Scattered light study in Advanced Virgo Plus

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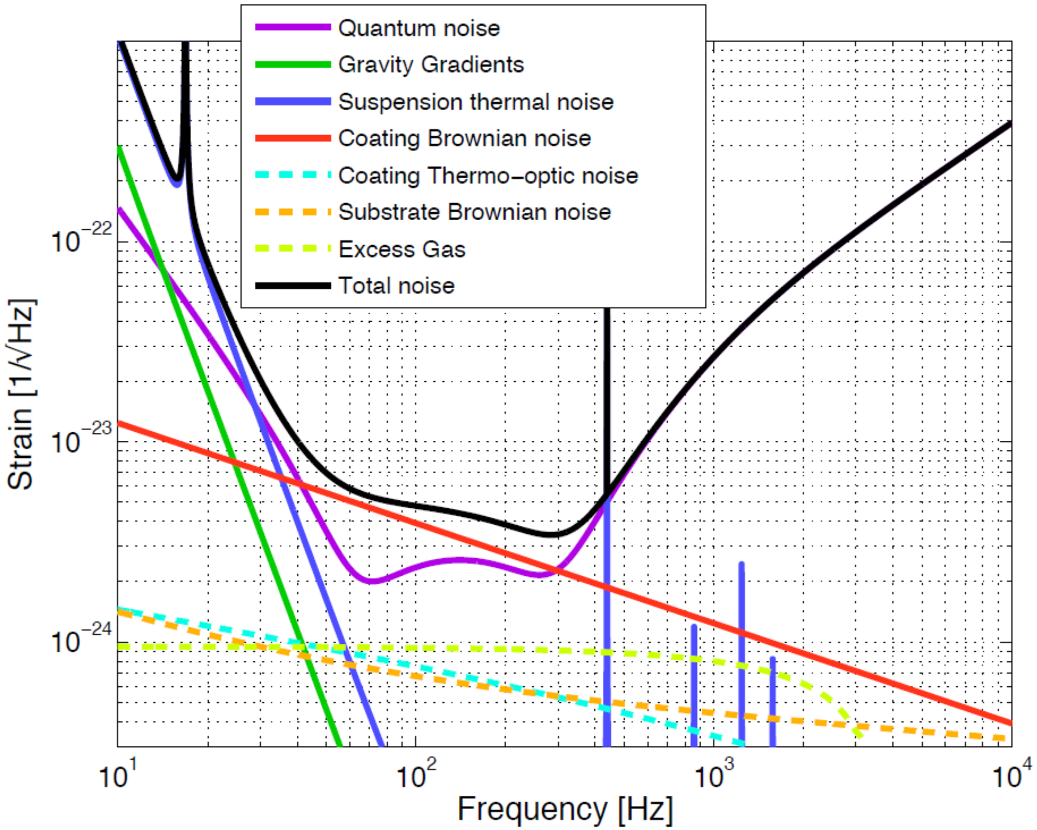
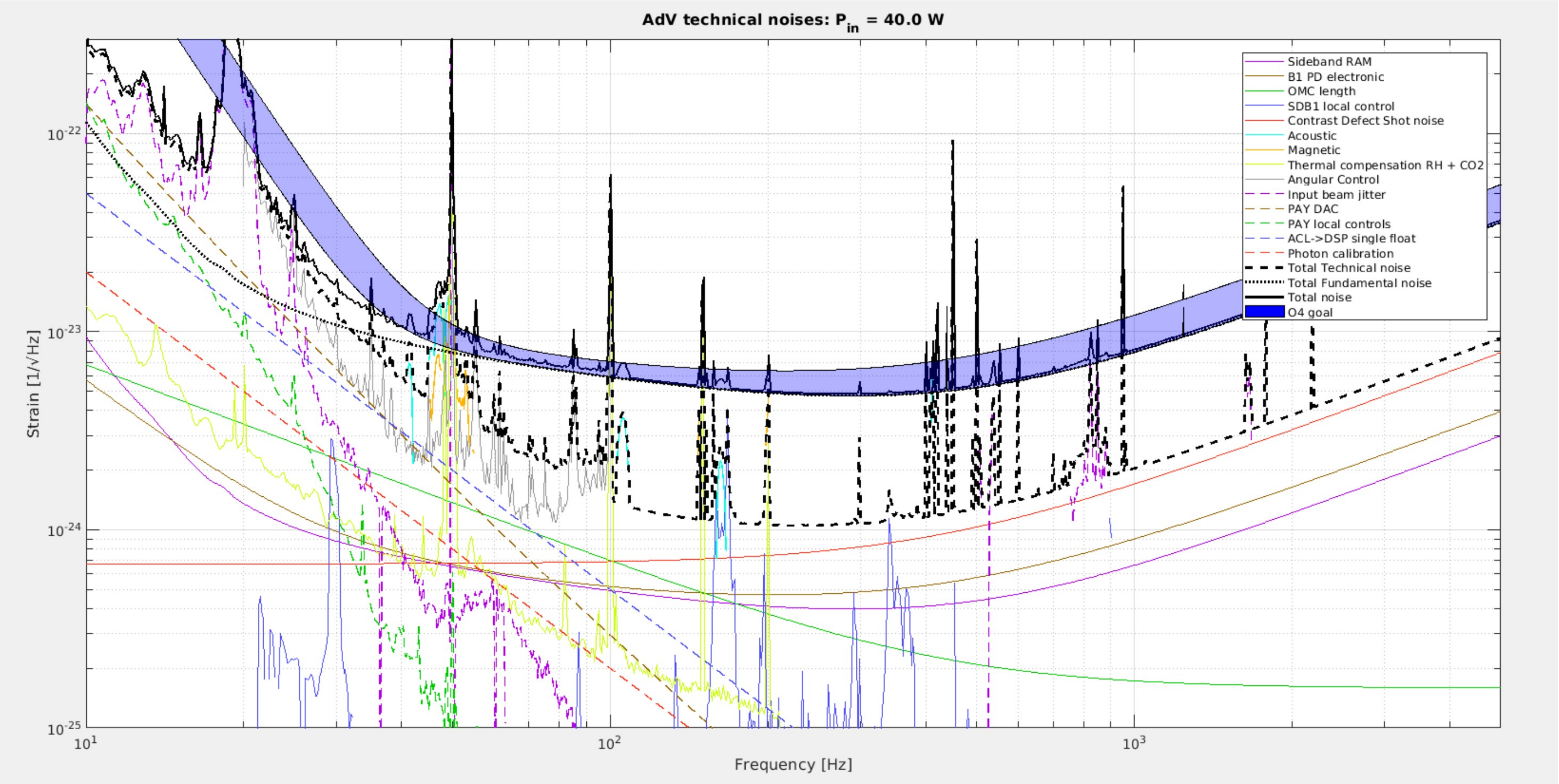
on behalf of the Scattered light studies team

GWADW
Scattered light workshop
17/05/2021

Fundamental noises



Beyond fundamental noises



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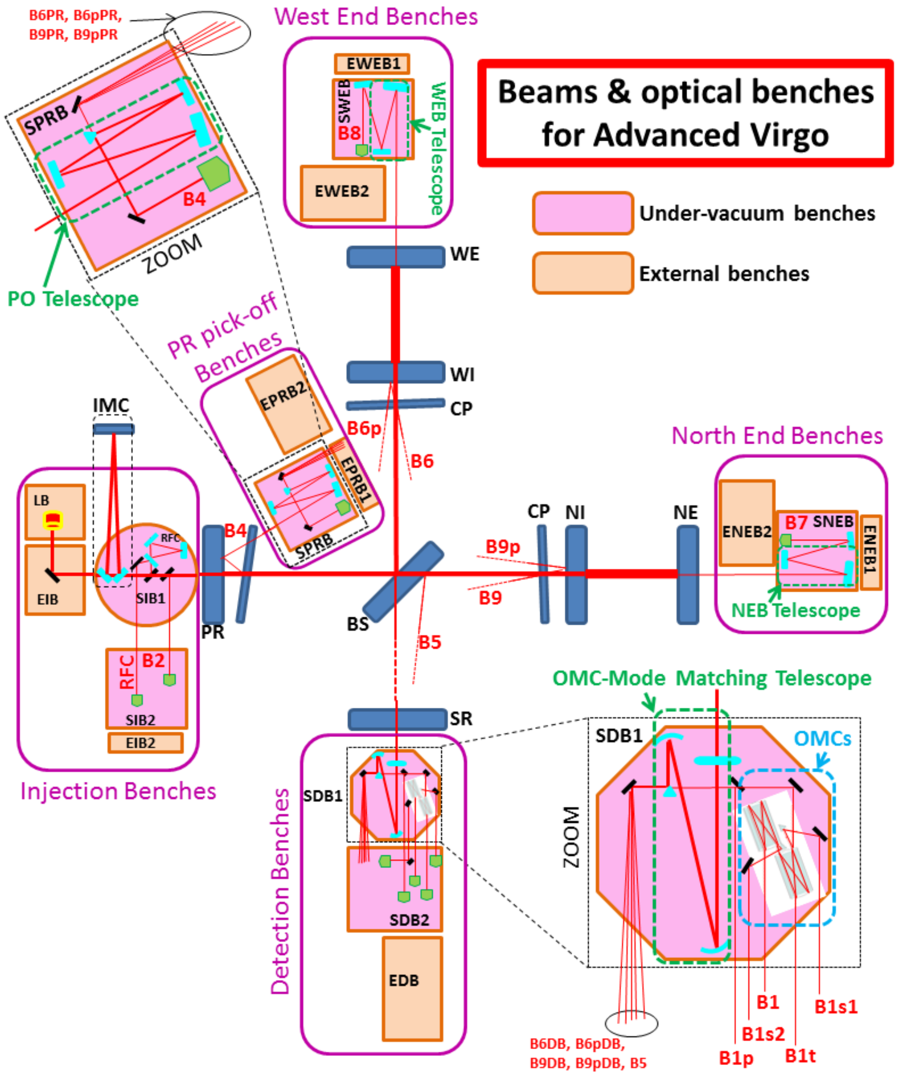
Scattered light studies

- ‘Scattered light studies’ : new activity started in September 2020 with the aim of working across AdV+ subsystems to identify gaps in the design or preparation
- Initially identifying issues with the current design or implementation
- To structure this, started with looking at one specific aspect, i.e. ghost beams
- Identifying gaps in knowledge or tools: do we have the right *tools* to understand and mitigate scattered light issues at the design and *noise-hunting* level? Are we collecting the expert knowledge for the whole team and for the next generation?
- Work organized in Reviews by subsystem
- Final goal: to take actions to limit scattered light problem in AdV+

Stray light - detection system



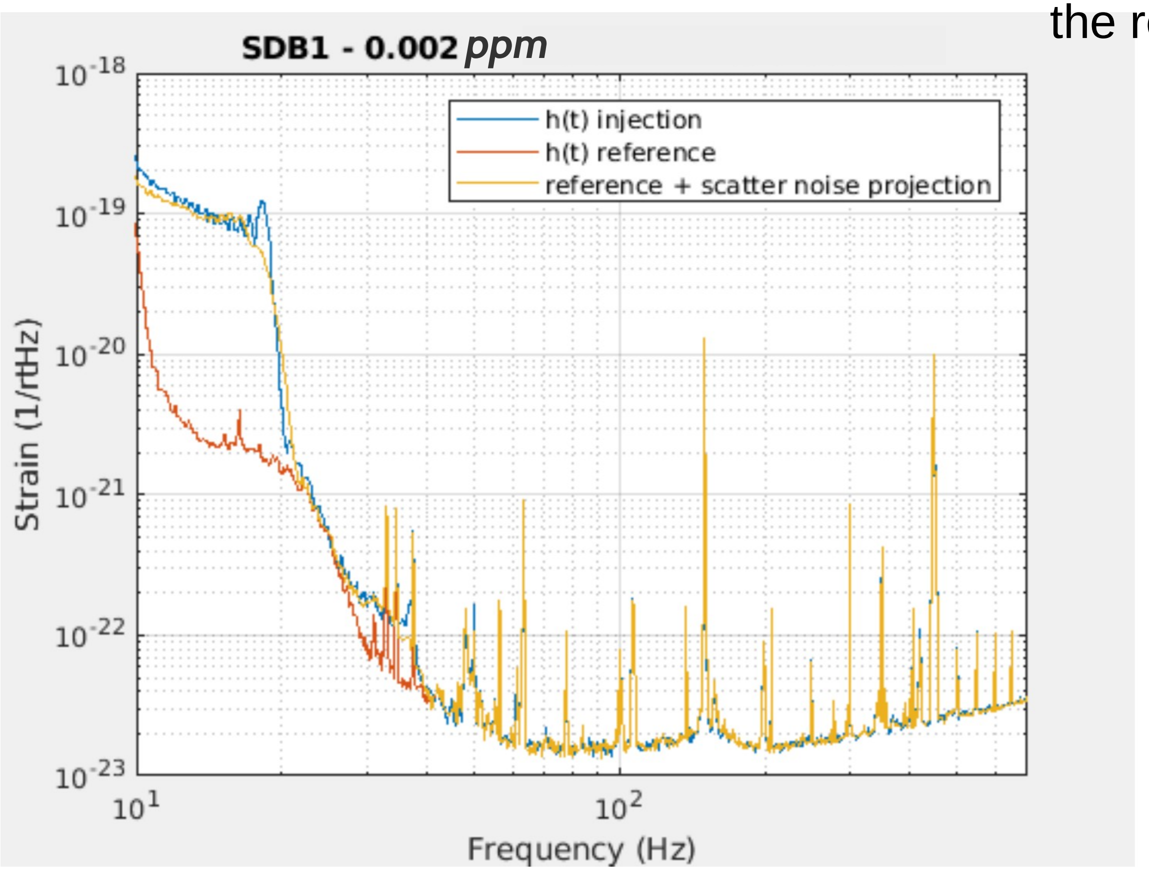
Stray light - detection bench

$$\tilde{h}(f) = T(f)\sqrt{\frac{f_r P_{out}}{P_{in}}}\,\mathscr{F}\left[\cos\left(\phi_r(t)\right)\right]$$

Fourier transform

variation of phase of the recoupled field

Transfer function : linear response of the ITF to noise



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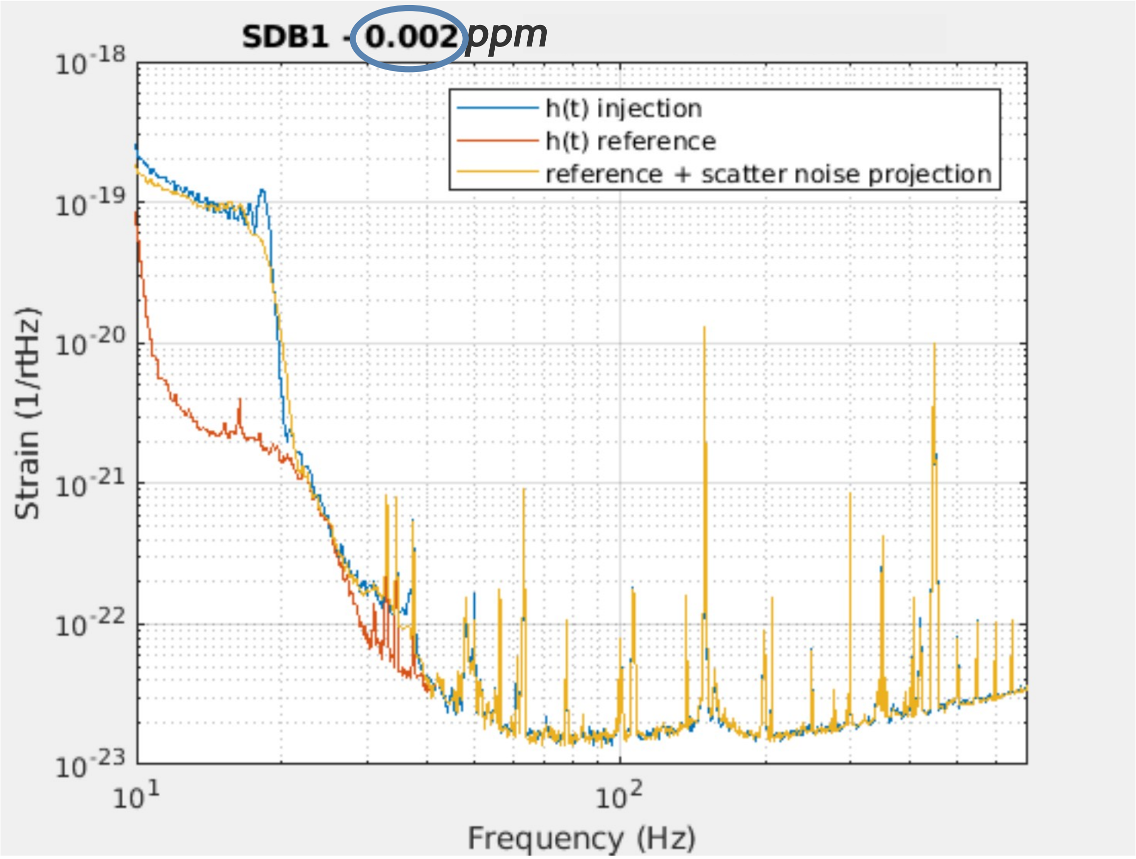
Stray light - detection bench

$$\tilde{h}(f) = T(f)\sqrt{\frac{f_r P_{out}}{P_{in}}}\mathscr{F}\left[\cos\left(\phi_r(t)\right)\right]$$

f_r = 0.002 ppm

fraction of light power coupled back with the main mode of the ITF



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Stray light

$$\tilde{h}(f) = T(f)\sqrt{\frac{f_r P_{out}}{P_{in}}}\,\mathscr{F}\left[\cos\left(\phi_r(t)\right)\right]$$

$$f_r = f_{sc} + f_{sp} + f_{Rayleigh}$$

- f_{sc}: Fraction of scattered light re-coupled to the main mode of the ITF (mirrors...)
- f_{sp}: Fraction of back reflected re-coupled light (lenses, photodiodes...)
- $f_{Rayleigh}$: Fraction of scattered light by atoms or molecules, i.e. crystals (TGG)

⚠ **SECONDARY BEAMS!!**

They are produced and propagates on the benches hitting mounts, optics, vacuum chambers and so on : ***extra*** *scattered light*!
We want to identify and stop them before they re-couple.

Ghost beams study

Ghost beams are unwanted secondary beams generated by not perfect HR and AR coating of optical components, like mirrors.

Goal of the work:

- Trace the ghost beam as a Gaussian beam through all the optics of AdV+ benches and get its information: position, size and power

  → done with **Optocad**: Fortran 95 module for tracing Gaussian TEM_{00} beams through an optical set-up

- Understand if and how we have to stop them to prevent extra scattered light

Ghost beams on Optocad

Optics definition on Optocad:

Input lines on the file.ocd :

c (General surface/component), d (dual surface component), h (hole in a component):
action xap yap phi reflectivity transmittivity + extra information

x, **y** positions of the center of the optics wrt a reference point

Angle of the optics

+ (secondary surface): action + extra information

letter	*action*
c	start cavity
d	dump beam
h	hide surface
i	interfere
n	neglect surface
r	reflect beam
s	split beam
t	transmit beam

Ghost beams on Optocad

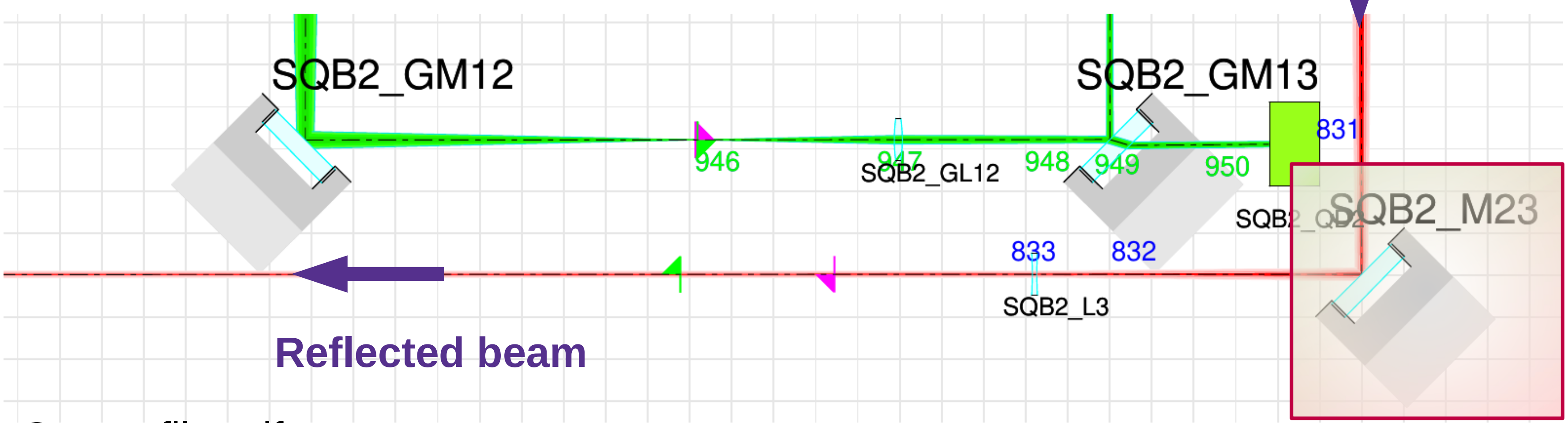
Mirror definition on Optocad:

d (dual surface component), reflect beam, x (meter), y (meter), angle (degree), reflectivity, transmittivity, RoC (meter)
+ (secondary surface) transmit beam, thickness (meter), wedge (degree)

Example: mirror **SQB2_M23**

d   r, 0.250, -0.660,   -45, 1.0, 0.0, rc=1e99
+   t,   dm=0.0105, da=179.5

Input beam



Output file.pdf

Ghost beams on Optocad

Ghost beam on Optocad:

Example: mirror **SQB2_M23**

d   srt, 0.250, -0.660,   -45, 1.0, 0.0, rc=1e99

Split of the beam: it is first transmitted and then reflected at the first surface

+   r,   dm=0.0105, da=179.5

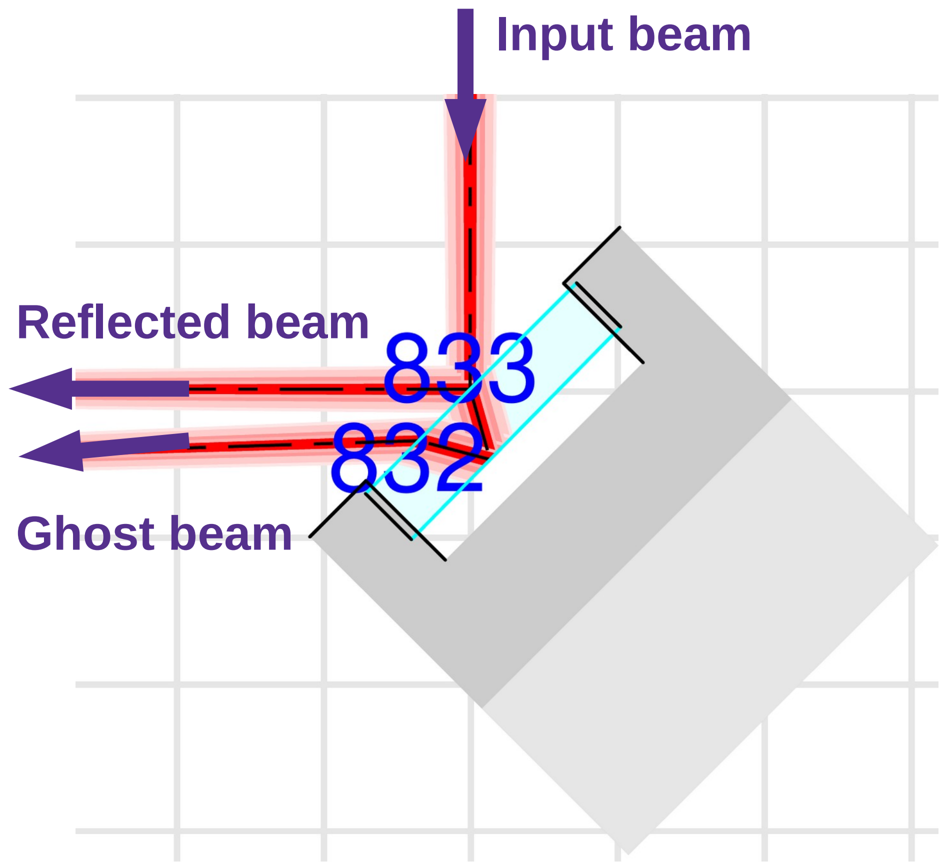
Beam reflected from the second surface and then transmitted again by the first surface.

Ghost beam power:

$$P_{GB} = \eta_{HR}^2 \eta_{AR} P_{in}$$

HR coating residual transmission

AR coating residual reflection



η_{HR} ~ few ppm, $\eta_{AR} < 500$ ppm

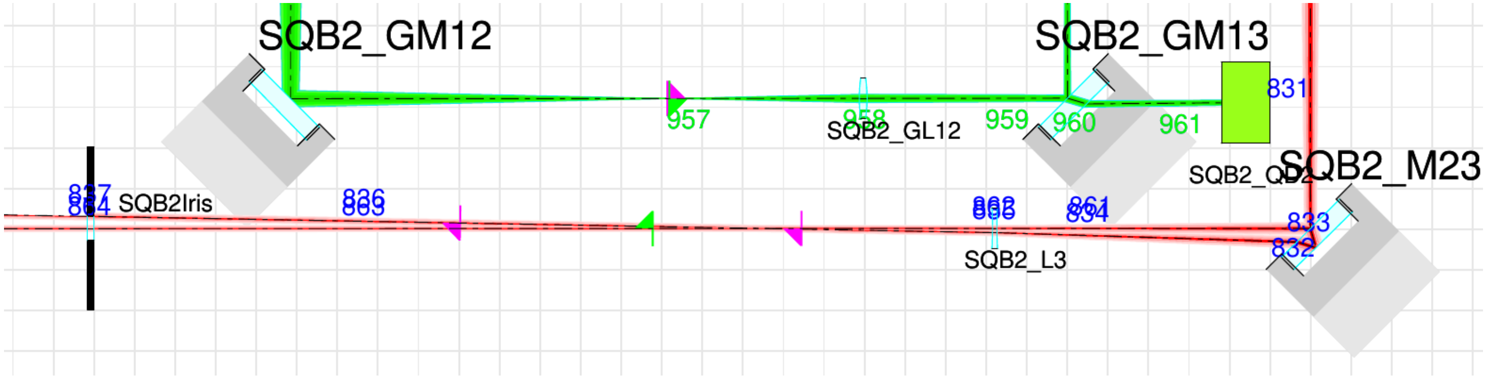
Ghost beams on Optocad

Wedge optimization:

d srt, 0.250, -0.660, -45, 1.0, 0.0, rc=1e99
+ r, dm=0.0105, da=179.5

Better!

+ r, dm=0.0105, da=180.5



Ghost beams on Optocad

Ghost beam dumping:

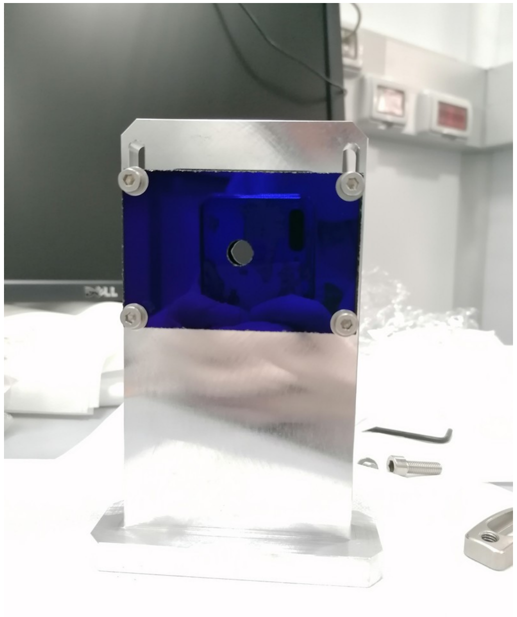
d   srt, 0.250, -0.660,   -45, 1.0, 0.0, rc=1e99
+   r,   dm=0.0105, da=179.5

Diaphragm to stop ghost beams

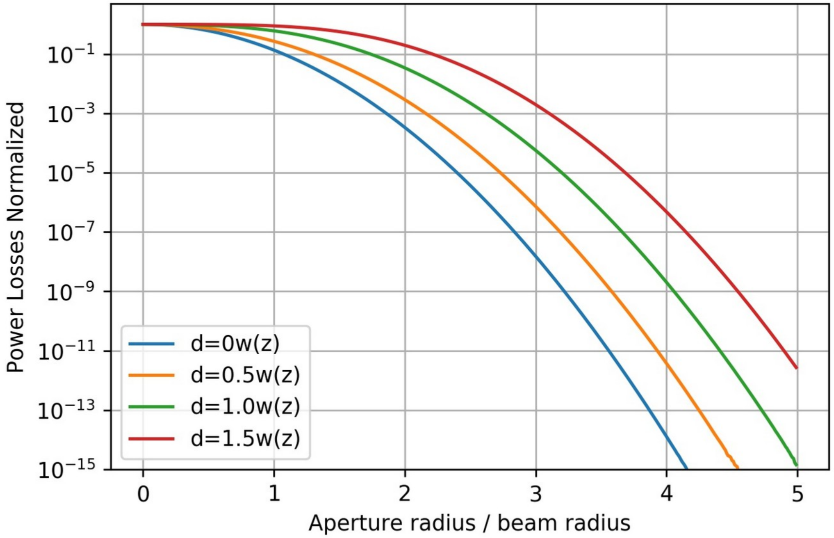
Ghost beam diaphragms

Diaphragm aperture and size chosen in order to:

1) don't clip the main beam
   - limit power losses due to clipping and lateral misalignment of the beam
   - limit mismatch losses due to hole diffraction
2) properly dump the ghost beam
   - design of the diaphragms



Different size and apertures,
depending on beam parameters



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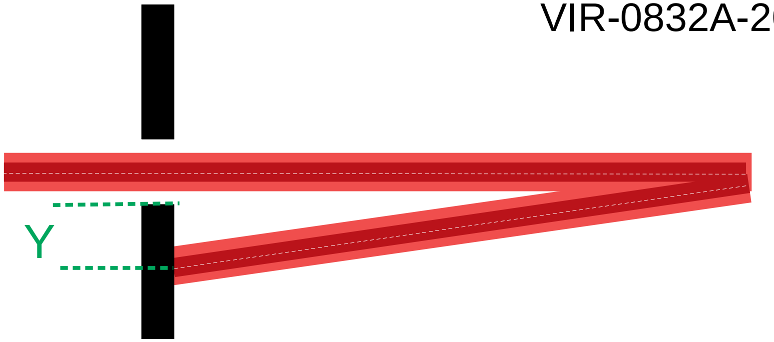
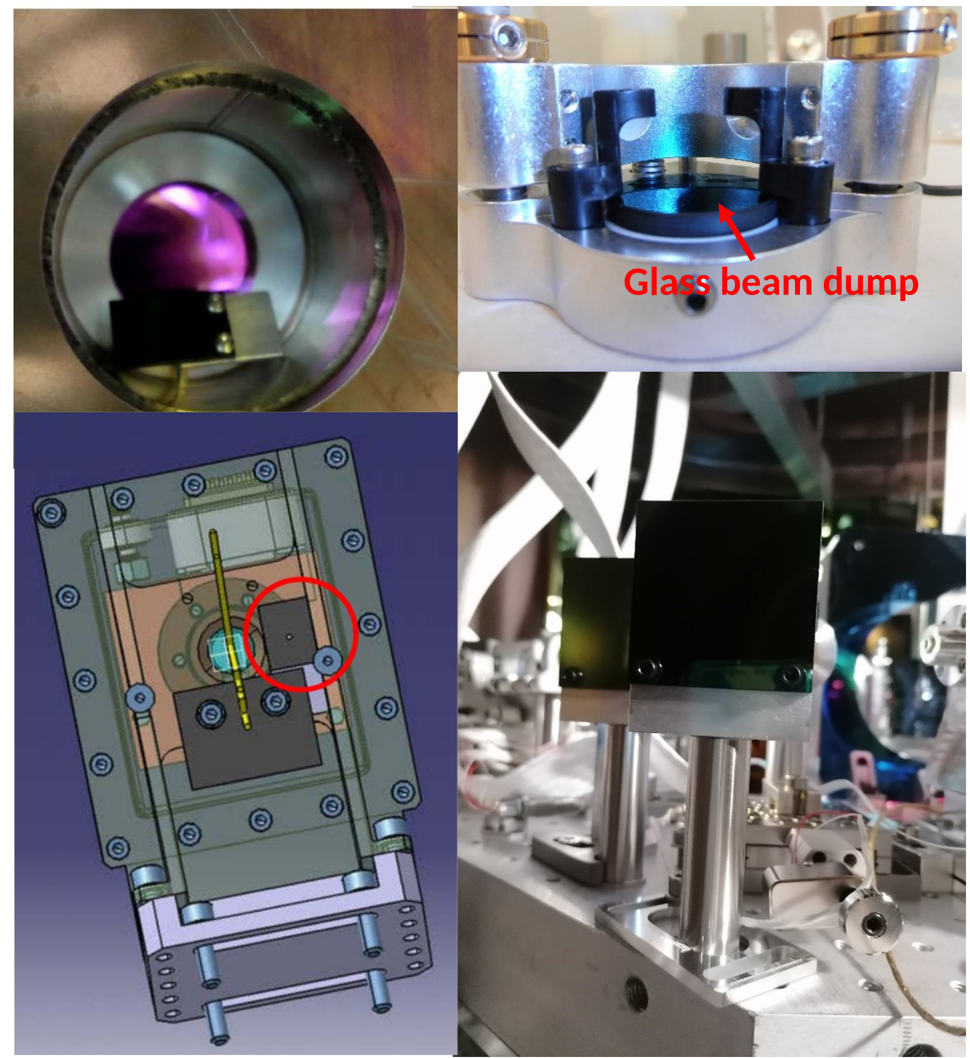


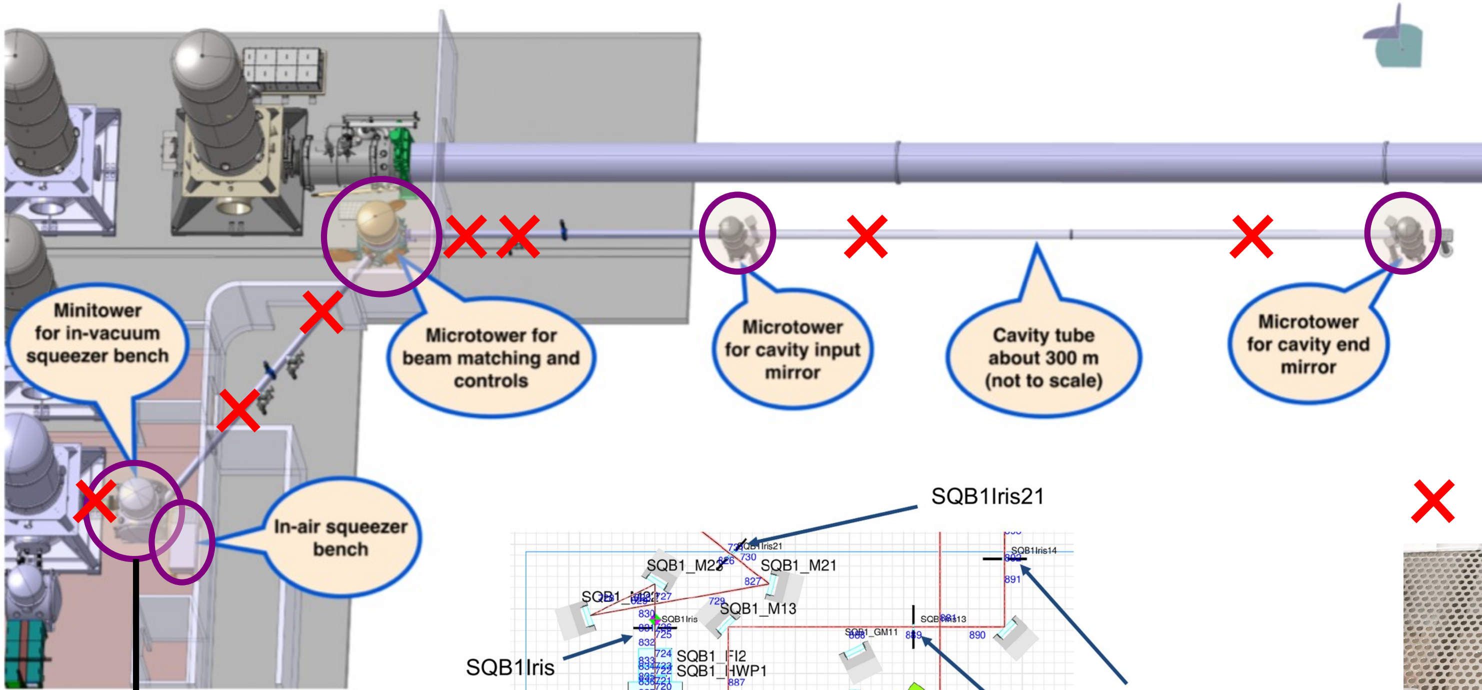
Mitigation strategies

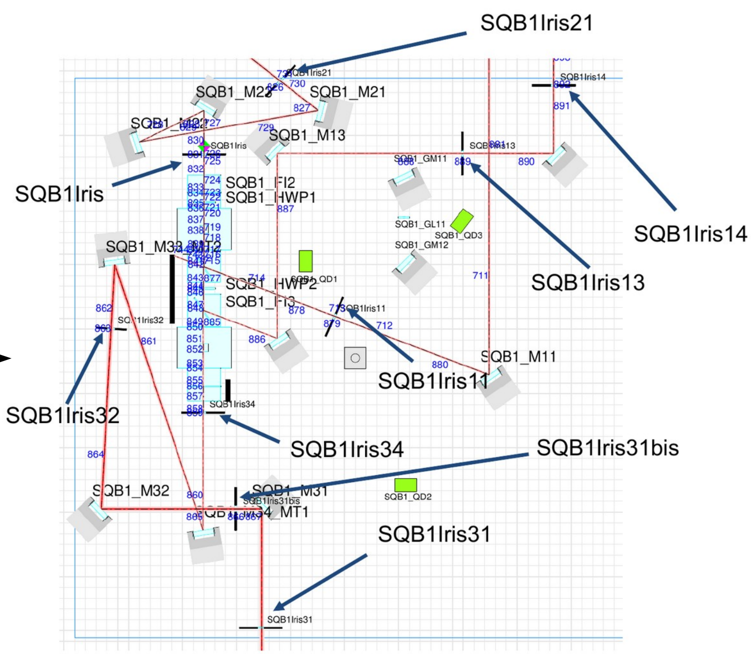
Some of the *mitigation strategies* adopted for Advanced Virgo Plus:

- Wedge optimization
- Diaphragms installation
- Baffle installation
- Absorbing disks behind mirrors
- Diaphragms on quadrants
- Small beam dumps
- Dumpers on photodiodes
- Lens tilting
- Absorbing screws

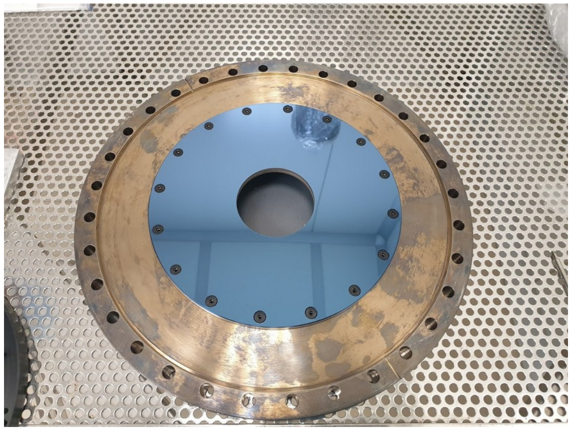


Mitigation on squeezing system





✕ : baffles



Credit to IFAE

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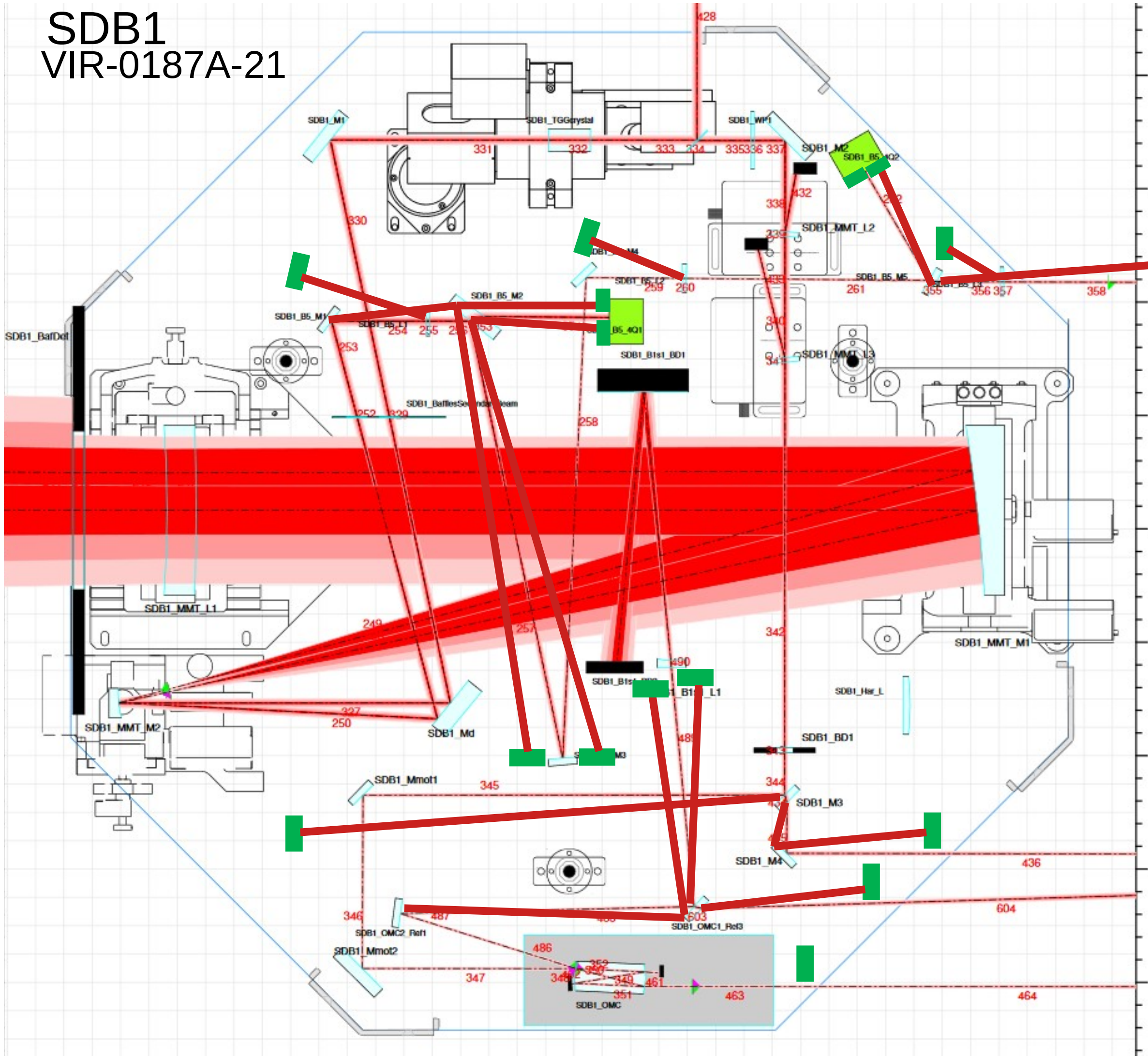
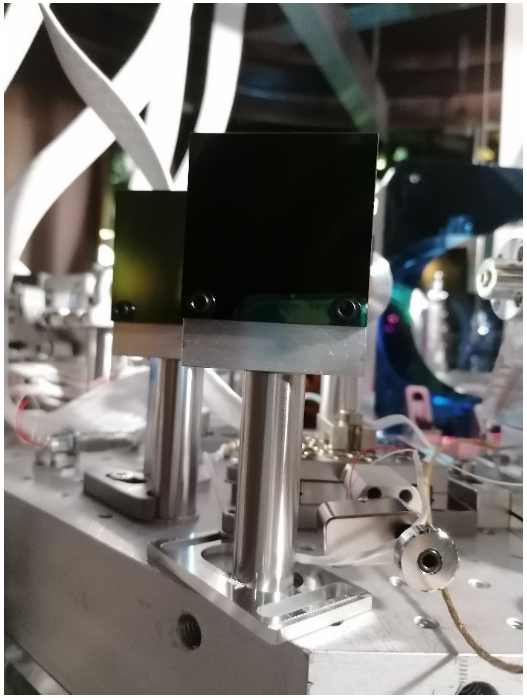
Mitigation on detection system





: beam dumps to be installed (31st May)

Conclusion and future works

- Scattered light is limiting the sensitivity of the detector
- We recently started a new activity in order to review the scattered light provisions in the Advanced Virgo plus design
- Initial tasks focused on ghost beams: they produce extra scattered light that propagates and hits objects that cause a phase modulation
- Ghost beams traced for squeezing/detection systems
- Dumping strategies already implemented or ongoing

Next steps:

- Conclude the ghost beam study also on the injection system
- Review simulation tools and mitigating solutions across all subsystems
- Scattered light 'noise hunting': ongoing discussion on more precise estimation of $\mathbf{f_r}$

Thanks for the attention

Extra slides

Stray light

$$\tilde{h}(f) = T(f)\sqrt{\frac{f_r P_{out}}{P_{in}}}\mathscr{F}\left[\cos\left(\phi_r(t)\right)\right]$$

$$f_r = f_{sc} + f_{sp} + f_{Rayleigh}$$

Fraction of scattered light re-coupled to the main mode of the ITF (mirrors...)

Fraction of back reflected re-coupled light (lenses, photodiodes...)

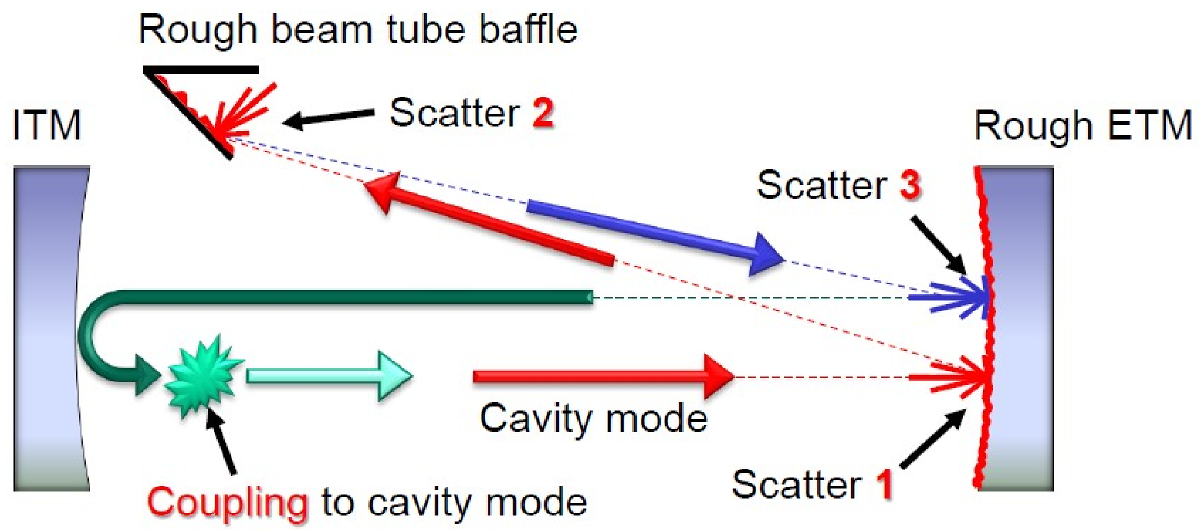
Fraction of scattered light by small particles, i.e. crystals (TGG)

$$f_{sc} \approx \frac{\mathrm{BRDF}\lambda^2}{\pi\omega_0^2} = \frac{\lambda^2}{\pi^2\omega_0^2}$$

$$\alpha_{sca} = \frac{8}{3}\frac{\pi^3}{\lambda^4}\left(n^4 p\right)^2 kT\beta_T$$

$$f_{sp} = \frac{\alpha R^2 z_o^2 \exp\left[-\frac{2\pi D^2 z_0 \beta^2}{2\lambda}\left(\frac{1}{D^2+z_0^2} + \frac{1}{(D-R)^2+z_0^2}\right)\right]}{(D^2+z_0^2)[(D-R)^2+z_0^2]}$$

Stray light



How much scattered light coupled into cavity mode?

Scatter 1 → Ok : Use FFT & mirror maps

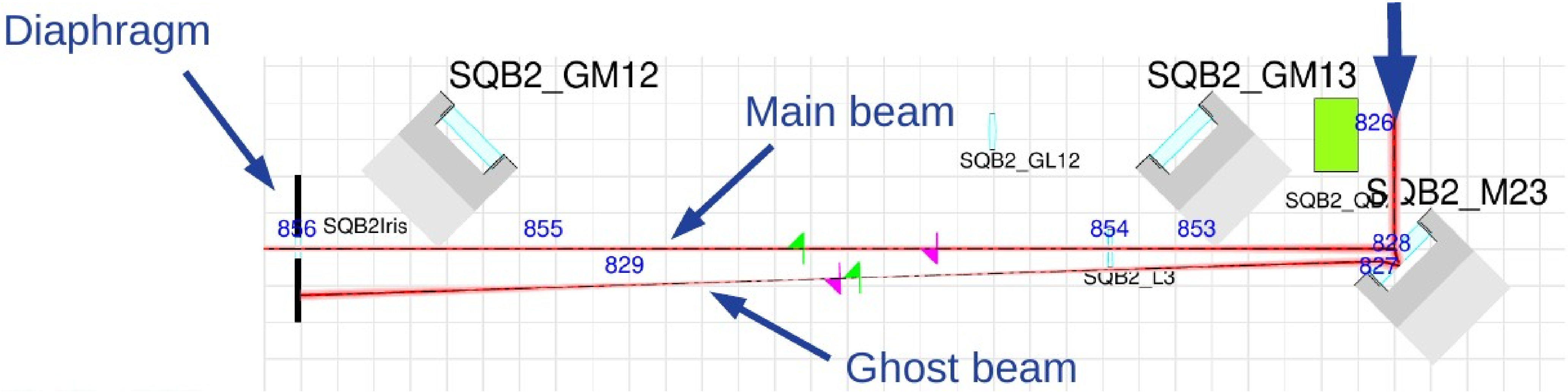
Scatter 2 → Tricky : Use BRDF to estimate

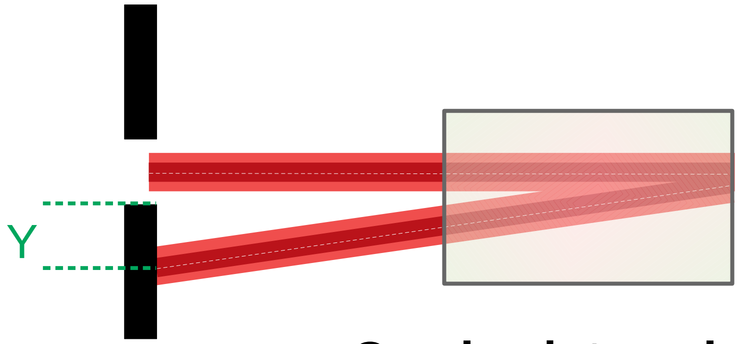
Scatter 3 → Ok?: Use FFT & mirror map (but what field?)

Coupling → ?: How exactly does it couple?

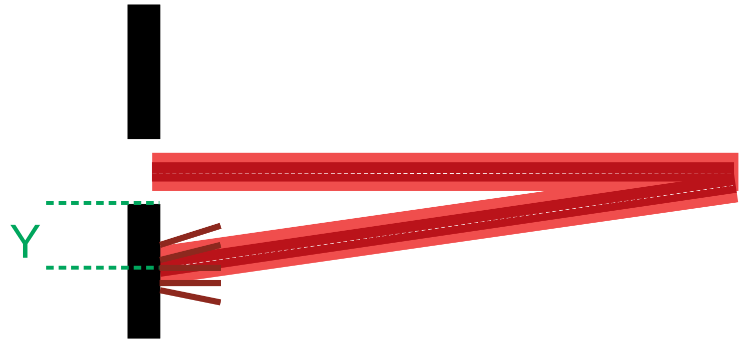
From R.Day, G1300532

Stray light from ghost beam



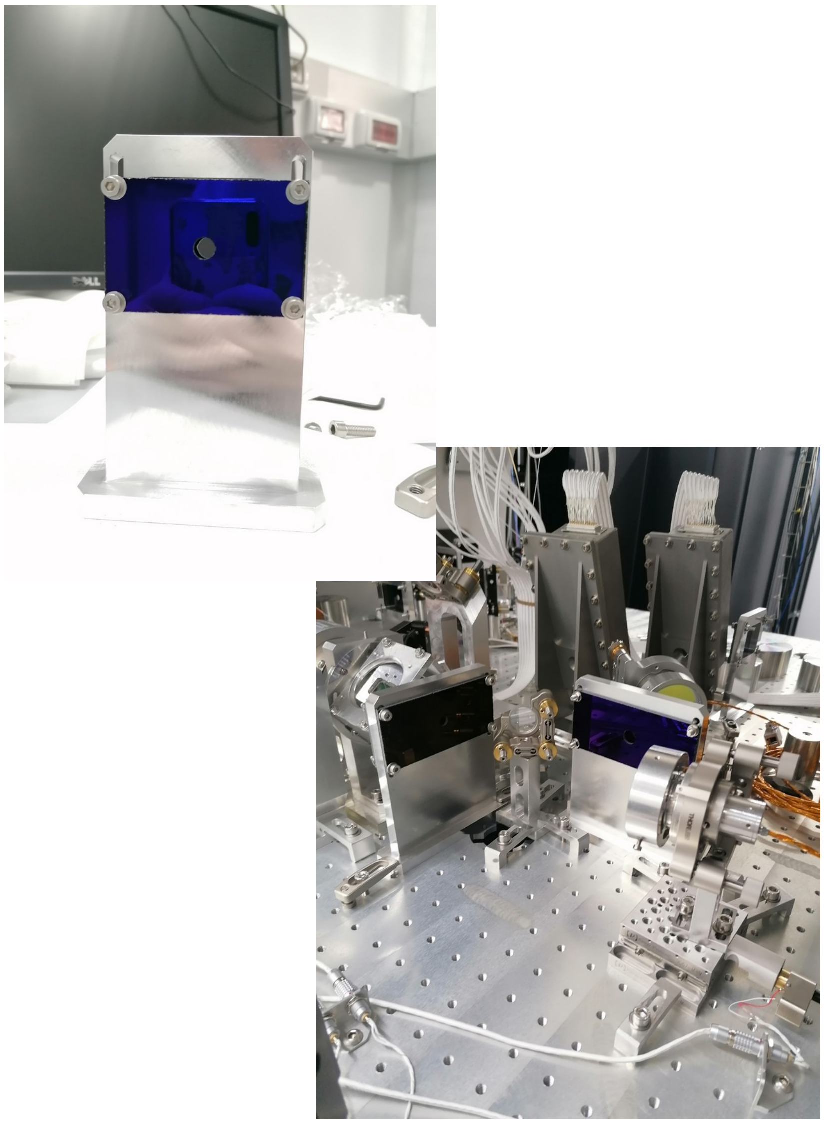


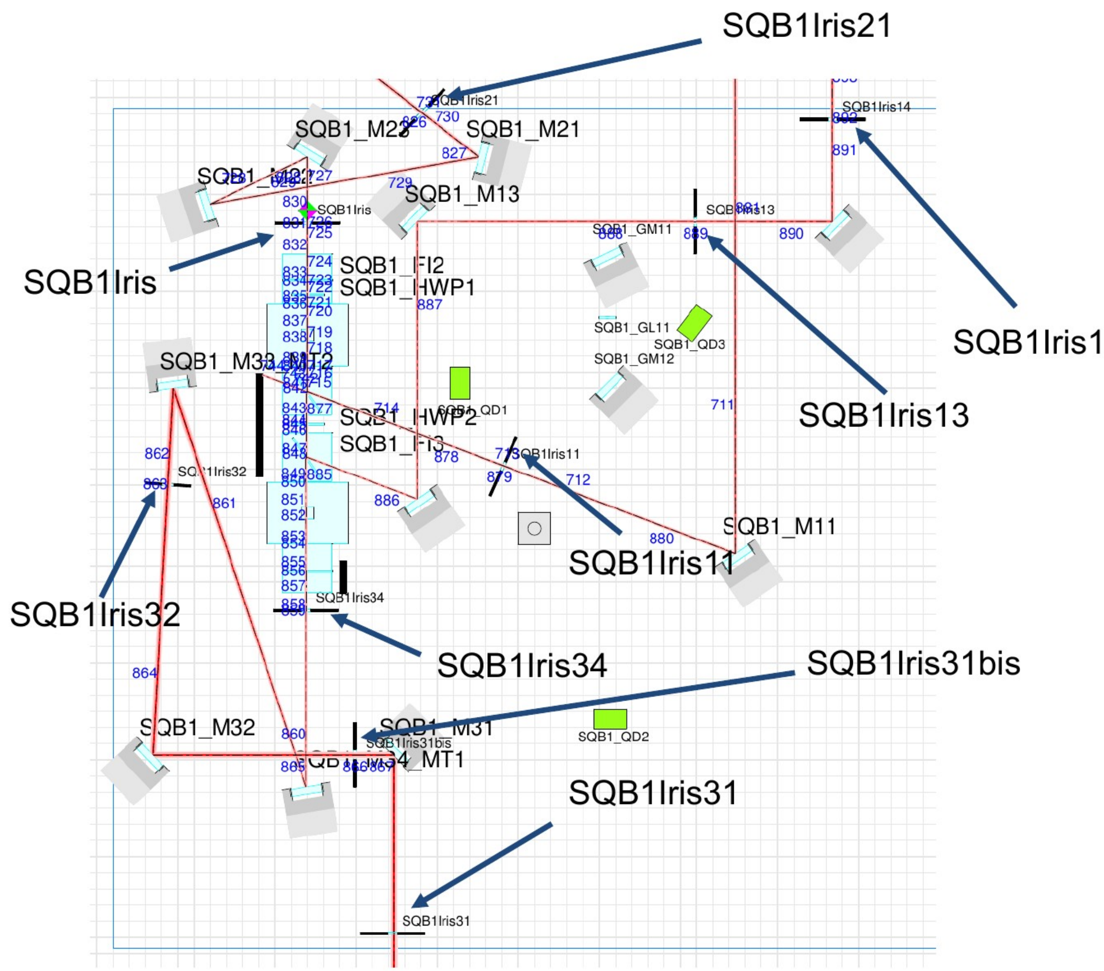
Overlap integral



Back reflected

Ghost beam dumping





Stray light from detection benches