Design and thermal noise modelling of cryogenic sapphire suspension for KAGRA detector

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Outline

- Layout of the cryogenic payload
- Cradle suspension
- Sapphire blade springs
- Thermal noise modelling (FEA)
- Ongoing/future work
- Conclusions
Cryogenic payload

- Cryogenic payload: 23 kg
- Test mass: Sapphire fibre, length 300 mm, diameter 1.6 mm
- Moving mass mechanism that works at 20K
- PF blade design: suitable both to heatlink's vibration isolation and to suspension thermal noise
- Should be careful about transition from room-temp to cryogenic-temp (need a remote adjustment mechanism?)
- Thrust bearing (can be copied from type-B7)
- Clamp mechanism needs to be revised
- Blade: f < 14Hz
- Sensors: noise performance, selection of OSEM vs LVD
- Actuators: requirements to control noise, size of coils and magnets
- Heatlink: vibration isolation
- Actuators on TM: need to make sure length/alignment control using a setup
Cradle suspension (prototype)

- Plan to fabricate the first prototype cryogenic payload system in ICRR (in 2014)
- Cradle suspension is the first phase towards the final design
- Includes sapphire fibres, sapphire cradle test mass and sapphire blade springs
- 30 kg test mass will used for the cradle test suspensions
- Develop assembly procedure, perform cooling test (20 kelvin), test and characterisation of various components (example blade springs, fibres, connections etc.)
Cradle test mass

We have a spare test mass (29 kg) in ICRR for use.

front view of the test mass

sapphire cradle (1 kg)

Indium coating

29 kg
• Maximum deformation - 1.3 microns
• Maximum equivalent stress - 7 MPa
• No internal modes observed till 2 kHz

FEA modelling (cradle)
Test mass with ears

Nail head of the fibre will be hooked under the ears.

Position of the ear can be moved depending on bending length of the fibre.
Sapphire blade springs

- **Why do we need them?**
  - Reduce the vertical (bounce) mode to below 15 Hz (Vela Pulsar is at 22 Hz)
  - Length compensation of the sapphire fibres
  - Reduce the frequency spread of the fundamental violin mode (less than 5%)

- **Sapphire breaking stress**
  - Average breaking stress of 450 MPa (thermo polished sample) - as shown by Giles Hammond (Glasgow) in the ELiTES meeting 2013. (Poster d-4)
Blade design

- Thickness 4.5 mm
- Thickness 2 mm
- Chamfers for stress distribution
- Clamped here
- Load (6 kg)
Static deformation

- Vertical (bounce) frequency: 14.5 Hz (drops from 108 Hz)
- First internal mode at 550 Hz

Equivalent stress

- 123 MPa
- 106 MPa
- 140 MPa
- 160 MPa
- 53 MPa
- 83 MPa
FEA - cradle suspension

- **30 kg mass**
- **Cradle weighs 1 kg**
- **Sapphire fibre** length 300 mm, diameter 1.8 mm
- **Sapphire pillars**
- **Bending length** 46 mm (FEA)
- **Fibre separation** 50 mm
- **Sapphire blade** springs

Diagram showing the placement of components.
Connections…

Bolted connection between nail head and blades.

Sapphire fibre with threads (1.8 mm)

1.8mm-dia Photoran sapphire rod

M1.8 by Shinkosha

M6 by Shinkosha
Results from FEA (ANSYS)

- Thin (400 microns) fibres usually bend right at the two ends.
- Thick (1.8 mm) fibre stores more energy (elastic) along the length.

\[ E_{\text{fibre}} : 94.5\% \]
\[ E_{\text{blades}} : 5.3\% \]

Dissipation dilution: 6

Ratio of gravitational energy (pendulum motion) to the elastic energy (in fibres).
Thermal noise

Thermal noise (pendulum mode) performance at 20 kelvin

Dominant loss term:
Surface loss
(surface depth over which loss occurs: 100 microns)

Mechanical loss of sapphire fibres - 1.56x10^{-7}

10 Hz - 1.8x10^{-19}
factor of 8 below baseline kagra

see Dan’s poster: e-1
Ongoing/future work

• Optimisation of the cryogenic pendulum design

• Estimation of thermal noise contribution from connections (fibre threads & bolts) using FEA

• Thermal noise from the Indium layer between the test mass & cradle

• Comparison of noise performance: cradle vs ear suspension (including noise from various joints - threads, HCB, Indium)

• Cradle suspension fabrication - sapphire blade springs, cradle and sapphire fibres with threads being fabricated by Shinkosha.

• Characterisation of the cradle suspension at 20 kelvin (comparison with results from FEA)
Conclusions

• R&D for the cradle & ear type suspension is ongoing

• Cradle suspension design will enable us to re-use the sapphire test mass

• We now have a sapphire blade spring design as per KAGRA requirement

• Sapphire blade springs have a maximum stress of 160 MPa and bounce mode frequency of 14.5 Hz

• Results from FEA shows that the cradle suspension design looks feasible for fabricating a prototype suspension

• Pendulum mode thermal noise is estimated to be $1.8 \times 10^{-19} \text{ m} \sqrt{\text{Hz}}$ at 10 Hz

• Various components for the cradle suspension are being fabricated for building the prototype cryogenic system in 2014.

Thank you