ET R&D: squeezing source and injection

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Referee meeting - 7 Settembre 2021

Quantum Noise Reduction fo ET

- Quantum Noise Reduction strategies in ET-LF cannot be directly mutuated from current room-temperature detectors:
  - Different wavelength (ET-LF-wl), in the process of being decided (new materials. coatings, light sources...)
  - Extremely-low frequency requirements (~1 Hz) compared to current detectors (10s of Hz)
- An international QNR working group exist inside the ET-ISB:
  - Co-chairs: **G. Ciani** and H. Vahlbruch
  - Scope of the WG is quite extensive: source development, frequency-dependent readout implementation, loss reduction, control schemes, etc…

- Goals of the research program proposed by the italian groups:
  - **Support QNR choices for ET:**
    - light TDR ~2023, full TDR ~2025 → urgent to answer some questions
  - **Develop (some of the) necessary technologies**
    - leveraging extensive italian community experience with QNR in AdVirgo
  - **Validate and test solutions**
  - **Explore longer term improvements**

Plan overview

	Line	Comment	k€ 2022	k€ 3-years
LLF	**Low-Loss Faraday Isolators**	essential component; needs adaptation to ET-LF-wl	**32**	72
BHD	**Balanced Homodyne Detector**	needs to be adapted to ET-LF-wl; an innovative shift to all-digital electronics will also be investigated.	**66**	184
PNR	**Phase Noise Reduction**	extension and improvement of the current effort to reduce phase noise between squeezed field and main laser to match tighter ET-LF requirements.	**0**	70
EPR	**Frequency Dependent Squeezing via EPR-entanglement**	squeezing-angle rotation in ET-LF requires ingent infrastructures. EPR entanglement as an alternative solution not fully addressed and discarded yet.	**50**	110
SPN	**Backaction-evading Readout based on Entanglement of Spin Systems**	longer term research; potentially very advantageous.	**20**	60
SRC	**Squeezing Source adaptation to ET-LF-wl**	necessary to enable the entire research program; innovative solutions will also be explored.	**85**	240
	Mode-matching	extremely important to reduce losses; developed in a broader context (WSC - See Alessio Rocchi's presentation)	**0**	0

Low-Loss Faraday Isolators (GE)

- Faraday isolators may represent a major contribution to optical losses along squeezed beam path
  - Several FIs required to get rid of noise from backscattered light
  - AdV+ FIs developed by EGO achieve **>99.5%** throughput with **40 dB optical isolation** @1064 nm
  - Similar (or possibly better) performance is desirable for ET
- R&D plan to develop high throughput FIs @ET-LF-wl
  - Selection and test of materials (polarisers, Faraday crystals)
  - Development of control methods to minimize the impact of polarisation errors, thermal and magnetic gradients

Milestone or Deliverable	Descrition	Estimated date
LLF.M1	Optical materials selected and characterized	2022-S2
LLF.D1	Complete low-loss faraday isolator prototype	2024-S2

Task	2022-S1	2022-S2	2023-S1	2023-S2	2024-S1	2024-S2
LLF.1		LLF.M1				
LLF.2						
LLF.3						
LLF.4						LLF.D1
Approx cost (k€)	32		20		20	
	optical components, sensors and laser		PCB prototyping electronic components, optics, detectors.		electronic components, optics, detectors, and mechanics for the final prototype	

ET- SQZ R&D BHD (RM1, PG)

We propose to realize the Balanced Homodyne Detector for ET:

- essential to characterise squeezing level (and for EPR implemetation).
- long-time experience in developing Balanced Homodyne Detector (BHD) for SQZ.

We intend to:

- ***adapt the current electronics readout to ET requirement and ET-LF-wl***
- ***Investigate an all-digital electronics design, exploring advantages and challenges.***

List of tasks:

- Task BHD.1: selection of QE photodiodes at ET-LF-wl (RM1)
- Task BHD.2: adaptation of existing electronic readout system (PG, RM1)
- Task BHD.3: testing of photodiodes, circuits and integrated HD with ET-LF-wl laser source (RM1, PG)
- Task BHD.4: noise optimisation (clearance, CMRR, Visibility) (RM1)
- Task BHD.5: design of mechanical support for the electronics and optics (RM1)
- Task BHD.6: noise mitigation with automatic alignment (PG, RM1)
- Task BHD.7: design of ultra-low frequency homodyne digital circuits (PG)

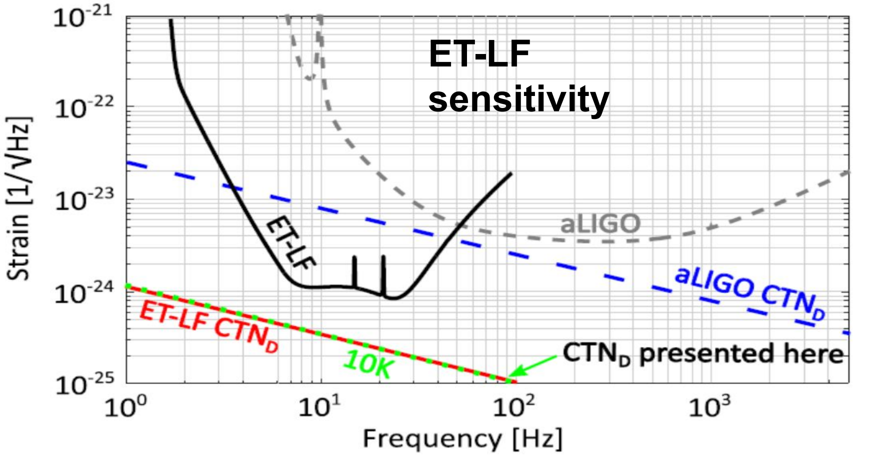
ET- SQZ R&D BHD (RM1, PG)

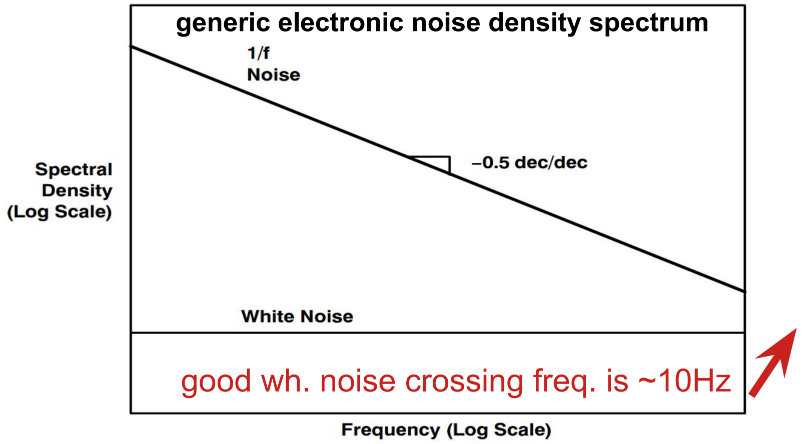
Issues addressed by all-digital design:

- 1/f noise
- parameters drift due to components aging

Construction steps:

- circuit topology design
- ADC selection
- prototype construction & tests
- performance characterisation with efficient PDs





ET- SQZ R&D BHD (RM1, PG)

At the end of 2022 we expect to have individuated digital electronics and in 2023 the best photodiodes

Estimated overall costs for 2022: 66 k€

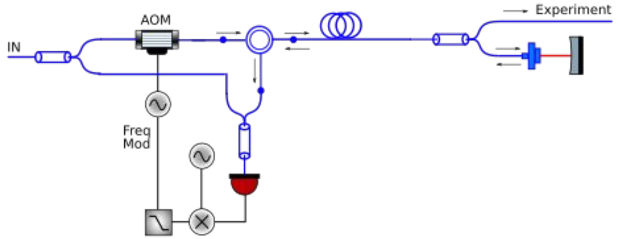
Roma 1 asks for: 40 k€

QNR.BHD.1	QE photodiodes for ET-LF-wl	15 k€
QNR.BHD.2	PCB and electronic components	5 k€
QNR.BHD.3	Optics for tests	5 k€
QNR.BHD.3	laser source at ET-LF-wl	10 k€
QNR.BHD.4	Instrumentations for test	5 k€

Perugia asks for: 26 k€

QNR.BHD.7	design of ultra-low frequency homodyne detector	15 k€
QNR.BHD.7	design of ultra-low frequency homodyne detector	10 k€
QNR.BHD.7	missioni per i test del circuito nei laboratori esterni	1 k€

Phase Noise Reduction (PD)



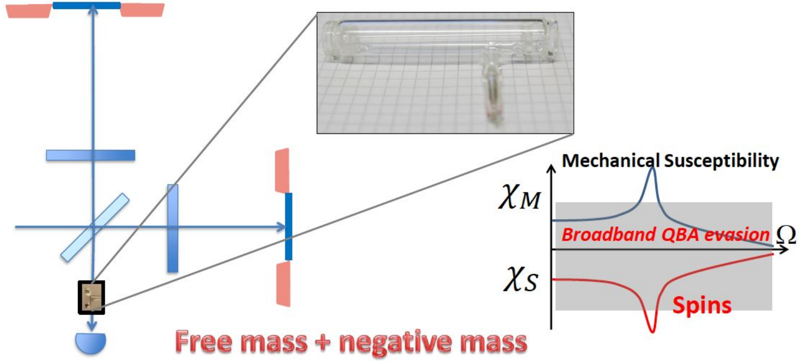
- **Development and optimization of feedback loops for the suppression of the fiber phase noise.**
  - phase-locked lasers placed at large physical distances. Laser light delivered via optical fibers.
- **Development of PLL electronic boards able to operate in the in the GHz range**
  - lasers phase locked with GHz-range frequency offset, well above the PLLs developed so far for AdV+
- **Development and test of new schemes (based on EOM and AOM) and actuators to improve bandwidth and range**
  - PLL and squeezing ellipse angular jitter control schemes currently limited by actuators bandwidth.
- **Small scale test of overall phase noise performance achievable**
  - Optical cavities used to rotate the squeezing ellipse are controlled with auxiliary lasers phase-locked to squeezing main laser.

Details of the research program depends on ET-Project requirements that have not been defined yet.
No funding request for 2022.

Task	2022-S1	2022-S2	2023-S1	2023-S2	2024-S1	2024-S2
PNR.1						
PNR.2					PNR.D	
PNR.3				PNR.M		
PNR.4						
PNR.5						
Approx cost			40		30	

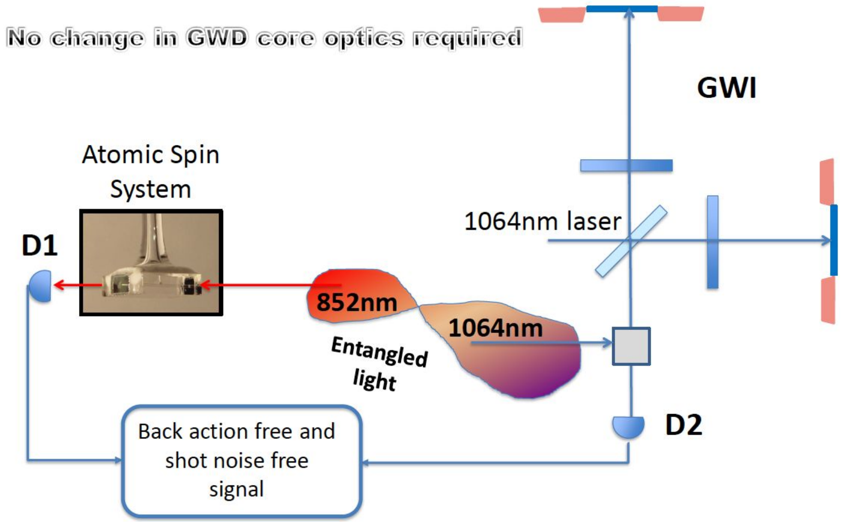
SPN (GE)

- Filter cavities: low-freq. extra losses and lage infrastructure cost
- EPR: 3-dB loss penalty due to the detection of two independent fields
- Alternative proposal: use entanglement with a squeezed atomic spin system
  - Single field injected into dark port of interferometer
  - SFG+PDC to entangle such field with a laser probing atomic spin system
  - No 3-dB penalty, no special infrastructural requirements
  - PRL 121, 031101 (2018)



$$X_-(t) = X(t) - X_0(t) = X - X_0 + \frac{Pt}{m} - \frac{P_0 t}{-m} = X_- + \frac{P_+ t}{m}$$

$$[\hat{X}_-, \hat{P}_+] = 0 \Rightarrow \Delta X_- \Delta P_+ \geqslant 0 \Rightarrow [\Delta X_-(t)]^2 \geqslant 0 \quad \text{(EPR)}$$



SPN (GE)

- A group (outside ET community) is already developing such scheme (E. Polzik @ Copenaghen)
- Demonstrated 8 dB entanglement and 4.6 backaction suppression [Nat. Phys. 17, 228 (2021)]
    - Actions to make such technology competitive for ET:
        - improve the squeezing level of the spin system (up to Polzik group)
        - further improve the level of entanglement
        - remove low-frequency noise sources

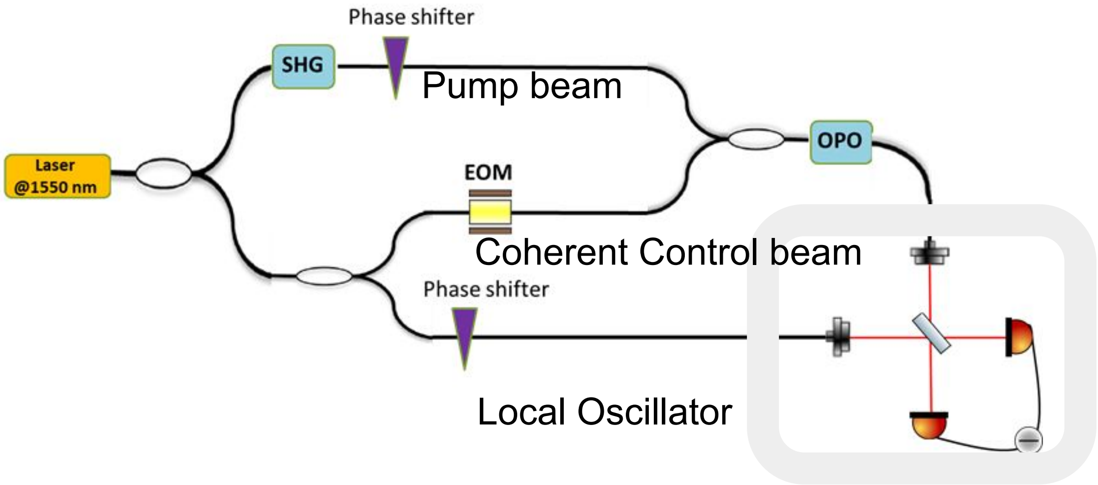
- **Plan is to provide key R&D for possible implementation at ET-LF-wl and audio frequencies**
    - Task SPN.1: demonstration of entanglement between photons at LF wavelength and spin system (GE)
    - Task SPN.2: demonstration of conditional squeezing at audio frequencies (GE)

Milestone or Deliverable	Descrition	Estimated date
SPN.M1	Demonstration of entanglement between photons and spin	2023-S2
SPN.M2	Demonstration of conditional squeezing at audio frequencies	2024-S2

Task	2022-S1	2022-S2	2023-S1	2023-S2	2024-S1	2024-S2
SPN.1				SPN.M1		
SPN.2						SPN.M2
Approx cost (k€)	20		20		20	
	Optical components for entanglement measurement; electronics for controls		Optical components for entanglement measurement; electronics for controls		Optical components for entanglement measurement; electronics for controls	

SRC: compact fibered squeezing source (NA, GE)

We want to use the acquired experience in the field of gravitational wave detectors to produce the first integrated squeezer in audio-band.
Encouraging results (squeezing measurement in radio-band): Photonics Research, vol. 7, no. 7, pp. A36{A39 2019}



- Laser source @1550 nm + Erbium Doped Amplifier
- SHG and OPO: periodically poled waveguided crystals
- in-fiber EOM
- integrated homodyne detector
- fiber stretcher to control pump and LO phase in order to have squeezing in audio-frequency band

- **2022: initial tests on fibers and crystals**
- Full development of the source will take several years
- At a later stage, we will investigate the integration of a photonic-crystal cavity

QNR.SRC.4	FIber components	20
QNR.SRC.4	fiber-coupled laser source at LF	5
QNR.SRC.4	Erbium Doped Fiber Amplifier (EDFA)	7
QNR.SRC.4	Fiber stretchers	
QNR.SRC.4	wave-guided crystals	8

SRC: adaptation of current squeezing source to LF wavelength

SQueeZing source @ET-LF wavelegth: production and characterization (optomechanical design already available)

→ Choice of the best crystal

→ Comparison between different material (bulk and doping)

QNR.SRC.1	Nonlinear crystals for OPO	15
QNR.SRC.1	Optics for OPO cavity	15
QNR.SRC.2	Electronics and sensors for controls	15
QNR.SRC.3	Optics for squeezing measurement	

- **2022s1:** crystal and cavity mirrors procurement
- **2022s2:** OPO and OPO characterization facility assembling*
- **2023-2024s1:** test with several crystal (parametric gain and intracavity losses characterization)
- **2024s2** : integration in the SQUEEZING EPR squeezing setup

Master thesis

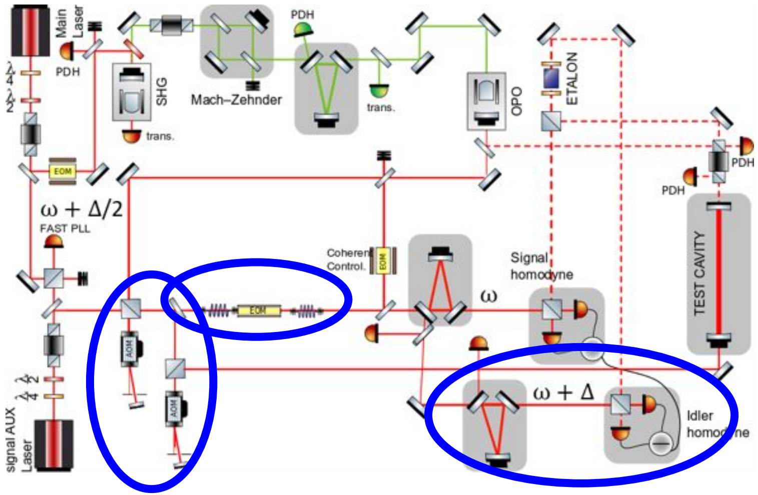
PhD thesis *(Quantum Information and Technologies Doctorate School)*

- *Test facility for parametric and intracavity losses measurements*
- *Scheme based on doubly resonant OPO*
- *Same cavity for all crystal tsts: OPO cavity mechanics is such that the crystal can be easily replaced without misalignment (already tested).*
- *Plan to test three material already individuated*
- *(KTP, BBO LNB) with several dopant concentration. Indicative cost for ready-to-use crystal (poling, polishing) ~ 2.5Keuro.*

EPR squeezing ET-LF-wl (NA, GE)

Frequency dependent squeezing for GW detectors via EPR entanglement described in Ma, Yiqiu, et al. "Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement." *Nature Physics* 13.8 (2017): 776-780. The technique has been already tested in table-top demonstrators @1064 nm: Yap, Min Jet, et al. "Generation and control of frequency-dependent squeezing via Einstein–Podolsky–Rosen entanglement." *Nature Photonics* 14.4 (2020): 223-226. Südbeck, Jan, et al. "Demonstration of interferometer enhancement through Einstein–Podolsky–Rosen entanglement." *Nature photonics* 14.4 (2020): 240-244.

Improved demonstrator (@1064) funded as part of the AdVirgo project under development @EGO



We want to reproduce the EPR set-up to produce conditional squeezing at ET-LF-wl:

OPO Source (see previous slides):
- PDH locking system
- Fibered EOM (for improved range)
- Fast photodiodes (GHz)

EPR set-up
- Double BHD and Mode cleaner

QNR.EPR.1	Electronics and sensors for non-degenerate OPO control	25 k€
QNR.EPR.2	Optics for EPR demonstrator	25 k€

ET R&D:
stray light mitigation

G. Ciani, L. Conti

Referee meeting - 7 Settembre 2021

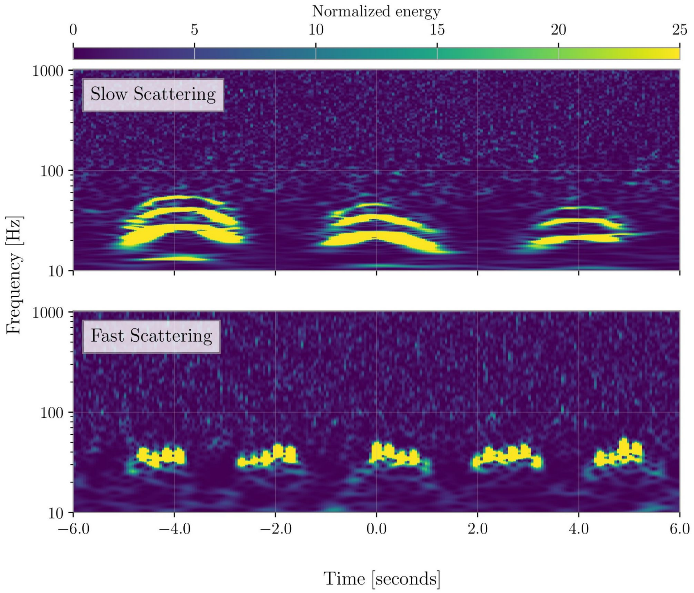
Stray light noise

The problem of stray light is a major issue at low GW frequencies and must be tackled to make ET sensitive down to 2 Hz.

A 3-step process:

1. **Producing stray light:**
   a. **imperfections on the optical surfaces or bulk material**
   b. **dust particles or residual gas**
   c. undumped secondary beams (ghost beams)
2. Picking up phase noise: reflection off surfaces moving wrt suspended optics
3. Recoupling: recoupling with main beam adding phase noise

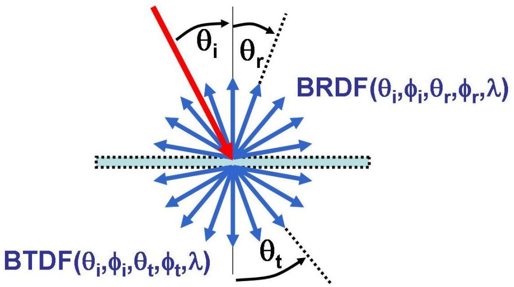
Scattered light arches due to upconversion of vibration noise via phase wrapping in the interference of scattered and main field.



From arXiv:2103.12104v

ET-Italia Plan

Bidirectional Scattering Distribution Function (BSDF):



Measure scattering from optical components and dust contamination at ET-LF wavelengths to correctly inform: estimates, simulations, procurement requirements and cleanliness practices and procedures.

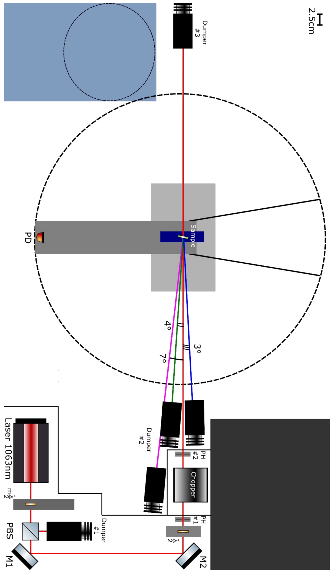
A BSDF measurement facility for Virgo is already under development at PD

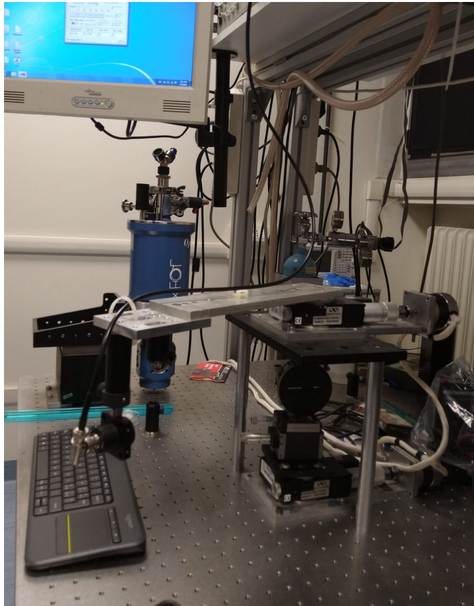
ET-related tasks:

1. **Upgrade facility for 1550nm (2022) and 2µm (2023)**
2. **Procure and test samples of interest for ET (2023→)**

Note: the facility will also be used to characterize scattering properties of new coatings being developed for ET

Task	2022-S1	2022-S2	2023-S1	2023-S2	2024-S1	2024-S2
SLM.1		SLM.M1				
SLM.2				SLM.M2		
SLM.3						
SLM.4				SLM.M3		
Approx cost (k€)	8		12		5	
	1550nm laser head (controller available from Virgo), optics and components, detectors, cleaning material.		2um laser head, optics and components, detectors; samples. Ionizing gun.		Samples	





Extra slides

ET- SQZ R&D BHD

We have a long-time experience in developing Balanced Homodyne Detector (BHD) for the detection of the squeezing. The current BHD used for the detection of the frequency dependent squeezing (FDS) in Virgo has been realized in collaboration between Roma1 (optics, mechanics, electronics) and Perugia (electronics).

Homodyne Detector for FDS of AdVirgo+

Characterized in Rome (July – Oct 2020):

- Clearence **17 dB** at 3.7mW of input power
- CMRR 60 dB

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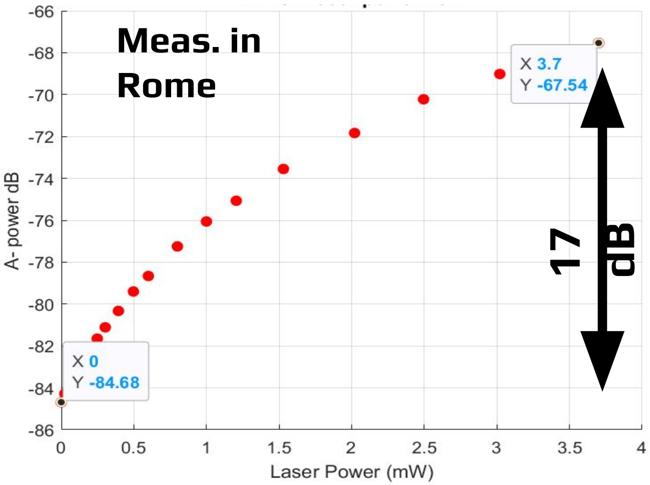
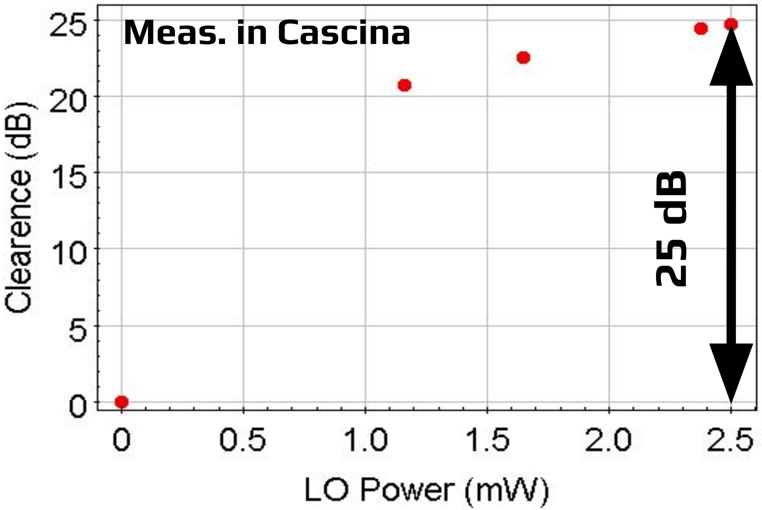


Installed at Virgo Nov 2020:

- Clearence **25 dB** at 2.5mW with LO max input power
- CMRR 40 dB



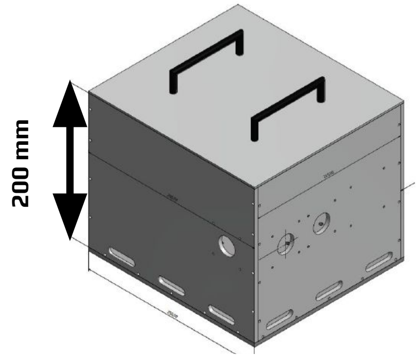
ET- SQZ R&D BHD

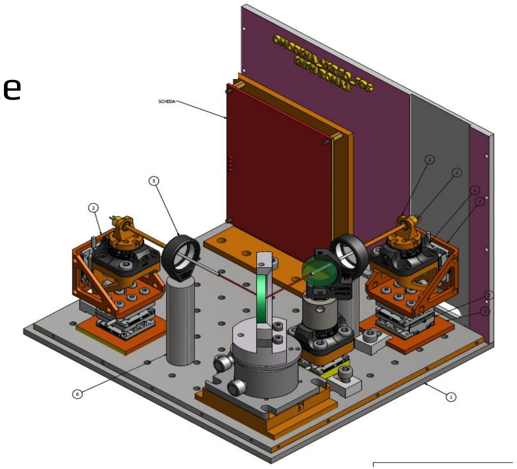
Homodyne Detector for FDS of AdVirgo+

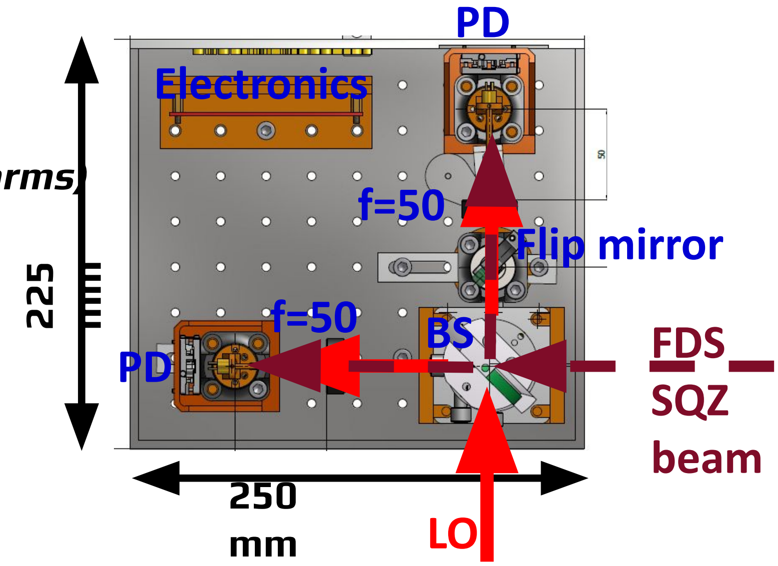
Upgrade of the circuit designed and used for the squeezing R&D bench at 1500W:

- Self-subtraction scheme for the difference channels
- Low noise electronics and 500μm high QE photodiodes connected by shielded cables
- 2 DC, Audio sum and difference (10Hz-100kHz) Radio difference (1-100MHz)
- ***New optical design (same number of optics on both arms)***
- CAD designed in Rome
- Anodized box to shield the circuit from EM disturbance

HD detector measures the level of produced squeezing w.r.t a bright local oscillator (LO)







Flip mirror:
used to fine tune the overlap of the 2 beams on CCD cameras

VIR-0698A-20 https://tds.virgo-gw.eu/ql/?c=15823