EXPERIMENTAL GOINGS-ON AT THE GLASGOW SAGNAC SPEED METER

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CONTENTS

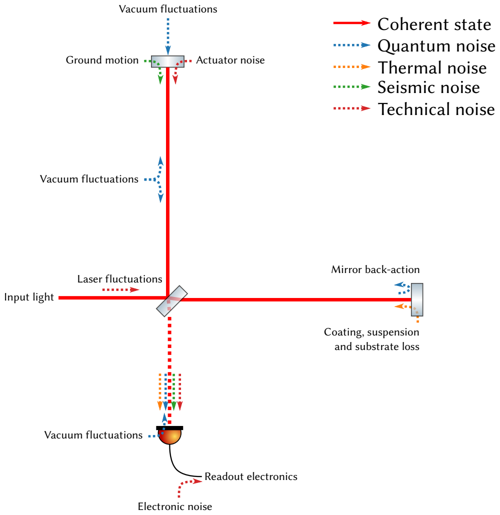
- Gravitational wave detectors
- Reduction of quantum noise
- Glasgow speed meter experiment and status
- Longitudinal control
- Electrostatic drives
- Future plans for Glasgow experiments

GRAVITATIONAL WAVE INTERFEROMETRY

and KAGRA, GEO600...

SOURCES OF NOISE

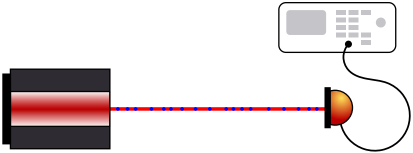
- Test masses need to be quieter than the thing you want to measure
- Laser, mirrors, actuators, control systems and photodetectors have noise
- The noise partly determines the sensitivity of the interferometer



QUANTUM SHOT NOISE

- Quantum vacuum enters at loss ports and propagates to the detector
- White in frequency spectrum

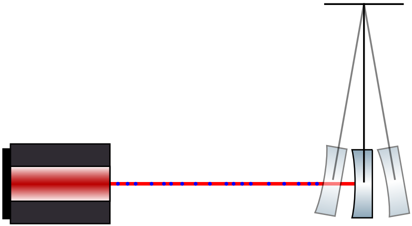
$$h_S(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$



QUANTUM RADIATION PRESSURE NOISE

- Quantum vacuum enters at loss ports and imparts momentum to mirrors
- Acts as a noisy parametric amplifier for the carrier light
- Creates noise proportional to the mirror's mechanical susceptibility

$$h_{RP}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$



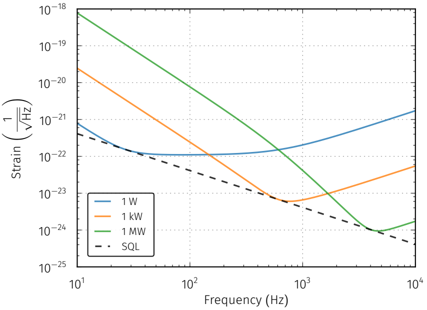
Radiation Pressure Noise

$$h_{RP}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

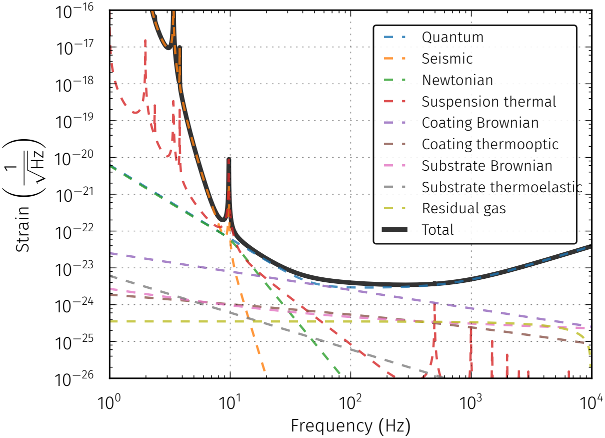
- QRPN and QSN combine to limit sensitivity at all frequencies - the **SQL**
- Sensitivity reaches the SQL at only one frequency
- Higher m, P and lower λ push the most sensitive frequency higher

Shot Noise

$$h_S(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$



Current generation detectors are already limited by quantum noise at their most sensitive frequencies

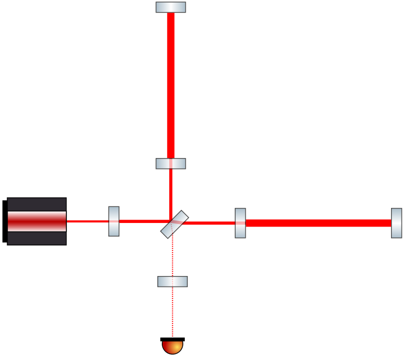


BEATING THE STANDARD QUANTUM LIMIT

- So far we used variants of the **Michelson interferometer** to measure **displacement**
- Subject to uncertainty principle:

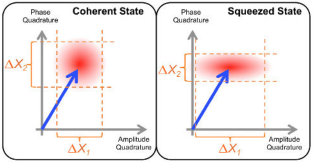
$$[\hat{x}(t), \hat{x}(t+\delta t)] \neq 0$$

- Manifests as the SQL

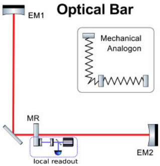


Sub-SQL techniques

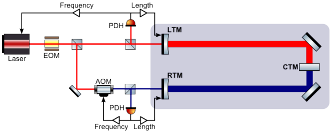
Manipulating the light quadrature: **squeezing** and **variational readout**



Local readout of an **optical bar**



Optomechanically coupled **optical springs**



In the 1930s, John von Neumann showed that some observables can be measured in pairs not subject to uncertainty.

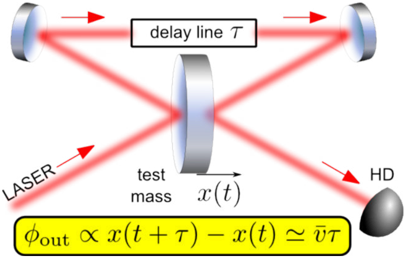
One pair is **momentum**:

$$[\hat{p}(t), \hat{p}(t+\delta t)] = 0$$

(From Wikimedia Commons)

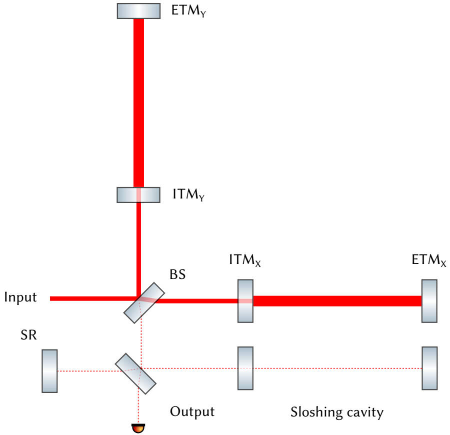
- Speed is a proxy for momentum
- So measure the mirrors at different times

$$\phi_{CW} \propto x_N(t) + x_E(t + \delta t)$$
$$\phi_{CCW} \propto x_E(t) + x_N(t + \delta t)$$
$$\Delta\phi = [x_N(t) - x_N(t + \delta t)] - [x_E(t) - x_E(t + \delta t)]$$
$$\Delta\phi \approx \delta t\,(\dot{x}_E(t) - \dot{x}_N(t))$$



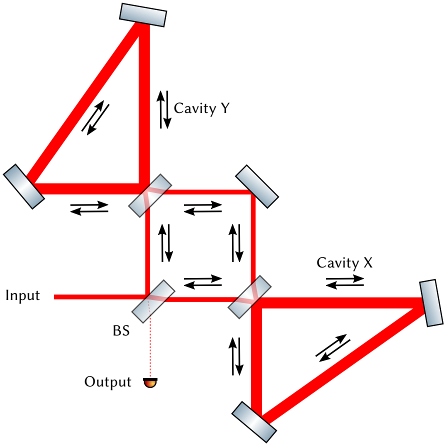
Speed meters have reduced quantum radiation pressure noise

First speed meter proposed in 2000 as a “sloshing Michelson”



Output contains light having sampled the same mirrors at different times, akin to speed measurement

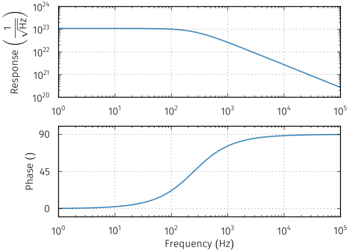
Later proposal (Chen, 2002) showed that the Sagnac interferometer was a QND speed meter



- Sagnacs are used to measure the Earth's rotation
- For gravitational wave detection the zero area Sagnac must be used to cancel it
- Arm cavities added to enhance response

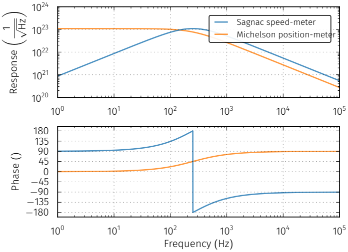
- The response of the interferometer determines the signal generated for a given test mass motion
- Higher is better

Position meter



Response flat below cavity pole

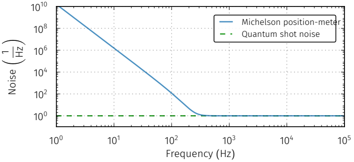
Speed meter



Response vanishes towards dc

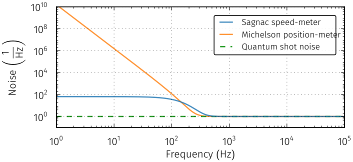
- Noise determines the minimum detectable signal, i.e. the SNR = 1
- Lower is better

Position meter



Shot noise at HF, radiation pressure at LF

Speed meter

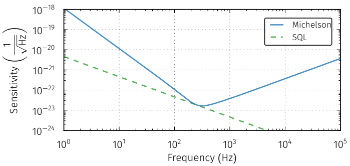


Shot noise at HF, **reduced** radiation pressure at LF (assuming lossless)

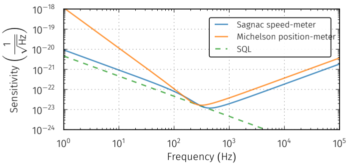
- QN limited sensitivity is

$$\text{QNLS} = \frac{\text{Noise}}{\text{Response}}$$

Position meter

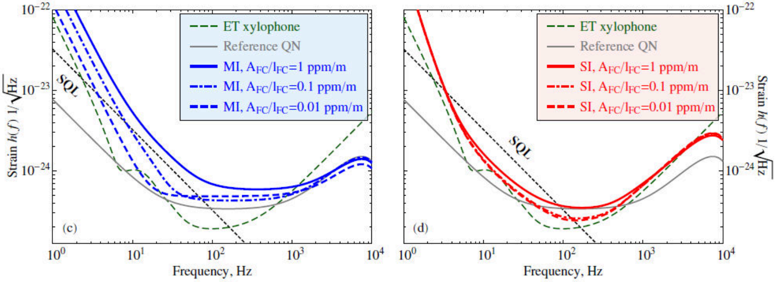


Speed meter



Despite having lower response at LF, speed meter has **better overall sensitivity**

- Speed meters relax filter cavity loss requirements for frequency dependent squeezing compared to Michelsons
- Potential for application in large-scale detectors in the long term



Presented by Stefan Danilishin, GWADW @ Alaska, 2015

SPEED METER ZOO

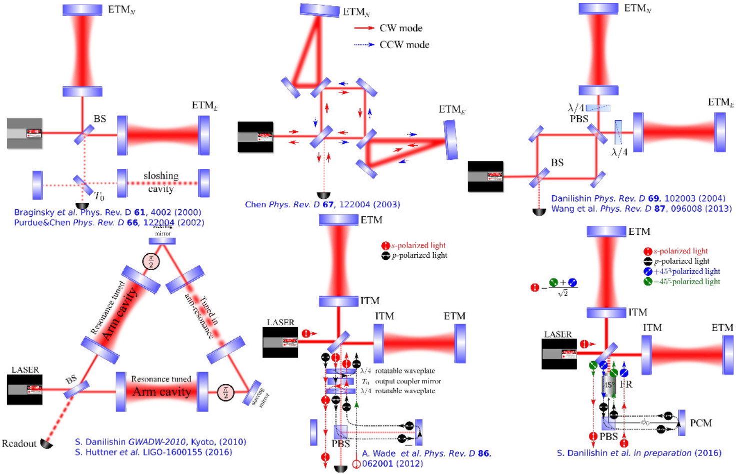


Image credit: Stefan Danilishin

SPEED METER ZOO

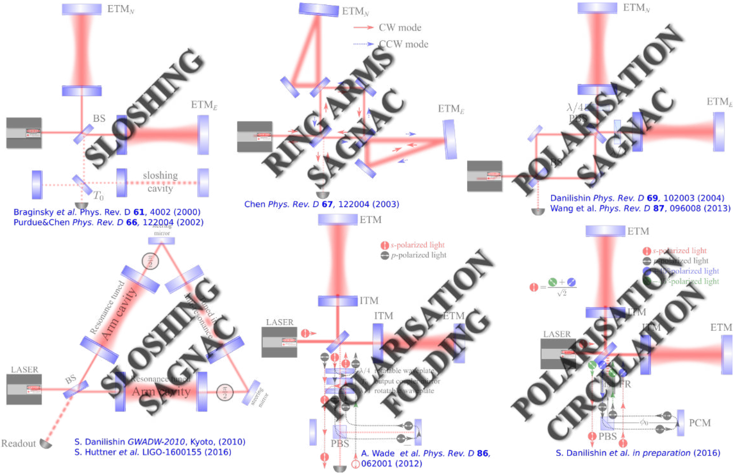


Image credit: Stefan Danilishin

If speed meter detectors are so great, why aren't we building one yet?

...Because there are no free rides

- Loss reintroduces QRPN
- This includes asymmetries
- Losses affect speed meters to a greater extent than position meters
- **Challenging technical requirements**

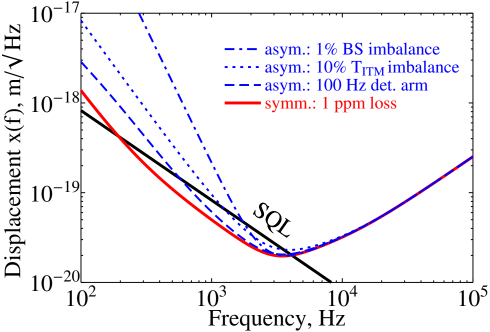
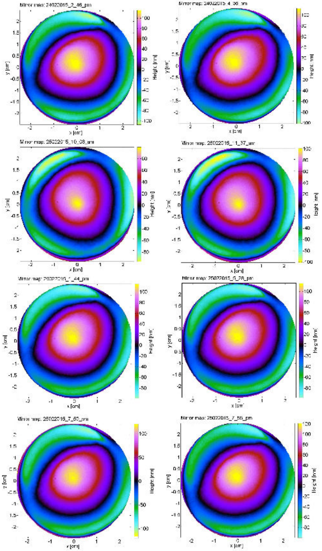
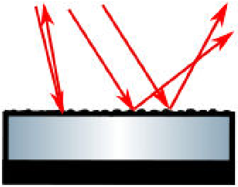


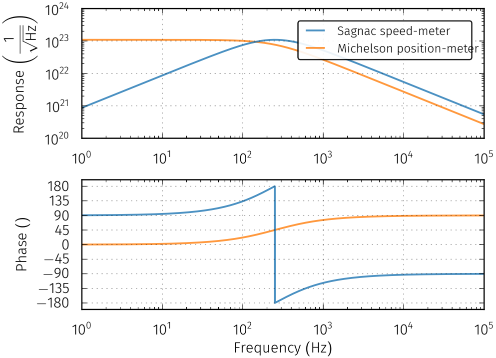
Image credit: Stefan Danilishin



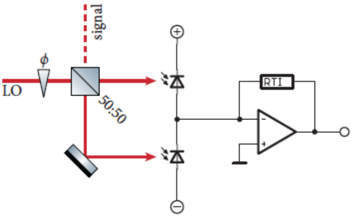
- Scattering is a particular killer in Sagnac speed meters
- Counter-propagating mode mixing
- A speed meter GW detector probably won't be a ring Sagnac



- Some control signals vanish at low frequencies
- When there are arm cavities, these need actively controlled at dc, but there's no signal at the output



- Existing detectors use dc readout
- Fixed readout quadrature
- To minimise noise the speed meter needs an adjustable readout quadrature
- Obvious candidate is balanced homodyne readout
- Not used before in suspended interferometers



These challenges merit some experimentation to prove the principle and find any show stoppers!

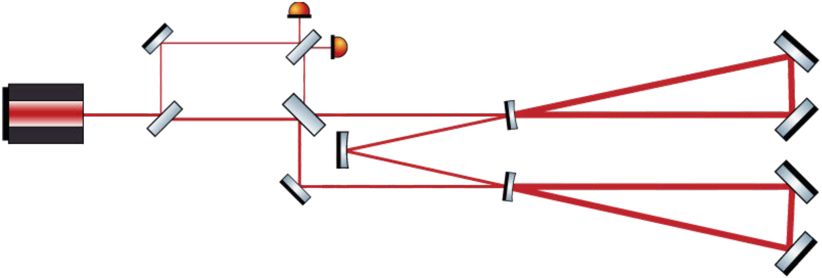
ERC SAGNAC SPEED METER EXPERIMENT

On-going experiment in Glasgow funded by ERC to:

- Create an ultra-low noise speed meter testbed **dominated by quantum radiation pressure noise**
- Demonstrate the **reduction of back-action noise** in the Sagnac interferometer topology
- Explore **challenges with speed meter technology** for future detectors

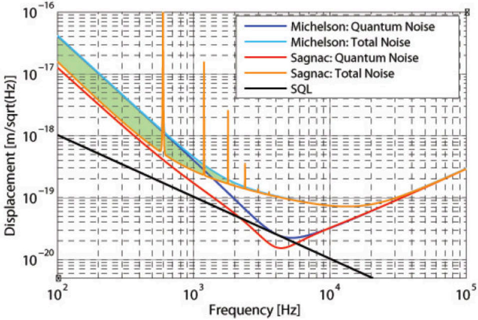
EXPERIMENTAL PARAMETERS

- Ultra-high vacuum
- Passive seismic isolation (possibly also active)
- Triangular arm cavities
- Silica suspensions
- 2.8 m arm round trip length
- Finesse approx. 9000
- 20 ppm round trip loss
- 5 kW circulating power
- In-vacuum BHD



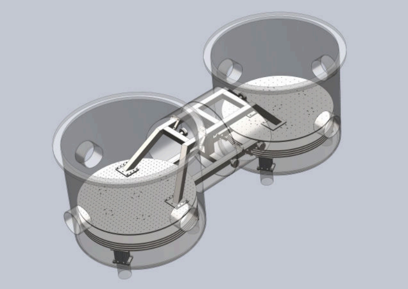
“DOMINATED BY QUANTUM RADIATION PRESSURE NOISE”

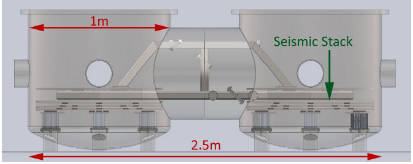
- We aren’t trying to beat LIGO sensitivity
- Want to show that radiation pressure noise is lower in a Sagnac speed meter than in an equivalent Michelson
- Aiming for a factor of 2-3 lower



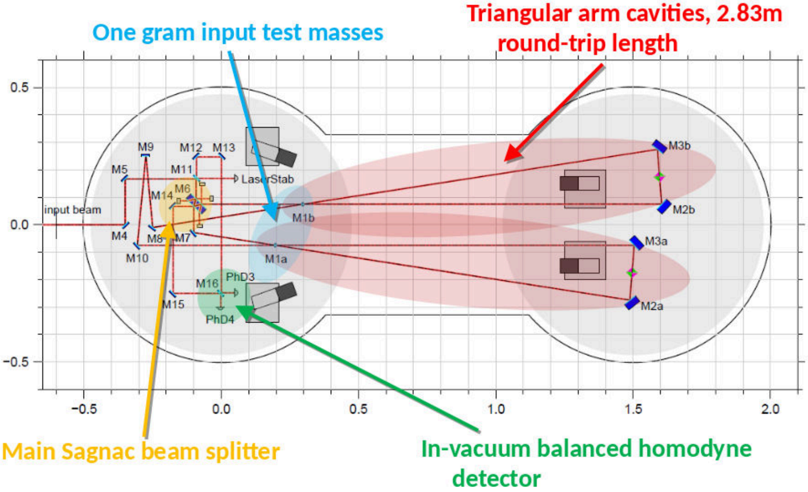
High finesse, low loss cavities and large beam spots improve response and decrease noise

- 2 x 1 m diameter GEO-style tanks
- Fluorel stacks for passive damping
- 60 kg steel disks
- Breadboard tables for experimental apparatus
- Bridge structure to rigidly connect tables

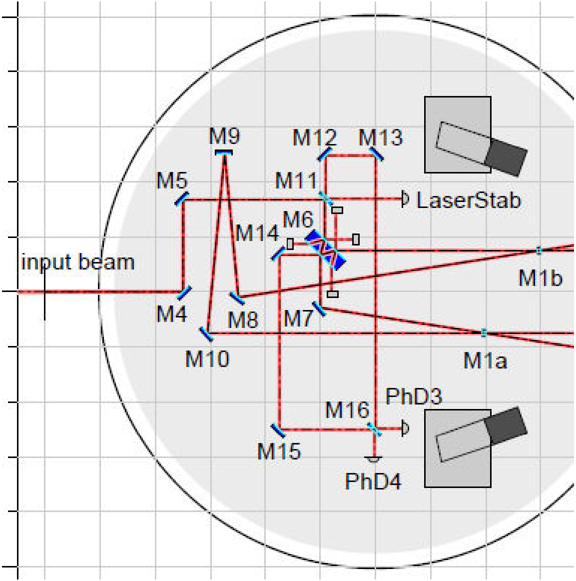




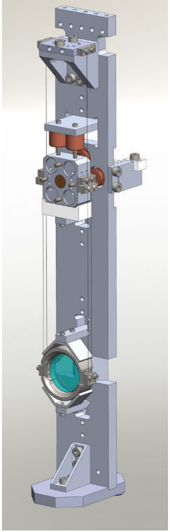
LAYOUT


One gram input test masses
Triangular arm cavities, 2.83m round-trip length
Main Sagnac beam splitter
In-vacuum balanced homodyne detector
input beam
M1a
M1b
M2a
M2b
M3a
M3b
M4
M5
M6
M7
M8
M9
M10
M11
M12
M13
M14
M15
M16
PhD3
PhD4
LaserStab
0.5
0.0
−0.5
−0.5
0.0
0.5
1.0
1.5
2.0

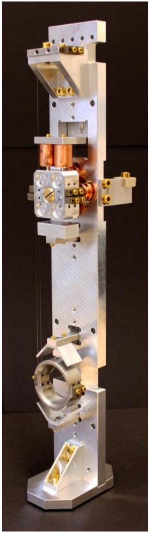
- 15+ suspensions
- Large BS for control pick-offs
- Mode matching mirror M9
- Suspended BHD



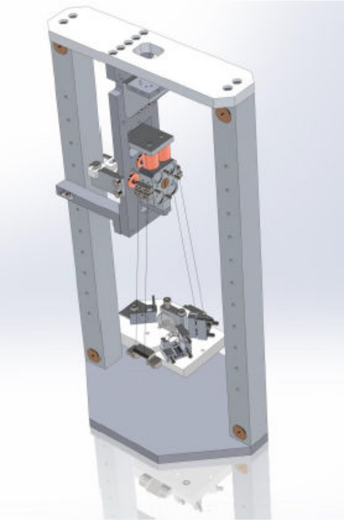
AUXILIARY SUSPENSIONS



- Auxiliary suspensions designed and assembled
- Two stages
- Steel wires
- Coil/magnet actuators for 4 DOF control
- Modified version in design for the main beam splitter

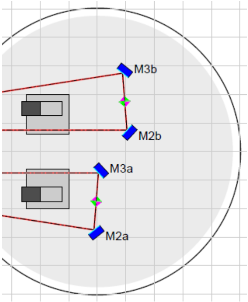


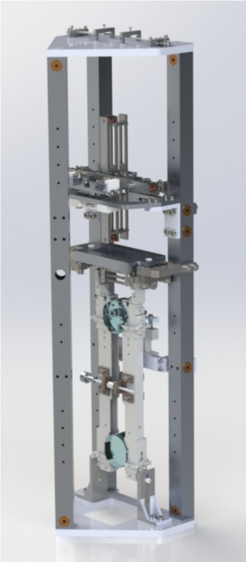
SUSPENDED BHD



- Local oscillator phase noise directly couples to GW channel
- Need to isolate BHD in same way as test masses
- Suspended in-vacuum BHD never before attempted
- Analytical work also making good progress to understand effect of beam jitter

REAR TANK

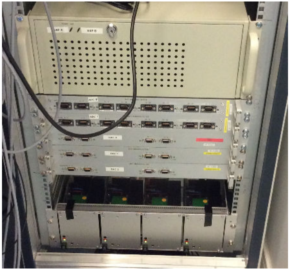


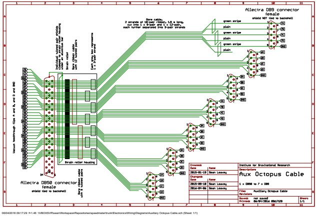


- Recycling ETM suspension design for AEI prototype
- Modified for 45°
- Will use silica fibres
- Electrostatic drive for high frequency actuation

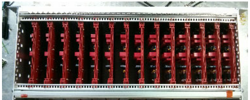
CONTROL

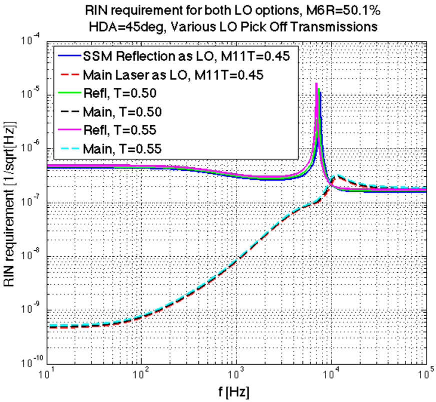
- LIGO CDS system for control of almost everything
- Approx 250 I/O channels required
- Fast actuation provided by LIGO CDS ADC/DAC front ends
- Slow controls via EtherCAT ethernet field bus
- Lock acquisition / automation with LIGO Guardian





- Suspensions controlled with modular coil driver subracks
- Signals combined into 50-way sub-D connectors compatible with feedthroughs
- “Octopus” cables split signals inside vacuum (AEI idea)



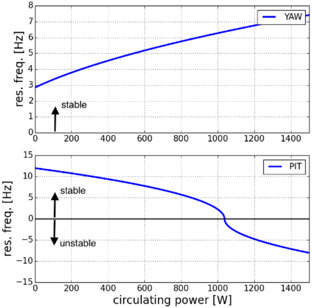


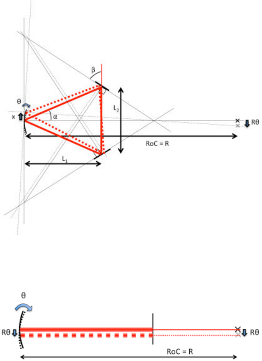
(Preliminary)

- Laser relative intensity noise (RIN) requirement set by quantum noise at BHD
- Use of common mode light as an LO reduces RIN requirement
- Without this convenience stabilisation electronics design would be extremely challenging

ANGULAR CONTROL

- Angular cavity control takes advantage of yaw radiation pressure spring
- Pitch needs stabilised once circulating power exceeds 1 kW



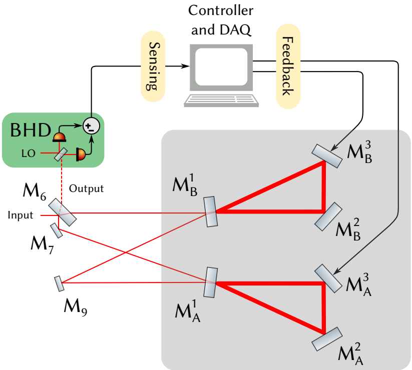


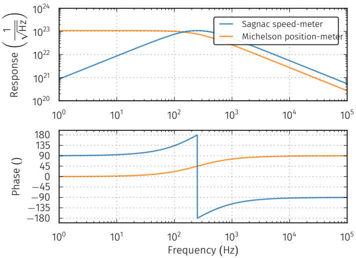
By Yutaro Enomoto and Koji Nagano

(Preliminary)

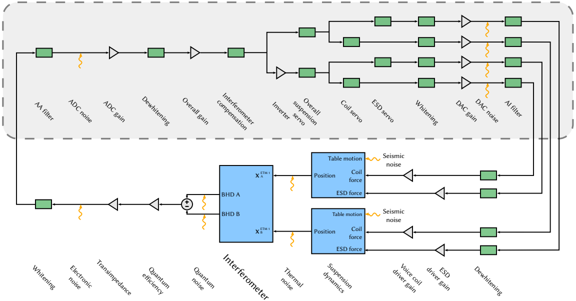
LONGITUDINAL CONTROL

- A simple Sagnac is automatically “locked” longitudinally
- However, the interferometer has resonant arm cavities
- Differential and common modes of the arms need active control
- Lack of error signal for cavities at dc leads to feedback of noise

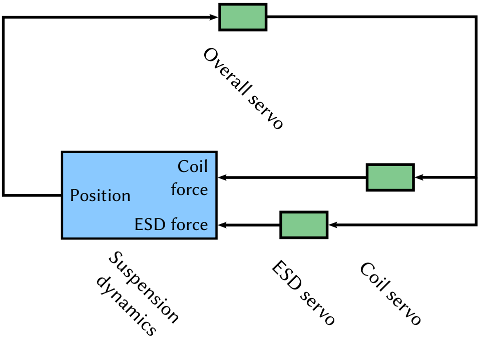




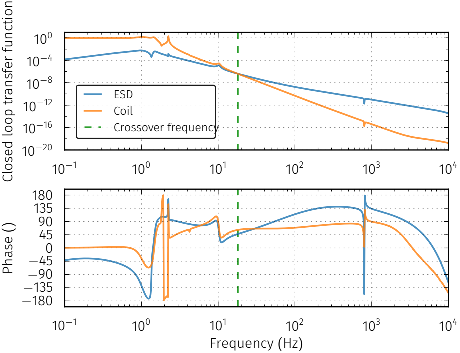
- To quantify drift due to lack of error signal, control loop modelling is needed
- Assume linear negative feedback from the balanced homodyne detector to the arm cavities (differential motion)
- Use numerical tools to model interferometer response, quantum and technical noise sources, electronics, suspensions and actuator response and range

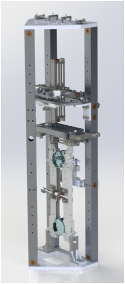


- To be realistic, need to assume finite actuator range
- Whitening/dewhitening needed to avoid ADC/DAC noise
- State-space model of ETMs to understand actuator response
- Designed a suspension control hierarchy to blend coil and ESD feedback

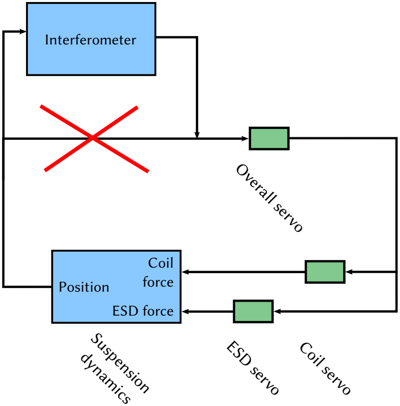


- Heuristic process
- Set unity gain frequency to determine bandwidth
- Choose cross-over frequency between coil and ESD feedback
- Enhance feedback at suspension resonances (inc. pitch coupling)
- Notch out violin modes at high frequencies

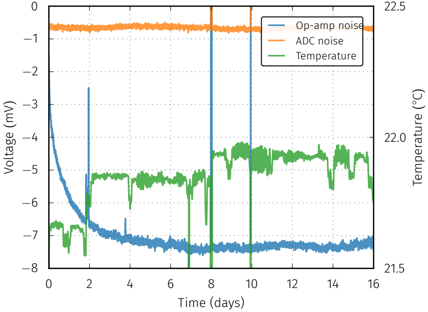




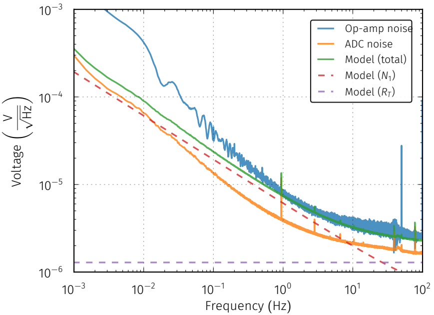
- As the suspension feedback was designed in a closed loop, we need to compensate for the interferometer plant
- Simple integrators approximate the slope of the interferometer response within the bandwidth of the feedback



- Op-amp noise at low frequencies is not well defined in data sheets
- Likely that the BHD electronics contribute feedback noise to the test masses at low frequencies
- This noise creates RMS drift that disrupts resonant condition over the course of minutes to hours
- Measured the BHD noise to understand long term effect



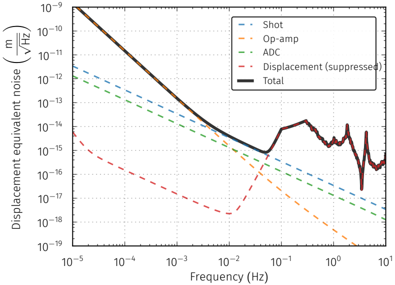
DRIFT OF BHD ELECTRONICS

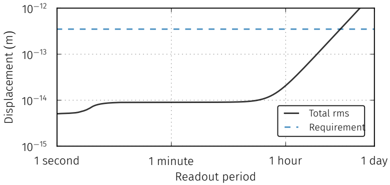


- Drift possibly caused by current noise, thermoelectric potentials, vibrations, etc.
- Represents a lower limit on low frequency noise in the lab
- Other effects such as fringe alignment, thermal expansion, etc. can cause additional noise

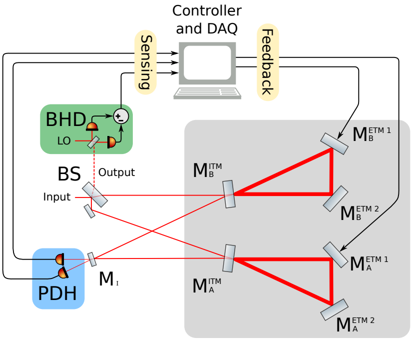
DRIFT OF TEST MASSES

- By modelling the control loop we can estimate the drift
- With the BHD readout, the cavities lose resonance after a few hours

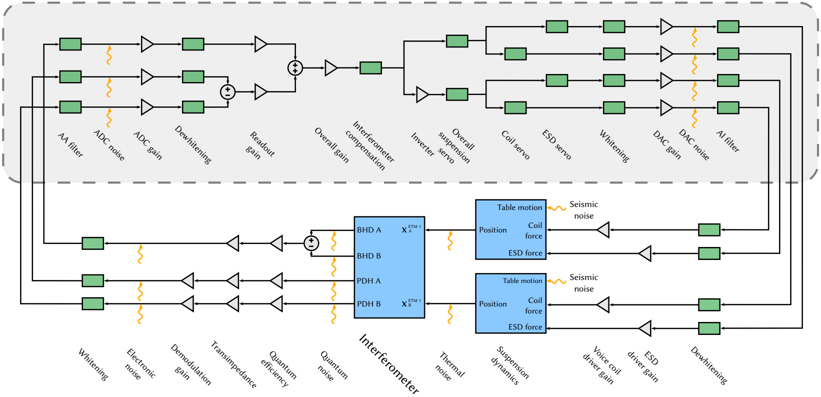




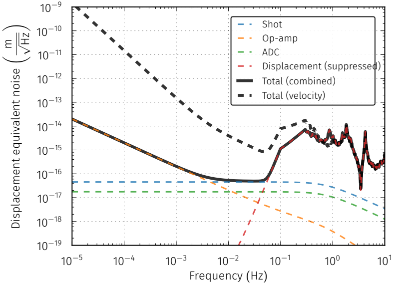
- The solution is to pick off light from the mode matching mirror from each cavity
- Can electronically create a differential arm signal
- This is displacement proportional and thus flat at low frequencies

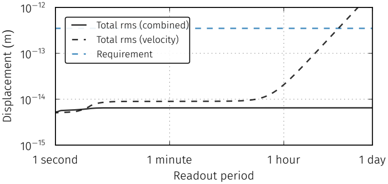


- Blending this feedback at low frequencies allows the speed meter QND behaviour at high frequencies while keeping the arms from losing resonance



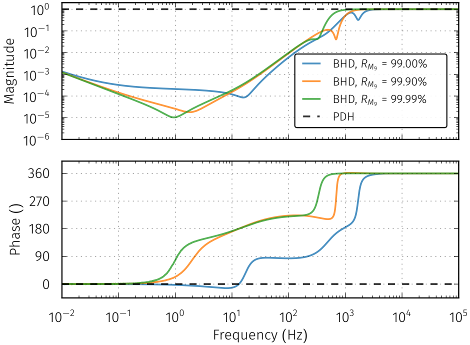
- Control simulations show the drift is suppressed
- The noise fed back by the displacement signal does not affect the QND character in the measurement band



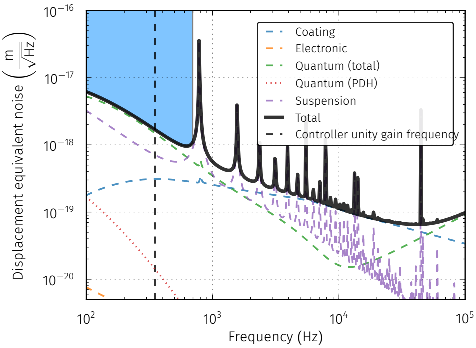


OPTIMAL BLENDING

- Optimal filter can be calculated to blend displacement and velocity signals
- Takes advantage of correlations between the quantum noise arriving at both readout ports
- Shape depends on transmissivity of mode matching mirror

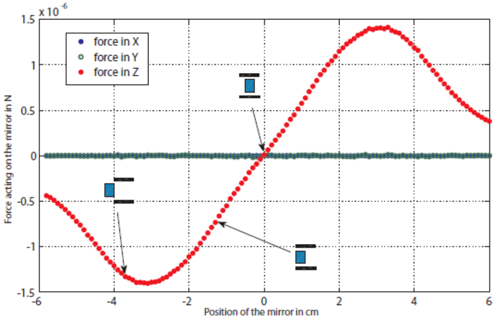


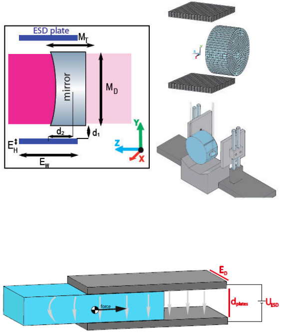
- With the control loop engaged we can calculate the out-of-loop noise budget
- Results show we are QRPN limited between 100 Hz and around 700 Hz



ELECTROSTATIC DRIVES

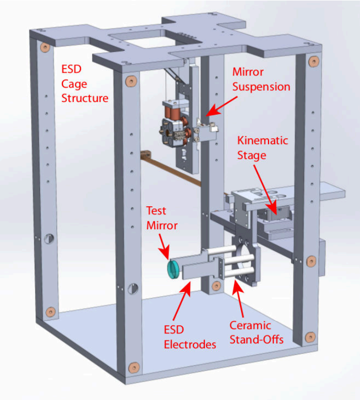
For low noise actuation directly on the test mass, electrostatic drives (ESDs) are used. These are low range but low noise actuators.

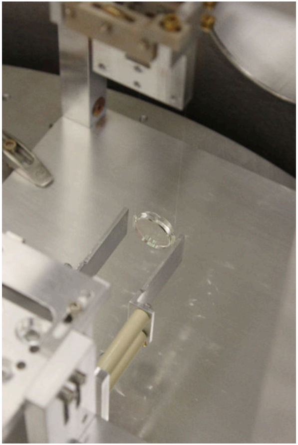




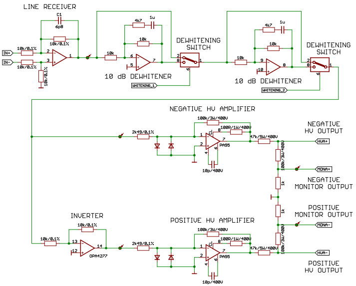
Credit: Wittel et. al. (arXiv)

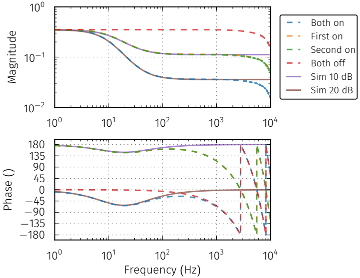
Experiment on-going to test plate capacitor performance using silica fibres



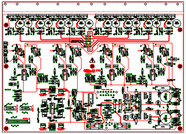


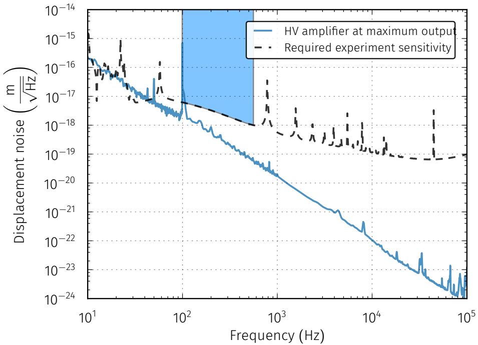
- Four-channel HV amplifier designed to produce low noise ESD actuation up to ±375 V up to 30 kHz
- Digitally switchable dewhitening for lock acquisition / low noise modes
- Noise around 10 μV $\sqrt{\text{Hz}}^{-1}$ in measurement band





- Noise meets the requirement in the measurement band

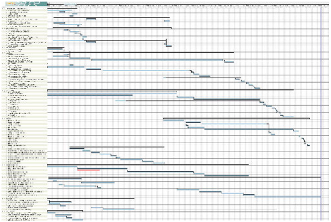


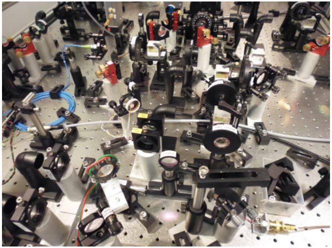


PROOF-OF-PRINCIPLE EXPERIMENT STATUS

ONE YEAR TO GO

- ERC project funded for 5 years, ends October 2017
- Most suspensions designed, some built
- Core and aux optics arrived or in manufacture
- Longitudinal control scheme designed
- Lock acquisition concepts available
- Much greater understanding of quantum and technical noise sources
- **Commissioning to begin soon!**





PLANS

CONCURRENT AND FUTURE ACTIVITIES

- **2017-2019**: possible installation of squeezer, signal recycling, other fancy add-ons
- **2014-2016**: tests of 1550 nm laser and polarisation optics
- **2016+**: tests of polarisation optics in the 10 m prototype towards a polarisation/circulating Sagnac
- **2017+**: building of 10 m scale sloshing Sagnac to test control and reduced quantum and coating noise

PEOPLE


Daniela Pascucci


Alasdair Houston

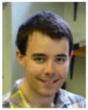

Teng Zhang


Christian Gräf


Russell Jones


Stefan Hild


Sebastian Steinlechner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Jan-Simon Hennig


Stefan Danilishin

+lots of help from Ken Strain, Bryan Barr, Angus Bell, Liam Cunningham, Borja Sorazu, Sabina Huttner, Jennifer Wright, Andrew Spencer

INTERNATIONAL COLLEAGUES

Questions?