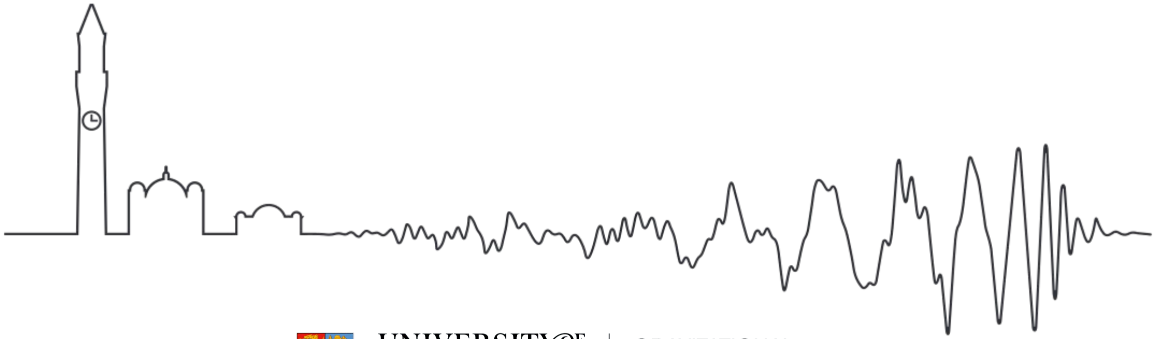
Progress towards a 6 DoF inertial sensor:

Commissioning and Application in Semi-classical Gravity Measurements

Jiri (George) Smetana

A. Dmitriev, A. Gill, D. Martynov, L. Prokhorov, T. Yan



UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

Overview

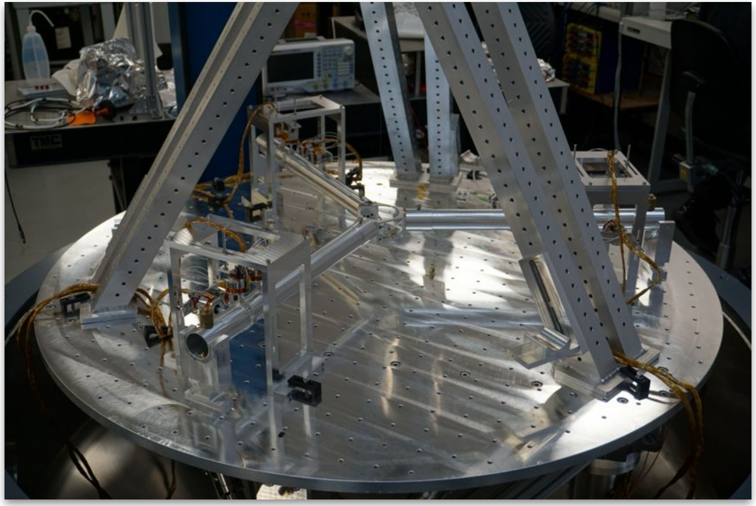
Six-degree-of-freedom inertial sensor that can decouple troublesome cross-couplings and help extend the GW detection band towards lower frequencies

Platform for torsion-bar experiments in fundamental physics (Schroedinger-Newton).

6D - Metal Prototype

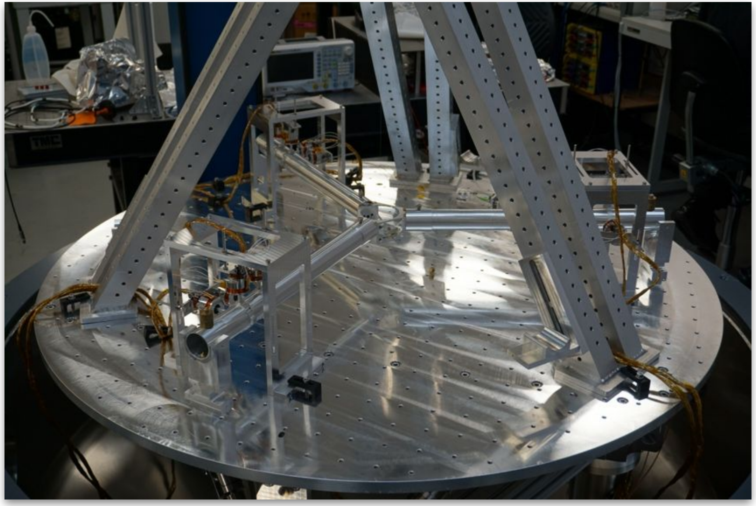
- Suspended 3 kg mass with large moment of inertia
- Decoupled readout of all 6 degrees of freedom
- Low readout noise due to interferometric sensors
- Last update in G2300542

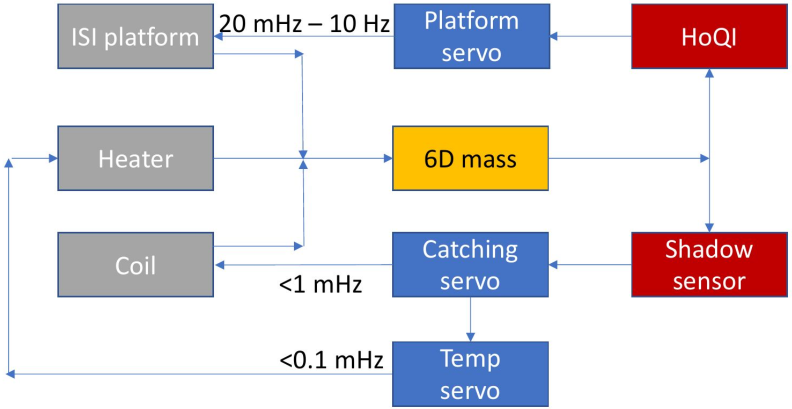
- Concluded testing of metal prototype, demonstrated:
  - Controllability
  - Sensitivity



Conclusions - Controllability

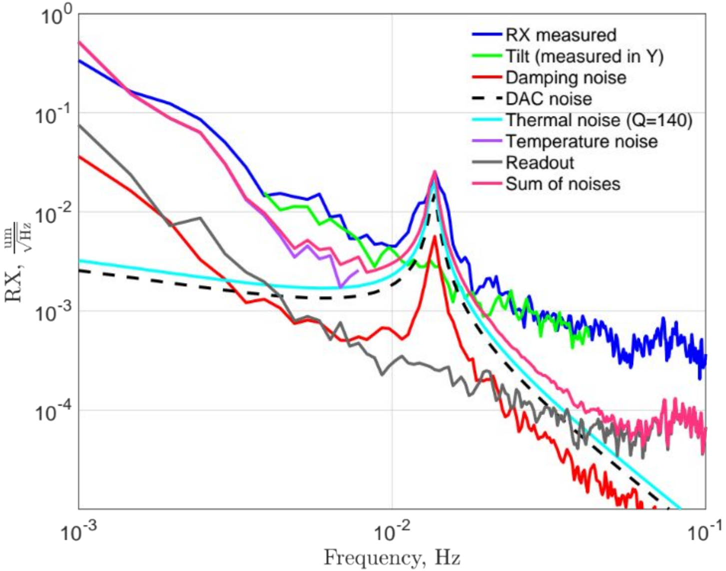
- Developed multi-layered control scheme
- Need to stabilise mass relative to ISI as well as ISI itself

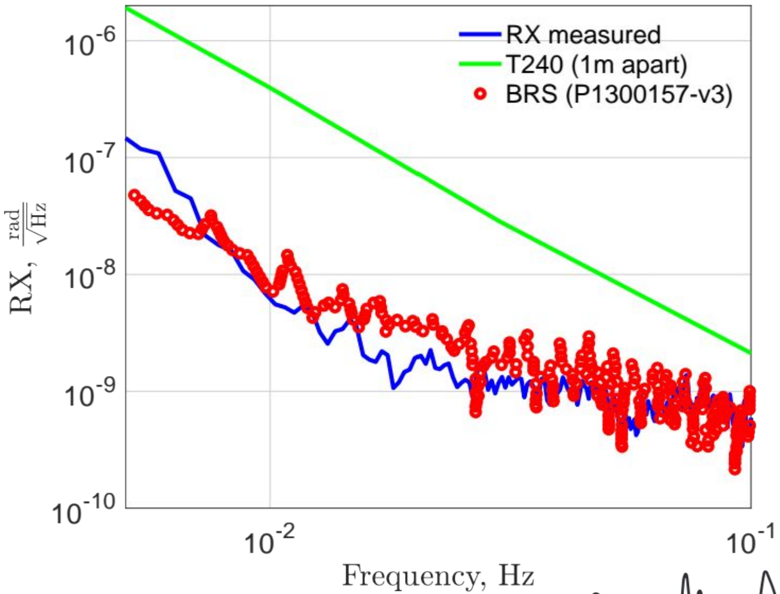




Conclusions - Sensitivity

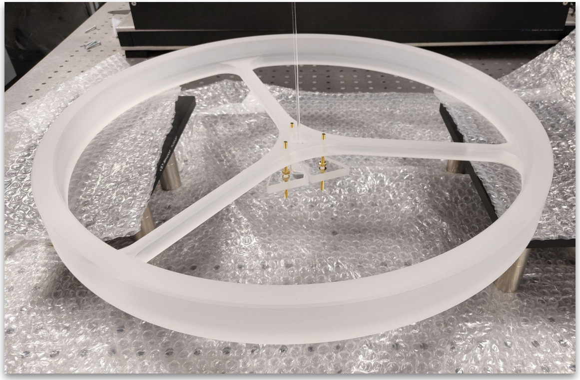
- Tilt measurement key focus of GW detector upgrades
- Our tilt sensitivity demonstrates significant gains that could be made from adopting 6D





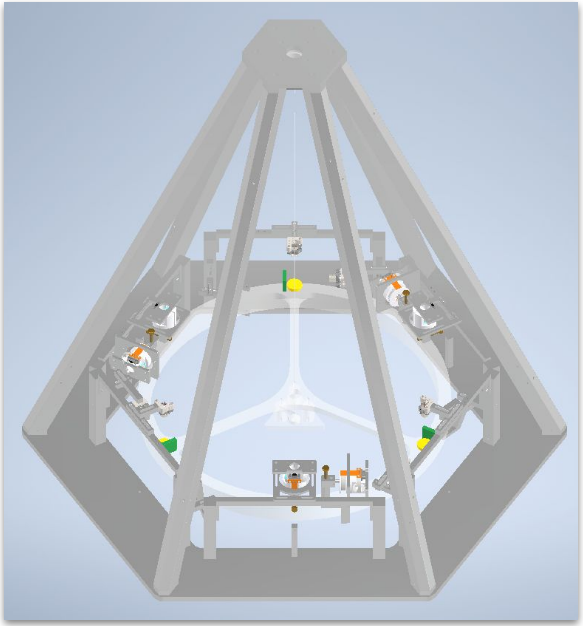
Next Step: Compact 6D

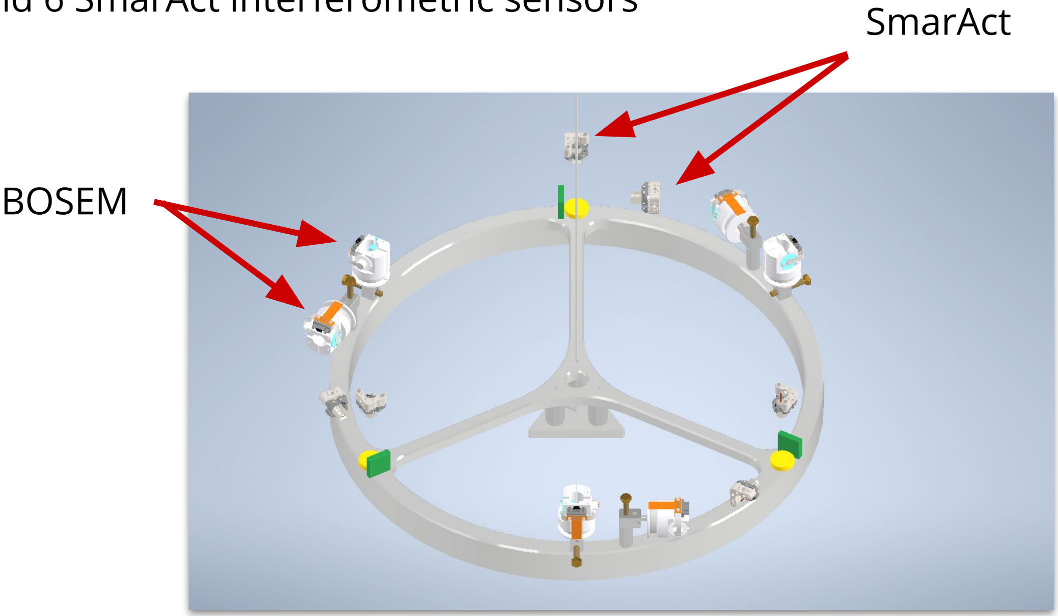
- Imminently starting next stage of 6D project
- Smaller mass made of fused silica: **Compact 6D**
  - Same sensitivity as metal prototype
  - Designed with LIGO BSC space constraints in mind
  - Better stability - thermal fluctuations affect angular DoF - suppressed by fused silica



Compact 6D - Frame and Sensor Design

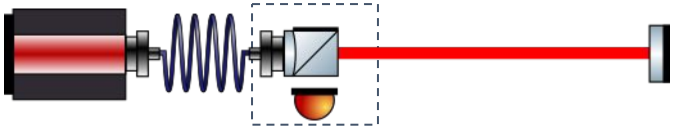
- Frame assembly designed and being manufactured for local UoB ISI testing.
- Sensor suite of 6 BOSEMS and 6 SmarAct interferometric sensors





Compact 6D - SmarAct Testing

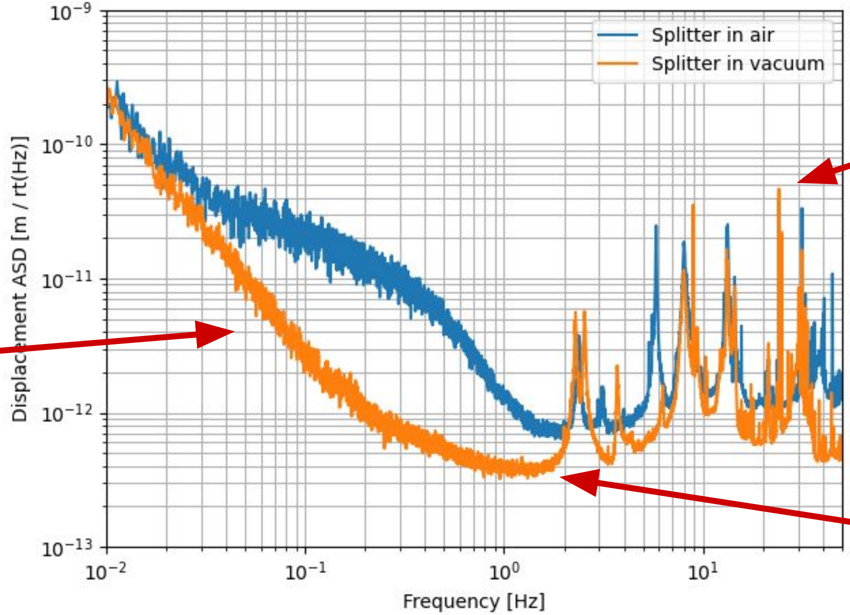
- Part of our strategy to make a robust, maintainable device
- Commercially supplied, customised design
- Mechanically simple, complexity in digital domain
- Michelson interferometer using deep frequency modulation
- More in G2202073



SmarAct

Compact 6D - SmarAct Testing

- Reached 3e-13 m/rt(Hz) sensitivity, limited by laser intensity noise (DOI: [10.1103/PhysRevApplied.18.034040](https://doi.org/10.1103/PhysRevApplied.18.034040))
- Verified in vacuum:



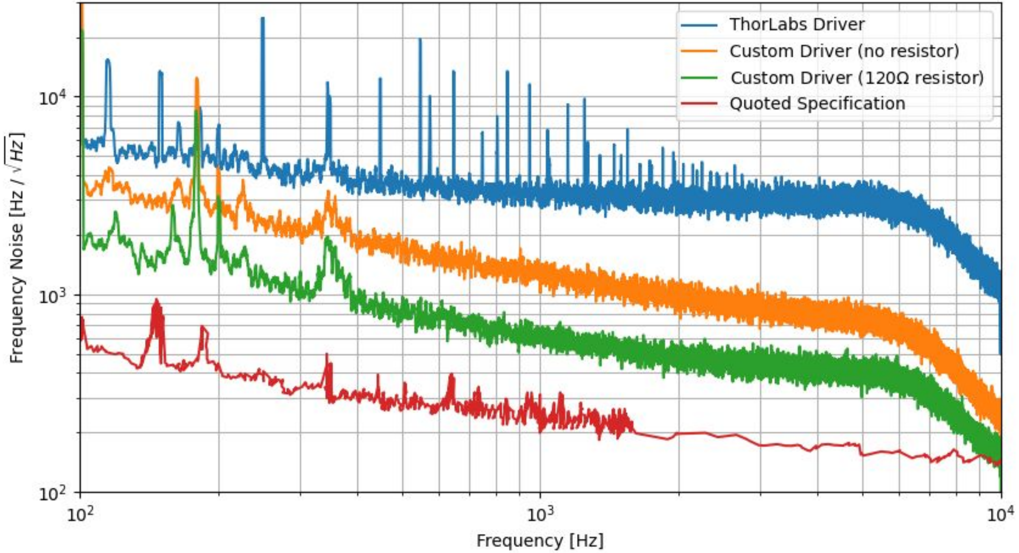
Residual Seismic

Thermal Fluctuations

Laser Intensity

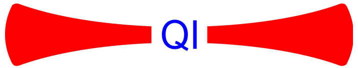
Compact 6D - SmarAct Testing

- Next stage, swap to Toptica DFB laser - simpler, cheaper, but need current driver
- Cheap commercial current drivers (ThorLabs) are noisy
- Just tested Rich Abbott’s custom LIGO driver - better, we’re getting there
- Possible success with active noise suppression, but...
- Laser broke!

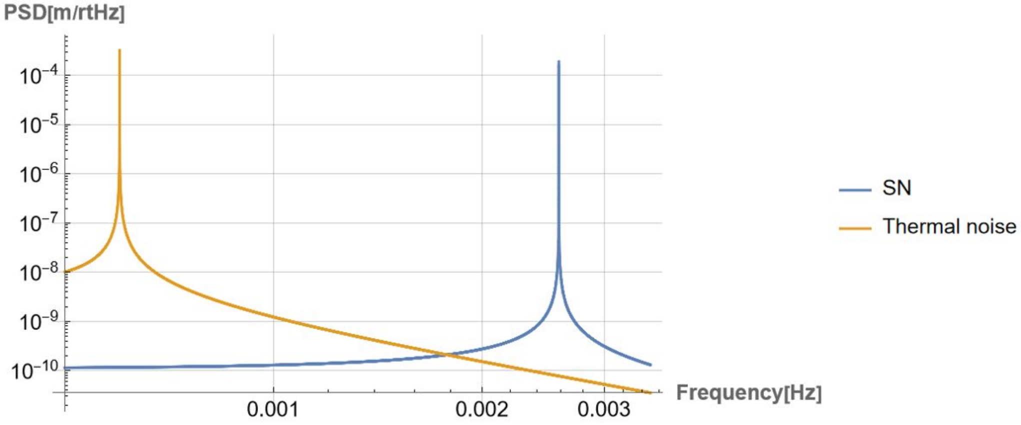


Exploring Fundamental Physics with 6D

- 6D can be used for torsion bar fundamental physics experiments
- We test Schroedinger-Newton semi-classical gravity model
- Nonlinear addition to Schroedinger equation
- We test one particular approach - preselection - leads to shift in resonance

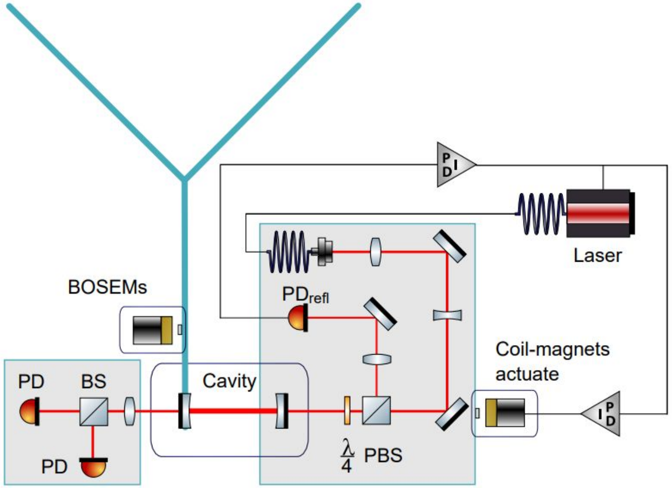


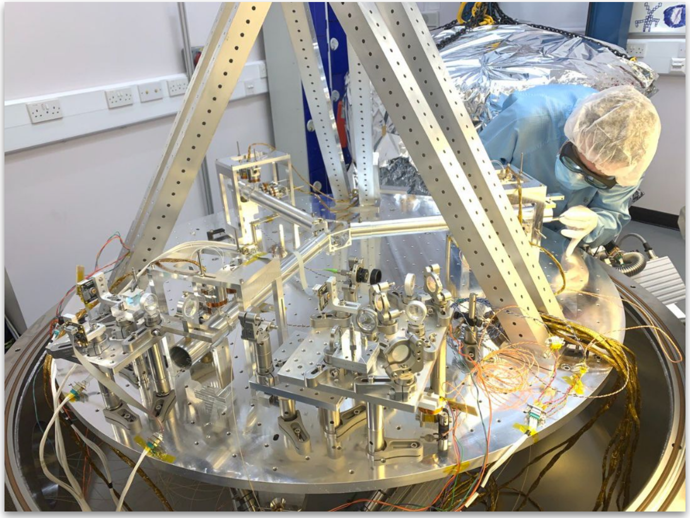
$$i\hbar\frac{\partial\Psi}{\partial t} = \left[-\frac{\hbar^2\nabla^2}{2M} + \frac{1}{2}M\omega_{\text{c.m.}}^2 x^2 + \frac{1}{2}\mathcal{C}(x - \langle x\rangle)^2\right]\Psi$$



Schroedinger-Newton with 6D

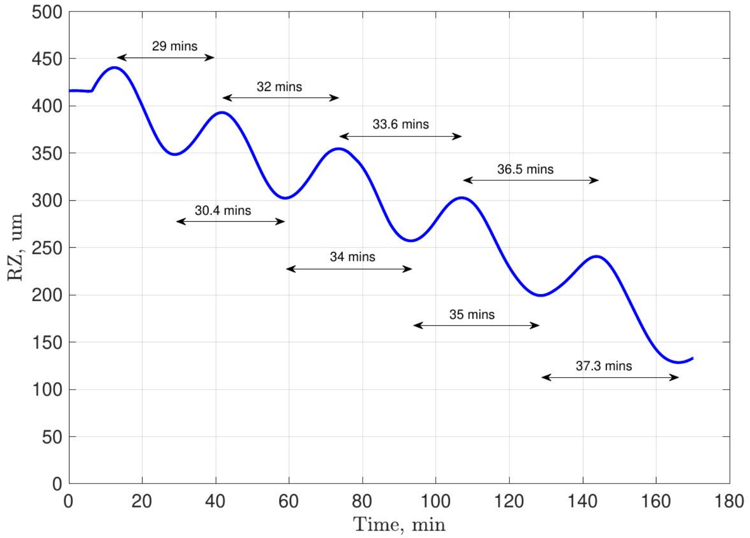
- Excite RZ mode with quantum radiation pressure
- High-finesse cavity to enhance QRPN
- Maximise Q to increase detectability of resonance above classical noise floor





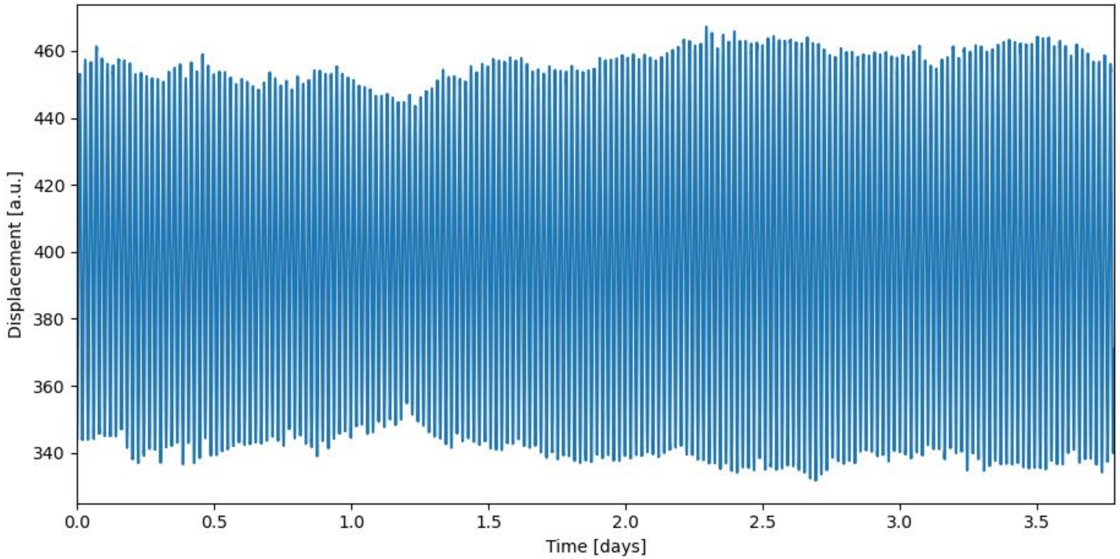
Improving RZ

- Soft RZ means we care about small changes in sources of additional rigidity
- BOSEMs hard to align to optimal (rigidity-free) position
- Catching servo causes shifts in RZ period due to DC force
- ‘Solved’ by carefully tuning RZ rest position to near 0 DC force



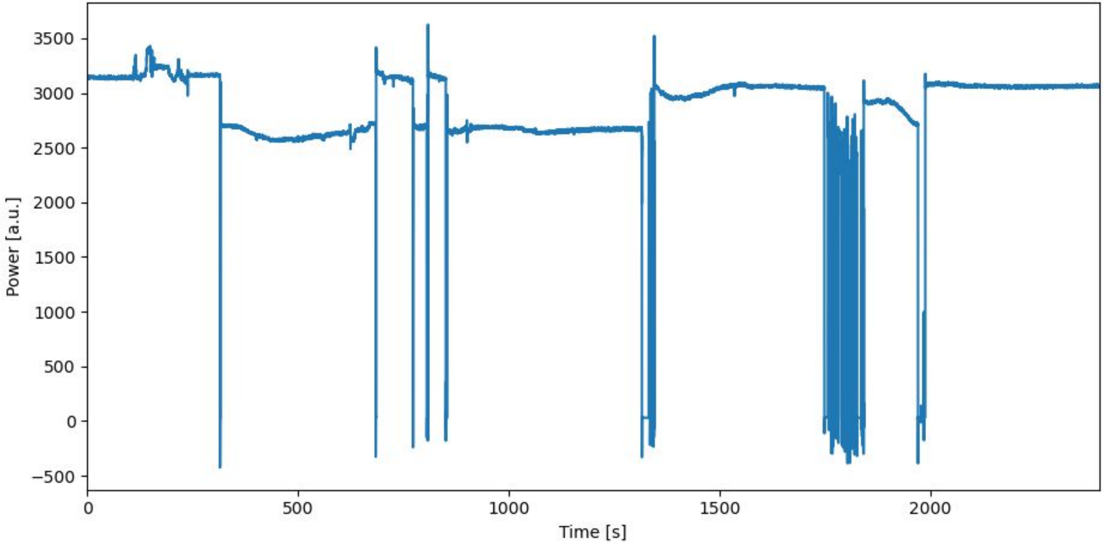
Understanding RZ

- High Q needed for SNR and to resolve splitting
- Vertical BOSEMs induced high eddy currents - removal increased Q from 1000 to 50,000
- Problem: Ring-up time is a year!



Optical System

- High finesse (350,000)
- Low loss (2-5 ppm)
- Observe birefringence in tantala coatings (currently working to suppress)

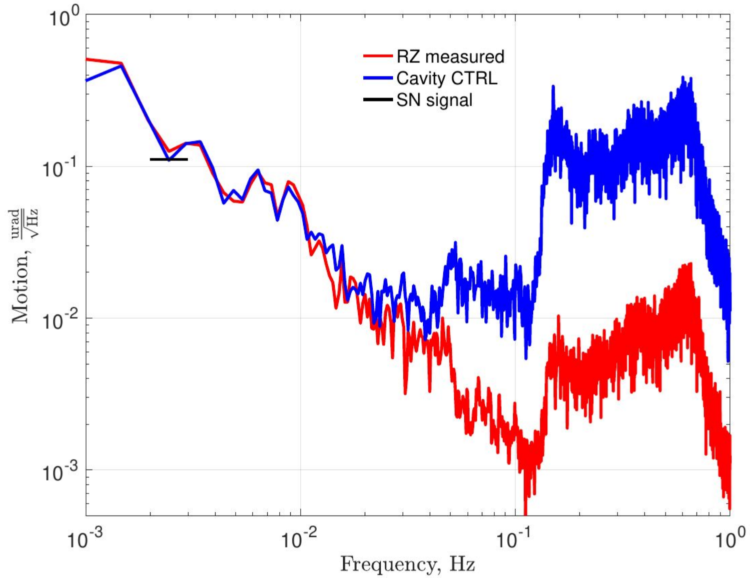


Optical System

- High finesse (350,000)
- Low loss (2-5 ppm)
- Observe birefringence in tantala coatings (currently working to suppress)
- Hierarchical locking scheme:
  - Actuate on laser frequency in broad band
  - Actuate on cavity (coil-magnet on optics base plate) at low frequency
  - Feed-forward to RZ BOSEMs from transmission PD to compensate DC radiation pressure buildup
  - Intensity stabilisation to suppress classical RPN

Current Outlook for 6D-SN

- Collect more data
- Investigate optical spring effect (as RZ is already so soft)
- Already significant improvement in Q factor
- But how to deal with 1 year ring-up time?



Conclusion

- Metal 6D prototype tests concluded:
  - Control scheme demonstrated
  - Sensitivity is good
- Compact 6D test imminent (awaiting manufacture of components):
  - Stable and robust mechanical system
  - Robust and cheap sensing solution

- Demonstrating 6D's use in fundamental physics
- High Q, high finesse, low loss... will we have time to finish experiment?