Beampipes for Gravitational Wave Telescopes 2023

Dust in the beampipe: contribution to noise

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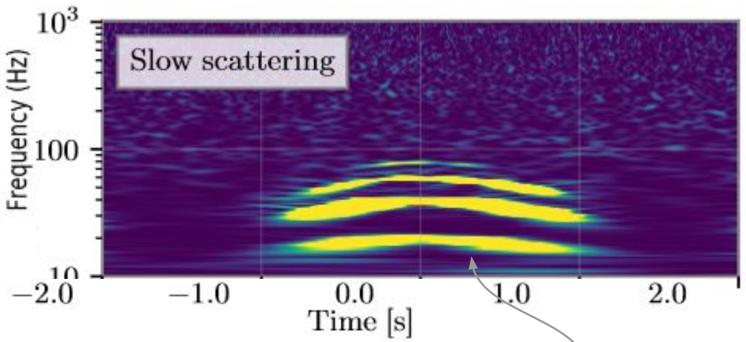
ET-0098A-23

Introduction

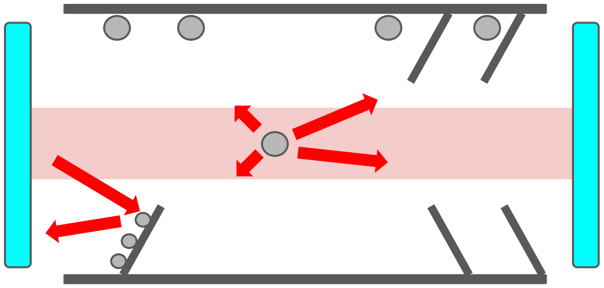
Straylight manifests as excess noise especially in the low-frequency region → scattered photons couple with the cavity mode: this will add phase and amplitude noise in the laser.

In our study, we focus on straylight caused by dust (D≳0.1μm) contamination in the arms and we do not account for dust particles in the towers: dust on TMs, TM's baffles and towers.



stray light as excess power in the detector

- when installing/general operations on arms dust can enter inside the arms:
  - dust deposits on the surfaces during general operations and installations (e.g. arm's walls, baffles…).
  - dust can be introduced by the pumps or gate valves
- once in vacuum, dust produce different effects:
  - particles can fall when walls are shaken and cross the beam and scatter light
  - dust deposited on baffles contribute to rescatter already scattered light reaching the baffles



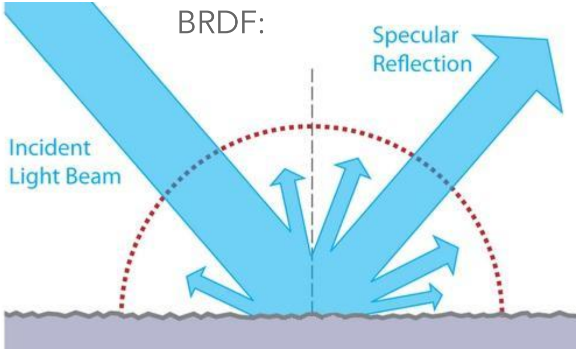
Dust on Baffles

The effect of dust deposited on baffles is to worsen their performances

- when/how dust enters:
  - during all baffles processes in clean rooms (related to ISO class, exposure time and surface orientation)
  - deposited after installation (dust entering from pumping/venting or shaking of tube walls)
- main effect: increase BRDF (BRDF: scattered light fraction as a function of the scattering angle per unit solid angle)

BRDF (i.e. scattering) of the baffles: this increases if dust is present

BRDF:



detector strain noise due to baffles backscattering

Baffle backscattering

$$\tilde{h}_{bs,M1}(f) = \frac{\varepsilon\kappa}{\sqrt{3\pi}} \frac{\lambda X(f)}{LR} \sqrt{\mathrm{BRDF}(60^\circ)} \sqrt{\ln\left(\frac{z_{last}}{z_{first}}\right)}$$

ET-0182A-22, following Vinet et. al. Phys.Rev.D 56, number 10 (1997)

Dust on Baffles: Particles Distribution Model

The quantity of scattered light depends on the dimension and number density of dust particles on the surface.

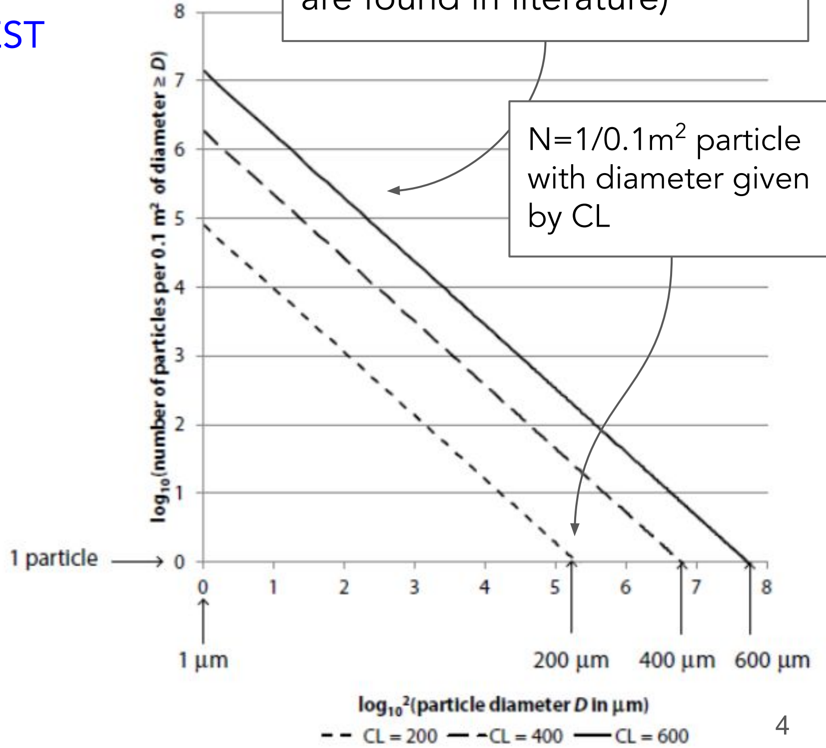
We can model the distribution of dust particles following the IEST cleanliness standard:

$$N_p(S, \mathrm{CL}, D) = 10^{|S|\left[\log_{10}^2(\mathrm{CL}) - \log_{10}^2(D)\right]}$$

- N_p is the number of particles/0.1m^2 with diameter ≥ D
- CL is the cleanliness level of the surface: CL=200 means 1 particle of >200um in 0.1m^2 (if S=-0.926 is assumed)
  - CL < 100 for pristine surfaces
  - CL = 600 for visible clean surfaces
  - CL > 1000 for visible dirty surfaces

S is the particles distribution slope (S=-0.926 given as standard, but different values are found in literature)

N=1/0.1m^2 particle with diameter given by CL



Dust on Baffles: CL in Clean Rooms

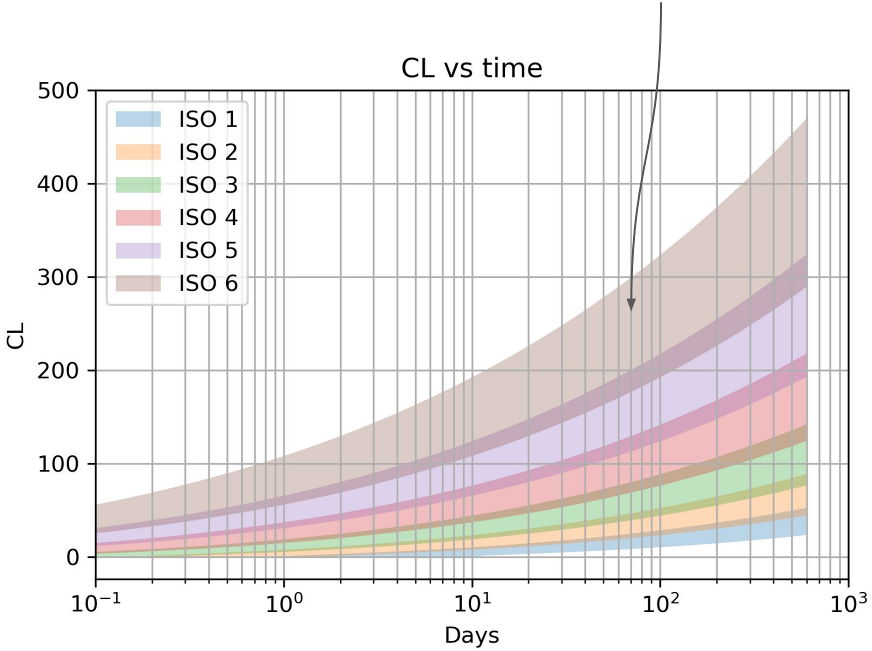
The Cleanliness Level CL increases with increasing time exposure, and depends on the ISO class of the environment [*Optical Engineering, 31(8):1775 – 1784, 1992*]

$$\log_{10}(\mathrm{CL}) = \sqrt{\frac{1}{S}\left[\log_{10}(h) + \log_{10}(\rho) + \log_{10}(t) + 0.773\log_{10}(X_c) - 1.24\right]}$$

- h: optics orientation (1 for horizontal, 0.1 for vertical)
- **ρ**: number of air-change per hour in the environments (ρ=2851 for an average non-laminar flow clean room)
- t: surface exposure time, in days
- X_C: air cleanliness class (related to ISO)

e.g. CL=200 can be obtained in 10 days for an horizontal surface in a ISO 6 clean room
→ DET lab @Virgo

Shaded region covers horizontally to vertically oriented surface

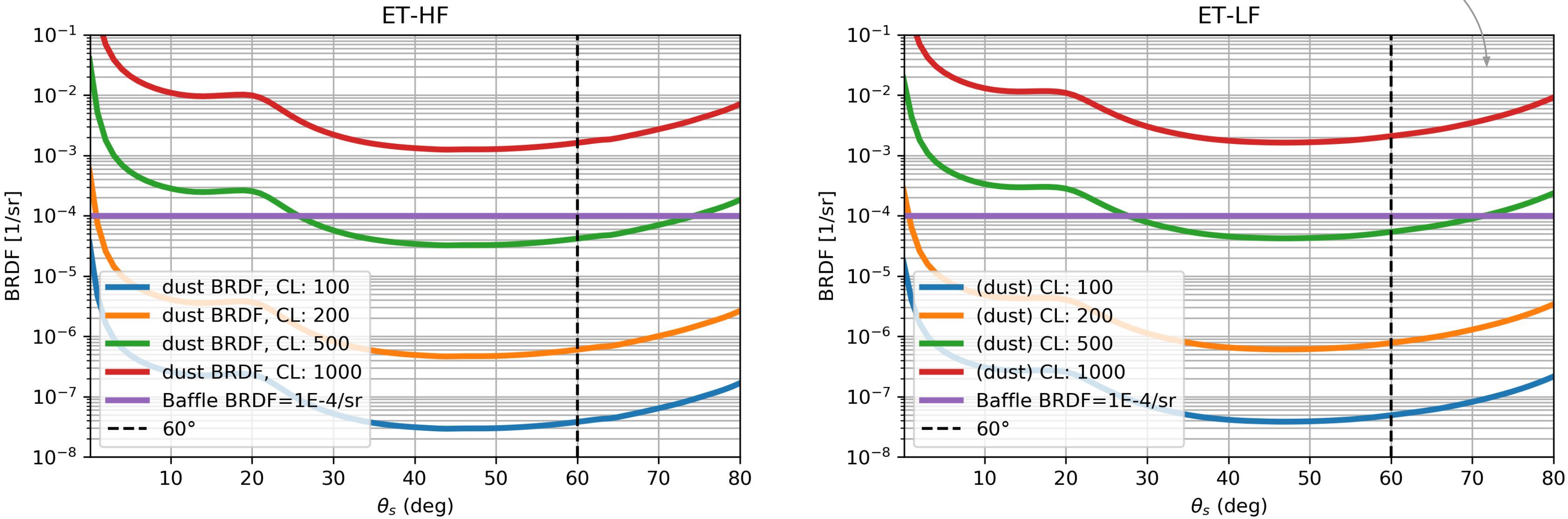


Dust on Baffles: BRDF vs CL

Those estimates assumes preliminary values ET-0212A-22:

- baffles BRDF(60°)=10^{-4}/sr
- baffles reflectivity: 10^{-2}

- Assuming the IEST dust distribution, the BRDF of the dust is computed from the CL level (both for ET-LF and ET-HF, since dust scattering is dependent on wavelength).
- Total BRDF is given by the linear sum of baffle's only and dust contribution



Dust on Baffles: BRDF vs Dimension

The BRDF for the baffles is assumed flat: but dust particles scattering has different angular dependence.

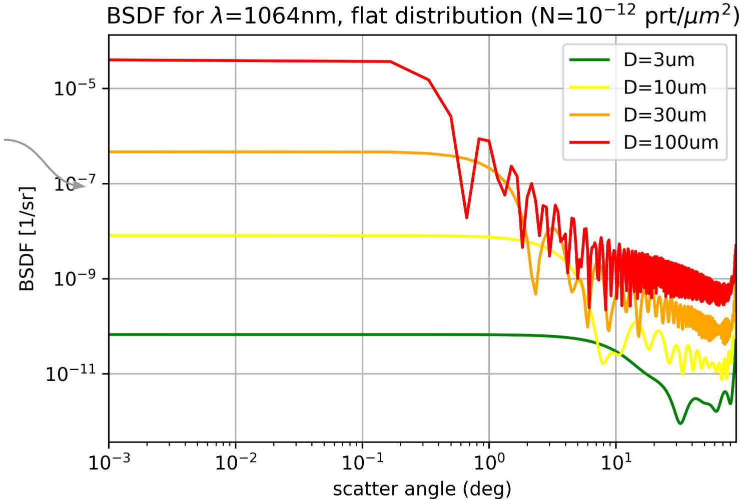
Size of particles also affects angular dependence of BRDF:

- larger particles tend to scatter more and at smaller angles wrt small particles
- but smaller particles are typically more numerous if one follows IEST distribution

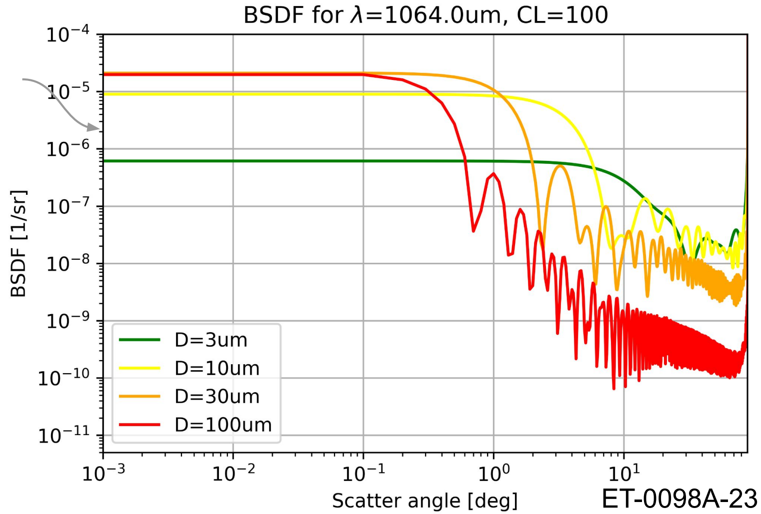
Summing up the contribution from smaller particles this becomes relevant, especially at mid-large angles.

This should be taken into account since it can be alter scattering properties of the baffles.

flat distribution of numerosity vs diameter



IEST, w/ S=-0.926, CL=100



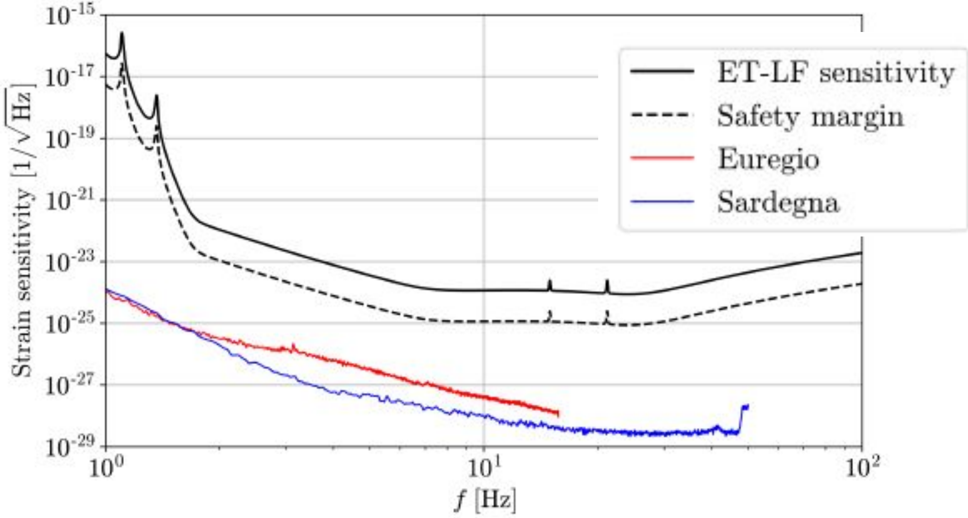
Dust on Baffles: Noise vs CL

From different CL values we can then compute the increment in BRDF and backscattered noise.

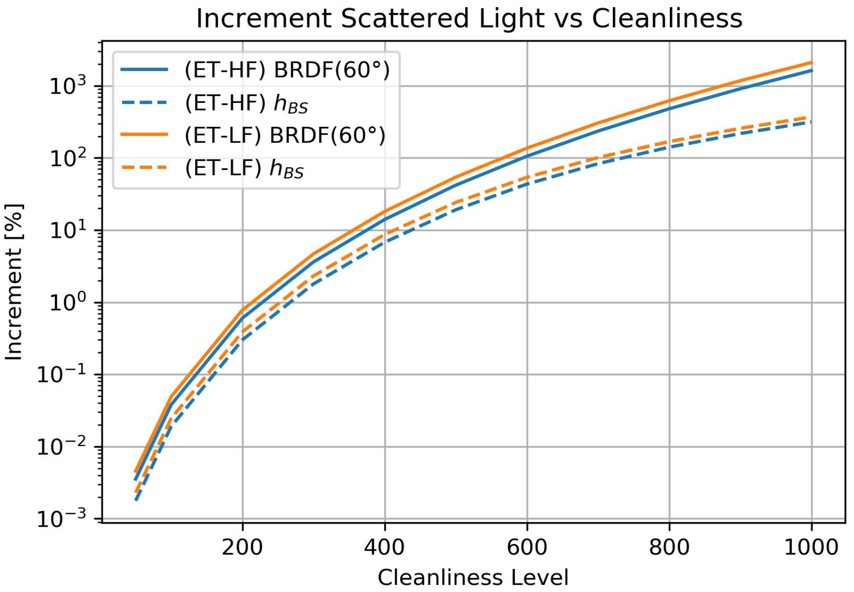
If typical operations are ≈10^1 days:

- CL≈100-200 with ISO 6 → ∆BRDF≈1%
- CL≈100 with ISO 5 → ∆BRDF <0.1%

ET-LF Baffle Backscattering noise:



M.Martinez et al. (this assumes worst baffles, BRDF=1E-2/sr)



Baffle backscattering

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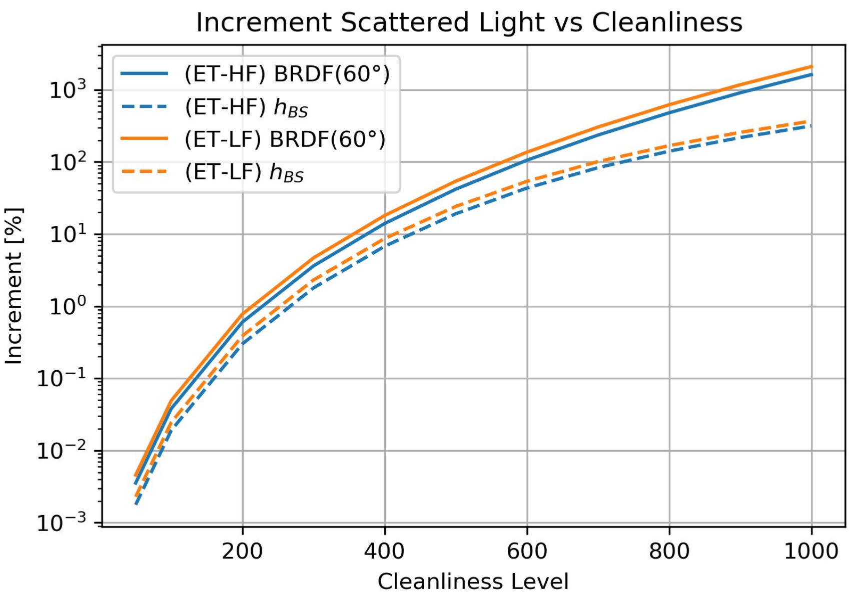
Exposure in cleanrooms does not seem harmful…

- but this is valid only if all the cleanliness procedures and standards are fulfilled
- attention must be paid to particles released by particular operation/machineries or procedures not respected

… the ISO class must be fulfilled even when work is performed!

As a reference: "For accelerator assemblies often class ISO 4 and ISO 5 are used. In mobile cleanroom tents in accelerator tunnels local environments of class ISO 5 can be established" ("*Proceedings of the 2017 CERN–Accelerator–School course on Vacuum for Particle Accelerators, Glumslov, (Sweden)*")



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Dust on Baffles: Pumps/Pipe walls/Gate valves

Dust is also released when the system is closed:

- pumps operation
- shocks on tube walls
- opening/closing of gate valves

In "Rev. Sci. Inst. 69, 3818 (1998)" dust contamination is measured in UHV:

- Ion Pump:
  - particles release at ignition, no particles during operation
  - N=30 particles on average (new pump) + and not diminishing along successive start/stop cycles
- Shocks on walls:
  - after 5-10 impacts no more particles but no data→ but if strength or place of impact is changed particles are released again
  - particles mainly accelerated by gravity
- Gate valves
  - distribution: 2400 particles, 90% with D<2um, and 50% with D<0.5um (over 6 open-close cycles)
  - with more open/close cycles: half particles after 10 cycles, then constant up to 30 cycles

Dust on Baffles: Pumps/Pipe walls/Gate valves

By accounting for all the pumps (~180) and gates (~150) (from *"ET Design Report 2020"* [ET-0007B-20]), we can compare the contamination (0.5um<D<2um) due to pumps and clean rooms:

- pumping/gate valves (no info on shaking): ~ $5*10^5$ part per arm (~10^2 baffles)

- e.g. @CL200 (≅10^2 days in ISO6) ~ $3*10^5$ part/m^2 → 10^5 part per baffle

→ Radius of tube: 0.6m
→ Baffles height: 0.08m
→ Baffles assumed flat

$$A_{baffle} = \pi R^2_{tube} - \pi(R^2_{tube} - h^2_{baffle}) \cong 0.3m^2$$

From ET-0182A-22 (provisionary) and assuming flat baffle

↓

Contribution from pumps/valves (no info shaking) seems not as significant…

- … even more so considering that the measurements were made with no cleaning of the system!
- … and particles are collected vertically (trajectory compatible with gravitational acceleration only)

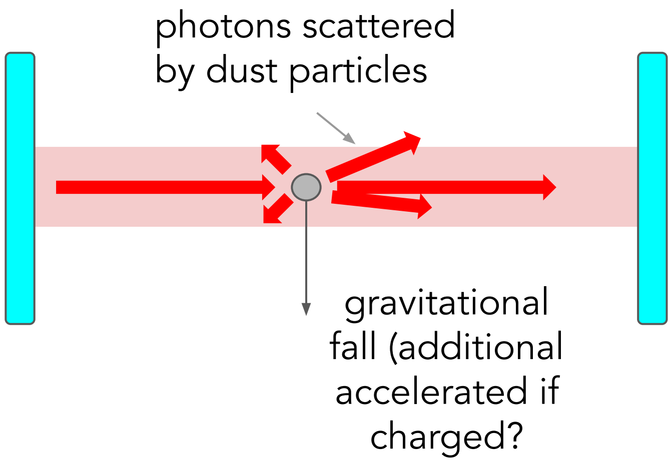
Dust Crossing the Beam

Dust particles crossing the beam adds two first-order contributions to stray light:

1) light scattered directly to the TMs
2) light scattered to the baffles and then on TMs

Scattered light can reach TMs in different channels:

- dust → ITM
- dust → ETM
- dust → baffle → I/E TM
- dust → baffle → dust→ I/E TM
- dust → dust → I/E TM
- …



Here we focus only on channels where scattered light directly reaches one TM: it can be a dangerous contribution since it scatters directly to the TMs

Dust Crossing the Beam

Recombination of scattered field causes noise in the ITF, which we will compute in the following way:

1. particles are on on pipe ceiling (or baffles) in random positions
2. each particle detaches at a random time t_0 and are accelerated only by gravity
3. particles see different intensity while falling
4. the scattered field arriving at (x,y)∈TM:

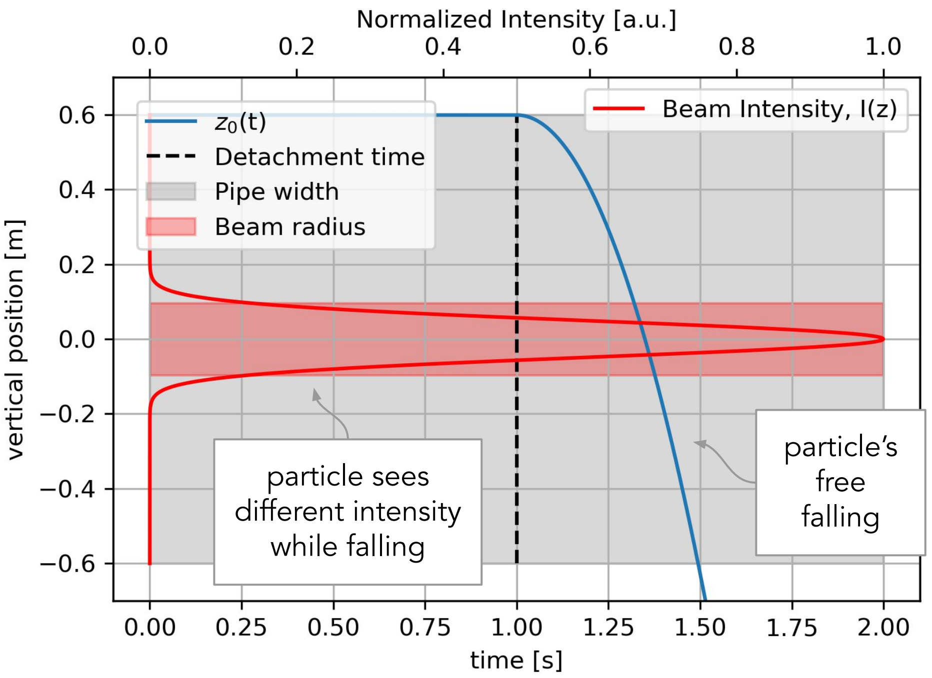
$$E^s_{1,2}(\vec{x_0}, \vec{x}, t, t_0) = \frac{e^{-ikr(t,t_0)}}{ikr(t,t_0)} \cdot S_{1,2}(\theta_s, D, m) \cdot \mathrm{TEM00}(\vec{x_0}(t, t_0))$$

scattered field

k: beam wavevector
r(t): vector from particle to point on TM

TEM00 mode incident on the particle

Mie scattering, depends on
- complex index of refraction (m)
- particles size (D)
- scattering angle



5. compute field that recouple with cavity mode from ensemble of all particles (random position, time and dimension)
6. compute phase and amplitude fluctuation

… work in progress…

Conclusion

- Dust particles inside the arm cause:
  - higher baffles BRDF
  - scattering by particles crossing the beam
- Conclusions:
  - clean rooms operations: ISO 5-6 may represent enough safe margin, but cleanliness standard must be kept during all operations
  - when running pumps/venting (no info on shaking): our first estimate seems to suggest that it is not impacting as dust deposited in CR…but data available are not representative and design not fixed + no data on shaking
- Open issues:
  - need more data for pump/shaking contamination
  - how dust settles in vacuum (different motion if particles are charged, spread evenly or concentrated in spots…)
  - particles crossing the beam: work in progress…
  - extend study to other part of the ITF (towers, TMs, filter cavity, injection…)

…anything else?

Backup slides - IEST distribution

The particles distribution over a surface is described by the IEST std as:

$$N_p(S, \mathrm{CL}, D) = 10^{|S|\left[\log_{10}^2(\mathrm{CL}) - \log_{10}^2(D)\right]}$$

But this is valid only for D>1um.

The distribution for D<1um is extrapolated from the IEST by exting is for smaller diameters, by extending the growth rate.

Points with D<1um are obtained with a linear fit of the curve between D=2um and D=3um.