Status of the frequency dependent squeezing experiment at TAMA

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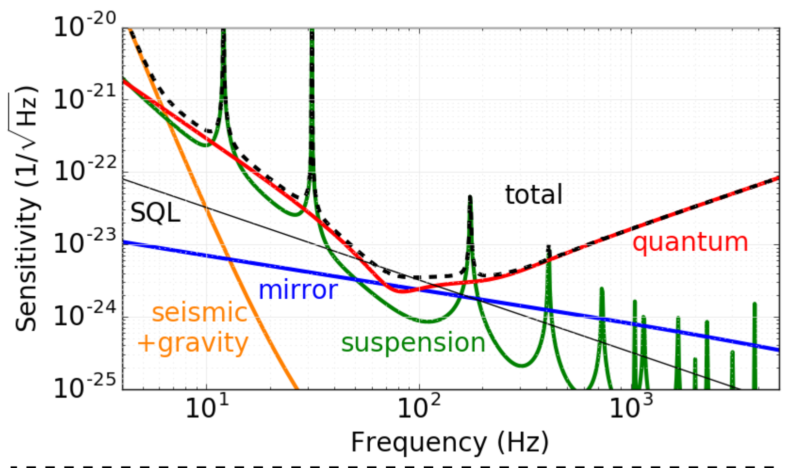
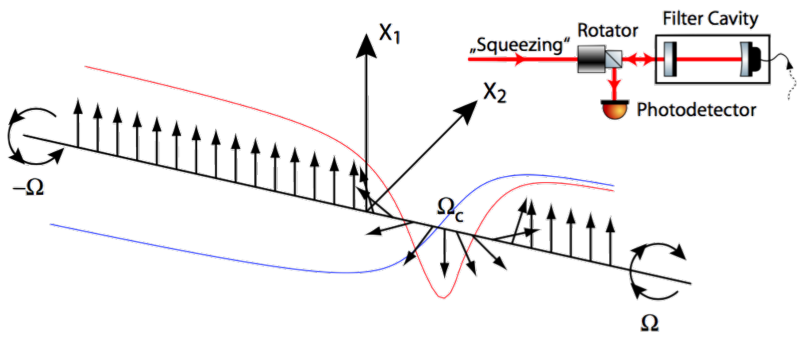
Squeezing and gravitational wave detector

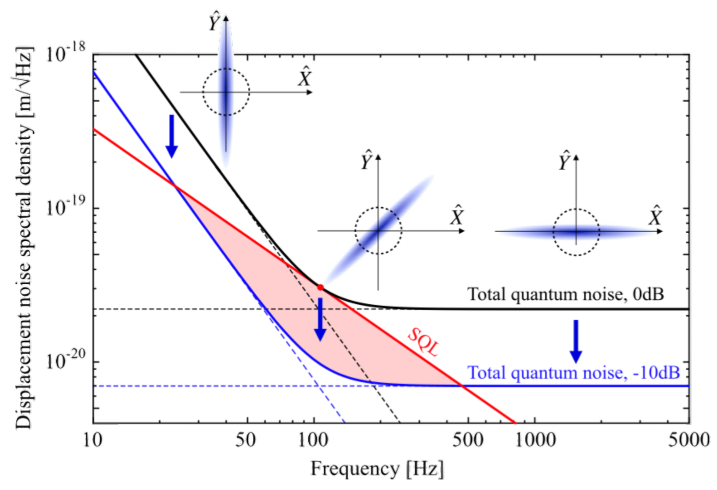
Quantum noise has already been the limiting noise for gravitational wave detector especially at high frequency. Squeezing is proven to be effective for reducing quantum noise and has already been used for O3.



Quantum noise is expected to limit KAGRA sensitivity in almost the whole spectrum.
Quantum noise can be reduced by injecting squeezing inside the detector.



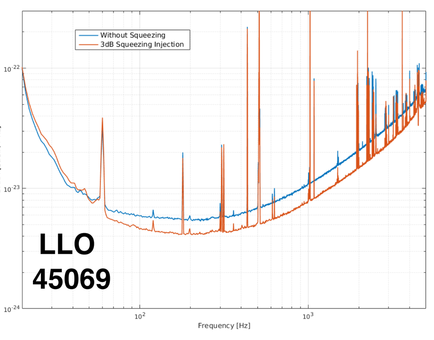
Filter cavity will change the phase of squeezed sideband to achieve frequency dependent squeezing.

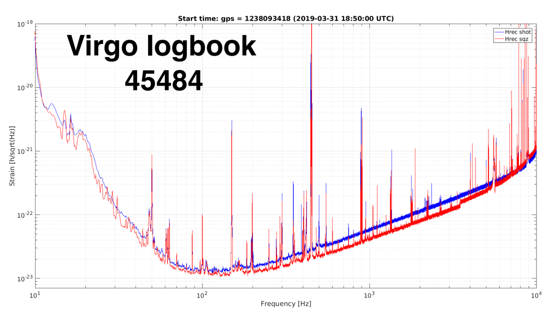


Low frequency quantum noise is due to radiation pressure noise and can be mitigated by amplitude squeezing.
High frequency quantum noise is due to shot noise and can be mitigated by phase squeezing.

Frequency independent squeezing:

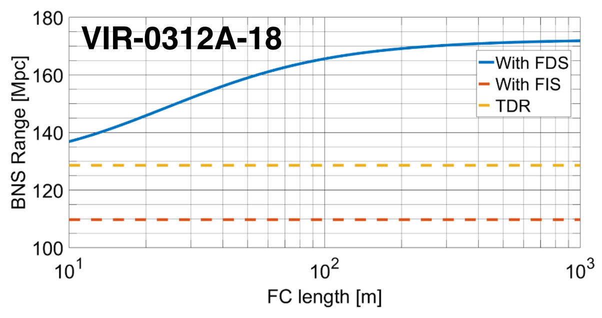
Now frequency independent squeezing is used for O3. LLO and Virgo sensitivity with and without squeezing are shown below.





Frequency dependent squeezing:

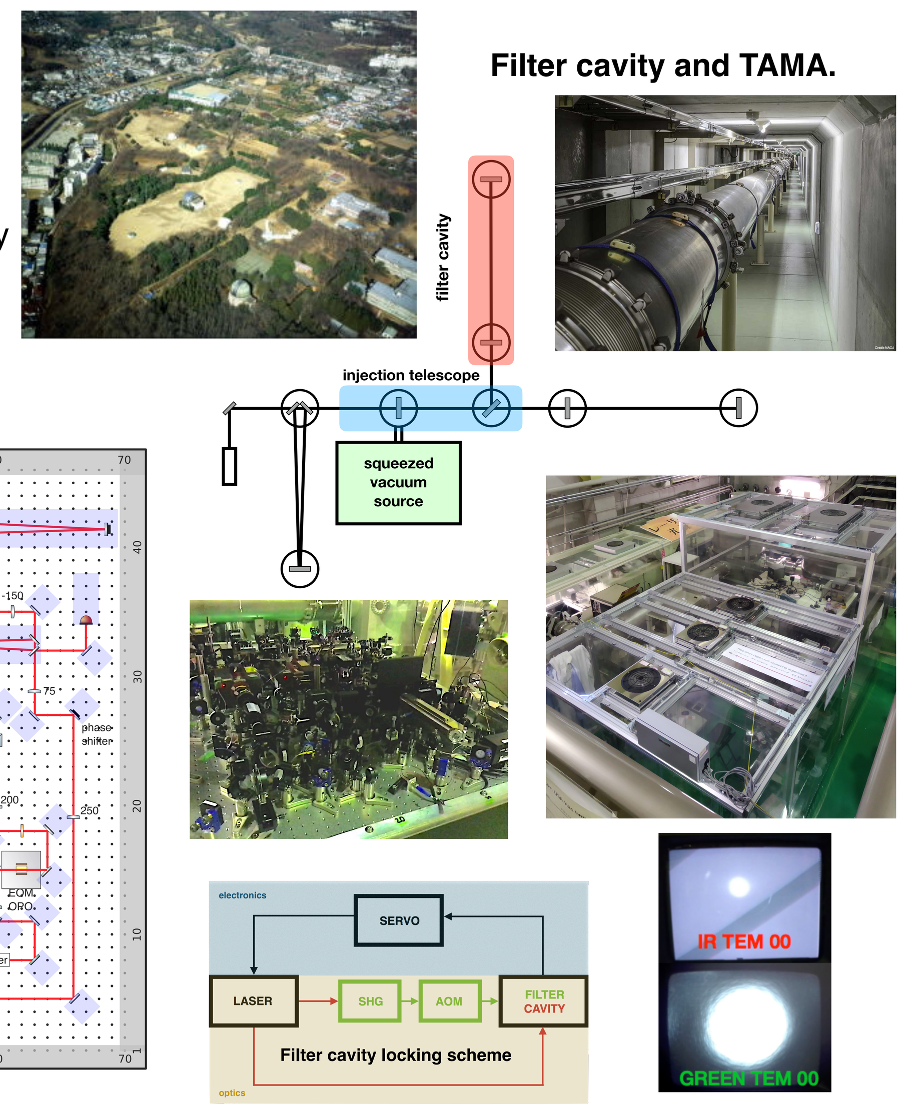
It is planned for O4 in LIGO and Virgo and is one of the candidate future upgrade plan for KAGRA. The optimal length should be hundred meter scale.

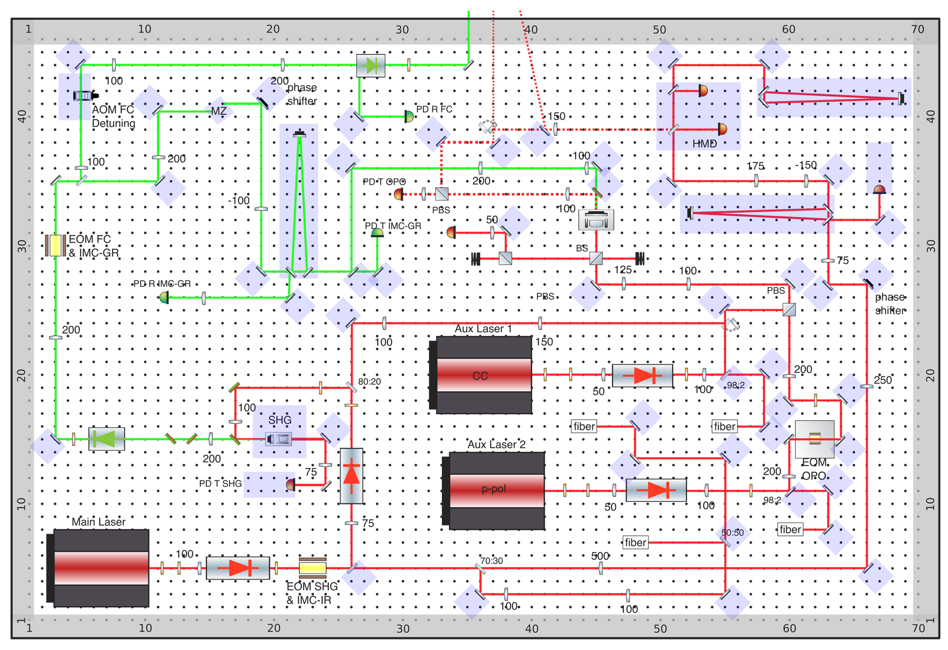


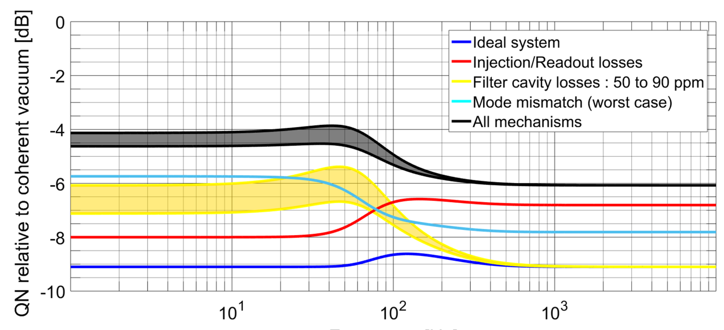
Project overview

Goal of experiment

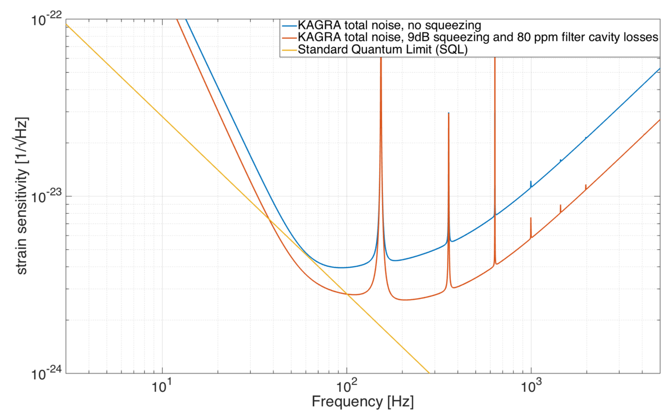
Full scale filter cavity prototype to demonstrate frequency dependent squeezing with rotation at ~70Hz.
1. Cavity length: 300m
2. Finesse: 4400 @1064nm
3. Storage time 2.8ms @1064nm







Squeezing degradation budget. Quantum noise relative to coherent vacuum in the signal quadrature for an ideal system (blue curve) is compared that with squeezing, taking into account degradation mechanisms (one by one).



Improvement in KAGRA sensitivity using 9 dB frequency-dependent squeezing, considering lossy cavity and other degradation mechanisms.

Status

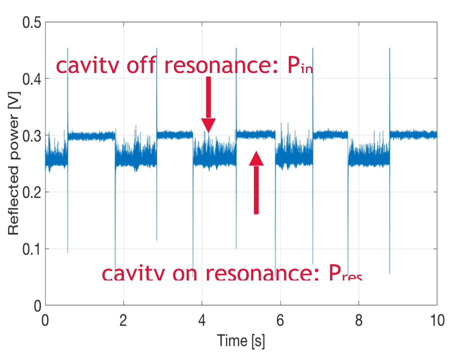
- •Filter cavity installation, control and characterization has been achieved
- •Squeezed vacuum source installation has been finished
- •4.4dB of squeezing and 15dB of anti-squeezing has been measured
- •Commissioning of the squeezed vacuum source is on-going
- •KAGRA-like DGS system implemented
- •Automatic alignment system design is finished

On-bench cavity parameters and control servo:

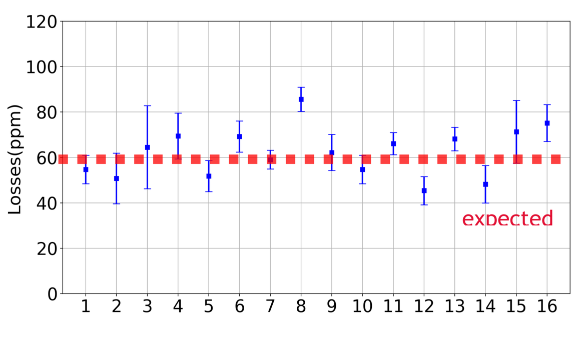
SHG and OPO have design Finesse of 70. Mode cleaners have design Finesse of 400.
We use seven different analog servos to control cavities length, pump power and phase fluctuation and LO phase fluctuation in the in air bench. They are all analog servos. The unity gain frequency of each loop is designed to be around several kHz.

Filter cavity losses measurement:

Assuming we know reflectivity and transmissivity of input mirror, we could get the information of losses by measuring the reflected power while cavity is on/off resonance.

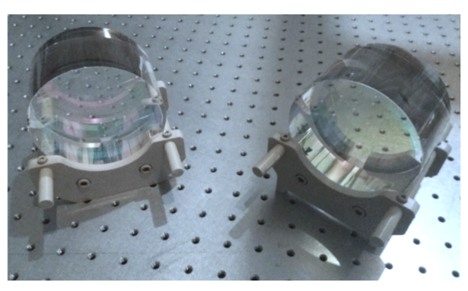


The measurement is the ratio of filter cavity reflection on/off resonance.



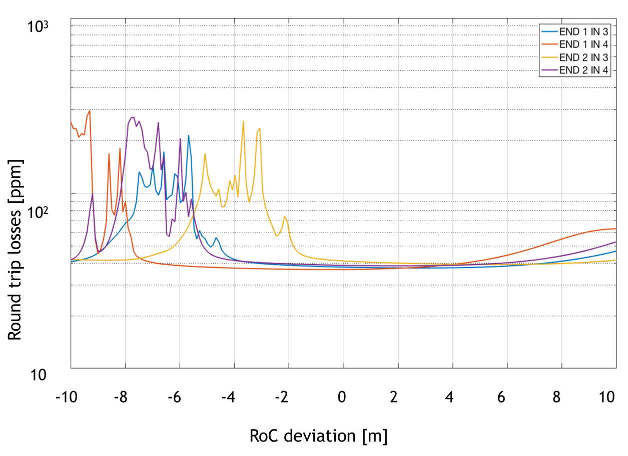
We performed measurement many times. The difference is due to different alignment condition.

Filter cavity mirror characterization:



Filter cavity mirrors have been characterized by LMA. The data is shown on the right side.

Mirror	diameter 0.05 m		diameter 0.02 m	
	RMS (nm)	PV (nm)	RMS (nm)	PV (nm)
#1	1.96	11.5	0.52	3.28
#2	2.09	12.2	0.52	3.28
#3	1.5	8.3	0.48	3.36
#4	1.94	14.8	0.48	3.28

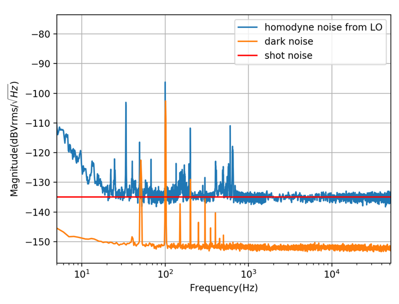


Loss estimation

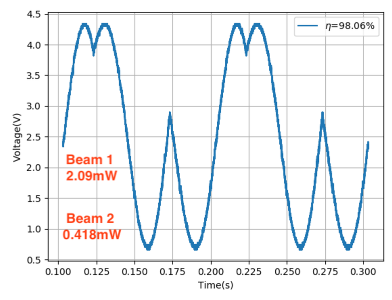
- ~ 40 ppm from flatness (simulation)
- ~ 15 ppm from roughness and point defect (measured)
- ~ 5 ppm from absorption and transmission (measured)
- Total expected loss is 60ppm.

Homodyne detector: The homodyne is realized under the calibration with AEI. When we send LO inside homodyne, we could see noise is limited mainly by shot noise. The peaks are mainly related with seismic and acoustic noise since now we didn't float bench and apply acoustic shield. Homodyne has a clearance of 15dB now.

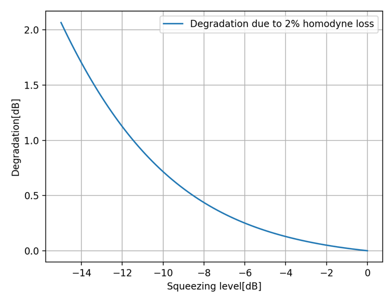
Homodyne noise spectrum while LO incidence

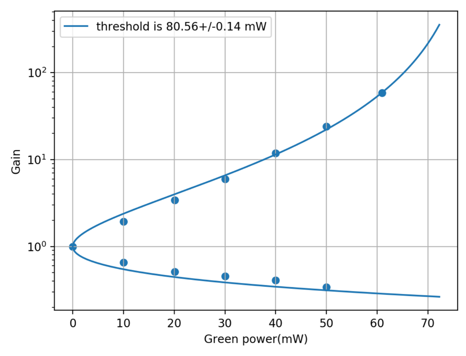


Alignment situation of homodyne

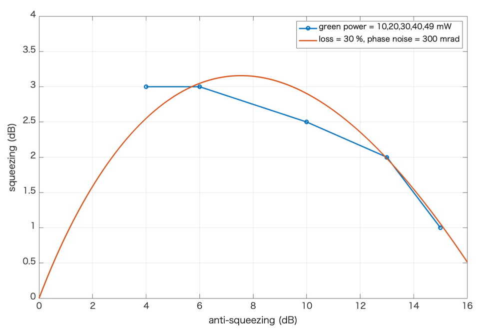


Degradation of squeezing in current homodyne



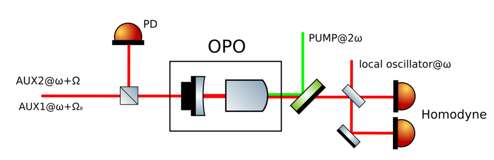


Parametric amplification and de-amplification measurement. It is a reference for the expected squeezing we should have.

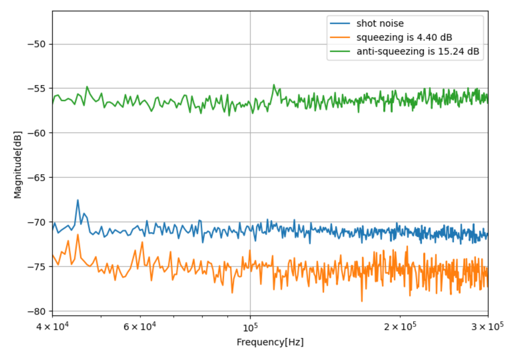


By assuming phase noise of 300 mrad and total loss of 30%, we could explain the squeezing we measured for each pump beam power. There are long way to improve.

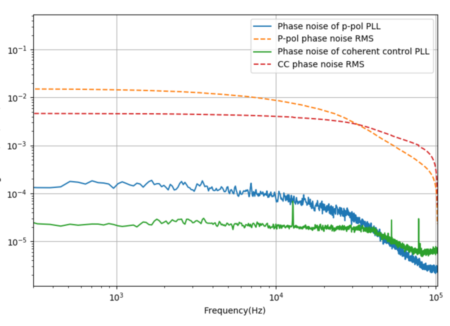
Squeezing and coherent control: Coherent control is used to stabilize the phase noise of squeezing.



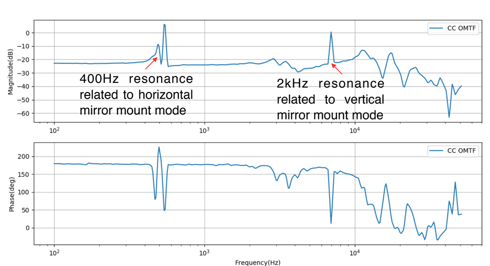
Coherent control scheme is shown on the left side.
OPO reflection PD is used to sense green pump phase.
OPO transmission homodyne is used to sense local oscillator phase.



We locked coherent control loop with a very low unity gain frequency(around 80Hz). With the locking of this loop, we could average noise spectrum of homodyne. We could see 4.4dB of squeezing in the 10kHz region.



On the left side, the measurement of PLL phase noise is shown. This phase noise will directly affect squeezing. The p-pol PLL has a residual phase noise of about 15mrad while the CC PLL has about 5mrad of phase noise.



On the left side, it shows opto-mechanical transfer function of coherent control loop. Peaks at around 400Hz and 2kHz are present. Those peaks limit the achievable bandwidth of the coherent control loop. The peaks come from the mechanical modes of the actuators.

Next step

- **•Squeezed vacuum source improvement**
- **•Installation of filter cavity automatic alignment**
- **•Injection of squeezing into the filter cavity**

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