Stray light noise from dust particles in GW interferometers

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Overview

- Particle contamination in GW interferometers
- Vacuum pipes of ET arms and baffles
- Cleanliness requirements for ET baffles
- Brief summary of work @Padova on SL

Cleanliness

Improvement in the surface quality of optical components needs to be accompanied by adequate cleanliness level of:

- the experimental halls, chambers and components
- work procedures

Presence of particles in the GW experiments:

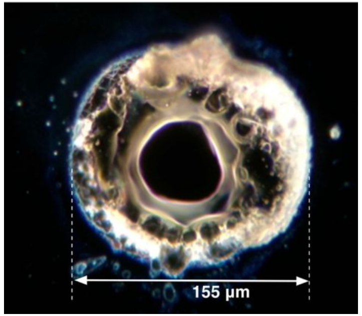
- within the GW detector
- in the distributed labs where parts are fabricated/assembled

We distinguish between:

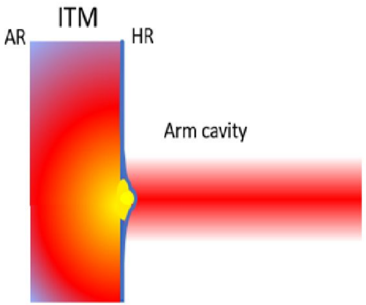
- single particles, affecting the sensitivity individually
- collection of particles, affecting the sensitivity as distribution

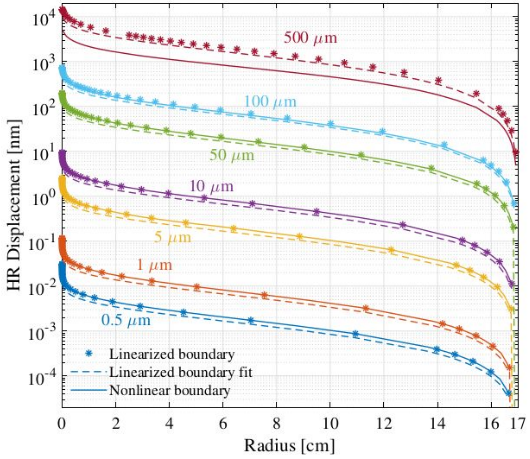
Point absorbers

Individual particles originate non-uniform absorption of light which deforms the optics thermo-elastically (both thermal lens and surface deformation).



[Brooks, Apl. Opt. 60 (2021) 4047]





[Jia, PRL 127 (2021) 241102]

Point absorbers in the test masses limit buildup of arm power by scattering light out of the resonant mode of the cavity

In AdV they are being tackled by adaptive actuator and reduced in numerosity by major cleaning of the coating large chamber

Distribution of particles

- A distribution of particles deposited on an optical surface is a source of scatter light and hence contributes to the stray light noise
- Particles crossing the laser beam can also scatter light [only marginally in this talk]

Surfaces needs to be clean:

- Ideal case with no deposited particle is not realistic
- Even moderate contamination levels can be leading scattering source for superpolished optics

Quantification of cleanliness requirements have attracted little attention so far

In this talk we mainly report on the role of dust contamination in the ET arm pipes

ET arm pipes

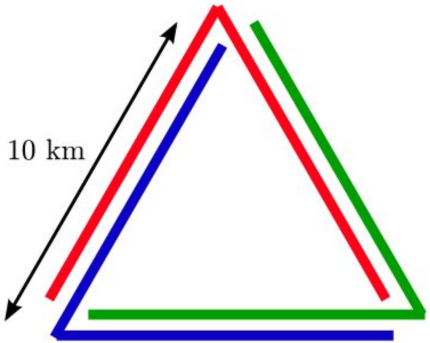
ET : a set of 3 HF and 3 LF interferometers, each made by 2 arms:

12 Fabry-Perot arm cavities, each 10 km in length.

Assuming 1 m diameter and a total length of 120 km:

UHV volume: 9×10^4 m^3

inner surface : 4×10^5 m^2



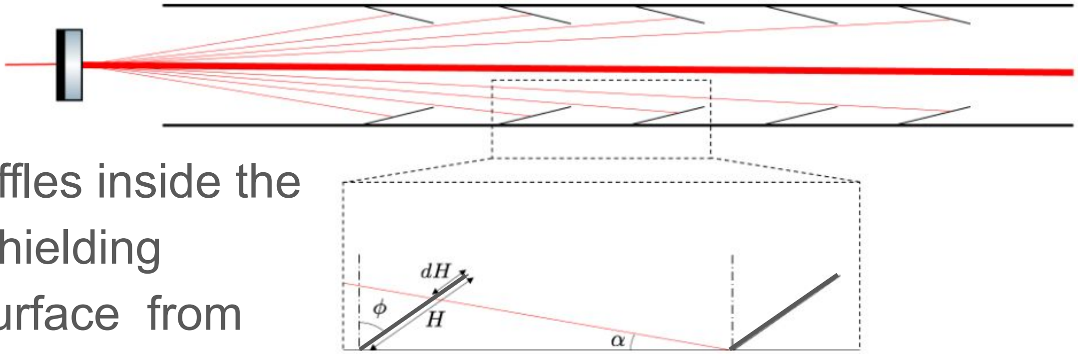
The ET vacuum system will be among the largest UHV apparatus in the world!

Additional vacuum elements:

- vacuum towers for suspended optics
- filter cavities for SQZ
- mode cleaner
- connecting pipes
- ..

A huge effort is required

Baffles in arm pipes



O(100) light-absorbing, conical baffles inside the arm pipe to mitigate SL noise by shielding geometrically the tube’s internal surface from photons scattered by the Test Masses.

TABLE III. Number of baffles for the ET-HF (using $R = 0.5$ m and $R = 0.6$ m) and ET-LF in different scenarios and assuming different baffle-to-baffle separations (see body of the text). ITF refers to “interferometer”.

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

[Andrés-Carcasona et al., PRD 108 (2023) 102001]

Baffles have a major impact on ET infrastructure as they contribute to set the requirement for pipe diameter

Cleanliness concerns for ET arm pipes

Large scale of the ET vacuum system

→

Requirements for cleanliness can make a big impact in terms of costs and time

Key questions regarding arm pipes:

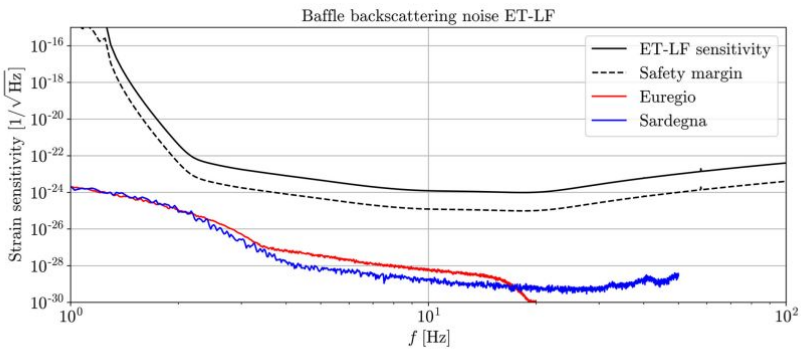
- How clean should the internal surface of the pipe be?
- How clean should the arm baffles be?

Why is cleanliness important?

SL from arm baffles

Not at zero-cost: baffles introduce their own noise! This includes SL noise

PHYS. REV. D **108,** 102001 (2023)



Light not absorbed but rather scattered by the baffles back to the TM can recouple to the main beam:

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

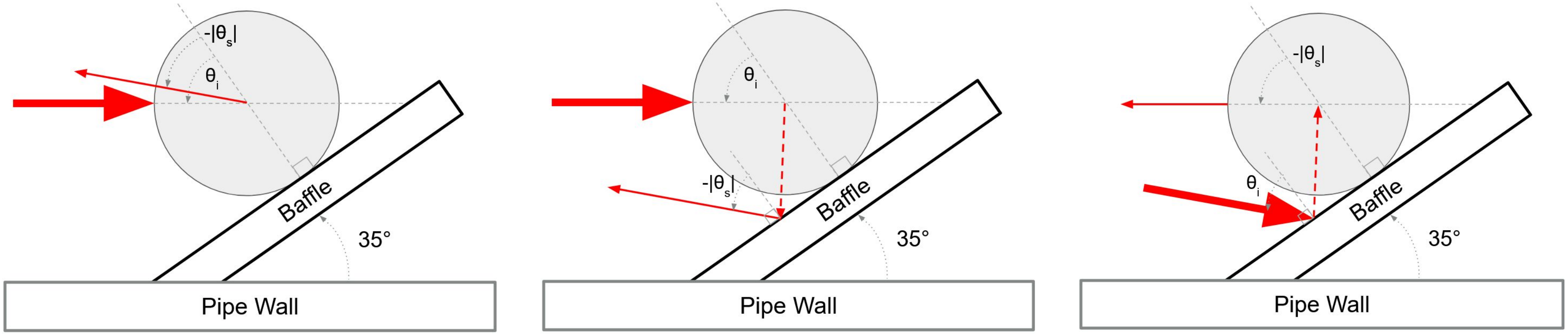
baffle scattering probability BRDF_{baffle}

A real world scenario: $\mathrm{BRDF}_{baffle}+\mathrm{BRDF}_{dust}$

Scattering by particles deposited on baffles

Three cases for scattering light back to the TM:

Assumption: light reaching the TM from the baffle by multiple reflections is highly suppressed



Backward scattered: B

Forward scattered and reflected: FR

Reflected and forward scattered: RF

Relevant for ET arms:
scattering angle = - baffle inclination angle (=55deg)

Probability of scattering depends on the particles properties:

- dimension
- surface density
- refraction index
- (shape)

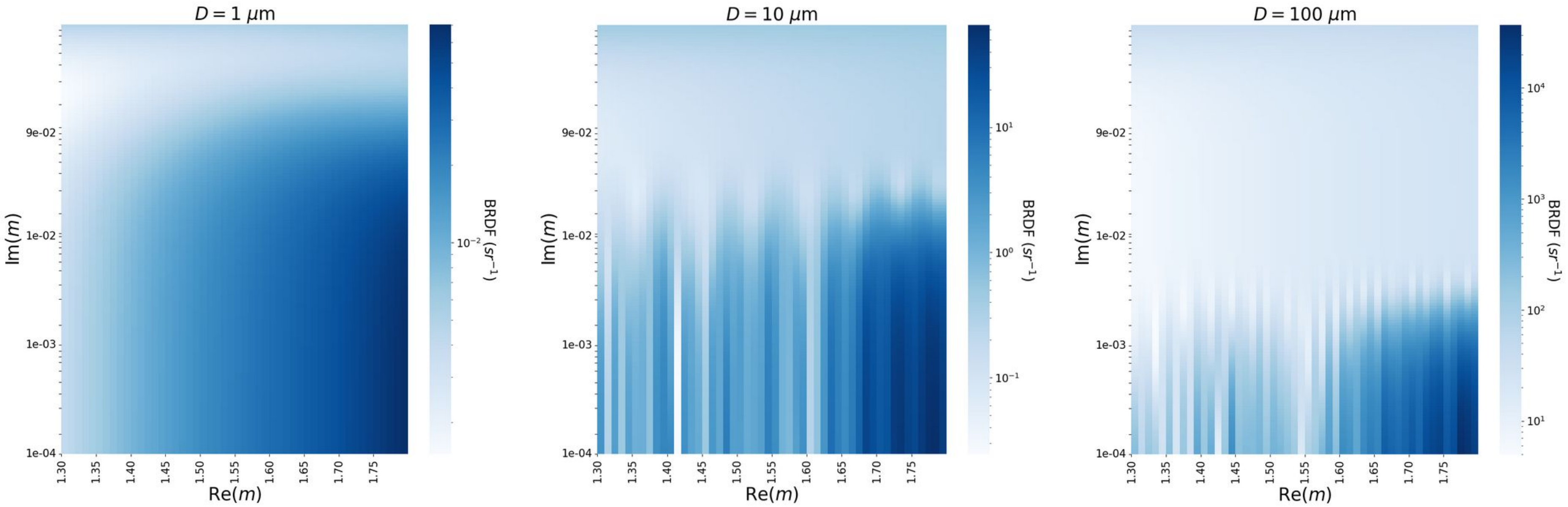
[ET-0385A-24 , ET-0139A-24]

Role of particle properties: fixed particle density

B+FR+RF summed up (B is typically larger), unpolarized light

m = refraction index

Plots for $f(D)=10^6 part/m^2$



In general: larger scattering for high Re(m) and low Im(m)

With increasing D :
- larger scattering
- larger dependance on m
- set of local min/max for specific combinations of m, D, λ

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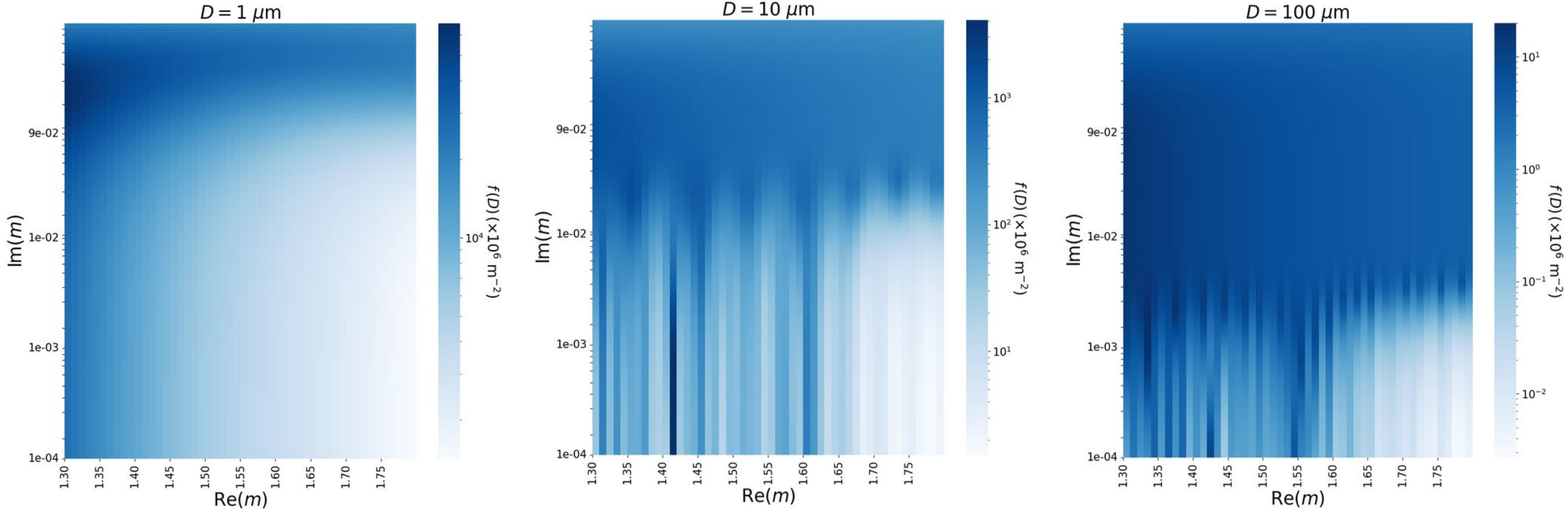
[paper in preparation]

Role of particle properties: fixed BRDF

Setting $BRDF_{dust} = BRDF_{baffle}$ we determine maximal distribution of particles on a baffle, at different diameters and for different materials



By solving $BRDF_{dust} = BRDF_{baffle}$ for each diameter & refraction index, we obtain the requirements for ET

[paper in preparation]

Cleanliness requirements for ET baffles

	Density (particles/m^2)		
diameter range (μm)	50%	90%	$m = 1.5 + i\,10^{-3}$
(0.1 - 0.3)	$9.3 \cdot 10^{11}$	$6.2 \cdot 10^{11}$	$2.0 \cdot 10^{12}$
(0.3 - 1)	$1.5 \cdot 10^{11}$	$1.1 \cdot 10^{11}$	$5.7 \cdot 10^{10}$
(1 - 3)	$2.0 \cdot 10^{10}$	$1.4 \cdot 10^{10}$	$6.4 \cdot 10^{8}$
(3 - 10)	$2.1 \cdot 10^{9}$	$1.4 \cdot 10^{9}$	$1.1 \cdot 10^{8}$
(10 - 30)	$2.3 \cdot 10^{8}$	$1.5 \cdot 10^{8}$	$2.5 \cdot 10^{7}$
(30 - 100)	$2.2 \cdot 10^{7}$	$1.4 \cdot 10^{7}$	$4.5 \cdot 10^{6}$

[ET beampipe requirements, ET-0385A-24]

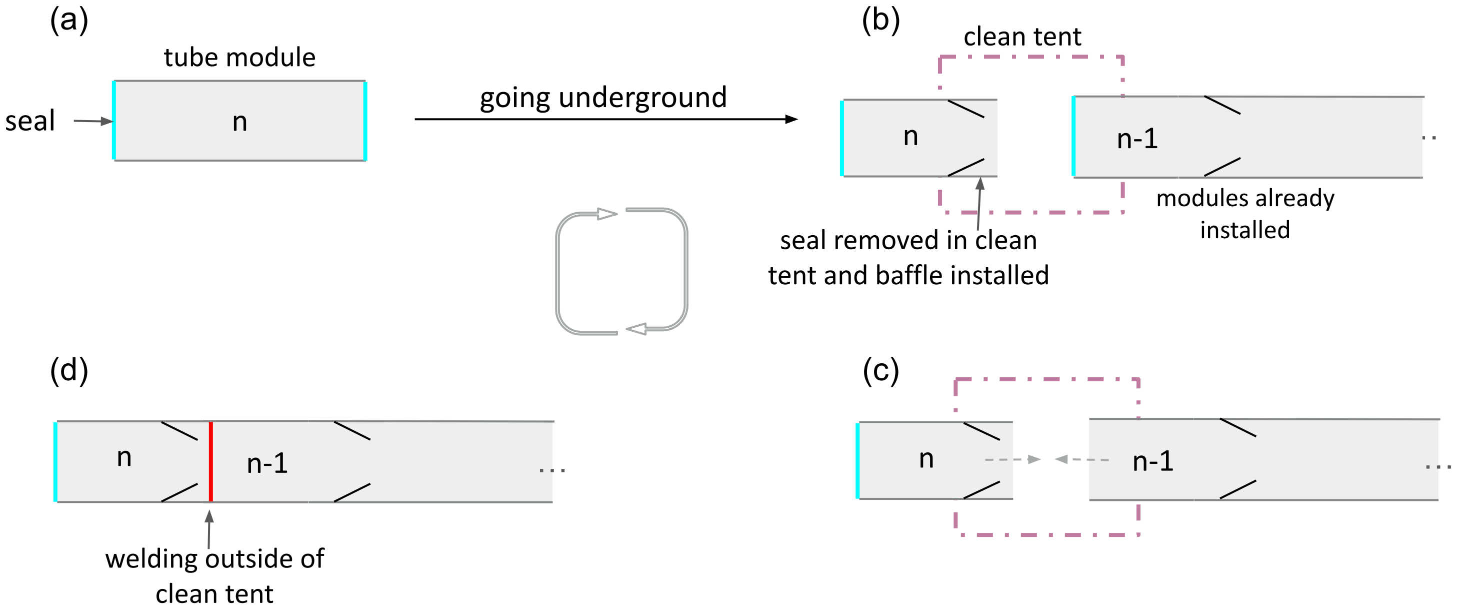
Amount of deposited dust depends on:

- volumetric concentration
- duration of exposure
- deposition velocity

ET requirements can be met with reasonable effort provided protocol for clean work is followed

Recommendations of ET pipe construction

To prevent contaminating baffles and pipes, care must be taken in their assembling



[ET-0385A-24]

Contamination by valves, pumps is negligible if standard clean procedures and materials are used

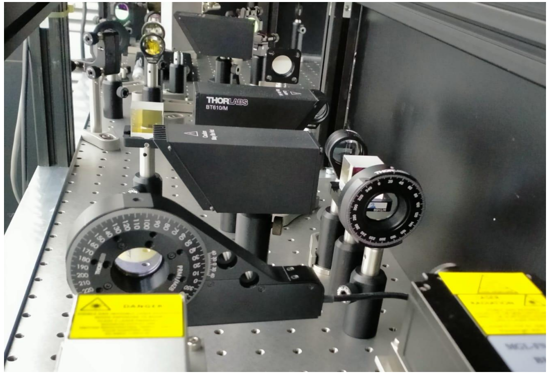
A quick view into some experimental work

Measuring scattering properties

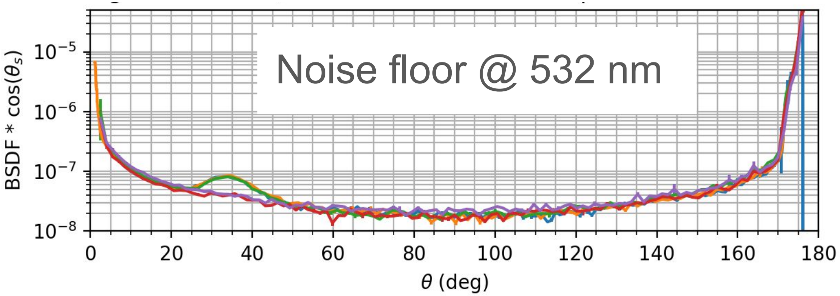
✅ at 532 nm and 1064 nm, 1550 nm soon

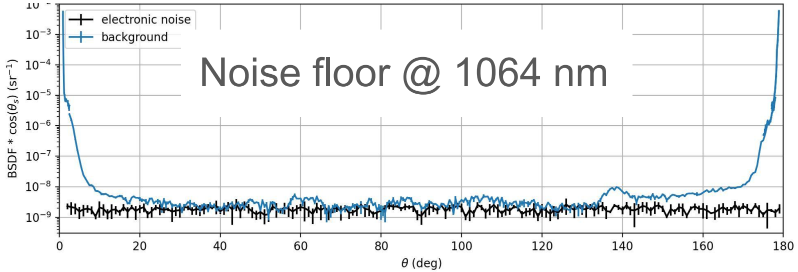
✅ control of polarization of input and scattered light, independently

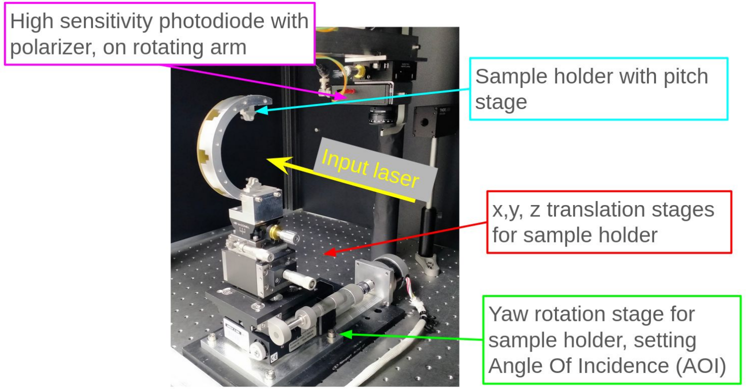
✅ variable spot size: 0.2-2mm



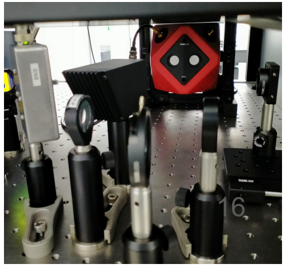
- BSDF (Bidirectional Scattering Distribution Function)







- TIS (Total Integrated Scattering): sensitivity 100ppm, targeting 10ppm



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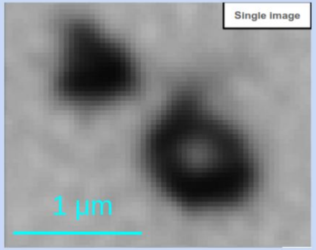
Monitoring dust deposition at Virgo

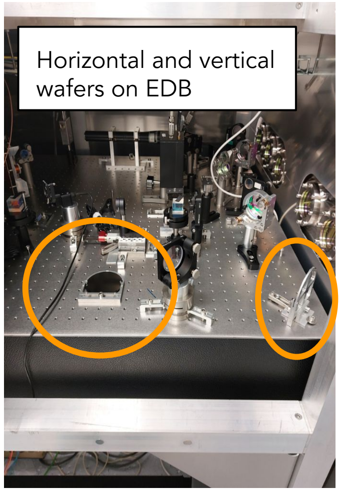
✅ set a procedure for imaging and analysing wafers we expose as dust witness samples. Use of digital microscopy
✅ completed first campaign of dust monitoring at Virgo. More in progress.

Keyence digital microscope



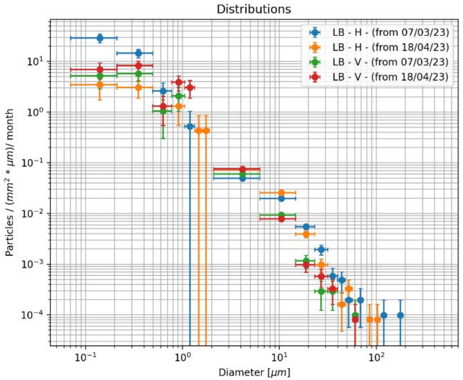
Microscope image of diam 0.8µm dust particle

Samples exposed @Virgo →

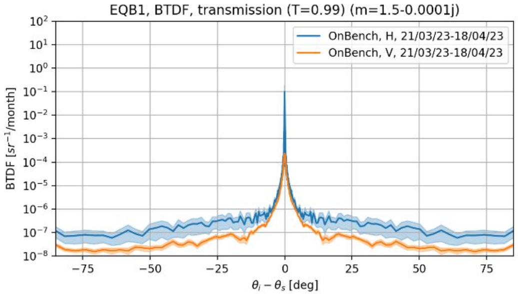


Contaminated samples imaged @Pd →

Distribution of dust particle is measured →

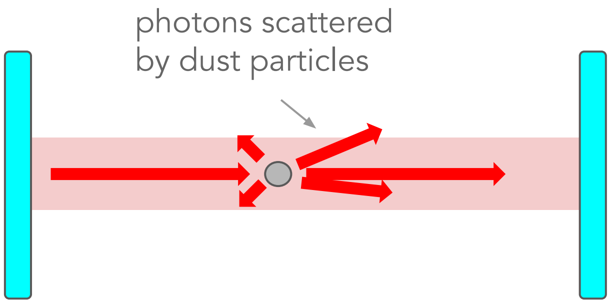


Light scattering by contaminated optics is inferred



Falling particles: numerical analysis

Light scattered by particles crossing the beam can reach the TMs and recouple with the main beam: we study scattered light reaching directly one TM.



TDS: ET-0139A-24

Montecarlo simulation

$$E'(t) = \int_{(y,z)\in \mathrm{TM}} \underbrace{E^s(x_{\mathrm{TM}}, y, z, t)}_{\text{field scattered to the TM}} \cdot \underbrace{e^{2ikf(y,z)}}_{\text{TM map}} \cdot \underbrace{\mathrm{TEM00}(y,z)}_{\text{normalized cavity mode}} dydz$$

Ensemble of N particles with:
- random starting position (x_0, y_0, z_0) on the pipe ceiling
- random detachment time t_0
- random diameter D
- random (complex) index of refraction

↓

Compute for each time instant:
- the scattered field
- amount of scattered field that couples with cavity mode
- power lost by interaction with particle

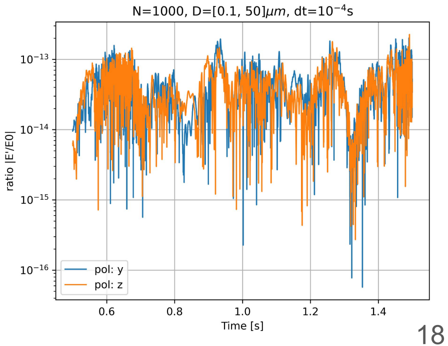
↓

Compute phase and amplitude fluctuations in the local field

↓

compute strain noise

→ depending on strain constrains the requirements are set



[work in progress, see also ET-0139A-24]

Summary

Cleanliness is a key aspect for the success of GW detectors.

Impact of single particles (point absorbers) and distribution of particles.

Lesson learned from current generation GW detectors: to avoid incurring in problems due to particulate pollution later in ET, we need to address cleanliness already now, setting requirements and giving guidelines for clean work to be followed during installation.

This has an impact on the ET infrastructure and procedures

As a first case study, we have addressed the problem of cleanliness for the arm-pipe baffles:

- highlighted the different mechanisms for light scattering;
- illustrated role of particle properties (size and material).
- set cleanliness requirements

This is a case study, and the same work can now be applied to other situations/systems of ET.

Our SL studies consist of modelling, numerical computations and experimental work @INFN&Univ Padova