ET INFN
Stray Light Control (SLC)

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ET: scienza e tecnologia in Italia
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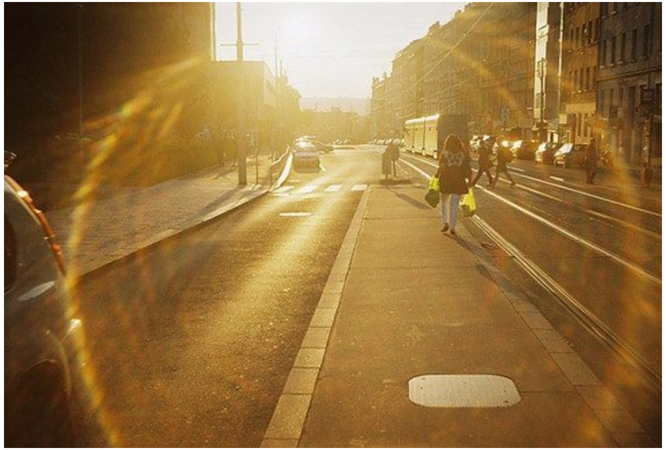
Stray light

Any light that does not follow the intended path



Scattered light is
a common problem in optical systems

If stray light is allowed to re-enter the GW detector, it brings-in additional noise which can:

- mimic a fake gravitational wave signal or
- spoil the control signals needed to keep the working point of the detector

Production of scattered light in a GW detector
→ and typical solutions

- **interaction with/in the propagation medium** (residual gas, suspended dust particles, optics substrates imperfections)
  → in vacuum propagation or in controlled environments, materials with no bulk inclusions or bubbles

- **at optical interfaces**: interface imperfections (eg surface roughness or defects), or by deposited dust particles which accumulate on surfaces.
  → very smooth optical surfaces, clean rooms

- **residual reflectivity (respectively trasmissivity)** of anti-reflection (respectively high-reflectivity) coatings produces so-called “ghost beams” that if not stopped can hit surfaces in uncontrolled way and become further sources of scattering.
  → absorption of ghost beams

- **clipping of laser beams** eg when passing through apertures
  → avoid small apertures

A common issue: SL mitigation is needed by many (all) subsystems of ET OPT Division.

Mitigation of stray light

To implement effective strategies for Stray Light (SL) mitigation we need to understand :

1. where stray light is generated and
2. its impact on the interferometer sensitivity.

A complex task that requires a **variety of activities**, including:

- **identification, modeling and experimental characterization** of scattering sources (optical surfaces and bulks, dust, etc.) and SL angular distribution
- **analytical and numerical modelling** of the recoupling of scattered light into the main beam and its effect on the interferometer output
- **design and installation** of scattered light (passive) mitigation systems

Stray light noise from dust contamination: cleanliness

At this stage we focus on the construction of the vacuum pipes of the ET arms:

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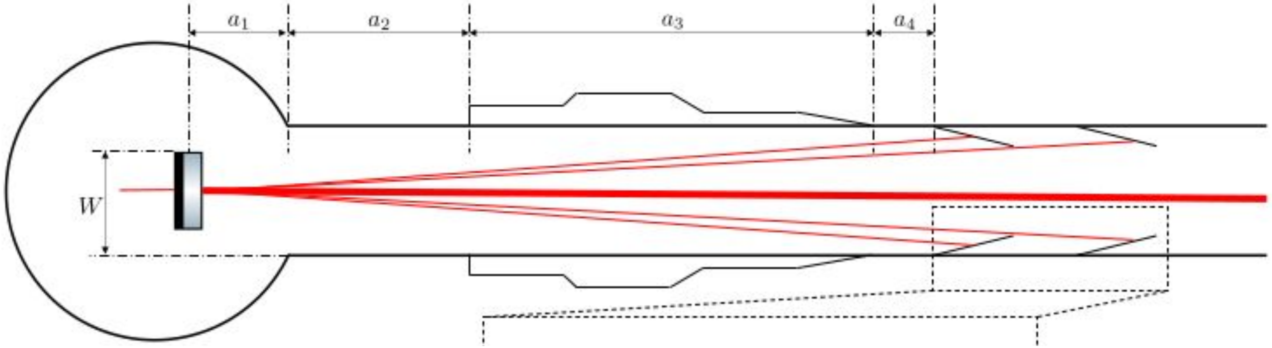


Vacuum tubes for ET arms:

- 12 x 10 km long, 1 m diameter steel pipes;
- conical baffles installed along the arm pipes to absorb any scattered light.

What cleanliness requirements for installation and operation of ET arm pipes?

Modelling effect of particle contaminants present inside the ET vacuum pipes

Two main occasions for light-particles interaction:

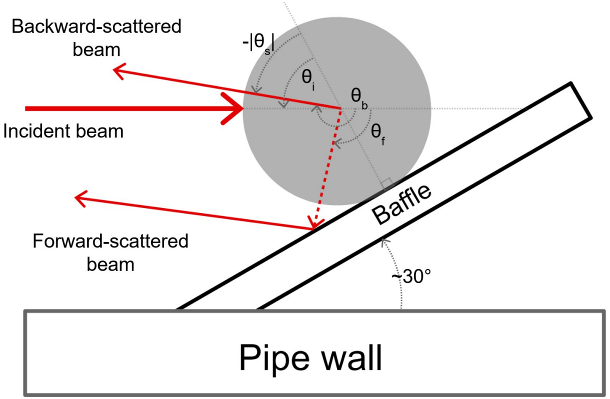
1. light from the main beam hitting a particle deposited on a pipe surface, typically a pipe baffle
   → How much dust can we tolerate on the baffles?

2. light from the main beam hitting a particle that crosses the beam, eg if falling from the pipe internal top surface
   →How clean should the pipes be?

All this sets the cleanliness requirements
for pipes, baffles and their handling and installation
as well set constraints to the vacuum pumps system

1 - Dust deposited on baffles of arm pipes

Effect of worsening the scattering performance of baffles: $\mathrm{BRDF} = \mathrm{BRDF}_{baffle} + \mathrm{BRDF}_{dust}$



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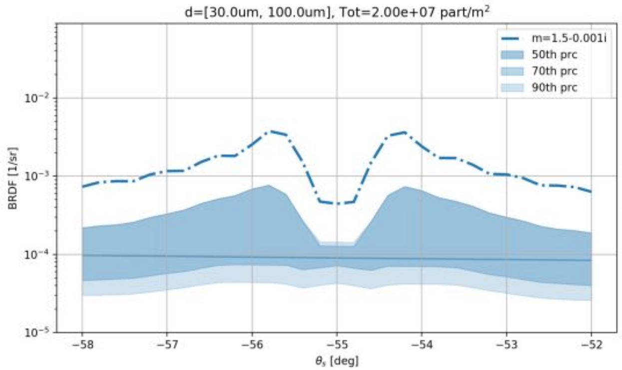
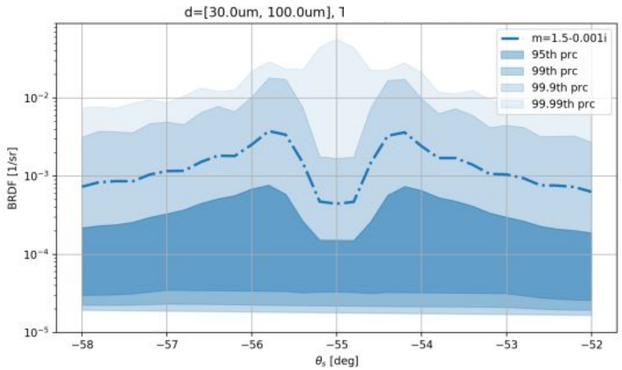
maximum tolerable superficial density of particles on the baffles:

	Density (particles/m^2)		
diameter range (μm)	50%	90%	$m = 1.5 + i\,10^{-3}$
(0.1 - 0.3)	$7.0 \cdot 10^{12}$	$5.0 \cdot 10^{12}$	$1.5 \cdot 10^{13}$
(0.3 - 1)	$2.0 \cdot 10^{11}$	$1.5 \cdot 10^{11}$	$1.0 \cdot 10^{11}$
(1 - 3)	$2.0 \cdot 10^{10}$	$1.5 \cdot 10^{10}$	$1.0 \cdot 10^{9}$
(3 - 10)	$2.0 \cdot 10^{9}$	$1.5 \cdot 10^{9}$	$1.5 \cdot 10^{8}$
(10 - 30)	$2.0 \cdot 10^{8}$	$1.5 \cdot 10^{8}$	$1.5 \cdot 10^{7}$
(30 - 100)	$2.0 \cdot 10^{7}$	$1.5 \cdot 10^{7}$	$4.0 \cdot 10^{6}$



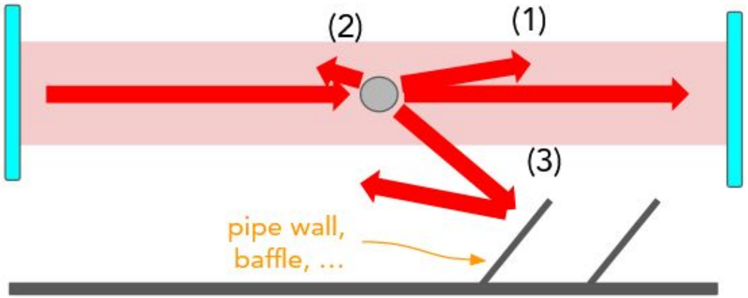


resulting BRDF around $\theta_s = -\theta_i$ for different refraction index of the particles

BRDF = Bi-directional Reflection Distribution Function

2 - Dust crossing the beam propagating in the arm pipes

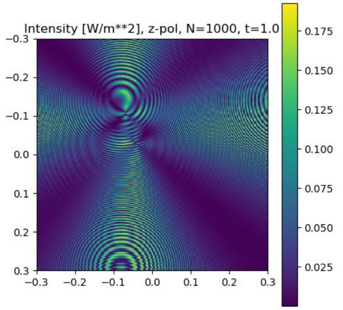
Particles crossing the beam, eg if falling from the beam pipe internal surface: different possible paths

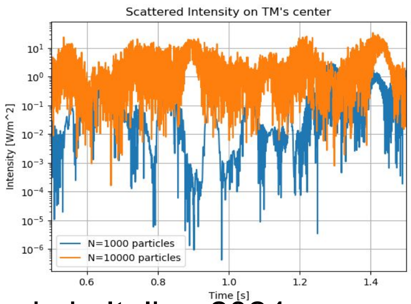


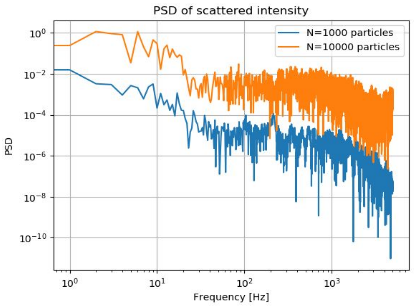
- Mie theory to model light-particle interaction
- Numerical simulation to account for a distribution of particles (of different sizes and detaching from random positions) crossing the beam - Paths (1), (2)

  →Maps of the scattered field at a test mass

  → computation of recoupling field and strain noise







To be continued

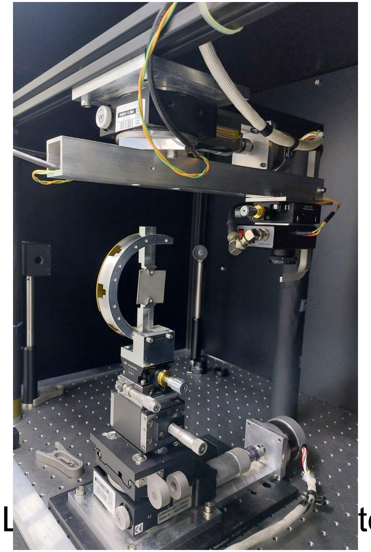
Experimental facility for light scattering measurements

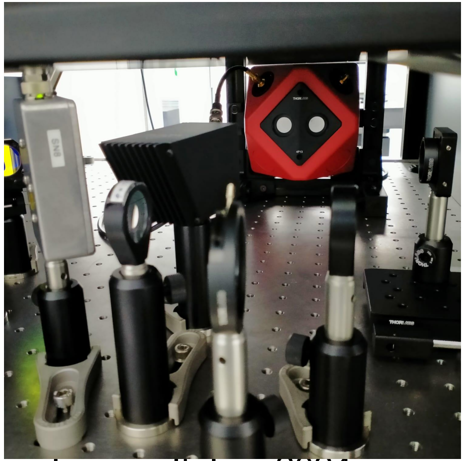
In synergy with Virgo and with ET R&D on coatings

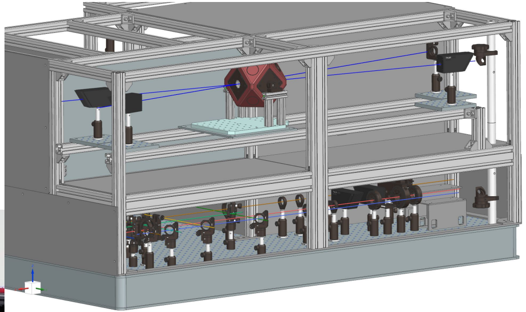
BSDF: bidirectional scattering function distribution : it describes the angular distribution of scattered light

TIS : Total Integrated Scattering : BSDF integrated over the full sphere

- **Integrated facility with BSDF & TIS measurements in a clean room** @Padova
- Lines at 532 nm & 1064 nm
- **Line at 1550 nm: planned for 2024**

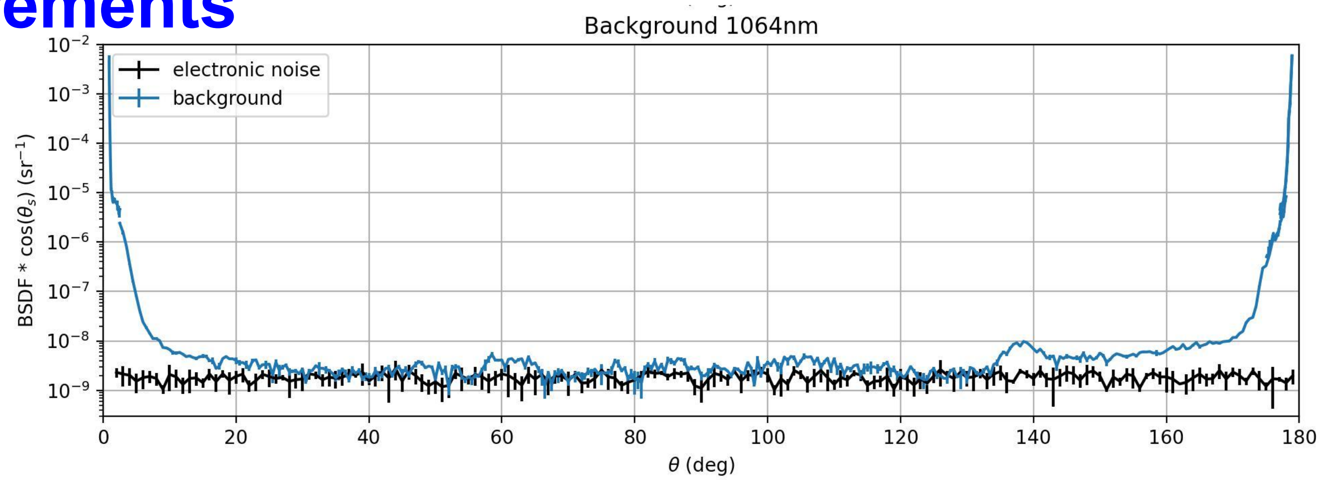




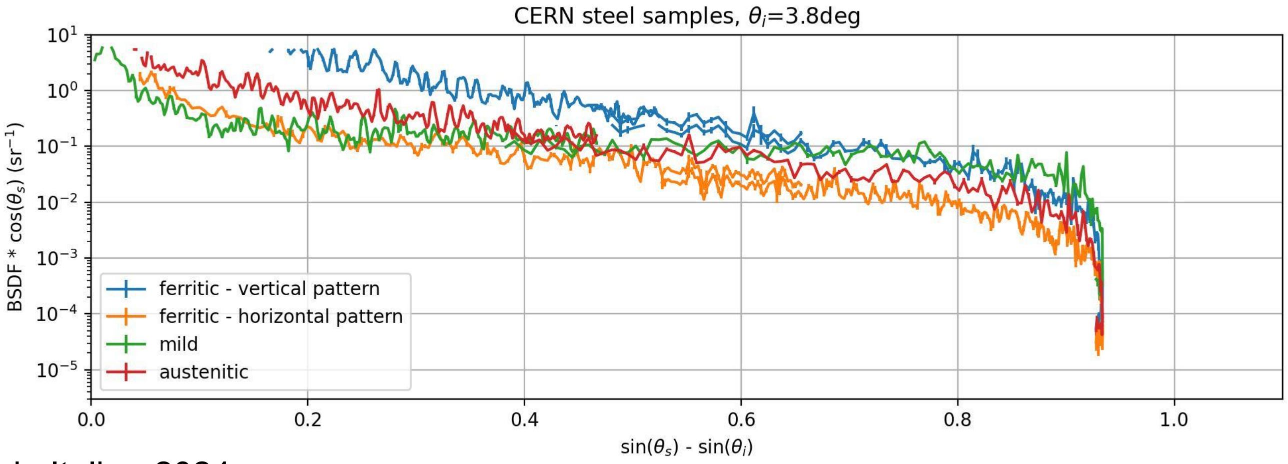


BSDF measurements

Noise floor



Samples of steel candidates for ET arm vacuum pipes



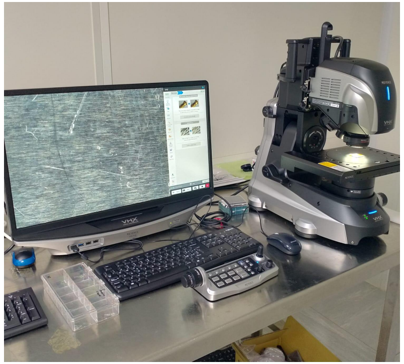
Sizing dust distributions and testing materials

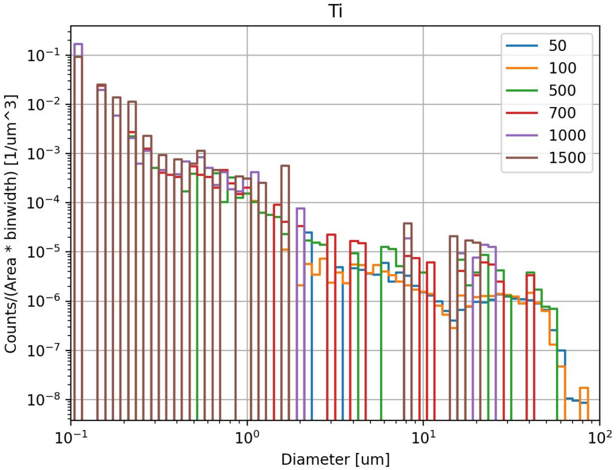
In synergy with Virgo and with ET R&D on coatings

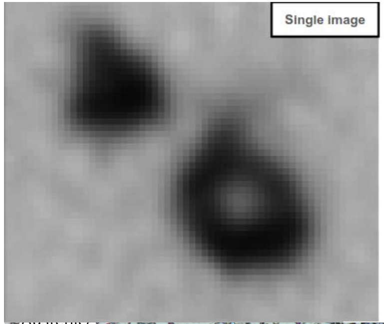
Digital microscopy to:

- count and size the dust particles deposited on exposed surfaces
- measure surface roughness (connected to TIS) of samples

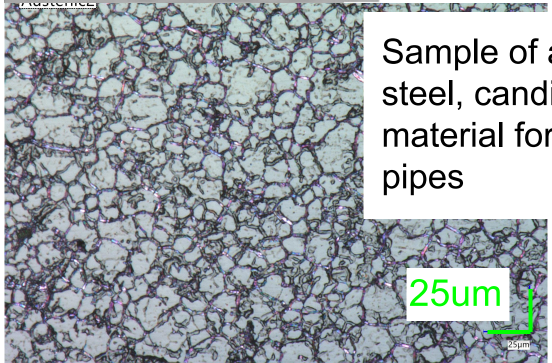
Resolution <1um







D=0.8um (20px)



Sample of austenitic steel, candidate material for ET beam pipes

Final remarks

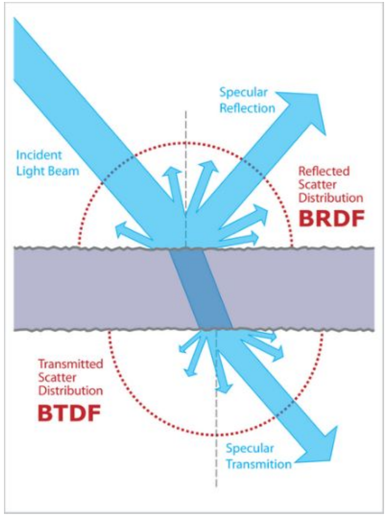
Stray Light Control is a key aspect of any Gravitational Wave detector, impacting typical at the low frequencies.

SLC is not a building element of the detector so in principle could be addressed at a later time. However past experience shows that it is much better to address SLC since the beginning.

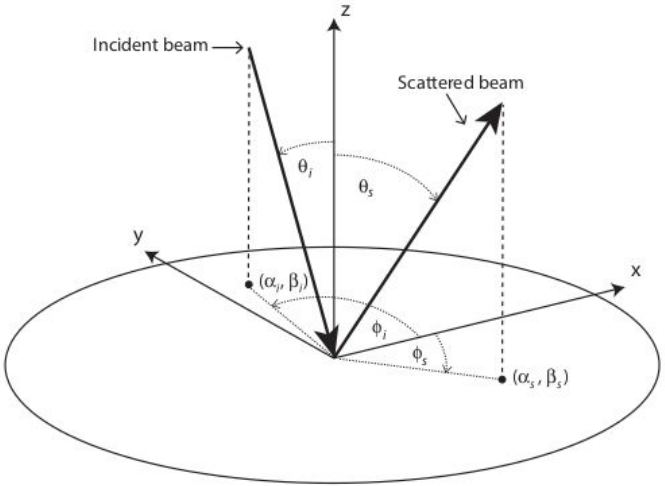
In ET SLC should be developed more, and is already a concern of many optics subsystems. There is room for more research. Interested people please contact me and subscribe to the et-isb-opt-scl mailing list.

Thank you

BSDF : the most complete metric of scatter



Bi-directional Scattering Distribution Function (BSDF), the ratio of the scattered radiance (ph/s-unit area -sr) to the incident irradiance (ph/s-unit area).
A sort of 'reflectance per solid angle'.



$$BSDF = \frac{d\Phi_s / d\Omega_s}{(d\Phi_i)\cos\theta_s}$$

$$BSDF(\theta_i, \phi_i, \theta_s, \phi_s) = BSDF(\theta_s, \phi_s, \theta_i, \phi_i)$$

Energy conservation: BSDF must be the same if the incident and scattered rays are reversed ('*Bidirectional*')

TIS : a common metric of scattering

Total Integrated Scattering (TIS)

the ratio of the total scattered power (over all angles) to the incident power.

$$TIS(\theta_i, \phi_i) = \int_0^{2\pi} d\phi_s \int_0^{\pi/2} d\theta_s \, \sin(\theta_s) \, \cos(\theta_s) \, BRDF(\theta_i, \phi_i, \theta_s, \phi_s) \leq 1$$

Easier to measure wrt the BSDF

For smooth surfaces it can be connected to the rms surface roughness (σ):

$$TIS = 1 - e^{-\left(\frac{2\pi \, \Delta n \, \sigma}{\lambda} \cos\theta_i\right)^2} \sim \left(\frac{2\pi \, \Delta n \, \sigma}{\lambda} \cos\theta_i\right)^2$$