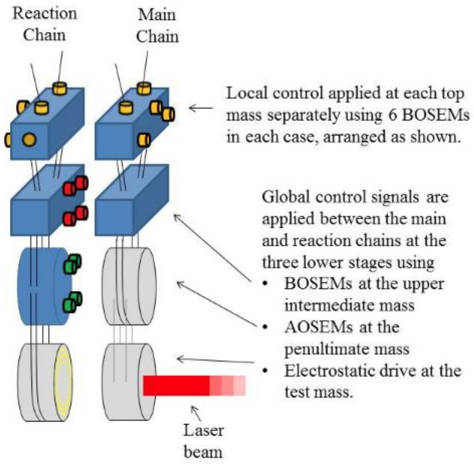
Overview of CE Seismic Isolation and Suspension Design

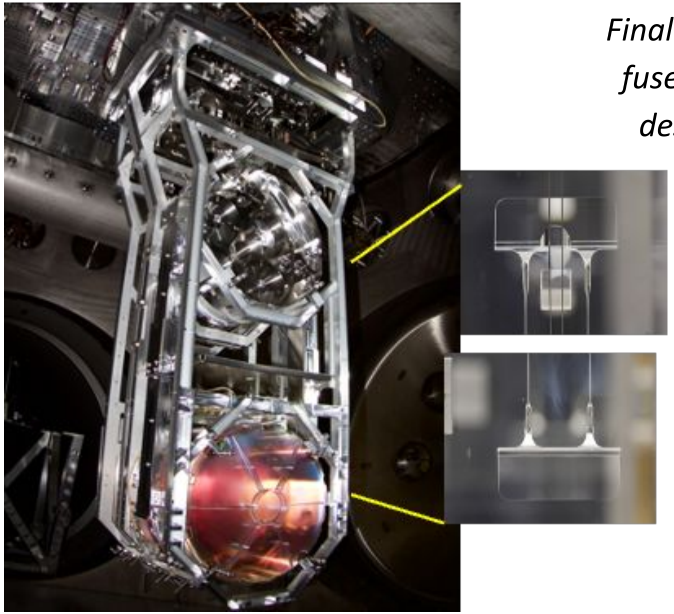
XGCD on October 21st, 2024

Cosmic Explorer’s team

LIGO Seismic Isolation (SEI) and Suspension (SUS) today

*Test mass suspended by a quadruple pendulum, attached to three stages of active isolation (**I**nternal **S**eismic **I**solation platform + HEPI) to reduce seismic noise*





Final stage of test mass suspension all fused silica, very high quality factor, designed to reduce thermal noise

LIGO-P1200056

A lot of lessons learned (summary by Brian Lantz and Giles Hammond)

Areas of R&D

Suspension design & modelling

- How do we incorporate isolation AND ISC control into the design choices?
- Masses/lengths to allow observation/damping of local modes (currently simple model to optimise seismic/suspension)
- Revisit QUAD design to mitigate pitch – length coupling
- Suspension control with lower frequency modes
- Topology: reaction chain or suspension cage (optimise main chain mass, damp pitch/vertical modes)

Monolithic stage

- Longer fibres and higher stress
- Redesign of ears and associated thermal noise
- Tooling to manipulate masses (engineering challenges)

Sensors/Actuators

- Define requirements for CE suspension (noise and bandwidth)
- Lots of LSC work on sensors with improved noise performance (e.g. interferometric,

Suspension Design & Modeling

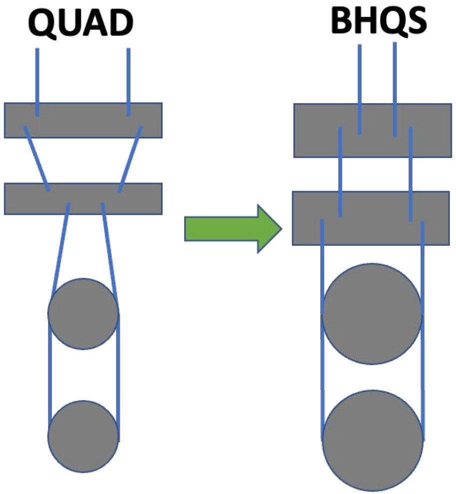
- Some work already underway to explore pitch-length coupling and making a more symmetric arrangements of wire form ISI to top mass (e.g. move from 2 to 4 wires)
- Work undertaken by Brett Shapiro to look at alternatives/ updates to the reaction chain (https://dcc.ligo.org/G1601426-v3.pdf)
- Put more mass at the top to lower the high-frequency modes and get better isolation
- Increase the moments of inertia of the upper stages to reduce the cross-couplings into pitch and yaw
- Improve the angle sensing for the local damping (lower noise sensors w/ more separation, optical levers, etc..)
- Improve our ability to diagonalize the controls. Now, there is cross coupling in the sensors (the OSEMs are have an uncertain relative calibration, and the OSEM calibration is sensitive to transverse motion), there is cross-coupling in the actuators (which also have uncertain calibrations, and can exert small torques if off-center), and the plant is highly cross-coupled. Can we update the design to make it easier to do the in-situ balancing & diagonalization? Can we do this without the full IFO?
- How about damping for the Sidles-Sigg hard mode locally without increasing the noise (it's badly coupled to the top mass) so we don't have to use the (noisy) WFS to do it?

Suspension under design for A# (**BH**eavy**Q**uad**S**us)

- A# suspension design elements (work led by Brian Lantz):
  - Several improvements over current suspension
  - See for example Edgard's talk at LVK [LIGO-G2401974]
- Incorporates many of the ideas in the previous slides

Design description: P1200056

- Great seismic isolation
- Low thermal noise
- 40 kg test mass / 120 kg total
- Cross-coupled translations and angles.
- Top mass is sufficient for damping
- Compact design
- Augmented with high-frequency dampers



Design procedure: T2300137

- Great seismic isolation
- Low thermal noise
- 100 kg test mass / 400 kg total
- Decoupled translations and angles.
- Damping with first two masses
- Local Interferometric sensors
- Built-in high-frequency dampers

Credit: Edgard Bonilla, LIGO-G2400740

Inspirational ideas for CE design

- Keep the basic seismic platform + suspension scheme as LIGO
- Rely on A# BHQS for many aspects of the design:
  - mass distribution concept, controllability improvement, etc.
- Since CE has fewer facility constraints, we can extend the parameter space a bit more
  - Brett Shapiro's "cage as reaction chain" redesign idea
  - Virgo payload design

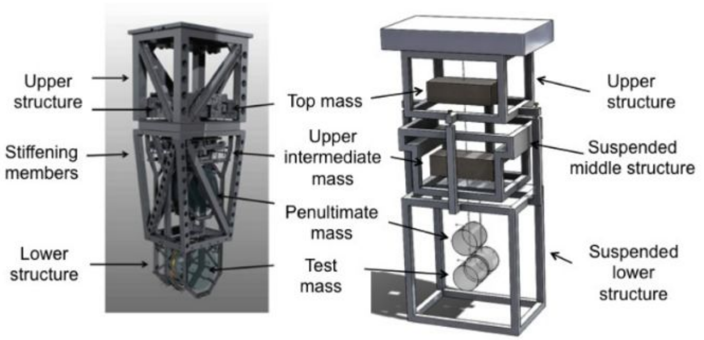
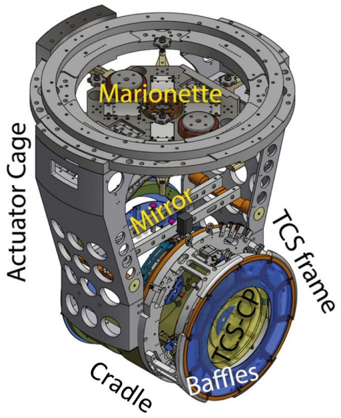


Fig. 1 Left: the aLIGO test mass suspension. Right: a concept for a future suspension with a suspended cage that doubles as the reaction chain. This alternative design might be simplified by doing away with the reaction mass behind the test mass and instead using an actuator similar to the photon calibrator. See text for further discussion. Image courtesy of Ian Gomez.

Brett Shapiro, LIGO-G1601426

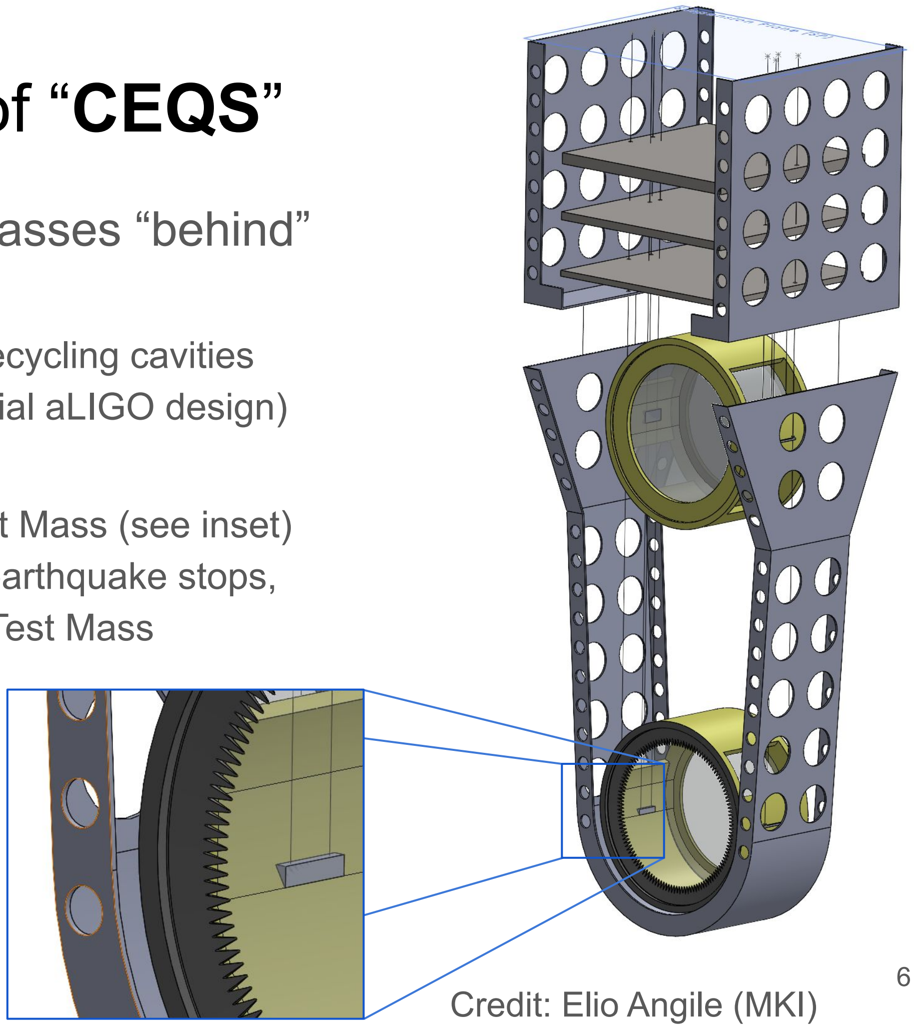


From: https://doi.org/10.3390/universe7090322

Virgo payload design

Design motivating principles of “**CEQS**”

- Compensation plates and reaction masses “behind” the test mass are problematic for CE
  - Need to keep loss as low as possible in recycling cavities
  - Gas damping noise (not considered in initial aLIGO design)
- Concentric reaction mass is useful
  - Allows for isolation of baffle closest to Test Mass (see inset)
  - Can replace the cage as the main-chain earthquake stops, reducing motion of objects closest to the Test Mass
- Concentric chains minimize the footprint of a very large suspension

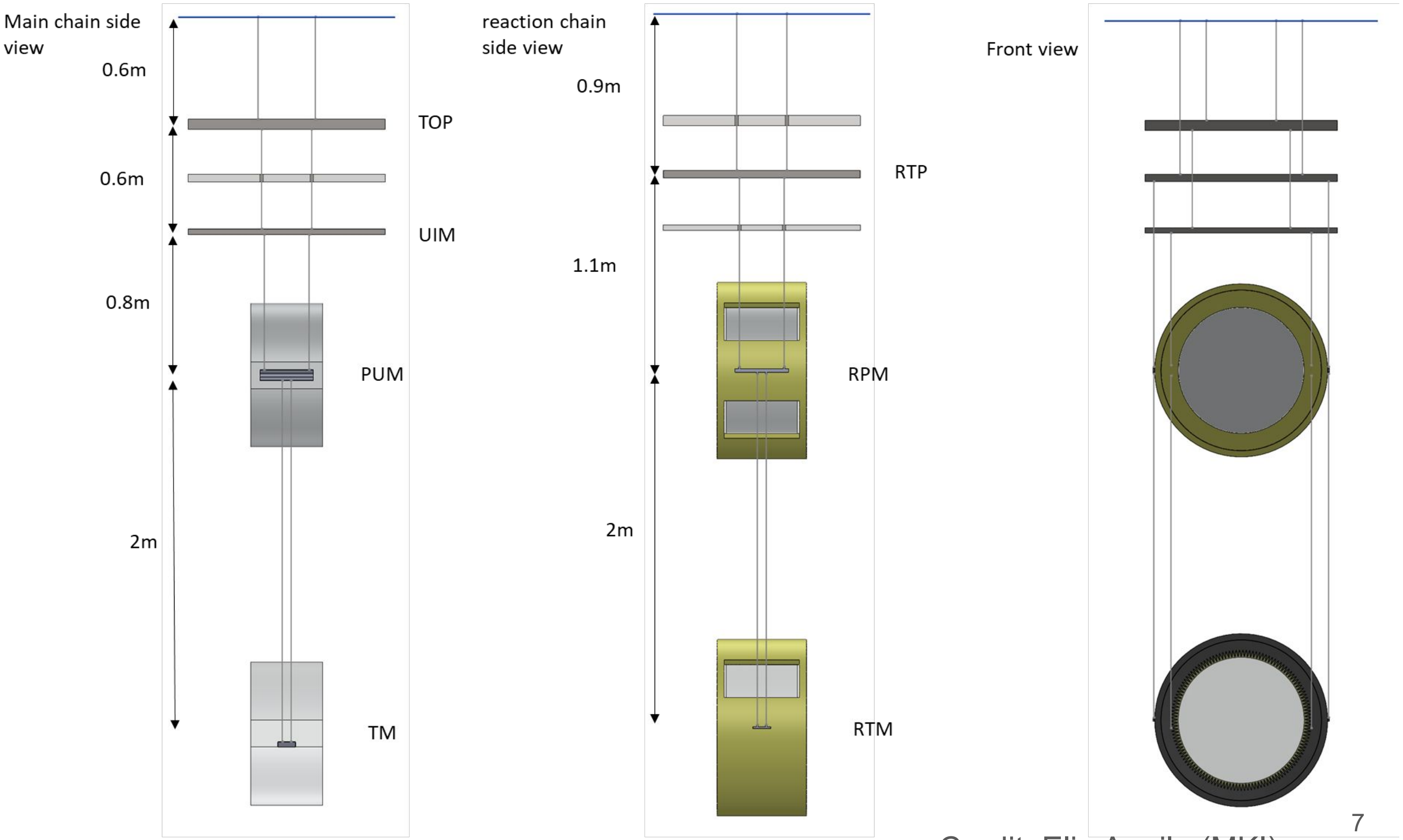


Credit: Elio Angile (MKI)

Suspension dimensions

Masses:
TOP: 560 kg
UIM: 300 kg
PUM: 400 kg
TM: 400 kg

Masses:
RTP: 300 kg
RPM: 400 kg
RTM: 400 kg

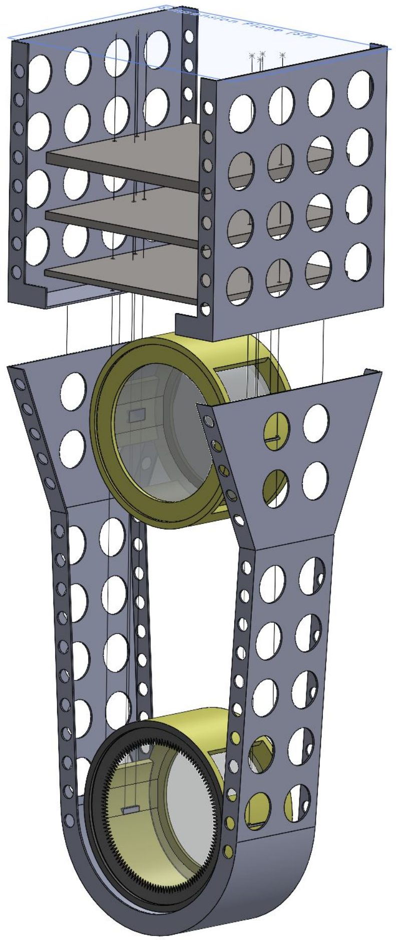


Distances are from center to center of mass elements

Credit: Elio Angile (MKI)

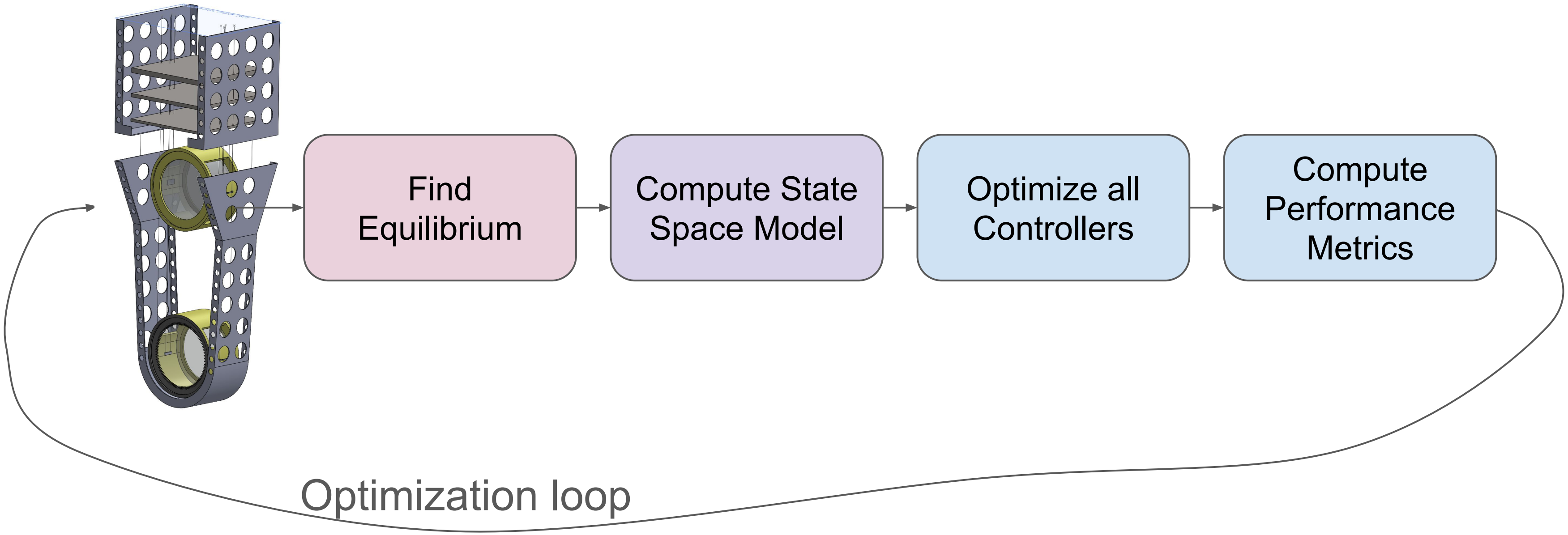
Other suspension features

- As with BHQS, avoid cross-couplings with
  - wires all vertical
  - Shorter blades, all parallel to beam direction
- Three-stage reaction chain
  - BHQS analysis shows that 4 stages are not necessary
- Split cage avoids long rigid structure
  - Also provides some isolation of cage near testmass to reduce spurious couplings (e.g., electrostatic)
- Cage is isolated (by ISI), and available to support
  - Additional baffles (not shown)
  - Thermal actuators
  - Thermal/electromagnetic shielding
  - etc.



Performance with Controls Driven Design

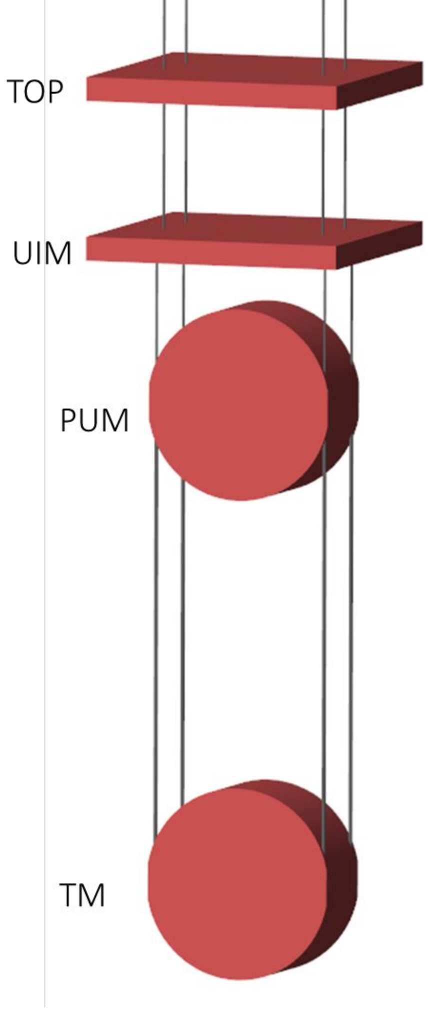
- We would like a way to optimize over suspension parameters based on performance as seen in the detector, including local and global controls



Suspension simscape model

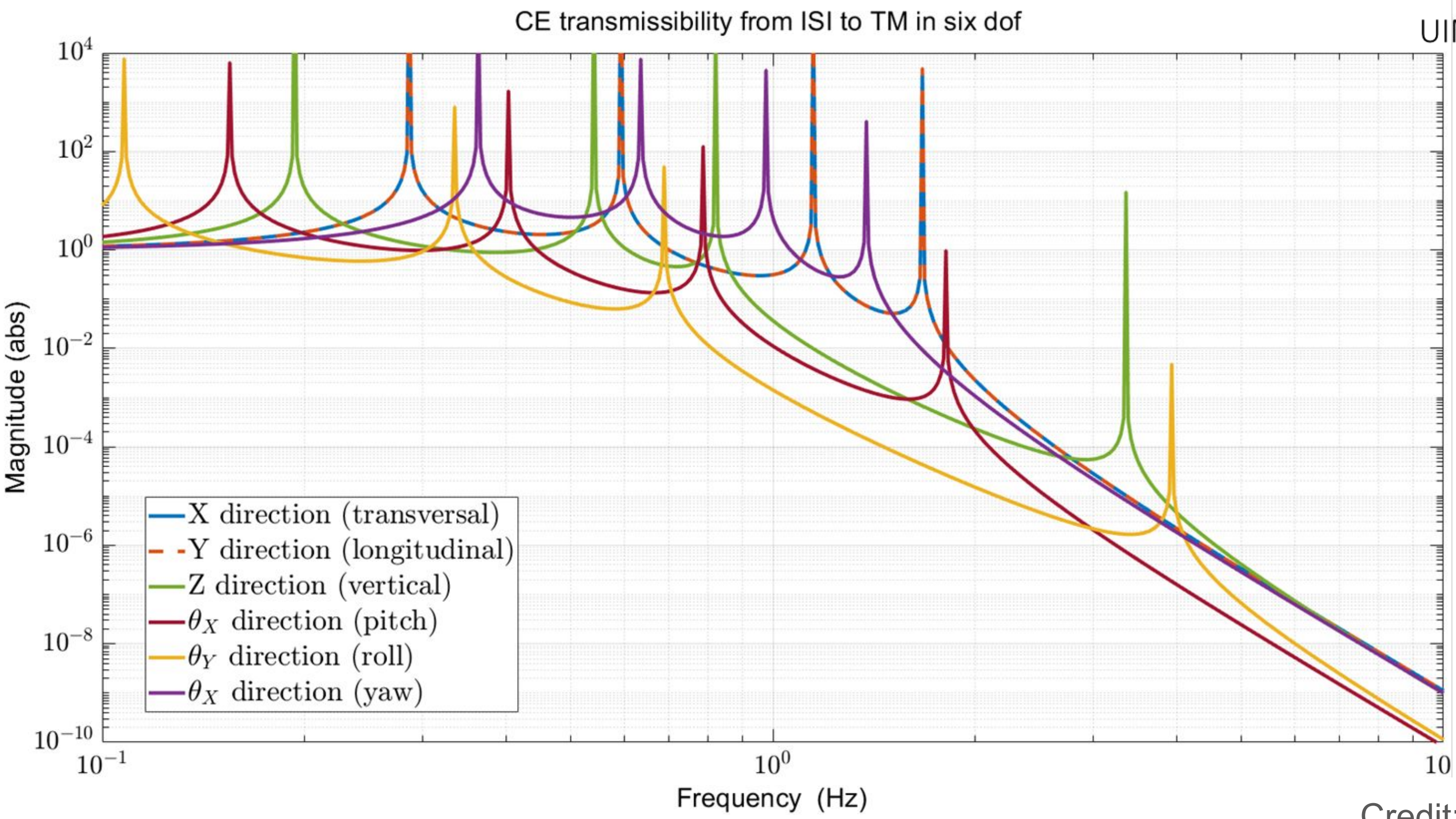
- Fully parameterized (easy to modify the model by changing parameters file)
- Returns state space model

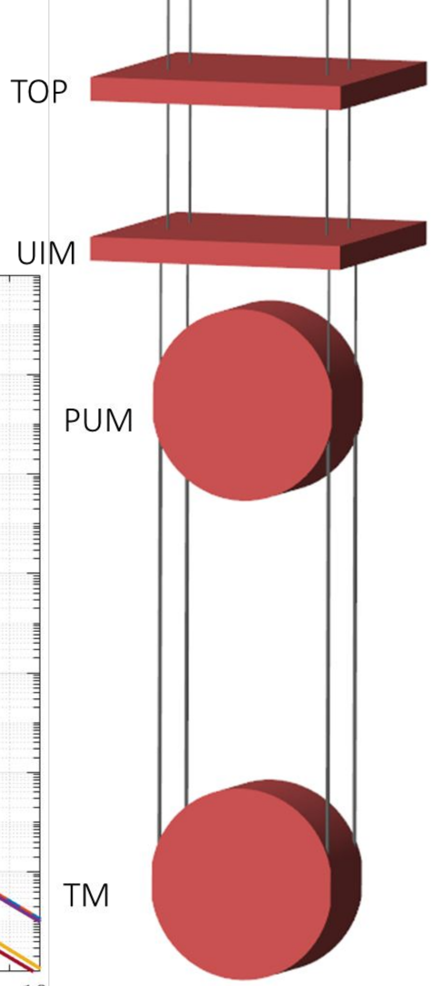
Symbol	Description	TOP	UIM	PUM	TM
$m1, m2, m3, m4$	Mass ()	520	340	320	320
$I_{1x}, I_{2x}, I_{3x}, I_{4x}$	Pitch moment of Inertia $(kg.m^2)$	52,9	34,6	32,5	17,1
$I_{1y}, I_{2y}, I_{3y}, I_{4y}$	Roll moment of Inertia $(kg.m^2)$	52,8	34,52	32,4	25,52
$I_{1z}, I_{2z}, I_{3z}, I_{4z}$	Yaw moment of Inertia $(kg.m^2)$	104,85	68,55	64,51	16,96
$k1, k2, k3$	Vertical springs stiffness per blade (kN/m)	1,27	0,83	0,77	N/A
$Y1, Y2, Y3, Y4$	Young's modulus of wires (GPa)	∞	∞	∞	72
$d_{y1}, d_{y2} d_{y3}, d_{y4}$	Longitudinal wire separation (cm)	67,2	67,2	28,6	28,6
$d_{x1}, d_{x2} d_{x3}, d_{x4}$	Transversal wire separation (cm)	36	28	70	70



Credit: Haidar Lakkis (Liege)

Suspension simscape model





Credit: Haidar Lakkis (Liege)

Many open areas of investigations

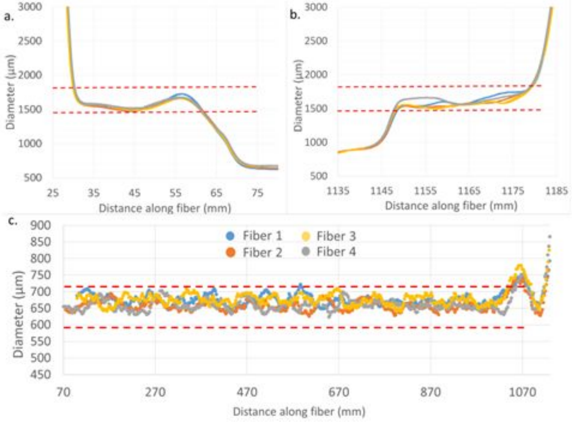
- Blade springs – how big do they need to be?
- Control aspects (length, angles)
- Cage design
- How to integrate thermal compensation
- How to incorporate better sensors (focus of next XGCD)

Suspension work at Glasgow

- We are currently investigating stress corrosion of fused silica fibres for both in-air and in-vacuum
- Fibres suspend mass at high stress range (4+GPa) to explore improvement under vacuum
- Building towards ET/CE, prototype fibre designs have been made for 100 kg BHQS scenarios, together with heavier ET-HF scenarios
- Fabricated from 5 mm diameter stock with thermoelastic nulling region of 1200 μm and central thin section of 442 μm (giving 1.6 GPa stress)

Humidity controlled fibre storage

Stress corrosion vacuum setup



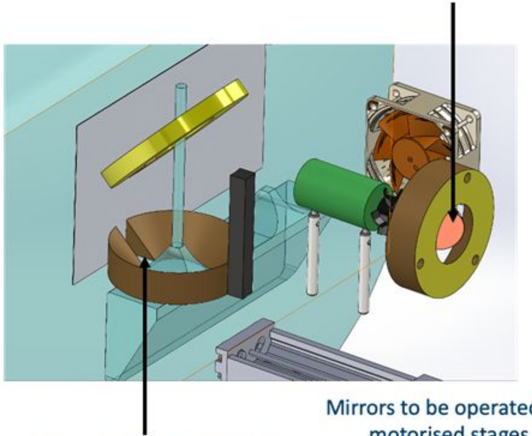
Fibres for heavier suspensions

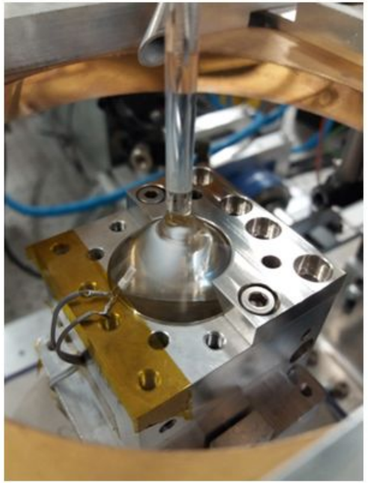
https://theses.gla.ac.uk/81461/
https://theses.gla.ac.uk/40954/

Suspension work at Glasgow

- Multiple single fibre heavy stress single fibre test hangs have been undertaken culminating in a 160 kg 4 fibre hang (5mm stock, 1.2m long, 1.2GPa
- Prototyping new ear geometries for A# and ET/CE
- Developing in-situ laser welding techniques for thicker stock

Ear geometries (3-D printed prototypes)





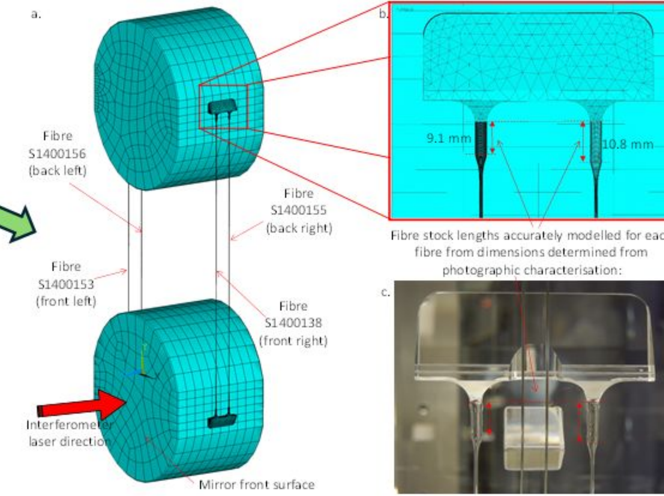
In-situ welding

Heavy suspension hangs

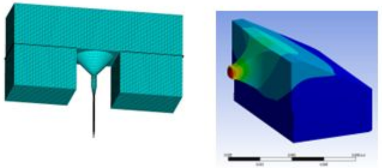
A V Cumming et al, PHYSICAL REVIEW APPLIED 17, 024044 (2022)

FE Analysis at Glasgow

- Existing FEA includes (i) monolithic 4 fibre models with accurate fibre profiles (ii) accurate loss terms and dissipation dilution calculations from energy distributions for Thermal noise evaluation
- Ongoing research areas:
  - Bond thermal noise
  - Violin mode frequencies (mode splitting, modelling of offsets, angles, non-symmetries in fibres)
  - Large geometry ear and anchor models – mechanical stresses



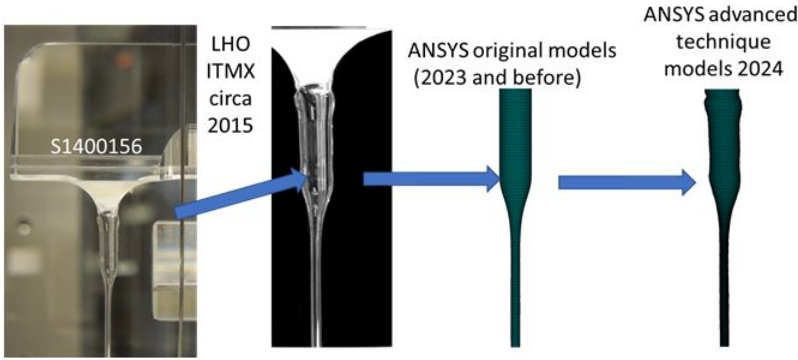
from Class. Quantum Grav. 37 (2020) 195019



BHQS anchor/ear

Future Work

- Under Next-Gen UKRI award we are developing a prototype lower stage suspension (100kg -400kg) to test A#(BHQS/ET/CE) geometries
- 2.7m tall vacuum tank installation 2025



A V Cumming et al, Class. Quantum Grav. 29 (2012) 035003
L Cunningham et al,Physics Letters A Volume 374, Issue 39, (2010), 3993-3998
A V Cumming et al, Class. Quantum Grav. 37 (2020) 195019