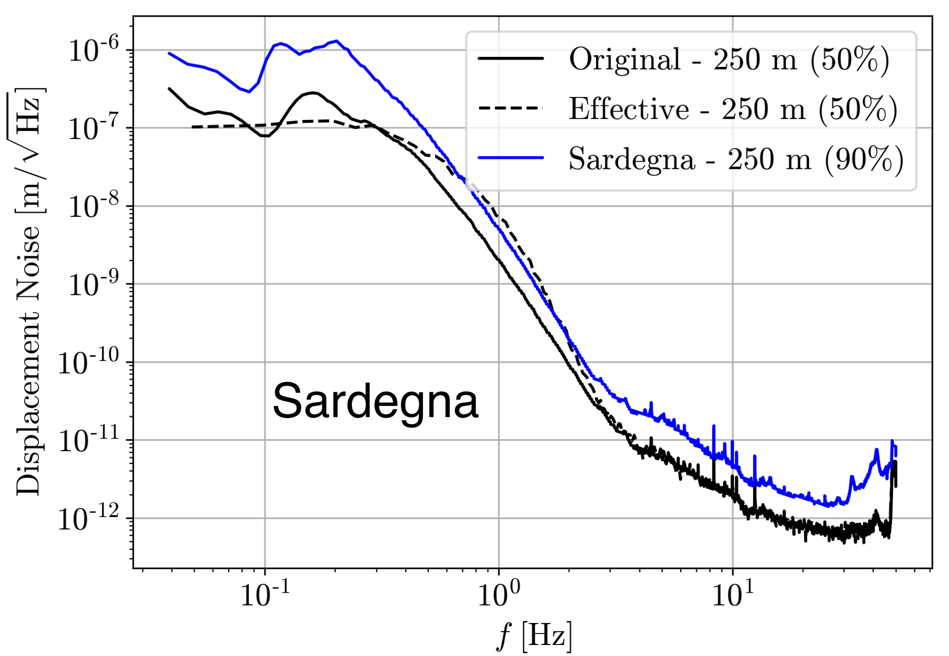
Obtain a time series from the PSD

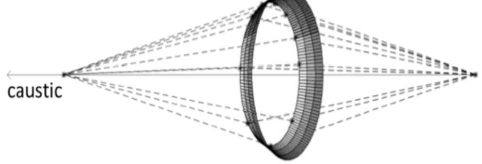
Apply the phase wrapping formula

$$\tilde{x}(f) = \frac{\lambda}{4\pi}\sqrt{PSD\left[\sin\left(\frac{4\pi}{\lambda}x(t)\right)\right]}$$

It is important to note we use at the moment the median ground noise

—> using 90% CL will boost up by ~10 the displacement





Diffraction

LIGO-T950101-00-R

Unserrated

$$\tilde{h}(f) = \frac{\kappa\lambda X(f)}{\sqrt{2}LR}\sqrt{N_B}$$

Diffraction from the limited baffles apertures can coherently accumulate and propagate thru the cavity leading to a sizable noise contribution

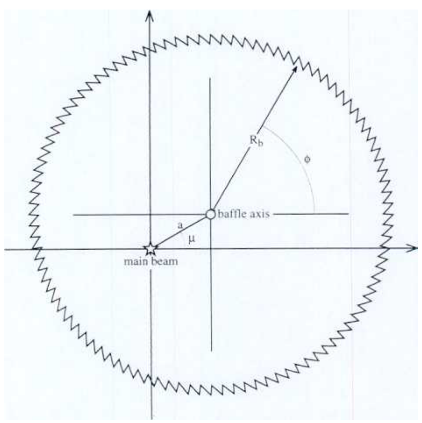
Parameter	Value
λ	1064 nm
R	0.6 m
L	10 km
κ	10^{-6}
ΔH	2 cm

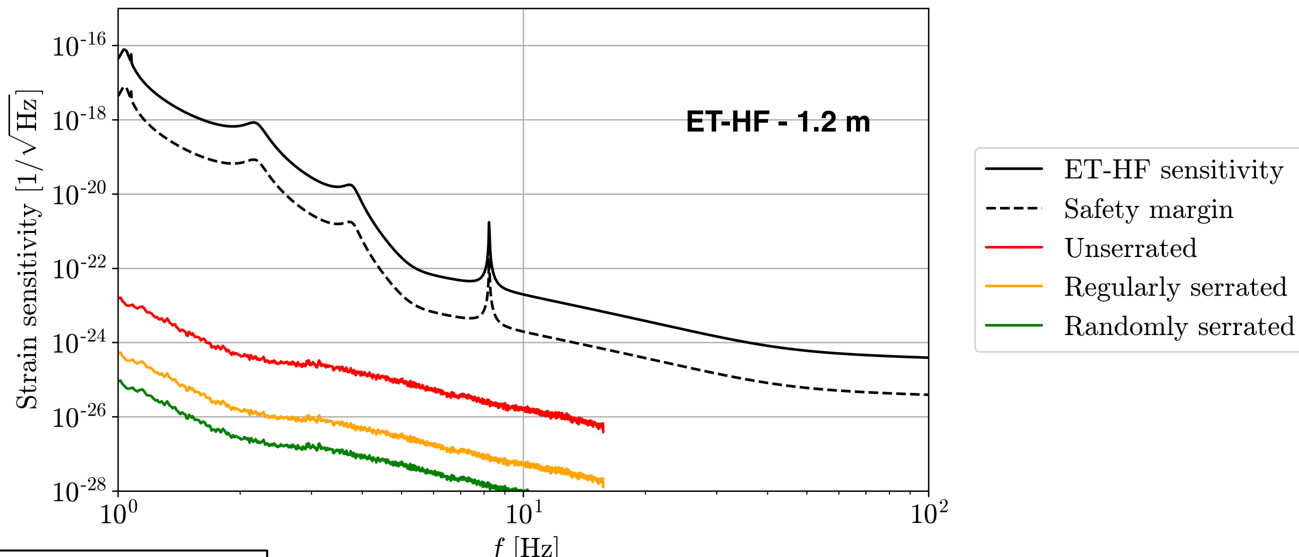
X(f) baffle displacement

NB # baffles

BRDF at the mirrors (κ/θ^2)

The coherence is destroyed when implementing serrated edges reducing the diffraction noise budget by magnitudes

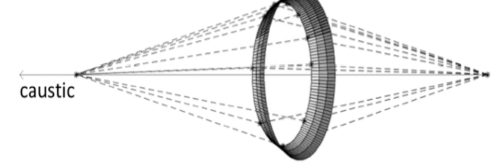




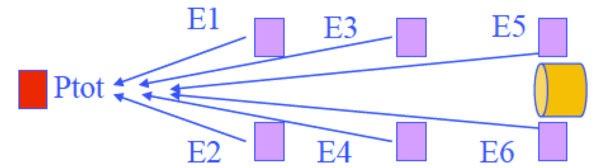
Randomly serrated

$$\tilde{h}(f) = \left[\frac{\kappa\lambda X(f)}{\sqrt{2}LR}\sqrt{N_B}\right]\left[\frac{\sqrt{2\lambda L}}{8\pi R\Delta H}\right]\overbrace{\left[\frac{\sqrt{\lambda L/4}}{2\pi R}\right]^{1/2}}^{\sim 0.1}$$

Effect from baffle edges becomes negligible



Backscattering



Taking into account both phase noise and radiation pressure to the mirror (LIGO-T1300354)

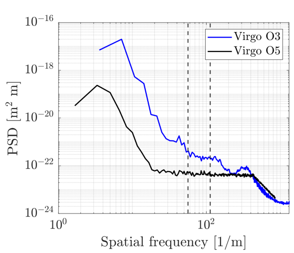
$$\tilde{h}^2(f) = \frac{1}{L^2}\left[\lambda^2 + \left(\frac{8\Gamma I_{mb}}{cM\pi f^2}\right)^2\right]\frac{\mathrm{d}P}{\mathrm{d}\Omega_{bs}}X^2(f)\sum_i K^i$$

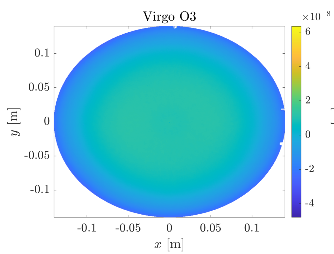
The parameters used are. (For ET-HF):

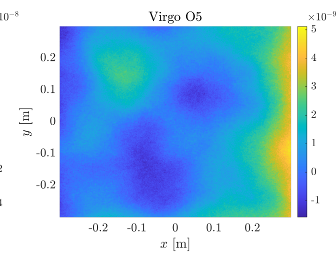
- $\Gamma = \dfrac{1}{1-\frac{r_{ITM}-r_{SRM}}{1-r_{ITM}r_{SRM}}} \approx 15.7$ Cavity signal gain. Value from LIGO-T1300354.
- $I_{mb} = 3\ \mathrm{MW}$. Circulating power in the arm.
- $M = 200\ \mathrm{kg}$. Mass of the mirror.
- $\dfrac{\mathrm{d}P}{\mathrm{d}\Omega_{bs}} = 0.01\ \mathrm{str}^{-1}$. BRDF of the baffles.
- $\lambda = 1064\ \mathrm{nm}$.

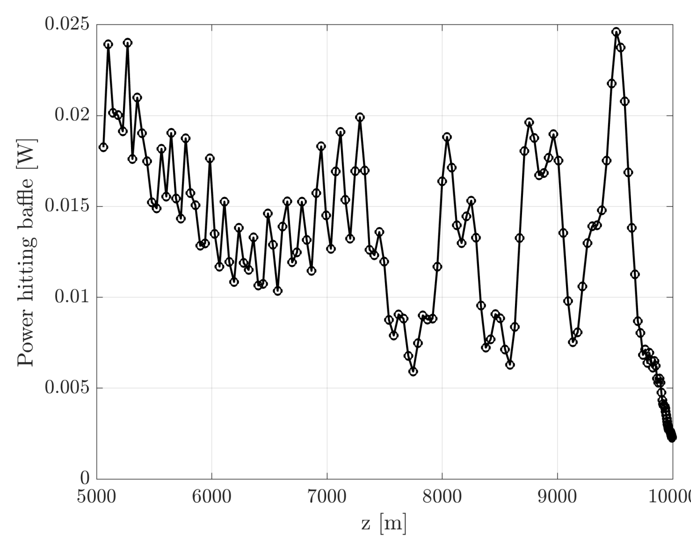
$$K^i = \frac{1}{r_i^2}\left(\frac{\mathrm{d}P^i}{\mathrm{d}\Omega_{ms}}\right)^2 \delta\Omega^i_{ms}$$

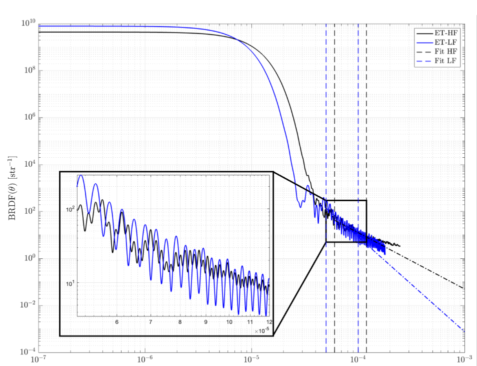
Sum over baffles telling the probability for light scattered from the mirror at a given solid angle
—> Computed analytically and using simulations
—> critical dependence on mirror quality

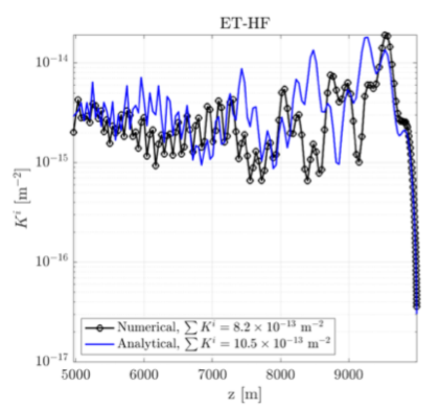




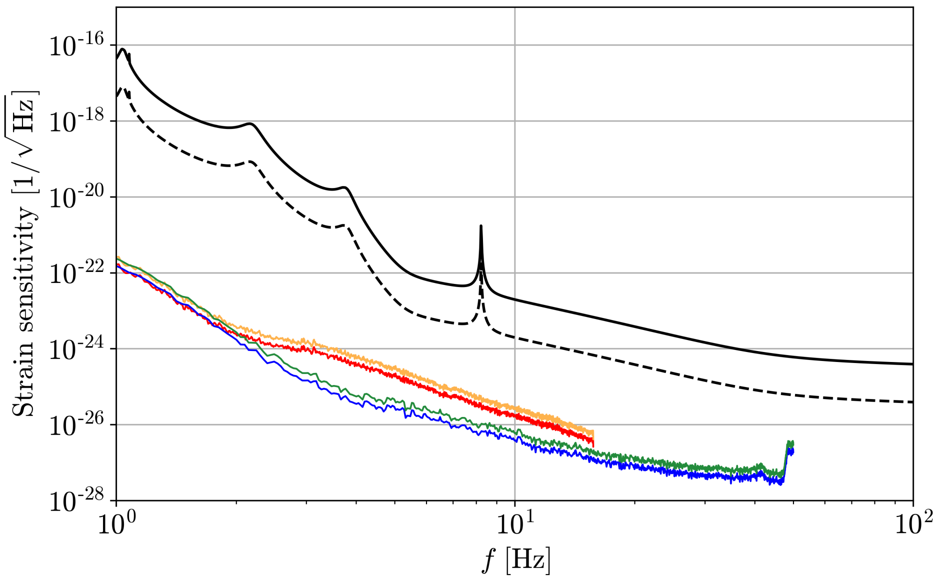






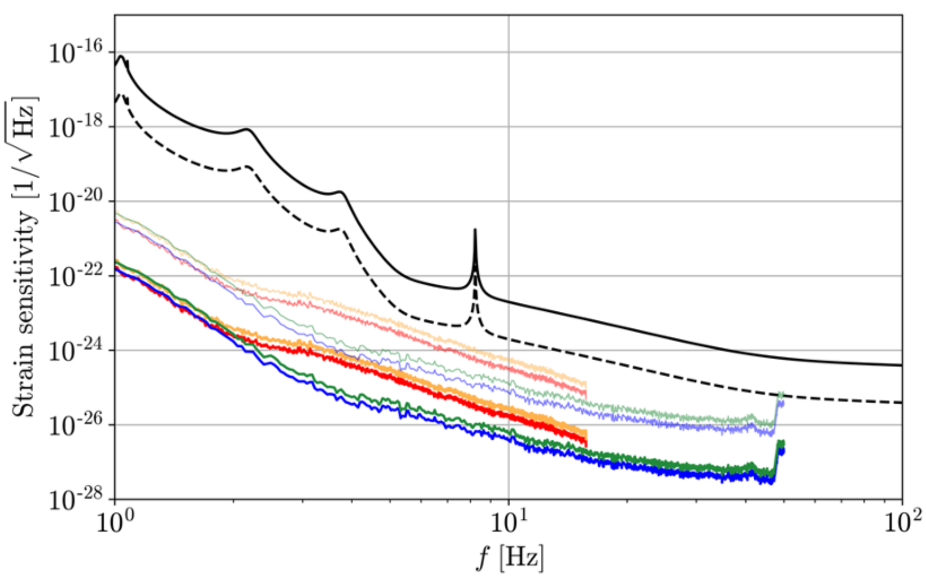


Backscattering noise ET-HF



We could consider factor 100 below solid line as a rather comfortable margin

The induced noise is well below the x10 safety margin assuming good mirrors, median seismic noise and moderate baffle BRDF



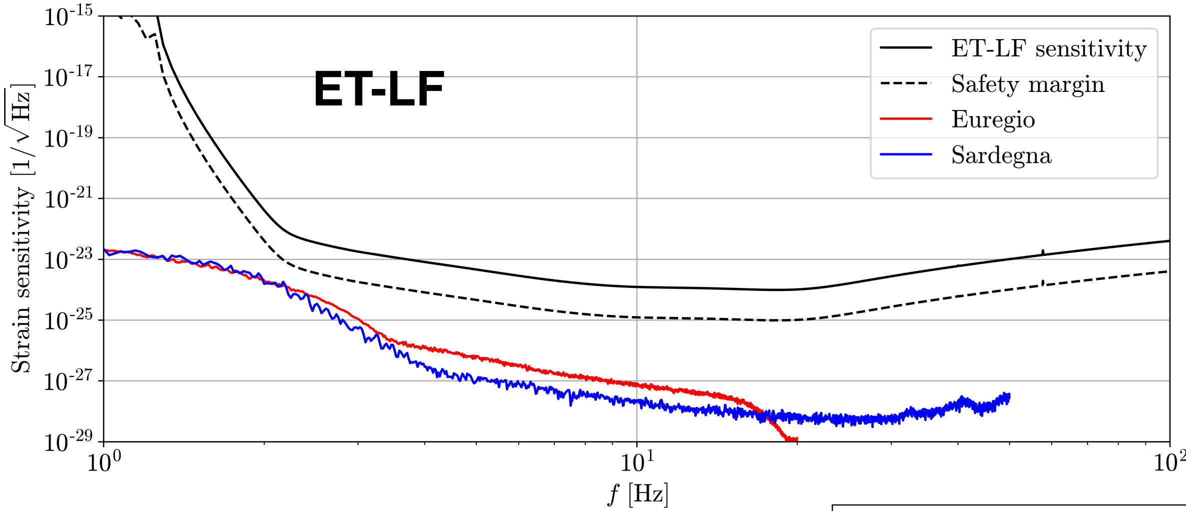
More confortable with 1.2 diameter tube

Worse mirror performance changes conclusions

—> comfortable margin will be gone for 1.0 m

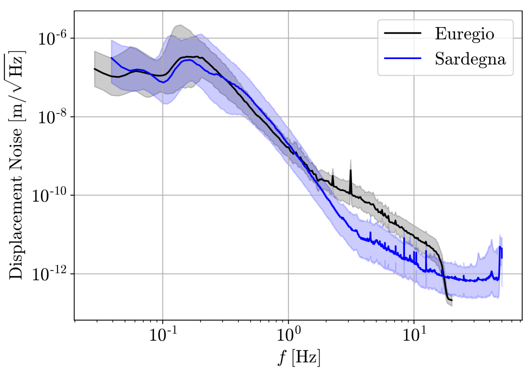
—> can be partially recovered with better baffles

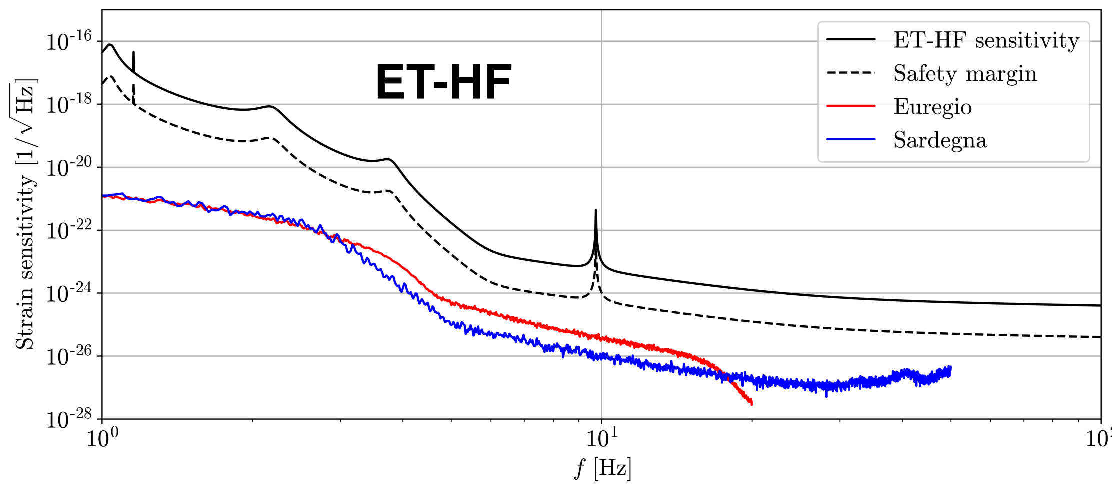
Latest updates

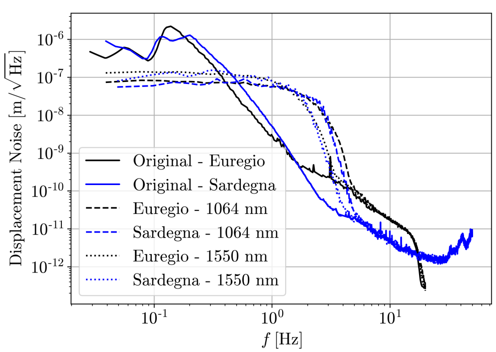


Comfortably below factor 10 of nominal sensitivity

—> improvements can be implemented using better baffle coatings —> factor ~3-10 down



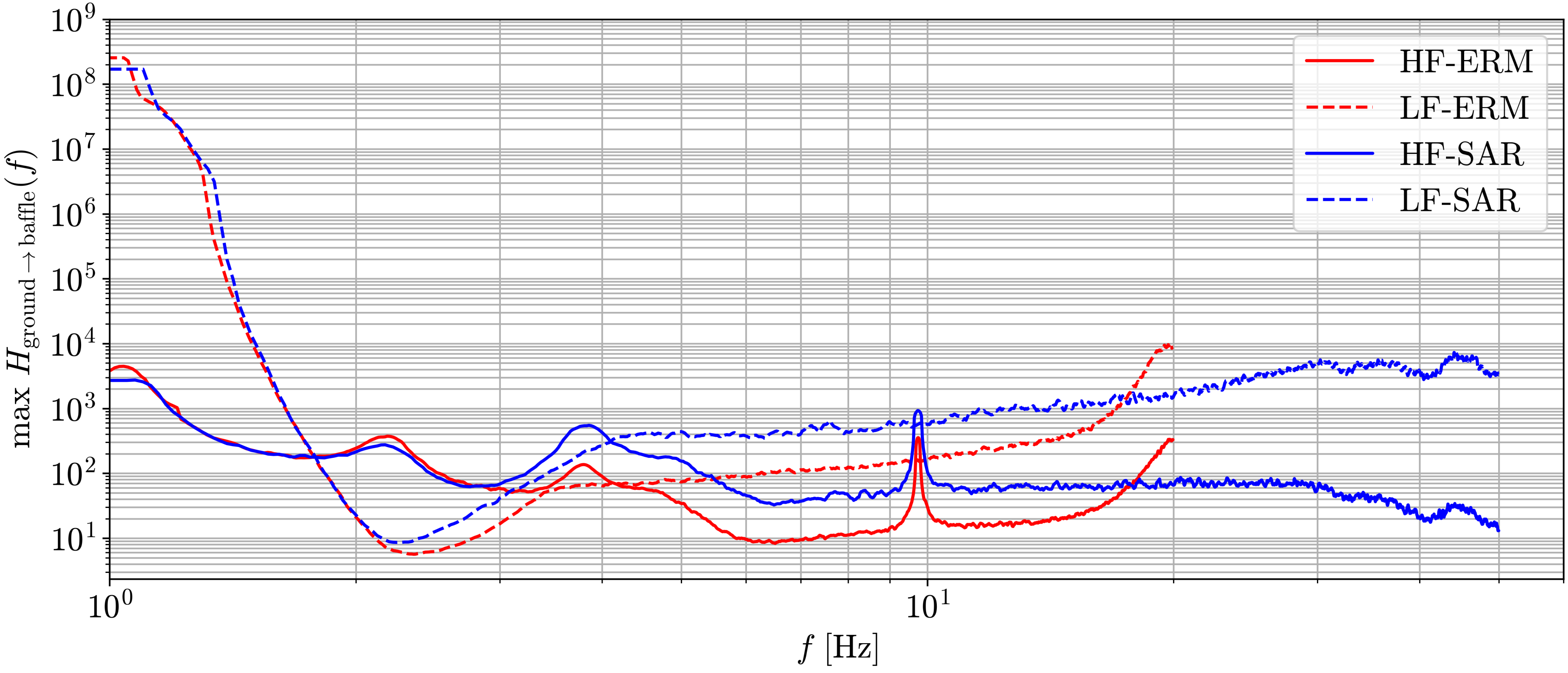




Includes updated results compared to those presented @ CERN by end of March

- **Using latest ET sensitivity curve (ET-0007B-23)**
- **Using 90% CL band on seismic displacement**

Transfer factors



Based on previous plots we can provide information on the maximum mechanical transfer factor (ground to baffle) that is acceptable before affecting ET performance

Notes on Baffle materials

- We shall profit from detailed studies made in LIGO and Virgo about the suitable materials (not only optical characteristics but also practical issues)

Materials comparison: robustness and availability vs performance

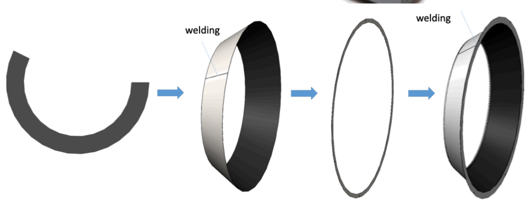
			Lowest BRDF		Specular	
	Handling	Price	8º AOI	57 º AOI	8º AOI	57 º AOI
Oxidized Stainless Steel (super #8)		$	9×10^{-3}	9×10^{-3}	5×10^{-2}	1×10^{-1}
Black Glass		$$	3×10^{-5}	1×10^{-5}	5×10^{-1}	2×10^{-4}
AR coated Black Glass (broad band coating)		$$$	2×10^{-5}	1×10^{-5}	3×10^{-2}	5×10^{-3}
Diamond-like Carbon on stainless steel mill finish	✓	$	1×10^{-3}	1×10^{-3}	2×10^{-2}	1×10^{-3}
Black Nickel on stainless steel mill finish		$	2×10^{-4}		3×10^{-2}	
Multi-layer AR (for 57 AOI) on SSTL (super #8)	✓	$$	1×10^{-4}	1×10^{-5}	1×10^{-1}	1×10^{-2}
Chromium Oxide on stainless steel		$$	2×10^{-2}	2×10^{-2}	2×10^{-5}	2×10^{-6}
Diamond-like Carbon on Cr Oxide on SSTL		$$	6×10^{-2}	6×10^{-2}	4×10^{-6}	1×10^{-6}
"Black Nickel" on bead blasted SSTL	✓	$	7×10^{-4}	5×10^{-4}	8×10^{-5}	8×10^{-6}
Structural coating 1	✗	$$$$	1×10^{-2}	1×10^{-2}	5×10^{-6}	2×10^{-6}
Structural coating 2	✗	$$$$$	1×10^{-3}	1×10^{-3}	5×10^{-6}	2×10^{-6}
Structural coating 3	✗	$$$$$	9×10^{-4}		2×10^{-6}	2×10^{-7}
graphite paint on aluminum	✗	$	1×10^{-2}	1×10^{-2}	2×10^{-4}	5×10^{-5}
organic paint coating on aluminum	?	$	5×10^{-3}	5×10^{-3}	5×10^{-6}	2×10^{-6}

Robust   Brittle/delicate   Handling only with special tooling

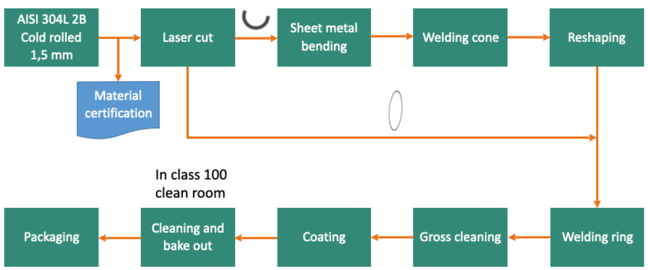
Alena Ananyeva @ GWADW 2021

Baffle Mass Production

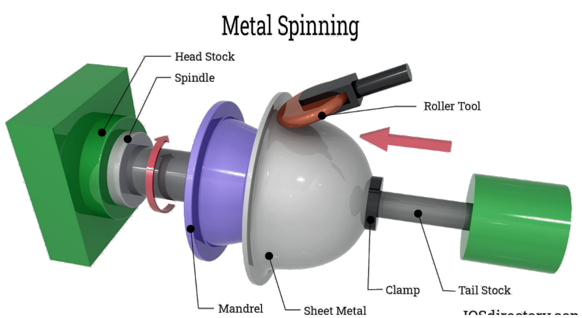
- We have explored two possible procedures
  - sheet metal bending



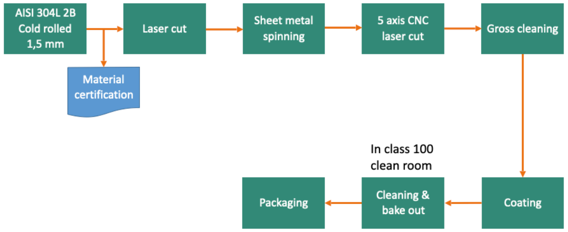
Sheet metal bending:
- Requires welding (twice)
- Welding may cause distortion, which can require additional reshaping
- Welding process may leave visible seams that require finishing
- Rollers of a sheet metal bending machine can leave small marks on surfaces
- Good for mass production

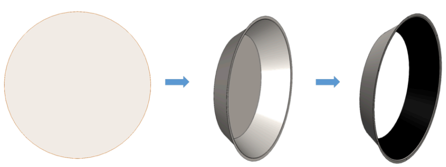


  - sheet metal spinning



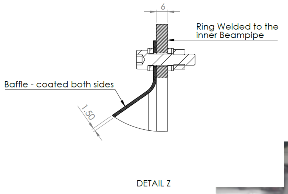
Sheet metal spinning:
- Can produce cones with high precision and surface quality
- No welding
- The inner surface of the cone remains in good condition
- Very good for mass production
- Cost efficient





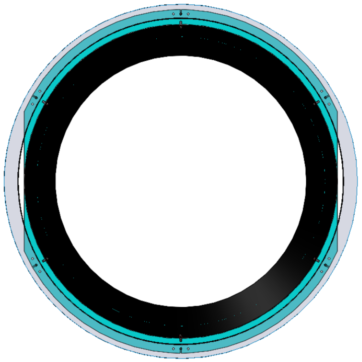
sheet metal spinning process seems a good candidate for the manufacturing of the ET beampipe baffles.

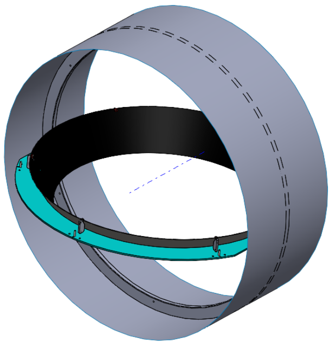
Baffle integration

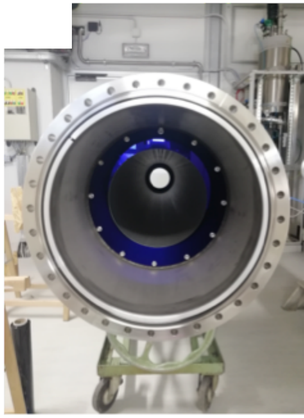


- We explored two possible models for baffle integration inside the tube

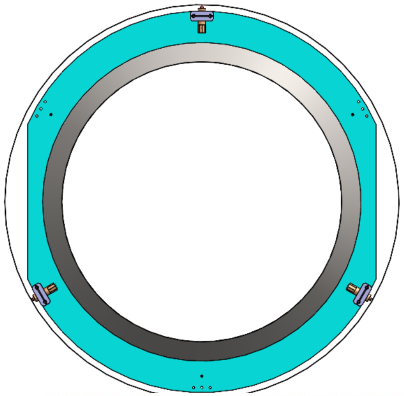
    A. Fixed using black screws on a welded beampipe inner ring (recently used in Virgo's Filter Cavity baffles)

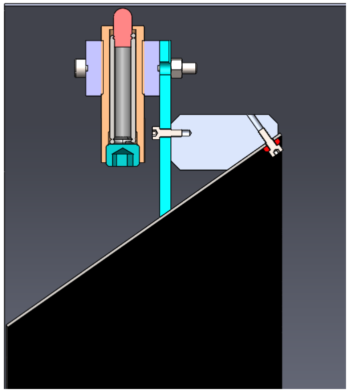






    B. Fixed directly to the inner wall using springs (recently used in LIGO filter cavity)

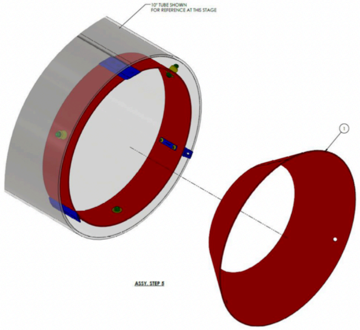


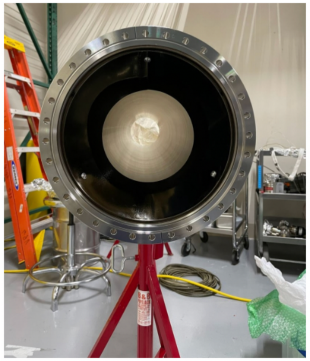


- We believe for a brand new infrastructure designed to last for at least 50 years the solution A is probably more adequate

- At the same time the ring in B can act as damper and is a valid solution for future baffles installed a posteriori

- **All the work on modal and thermal studies (next slides) is carried out for solution A**





LIGO-D1900-424

Modal analysis

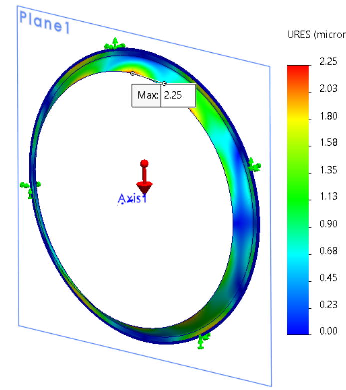
ET-HF 1.2 m configuration

Flange outer diameter 1180 mm < 1200 mm (Beampipe)

Angle 35º

Height 65.2 mm

Minor diameter (aperture) 1040 mm



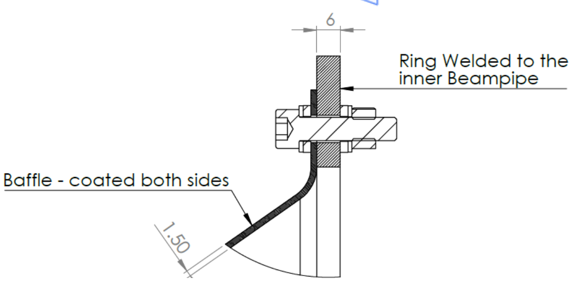
TOTAL MASS = 8.8 kg

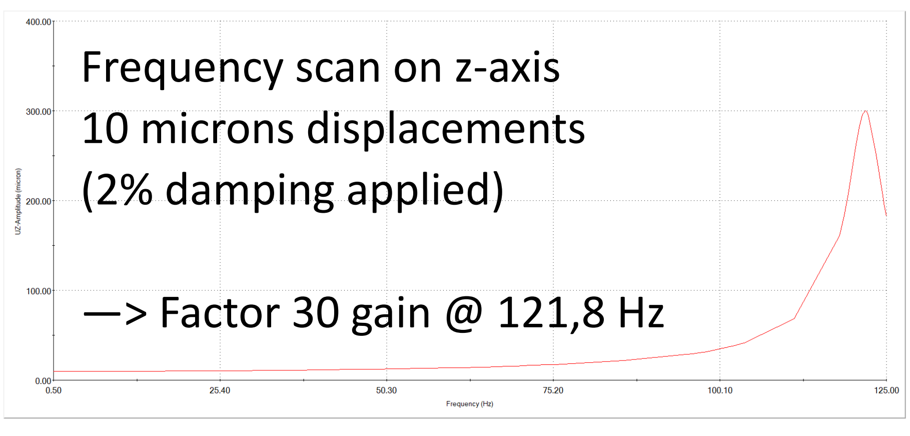
BAFFLE + RING + WASHERS + BOLTS + NUTS

Baffle mass = 4.3 kg

Ring mass = 4.2 kg

Static deformation due to gravity no more than 2 microns





Frequency scan on z-axis

10 microns displacements

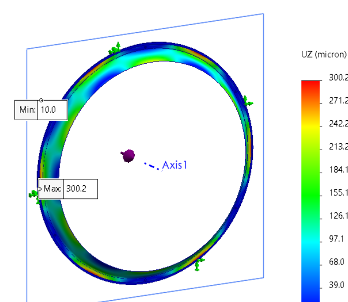
(2% damping applied)

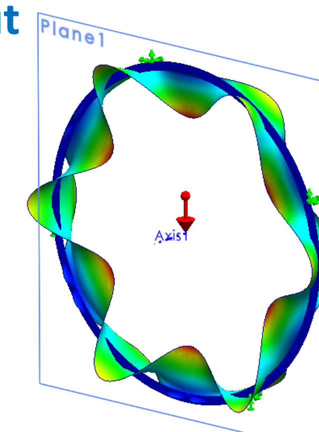
—> Factor 30 gain @ 121,8 Hz

6th eigenmode @ 121.87 Hz

the participation mass is about

21.1 % in the z-axis direction





Modal analysis

ET-LF 1.0 m configuration

Flange outer diameter 980 mm < 1000mm (Beampipe)

Angle 35º

Height 65.2 mm

Minor diameter (aperture) 840 mm

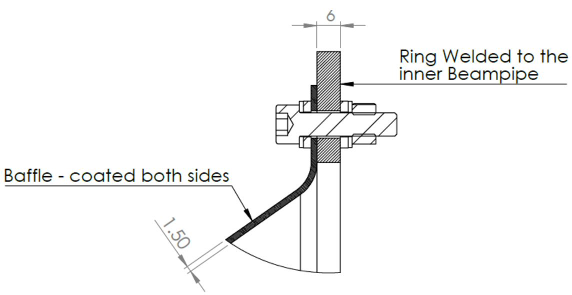
TOTAL MASS = 8.0 kg

BAFFLE + RING + WASHERS + BOLTS + NUTS

Baffle mass =3.5 kg

Ring mass = 4.2 kg

Static deformation due to gravity no more than 1.6 microns



6th eigenmode @ 156.0 Hz

the participation mass is about

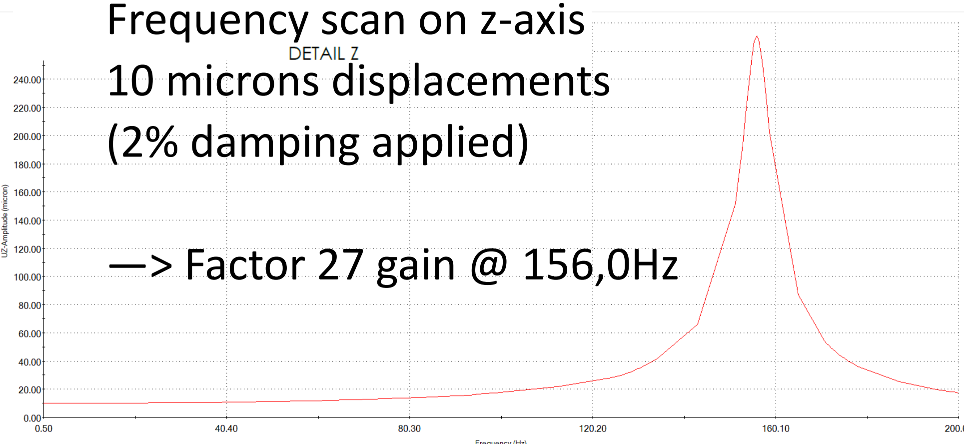
18.6 % in the z-axis direction

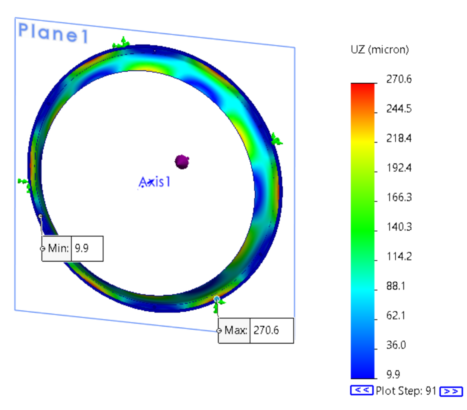
Frequency scan on z-axis

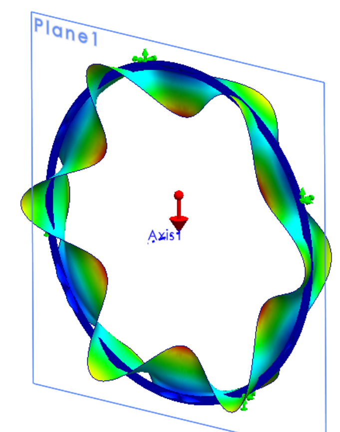
10 microns displacements

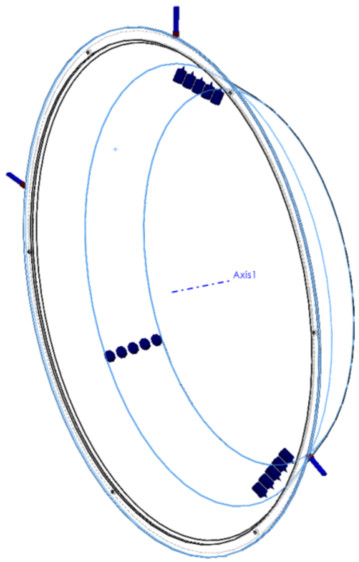
(2% damping applied)

—> Factor 27 gain @ 156,0Hz

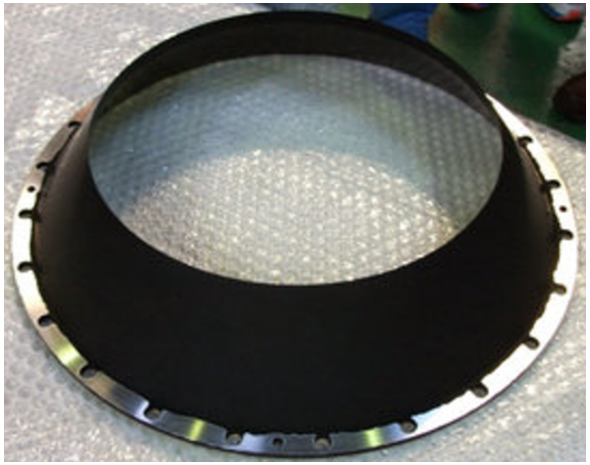


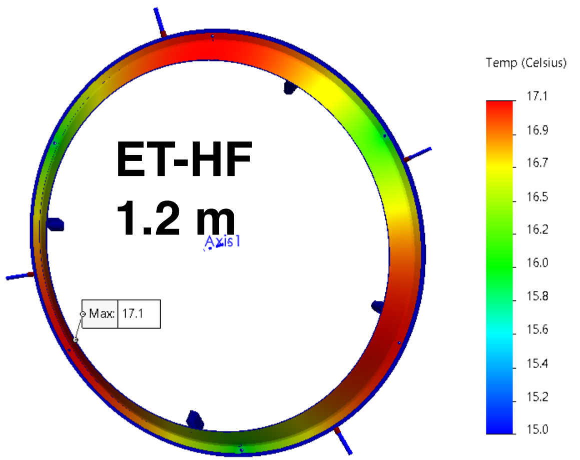






Thermal analysis

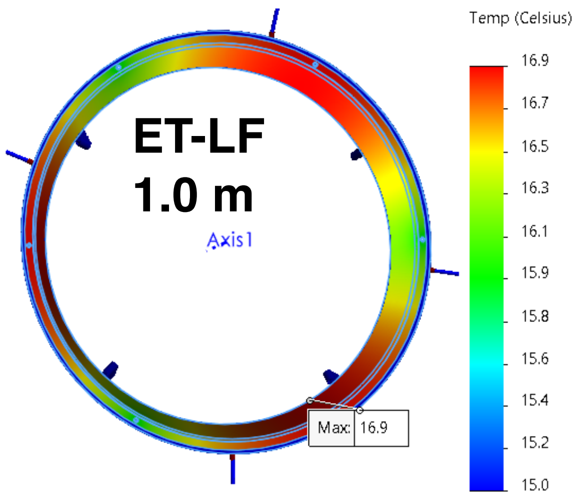




AISI 304 for all the parts

- Ring 3D mesh
- Baffle 3D mesh
- Heat power 0.05 W **(x2 expected)** distributed over the inner surface of a truncated cone
- Interfacial conductance between Baffle and Ring of 300 W/m²K, we analyse 3 contacts instead of 6

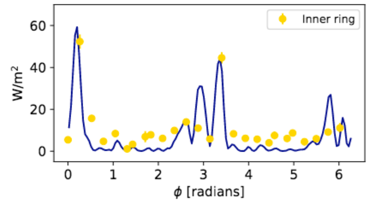
- Ring outer surface fixed @ 15 degrees Celsius

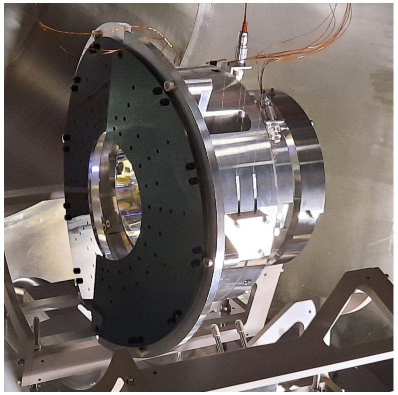


Bottom line: maximum variations up to 2 C

Final notes and next steps

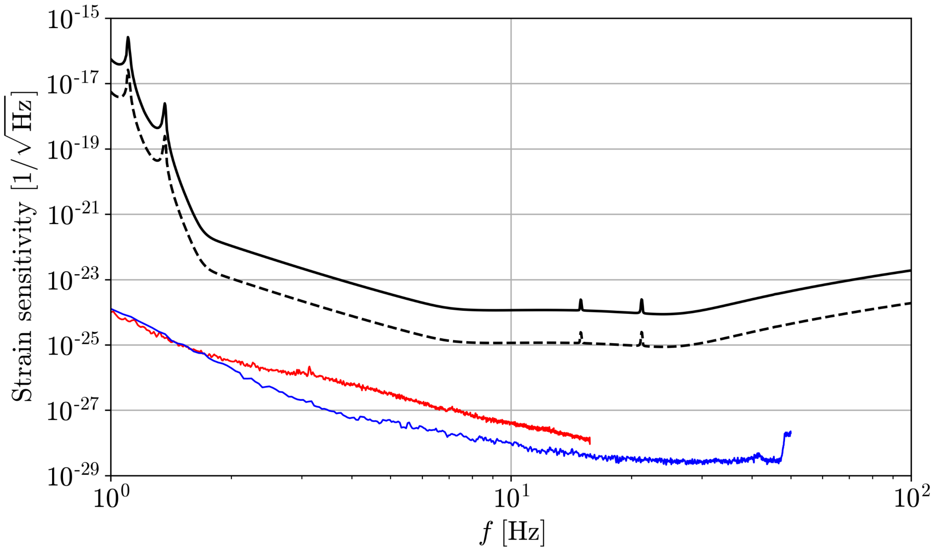
- Calculations rather solid
  - Some work still needed to consider off-sets of the laser beam
  - Work to be done on the cryotrap area
- We explored baffle designs and possible installation in the main arms
  - *More work needed to determine the strategy for instrumented baffles in arms for monitoring the mirrors and pre-alignment*
- We completed the modal and thermal analysis for the baffles and determine the mechanical transfer factors of the baffle themselves and the maximum acceptable transfer factor from ground to the baffle that the ET performance.
- We are in contact with Optical Engineers
  - to re-validate the SLC calculations using expensive commercial software tools (as much as possible).
  - To determine induced SL noise at large angles and in the tower-pipes interfaces



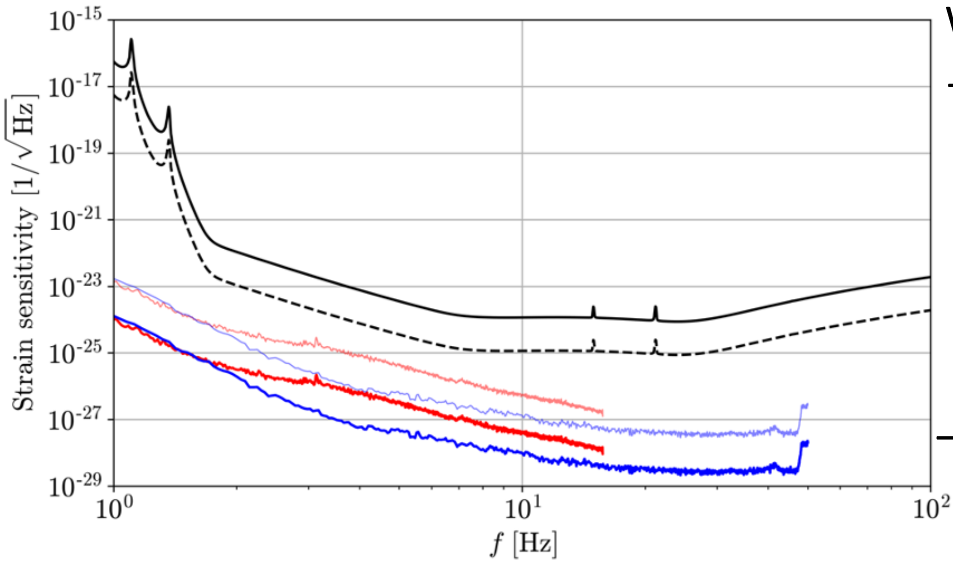


- We are in contact with a number of companies to determine the cost of massive baffle production. At a given point we could determine the total cost including coatings, bake out, transportation and installation.
- Work is needed to fix/determine the final baffle requirements in terms of BRDF and coatings —> *we will initiate a comprehensive review of suitable coatings and costs*
- **A coordinate discussion inside ET is needed to fix the parameters taking into account a cost/benefit and risk analysis.**

Backscattering noise ET-LF



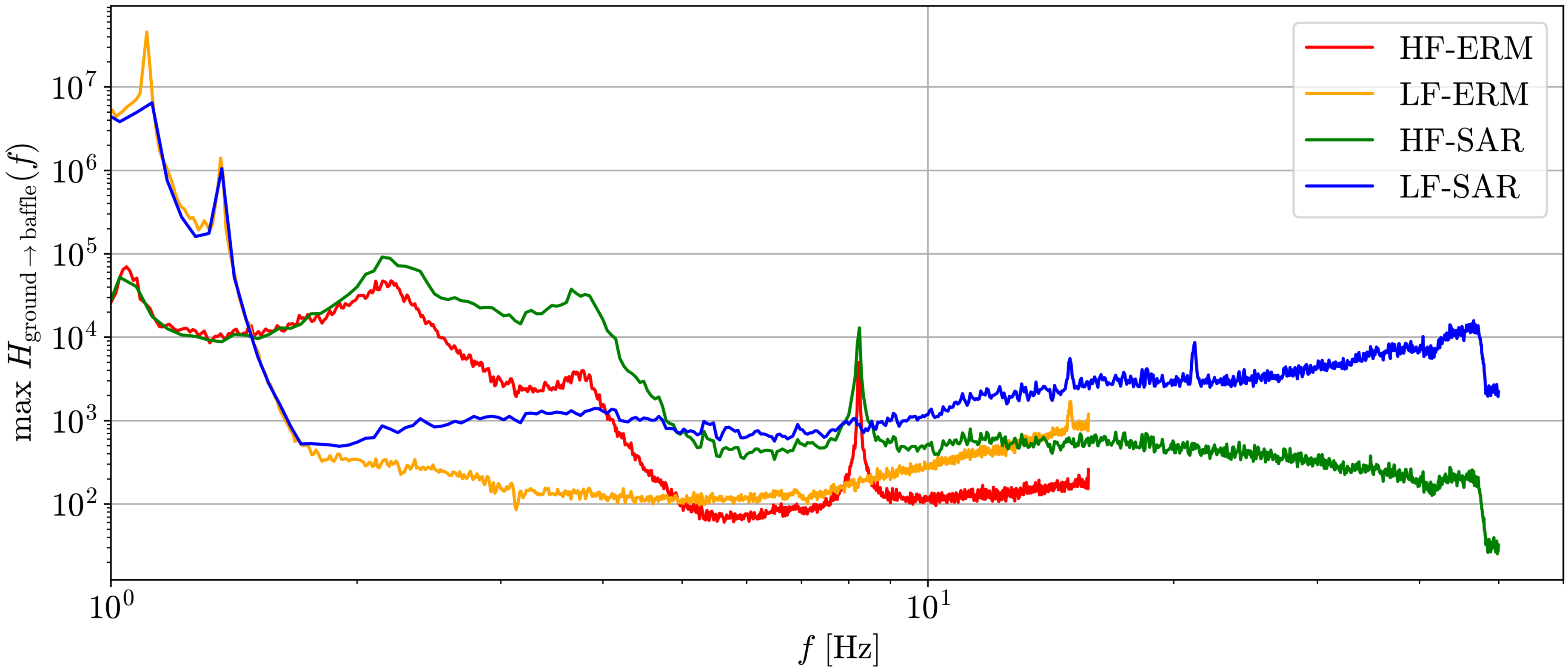
The induced noise is well below the x10 safety margin assuming good mirrors, median seismic noise and moderate baffle BRDF



Worse mirror performance changes conclusions —> comfortable margin will be gone

—> can be partially recovered with better baffles

Transfer factors



Based on previous plots we can provide information on the maximum mechanical transfer factor (ground to baffle) that is acceptable before affecting ET performance