Study of the optical losses as a function of beam position on the mirrors in the filter cavity

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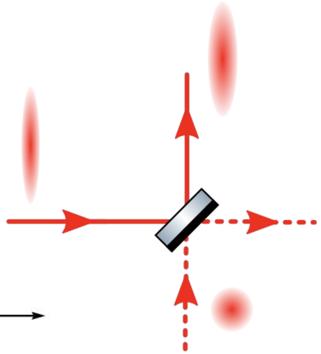
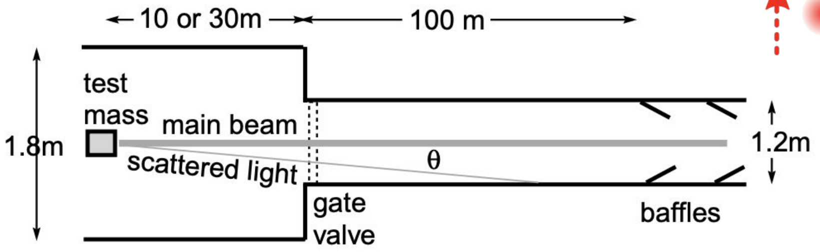
GDR Ondes Gravitationnelles

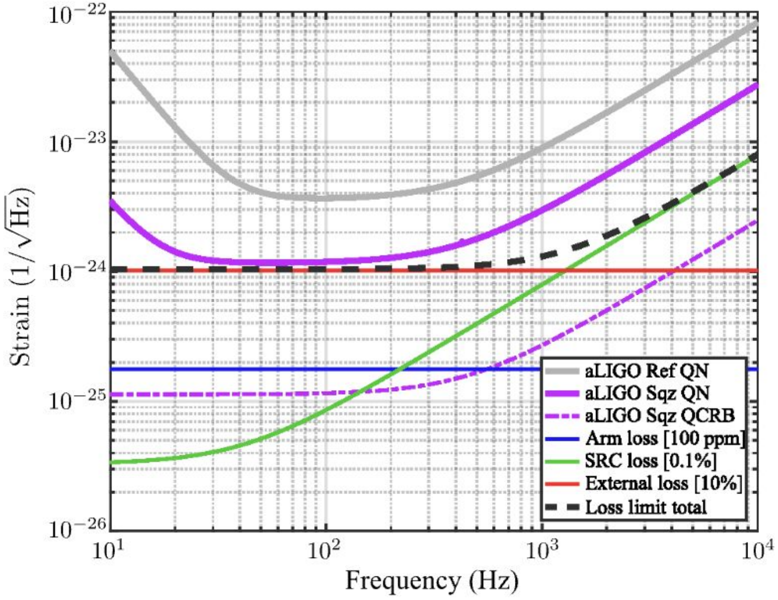
Paris, 17 June 2024

Optical losses in gravitational wave detectors

- Introduce noise
- Impair noise reduction (for squeezing)
- Degrade signal gain







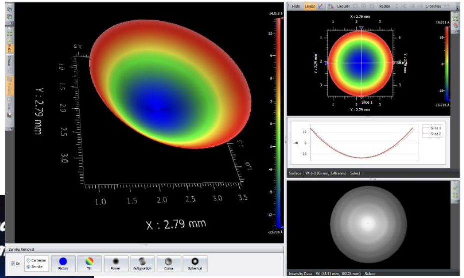
Characterization of scattering losses

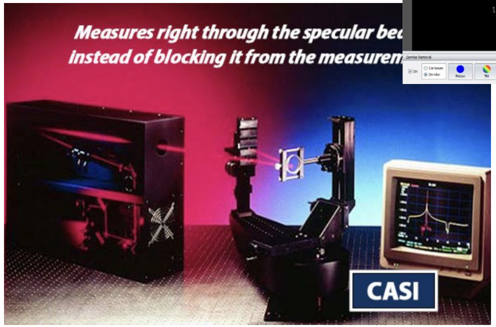
Several methods can be use:

Characterize a single mirror

(During fabrication)

Measure surface height

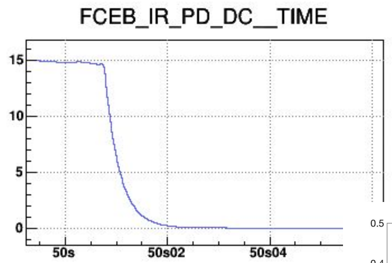




Measure scattering

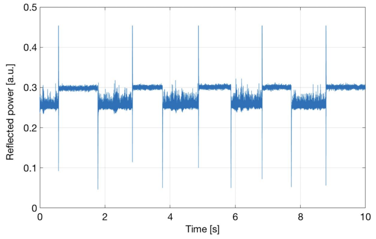
Characterize a cavity

(After integration)



Measure storage time

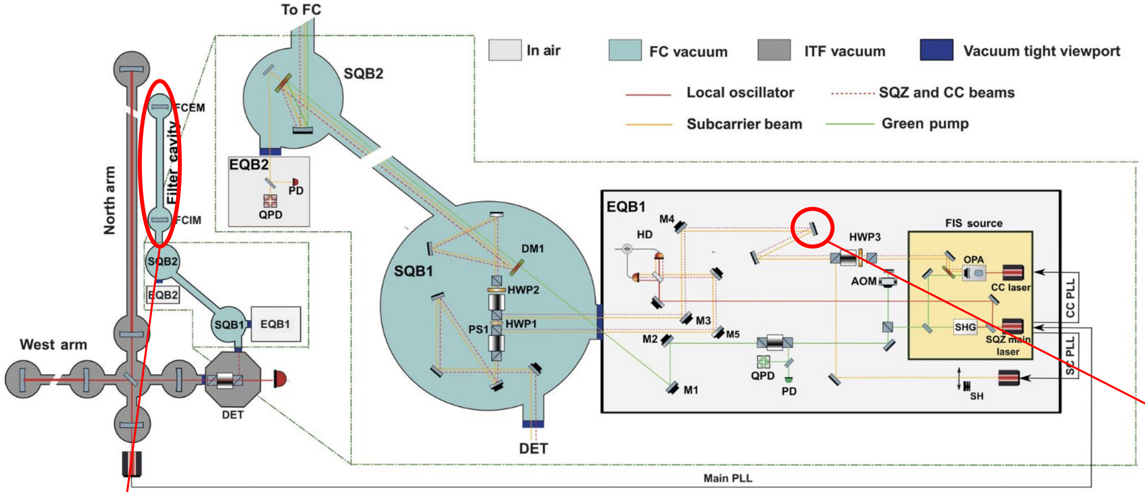
Measure cavity reflection

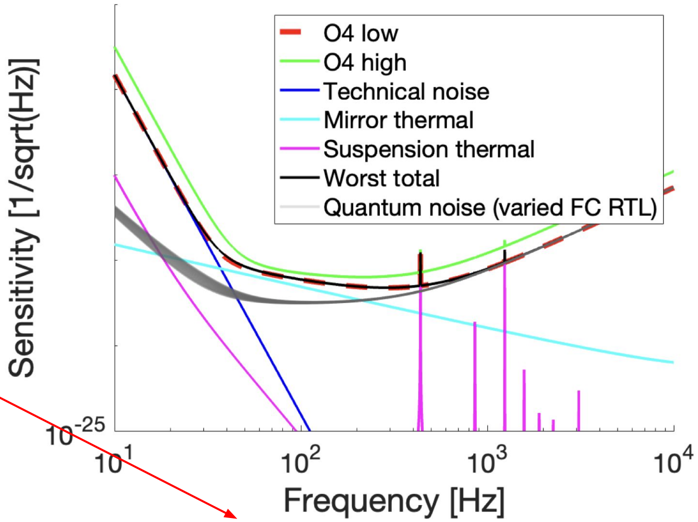


Losses and sensitivity of Virgo

A visible influence of filter cavity losses on sensitivity

RTL uncertainty: 30-100 ppm



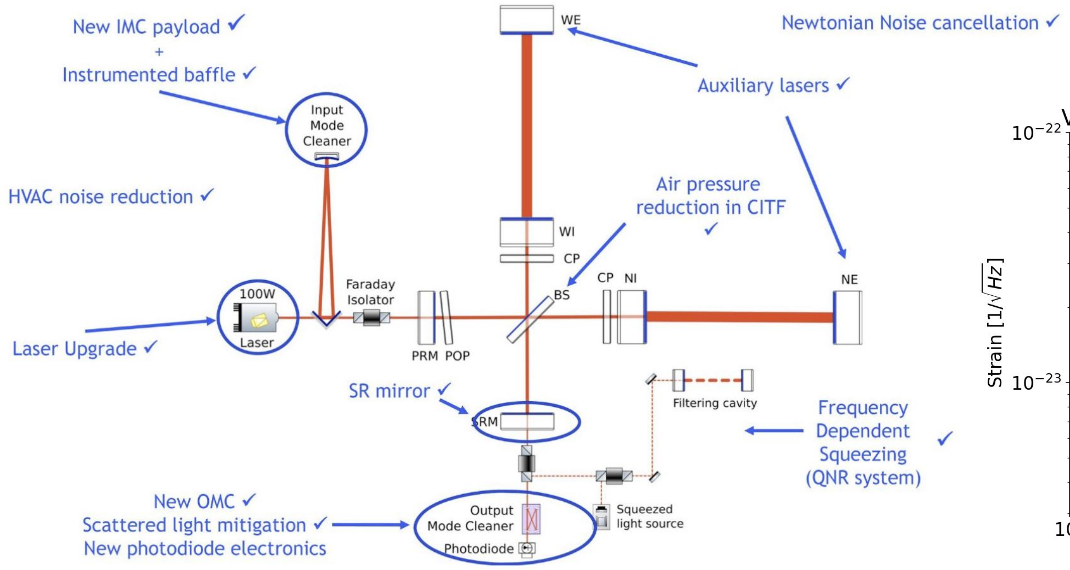


30-100 ppm has visible effect due to **light bouncing back forth between mirrors**

Single bounce, 30-100 ppm will not make a difference

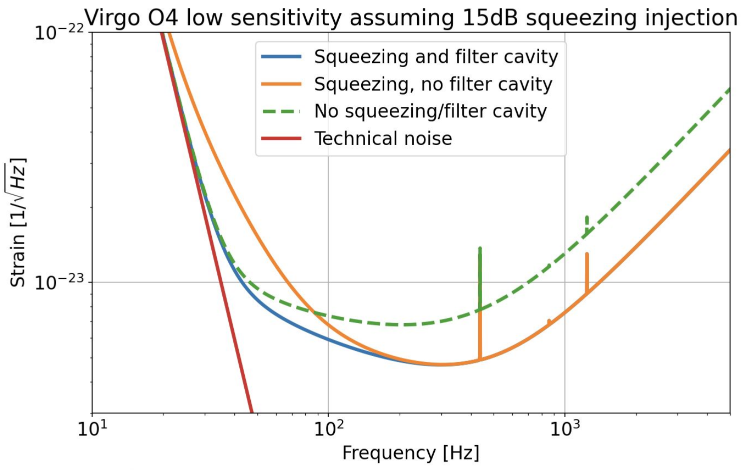
The filter cavity in Virgo

Filter cavity is one of the upgrade for Advanced Virgo+ phase one, with the goal of broadband quantum noise reduction



PHASE I OF THE UPGRADES TO ADVANCED VIRGO + COMPLETED

May 5, 2021



The filter cavity construction and characterization history

During filter cavity commissioning, **very different optical losses are measured**

April, 2021	August, 2021	October, 2021	May, 2022	August, 2023
Filter cavity local control commissioning (VIR-0325A-21)	Filter cavity locked for both green and infrared (VIR-1086A-21)	First filter cavity losses measurement	Follow up filter cavity losses measurement (VIR-1086A-21)	A PyALP MACRO code for automatic measurement (VIR-1086A-21)

AdV-SGD (FDS commissioning)

guo, vardaro - 20:46 Tuesday 05 October 2021 (53392)

Filter cavity round trip losses measurement with EQB2 PD

AdV-SGD (FDS commissioning)

Zhao, Msihid, Ding, Guo, Grimaldi, Capocasa - 11:29 Tuesday 24 May 2022 (55947)

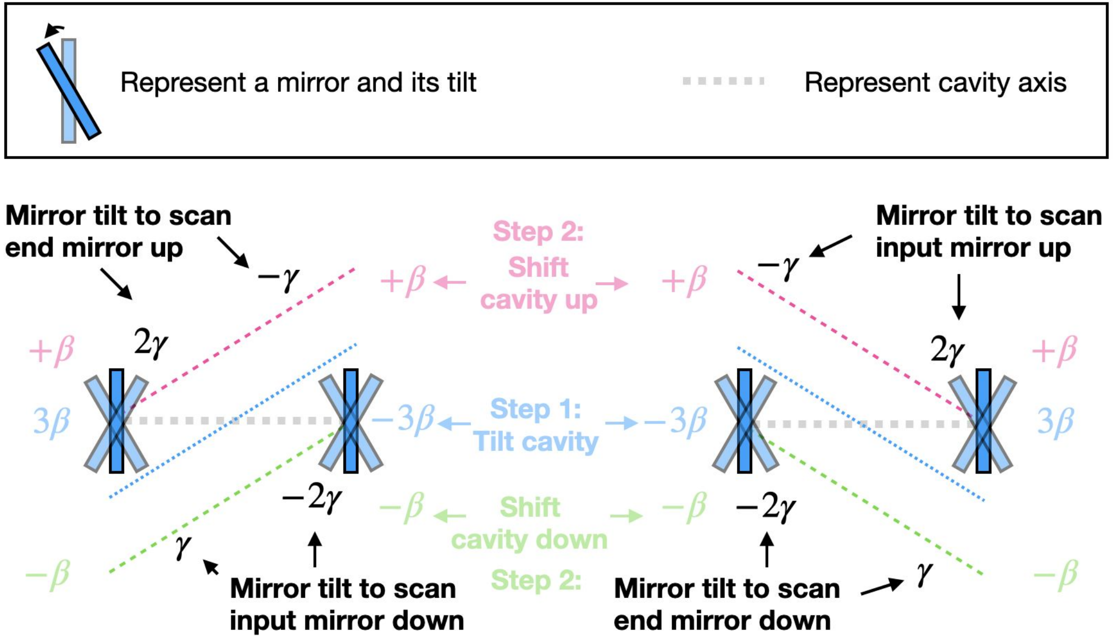
Comment to IR loss budget (55651)

About 31 ppm

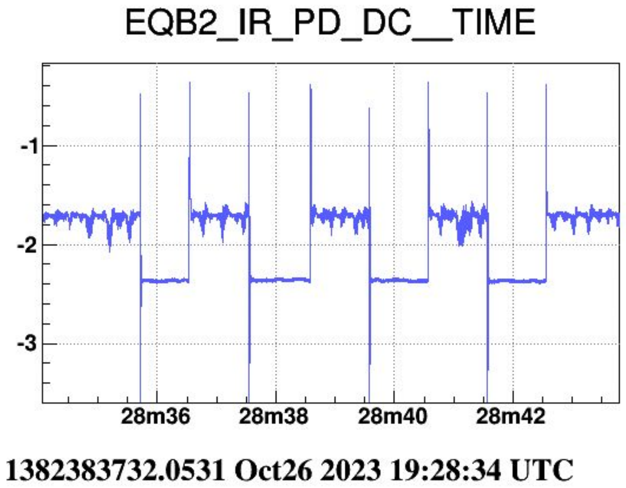
About 89 ppm

Measurement methodology

1. Scan mirrors separately

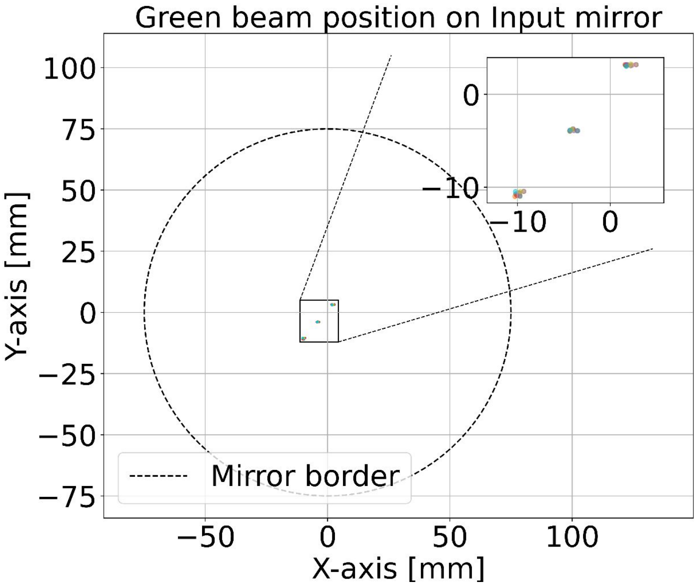


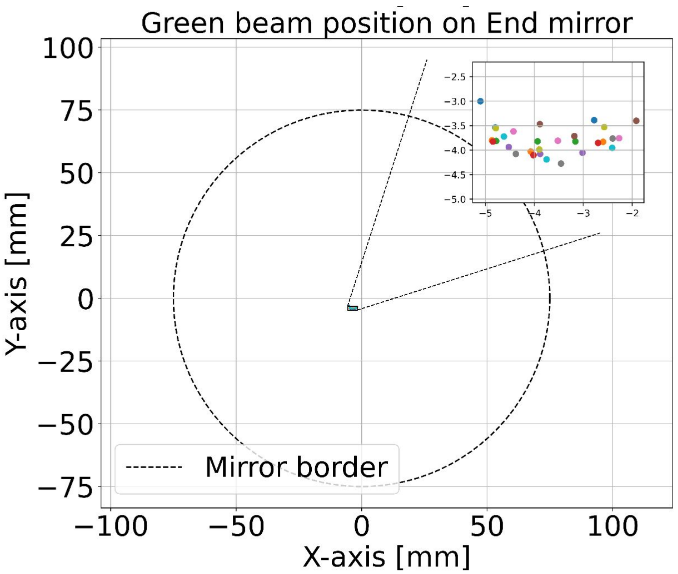
2. Measure losses



Study of the repeatability

Losses measurements were performed for three points during ten days





Losses measurements

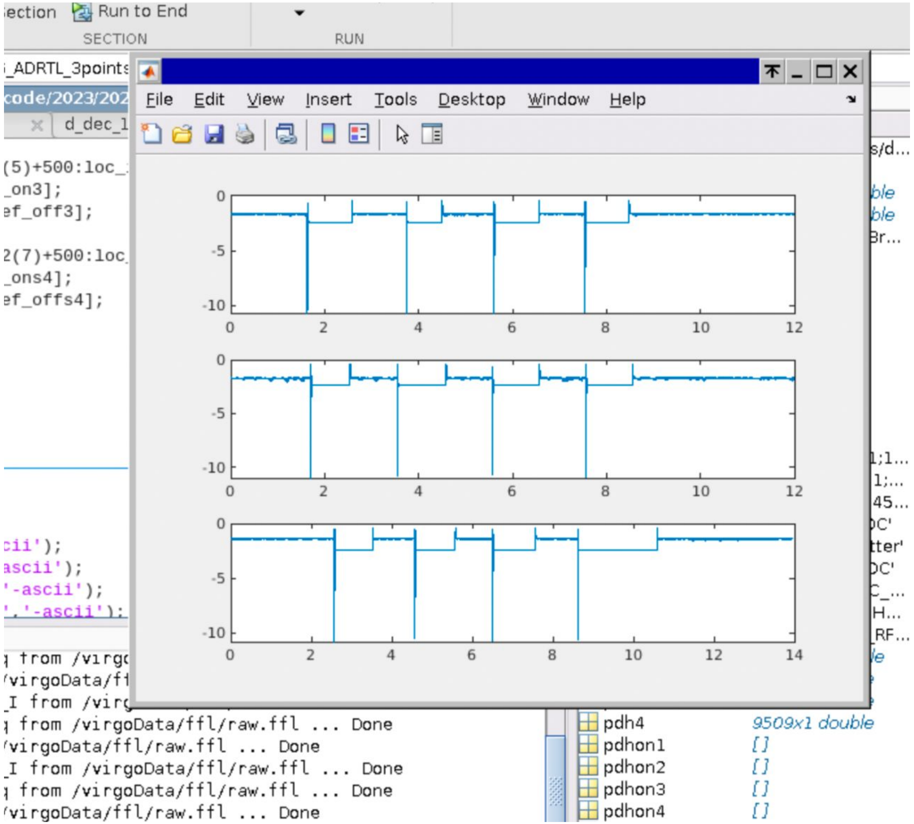
- Usual technique reported in **Phys. Rev. D 98, 022010**

$$L \sim \frac{T_1}{2}\frac{1-R_{\mathrm{cav}}}{1+R_{\mathrm{cav}}} = \frac{T_1}{2}\frac{1-P_{\mathrm{res}}/P_{\mathrm{in}}}{1+P_{\mathrm{res}}/P_{\mathrm{in}}}$$

- We considered the estimation the uncoupled power due to mismatch, sidebands

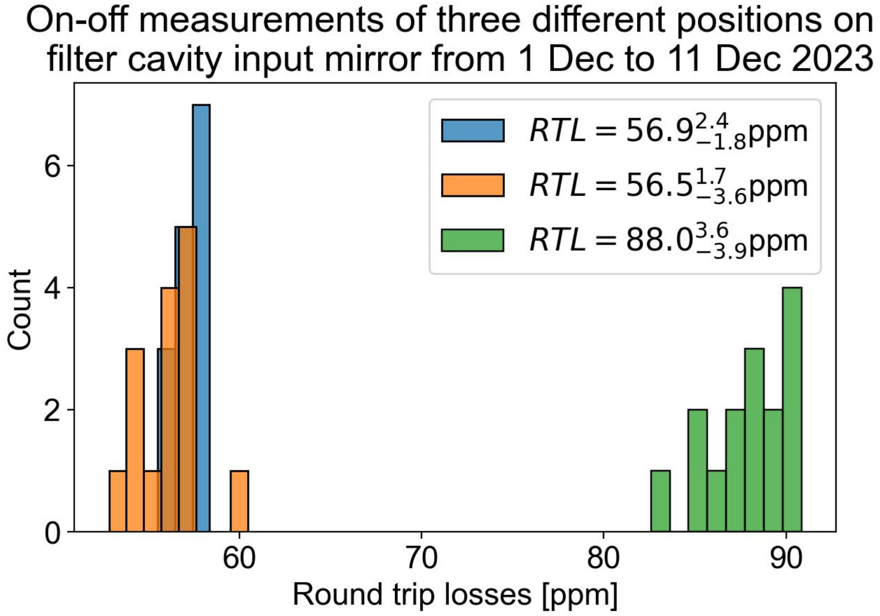
$$R_{\mathrm{cav}} = \frac{R_{\mathrm{cav}}^{\gamma} - \gamma}{(1-\gamma)}$$

- Effect of a small clipping on the measurement is not relevant

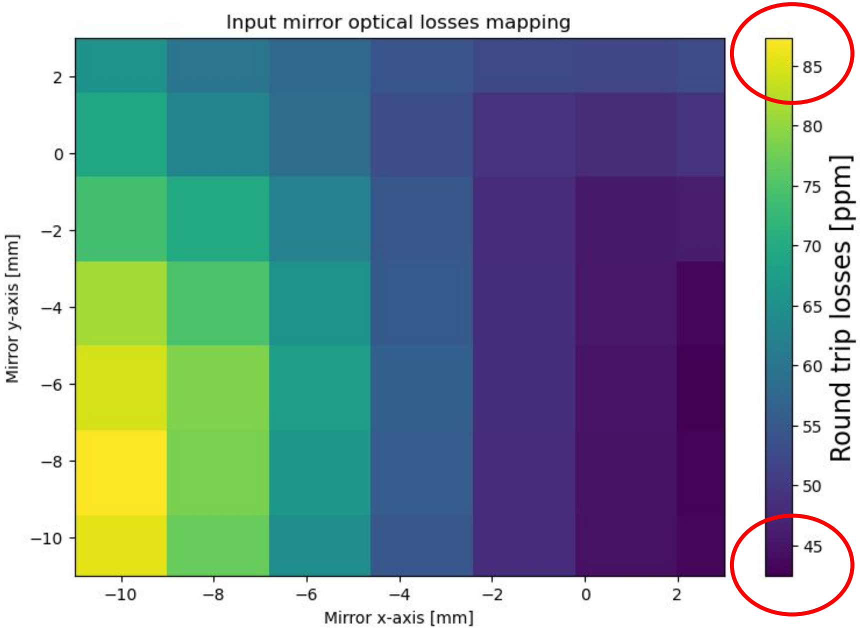


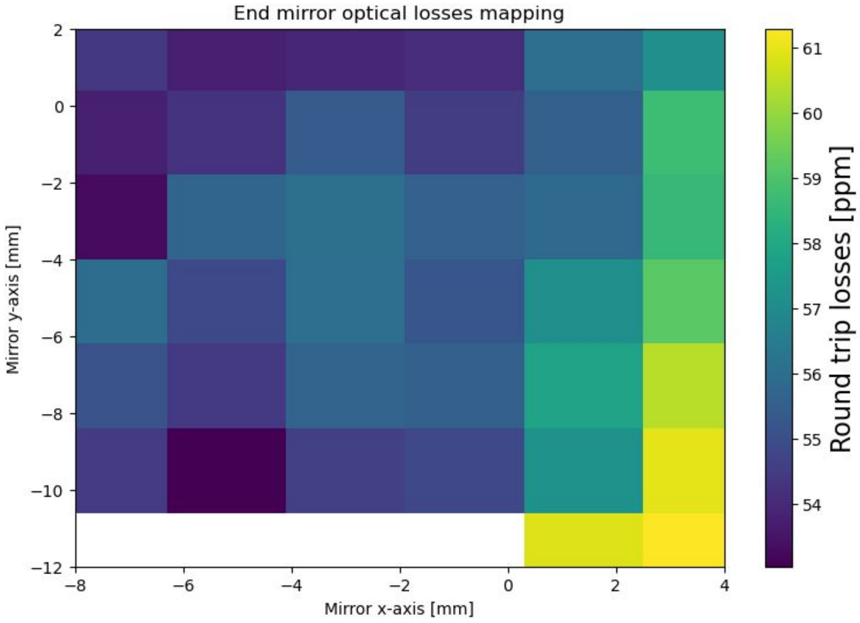
The repeatability of measurements

A ten-days characterization proves the repeatability of our result



A losses map for input and end mirrors

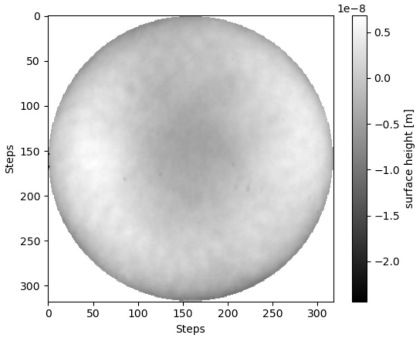


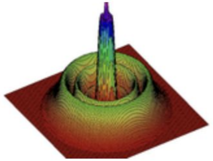


Estimation of optical losses

Mirror characterizations before cavity integration is very useful for predicting the total losses that can be achieved in an optical cavity

- Small angle scattering
- Large angle scattering
- Middle angle scattering





OSCAR

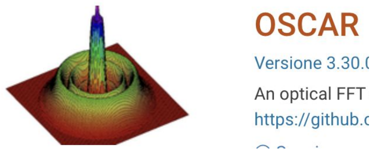
Versione 3.30.0.0 (3,29 MB) da Jerome Degallaix

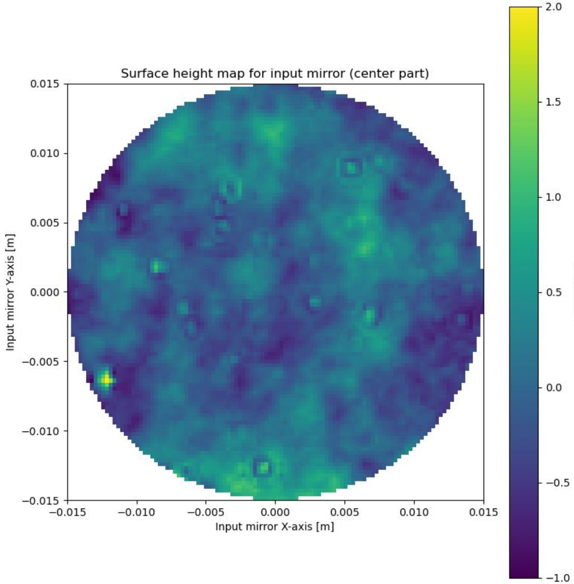
An optical FFT code to simulate Fabry Perot cavities with arbitrary mirror profiles

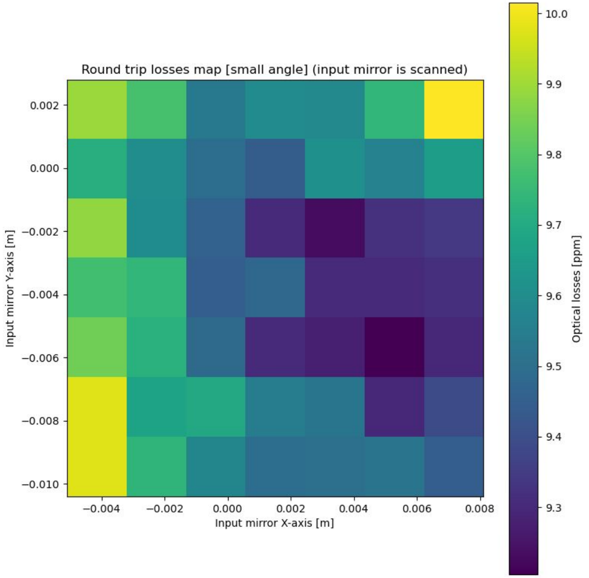
https://github.com/Jerome-LMA/oscar

Mirror characterization at low spatial frequency

The mirror surface was characterized with Zygo interferometer with a resolution ~0.3mm. This map was used in Oscar to predict small angle scattering losses

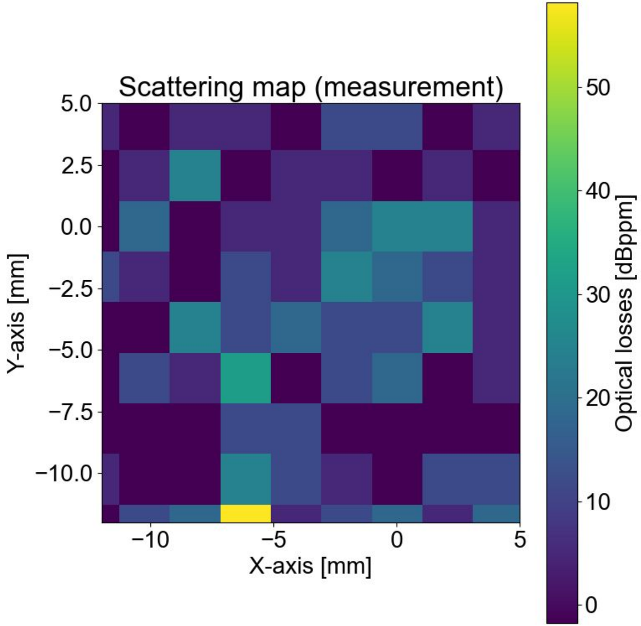


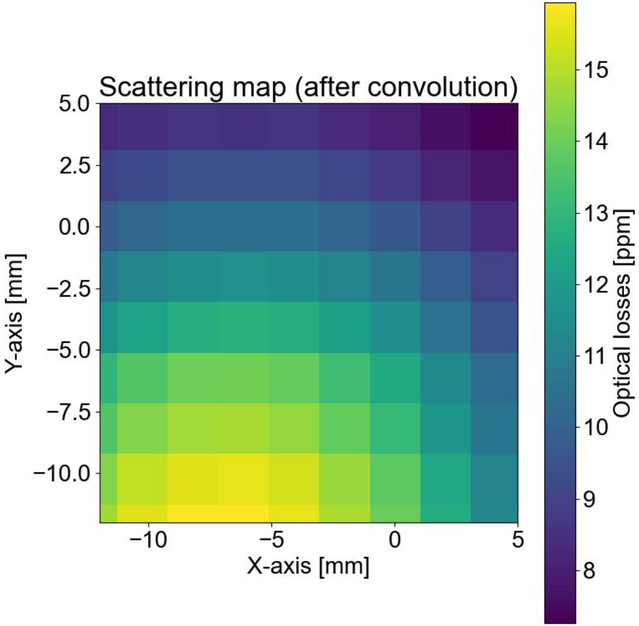




Mirror characterization at high frequencies

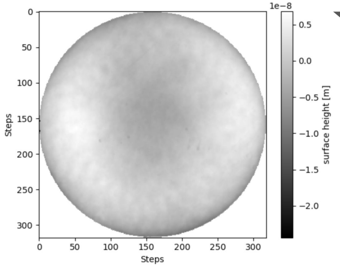
A scatterometer was used for measuring scattered light larger than 3 degree

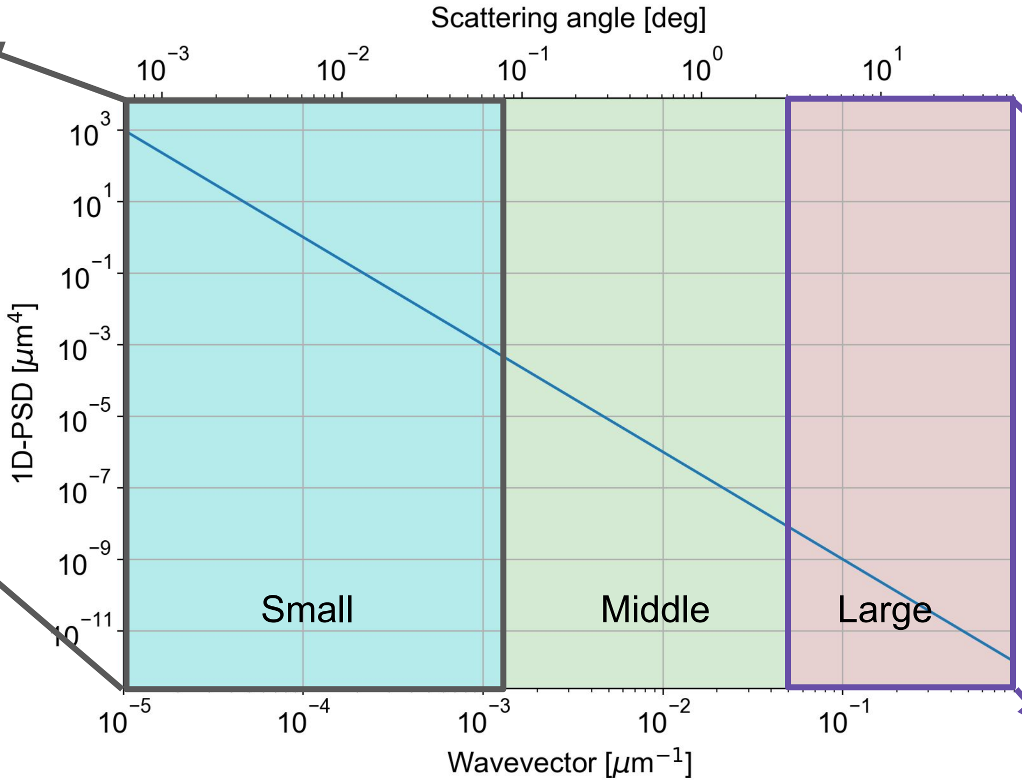


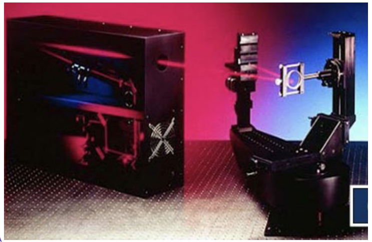


Remark: due to time limitation, angular resolved scattered was not measured for each pixel

Loss estimation from mirror characterization after fabrication

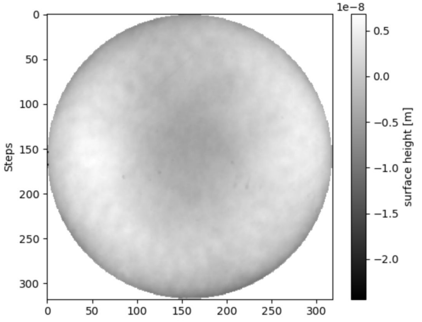


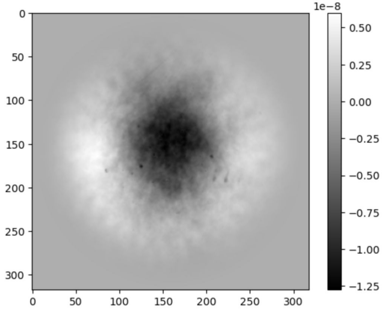


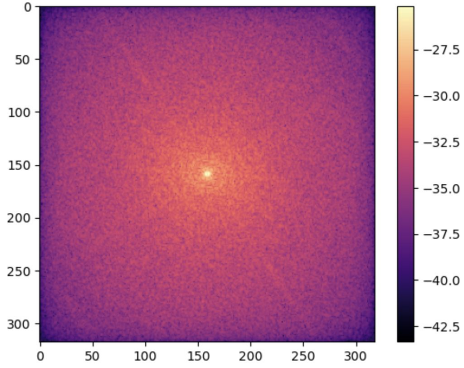


Acquire 1D-PSD

Remove offset/tilt/radius of curvature > apply window > get 2D PSD > get 1D PSD

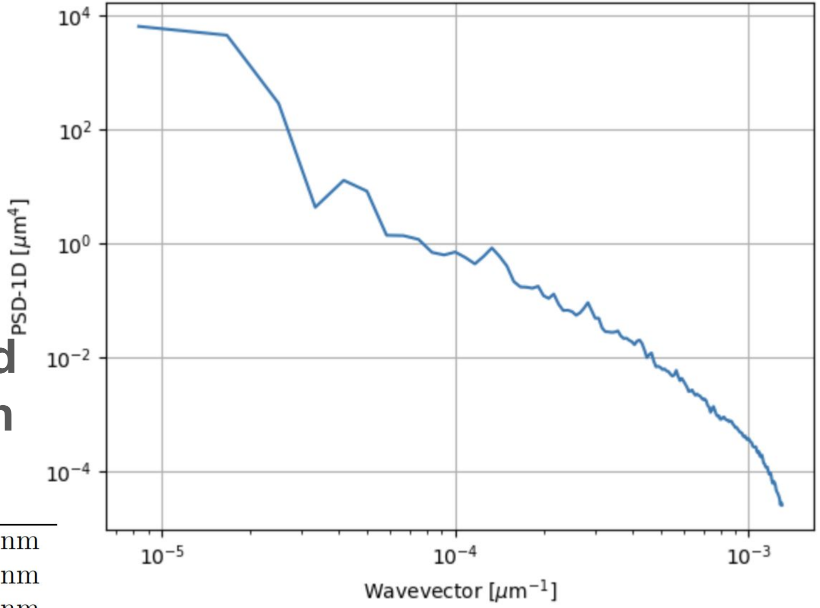






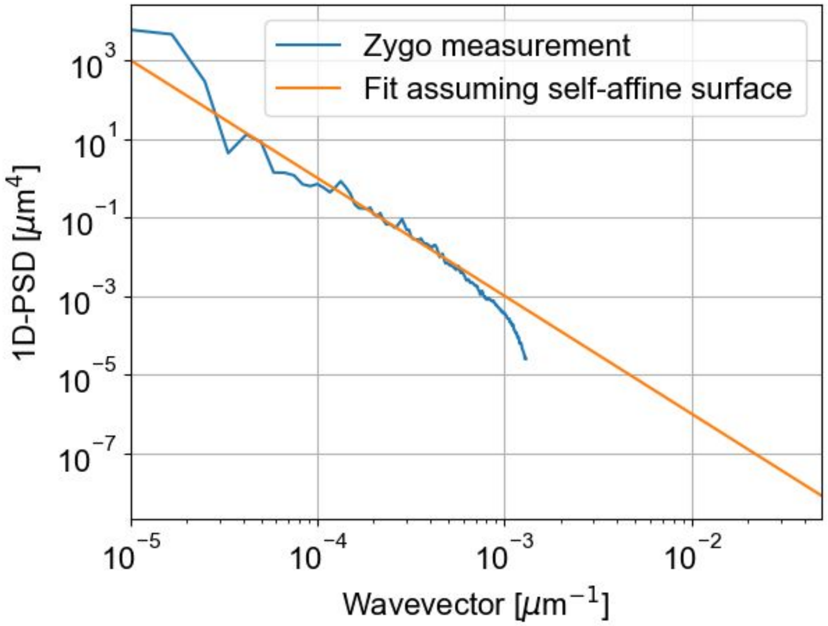
Surface standard deviation at each step

Oscar processed surface	2.8 nm
Windowed surface	2.7 nm
Integrated C^{2D}	2.7 nm
Integrated C^{iso}	2.4 nm



Extend 1D PSD and estimate middle angle scattering

Assuming the mirror surface is self-affine, we made a fit of the 1D-PSD



Equation to integrate 1D-PSD

$$\sigma^2_{\mathrm{middle}} = 2\pi \int_{\mathrm{f}_{\mathrm{max-map}}}^{\mathrm{f}_{\mathrm{min-CASI}}} \mathrm{C}^{\mathrm{iso}}(\mathrm{f}) f \, df$$

Equation to calculate scattering

$$TIS = (\frac{4\pi\sigma}{\lambda})^2$$

0.7 ppm losses are estimated for middle angle scattering

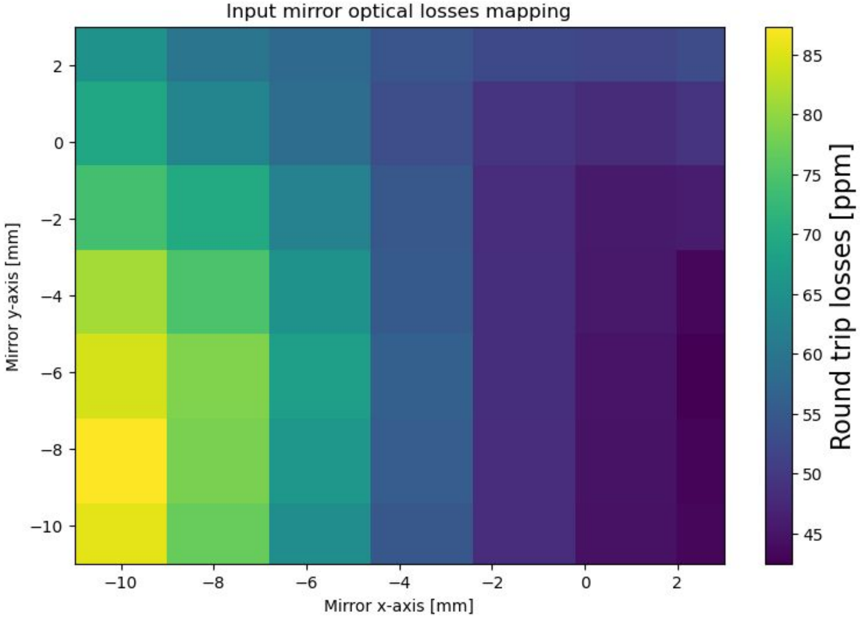


TABLE III. Estimated losses from mirrors characterization before cavity integration

Small angle scattering	10 ppm
Middle angle scattering	0.7 ppm
Large angle scattering	15-24 ppm
End mirror transmission	3.9 ppm
Absorption and clipping	< 1 ppm
Total	**29.6-38.6 ppm**

Summary

- Optical losses reduction is crucial for achieving the ambitious sensitivity goal of GW detectors
- Using Virgo filter cavity hardware, we have developed a methodology to characterize optical losses on cavity mirrors separately
- The optical losses varies from 42 to 87 ppm on the input mirror, but 53 to 61 ppm on the end mirror
- The lowest measured losses are comparable with what expected from mirror characterization before filter cavity integration, and **representing smallest optical losses for 300 meter scale filter cavity**
- This work has been summarized in a paper (VIR-0372A-24) which is going to be submitted to a journal

Next step

- The input mirror losses inhomogeneity may come from contamination -> potential cleaning could be scheduled in the near future
- Middle angle scattering could be larger than our estimation from the surface roughness due to point defects (need to consider it more carefully)
- The optical losses could be measured also for 532nm, such measurement would be interesting for understanding scattered light as a function of wavelength
- Other methods of measuring optical losses were used in this work but not reported since we have some unknown systematic errors, a future instrument upgrade would solve this issue
- The large angle scattering measurement with each pixel angularly resolved would provide more precise estimation