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Optical design of the laser injection line into a small-scale suspended interferometer for Quantum Noise reduction in gravitational-wave (GW) detectors

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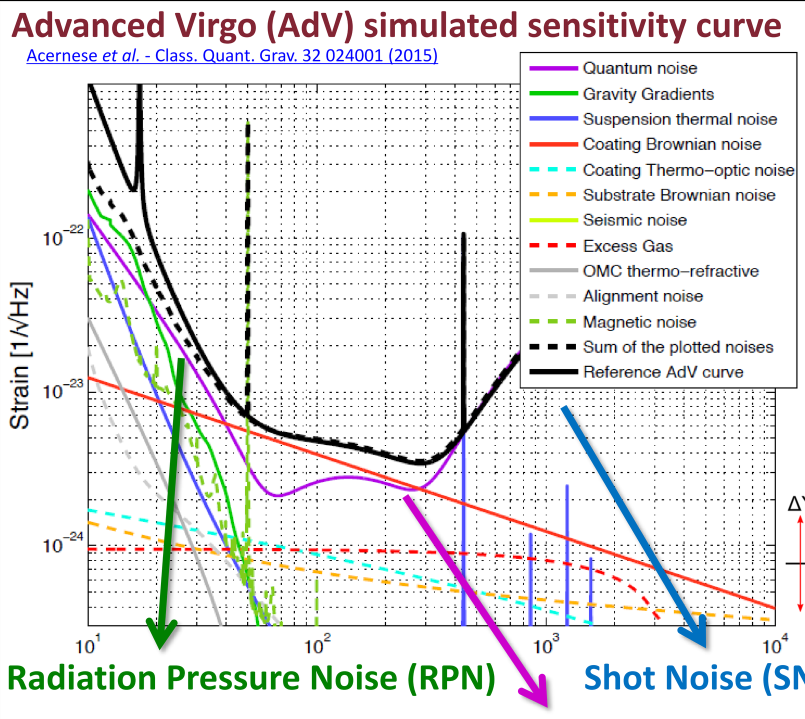
Scientific Background: frequency-dependent squeezing for broadband QN reduction

Quantum noise (QN) already dominates the sensitivity curve of ground-based GW detectors in the high frequency band ($\gtrsim$ 300 Hz), and this trend is expected also in the other bands. Currently, the technique adopted by the LIGO and Virgo collaborations, with the goal of a broadband QN reduction, consists of a frequency-independent squeezing (FIS) source coupled with a 300-m-long detuned filter cavity (FC), which produces in reflection frequency-dependent squeezing (FDS) to be injected through the dark port of the interferometer. However, a more compact and cheaper FDS setup could be developed exploiting two other FDS ways: the ponderomotive squeezing and the EPR entanglement. This is of great importance especially in view of the third generation GW detectors such as the Einstein Telescope (ET).

Advanced Virgo (AdV) simulated sensitivity curve

Acernese *et al.* - Class. Quant. Grav. 32 024001 (2015)



Radiation Pressure Noise (RPN) **Shot Noise (SN)**

Quantum Noise (QN) is their uncorrelated sum

Complex amplitude of the quantized electro-magnetic field:
$$\hat{a}_\omega = \hat{X}_\omega + i\hat{Y}_\omega$$

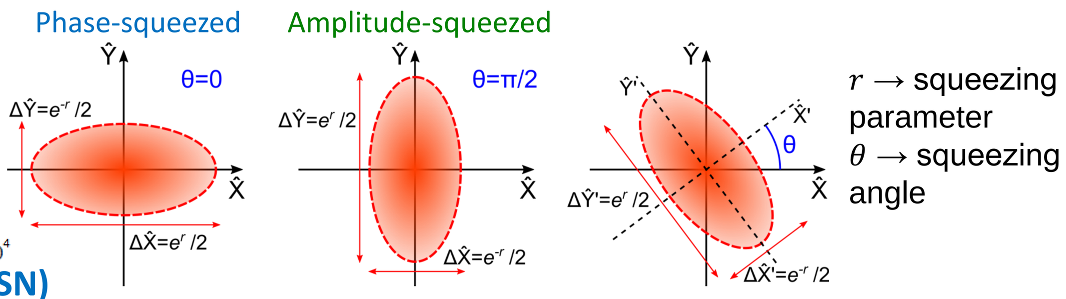
Amplitude quadrature error $\Delta\hat{X}_\omega$ related to **Radiation Pressure Noise (RPN)**

Phase quadrature error $\Delta\hat{Y}_\omega$ related to **Shot Noise (SN)**

$$S_h^{RPN}(\nu) = \left(\frac{16\mathcal{F}}{mL(2\pi\nu)^2}\right)^2 \frac{\hbar P_{in}}{\pi\lambda_L c}\frac{1}{1+(\nu/\nu_p)^2} \qquad S_h^{SN}(\nu) = \frac{\pi\hbar c\lambda_L}{16P_{out}}\left(\frac{1}{L\mathcal{F}}\right)^2\left[1+\left(\frac{\nu}{\nu_p}\right)^2\right]$$

$$S_h^{QN}(\nu) = S_h^{RPN}(\nu) + S_h^{SN}(\nu)$$

Squeezed vacuum states

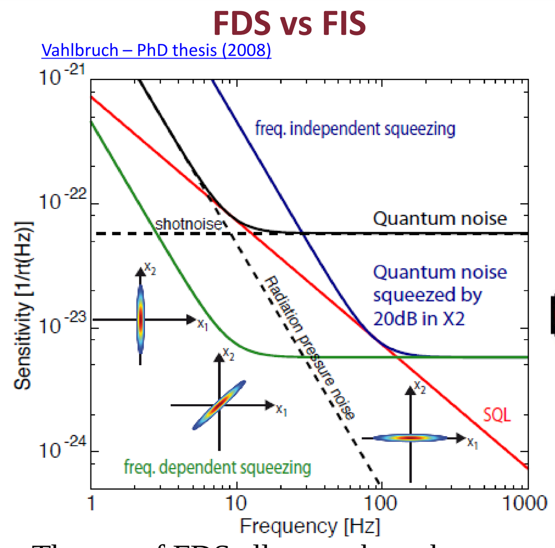


$r \to$ squeezing parameter
$\theta \to$ squeezing angle

Heisenberg Uncertainty Principle remains satisfied! $\Delta\hat{X}_\omega\,\Delta\hat{Y}_\omega \geq \frac{1}{4}$

FDS vs FIS

Vahlbruch – PhD thesis (2008)

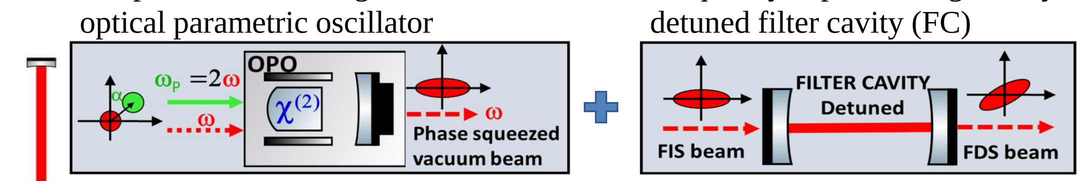


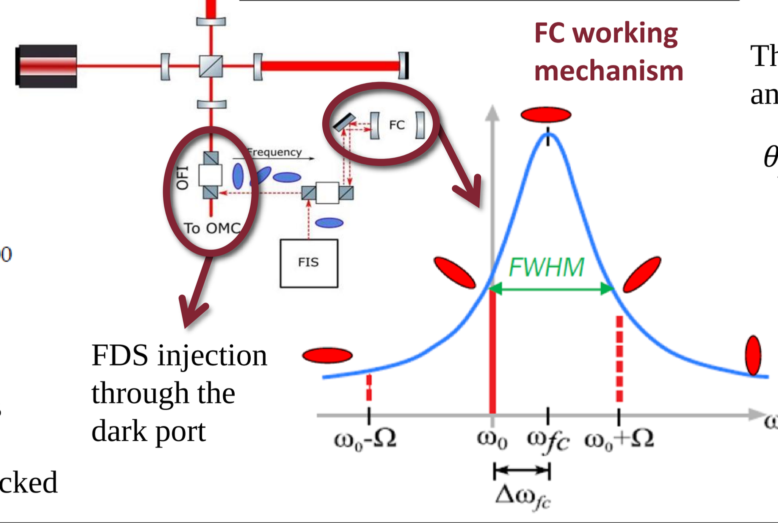
The use of FDS allows to beat the **Standard Quantum Limit (SQL)**

FDS in AdV+ phase I – filter cavity

FIS production via degerate optical parametric oscillator

Frequency dependance given by a detuned filter cavity (FC)





An additional cavity requires dedicated infrastructures and needs to be controlled and locked

The frequency-dependent rotation angle of the squeezing ellipse is:
$$\theta_{fc}(\Omega) = \arctan\left(\frac{2\gamma_{fc}\Delta\omega_{fc}}{\gamma_{fc}^2 - \Delta\omega_{fc}^2 - \Omega^2}\right)$$

Necessary condition:
$$\Delta\nu_{fc} = \gamma_{fc} = \frac{c}{2L\mathcal{F}} \approx 50\ \mathrm{Hz}$$

This imposes
- **long cavity** $L = 285$ m
- **low optical losses** $\mathcal{F} = 11000$

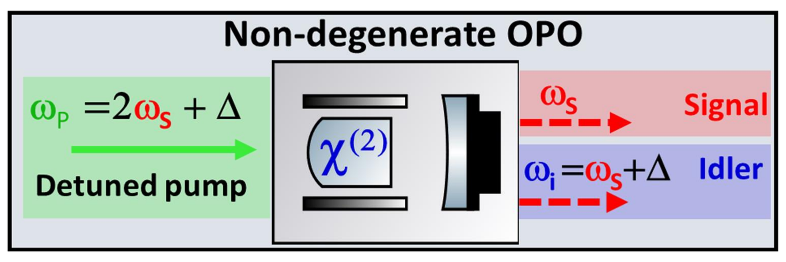
EPR experiment and integration with SIPS

A table-top experiment for testing FDS via EPR entanglement is under implementation at the EGO R&D squeezing laboratory. EPR squeezing imposes two squeezed beams instead of one (named as **signal** and **idler**), and it suffers from an intrinsic loss of 3 dB with respect to the FC solution. However, it presents great advantages such as: no need of hosting infrastructure, and no optical losses due to the FC (1 ppm/m).

The EPR set up foresees three IR laser lines. The first ("main" laser) experiences a parametric up-conversion process in a Second Harmonic Generator (SHG) cavity, and it is then sent into an Optical Parametric Oscillator (OPO), producing two EPR-entangled squeezed vacuum beams. These are injected form the dark port of a small-scale suspended interferometer called SIPS (Suspended Interferometer for Ponderomotive Squeezing). The second laser source provides control and locking beams ("auxiliary" laser), whereas the third one is a MOPA laser dedicated to SIPS. The scientific goal is to measure a broadband QN reduction in the SIPS sensitivity curve.

FDS via EPR entanglement

Detuned pump into non-degenerate OPO produces ***signal*** ***and idler squeezed beams*** that are ***EPR entangled***



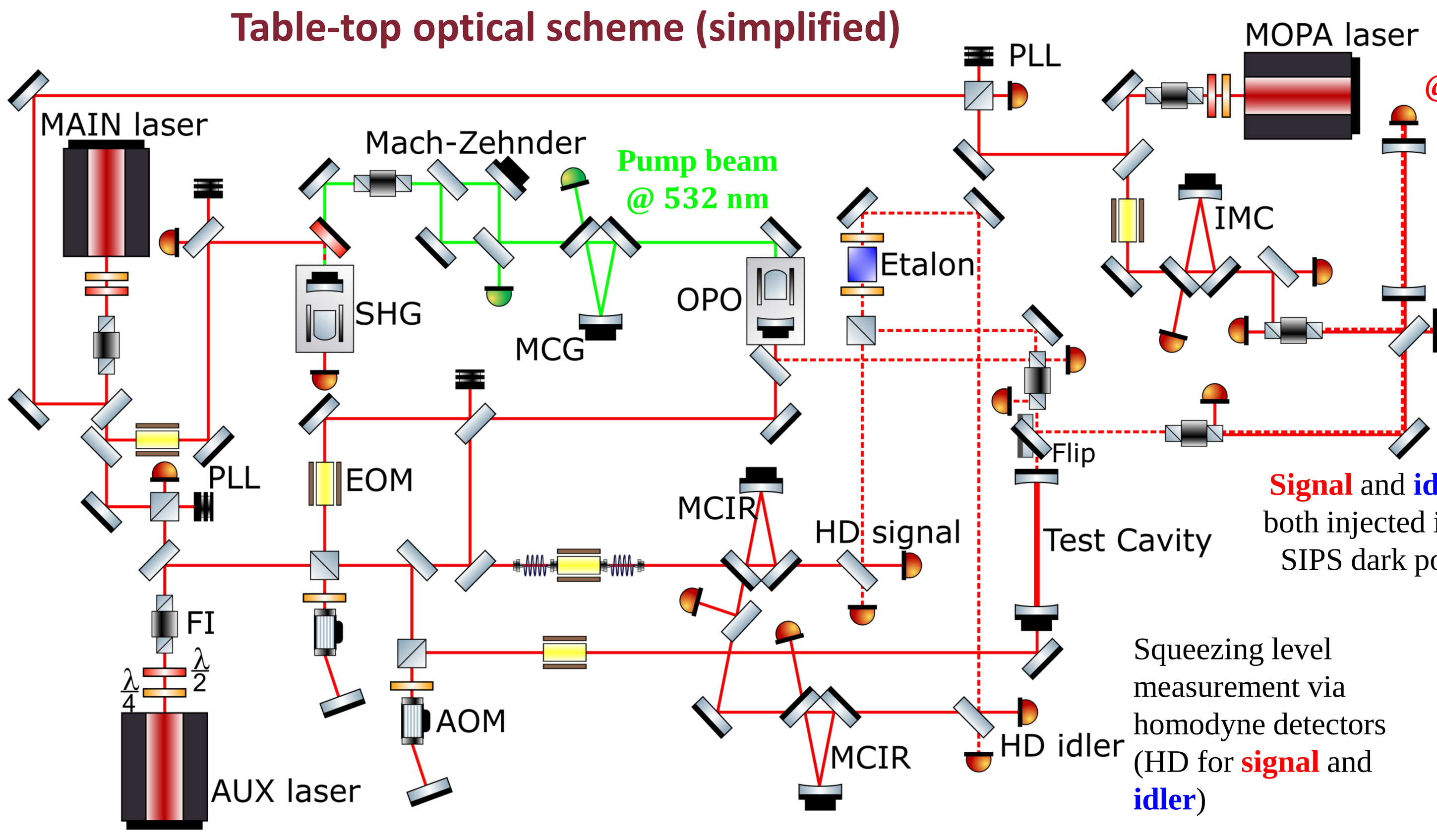
The interferometer itself acts like a detuned filter cavity for the idler! **Idler** experiences FDS

Idler measured on a fixed quadrature → **Signal conditionally squeezed in a freq.-dependent way**

Status of the EPR set up @ EGO

- MAIN laser line aligned and characterized up to the SHG cavity
- SHG is about to be aligned and locked
- Mach-Zehnder interferometer and mode cleaner cavity for green line (MCG) already present on the bench
- AUX laser line aligned and characterized up to the mode cleaner (MCIR) cavity for local oscillator signal
- OPO and SIPS control and locking lines to be set up
- MCIR cavities and SIPS input mode cleaner (IMC) designed
- Etalon tested in a separate laboratory (Nguyen *et al.* – Applied Optics (posted 2022/05/24))
- Mode-matching telescopes (MMTs) under design

Table-top optical scheme (simplified)

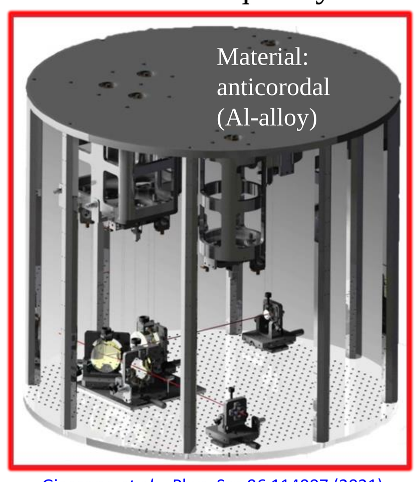


All laser sources are solid state Nd:YAG **@ 1064 nm** (near IR)

Signal and **idler** both injected into SIPS dark port

Squeezing level measurement via homodyne detectors (HD for **signal** and **idler**)

SIPS is a Michelson-Fabry-Pérot interferometer designed (suspended optics, monolithic suspensions) to be sensitive to QN in the audio-frequency band

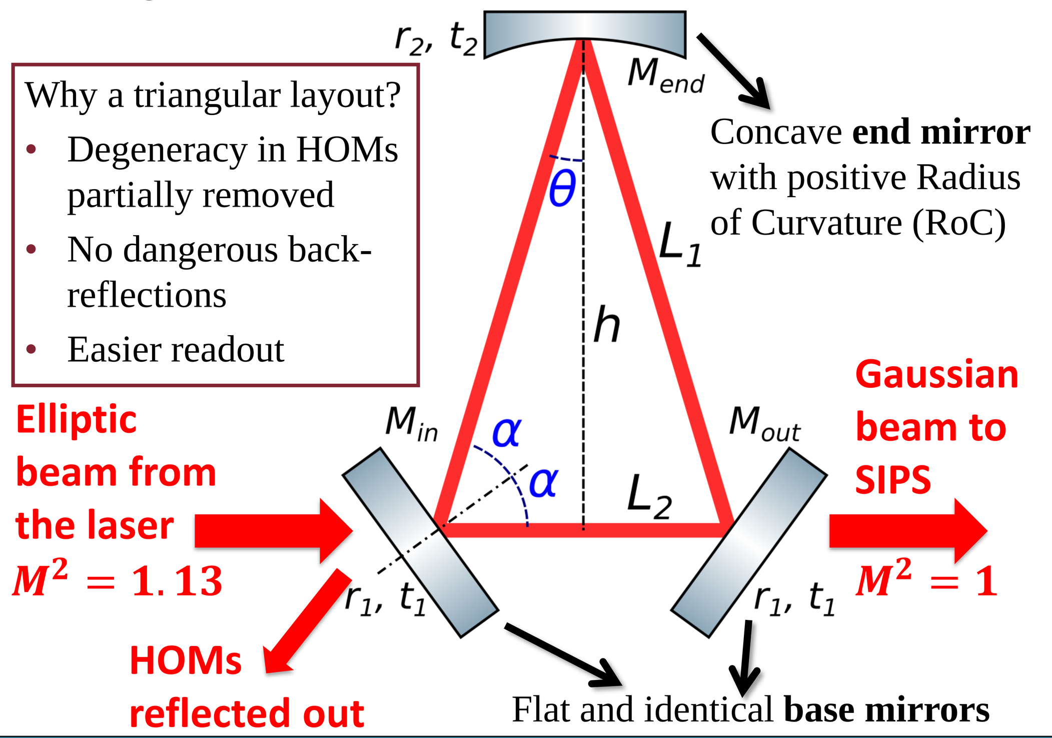


Giacoppo *et al.* - Phys. Scr. 96 114007 (2021)

SIPS Input Mode Cleaner (IMC) cavity design

A mode cleaner cavity is used to reflect out the higher order modes (HOMs) in the transverse intensity profile of a beam, thus delivering a zero-order Gaussian beam, which is fed into SIPS.

Why a triangular layout?
- Degeneracy in HOMs partially removed
- No dangerous back-reflections
- Easier readout



Requirements

The IMC is the most important element along the SIPS injection path.

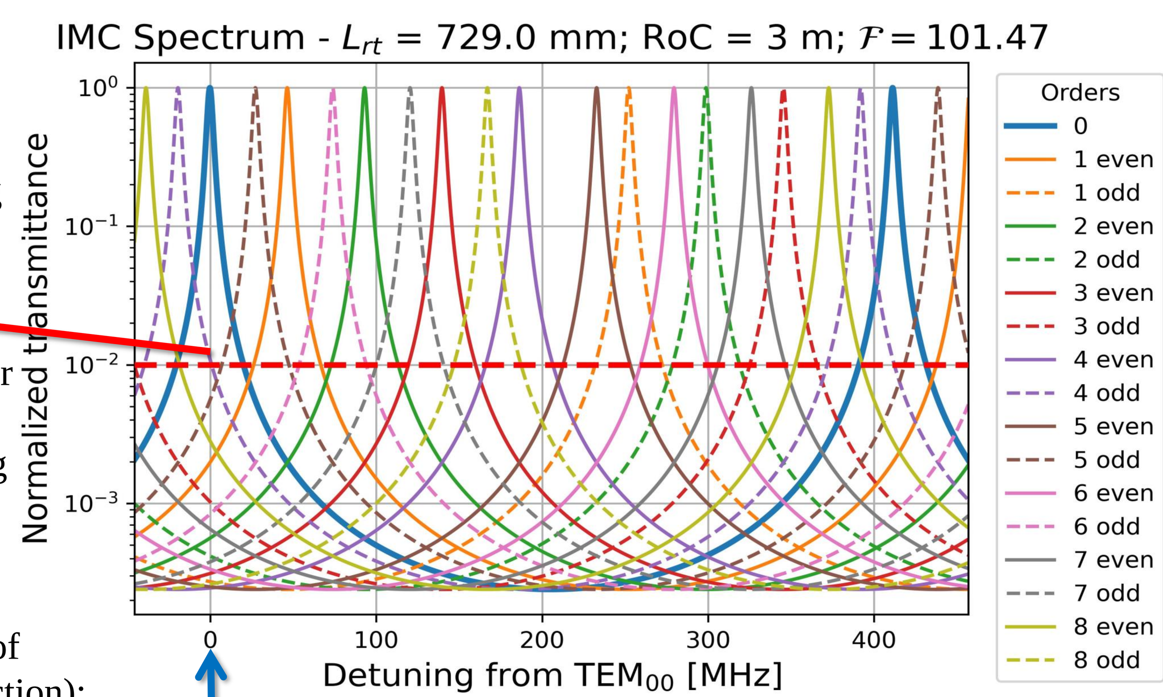
We fixed some requirements to be fulfilled by our final best candidate:
- **Optical stability**
- **Low astigmatism**
- **Proper transmitted power**
- **High HOM suppression**
- ***Lowest circulating power***

Optical simulations were performed via FINESSE software (Bond *et al.* – Living Rev. Relativ. 19, 3 (2016))

IMC final candidate choice

The preliminary tests allowed to find good ranges for the set of cavity parameters: round-trip length L_{rt}, end mirror RoC R_c, angle of incidence on the end mirror θ, and power reflectivities R_1 and R_2:
- $L_{rt} \in [500; 800]$ mm → allowed space on the optical bench
- $R_c \in [1.0, 1.5, 2.0, 3.0, 4.0]$ m → standard substrate values
- θ → lowest possible value (to limit astigmatism)
- $R_1 = 0.970$ and $R_2 = 0.999 \to \mathcal{F} = 101.5$ ($R_2 > R_1$ to avoid power leakage from the end mirror)

The best candidate has been chosen by simulating all the configurations within these intervals. The discriminating factors were:
- HOMs suppression factors: $S_{nm} \gtrsim 20$ dB
- Intensity peak on the inner face of the base mirrors, limited to avoid damaging the coatings.



Gaussian TEM$_{00}$ mode resonates and is transmitted

Transverse intensity profile of TEM$_{00}$ mode (Gaussian function):
$$I(r) = \frac{2P}{\pi w^2(z)}e^{-2r^2/w^2}$$
where $P = \frac{\mathcal{T}}{1-r_1^2}P_{IMC}$ (stored power)

Suppression factor of a TEM$_{nm}$ mode:
$$S_{nm} = 1 + \left[\frac{2\mathcal{F}}{\pi}\sin\left((n+m)\arccos(\sqrt{g}) + \frac{\pi}{2}\frac{1-(-1)^n}{2}\right)\right]^2$$

IMC preliminary tests

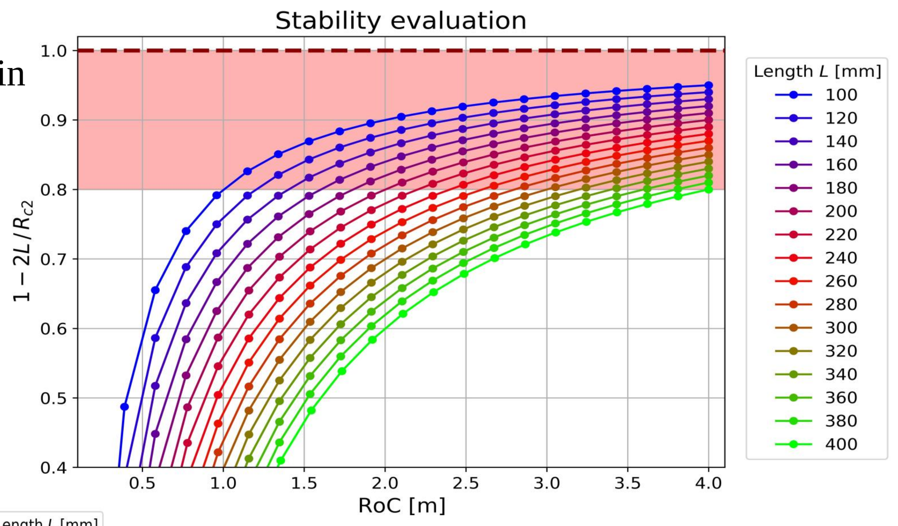
We performed preliminary tests on the necessary physical conditions, in order to limit the ranges of interest in the available parameters' space.

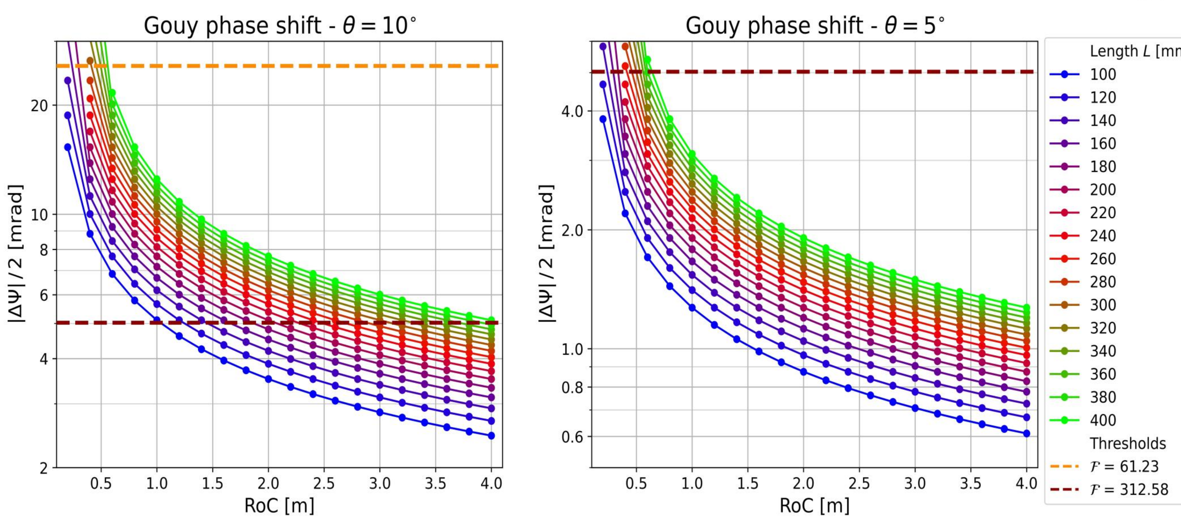
1) Optical stability

Generic stability condition: $|A+D|/2 < 1$

ABCD matrix of the cavity: $\begin{pmatrix} 1 & L_{rt} \\ -2/R_c & 1-2L_{rt}/R_c \end{pmatrix}$ with $\theta \approx 0$

$$\frac{L_{rt}}{2} < R_c\cos\theta$$





2) Low astigmatism

The Gouy phase shift between tangential and sagittal planes along a round trip must not exceed the cavity linewidth

Gouy phase: $\Psi(z) = 2\arccos\sqrt{g^{tan,sag}}$

$$\left|\arccos\left(\sqrt{g^{tan}}\right) - \arccos\left(\sqrt{g^{sag}}\right)\right| < \frac{\pi}{2\mathcal{F}}$$

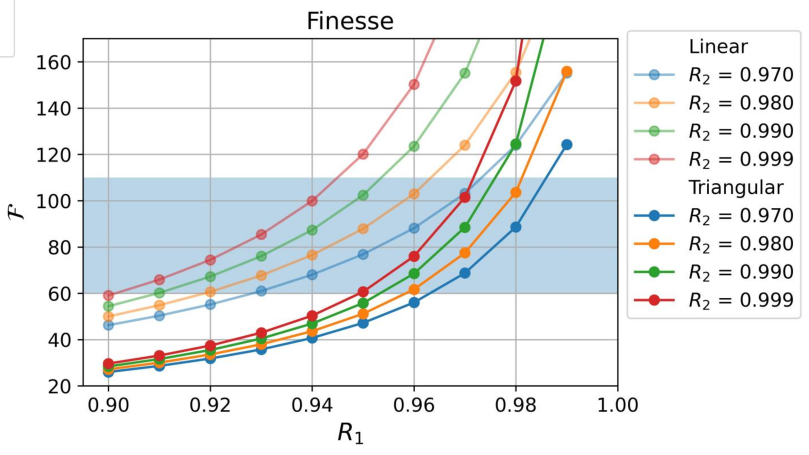
3) Transmitted power

SIPS requires 2.5 W as input power. Mirrors' reflectivity must be chosen in such a way that enough power is transmitted, without exceeding in the stored power, given the high input value of $P_{IMC} = 4$ W

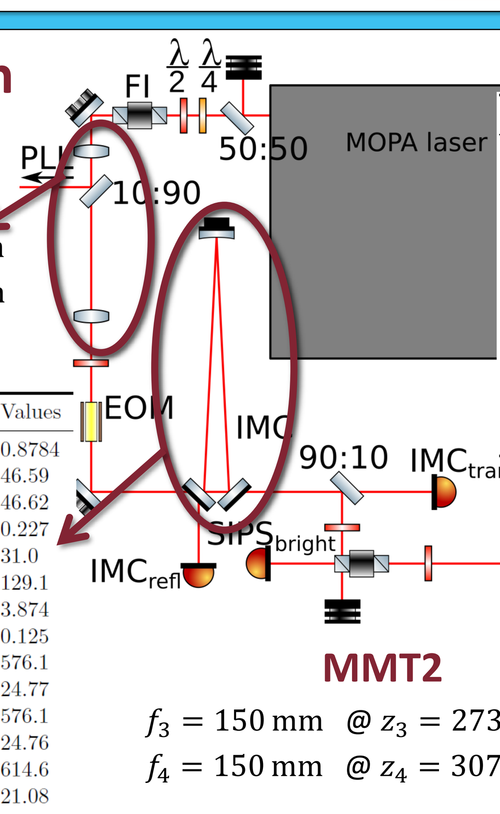
$$P_{tr} \equiv \mathcal{T}P_{in} > 2.5\ \mathrm{W}$$

where $\mathcal{T} = \frac{t_1^4}{(1-r_1^2r_2)^2}\left[1+\left(\frac{2\mathcal{F}}{\pi}\sin\left(\frac{kL_{rt}}{2}\right)\right)^2\right]^{-1}$ $\Rightarrow$

$$60 \lesssim \mathcal{F} \lesssim 110$$
$$\mathcal{F} \simeq \frac{\pi\sqrt{r_1^2r_2}}{1-r_1^2r_2}$$



SIPS injection path



MMT1

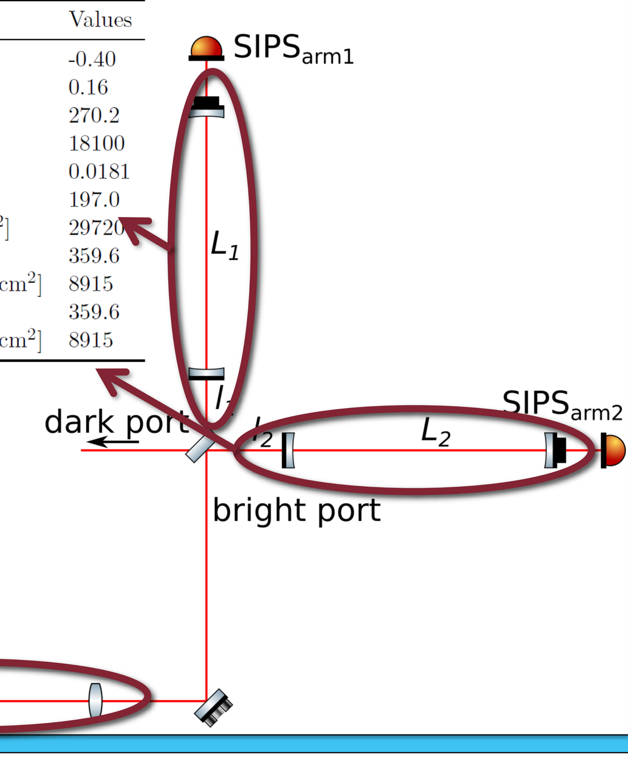
$f_1 = 100$ mm @ $z_1 = 300.0$ mm
$f_2 = 100$ mm @ $z_2 = 529.5$ mm

IMC

Parameters	Values	Parameters	Values
L_{rt} [mm]	729.0	g_t	0.8784
L [mm]	364.5	TMS$_s$ [MHz]	46.59
θ [deg]	2.0	TMS$_t$ [MHz]	46.62
α [deg]	44.0	$\lvert\Delta\Psi\rvert$ [mrad]	0.227
L_1 [mm]	352.2	$\pi/\mathcal{F}$ [mrad]	31.0
L_2 [mm]	12.3	P_{st} [W]	129.1
h [mm]	352.0	P_{tr} [W]	3.874
RoC [m]	3.0	P_{end} [W]	0.125
R_1	0.970	w_0 [μm]	576.1
R_2	0.999	I_{max} [kW/cm²]	24.77
$\mathcal{F}$	101.47	w_{in} [μm]	576.1
FSR [MHz]	411.2	$I_{max,in}$ [kW/cm²]	24.76
FWHM [MHz]	4.053	w_{end} [μm]	614.6
g_s	0.8786	$I_{max,end}$ [kW/cm²]	21.08

SIPS arms

Parameters	Values	Parameters	Values
L [mm]	350.0	g_2	-0.40
R_{c1} [m]	-0.250	g	0.16
R_{c2} [m]	0.250	TMS [MHz]	270.2
T_1	$270\cdot10^{-6}$	P_{st} [W]	18100
T_2	$1\cdot10^{-6}$	P_{tr} [W]	0.0181
A_1	$1\cdot10^{-6}$	w_0 [μm]	197.0
A_2	$1\cdot10^{-6}$	I_{max} [kW/cm²]	29720
$\mathcal{F}$	23010	w_{M1} [μm]	359.6
FSR [MHz]	428.3	$I_{max,M1}$ [kW/cm²]	8915
FWHM [kHz]	18.61	w_{M2} [μm]	359.6
g_1	-0.40	$I_{max,M2}$ [kW/cm²]	8915



MMT2

$f_3 = 150$ mm @ $z_3 = 2731.97$ mm
$f_4 = 150$ mm @ $z_4 = 3076.11$ mm

Acknowledgements

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