Frequency dependent squeezing experiment at TAMA

N. Aritomi, Y. Zhao, E. Capocasa, Y.-C. Huang, C.-M. Wu, R.-K. Lee, H. Vahlbruch, H. Lück, Y. Guo, M. Tacca, Y. Aso, R. Takahashi, P. Prat, M. Barsuglia, E. Polini, M. Eisenmann, R. Flaminio, M. Leonardi

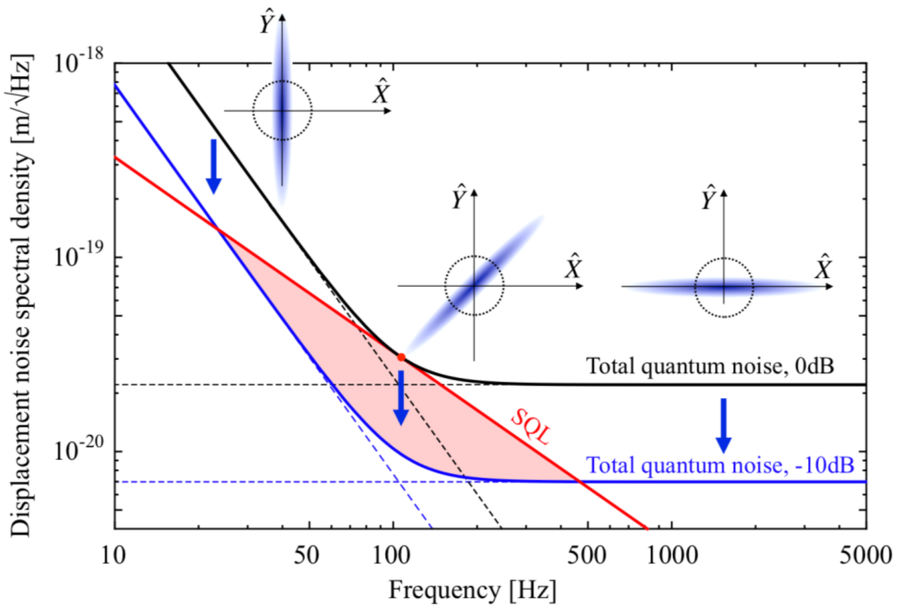
Supported by the JSPS Grant-in-Aid for Scientific Research (Grant code 15H02095 & 18H01235)

Talk summary

1. Why we do what we do
   (Relevance of frequency dependent squeezing for GW detectors)
2. How we should do what we do
   (Theory, project layout and targets)
3. What we do in the lab in reality
   (Implementation details and intermediate results)
4. Results we do get

Quantum noise in GW detector

<u>The sensitivity of gravitational wave detectors will soon be limited for all frequencies by quantum noise</u>

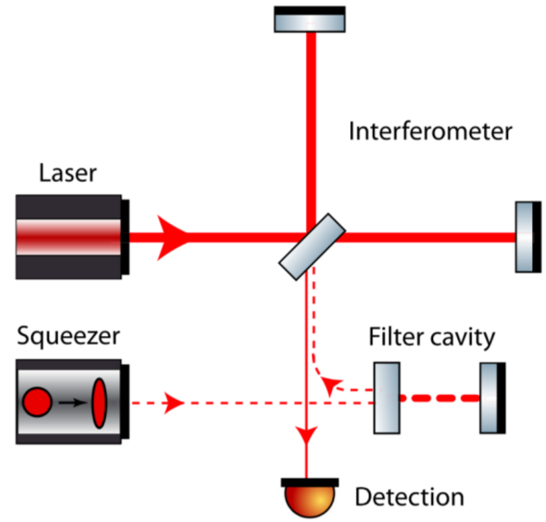


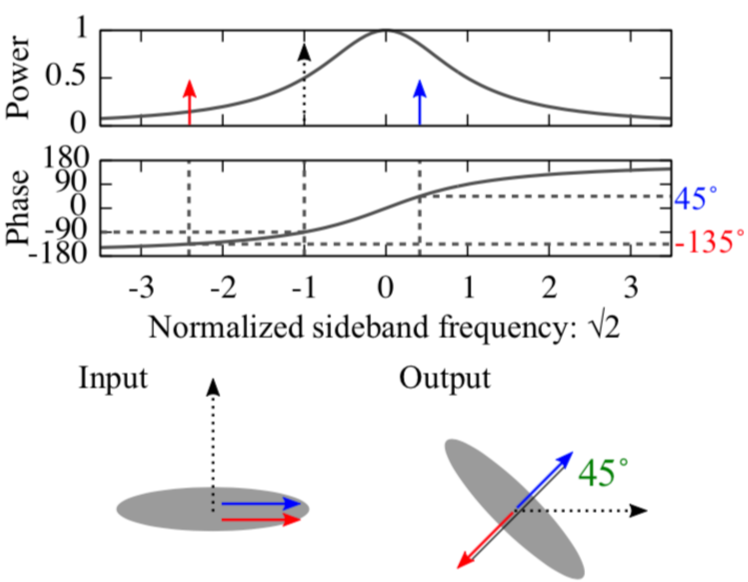
To achieve broadband quantum noise reduction, injection of frequency dependent squeezed vacuum (which is phase squeezed at high frequency and amplitude squeezed at low frequency) is required

Frequency dependent squeezing production

To realize frequency dependent squeezing, we reflect frequency independent squeezing off a detuned Fabry-Perot cavity, called Filter Cavity

(H. J. Kimble et al, PRD 65, 022002 (2001))



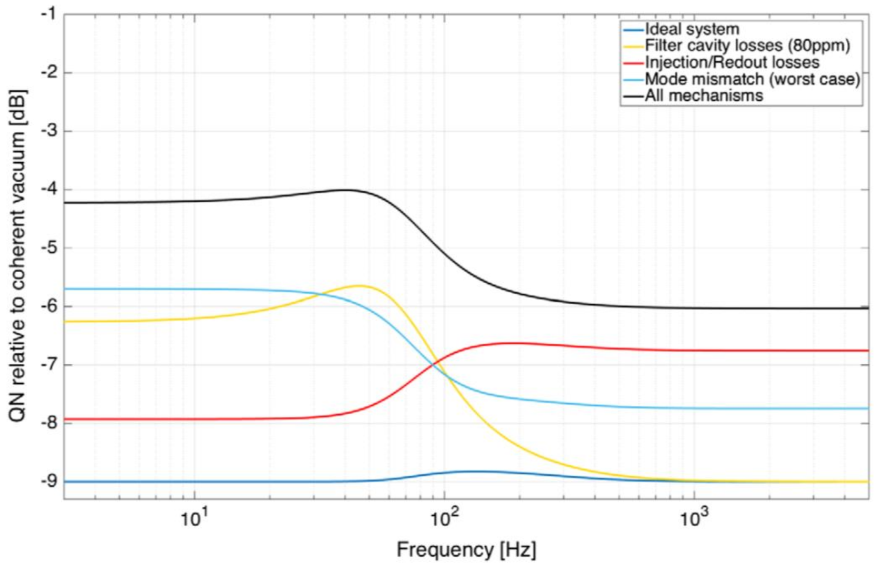


Upper sideband and lower sideband experience different phase rotation → squeezing angle rotates around detuning frequency

Goal of the experiment

Achieve frequency dependent squeezing (squeeze angle rotation around 70 Hz) by reflecting 9dB of frequency independent squeezing off a 300 m long filter cavity

Squeezing degradation budget:



Parameter	Symbol	Value
Filter cavity losses	Λ^2_{rt}	80 ppm
Injection losses	Λ^2_{inj}	5 %
Readout losses	Λ^2_{ro}	5 %
Mode-mismatch squeezer-filter cavity	$\Lambda^2_{\mathrm{mmFC}}$	2 %
Mode-mismatch squeezer-local oscillator	$\Lambda^2_{\mathrm{mmLO}}$	5 %
Frequency independent phase noise (RMS)	$\delta\zeta$	30 mrad
Filter cavity length noise (RMS)	δL_{fc}	0.3 pm
Injected squeezing	σ_{dB}	9 dB

E. Capocasa et al, PRD 93, 082004 (2016)

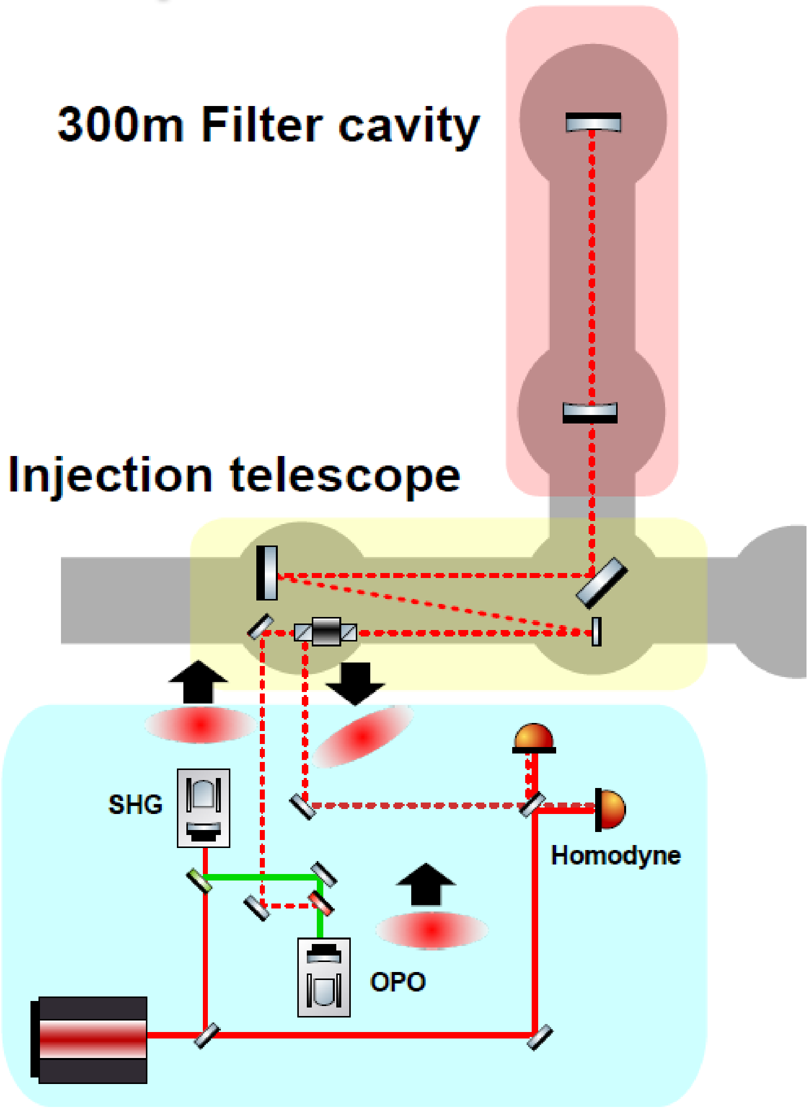
Experimental setup

300m long cavity (TAMA South arm):

- Finesse = 4400 @1064nm
- RTL = 80ppm
  - Initial Virgo class mirror
  - TAMA suspension (double pendulum)

FIS source:

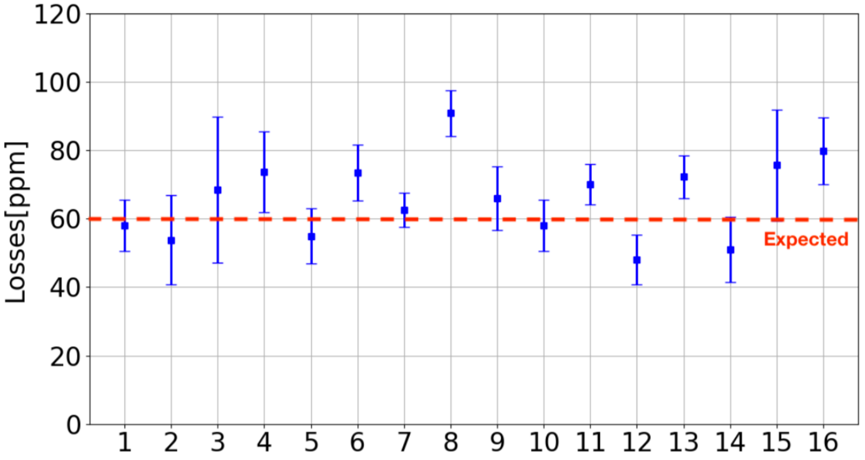
- 9dB above 10Hz
- Based on AEI design (GEO600 and AdV squeezer)

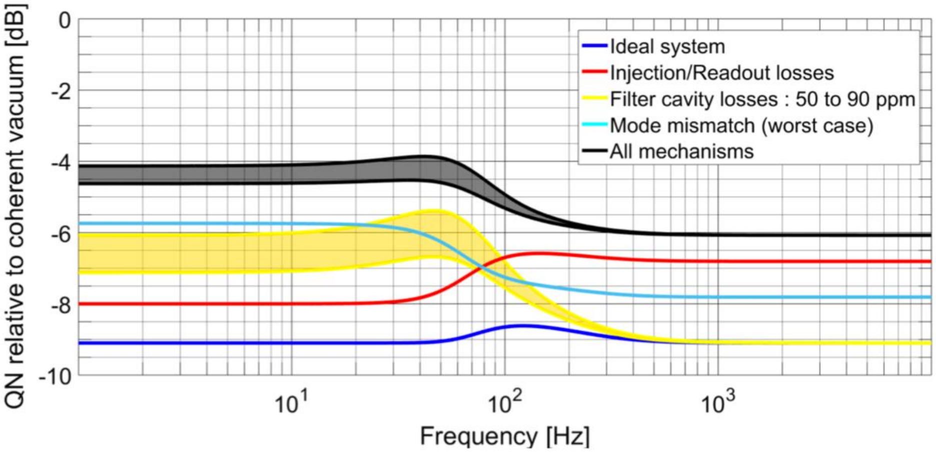


RTL characterization

Multicolor lock (IR and green) successfully implemented since last summer and RTL characterized

E. Capocasa et al, PRD 98, 022010 (2018)

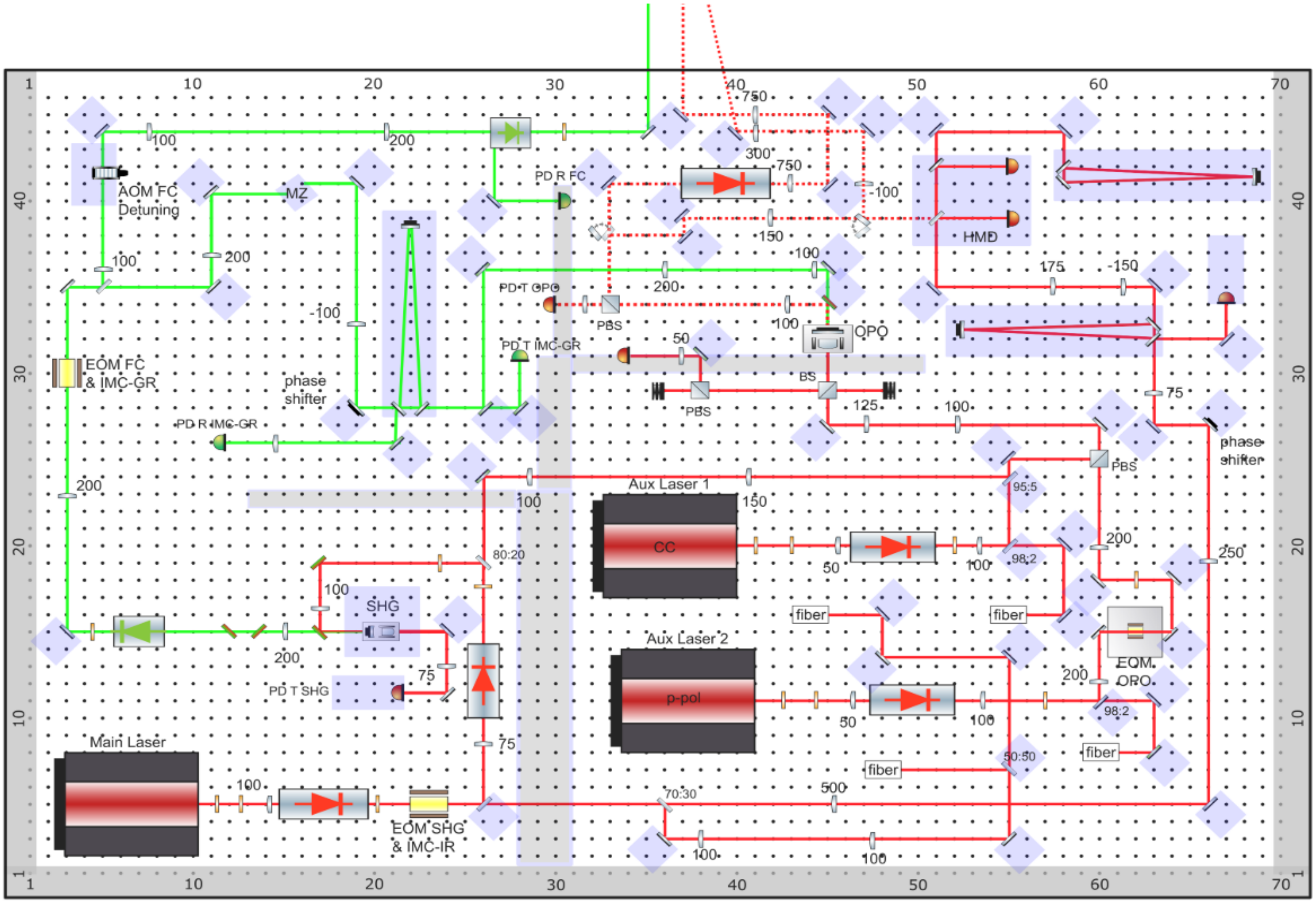




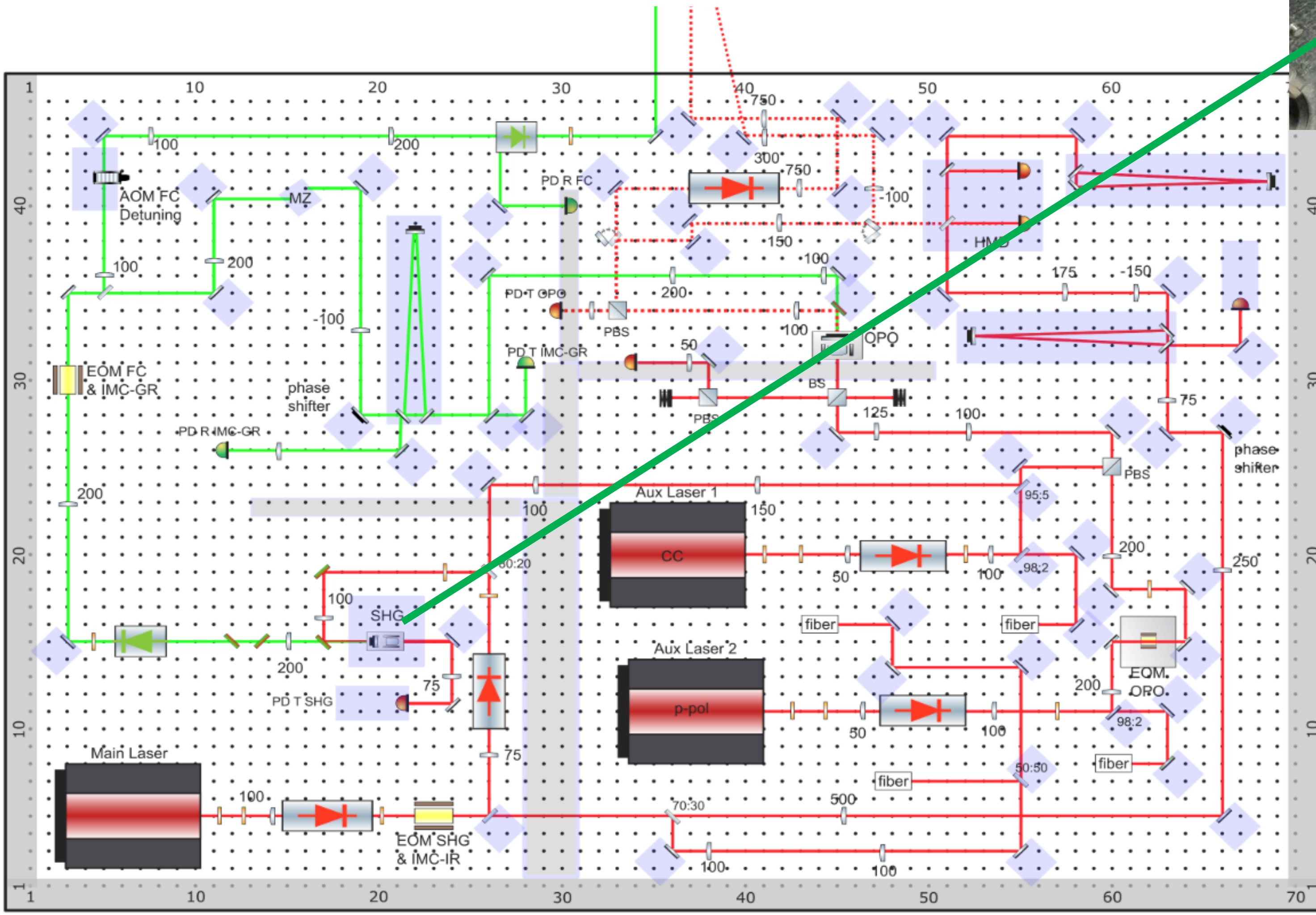
Measured RTL = 50-90ppm

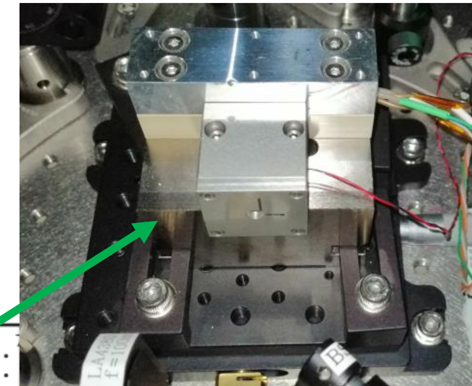
Measured finesse = 4425

FIS source layout



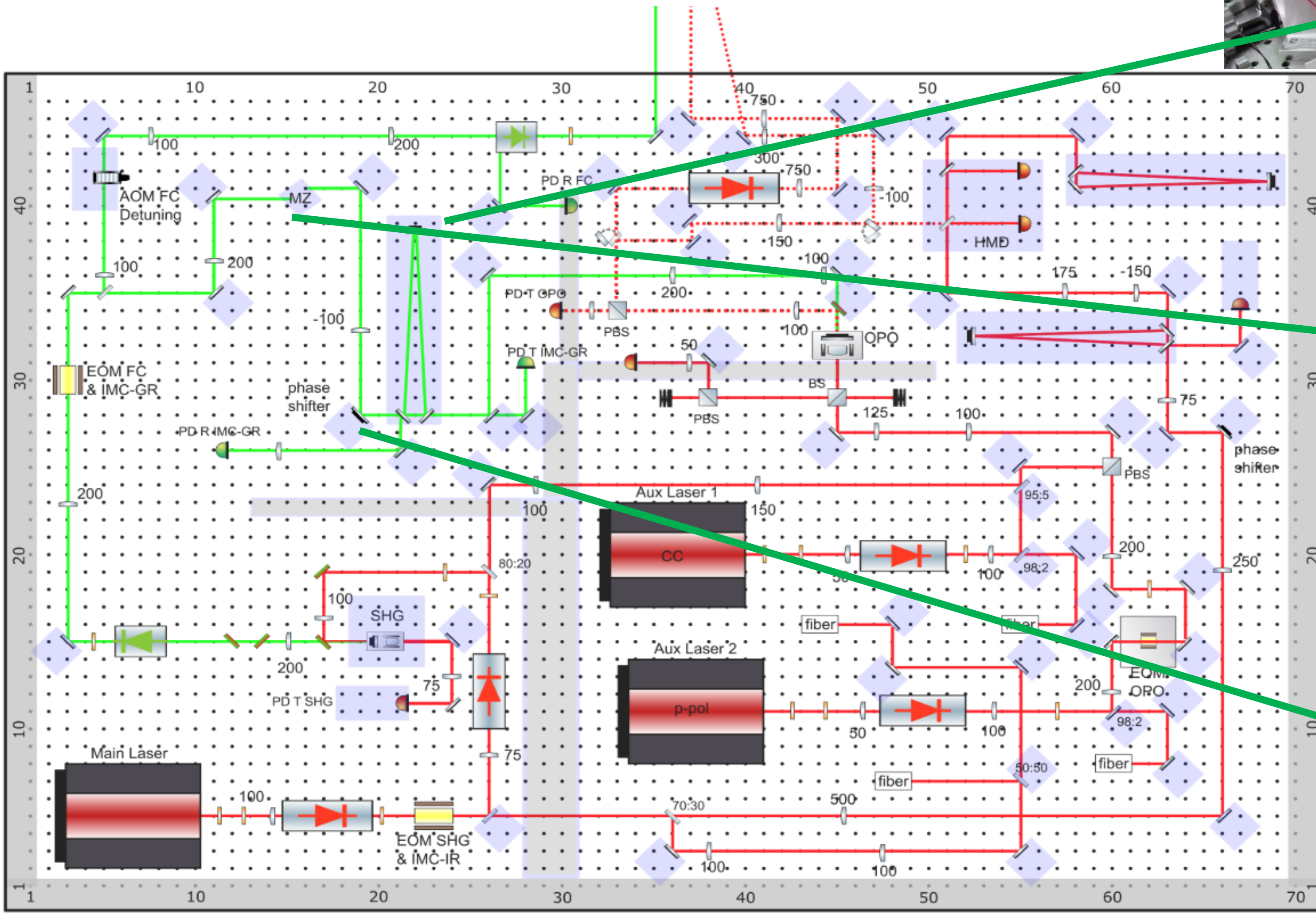
FIS source layout

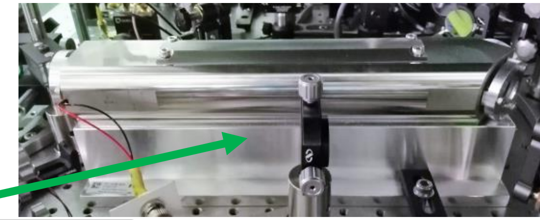




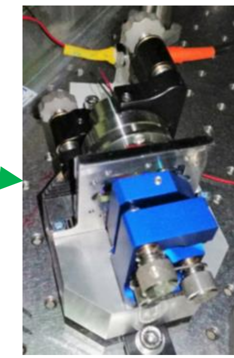
Second Harmonic Generator (SHG)

FIS source layout

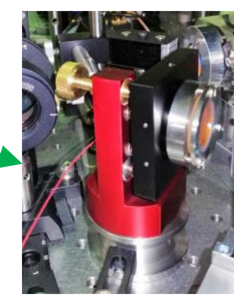




Green Mode Cleaner (GRMC)

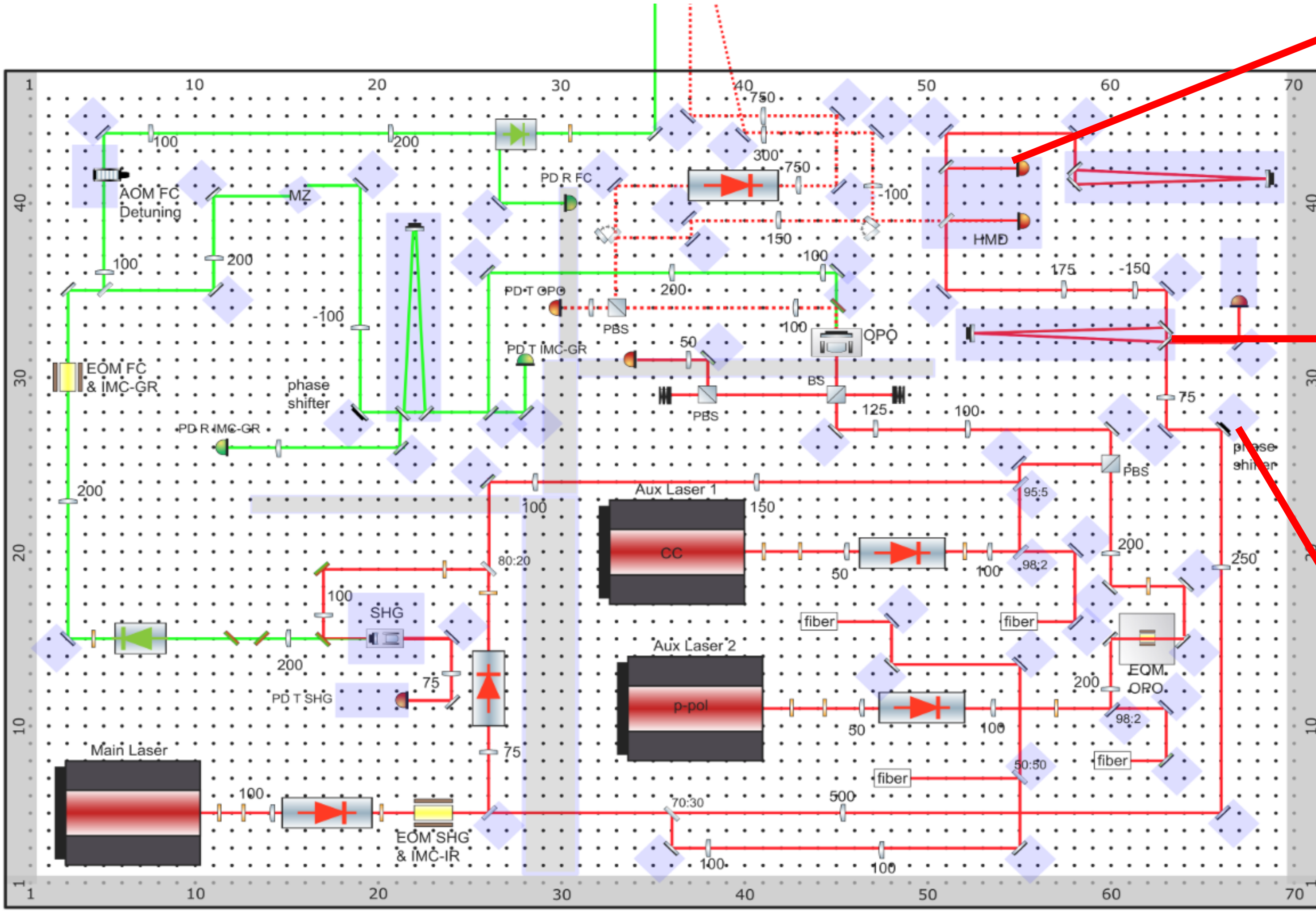


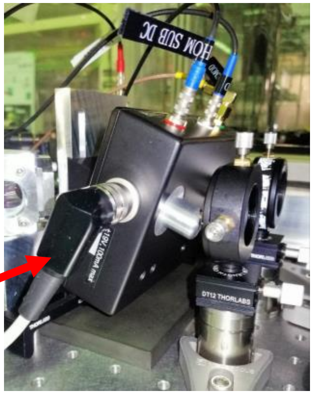
Mach-Zehnder (MZ)



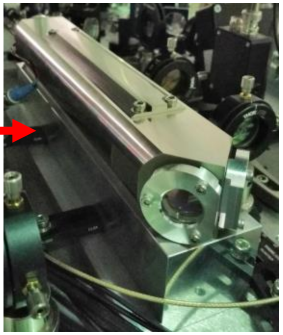
Green Phase Shifter

FIS source layout

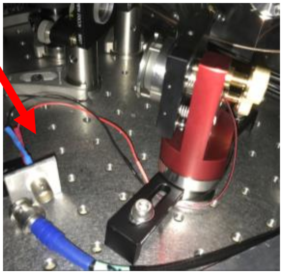




Balanced Homodyne Detector (HOM)



IR Mode Cleaner (IRMC)



IR Phase Shifter

FIS source control

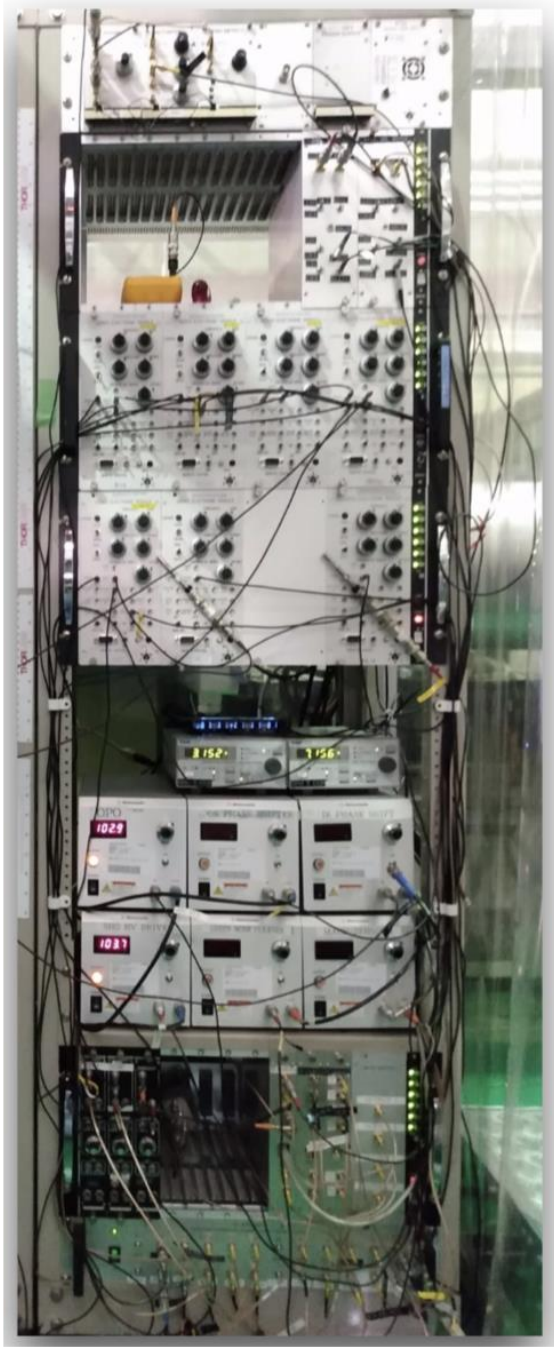
The FIS source needs several control loops:

- 4 PDH (SHG, OPO, GRMC, IRMC)
- 1 DC control (MZ)
- 2 temperature control (SHG, OPO)
- 2 PLL (AUX1 and AUX2 to ML)
- 2 coherent control

And several other electronics:

- DDS (12 RF channels)
- Homodyne
- …

Most of it is custom and it has been developed in collaboration with APC, AEI and UniPd/INFN PD groups

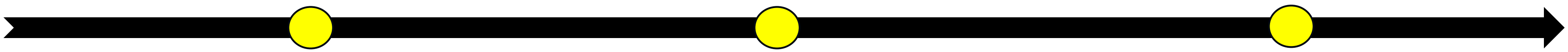


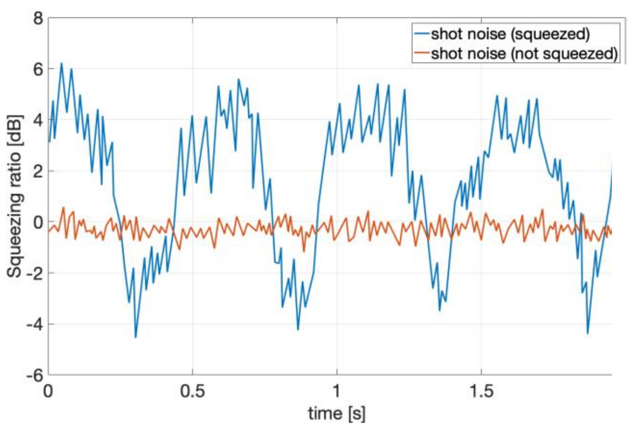
Squeezing time evolution

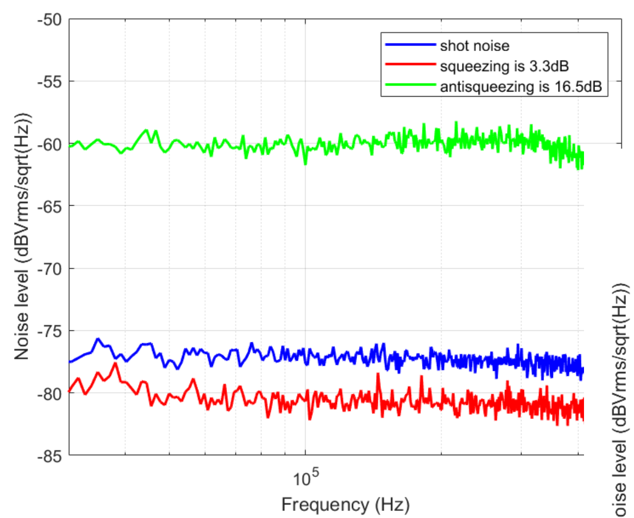
January 2019
3dB at 200kHz

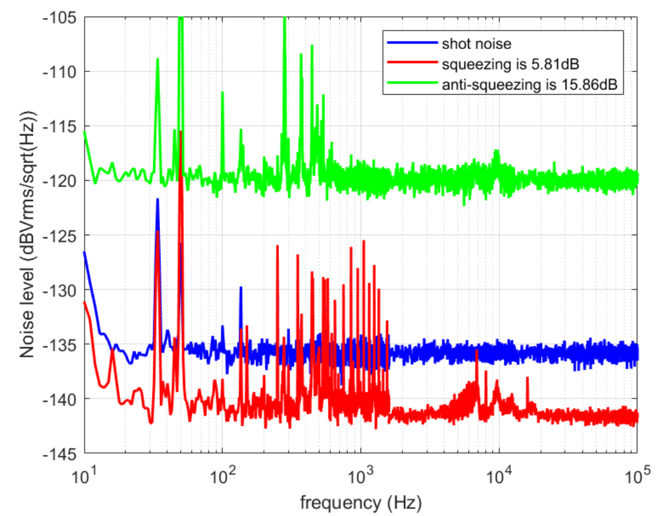
March 2019
3.3dB down to 30kHz

August 2019
5.8dB down to 20Hz

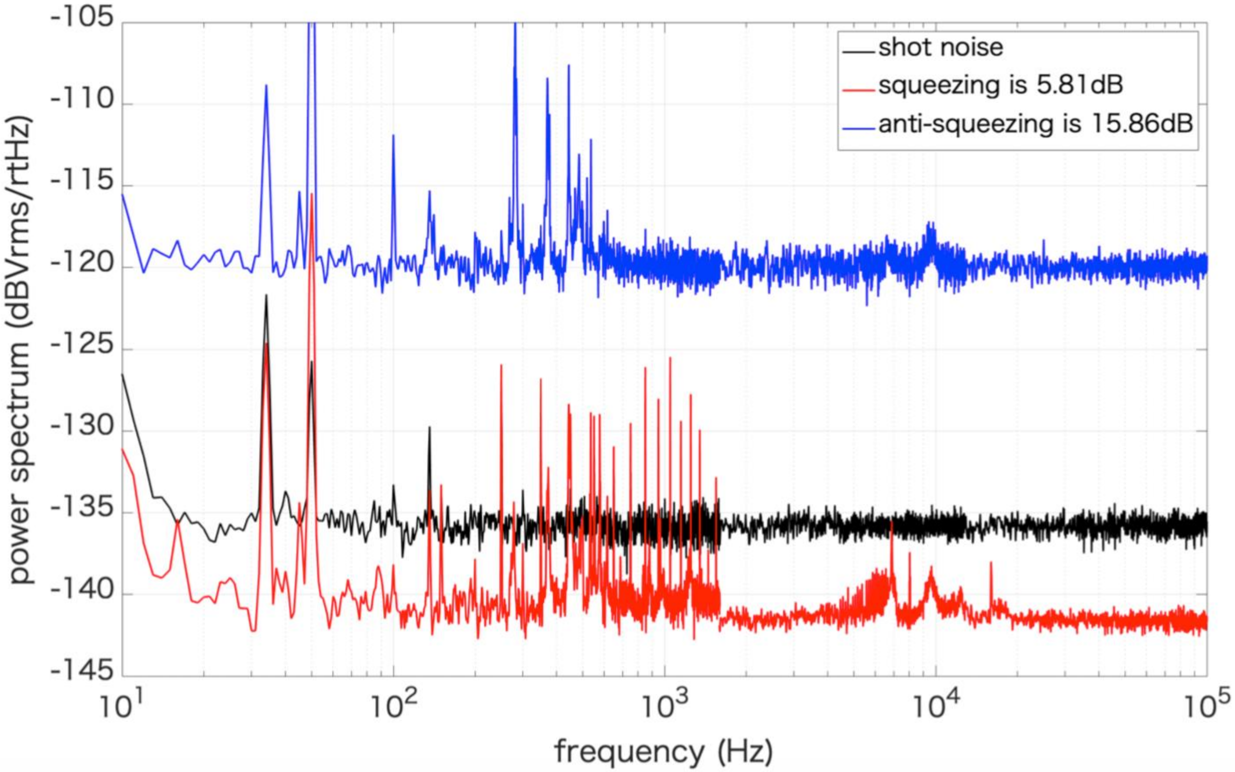








Squeezing measurement



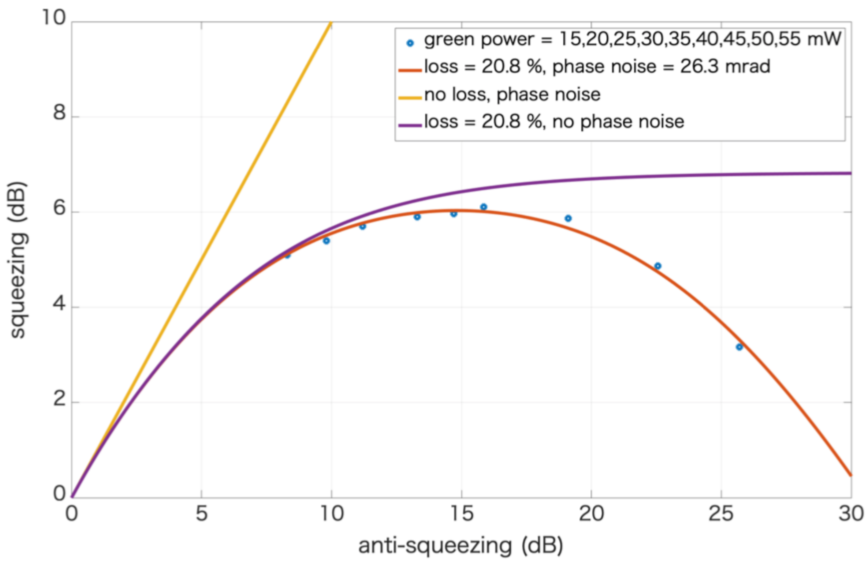
Typical squeezing spectrum:

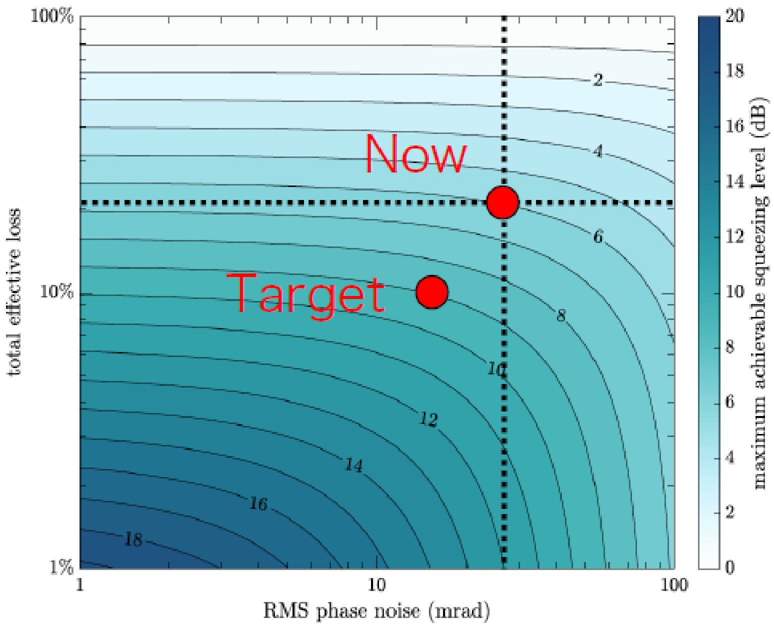
- Not pure squeezed state (sqz ≠ asqz)
- Lots of lines at low freq

FIS degradation measurement

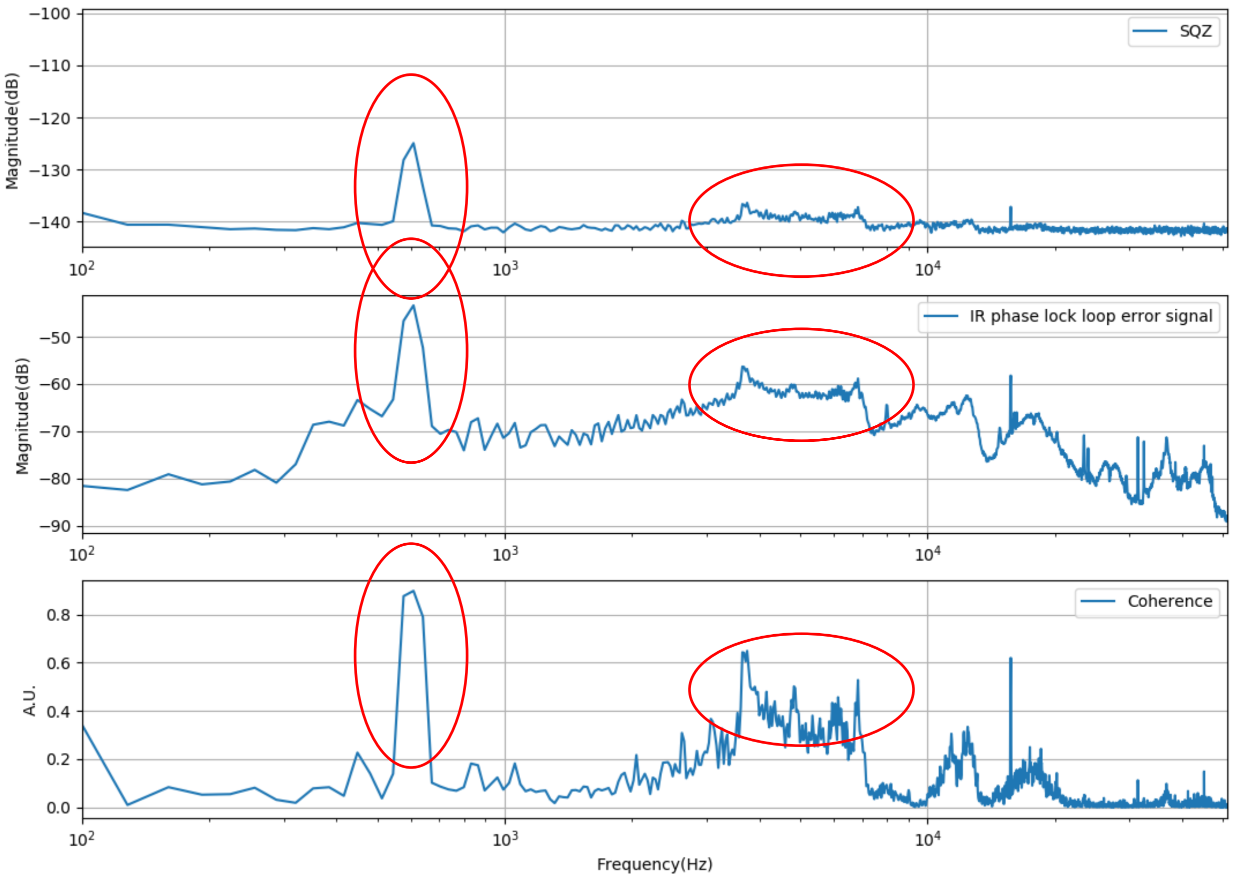
From squeezing and anti-squeezing measurements, losses and phase noise can be estimated:

- losses are approx. 21% and phase noise is approx. 26mrad





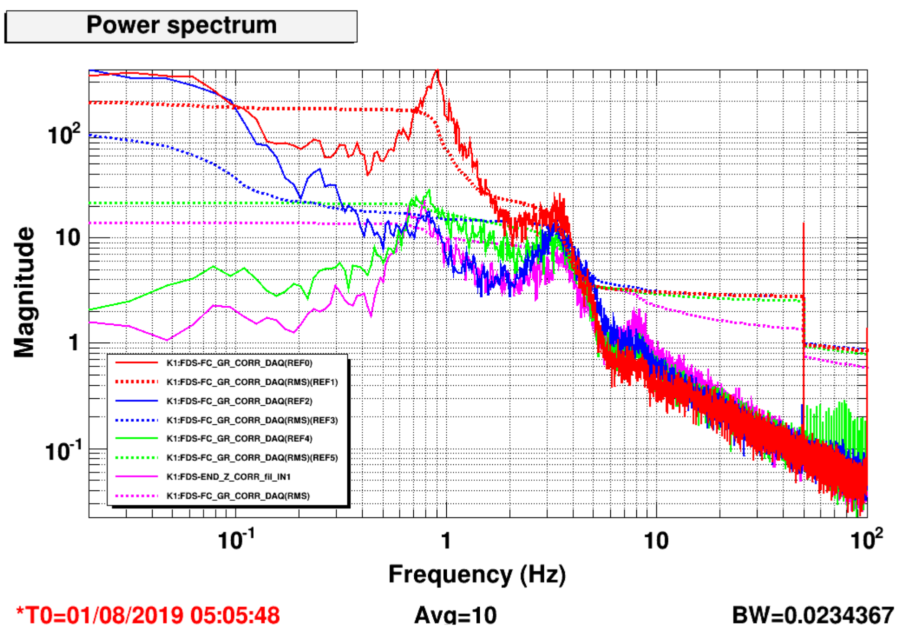
Coherence measurement between squeezing and CC2

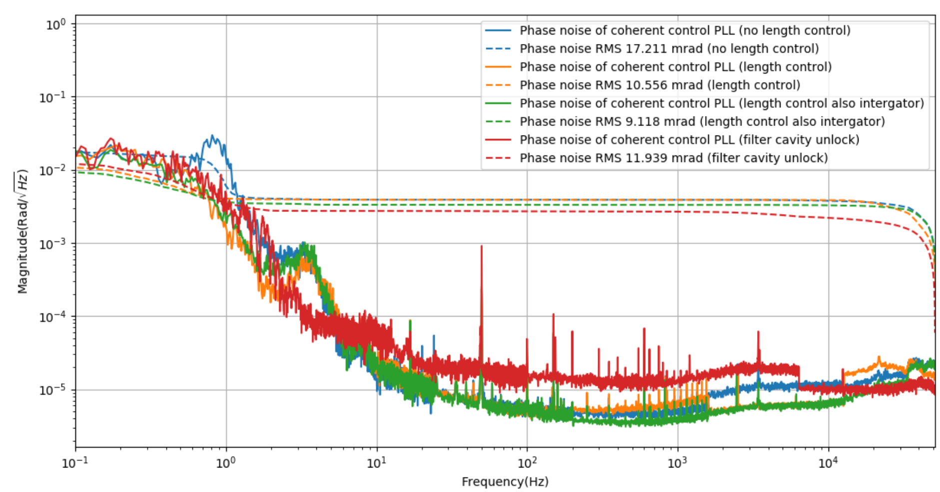


Non negligible coherence in some frequency region.

Implementation of end mirror feedback

- We succeeded in feeding back the low frequency part of the filter cavity PZT correction to the end mirror of the FC
- This allowed to reduce the correction sent to the laser and consequently the PLL noise





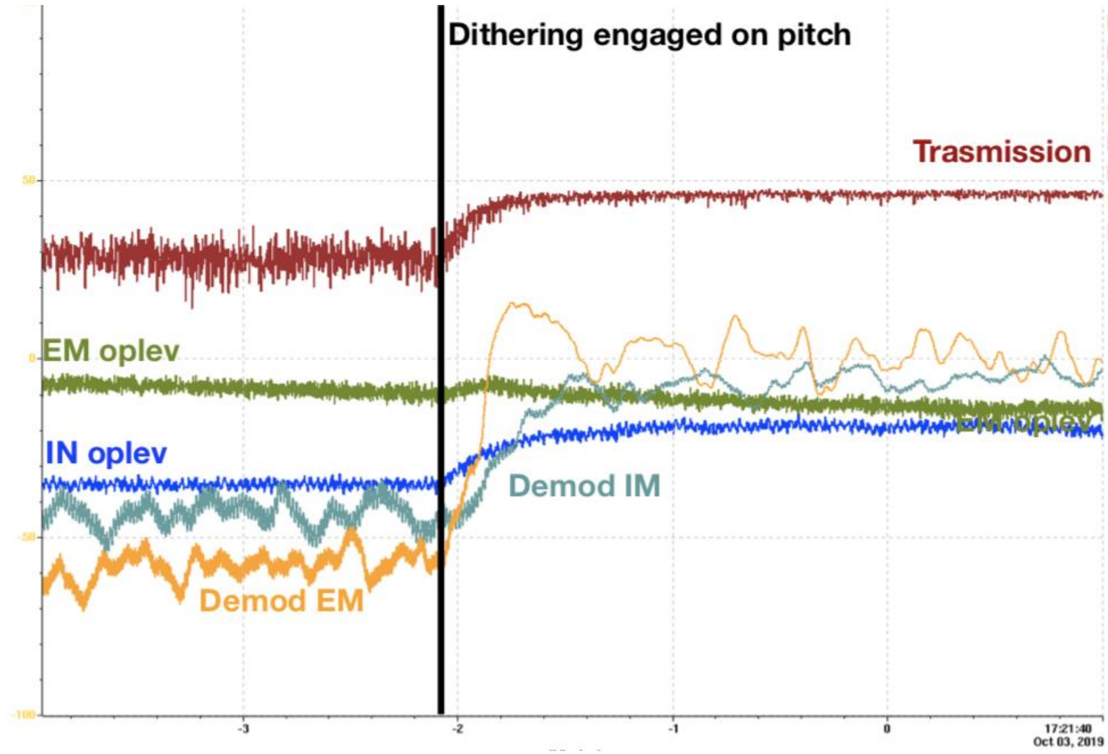
FC automatic alignment

"dithering" control loop was implemented to have cavity axis follow the input beam direction (bandwidth of hundred mHz)

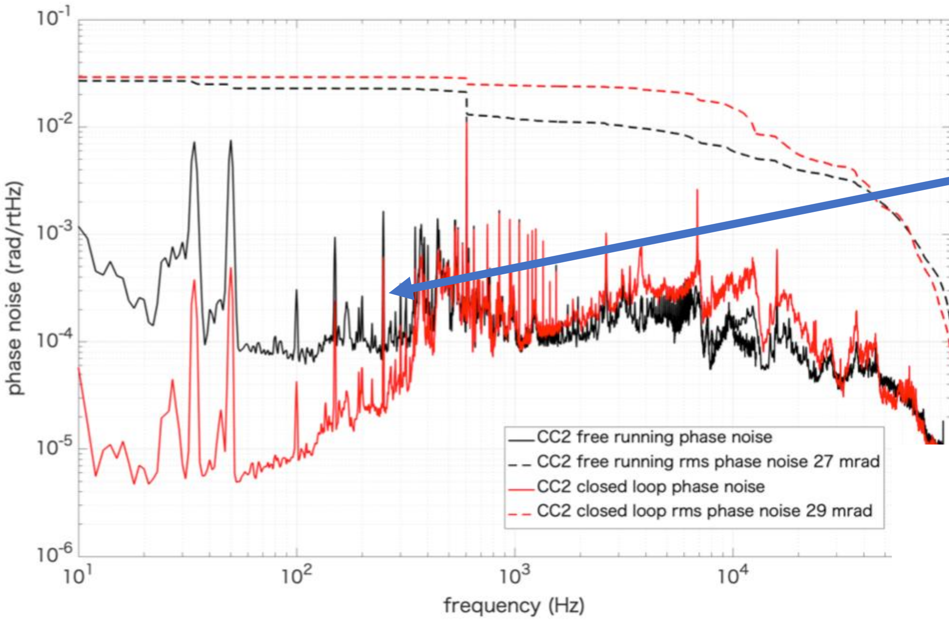
Currently implemented in pitch only.

Final design:

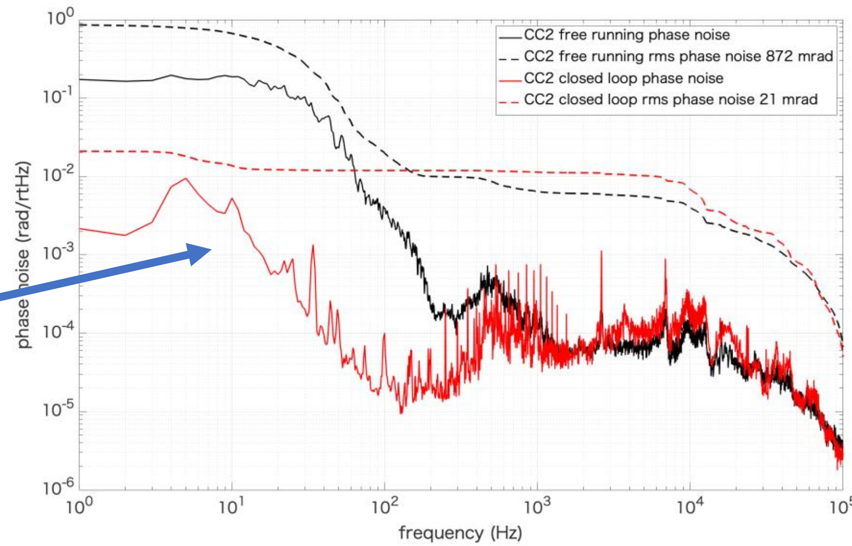
- implement also yaw
- implement the loop for centering the beam on the mirrors



CC2 behavior when going toward FC

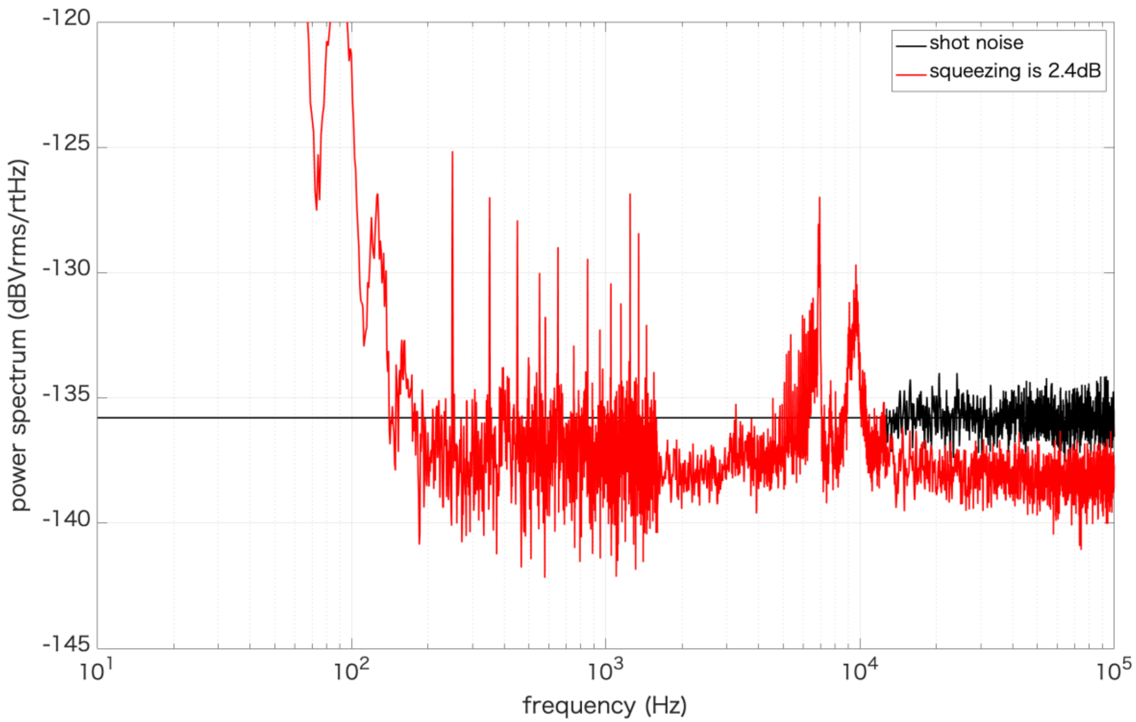


Low frequency successfully suppressed



Low frequency has a lot of excess noise due to relative motion between in-air bench and suspended optics

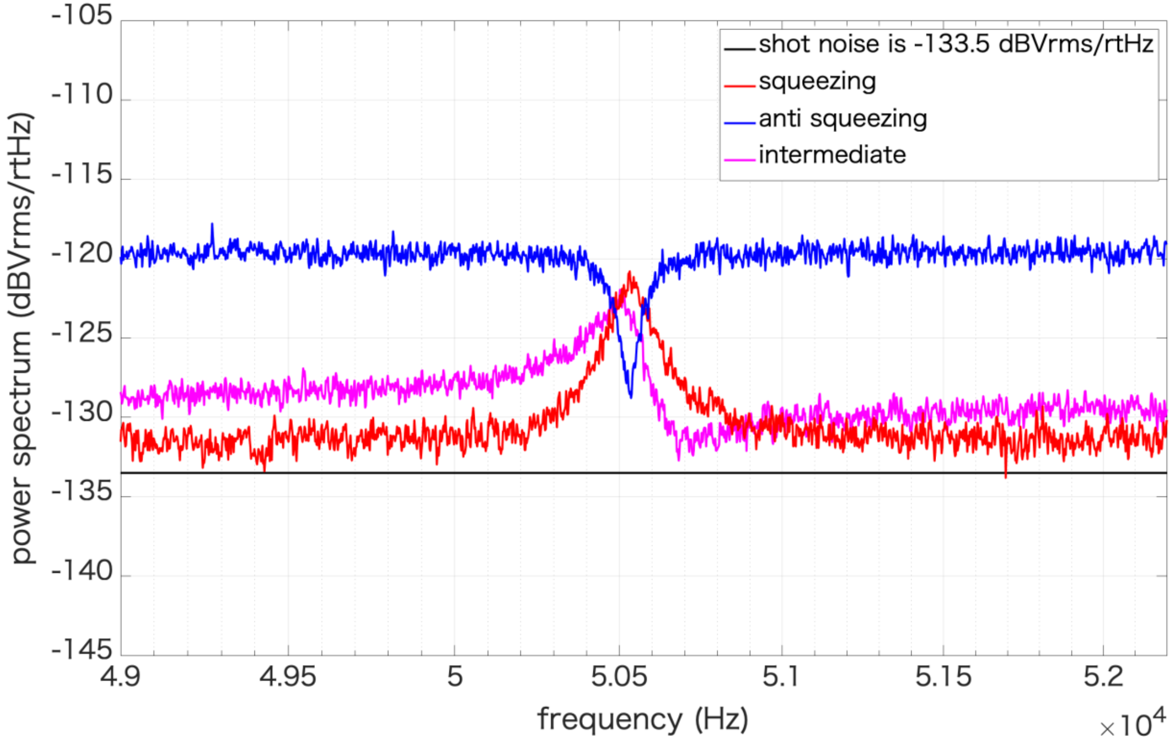
Squeezing injection: first try



Squeezing measurement with unlocked FC:

- Takes into account the injection and detection losses
- Low frequency limited by phase noise

First ellipse rotation evidence



Preliminary measurement performed yesterday!

Modelling of the data ongoing…

FC operated with 50kHz of detuning to avoid low frequency noise

Summary

- 6dB of squeezing above 20Hz has been measured
- Characterization of losses and phase noise of FIS was performed
- First evidence of squeezing rotation from 300m long FC

Future plan

- Investigation of low frequency noises
- Improvement of CC loops
- Loss reduction required

Visitors and collaborators

Emil Schreiber
GEO600/AEI

Shu-Rong Wu
Tsing Hua University

Marco Vardaro
Padova University

Matteo Barsuglia
APC/CNRS

Eleonora Polini
La Sapienza Roma

Matteo Tacca
Nikhef

Federico Paoletti
INFN-Pisa

Marc Eisenmann
LAPP/CNRS

Yuefan Guo
Nikhef

Chien-Ming Wu
Tsing Hua University

Pierre Prat
APC/CNRS

Marco Banzan
Padova University

Irene Fiori
EGO