The POLIS interferometer for ponderomotive squeezed light generation

Andrea Conte*, Martina De Laurentis°, Luca Naticchioni*, Paola Puppo*
*on behalf of POLIS collaboration***

*Università di Roma La Sapienza, INFN Roma1 Gruppo Roma1 - °Università di Napoli Federico II, INFN Napoli

** (Università di Roma Tor Vergata) INFN Roma2 - (Università di Pisa - INFN Pisa) Gruppo Pisa - (INFN Genova), (INFN Perugia), (INFN Pisa), (Università del Sannio, INFN Napoli) Gruppo INFN

(Università di Firenze, INFN Firenze, CNR) Gruppo Firenze - (Università di Salerno, INFN Napoli) Gruppo di Salerno - (Università di Napoli Federico II, INFN Napoli, CNR) Gruppo Napoli-

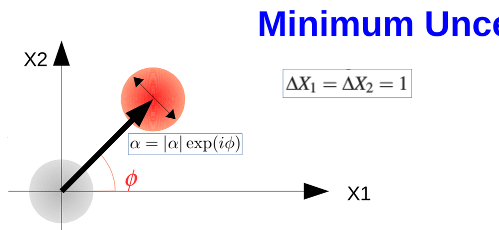
(Università di Trento, INFN Padova-Trento, *Fondazione B. Kessler) Gruppo di Trento

(Università di Camerino, INFN Perugia) Gruppo di Camerino - (Università di Urbino, INFN Firenze) Gruppo di Urbino

POLIS is a suspended interferometer, presently under construction, devoted to the generation of ponderomotive squeezed light and to the study of the interaction of non classical quantum states, of light, and macroscopic objects. The interferometer is a Michelson whose half-meter long arms are constituted by high-finesse cavities, suspended to a seismic isolation chain similar to the Virgo SuperAttenuator. – The mass of the suspended cavity mirrors are chosen to be tens of grams: this value is sufficiently high to permit the use of the well tested Virgo suspension techniques but also sufficiently small to generate the coupling among the two phase quadratures with a limited amount of light in the cavity, of the order of few tens of kW. – In this poster the main features of the interferometer are shown, together with the expected sensitivity and squeezing factor.

Squeezed State of Light and Sensors

Minimum Uncertainty States $\Delta X_1 \Delta X_2 = 1$

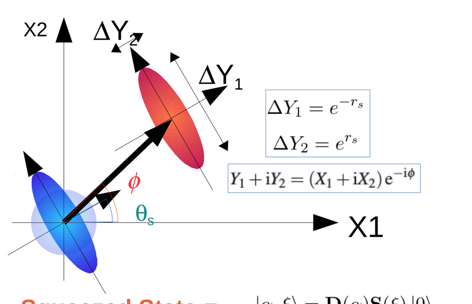


Coherent State= Displaced Vacuum
$|\alpha\rangle = D(\alpha)|0\rangle \quad D(\alpha) = \exp(\alpha a^\dagger - \alpha^* a)$

A bright beam (α>0) has the same fluctuation of the vacuum

Light as '*sensitive*' element

its intrinsic quantum fluctuations Determines the final sensitivity



Squeezed State = $|\alpha,\xi\rangle = \mathbf{D}(\alpha)\mathbf{S}(\xi)|0\rangle$
Displaced Squeezed Coherent Vacuum
$\mathbf{S}(\xi) = \exp\left(\frac{1}{2}\xi^* a^2 + \frac{1}{2}\xi a^{\dagger 2}\right)$ $\quad \xi = r_s \exp(i2\theta_s)$
Squeezing factor — Orientation of the squeezing axis

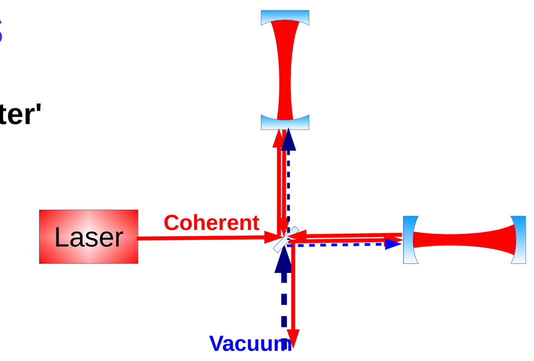
We cannot violate the uncertainty principle
but
we can squeeze the quantum fluctuations on one quadrature and 'use' that quadrature as sensitive element

Squeezed States

Squeezing in Interferometers

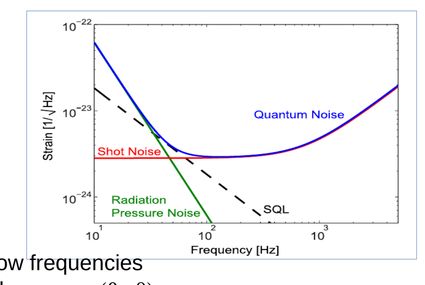
*C. M. Caves, '***Quantum noise in an interferometer***' Phys. Rev. D 23 (1693–1708), 1981*

Noise in the output as beat between the coherent input beam and the vacuum that enters in the unused port of a beam splitter (dark port of interferometer)



Vacuum Squeezed in the unused port

Noise Reduction (sensitivity improvement)



RPN dominates at Low frequencies
Amplitude squeezed vacuum (θ_s=0)
SN dominates @ High frequencies
Phase squeezed vacuum (θ_s=π/2)

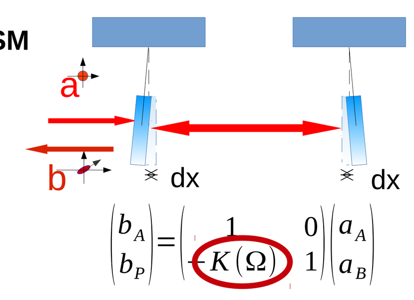
Interferometric Gravitational Waves Detectors (IGWD) require a frequency-dependent squeezing quadrature: squeezing angle $\theta_s = \theta_s(\Omega)$, with Ω = detection frequency

Frequency dependent & independent Ponderomotive Squeezing

USE OF RADIATION PRESSURE AS SQUEEZING MECHANISM

Laser Intensity fluctuations ⟷ test mass motion
Phase-shift proportional to intensity fluctuations
(**FREQUENCY DEPENDENT SHIFT**)

Coupling between *phase quadrature* and *amplitude quadrature*



$$\begin{pmatrix} b_A \\ b_P \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -K(\Omega) & 1 \end{pmatrix} \begin{pmatrix} a_A \\ a_B \end{pmatrix}$$

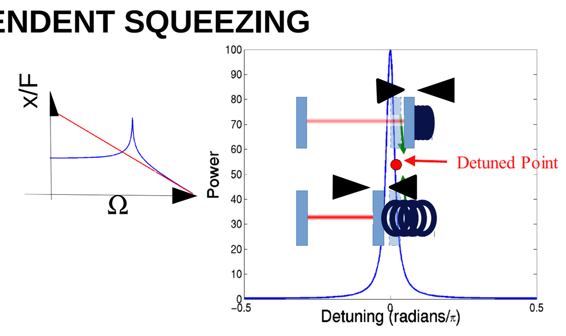
Squeezing $\xi(\Omega)$ (*frequency dependent*)

OPTICAL SPRING FOR FREQUENCY INDEPENDENT SQUEEZING

Optical Spring modifies the cavity dynamics

$\xi(\Omega)$ ⟶ ξ constant for $\Omega << \Theta$

optical spring characteristic frequency



gives the *frequency independent squeezing band*

What is interesting in ponderomotive squeezing?

Squeezing generation in MOEMS (Micro-Opto-Electro-Mechanical Systems) → Communication and integrated sensors;
on chip devices OPO integration in the well consolidate silicon technology (mixed technology with KTP and LiNb on Si) is more expensive and does not allow the same integration factor

Study of the coupling between macroscopic opto-mechanical objects and their quantum mechanical behavior → Theoretical interest

Low frequencies and frequency independent squeezing → **GW detectors**

PS is a completely suspended system → we expect that could be, *a regime*, a more robust system In long period operation OPO sequeezer seems *experimentally* frequency limited due to losses mechanism in the medium (photo-thermal fluctuations) even if progress in material engineering and dedicate mechanical design promises to overcome these limits.

Polis Optical Parameters

$$\xi_{min}(\Omega << |\Theta|) = \frac{|\bar{\delta}_\gamma|}{1+\sqrt{1+\bar{\delta}_\gamma^2}}$$

squeezing factor

Optical stiffness of the Optical Spring

$$\Theta^2 \equiv \frac{K_{opt}}{M} = -\frac{4\omega_0 I_0 \delta_\gamma}{Mc^2}\left(\frac{2\mathcal{F}}{\pi}\frac{1}{1+\delta_\gamma^2}\right)^2$$

Optical spring resonance

Fixed the ξ and Θ
key parameters are:

Input power I_o, Cavity Finesse $\mathcal{F}$, Cavity detuning δ_γ, Suspended mirrors mass M

Parameters value optimization
to have
A large enough squeezing factor and the desired **frequency band**

Cavity detuning: *trade-off between squeezing value/band*

Low level increases squeezing
High level *increases band*

We fix: δ=0.3 => ξ=18 dB and Θ=2π kHz

By considering the losses, this assures more than 10 dB of potential squeezing delivered by the interferometer

It covers the GWD band (but is not vacuum squeezed)

P_{in}=2.5 W $\mathcal{F} \leq$ **30 000**

Constrain for the cavity length: inner SAFE diameter **L = 440 mm**

Negative stability factors, g_i, in the cavities with low suspended masses reduce the angular instability **g_i = −0.76**

Available Radii of Rurvature of the commercial substrates **$RoC_{INPUT} = RoC_{End}$ = 250 mm**

This value of the RoC assures the maximum spot size, w_i, on the mirrors with the available commercial radii
(large spot => reduces thermal deformation of the coating) **w_i = 0.447 mm**

Gouy phase = 2.43 rad = 0.773493 π

well stable cavity:
avoiding the couplings with thermal deformations or imperfections, mis-match problems and the higher order modes resonance

POnderomotive LIght Squeezing POLIS project

Project to realize a completely suspended low frequencies ponderomotive squeezer,
moving from the pioneers' work made in the LIGO laboratory at the MIT
[*Corbitt et al.* Phys. Rev. A 73 (2 Feb. 2006), p. 023801]
and
taking the advantage of the available Virgo Super Attenuator Facility at EGO, SAFE
to control the main noises sources in the low frequencies range

Critical Points

Ponderomotive Squeezing:

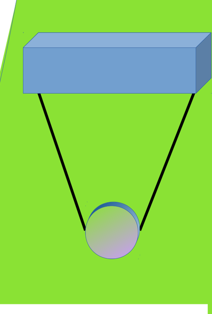
large squeezing values *without use* high laser power and/or very high cavity finesse *requires* very small suspended mirrors mass

very critical point is the mass suspension

Chance of success for the project

A relative large mass allows us to use the available well consolidate technologies of Virgo to control the low frequency noise

higher chance of success

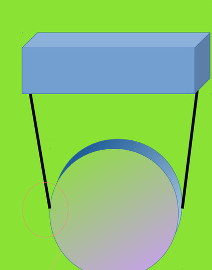


Low value of mass

- Large optical Spring resonance (*frequency independent squeezing Band*)

High value of mass

- ease of construction;
- ease to sense and actuate motion;
- use commercial size



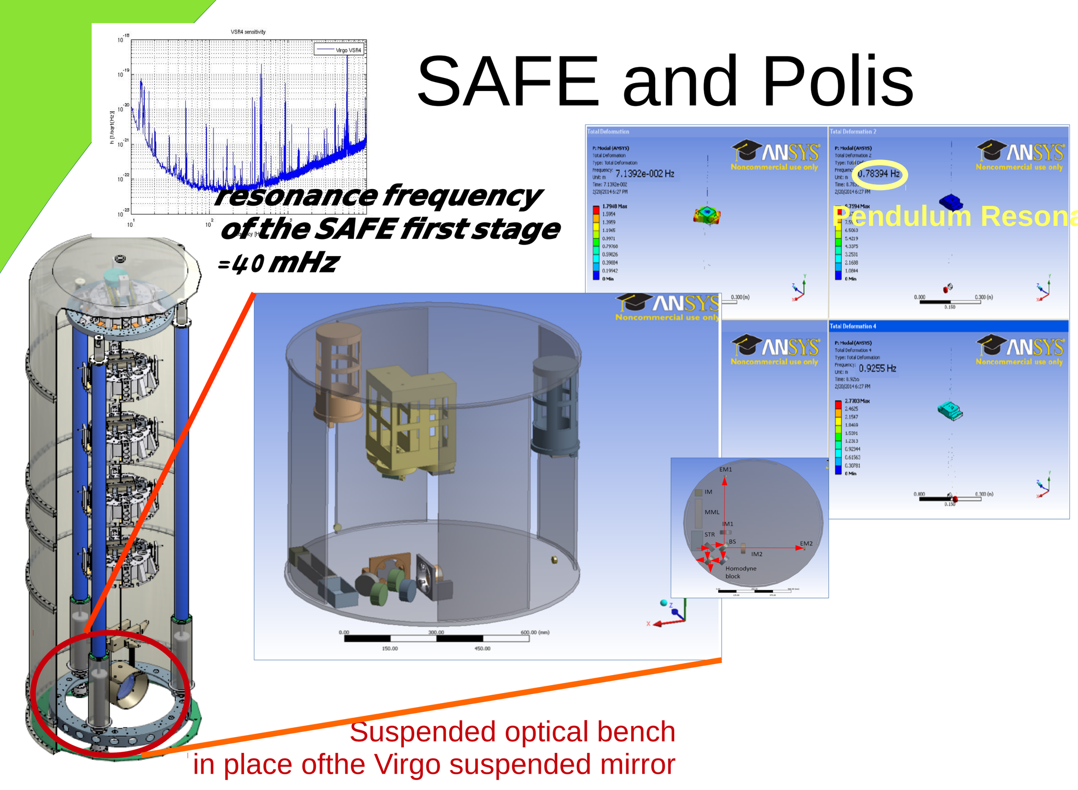
Use of **SAFE** → **High sensitivity in the low frequency range thanks to better seismic isolation** → **we can choose slightly higher mass: M=10 g**

A standard 25.4 mm mirror in fused silica with a 6.35 mm thickness has a mass of about 7.8 g, while with a 10 mm of thickness it can reach a mass of 11.1 g: It can be suspended with the available technology in Virgo

Moreover
We expect no particular problem with the suspension fibre welding

macroscopic masses reduce the thermal noise

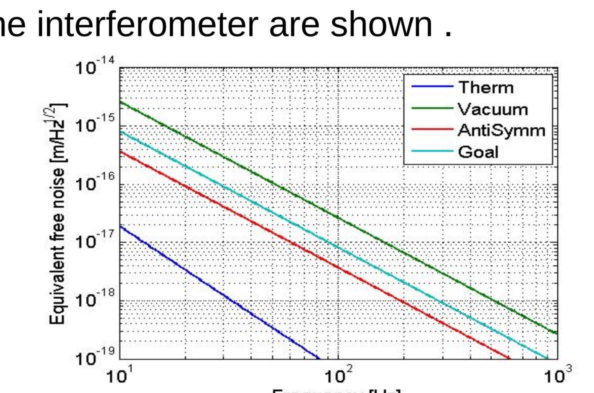
SAFE and Polis



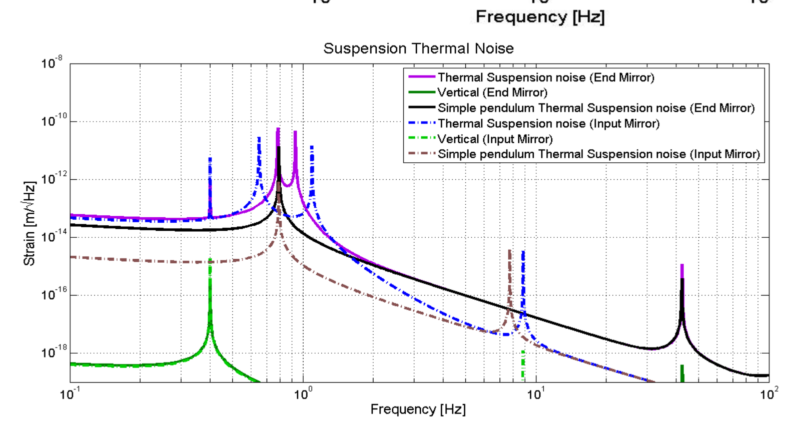
Suspended optical bench in place ofthe Virgo suspended mirror

Polis Interferometer expected noise

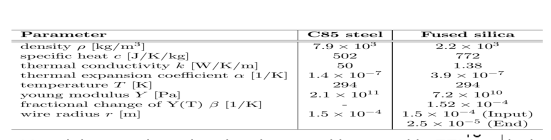
Maximum equivalent interferometer noise on the differential mode in order at least to reach the non-squeezed noise level.
The three curves for the equivalent noise of the interferometer are shown.
In case of **7 db of squeezing**, taken as *realistic value* due to losses, the **interferometer sensitivity limit** is **10^{-15} m/sqrt(Hz) @ 10 Hz** and **10^{-17} m/sqrt(Hz)@100 Hz**.
These requirements can be fulfilled by careful design of the interferometer.



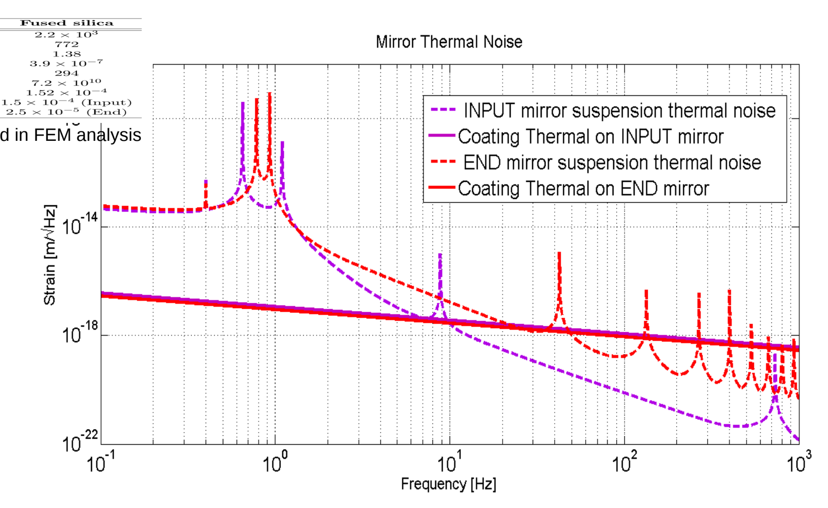
With our choice of parameters the FEM simulations predict a suspension and coating thermal noise below the expected squeezing value at low frequencies. They are expected to be the major source of fundamental noises in the 10-20 Hz frequency region.



The expected noise is within the requirements, as shown in figures



Material properties related to the quantities used in FEM analysis



REFERECES:
[1] T. Corbitt, Y. Chen, F. Khalili, D. Ottaway, S. Vyatchanin, S. Whitcomb, and N. Maval- vala: Squeezed-state source using radiation-pressure-induced rigidity. Phys. Rev. A 73, 023001 (2006)
[2] T. Corbitt, Y. Chen, and N. Mavalvala: Mathematical framework for simulation of quantum fields in complex interferometers using the two-photon formalism. Phys. Rev. A 72, 013818 (2005)
[3] F. Della Valle, U. Gastaldi, G. Messineo, E. Milotti, R. Pengo, L. Piemontese, G. Ruoso and G. Zavattini: Measurements of vacuum magnetic birefringence using permanent dipole magnets: the PVLAS experiment. arXiv:1301.4918v1 [quant-ph] 21 Jan 2013
[4] Y. Levin: Internal thermal noise in LIGO test masses: a direct approach. Phys. Rev. D, vol. 57, 659-663 (1998)
[5] G. M. Harry et al.: Titania-doped tantala/silica coatings for gravitational-wave detection. Class. Quantum Grav. vol. 24, 405 (2007)
[6] K. Srinivasan: Coating strain induced distortion in LIGO optics, LIGO document T970176 (1997)

FRONTIER DETECTORS FOR FRONTIER PHYSICS
13th Pisa Meeting on Advanced Detectors
24-30 May 2015 - La Biodola, Isola d'Elba (Italy)