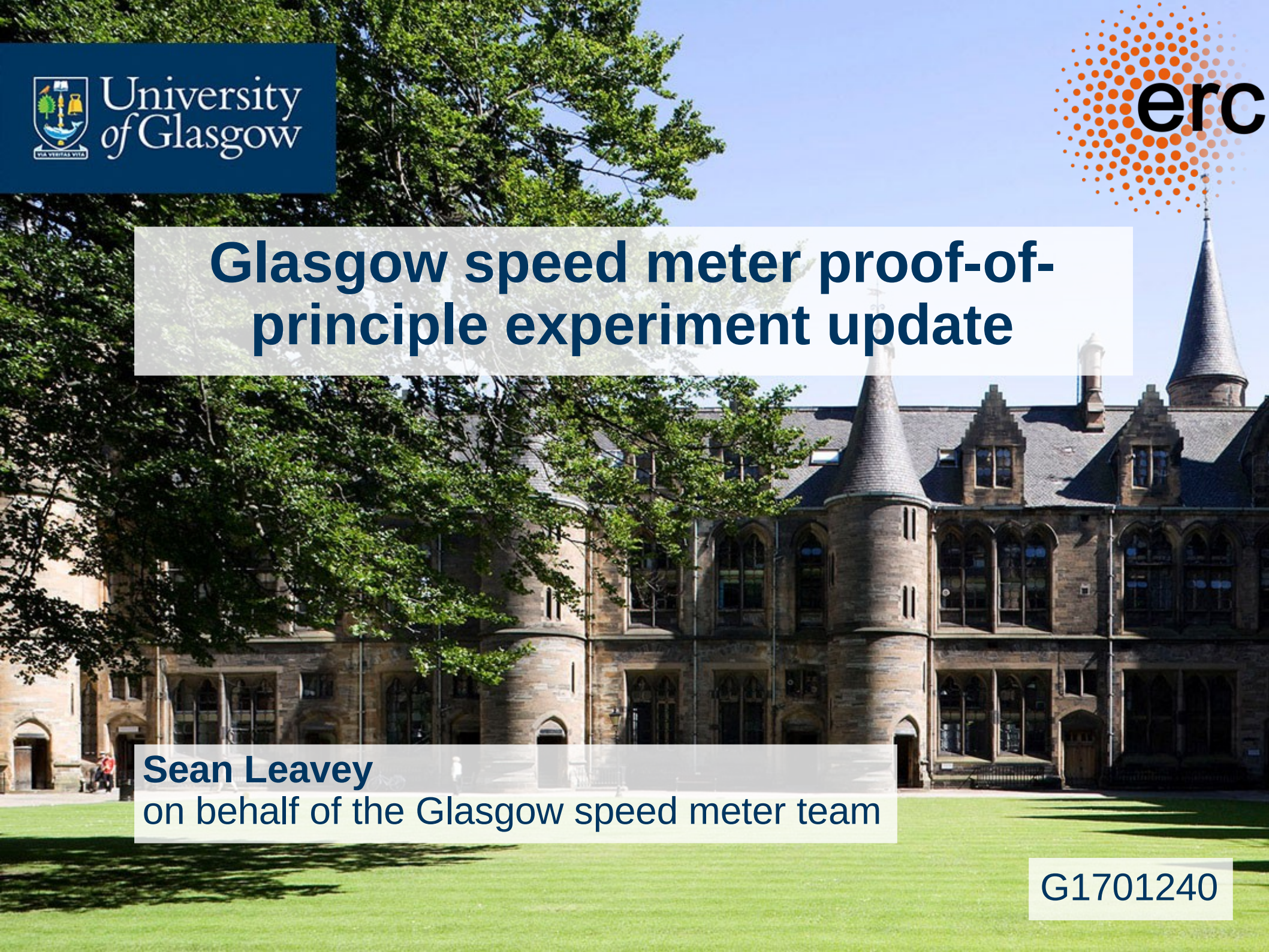


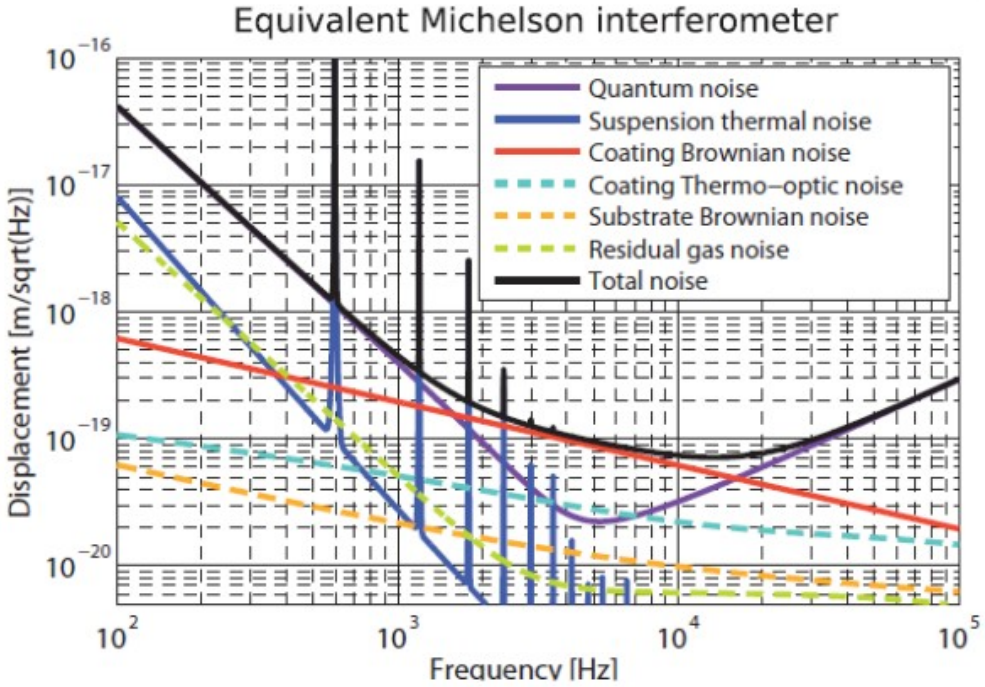
Glasgow speed meter proof-of-principle experiment update

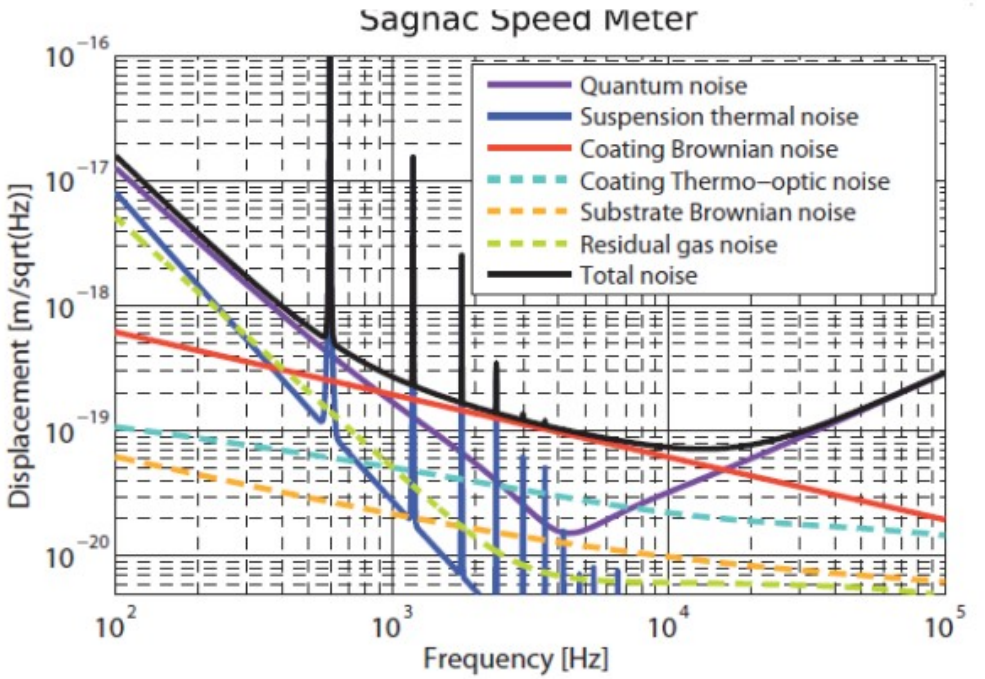
Sean Leavey
on behalf of the Glasgow speed meter team

G1701240

The Glasgow speed meter

- ERC-funded project to test the Sagnac speed meter concept
- **Aim:** show reduced back-action noise over an equivalent Michelson
- Target frequency: 100-1000 Hz
- 1g, 4-stage monolithic ITMs
- 100g, 3-stage monolithic ETMs
- Finesse ~7000, 1kW circulating power
- Sophisticated seismic isolation
- 2.8m round trip length

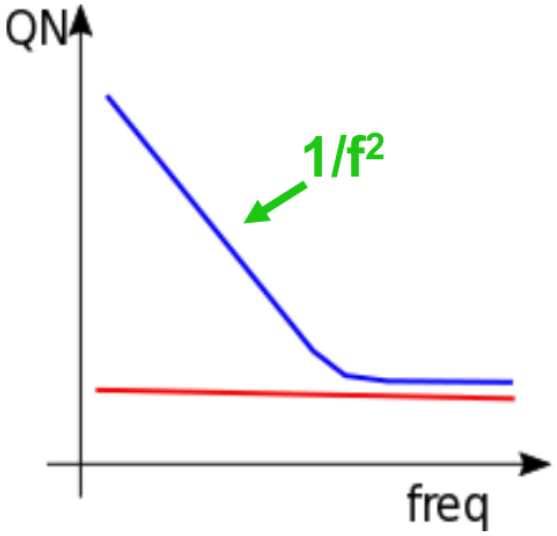


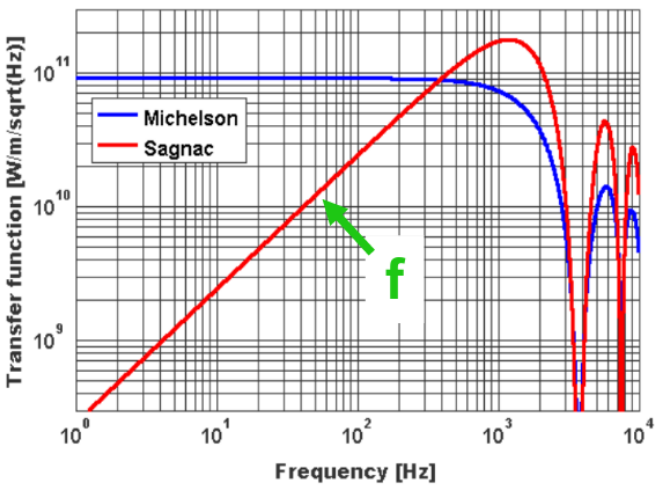


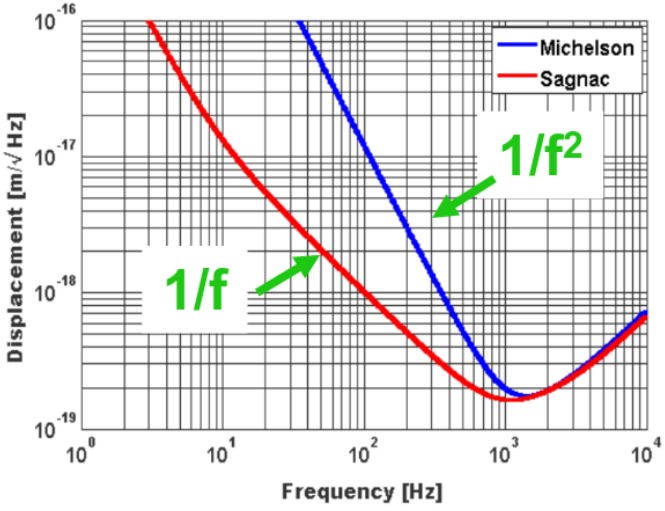
Speed meters

- Reduced response at low frequencies...
- ...But even further reduced quantum noise
- So in theory, sensitivity improved by 1/f below pole...
- ...But speed meters more sensitive to certain types of loss
- Many potential reasons to explore speed meters in GW detectors: better LF sensitivity, less stringent requirements for squeezing filter cavity and injection loss, coating noise reduction

Quantum noise / **Signal transfer function** = **Quantum noise Limited sensitivity**

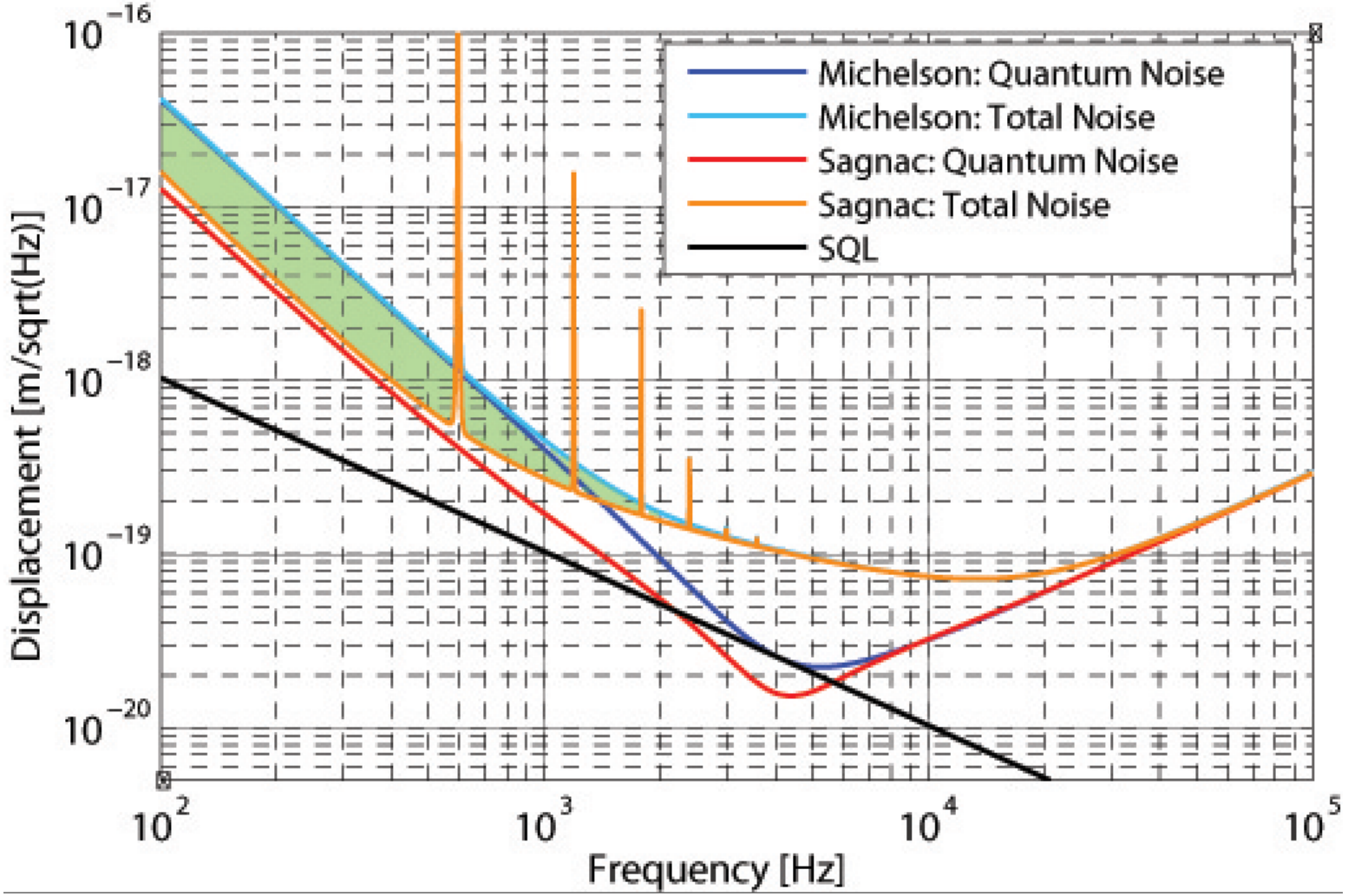




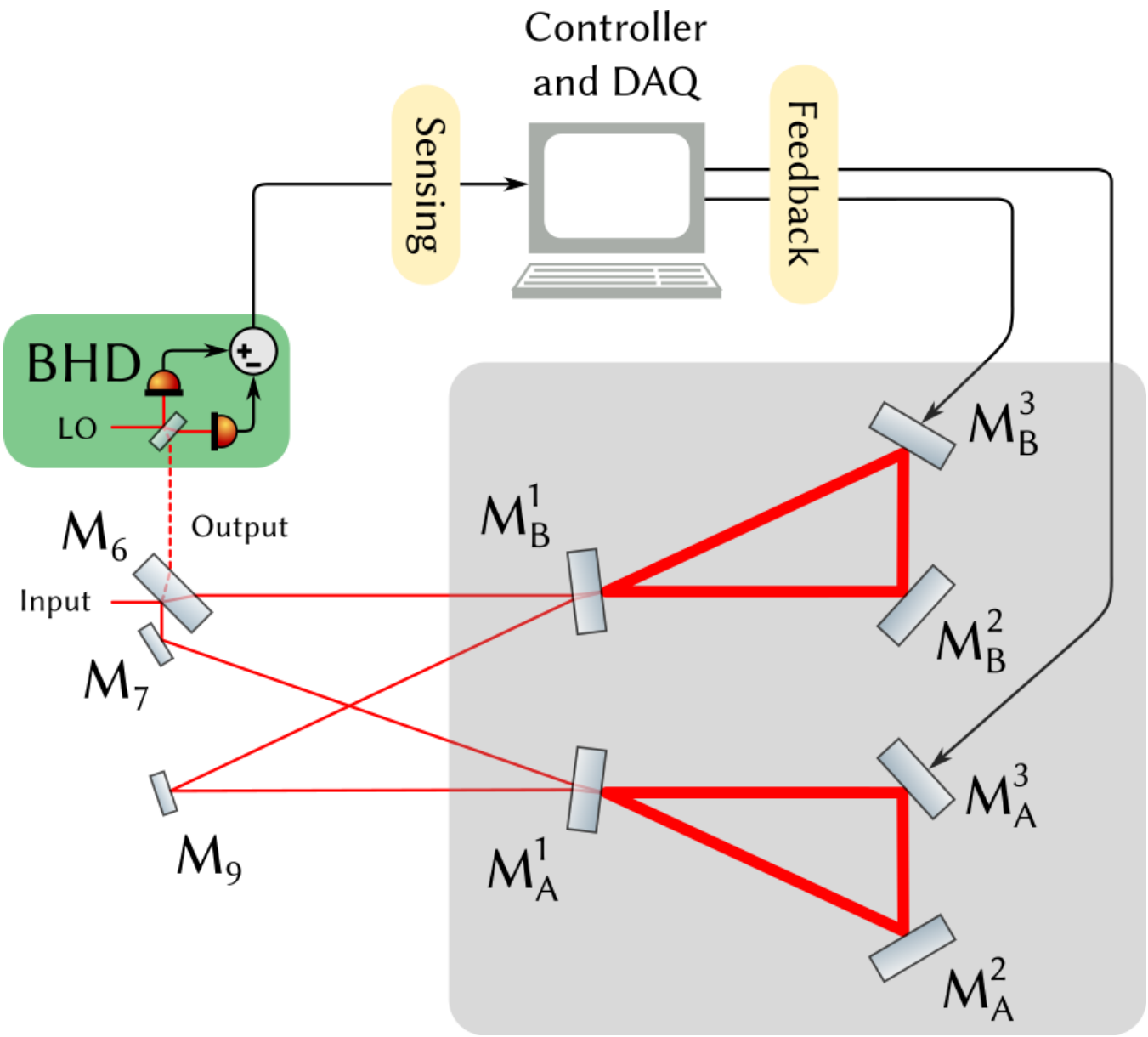


The Glasgow speed meter

- We want to get into the green area
- Target band: 100-1000 Hz
- Limited above by coating noise, below by suspension cross-couplings



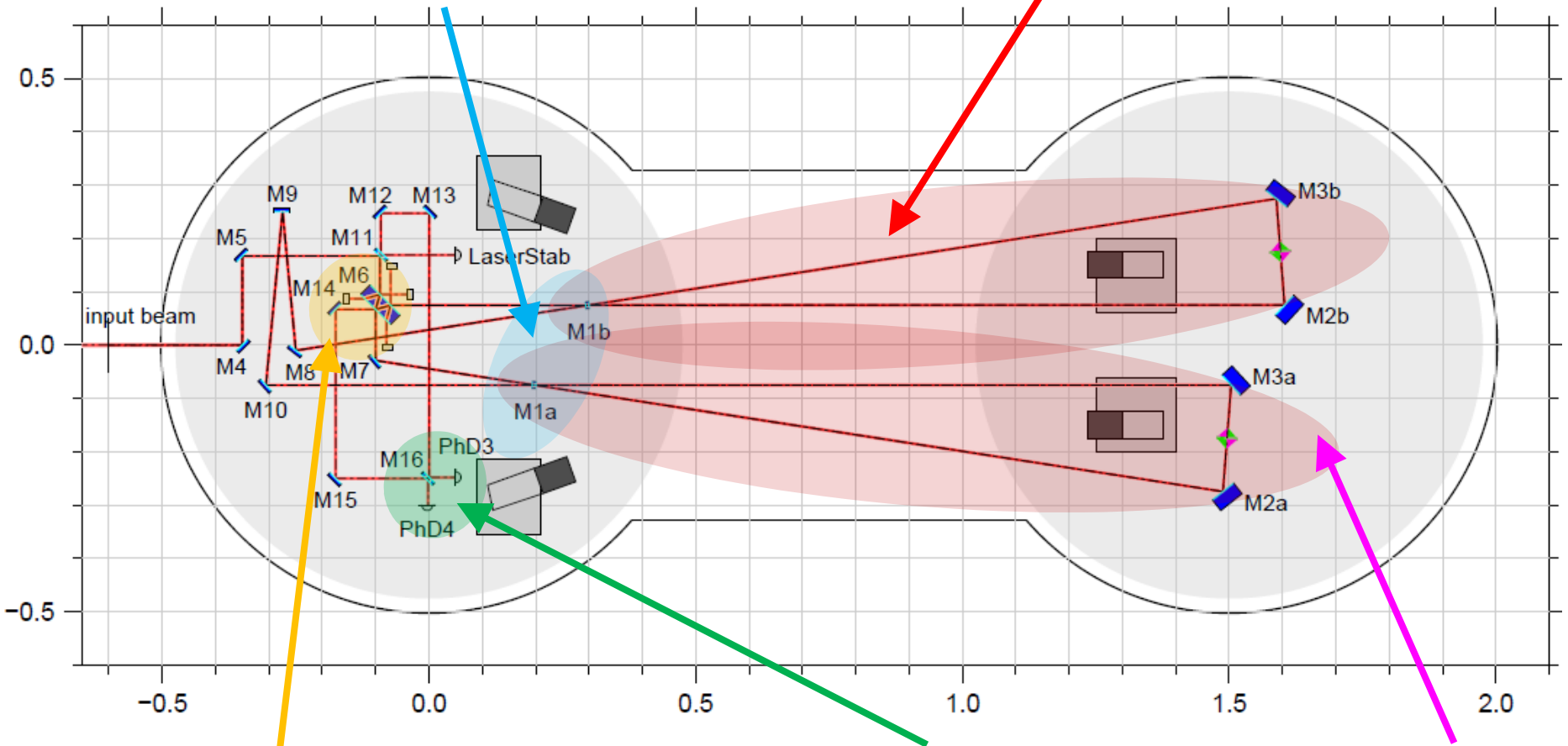
The Glasgow speed meter



Looks simple on paper!

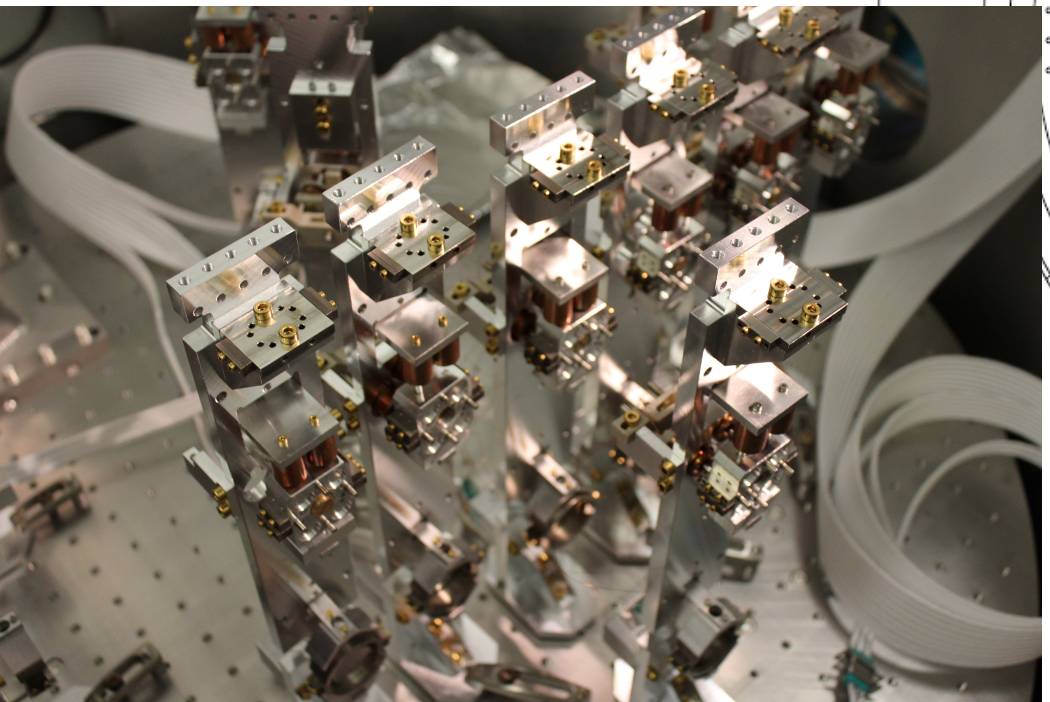
The Glasgow speed meter

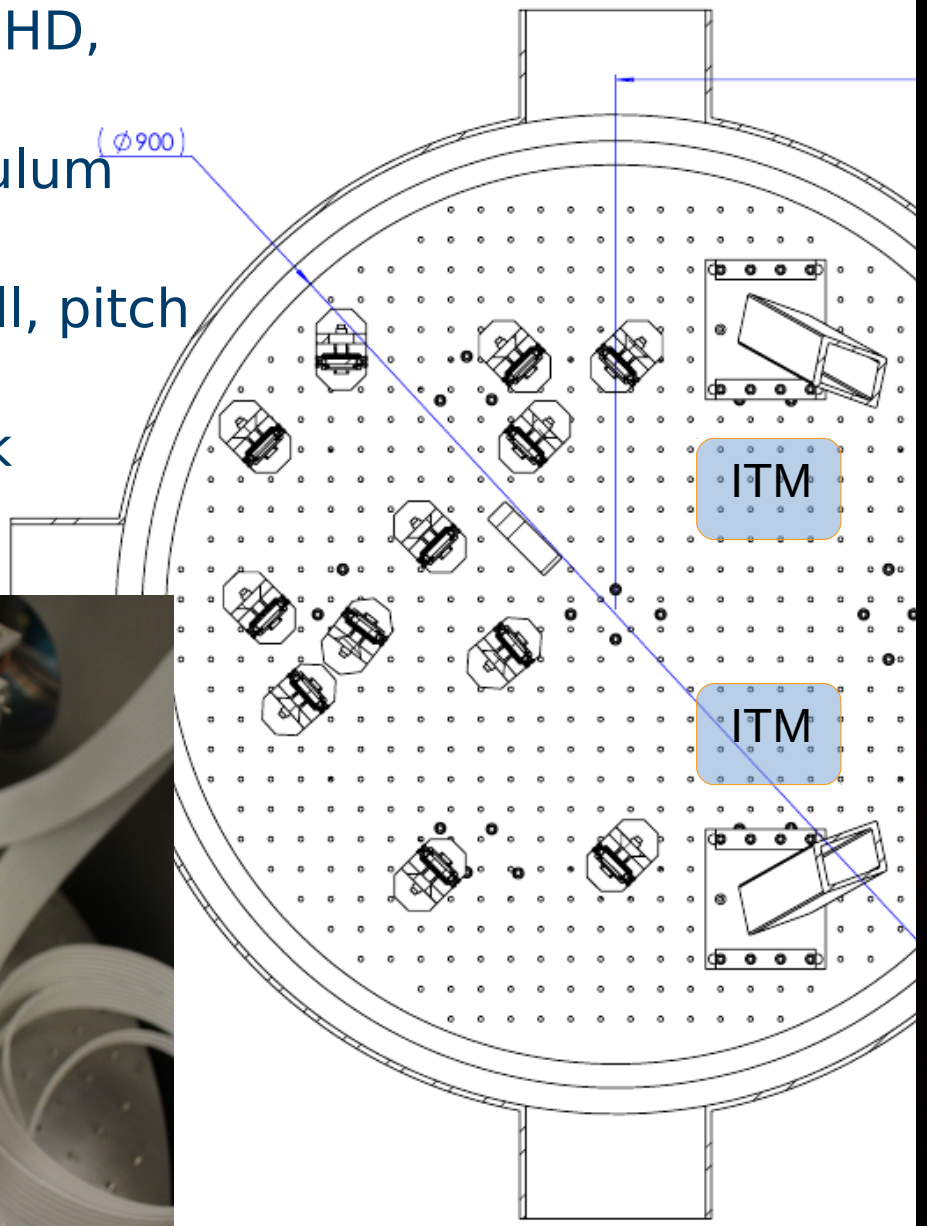
- 1m-scale vacuum experiment in seismically isolated tanks

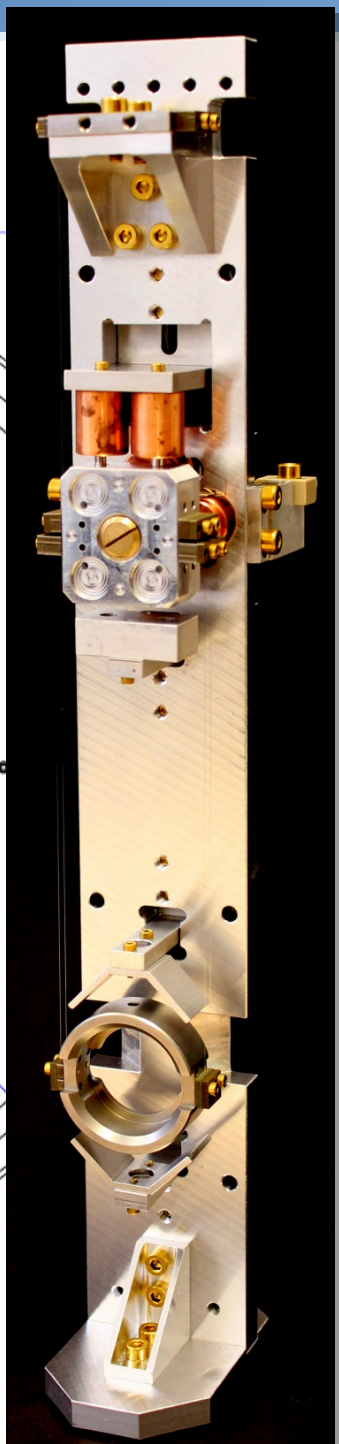


Auxiliary suspensions

- Beams need steered in vacuum to various locations (cavities, BHD, photodiodes)
- Low profile, two-stage pendulum design
- Eddy current dampers for roll, pitch and yaw
- We have to fit 12 in one tank
- All suspensions assembled

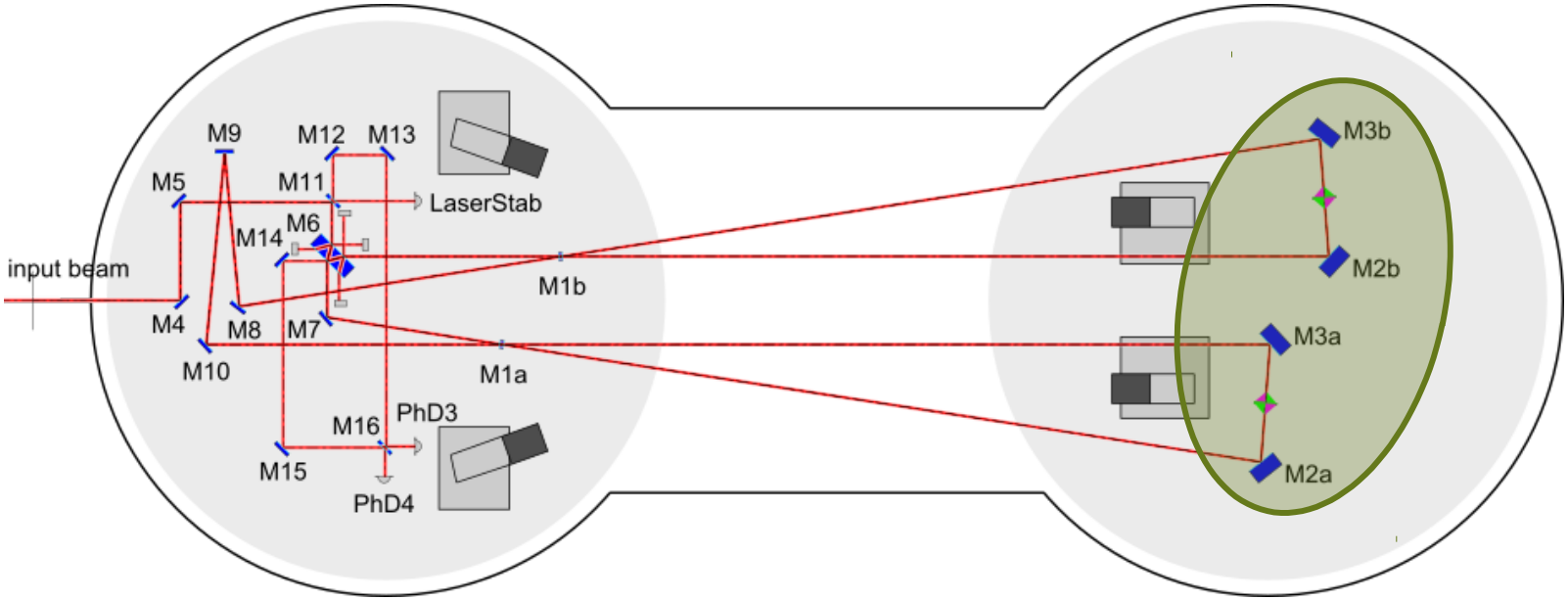






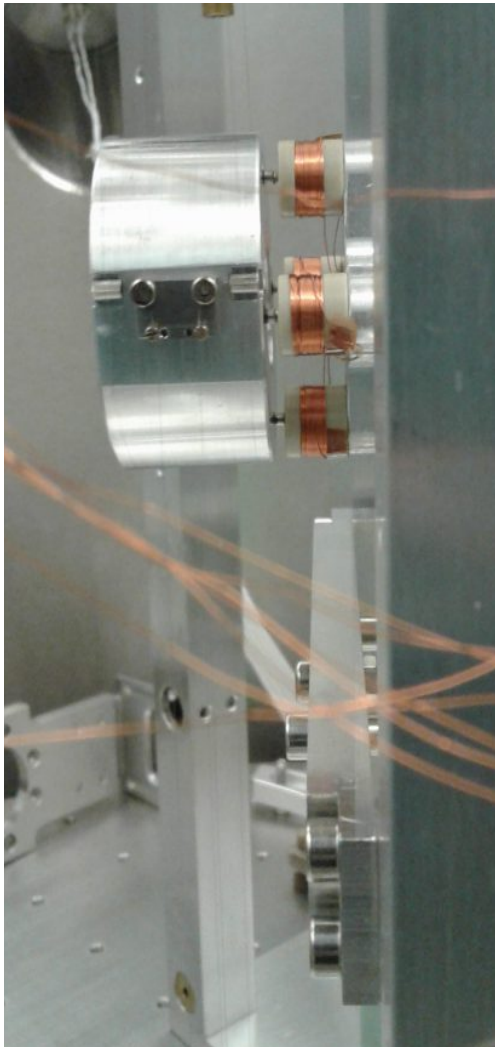
100g ETM suspensions

- Initially designed in Glasgow for the AEI 10m SQL prototype (see David Wu's talk)
- Recycled for speed meter ETMs, modified for 45° incidence and smaller footprint
- Triple stage pendulum, two stages of cantilever blades, eddy current damping / coils on top mass, coils on penultimate mass, ESD actuator on test mass



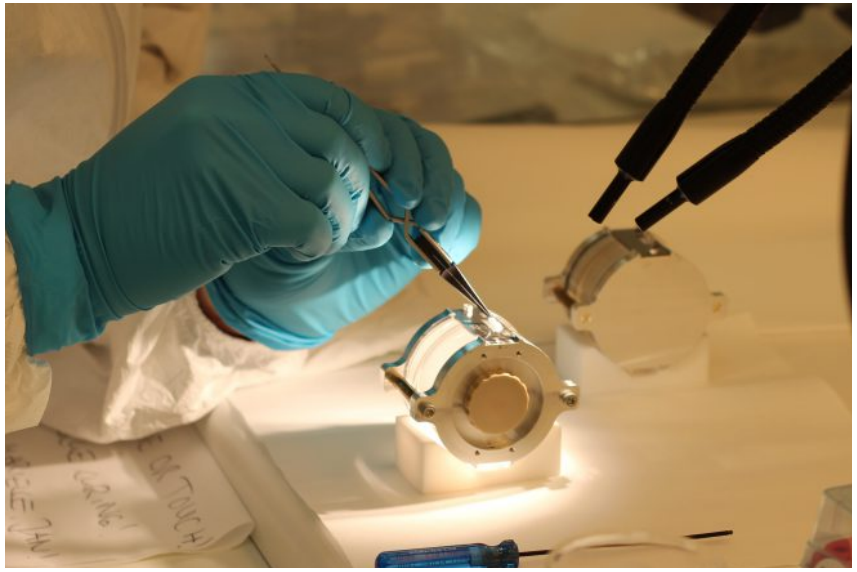
100g ETM suspensions

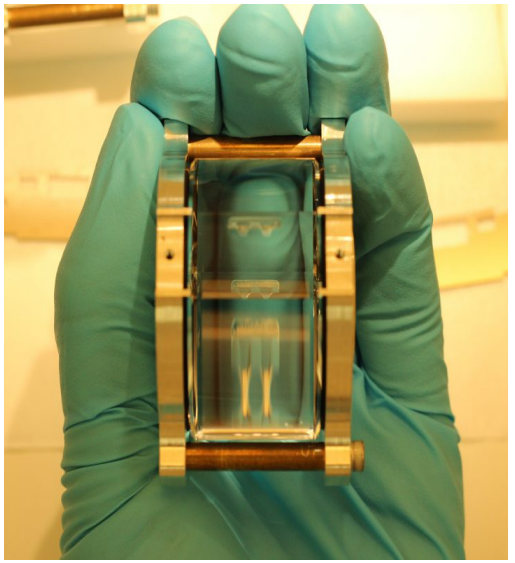
- All ETM structures fully assembled, 2/4 have hanging optics
- Suspended with mock metal masses while monolithic stages are being prepared
- Measured mode frequencies close to design values

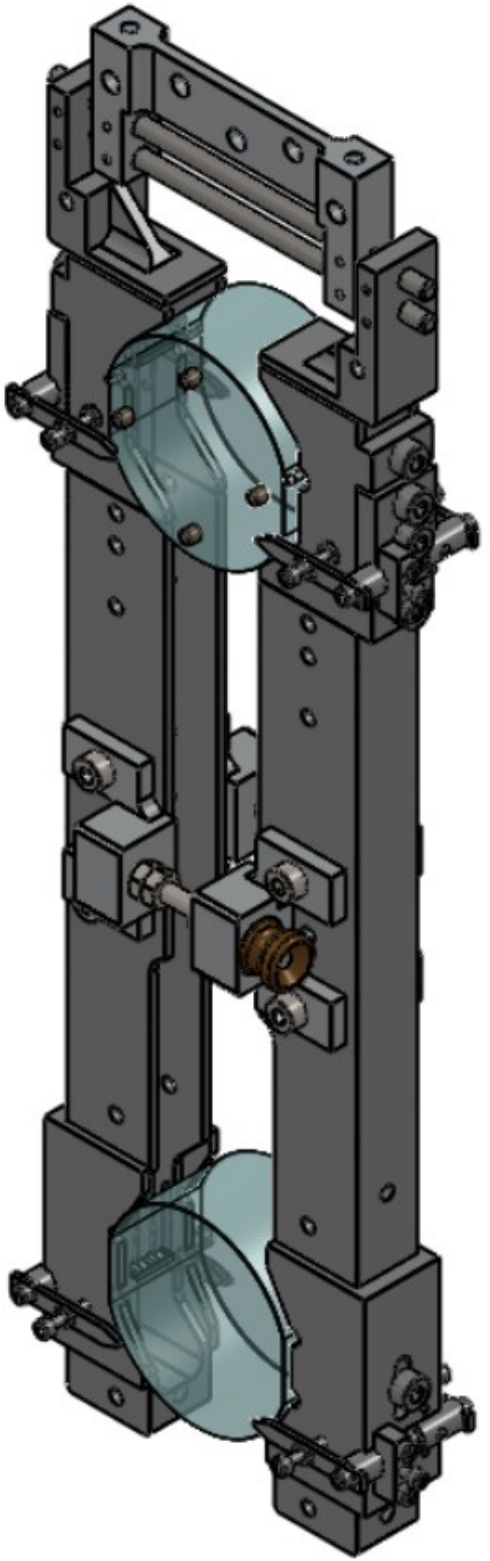


100g ETM monolithic stages

- Silica PUM/TMs connected with 20µm silica fibres
- Silica ears bonded to masses using hydroxy catalysis
- Welding melts fibre stock to silica ears for low-loss joints
- Should keep suspension thermal noise from spoiling quantum noise
- PEEK fibre guards prevent damage during transit, installation and “earthquakes”

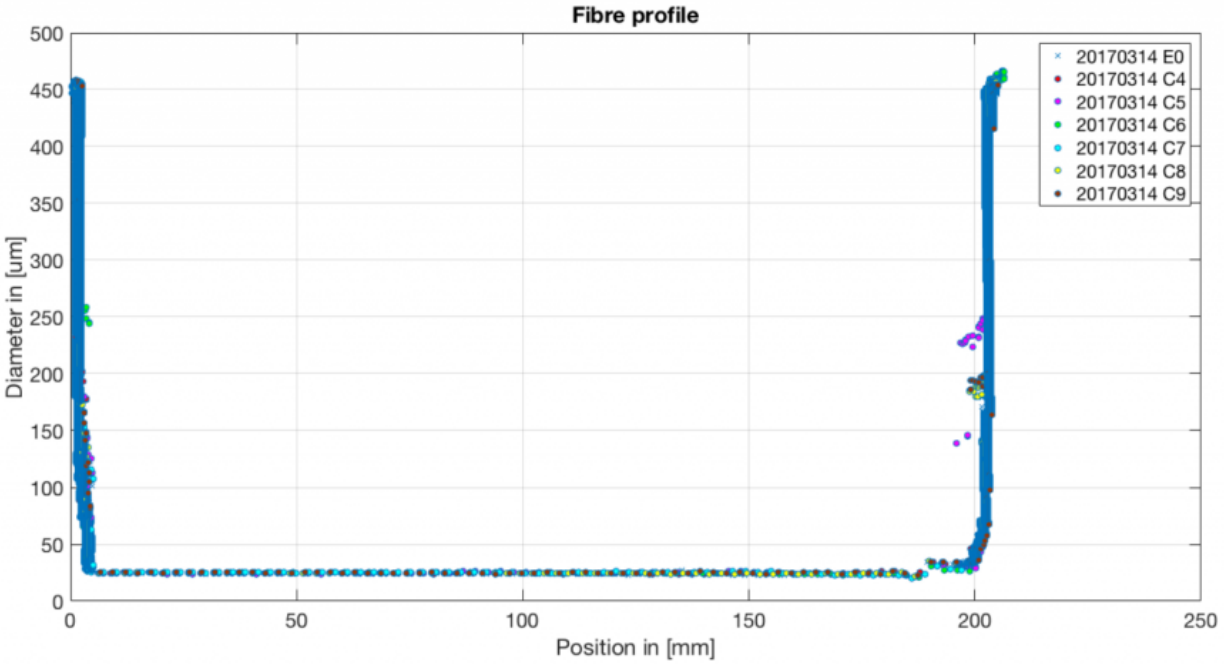


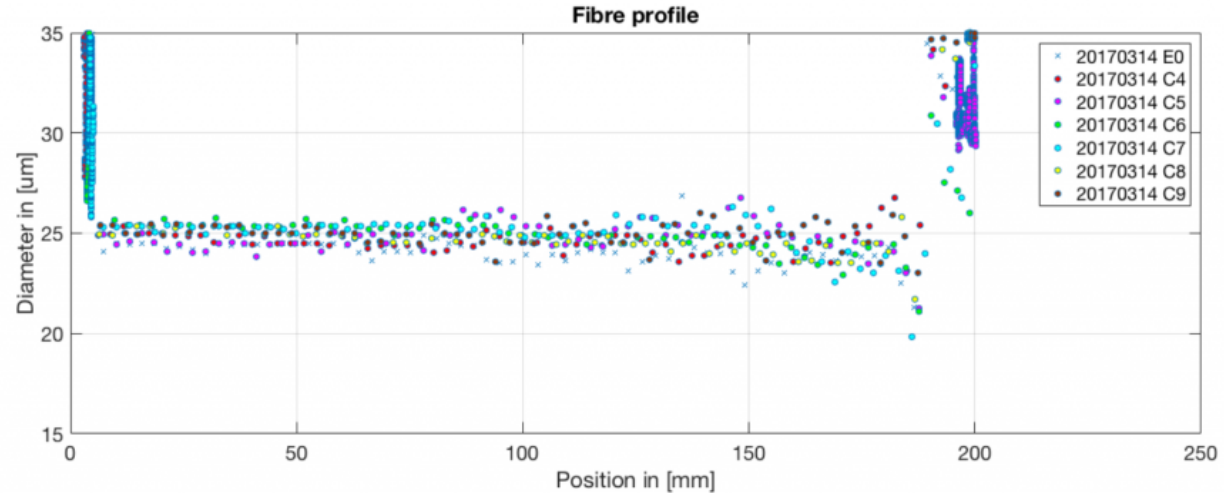


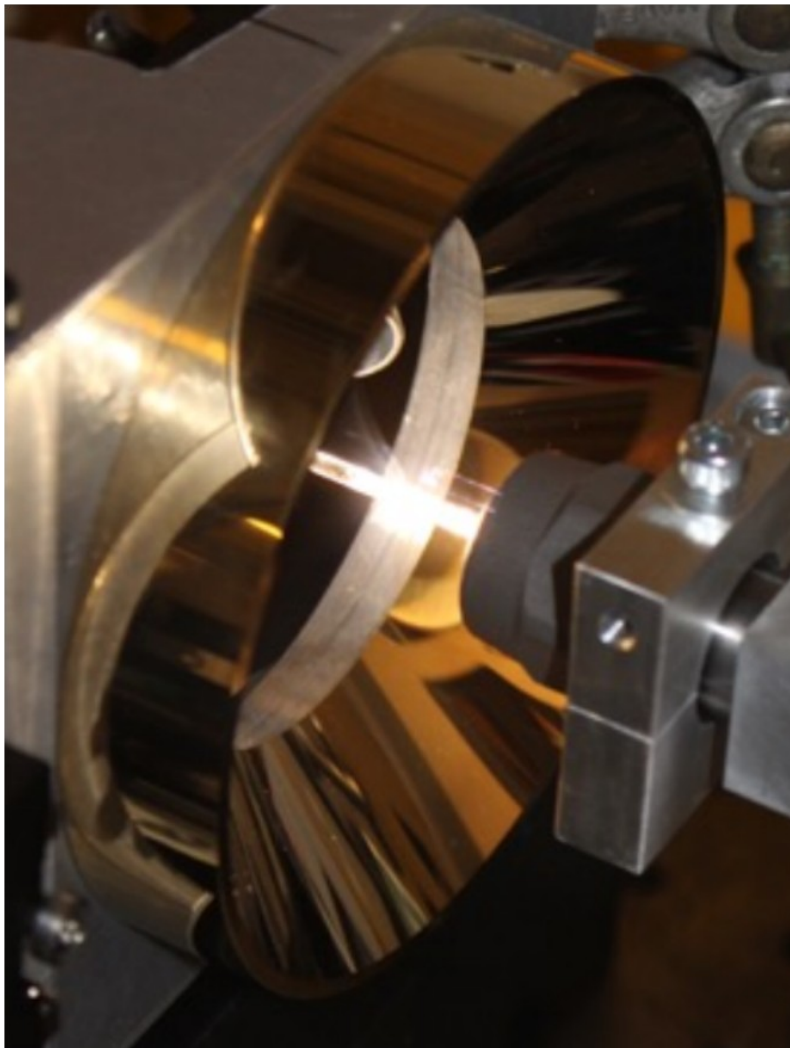


100g ETM monolithic stages

- Fibres show good uniformity along length



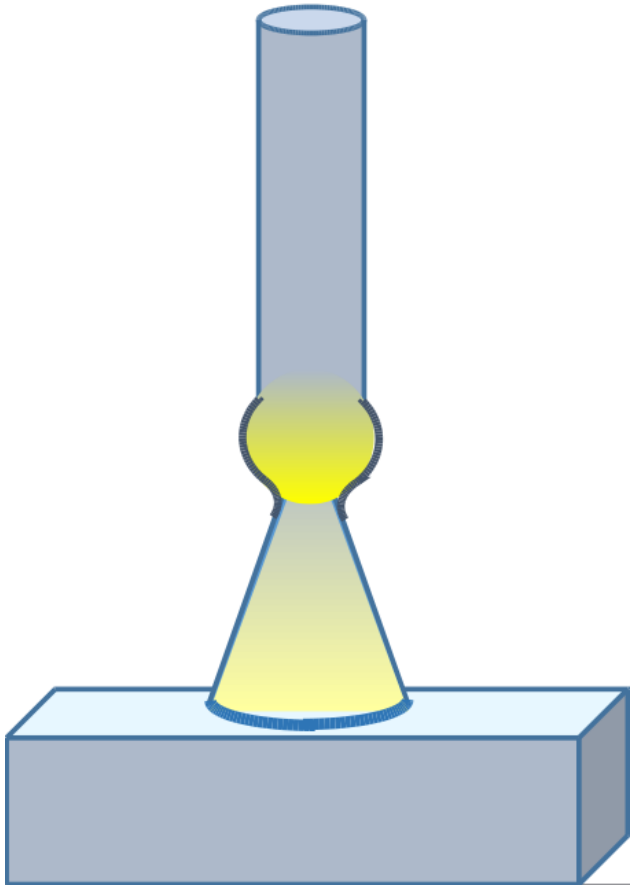


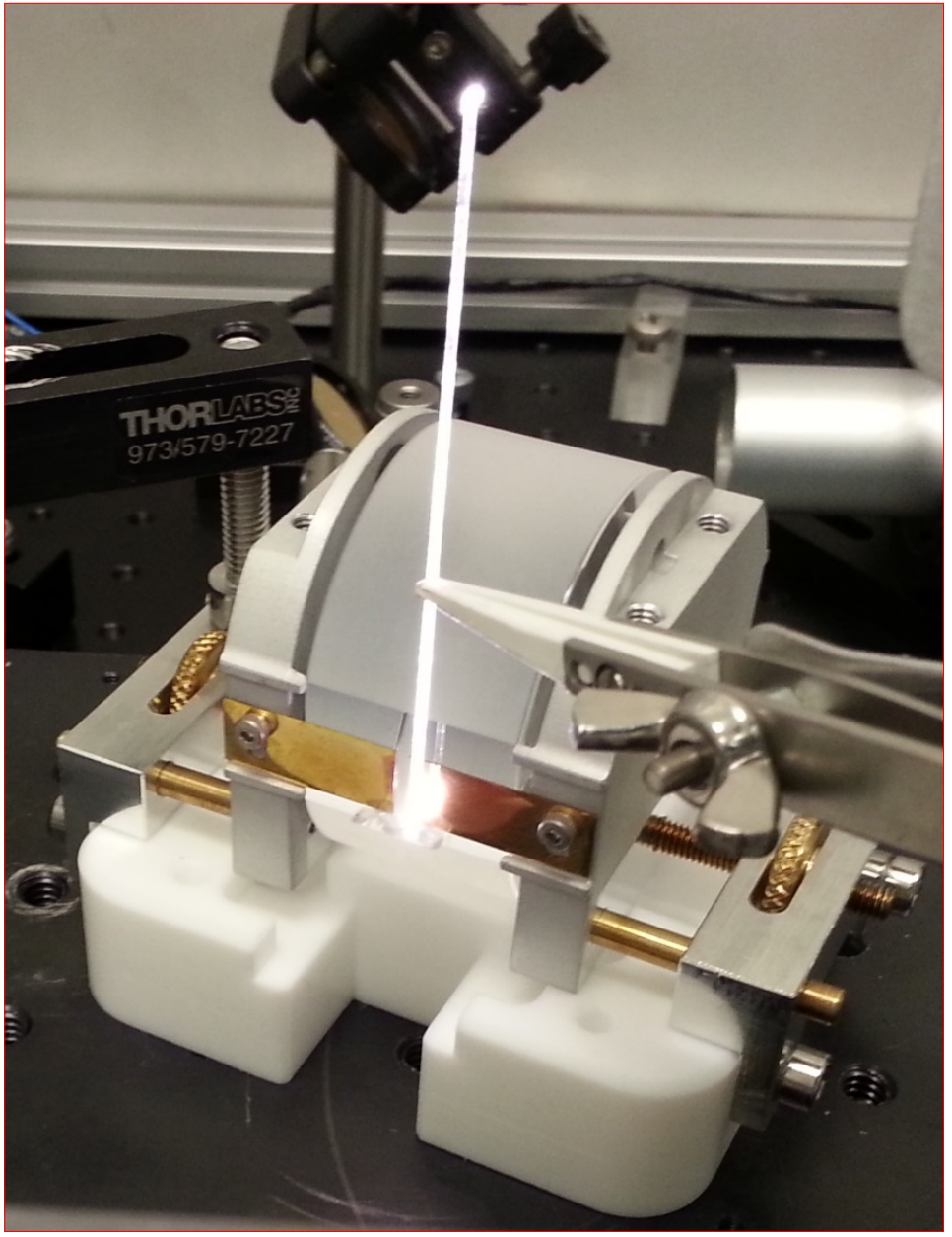


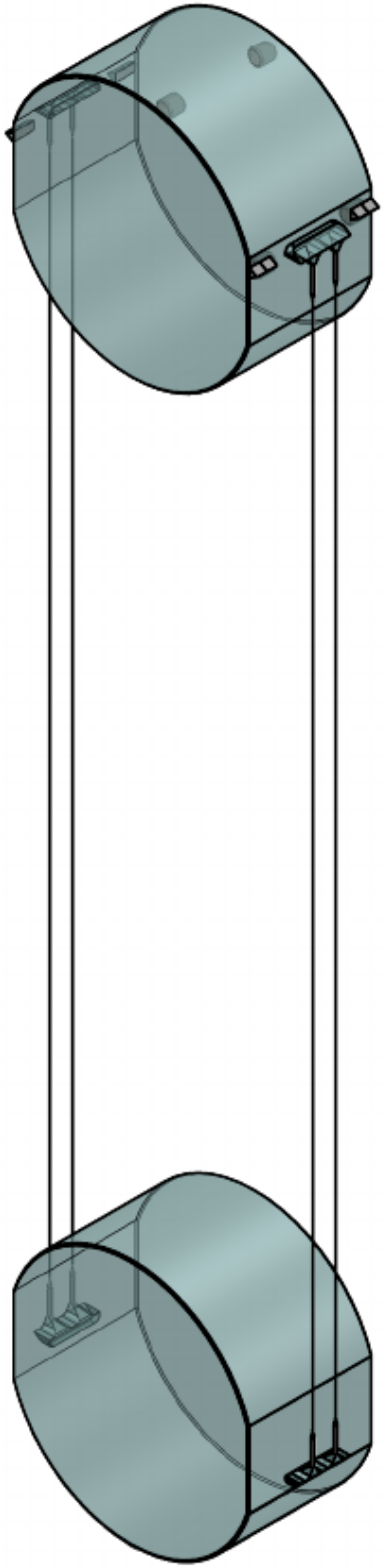
See G1700805 (Jan Hennig)

100g ETM monolithic stages

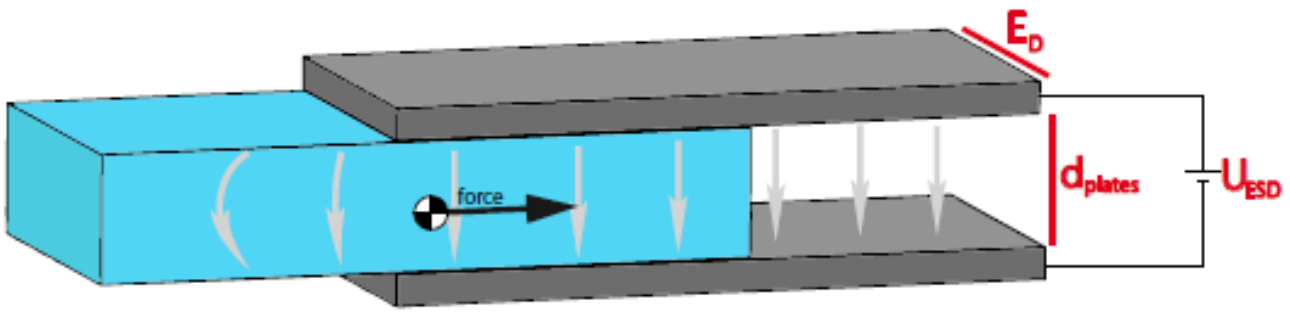
- Welding in progress right now







100g ETM ESD actuators



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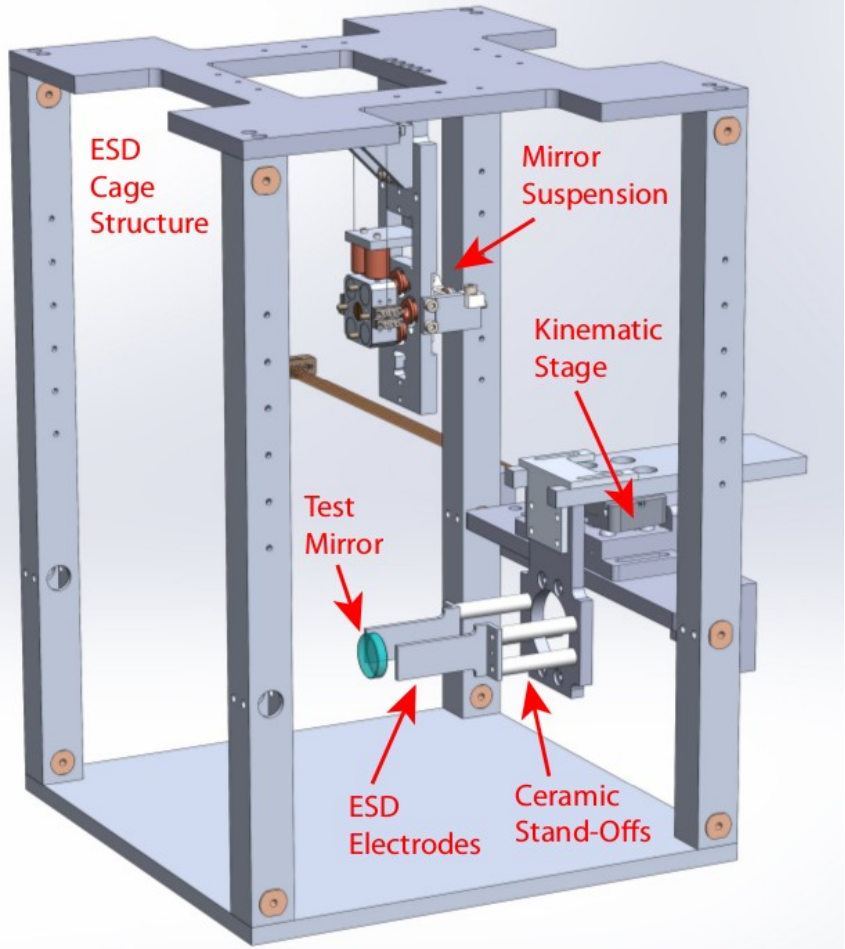
IOP Publishing
Classical and Quantum Gravity
Class. Quantum Grav. 32 (2015) 175021 (11pp)
doi:10.1088/0264-9381/32/17/175021

New design of electrostatic mirror actuators for application in high-precision interferometry

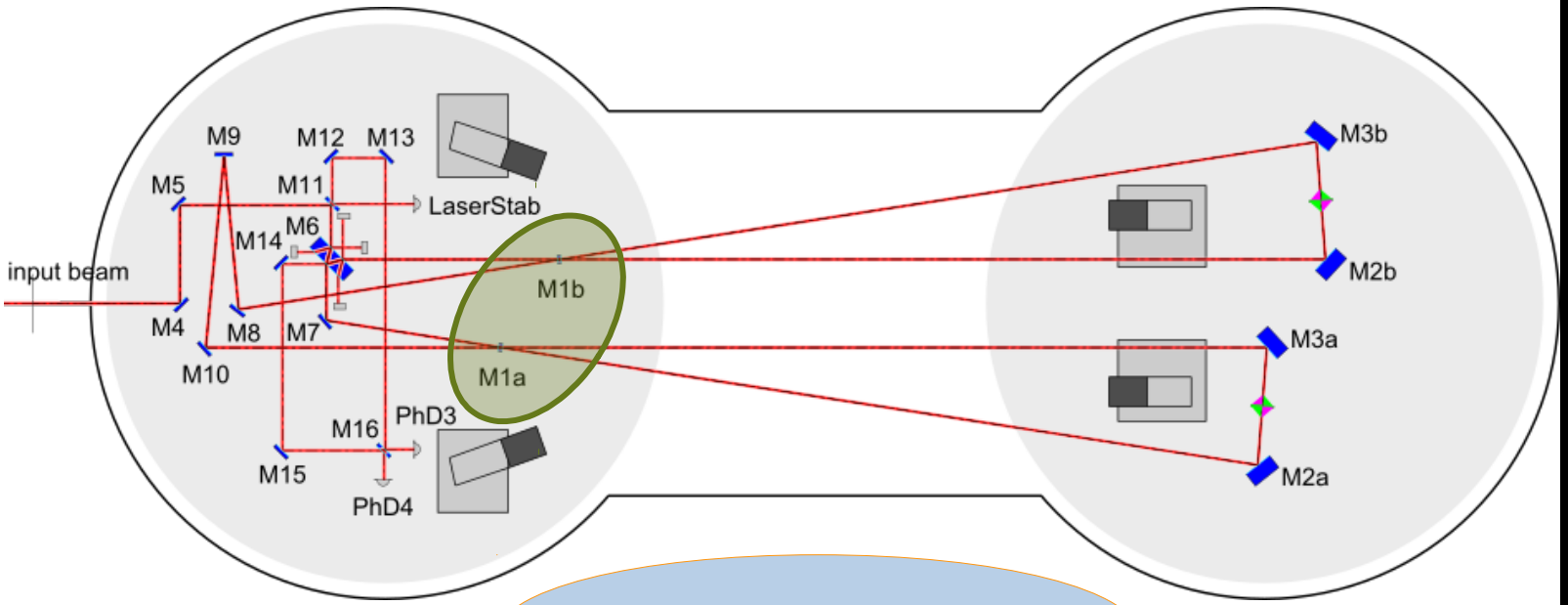
H Wittel[1], S Hild[2], G Bergmann[1], K Danzmann[1] and K A Strain[1,2]

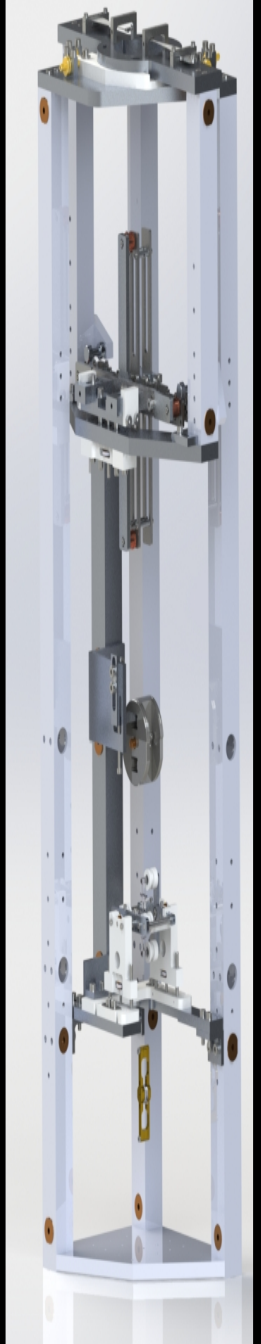
- ESD actuators based on concept by Holger Wittel and Ken Strain
- Allows access to transmitted beam
- Force scales as V^2
- Fringe field from parallel plates creates force on optic while allowing transmission
- Low coupling of seismic noise even when mounted on table
- LIGO-style HV drivers built to provide 750V potential difference
- Test experiment to assess plate alignment requirements nearing completion



1g ITM suspensions

- Quadruple suspension with monolithic 10µm fibre stage
- Identical suspension point and top stage to 100g ETM design
- Four stages required for isolation
- Parts in production now, soon to be assembled

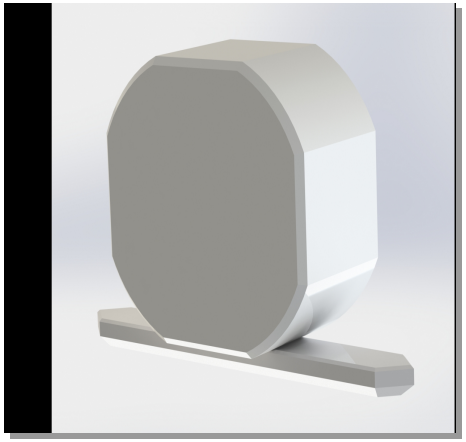


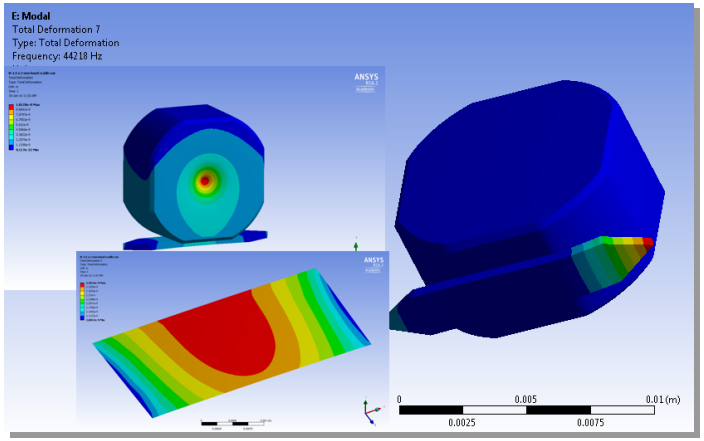


See G1700805 (Jan Hennig)

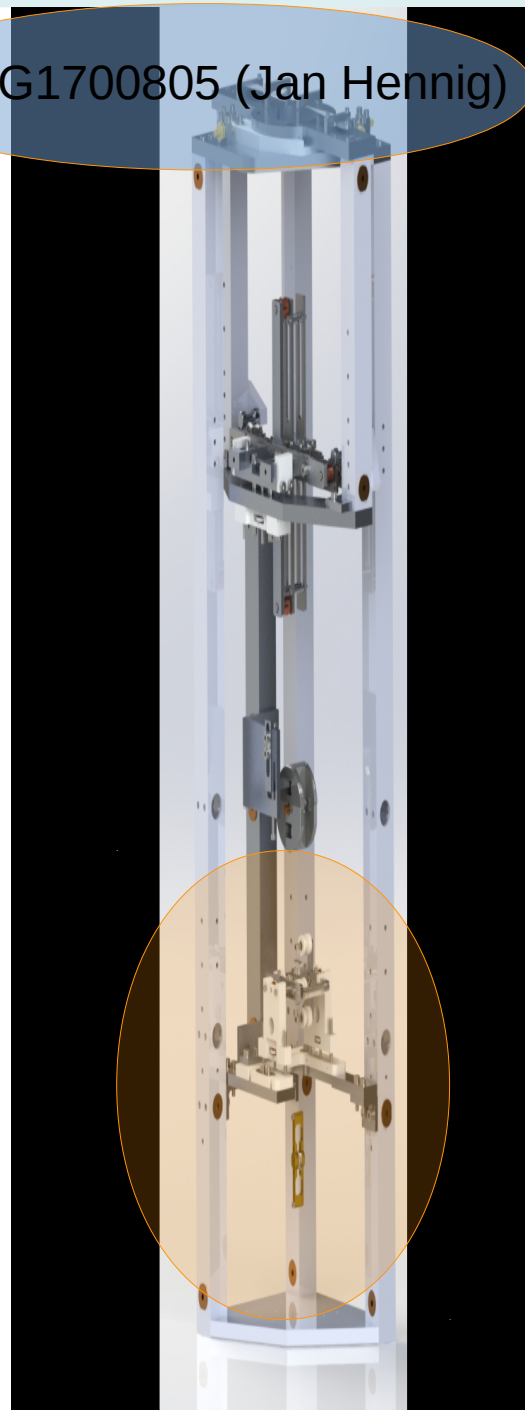
1g ITM monolithic stages

- Fused silica “cross” penultimate mass
  - Fibres from test mass hydroxy catalysis bonded to block on cross piece
  - Retractable coil actuators
- Fused silica final stage fibres
  - 10cm long, 10um thick
- Fused silica 1g test mass
  - Size of finger nail
  - Too fiddly to attach ears
  - Low-loss cradle design to hold mass



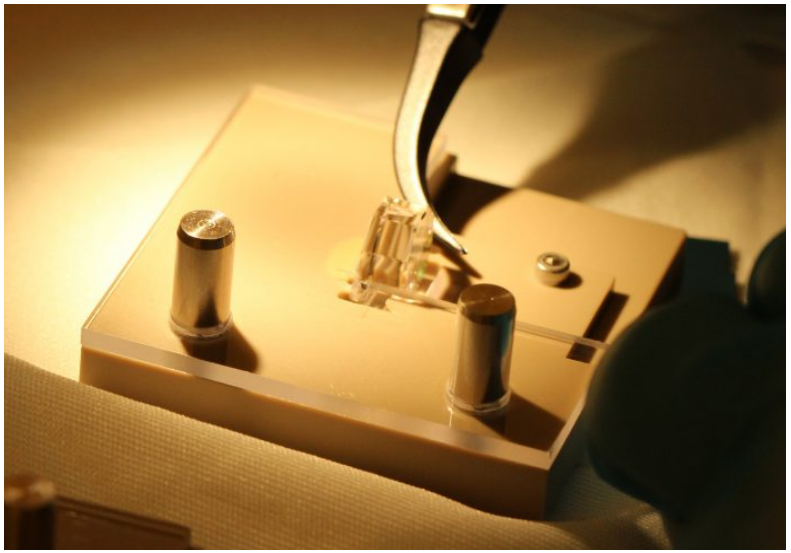


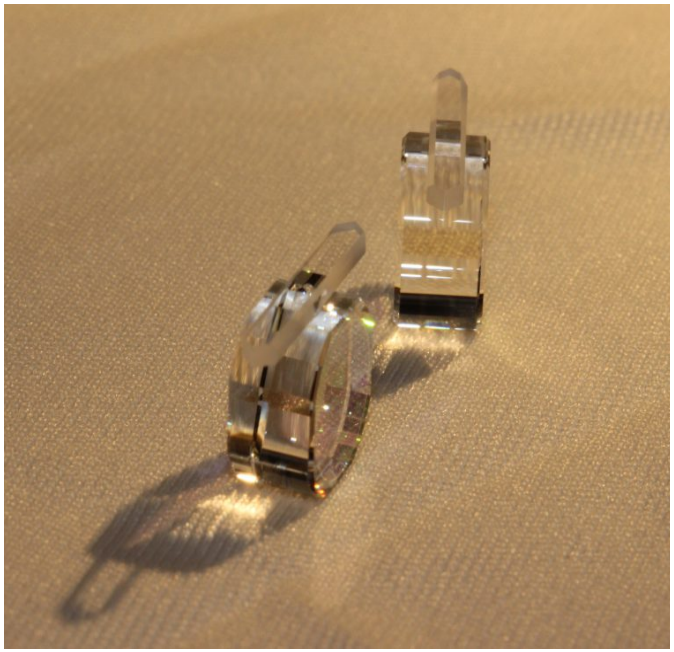
See G1700805 (Jan Hennig)

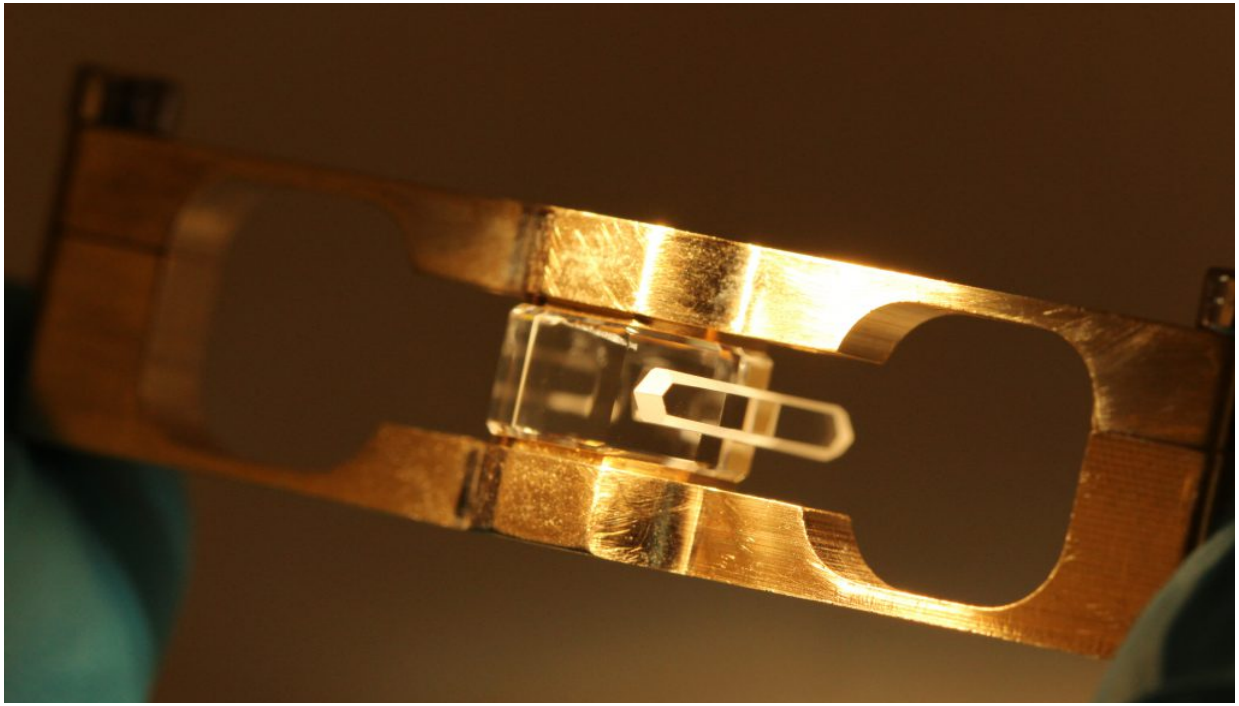


1g ITM bonding

- Cradle bonding complete

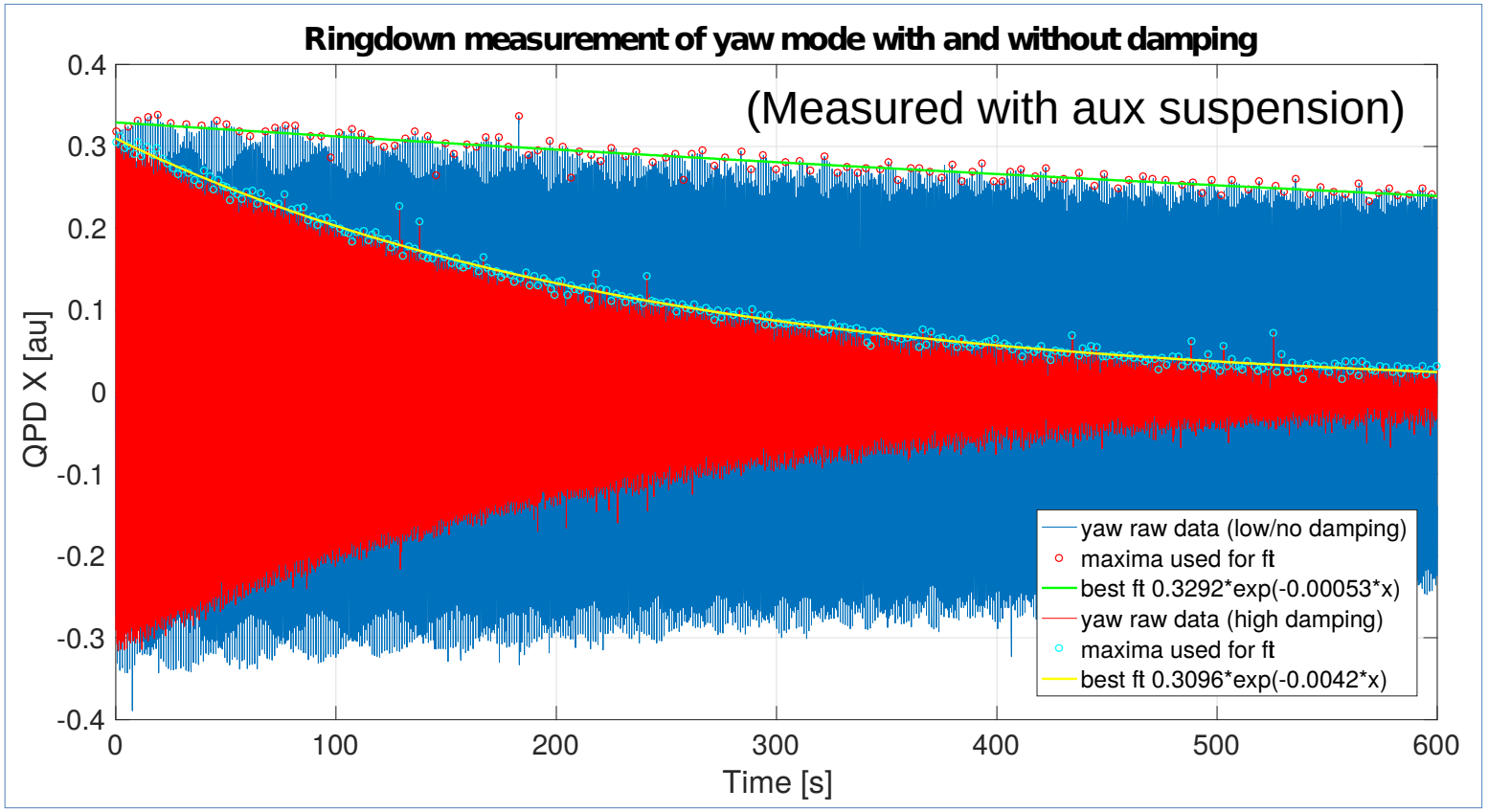






1g ITM switchable eddy current damping

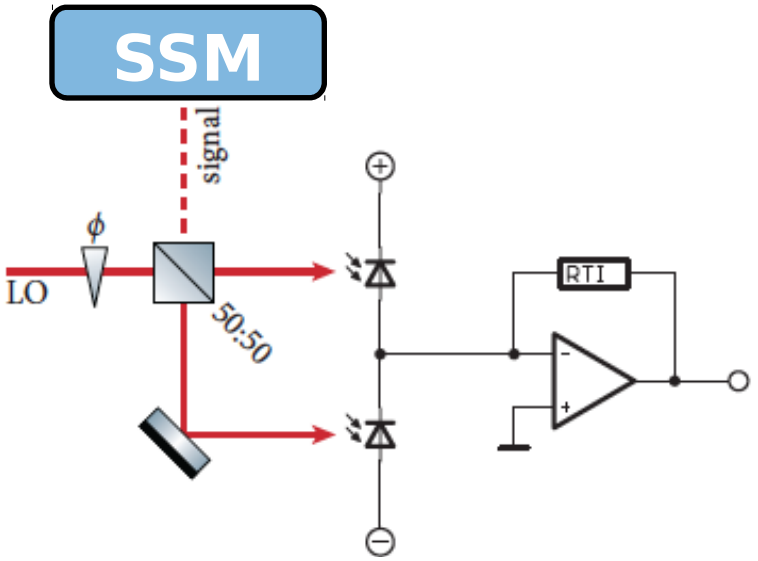
- Switchable eddy current damping on PUM
  - Required damping too high due to Q of system
  - Noise of large coil-magnet actuators would spoil sensitivity
  - Eddy current damping must be **switchable**
  - Extra order of magnitude damping on command

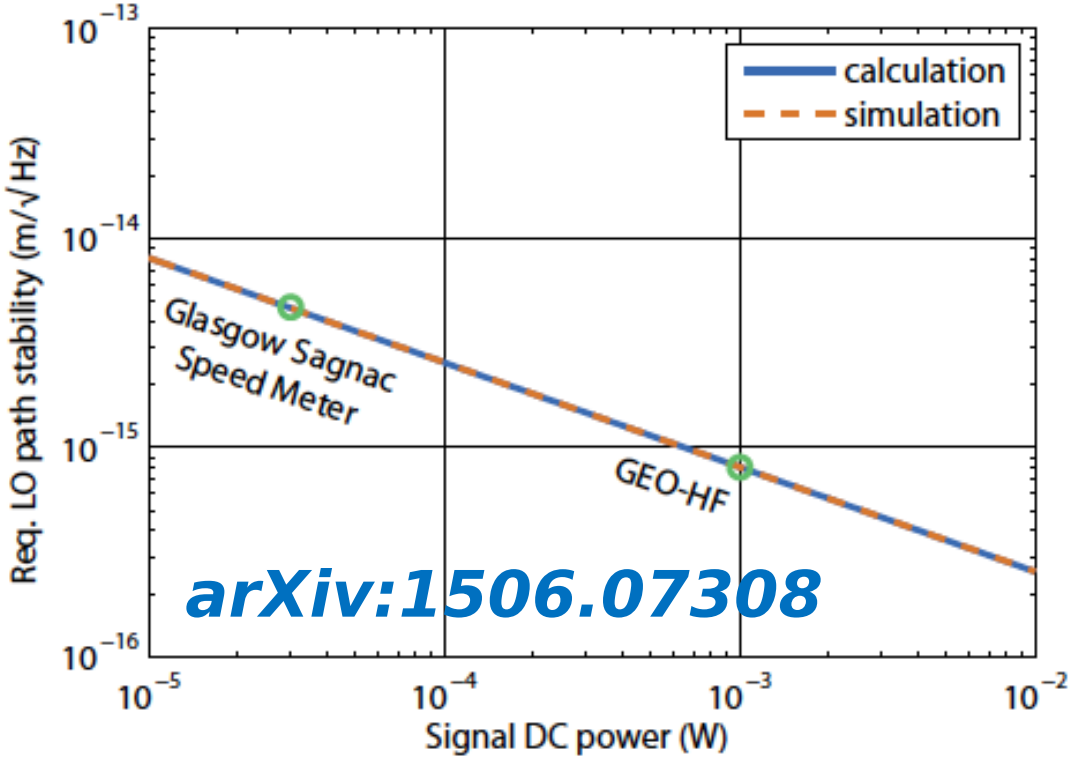


See G1700805 (Jan Hennig)

Balanced homodyne readout

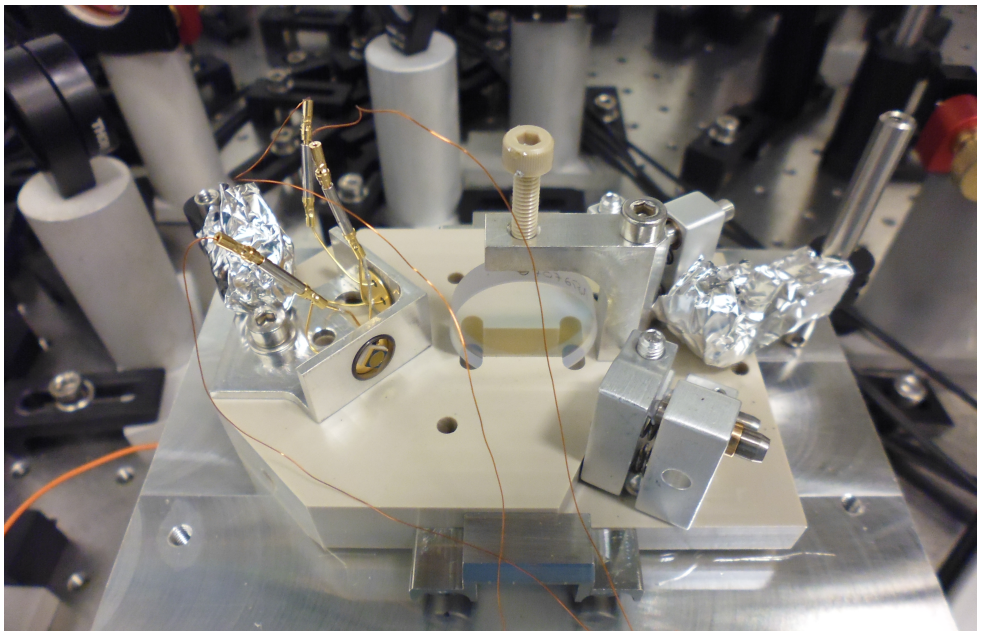
- DC readout doesn‘t work, need external LO
- Selecting the right readout quadrature is essential
- LO phase stability critical for noise
- Well established tool in bench-top quantum optics experiments, less so in suspended interferometers…
- Results may inform aLIGO+

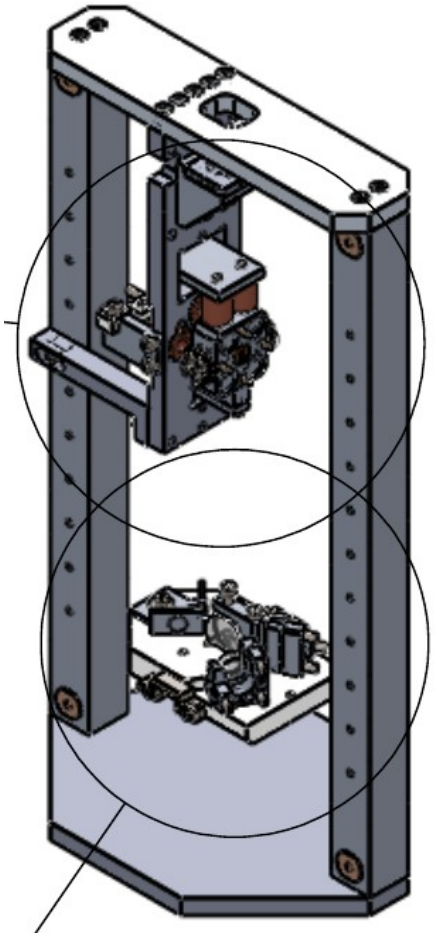


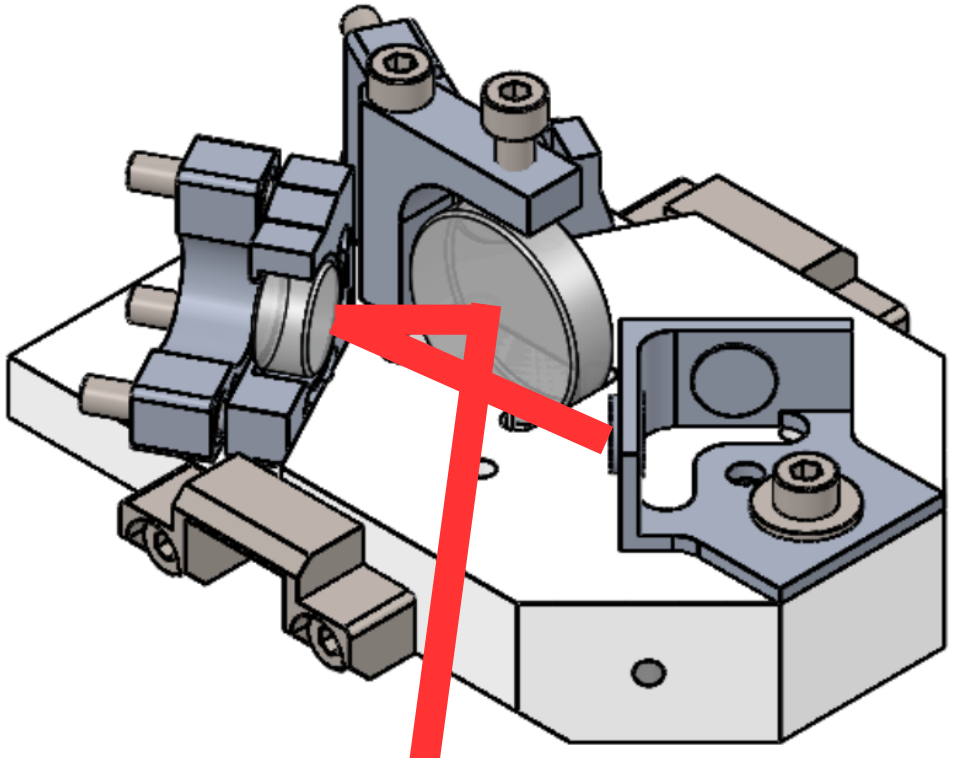


Balanced homodyne readout

- Designed in-vacuum BHD readout
- Displacement noise being measured in air with same input optics
- Soon to be moved to vacuum system for LO stability tests

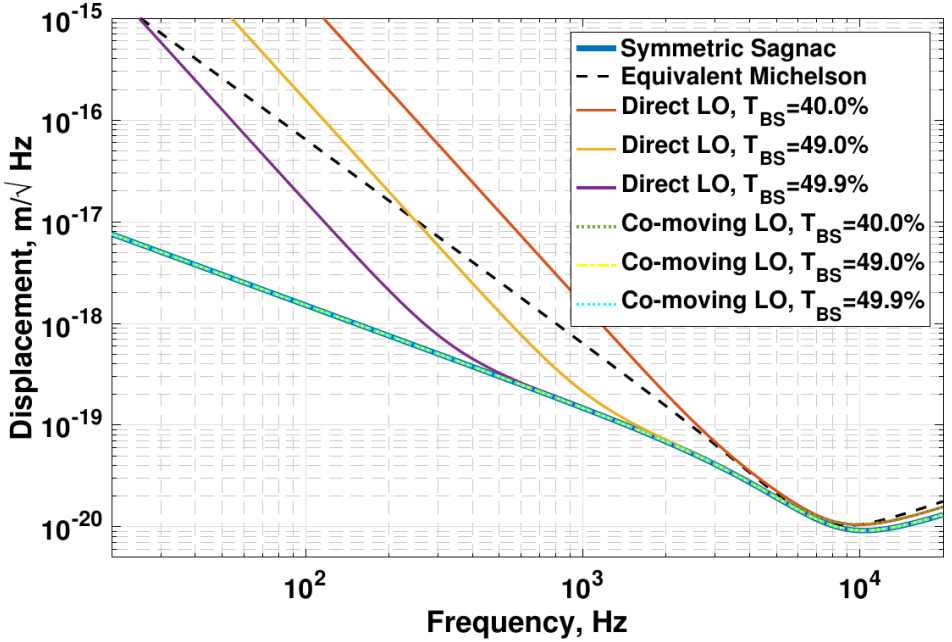


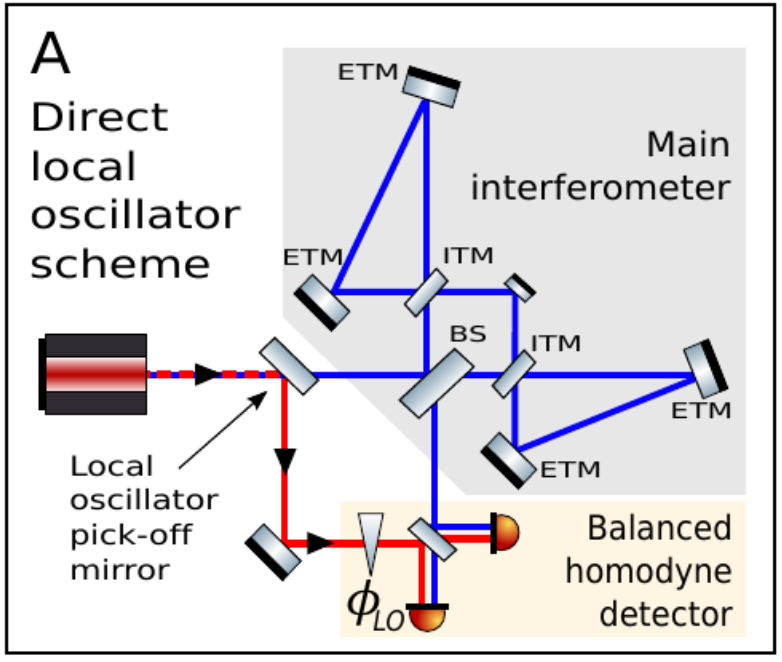


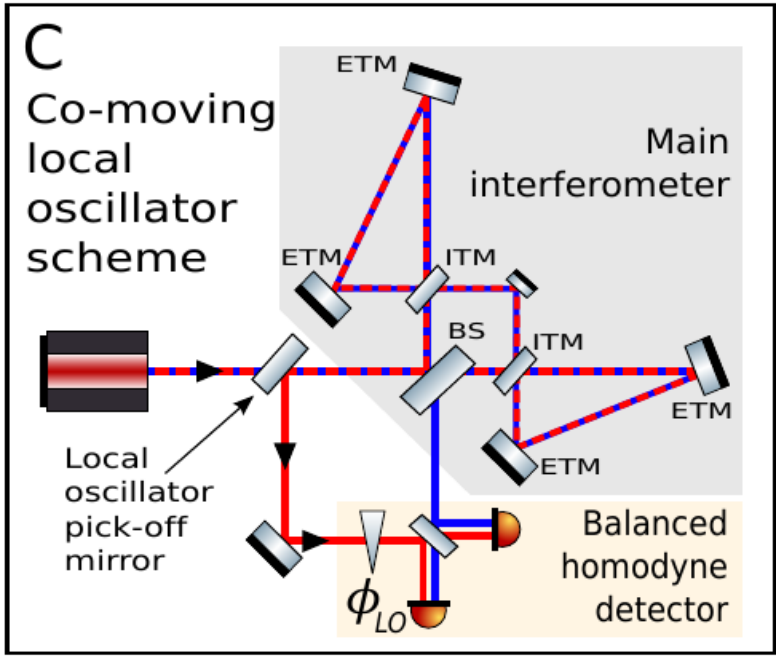


Co-moving local oscillator

- Asymmetric main beam splitter leads to loss in speed meters
- Input vs reflected light as choice of LO has noise consequences
  - Reflected “co-moving” LO cancels noise from beam splitter asymmetry!
- Also reduces otherwise challenging input laser RIN requirement







E. Houston et al., in preparation

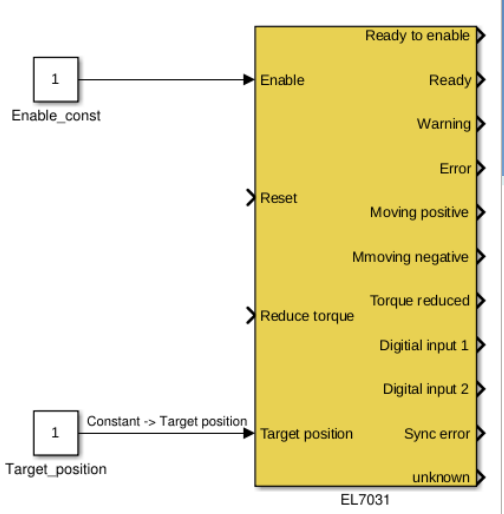
EtherCAT slow controls

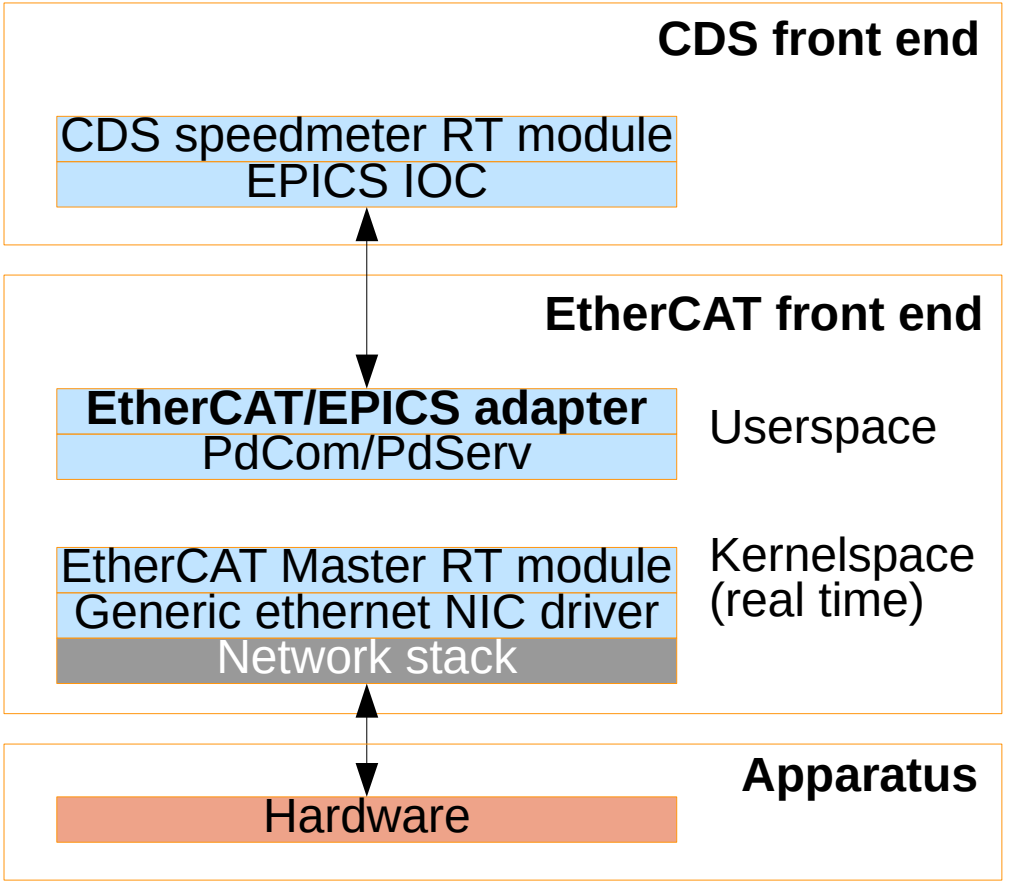
- We need ~270 DAQ channels
- CDS channels are expensive (~$500/channel)
- Most of these (~200) will be static or slowly changing signal inputs or outputs (<< 2kHz, e.g. coarse suspension alignment)
- Industrial EtherCAT fieldbus provides alternative (~$70/channel)
- Used in LIGO, but with proprietary Windows-based software; doesn't interface with CDS easily (or cheaply)
- We have implemented an open-source solution

See Peter Dupej's poster

Our EtherCAT solution

- EtherLab real time control software (Debian 8, real time)
- Models built with Simulink, compiled into real-time code (just like CDS)
- Our software adapts control variables to/from CDS EPICS
- EtherCAT loops can be controlled within fast CDS models
- Channels hot-swappable between EtherCAT and CDS (differential +/- 10V, similar input impedance)
- Successful tests made of communication between CDS EtherCAT modules
- Front end, AA/AI filters, power supplies, etc. being built now

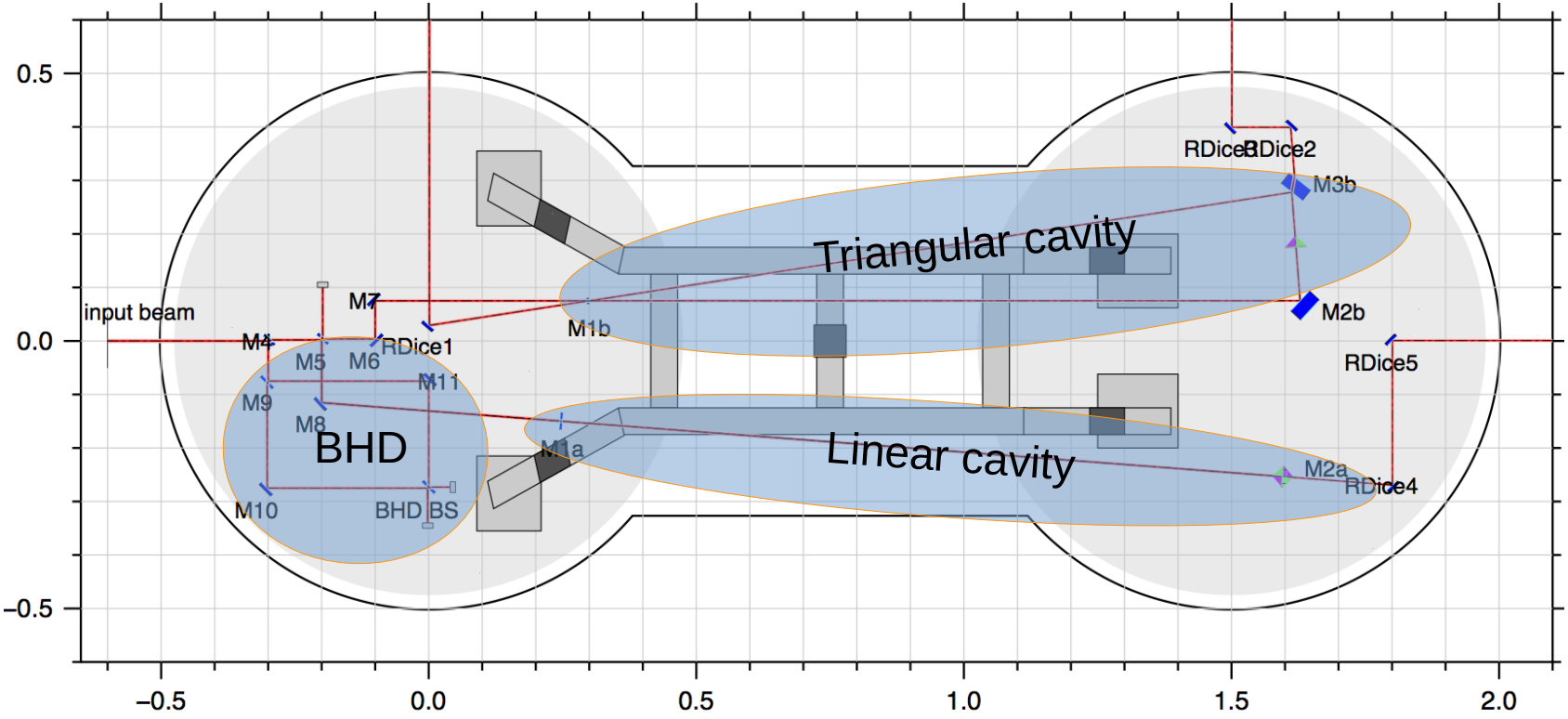




See Peter Dupej's poster

Commissioning progress

- Currently operating three “stepping stone” experiments
  - Linear cavity to test infrastructure, noise and ESD actuators
  - First triangular cavity of the full experiment to test monolithic ETMs, angular control, EtherCAT slow controls
  - BHD readout with auxiliary optics to test LO path stability
- **Push towards final layout starts now**



Plan

- Ready NOW:
  - Seismically isolated platforms
  - Electronics + sensors
  - Monolithic 100g optics + suspensions
  - Auxiliary + input optics, suspensions and laser
  - EtherCAT software
- Ready soon:
  - Monolithic 1g optics + suspensions
  - Beam splitter + BHD readout
  - EtherCAT hardware
- Then comes:
  - Interferometer commissioning / noise hunting
  - Measuring reduced back-action!
- Long term plan:
  - Add recycling, squeezing, scale up to 10m experiment

Thanks to the team and community


Peter Dupej


Christian Gräf


Jan-Simon Hennig

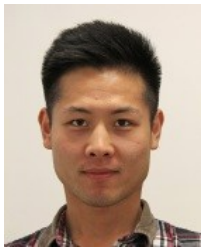

Stefan Hild


Alasdair Houston


Russell Jones


Sean Leavey


Daniela Pascucci


Teng Zhang

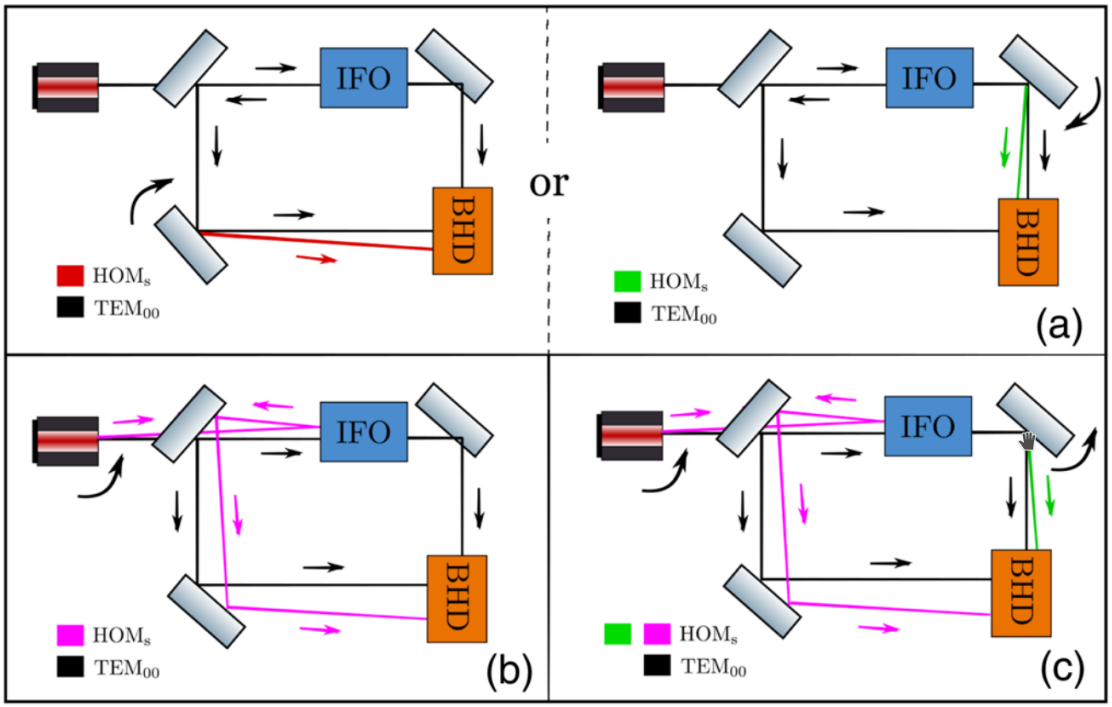
+ lots of help from our ex-members, Sebastian Steinlechner and Stefan Danilishin; and our IGR colleagues, Bryan Barr, Angus Bell, Alan Cumming, Liam Cunningham, Kentaro Somiya, Borja Sorazu, Giles Hammond, Jim Hough, Sabina Huttner, Sheila Rowan, Andrew Spencer, Karl Toland, Mariëlle van Veggel, Jennifer Wright, Ken Strain, Sergey Vyatchanin + many summer students and visitors!

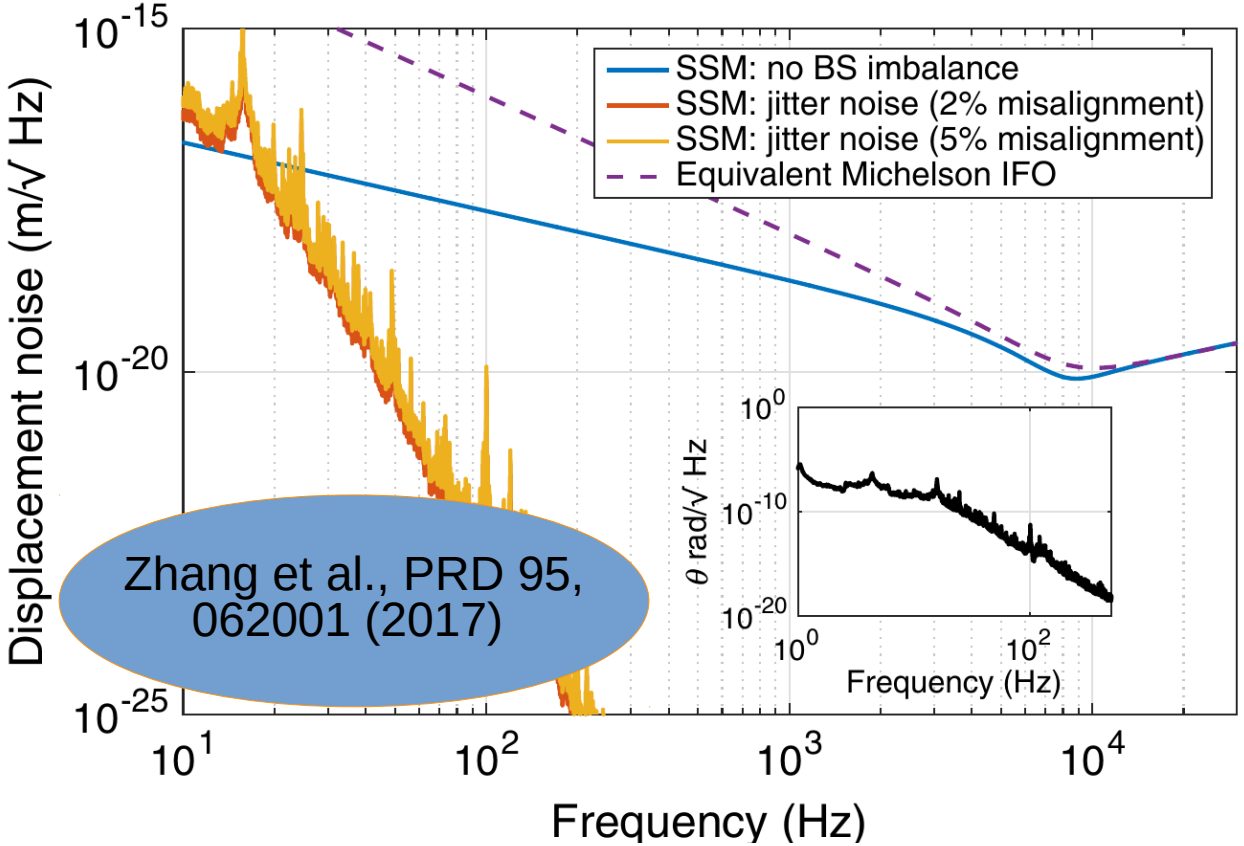
Second international speed meter workshop attendees, “The Burn”, Angus, Scotland, June 2016


University of Glasgow
Thanks for listening!
Visit us at speed-meter.eu

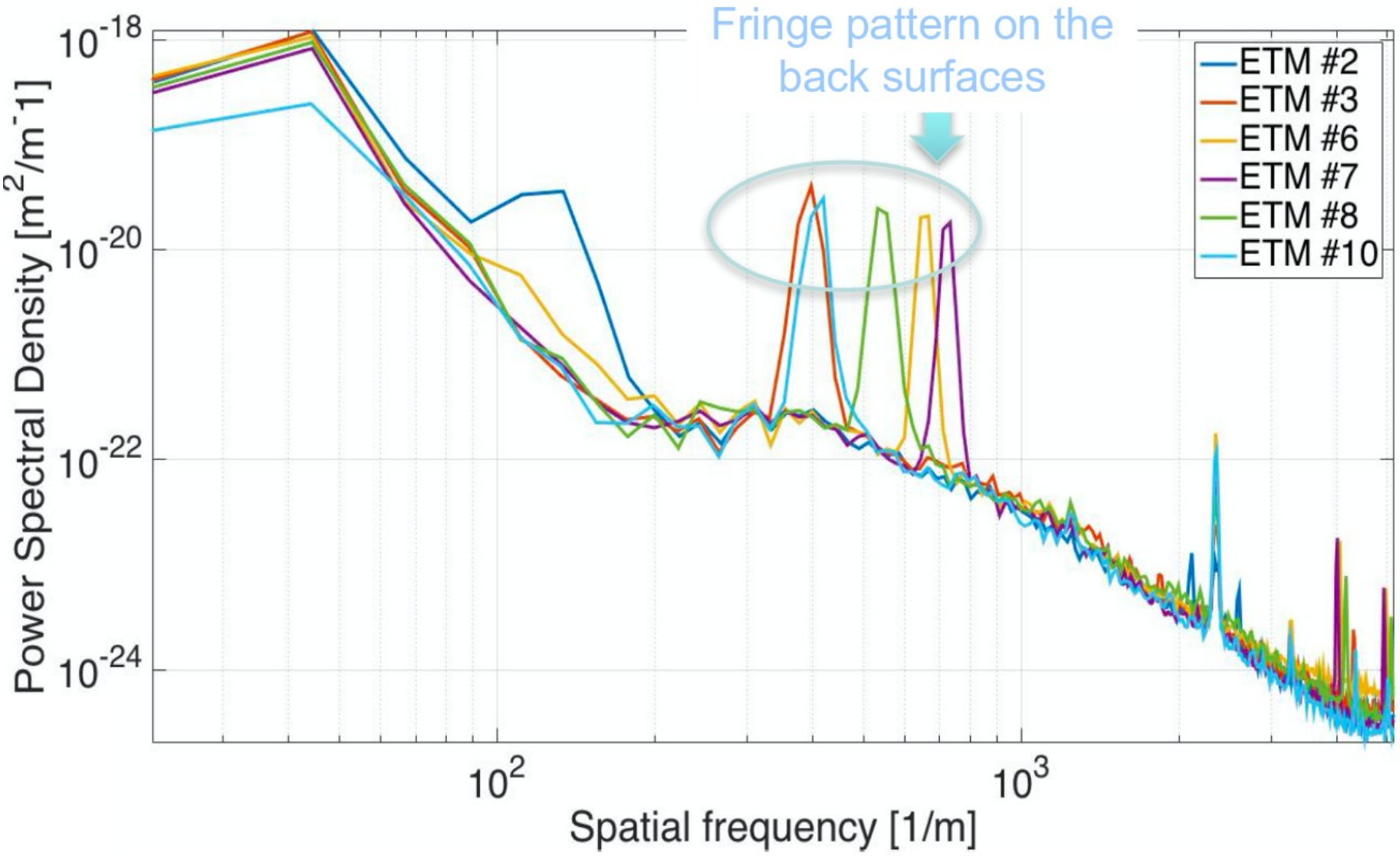
Misalignments

- Effect of higher order modes at BHD on noise studied
- Influence same in Michelsons and Sagnacs
- Static LO/BHD misalignments only affect high frequency sensitivity
- Dynamic noise from seismic induced jitter is below quantum noise in measurement band



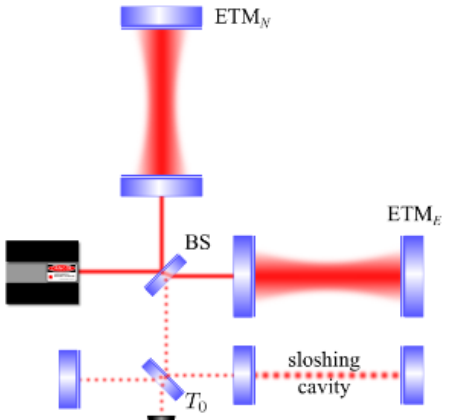


ETM scatter loss

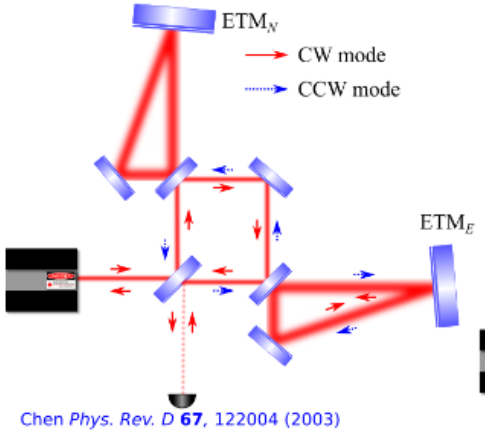


Measured scattering of our ETMs (ppm): **2.2, 2.8, 4.0, 4.5, 7.7, 9.0**

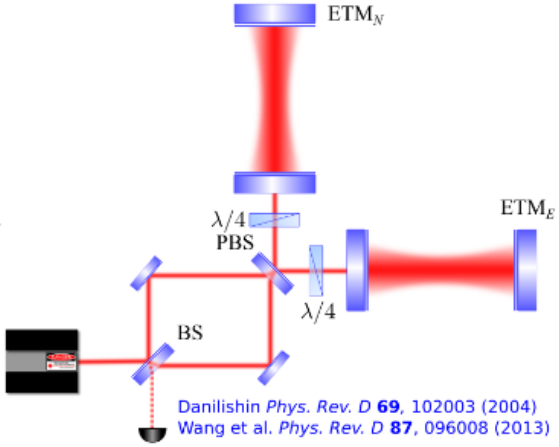
Speed meter zoo



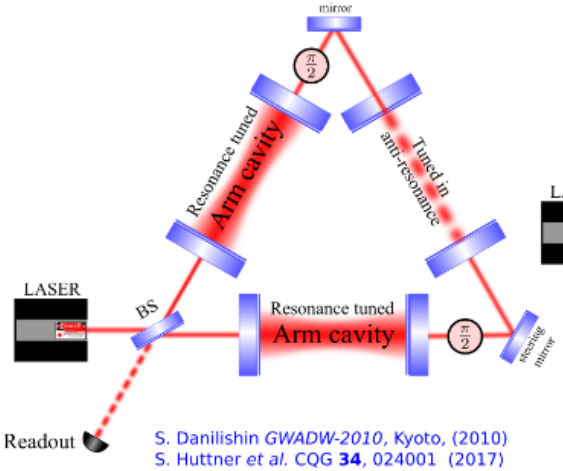
Braginsky *et al.* Phys. Rev. D **61**, 044002 (2000)
Purdue&Chen *Phys. Rev. D* **66**, 122004 (2002)



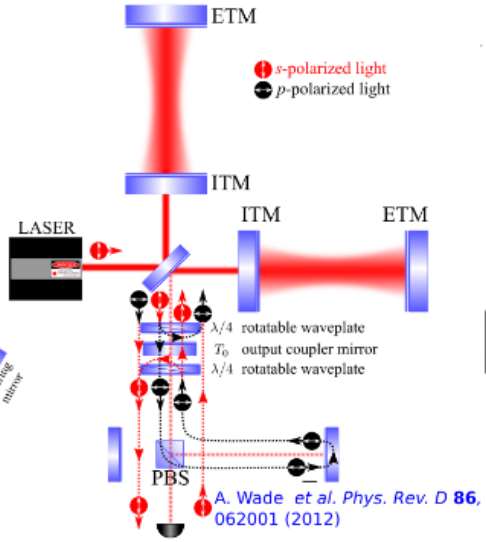
Chen *Phys. Rev. D* **67**, 122004 (2003)



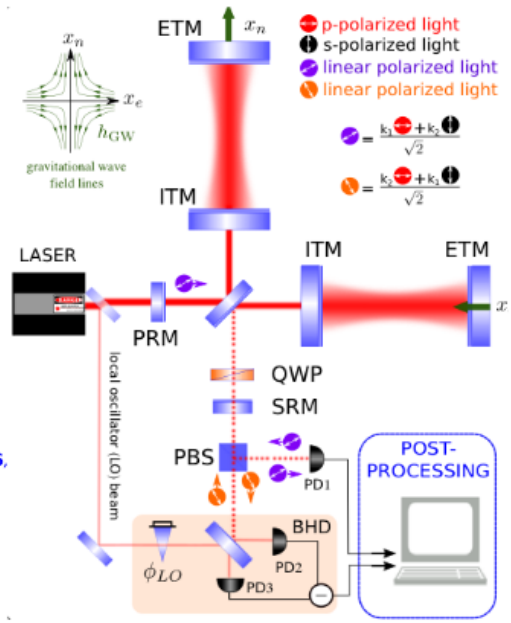
Danilishin *Phys. Rev. D* **69**, 102003 (2004)
Wang et al. *Phys. Rev. D* **87**, 096008 (2013)

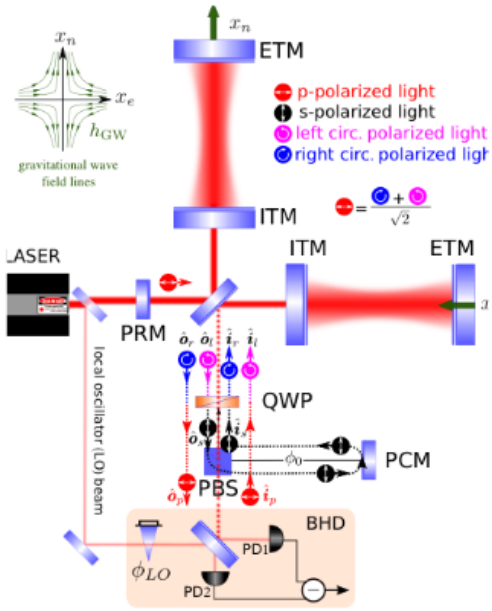


S. Danilishin *GWADW-2010*, Kyoto, (2010)
S. Huttner *et al.* CQG **34**, 024001 (2017)



A. Wade *et al. Phys. Rev. D* **86**, 062001 (2012)



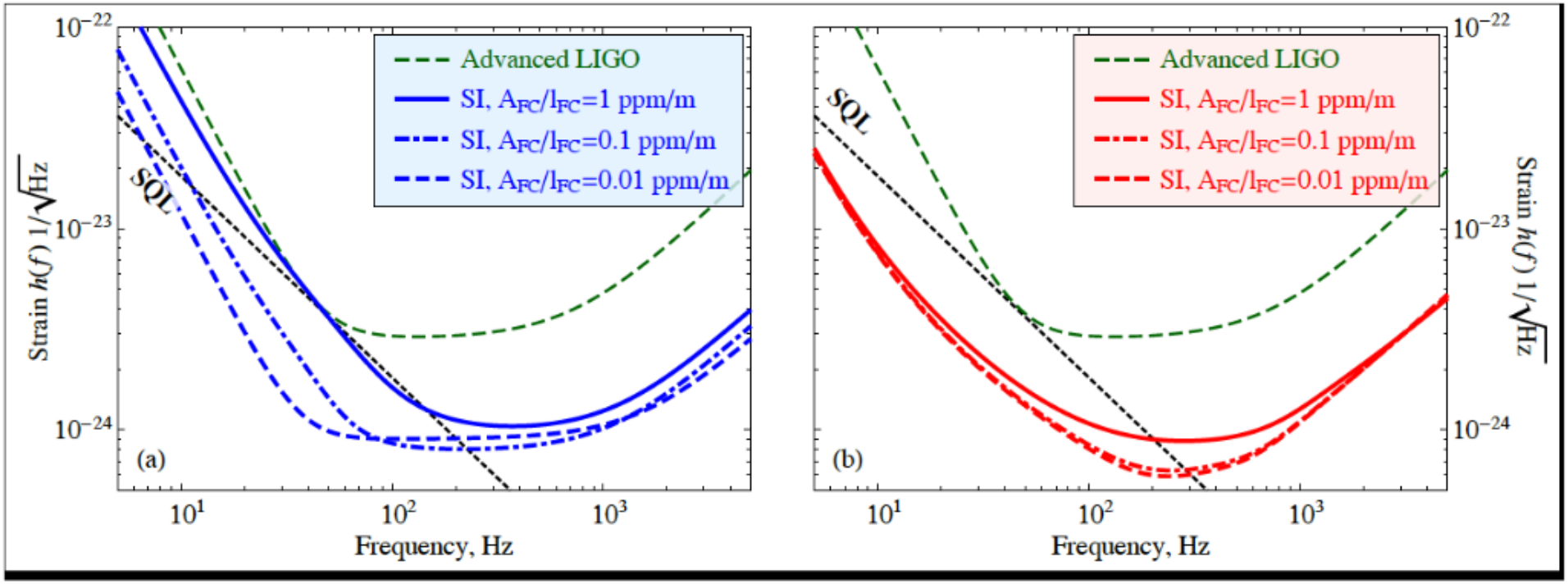


Filter cavity loss in ET

Broadband detuned Sagnac interferometer for future generation gravitational wave astronomy.

N.V. Voronchev,[1] S.P. Tarabrin,[2,3] and S.L. Danilishin[4,5,*]

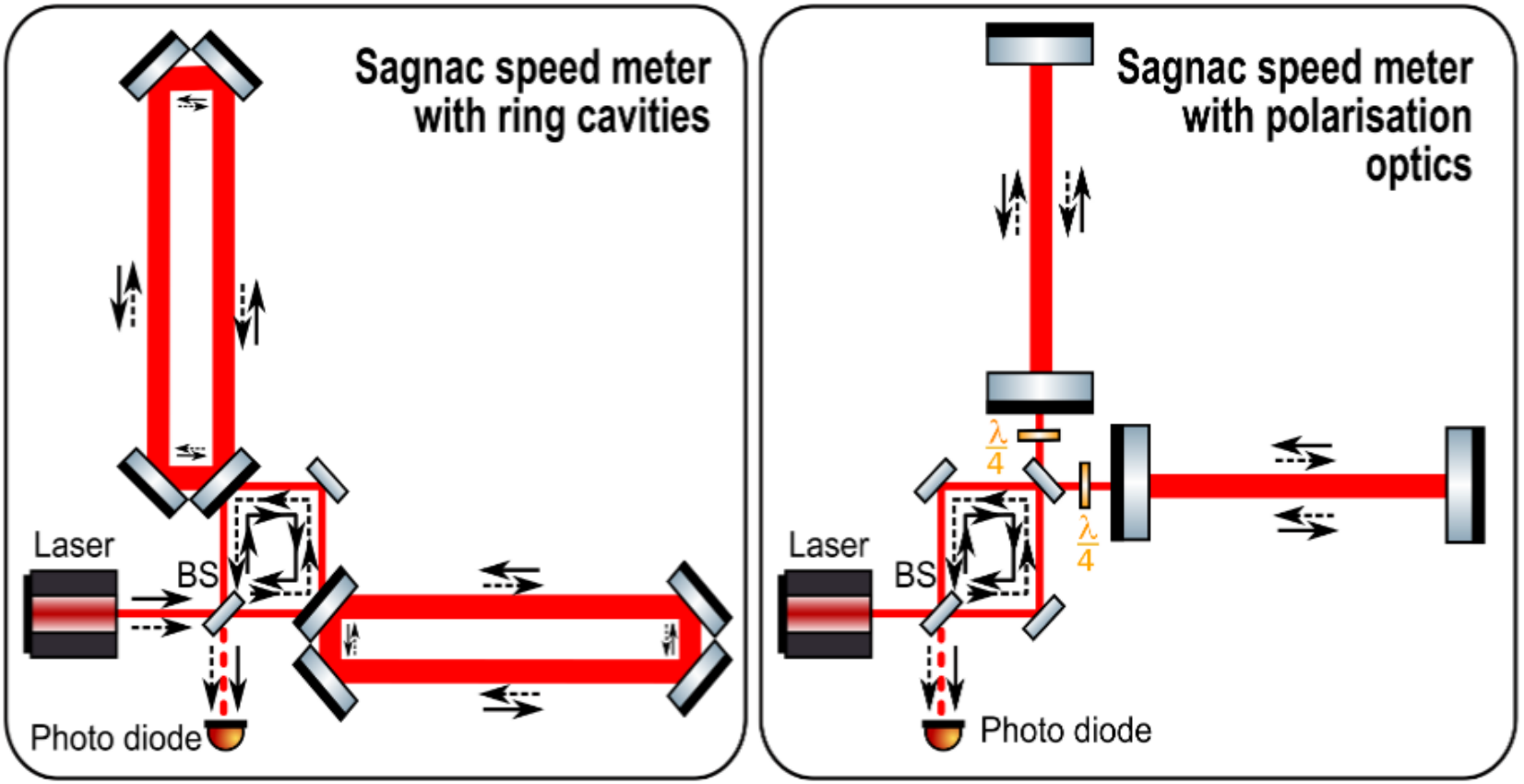
arXiv:1503.01062



Michelson-based single ET design

Sagnac-based single ET design

Ring-cavity vs Polarisation

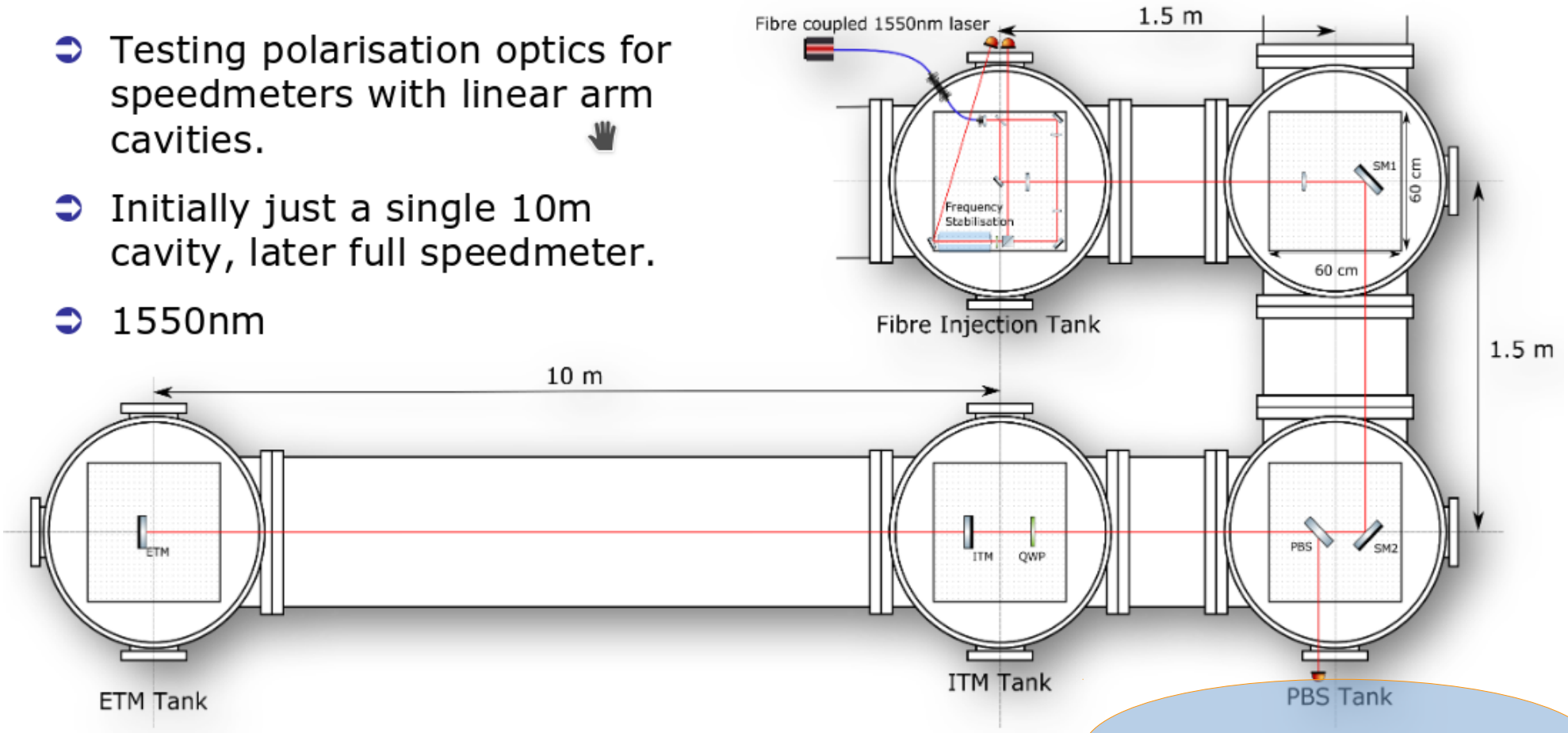


D. Pascucci et al: "Quantum noise limitations due to coherent scattering in Sagnac Speedmeter with ring cavities", in prep

See G1700832 (Stefan Hild)

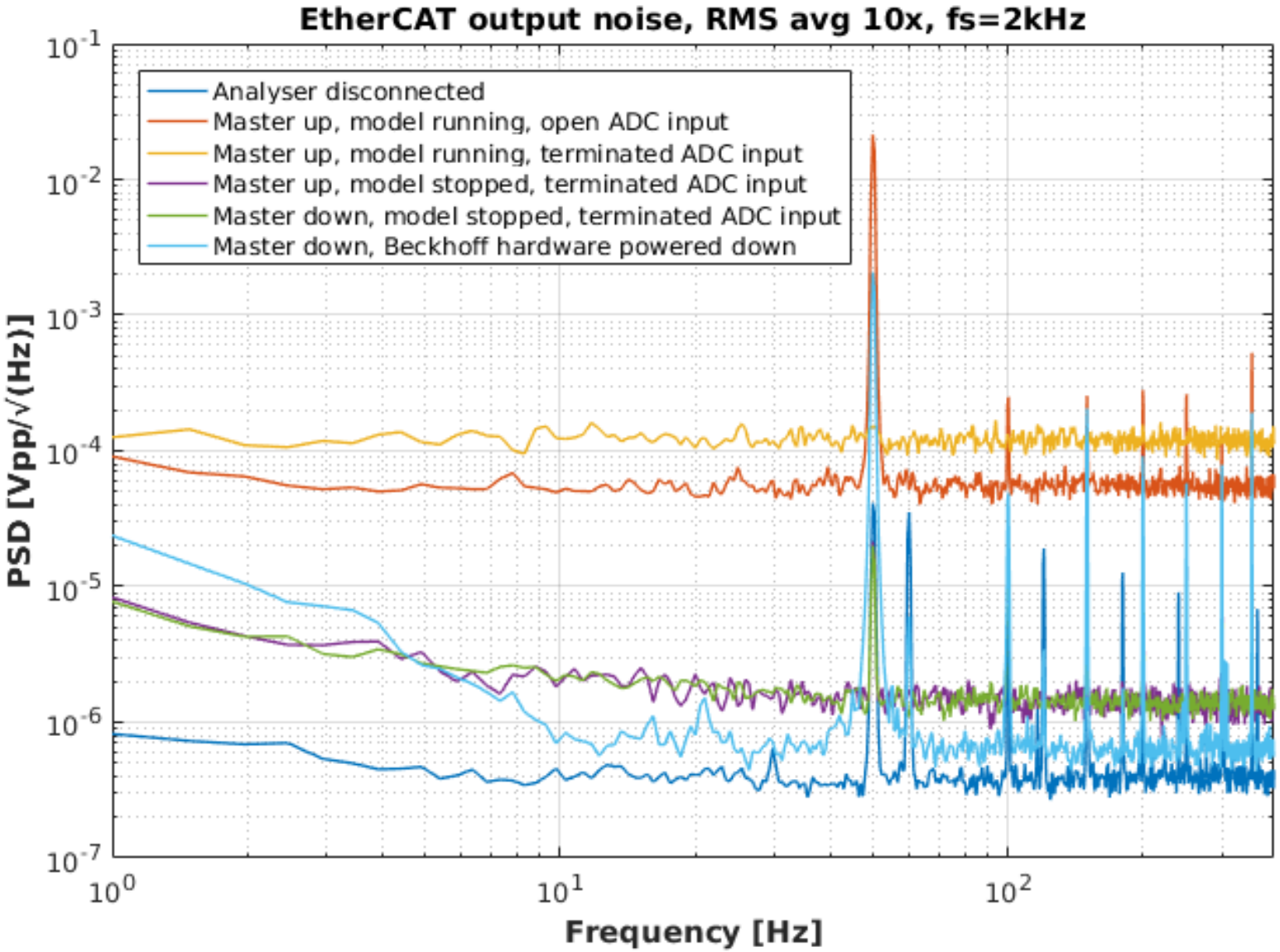
Polarisation speedmeter in Glasgow 10m prototype

- Testing polarisation optics for speedmeters with linear arm cavities.
- Initially just a single 10m cavity, later full speedmeter.
- 1550nm

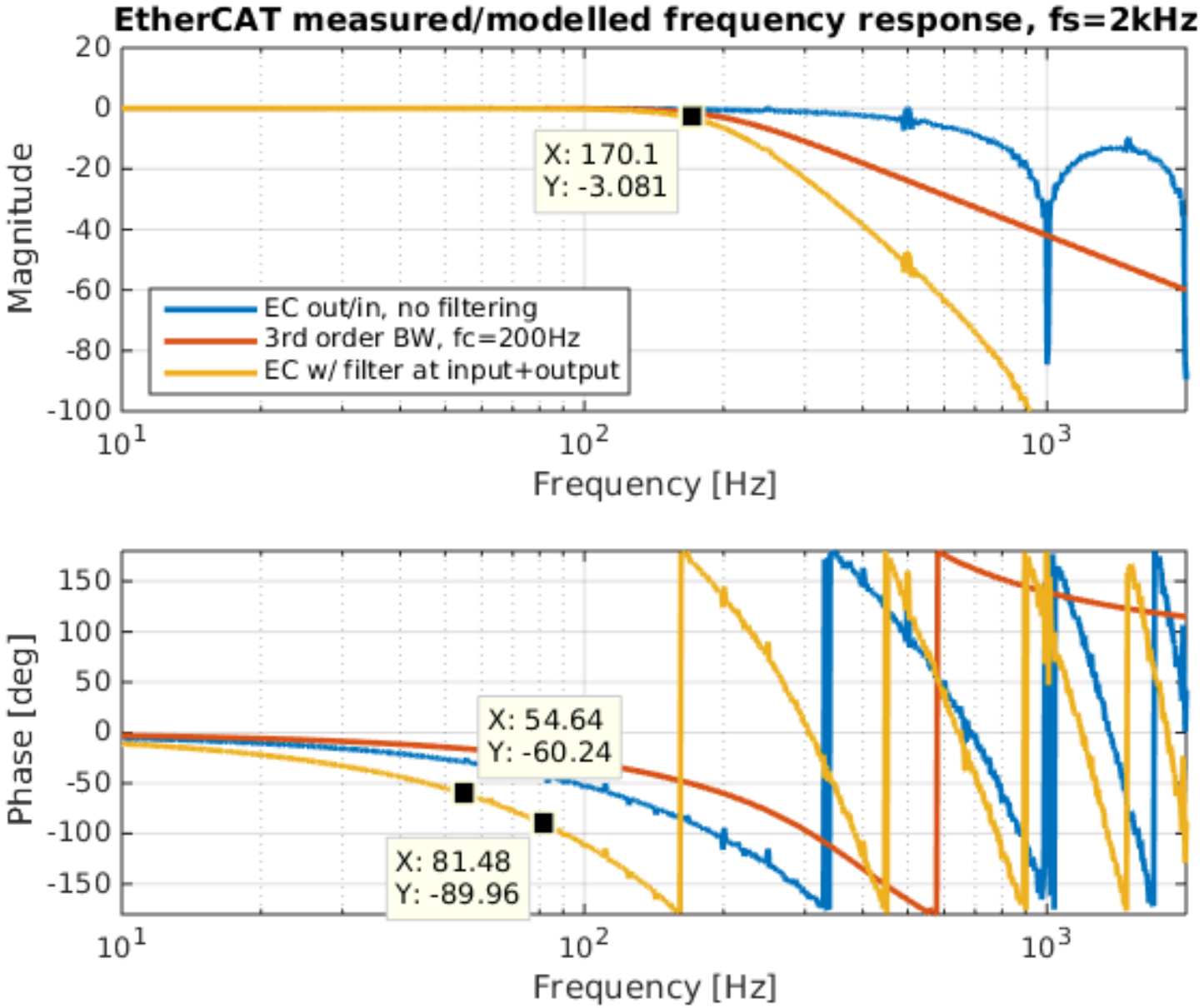


See G1700832 (Stefan Hild)

EtherCAT noise



EtherCAT response



EtherCAT slow controls