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Status of the cryogenic payload system for the KAGRA detector

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Abstract. KAGRA is a large scale cryogenic gravitational wave telescope currently under construction in Japan. The detector is located 200 m underground in the Kamioka mine and will employ cryogenic technologies to achieve high sensitivity. The mirrors of the interferometer will be in the form of multiple pendulums and the final stages will employ cryogenic sapphire suspension system operating at 20 Kelvin. In this paper we report the ongoing activities of the cryogenic payload group involved in the design and fabrication of the cryogenic payload system for the KAGRA detector

1. Introduction

The existence of gravitational waves was proposed by Einstein in his General Theory of Relativity published in 1916 [1]. Gravitational waves are described as ripples in the curvature of space-time fabric and they interact very weakly with matter, which makes it very difficult for direct detection. The effort for directly detecting gravitational waves began in 1960 with Joseph Weber's bar detectors [2]. However, till this date there has been no success and with increased sensitivity of the instruments only the upper limits of gravitational waves signals have been defined. The first indirect evidence of gravitational waves was provided by Hulse [3] and Taylor [4] who were awarded Nobel Prize for Physics in 1993. Their discovery of binary pulsar 1913+16, along with Taylor and Weisberg's [5] estimation of the decay of orbital period with time were consistent with the predictions of general relativity.

Currently there is a global network of ground based laser interferometers being built for the first direct detection of gravitational waves. The first generation of detectors like LIGO (USA) [6], GEO 600 (Germany) [7], VIRGO (Italy) [8] and TAMA 300 (Japan) [9] were not successful in detecting gravitational waves, however they achieved very high sensitivity resulting in an upper limit of 0.015 events per day at signal level less than equal to 5×10^{-21} /•Hz [10]. The first generation of detectors are currently being upgraded to advanced LIGO, advanced Virgo and GEO-HF. There have been some new initiatives in the form of a Large-scale Cryogenic Gravitational-wave Telescope (LCGT) [11] project in Japan, also called as KAGRA. The arm length of the KAGRA detector is 3 km and is located 200 m underground in the Kamioka mine (250 km west of Tokyo). The seismic noise levels at the underground site has been measured using seismometers and is found to be in the order of 10^9 m/•Hz at 1 Hz, which is at least two orders of magnitude lower than other detectors around the world [12]. Another key feature of the KAGRA detector is the use of cryogenic technologies to



achieve strain sensitivity of the order of $h_{rms} \sim 10^{-23}$ which is key to define the emerging field of gravitational wave astronomy. The detection range of the KAGRA detector is expected to be around 173 Mpc in full sky average, however signals from neutron star binary coalescence at a distance of 280 Mpc can also be observed at a certain detector orientation [13].

2. Current status

The KAGRA project is initiated by the Institute for Cosmic Ray Research (ICRR) at The University of Tokyo, in collaboration with the High Energy Accelerator Research Organisation (KEK) and the National Astronomical Observatory of Japan (NAOJ) in Japan. The excavation of the underground site of the detector at Kamioka began in 2012 and 7 km of tunnel work was completed in March 2014 [14]. The installation of vacuum chambers, cryostat and beam tubes began soon after and currently they are undergoing tests for detecting vacuum leakage. The KAGRA project will be operational in two phases, the first phase is iKAGRA which will operate at room temperature with a simple Michelson interferometer setup. iKAGRA is expected to be online by March 2016. The second phase is the baseline design - bKAGRA which is expected to be online by 2018. bKAGRA will employ cryogenic technologies and dual recycled Michelson interferometers with input and out mode cleaners along with 400 kW arm cavities.

3. Design of the cryogenic payload system

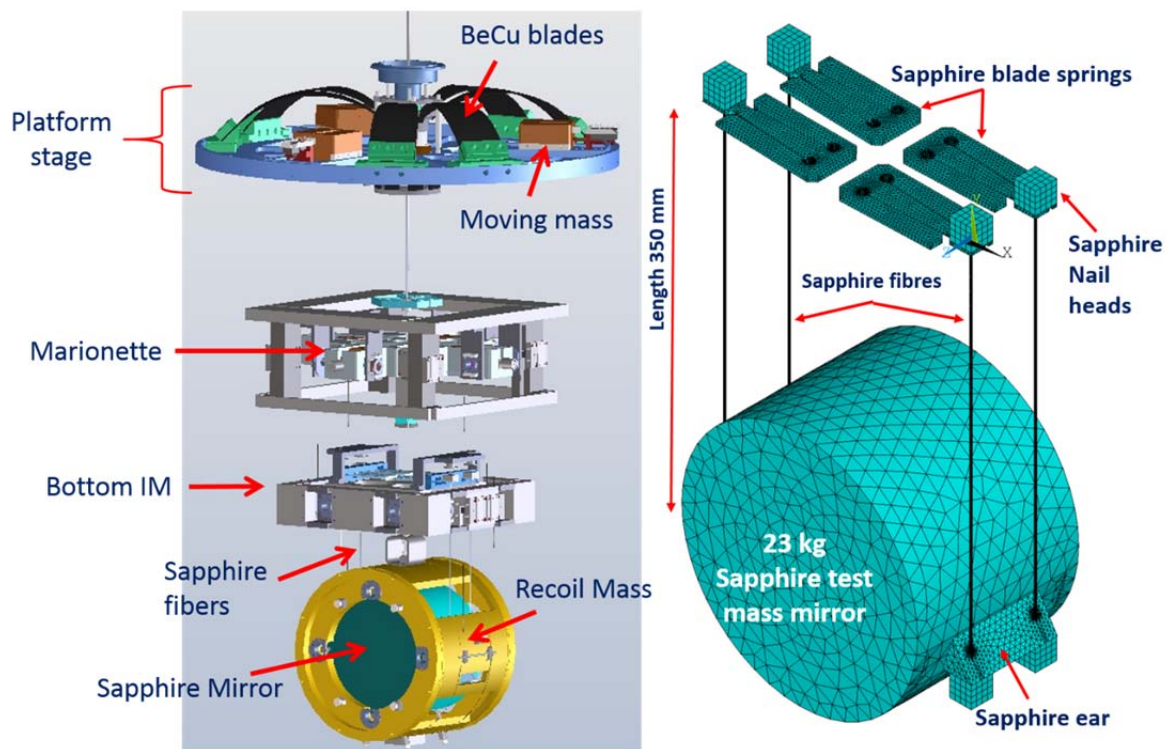


Figure 1. CAD layout of the cryogenic payload system for the KAGRA detector, figure on the right shows the FEA (ANSYS) model of the sapphire suspension system.

The mirrors of the KAGRA detector are made of sapphire. The mirror and its suspensions (called as payload) are cryogenically cooled. The payload is jointly developed by KEK and ICRR. The cryogenic payload system is suspended by room temperature multistage Vibration Isolation System (VIS) developed by NAOJ. Mirror thermal noise strongly depends upon temperature and at 20 K thermoelastic noise in the substrate (sapphire) material is nulled [15]. The cryogenic payload system will be housed in a cryostat and the mirror will be cooled to 20 K using four cryo-coolers, however the

temperature at other parts of the system will be lower than 20 K for heat transfer. Figure 1 shows the CAD model of the cryogenic payload system developed for the KAGRA detector. This payload system will employ four vertical stages for seismic isolation and for achieving lower thermal noise. The uppermost is the platform stage made of stainless steel and will employ beryllium copper (BeCu) blades springs for vertical isolation. The next stage is the marionette which will control the pitch and roll movement of the mirror. The final two stages include a stainless steel intermediate mass followed by the sapphire suspension system. The 23 kg sapphire test mass mirror is suspended by four sapphire fibres of length 350 mm and diameter 1.6 mm. The fibres will be suspended using four sapphire blade springs [16]. The purpose of the blade springs is to compensate the difference in the length of the fibres having a manufacturing tolerance of 100 microns, which could result in an unequal tension between the four fibres in the suspensions. In this scenario the violin mode frequency which is currently at 175 Hz, could spread by 10%, thus reducing the bandwidth of the detector in the most sensitive region. The assembly of the sapphire parts will involve bonding of sapphire ears to the sides of the test mass. Hydroxide catalysis bonding technique [17] will be used for this purpose. The sapphire fibres have rectangular parallelepiped sapphire nail heads attached at both the ends (fabricated by IMPEX, Germany). The nail heads of the fibres will be attached to the blade springs and ears by depositing a thin layer of Indium foil using 35 W Halogen lamp [18]. The sapphire blade springs will be rigidly fixed to the intermediate mass using copper clamps.

4. Prototype test suspensions

Currently there are two types of prototype test suspensions being studied to realise and develop an assembly procedure for the final cryogenic suspension system. In KEK, parts of the prototype of the cryogenic payload system have been fabricated (shown in Figure 2(a)). In order to simplify the experiment, the sapphire components are replaced by dummy made of stainless steel. The metal prototype has beryllium copper blade springs suspending the 23 kg test mass. However, the thickness of this blade springs has been optimised to obtain spring constant and displacements values similar to the sapphire blade springs under tension.

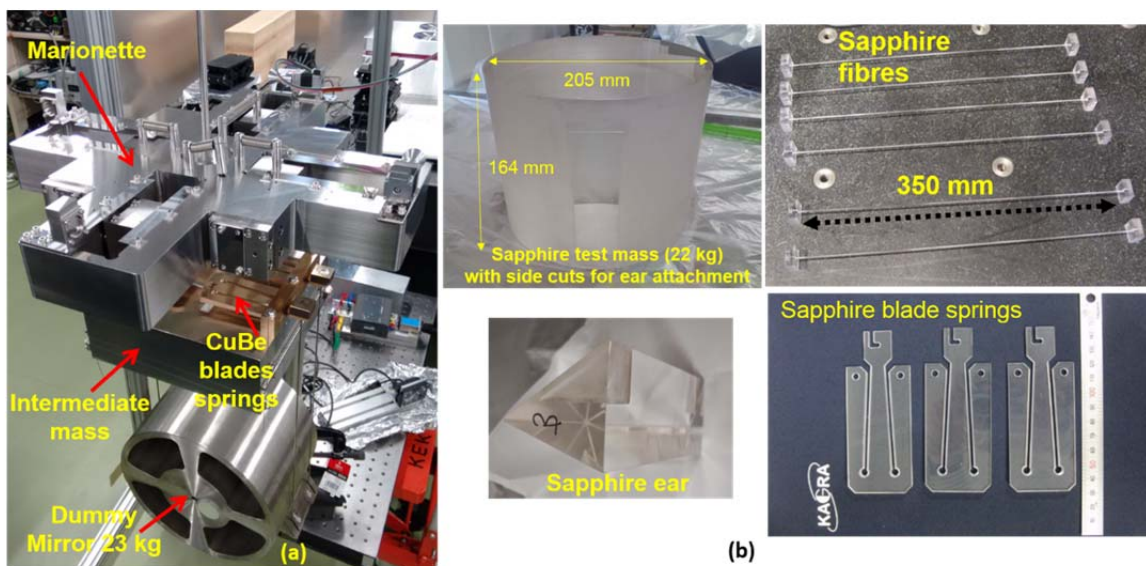


Figure 2. (a) shows the metal prototype of the cryogenic suspension system, comprising of marionette, intermediate mass with BeCu blade springs and a 23 kg dummy test mass suspended on four metal wires of length 350 mm and diameter 2.0 mm. (b) shows the sapphire components at ICRR to be used for the fabrication of prototype test sapphire suspension system.

Using this metal prototype suspension, the pitch and roll measurements of the system are currently being studied at room temperature using probe indicator and displacement meter.

A second prototype test suspensions is currently under development and will include a 22 kg sapphire mirror, four sapphire fibres, sapphire blade springs and a metal intermediate mass. For the prototype test, we have a sapphire mirror of diameter 205 mm and height 164 mm which is smaller in dimensions as compared to the real KAGRA test mass mirror (220 mm by 150 mm ~ 23 kg). The mirror has side cuts for the attachment of sapphire ears using hydroxide catalysis bonding. High quality sapphire fibres with rectangular parallelepiped nail heads have been fabricated and delivered by IMPEX, Germany. The sapphire blade springs have been fabricated by Shinkosha optics in Japan. Figure 2(b) shows the sapphire components at ICRR which will be used for the assembly of the prototype sapphire test suspensions. KEK and ICRR have the necessary facilities like cryostats and clean rooms suitable for the assembly and test of the system. The assembled system will be installed in a cryostat and cooled to 20 K and will be studied for static displacements values and thermal conductivity. The study of mechanical loss in the fibres for the fundamental violin mode (at around 175 Hz) will also be undertaken and is of utmost importance for us from thermal noise perspective. Finally, the value of mechanical loss measured experimentally will be compared with the predicted loss using FEA modelling techniques.

5. Conclusions

KAGRA is an underground detector with cryogenic technologies where the mirrors and suspensions will be cooled to 20 K. The construction, installation and testing of various components of the detector are ongoing and iKAGRA (room temperature operation) is expected to be online by March 2016. The baseline design of the KAGRA detector will be cryogenic and is expected to be online by 2018. The R&D for the cryogenic payload system for the bKAGRA is currently under progress at KEK and ICRR. The first cryogenic prototype payload system is expected to be fabricated and characterized in 2016.

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