FDS via EPR entanglement

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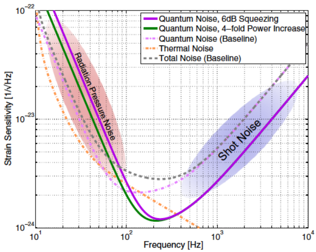
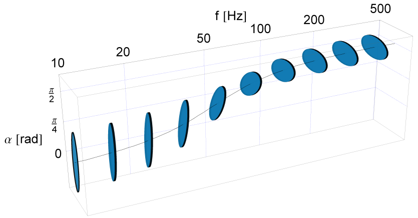
Overview

1. Motivation
   - FDS with filter cavities
   - EPR entanglement
2. Technical implementation
   - Changes to the 1500W optical bench
     - Optical setup
     - Electronic setup
   - External optical resonator
     - Producing the frequency-dependent ellipse rotation
     - Demonstrating the broadband reduction of noise from different quadratures
3. Planning and financial request
   - Connection with other activities on the OPO squeezer
     - Mitigation of noise sources
     - Development for in-vacuum components
     - Mitigation of optical losses
   - Time schedule
   - Cost estimate

Limitations of frequency independent squeezing

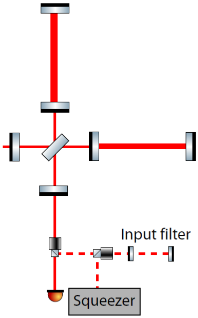
- In principle, injecting phase-squeezed vacuum improves the sensitivity at high frequency where ITF is dominated by shot noise
- At the same time, the corresponding amplitude anti-squeezing makes radiation pressure noise at low frequencies increase
- With increasing level of injected squeezing, this advantage is reduced by the increased low frequency noise
- A broadband sensitivity enhancement would require a frequency-dependent rotation of the squeezing ellipse

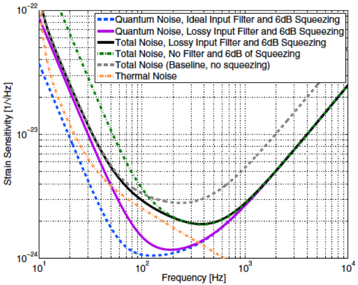




FDS and filter cavities

- Tune phase angle of squeezing ellipse vs signal frequency
- E.g. using a filter cavity with resonance width $\sim$ crossover frequency between radiation pressure and shot noise in ITF ($\sim 200\,\mathrm{Hz}$)
- stringent requirements
  - either medium length cavity ($\sim 3\,\mathrm{m}$) with high finesse ($\sim 4 \times 10^5$)
  - or very long cavity ($\sim 300\,\mathrm{m}$) with moderate finesse (~ 4000)
- management of losses is rather challenging





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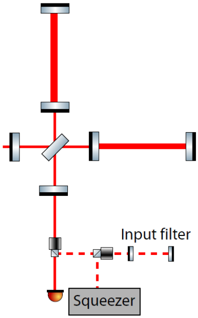
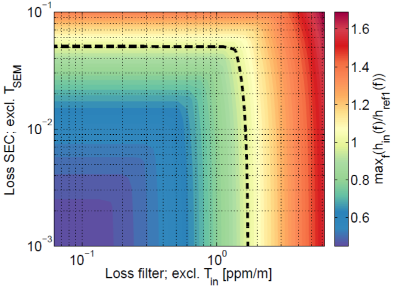
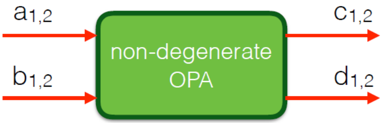


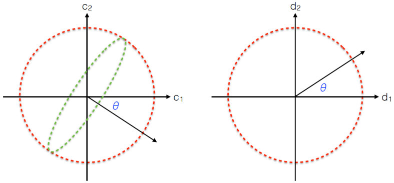


EPR entanglement

Non-degenerate OPA

Quantum noise in *c* and *d* enhanced, but measuring *c*, one can subtract from measurement of *d* and obtain (conditional) squeezing.

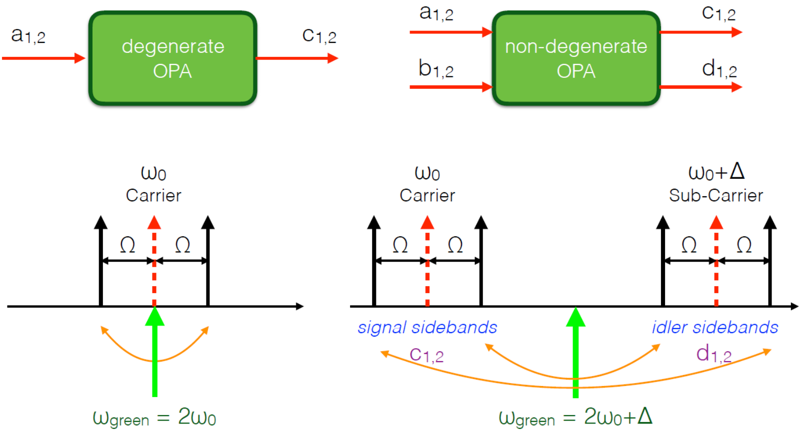




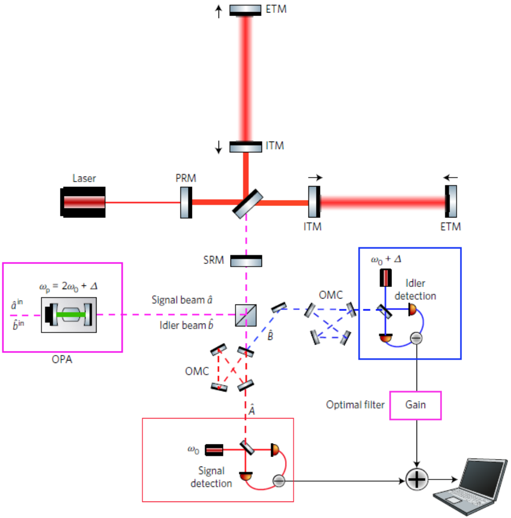
can predict $c_{-\theta} = c_1\cos\theta - c_2\sin\theta$
after subtraction: conditionally squeezed!

measuring $d_\theta = d_1\cos\theta + d_2\sin\theta$

Sideband correlations



FIS injection with EPR entanglement

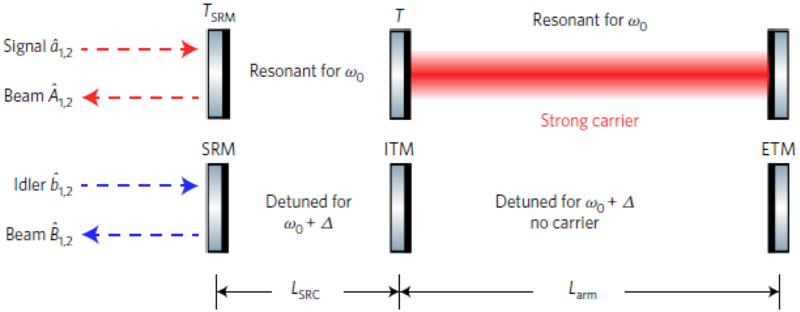


Y. Ma et al., Nature Physics 13, 776 (2017)

FIS injection with EPR entanglement

Auto-filtering

Given an OPA offset Δ, arm-cavity and SEC lengths can be fine-tuned to mimic filter cavity for idler



EPR vs filter cavity

Disadvantages

- There is an overall 3dB penalty
- Loss at the output port (injection as well as readout) counts twice

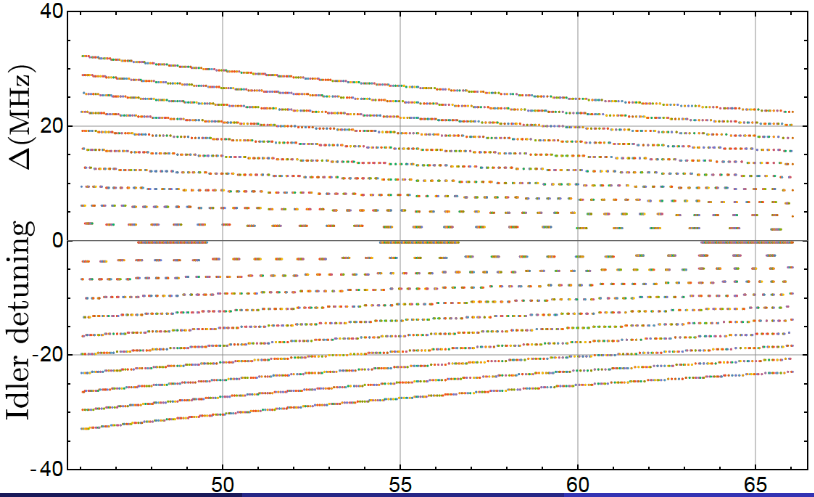
Advantages

- Easier to implement than a filter cavity
- Lower cost than a filter cavity
- optical loss inside the EPR filter (i.e., the ITF) is negligible as compared to the case of filter cavities
- lower influence of low frequency noise sources
- higher flexibility: without modification of the optical system of Virgo, one can filter either at high-f (for detuned SRC), or at low-f (for tuned SRC)

Configuration flexibility

Working points

Fixing other parameters: L_{arm}, P_{arm}, T_{ITM}, T_{SRM},



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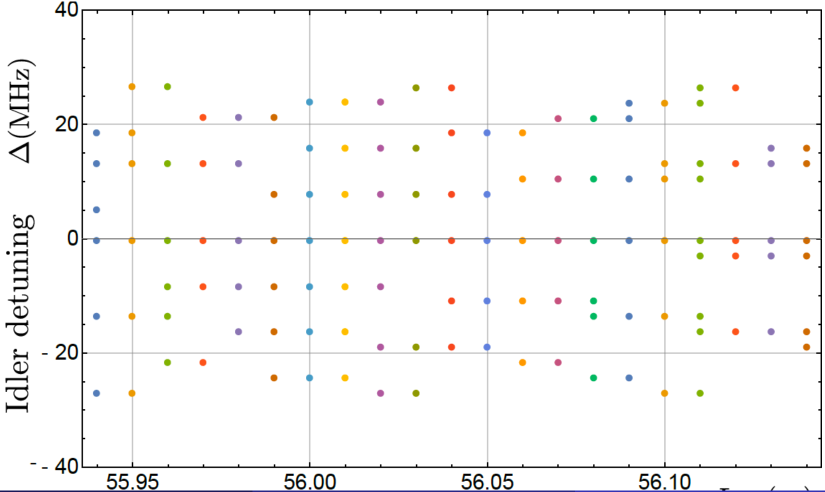
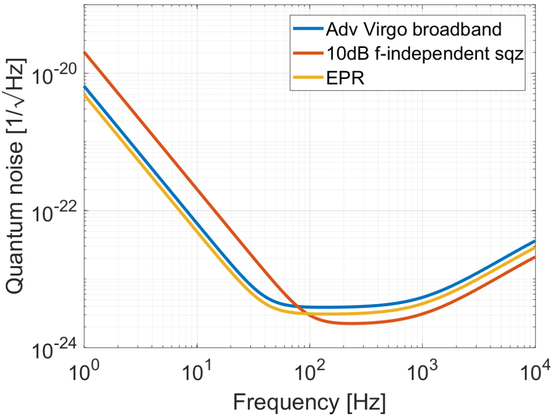


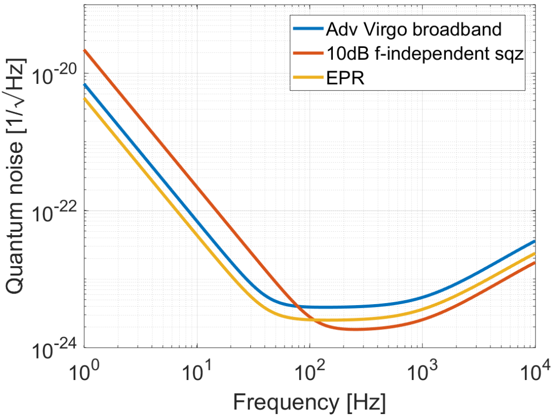
Sensitivity improvement with EPR entanglement

- AdV Virgo design configuration
  - 650 kW arm-cavity power
  - SR mirror in broadband configuration
- 24% losses (10.5% injection loss, 13% detection loss, O3 target)



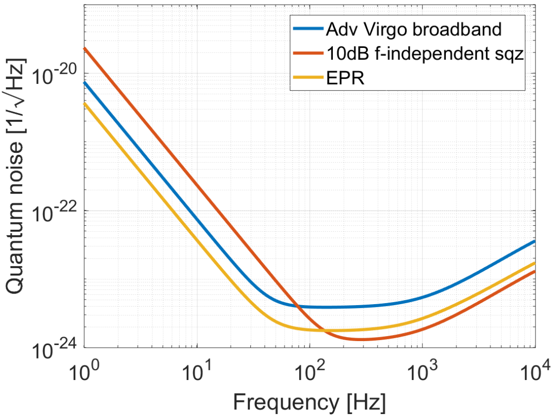
Sensitivity improvement with EPR entanglement

- AdV Virgo design configuration
    - 650 kW arm-cavity power
    - SR mirror in broadband configuration
- 12% losses (6% injection loss, 7% detection loss)



Sensitivity improvement with EPR entanglement

- AdV Virgo design configuration
  - 650 kW arm-cavity power
  - SR mirror in broadband configuration
- only ITF losses (100 ppm arm RTL, 2000 ppm Michelson RTL)



R&D on FIS worldwide

LIGO

- Quickly tested FIS injection, about 2 dB high$-f$ sensitivity gain
- Plan to install a short filter cavity, preliminary lab dfemonstration
- Theoretical proposal for EPR, no plans to install in LIGO, possible table-top experiment starting in Australia

GEO

- FID routinely operated with 90% duty cycle
- No plans about filter cavity
- Theoretical proposal for application of EPR in detuned configuration
- possible table-top experiment starting in Hamburg (Schnabel)

KAGRA

- Currently setting up long filter cavity (300 m, TAMA heritage)
- Started set-up of OPO squeezer (support from Virgo people)

R&D on FIS in Virgo

LAPP/LKB

- program on national funding to test a filter cavity at CALVA (50 m)
- developing a vacuum-compatible OPO squeezer (no news on current status)

NIKHEF

- will submit a funding proposal to national agency including the development of a filter cavity (300 m, KAGRA-like)

INFN

- OPO squeezer already operating (see J. P. Zendri's talk)
- proposal to test the EPR entanglement on current setup

Detector meeting on next Thursday to discuss post-O3 plans

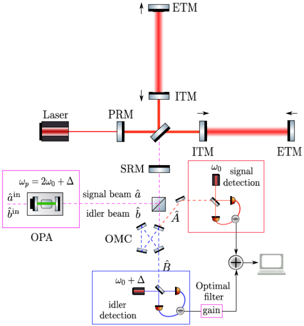
Optical setup

Already in the 1500W bench

1. Singly resonant OPO
2. Two lasers for OPO pump
3. One more laser for coherent control (to arrive soon)
4. SHG, green and IR mode cleaners
5. Phase modulators for SHG, MC and OPO locking

Missing components

1. Additional modulator for Δ freq. offset of OPO pump
2. OMC for separating signal and idler beams
3. additional OMC to filter HOMs from signal beam?
4. External reference cavity or ITF



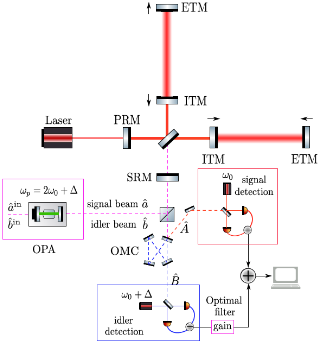
Electronic setup

Already present in the 1500W setup

- Drivers for the components of the OPO squeezer
  - PZT for cavity mirrors and phase shifters
  - Locking photodiodes
  - RF modulators
- Homodyne detector

Missing components

- Electronics for Δ offset OPO pump
- One more homodyne detector (indeed we have a spare)
- Electronics for OMC locking
- Wiener filter and mixer for combining the two homodyne detectors
- Control for the external cavity



Main additions to the 1500W setup

Non-degenerate OPO

Detune the pump frequency from the OPO resonance, to generate signal and idler beams with frequency separation Δ.

Detection

A single OMC to separate the idler and signal beams before detection. For the application to Virgo, it will be used to filter out HOM from the signal beam, while the LAPP OMC will separate signal from idler. We'll also need to duplicate our homodyne detector (the spare in Roma1 is ok). Finally we must set up the Wiener filter to optimally combine idler and signal.

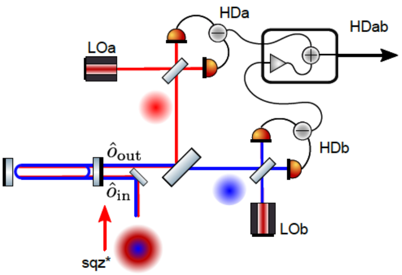
External cavity

Optical resonator to provide both the frequency-dependent rotation and the optical reference to demonstrate the broadband noise reduction before we can directly use the Virgo ITF.

Producing the frequency-dependent ellipse rotation

Requirements

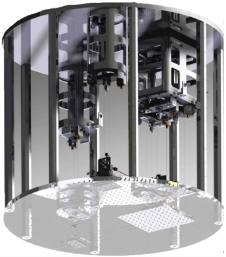
One needs an optical cavity to provide off-resonant frequency-dependent phase shift to the idler while the signal beam is resonant. In principle a simple Fabry-Pérot would do the job, choosing $\Delta \sim$ *fsr* or $\Delta \sim$ linewidth.



Use of the SIPS setup

The SIPS project

INFN Comm. 5 project on ponderomotive squeezing (SIPS, Call giovani 2016, PI L. Naticchioni). The Michelson interferometer with suspended arm cavities is designed to reach radiation-pressure limited displacement noise below the optical spring frequency. Cavity length 35 cm, finesse $15000 \div 3000$, end mirror masses 10 g, optical spring frequency 2 kHz with 2.5 W input laser power.



- radiation pressure noise below 2 kHz
- cavity pole around 15 kHz
- with EPR squeezing, noise reduction above 15 kHz and below 2 kHz

Possible implementation

Multi-step approach

There are different possible ways to test the operation of the EPR entanglement on the control of the squeezing ellipse, in principle we can proceed in steps of increasing complexity:

1. use a Fabry-Pérot with solid spacers to provide ellipse rotation and set up the conditional detection;
2. build a SRC with solid spacers to show the broadband sensitivity enhancement with detuned SR as in GEO.
3. integrate the SIPS setup (see next slide), if meanwhile it reaches radiation pressure limited displacement noise.

Upgrades on the OPO squeezer

Mitigation of noise sources

In the end we should produce a system ready for injection in the Virgo ITF. While setting up the conditional detection for EPR entanglement and the external cavity for ellipse rotation, we will work on improvements to the current bench at 1500W, aimed at minimising light scattering and reducing phase noise;

Development of compact bench

In parallel we might develop a compact version of the optical bench, to be implemented for the injection in Virgo ITF, possibly in cooperation with GEO.

Mitigation of optical losses

Main limitations with the EPR entanglement will be from optical losses. We plan to work on lossless components and to study adaptive optics methods for minimising optical losses (see talk by J. P. Zendri).

Time schedule

2018

- Preparation of OMC, ellipse rotation cavity, and optical setup for conditional detection.
- Non-degenerate OPO pumping.
- Scattered light reduction
- Design of the compact optical bench.

2019

- Implementation of the EPR scheme using a Fabry-Pérot with rigid spacer.
- Prepare the integration of SIPS.
- Mitigation of optical losses, development of in-vacuum components.

2020

- Demonstration of frequency-dependent squeezing and optimisation of noise reduction
- Prepare the compact optical bench for injection in Virgo

Cost estimate

Item	Cost	Notes
Non-degenerate OPO	5 kEuro	1 month
OMC	30 kEuro	4 monts
Rotation cavity	30 kEuro	$\sim$twice if we go for the SRC
New electronics	30 kEuro	Cavity controls, Wiener filter
Optical components	40 kEuro	including optomechanics
Total cost	$<$ 150 kEuro	

Conclusions

- FDS is the most promising tool to improve 2nd generation detectors beyond design sensitivity
- we should target to operate in O4
- CNRS and NIKHEF have plans about filter cavities, projects have substantial risk
- EPR entanglement is a solid alternative, with several scientific and technical advantages
  - lower cost and complexity
  - avoid issues with cavity losses
  - operation flexibility (works for many SRC configurations)
- we have the chance for a low-cost test of EPR entanglement
  - best exploitation of the INFN investment for the 1500W setup
  - several (young) people with experience in quantum optics in Virgo
  - interesting research topic to strengthen the cooperation with GEO and possibly to attract external fundings (see also the Quantum Flagship)

The End