Ponderomotive Squeezing R&D with SIPS

Luca Naticchioni (INFN Roma)


L. Naticchioni - KIW8 – 8th July 2021
Summary

- Squeezing for the Quantum Noise mitigation in GWID
- Ponderomotive squeezing
- SIPS experiment
- SIPS as test bench for EPR squeezing technique
- Conclusions
Squeezing for the Quantum Noise mitigation in Gravitational Wave Interferometric Detectors

**QUANTUM NOISE (SHOT NOISE & RADIATION PRESSURE NOISE)** constitutes an intrinsic limit in the position measurements of a free mass using coherent light:

**Photon Shot Noise** *(SN, sensing noise)*

Power fluctuation due to statistical (Poissonian) fluctuations of incident photons (above 200Hz)

**Photon Radiation Pressure** *(RPN, backaction noise)*

Stochastic force originated by the fluctuation of the number of photons hitting the mirror (low frequency)

L.Naticchioni - KIW8 – 8th July 2021
Squeezing for the Quantum Noise mitigation in Gravitational Wave Interferometric Detectors

Quantization of Electric field: \( \hat{E}_x(z, t) = E_0 \sin(kz)(\hat{X} \cos \omega t + \hat{Y} \sin \omega t) \)

**Quadrature Operators**
- \( \hat{X} \): Phase quadrature \( \rightarrow \Delta X \) Shot Noise
- \( \hat{Y} \): Amplitude quadrature \( \rightarrow \Delta Y \) Radiation Pressure Noise

In a standard coherent state Shot Noise and RPN are *uncorrelated*

**Heisenberg Uncertainty Principle** \( (\Delta X)^2 (\Delta Y)^2 \geq \frac{1}{16} \)

**Standard Quantum Limit:** \( \tilde{h}_{QL} = \sqrt{\frac{4h}{M\Omega^2 L^2}} \)

Quantum noise squeezed by 20dB in \( \Delta Y \)

- Squeeze one quadrature
- Anti-squeeze the other
- Correlate SN and RPN

\[ f > 0.1 \text{ Hz} \]

L. Naticchioni - KIW8 – 8th July 2021
Summary

- Squeezing for the Quantum Noise mitigation in GWID
- Ponderomotive squeezing
- SIPS experiment
- SIPS as test bench for EPR squeezing technique
- Conclusions
Ponderomotive squeezing

In an **empty optical cavity** with suspended mirrors the Radiation Pressure (RPN) on the suspended mirror induces a **coupling** between its **position** and the **intensity of light beam**

**correlation** between **phase** and **amplitude** quadrature of the output state

**Squeezing** effect on the output field!

**Pros:** High squeezing factor achievable, low frequency, conceptually simple

**Cons:** difficult to be realized with \(\leq 1''\)-scale mirrors; thermal noise and seismic noise vs. RPN

L.Naticchioni - KIW8 – 8th July 2021
Ponderomotive squeezing

Opto-Mechanical coupling in a detuned cavity

Optical spring

\[ F \approx kx - \gamma \dot{x} \]

\[ F \approx -kx + \gamma \dot{x} \]

- cavity becomes longer
  - detuning increases
  - power decreases
  - restoring force decreases

- cavity becomes shorter
  - detuning decreases
  - power increases
  - restoring force increases

*\( \gamma \): (anti)damping term ↔ spring instability

L. Naticchioni - KIW8 – 8th July 2021
Ponderomotive squeezing

Ponderomotive squeezing in a cavity with suspended mirrors

Gravity + RP acting on the mirrors → optical spring

Intensity (amplitude) fluctuations inside the cavity cause suspended mirror motion

Displacement of mirrors produces a phase shift in the reflected light

Phase shift proportional to intensity fluctuations → coupling between phase and amplitude quadrature fluctuations → squeezing

Ideally it is possible to achieve broadband and high value squeezing (>10dB) in audio frequency (10Hz-10kHz) and at room temperature
Ponderomotive squeezing

Ponderomotive squeezing in a cavity with suspended mirrors

Gravity + RP acting on the mirrors → optical spring

\[
\begin{pmatrix}
b_A \\ b_P
\end{pmatrix} = \begin{pmatrix}
1 & 0 \\ -2\mathcal{K}(\Omega) & 1
\end{pmatrix} \begin{pmatrix}
a_A \\ a_P
\end{pmatrix}
\]

coupling factor (frequency-dependent):

\[
\mathcal{K}(\Omega) = \left( \frac{1}{1 - (\Omega^2 - \Omega_P^2)/\Theta^2} \right) \frac{1}{\delta_\gamma}
\]

\textit{ponderomotive squeezing factor:}

\[
\xi_{\text{min}}(\Omega) = \frac{1}{|\mathcal{K}(\Omega)| + \sqrt{1 - \mathcal{K}(\Omega)^2}}
\]

When \( \Omega_P \ll \Omega, |\Theta| \) the mirror mechanical resonance depends only on the optical spring resonant frequency \( \pm \Theta \)

\[
\mathcal{K}(\Omega) \gg |\Theta| \quad \rightarrow \text{Output not squeezed}
\]

\[
\mathcal{K}(\Omega) \approx |\Theta| \quad \rightarrow \text{Frequency-dependent squeezing}
\]

\[
\mathcal{K}(\Omega) \ll |\Theta| \quad \rightarrow \text{Frequency-independent squeezing}
\]

\[
\mathcal{K} = \frac{1}{\delta_\gamma} \quad \xi_{\text{min}}(\Omega \ll |\Theta|) = \frac{|\delta_\gamma|}{1 + \sqrt{1 + \delta_\gamma^2}}
\]

L. Naticchioni - KIW8 – 8th July 2021
Ponderomotive squeezing

Ponderomotive squeezing in a cavity with suspended mirrors

Gravity + RP acting on the mirrors → optical spring

\[
\begin{pmatrix}
  b_A \\
  b_P
\end{pmatrix} =
\begin{pmatrix}
  1 & 0 \\
  -2\mathcal{K}(\Omega) & 1
\end{pmatrix}
\begin{pmatrix}
  a_A \\
  a_P
\end{pmatrix}
\]

Coupling factor (frequency-dependent):

\[
\mathcal{K}(\Omega) = \left( \frac{1}{1 - (\Omega^2 - \Omega_P^2) / \Theta^2} \right) \frac{1}{\delta_\gamma}
\]

The optical spring frequency $|\Theta|$ depends on:

- input power, cavity finesse, detuning factor, mirror mass

\[
\Theta^2 = \frac{K_{opt}}{M} = -\frac{4\omega_0 W}{\gamma MLc} \frac{\delta_\gamma}{1 + \delta_\gamma^2} = \frac{4\omega_0 \bar{I}_0 \delta_\gamma}{Mc^2} \left( \frac{2F}{\pi} \frac{1}{1 + \bar{\delta}_\gamma^2} \right)^2
\]

Once these parameters (and then $|\Theta|$) are fixed, we design the system in order to have $\Omega_P \ll |\Theta|$ by choosing an appropriate pendulum length.

Real parameters must be chosen ensuring a large squeezing factor and a suitable squeezing band, taking into account the mechanical feasibility.

L.Naticchioni - KIW8 – 8th July 2021
Summary

- Squeezing for the Quantum Noise mitigation in GWID
- Ponderomotive squeezing
- SIPS experiment
- SIPS as test bench for EPR squeezing technique
- Conclusions
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

The path towards a ponderomotive squeezer

from 2014

POLIS

Preliminary R&D on a low frequency ponderomotive squeezer
(funded by a PRIN of the Italian Ministry of University and Research) involving many research institutions:

Università di Roma Sapienza & INFN-Roma, Università di Napoli Federico II & INFN-Napoli, Università di Roma Tor Vergata & INFN-Roma2, Università di Pisa & INFN-Pisa, INFN-Genova, INFN-Perugia, Università del Sannio, Università di Firenze & INFN-Firenze, Università di Salerno, Università di Trento & INFN-Padova-Trento & Fondazione B.Kessler, Università di Camerino, Università di Urbino, CNR

Preliminary mechanical design and realization (Roma1)  Main laser (Urbino, Napoli)
First optical design (Napoli, Roma2)  Optical benches (Pisa)

from 2017

SIPS

The experimental setup was then funded with the 2-years grant SIPS (2017-2019) by INFN, with the participation of the local sections of Roma1, Perugia and Pisa + collaboration with the sections of Napoli and Firenze-Urbino

Mechanical components and optics (Roma1)
Monolithic Suspension (Perugia)
Suspended optical bench (Pisa)

from 2019

SIPS enters in the squeezing R&D of Advanced Virgo+

Experimental setup finalisation and collaboration with EPR squeezing experiment: SIPS interferometer as test bench of the EPR squeezing technique

L.Naticchioni - KIW8 – 8th July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

The parameter choice

**Cavity detuning:** $\delta = 0.3 \rightarrow \xi = 18 \text{ dB} , \Theta = 2\pi \text{ kHz}$  
(large values increase the band; low values increase the squeezing factor)

**Cavity finesse:** $\mathcal{F} \leq 3 \cdot 10^4$  
(large values increase $\Theta$ and reduce intracavity losses; low values increase the optical spring stability)

**Input power:** $I_0 = 2.5 \text{ W} \rightarrow 0.1 \text{ MW}$ circulating power  
(large values increase $\Theta$ but above 0.2MW thermal effects lead to degradation of the cavity behaviour)

The other parameters depends on trade-off with other experimental constraints: seismic noise pre-insulator, optical bench dimension ($\phi < 1m$) ...

**Cavity length:** $l = 350 \text{ mm}$  
**Mirror RoC:** $RoC = 250 \text{ mm}$  
**Squeezing factor and band**  
**Optical spring**  
**Cavity stability**
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

The parameter choice

Suspended mirror mass

**High values:**
- easy to suspend
- easy to sense and actuate (feedback control)

**Low values:**
- Large optical spring resonance (frequency-independent band)

Given a suitable seismic pre-insulation we can choose a relatively high mass value:

\[ 10g \leq m \leq 300g \]

NB: a commercial 25.4 mm fused silica mirror with a thickness of 6.35 mm has a mass of \( \approx 7.8 \) g, if we increase the thickness to 10 mm we can achieve 11.1 g of mass.

Can be suspended with a monolithic Virgo-like technique (\( \rightarrow \) thermal noise reduction)  

Higher mass value relaxes the sensitivity requirements

*L.Naticchioni - KIW8 – 8th July 2021*
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Seismic and thermal noise mitigation

**Seismic and thermal noises** are the main limitations to exploit the RP effect with 10-100g-scale mirrors

**Solutions:** well-known technologies from GW detectors like Virgo

---

**Efficient seismic filter:** the *SuperAttenuator* (SA) of Virgo, an inverted pendulum + a chain of pendula, passive+active damping. Provides a seismic attenuation of \(-180\text{dB}\) at 10Hz. *The idea is to suspend the optical bench to a SA.*

**Monolithic suspension:**
*SiO\(_2\)* fibers welded to mirrors as in Virgo and LIGO GW detectors: low thermoelastic losses with respect to metallic wires

---

*L.Naticchioni - KIW8 – 8\(^{th}\) July 2021*
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Bench Requirements: compliant with allowed size and weight to be suspended at SAFE (SuperAttenuator Facility at EGO-Virgo)

Height: 800 mm  
Diameter: 960 mm  
Weight: ~ 150 kg

Minipayload: Monolithic suspension system of the main optics  
2 fused silica fibers of 50μm

Controls: magnet-coil actuators on mirror & marionette

L.Naticchioni - KIW8 – 8th July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

$L_n = 2.5W$

**LIM**: Laser input mirror
**L1 L2**: Mode Matching Lenses
**STR**: Beam Steering Mirrors
**BS**: Beam Splitter
**EM1, EM2**: Cavity End Mirror
**IM1, IM2**: Cavity Input Mirror

**Cavity stability**

- **Cavity length**: $L = 350\,\text{mm}$
- **Mirror RoC**: RoC = 250 mm

**Substrates (SUPRASIL):**
- IM: 3”, 30mm, RoC 250mm, 300g
- BS: 3”, 30mm, 300g
- EM: 1”, 10mm, RoC 250, 10g

**Coatings (done at LMA):**
- IM: $T=260\,\text{ppm} @0^\circ$
- EM: $T=1\,\text{ppm} @0^\circ$
- BS: 50%±0.05% @45°

---

*L.Naticchioni - KIW8 – 8th July 2021*
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Monolithic suspension system of the main optics
(fused silica fibers of 50\(\mu\)m x 40 cm from a silica seed of 3mm diameter)

CO\(_2\) Laser Machine @ EGO

50\(\mu\)m diameter fused silica fibers

Anchor system

Prototype Dummy end mirror suspension

Test of local control of suspended elements:
Coils behind mirror and magnets glued on the mirror

Coils-magnets also on the marionette

L. Naticchioni - KIW8 – 8\(^{th}\) July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Thermal noise expectation

![Graphs showing thermal noise expectation for different mirror masses and frequencies.]

- **1” mirror, 10g**
- **3” mirror, 300g**

L. Naticchioni - KIW8 – 8th July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Thermal noise expectation

\[ X_{RPN}(10\,Hz) \approx 3 \times 10^{-15} \text{m}/\sqrt{\text{Hz}} \]

\[ X_{ThNS}(10\,Hz) \approx 5 \times 10^{-18} \text{m}/\sqrt{\text{Hz}} \]

\[ X_{RPN}(10\,Hz) \approx 6 \times 10^2 \, X_{ThNS}(10\,Hz) \]


L. Naticchioni - KIW8 – 8th July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Local control with optical levers

➢ To damp the angular and longitudinal modes involving the mirror and to be able to set and recover the reference angular position of each mirror
➢ Longitudinal and angular local positions of the mirror are reconstructed measuring the position of one SLED beam reflected by the mirror surface and another one reflected by the marionette, which both work as optical levers:

- 2 SLED + 3PSDs:
  - PSD1 → mirror focal plane
  - PSD2 → mirror image plane
  - PSD3 → marionette focal plane

Controlled DOF
Mirror: $\theta_x, \theta_y$ with PSD1
$z$ with PSD2
Marionette: $\theta_z, \theta_y$ with PSD3

L. Giacoppo et al. submitted to Focus Issue of Physica Scripta journal (2021)
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Local control with optical levers

Labview software: implement the digital control loops for monitor and real-time feedback cancellation

Pre-alignment recovery of the (dummy) end mirror

Attenuation of the amplitude relative to $\theta_x$, $\theta_y$ and $z$ DOFs. $\theta_z$ control will be done acting on the marionette

L.Naticchioni - KIW8 – 8th July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Control strategy

Initial status

UNCONTROLLED STATE

$V_{\text{mirror}} > 0.1 \, \mu m/s$

LOCAL

Mini-pay $\times 4$

DataDisplay $\times 4$

Search condition to engage lock $\times 4$:

$V_{\text{mirror}} \leq 0.1 \, \mu m/s$

GLOBAL

LOCK F-P 1

LOCK F-P 2

CARM

DARM

LOCKED

Out of lock

L. Naticchioni - KIW8 – 8th July 2021
**SIPS**  (Suspended Interferometer for Ponderomotive Squeezing)

**Monolithic suspension upgrades**

**Potential issue:** alignment and mirror pitch damping due to *technical noise* (local control), may spoil the sensitivity

**Solution:** a new fully monolithic suspension with 4 SiO$_2$ fibers

With a 2-fibers-suspension the *pitch* can be damped only at the mirror level

**Smoothed-fiber** silicate-bonding to mirror flat and to SiO$_2$ marionette block $\Rightarrow$ modified marionette design, pitch actuation at the marionette level

---

**Fiber production with HP laser**

**Marionette SiO$_2$ block, integrated in marionette body**

**Silicate bonding to mirror polished flats**

L.Naticchioni - KIW8 – 8th July 2021
SIPS (Suspended Interferometer for Ponderomotive Squeezing)

Next steps

2021:
- vacuum test and finalisation of the LC in Roma1 Lab
- monolithic suspension assembly test

2022-23:
- the setup will be moved to the squeezing R&D Lab at EGO (Virgo)
- mechanical assembly on the definitive optical bench
- integration of (monolithic) suspended optics
- Global control finalisation
- integration of the SIPS setup with the EPR squeezing experiment
Summary

- Squeezing for the Quantum Noise mitigation in GWID
- Ponderomotive squeezing
- SIPS experiment
- SIPS as test bench for EPR squeezing technique
- Conclusions
SIPS as test bench for EPR squeezing

A promising new technique to achieve FDS is to use the Einstein-Podolski-Rosen (EPR) entangled signal and idler beams (Y. Ma et al., *Nature Physics*, 13(8):776-780, Aug 2017).

To do so, we will use the OPO in non-degenerate condition, with the squeezing pump field detuned, producing two entangled beam: a signal around the carrier frequency and an idler shifted by the detuning frequency.

The idler will see the ITF as a *detuned cavity → quadrature rotation*. The homodyne measurement of a fixed quadrature of the outgoing idler will **conditionally** squeeze the input signal field in a frequency-dependent way.

*L.Naticchioni - KIW8 – 8th July 2021*
SIPS as test bench for EPR squeezing

**OPO based squeezer in R&D SQZ LAB @ EGO Virgo**

- Existing FIS R&D bench will be upgraded into an EPR setup
- **Novelty: inject EPR SQZ into SIPS** small-scale suspended ITF RPN-limited in the same freq. band of Virgo
- **SIPS suitable demonstrator of EPR principle before possible integration in AdVirgo**
- We expect to see QN reduction below 2 kHz

**Preliminary scheme of EPR-SIPS integration**

- FIS setup at Virgo R&D SQZ lab (C.Nguyen et al, Review of Scientific Instruments 92, 054504 (2021))
- Measured -6 dB of SQZ and 15 dB of anti-SQZ @ Central freq: 1 MHz
- New control techniques with finite state machines

_L.Naticchioni - KIW8 – 8th July 2021_
SIPS as test bench for EPR squeezing

Table-top sensitivity expectation at EGO

Seismic noise* at the mirror (double stage suspension) without SuperAttenuator (SA) pre-insulation

*calculated from the seismic background measured at EGO, close to the 1500W laboratory

Effective RP-limited bandwidth:
(40-500)Hz
(40-700)Hz

Mitigation strategy: passive dampers below the setup

L. Naticchioni - KIW8 – 8th July 2021
Conclusions

- Ponderomotive squeezing is an interesting alternative to well-established OPO-based squeezing technique;

- We are setting-up an experiment to demonstrate the feasibility of a squeezer based on a suspended “table-top” interferometer;

- SIPS Prototype assembled and under test with dummy mirrors at Roma1 lab, the experimental setup will be finalised at the EGO-Virgo site in the next few years;

- SIPS will be integrated in the R&D setup for EPR squeezing as a RP-limited interferometer for the demonstration of this novel squeezing technique.
Thank you for your attention!
From the **Fluctuation-Dissipation Theorem**:

$$S_X^{FDT}(\omega) = \frac{4k_BT}{m\omega} \frac{\omega_0^2\phi(\omega)}{(\omega^2 - \omega_0^2)^2 + [\omega_0^2\phi(\omega)]^2}$$

The overall $\Phi$ is given mainly by the Thermoelastic and Surface loss angles:

$$\phi_{te} = \Delta \frac{\omega \tau}{1 + (\omega \tau)^2} \quad \phi_s = \phi_{bulk}(1 + \frac{d_s}{d})$$

where:

$$\Delta = \frac{YT}{c\rho} \left(\alpha - \beta \frac{\sigma}{Y\pi}\right)^2 \quad \tau = \frac{c\rho d^2}{2.16 \cdot 2\pi k}$$

**Suspension wires:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\varphi_{bulk,SiO_2} = 4 \times 10^{-10}$</th>
<th>$\varphi_{bulk,C85} = 10^{-4}$</th>
<th>$d_{s,SiO_2} = 1.5 \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>density $\rho$ [kg/m$^3$]</td>
<td>$7.9 \times 10^9$</td>
<td>$2.2 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>specific heat $c$ [J/K/kg]</td>
<td>502</td>
<td>772</td>
<td></td>
</tr>
<tr>
<td>thermal conductivity $k$ [W/K/m]</td>
<td>50</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>thermal expansion coefficient $\alpha$ [1/K]</td>
<td>$1.4 \times 10^{-7}$</td>
<td>$3.9 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>temperature $T$ [K]</td>
<td>294</td>
<td>294</td>
<td></td>
</tr>
<tr>
<td>young modulus $Y$ [Pa]</td>
<td>$2.1 \times 10^{11}$</td>
<td>$7.2 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>fractional change of $Y(T)$ $\beta$ [1/K]</td>
<td>-</td>
<td>$1.52 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>wire radius $r$ [m]</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

Strain energy and silicate bonding contribution estimated with a **FEM**

**L. Naticchioni - KIW8 – 8th July 2021**
EPR squeezing

DEGENERATE OPO

pump
\( \omega_p = 2 \omega_s \)

\( \chi^{(2)} \)

signal
\( \omega_s \)

idler
\( \omega_l = \omega_s \)

\( \omega_s - \Omega \)
\( \omega_s \)
\( \omega_s + \Omega \)

correlated sidebands

NON-DEGENERATE OPO

detuned pump
\( \omega_p = 2 \omega_s + \Delta \)

\( \chi^{(2)} \)

signal
\( \omega_s \)

idler
\( \omega_l = \omega_s + \Delta \)

\( \omega_s - \Omega \)
\( \omega_s \)
\( \omega_s + \omega_s + \omega_s + \Delta/2 \)
\( \omega_s + \Delta - \Omega \)
\( \omega_s + \Delta \)
\( \omega_s + \Delta + \Omega \)

correlated sidebands

The two produced beams are Einstein-Podolsky Rosen (EPR) entangled

credit to V. Sequino, VFNG conference 2019

L. Naticchioni - KIW8 – 8th July 2021
EPR squeezing

Comparison with Filter Cavity

**Loss sources**

- Loss due to arm cavities (90 ppm per round trip, around~ 4%)
- Loss due to Signal Recycling Cavity (2000 ppm per RT)
- Input and Readout losses

**BUT**

- Two squeezed beams: double losses

- Need for two Homodyne Detectors and extra OMC

- Less expensive
- Avoids the 1ppm/m round trip losses for the FC
- **Flexible vs Signal Recycling Cavity configuration**

*credit to V. Sequino, VFNG conference 2019*

*L.Naticchioni - KIW8 – 8th July 2021*
EPR squeezing at EGO

Starting from the current R&D squeezer, we plan to modify its design for the EPR setup

Main changes WRT current design:

- Test Cavity
- SIPS ITF

L. Naticchioni - KIW8 – 8th July 2021