Large-scale cryogenic gravitational-wave telescope in Japan: KAGRA

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Abstract. KAGRA, the large-scale cryogenic gravitational-wave telescope (formerly known as LCGT), is a laser interferometric detector under construction at the Kamioka mine in Japan. We report on the current status of the project as well as the overview of the main features and the schedule. The construction has been underway since 2012, and the tunnel excavation in the mine for two 3-km arms finished at the end of March 2014. As with the other advanced terrestrial interferometers, KAGRA will have two long Fabry-Perot cavities to sense gravitational waves, but they are to be installed underground for lower seismic noise. KAGRA will be the first large interferometer having cryogenic cavities, the mirrors for which are planned to be cooled down to around 20 K for reducing thermal noise.

1. Introduction
KAGRA is a Japanese large-scale cryogenic gravitational-wave telescope, formerly called LCGT, under construction at the Kamioka mine in Gifu prefecture [1]. Unlike other advanced ground-based interferometers [2, 3, 4], the KAGRA project is not a simple upgrade of existing facilities; it started from scratch for the construction of infrastructures underground such as a tunnel for the two 3-km length arms, drainage for ground water, and clean booths for installation works.

The KAGRA project is hosted by Institute for Cosmic Ray Research (ICRR) in the University of Tokyo together with two co-hosts, KEK (High Energy Accelerator Research Organization) and National Astronomical Observatory of Japan (NAOJ). The KAGRA collaboration has grown to include over 200 members from more than 60 universities and institutions in Japan and abroad.

Completing a long L-shaped tunnel in the Kamioka mine, Japan, is the first milestone of the KAGRA project, and finished on time at the end of March in 2014. The tunnel excavation started in 2012, which was delayed due to the impact of the Earthquake in 2011.

This article is part of a series of the conference proceedings looking over advanced ground-based gravitational-wave detectors, and here mainly covers KAGRA. If you wish to find common basic knowledges of ground-based laser interferometers, or an overall summary of the worldwide network of them, see the first one of the series. This short article briefly describes main features of KAGRA in section 2, the current status in section 3, and a summary in the last section.

2. Main features of KAGRA
KAGRA has two features that differ from other advanced ground-based interferometers [5]. One is that the whole interferometer will be built more than 200 m underground, below a mountain, for low seismic noise. The base rock of the mountain, in which the L-shaped tunnel
for the interferometer is excavated, is expected to be quite stable with low seismic fluctuations. Seismic fluctuations in another tunnel but under the same mountain were measured to be about $10^{-9}/f^2$ m/Hz$^{1/2}$, where $f$ is frequency, above 1 Hz frequency region; it was smaller by about 1/100 compared to TAMA300 in Tokyo in the same frequency region.

The other difference is that test masses for the 3-km Fabry-Perot cavities will be cooled down to 20 K for reducing thermal fluctuations, while a circulating power in each arm cavity will rise to the order of 100 kW. The reduction of mirror thermal noise with cryogenic mirrors has been already demonstrated in CLIO, a 100 m prototype interferometer in Kamioka [6]. The test masses for KAGRA (and also CLIO) are made of sapphire, which has better thermal conductivities than that of traditional silica mirrors at the low temperature. Thermal lensing effects in the test masses, which is due to the stored power in the arm cavities, can be reduced as well.

3. Overall plan and current states of KAGRA

3.1. Overall plan

Two major configuration phases are set in the overall schedule of KAGRA [5]. We are now in the first phase, called initial KAGRA (iKAGRA), and aim to develop basic technologies to operate a large interferometer as a gravitational-wave observatory in the underground; we will build a Michelson interferometer with two 3-km Fabry-Perot arm cavities, detector characterization system, data taking system, and data management system for an engineering run planned at the end of 2015. The test masses of the arm cavities are made of silica, suspended by rather simplified pendulums, and the whole interferometer is operated at room temperature.

The second phase, called baseline KAGRA (bKAGRA), will start from the beginning of 2016. In this phase, the iKAGRA interferometer will be upgraded, and it will reach the goal sensitivity (Figure 1). The silica test masses will be replaced by cryogenic ones made of sapphire, which will be cooled down to 20 K, and suspended by cryogenic suspensions. The interferometer will be modified with power recycling and signal recycling cavities, and operated with the resonant sideband extraction (RSE) technique to reach beyond the standard quantum limit [7].
3.2. Construction status of iKAGRA

Tunnel excavation for KAGRA was completed at the end of March 2014. In the tunnel, two branches are separated by nearly 90 degrees with respect to one another and extend 3 km for the X and Y arm cavities (Figure 2). The branches are tilted by 1/300 for drainage of ground water; the highest altitude is at the X end, and the lowest at the Y end. The halfway point is at the corner of the branches, where a beam splitter will be installed. The corner station is 372 m above sea level. It is excavated by New Austrian Tunneling Method (NATM), and takes no more than two years. There are two teams for the tunneling; one starts from the corner of the branches toward both X and Y ends, and the other from the end of the Y arm branch. You can see a movie of the final blast to penetrate the Y arm at the halfway (1.5 km away from the corner) point here [9]. In bKAGRA phase, test masses will need long suspensions of 14 m height for their seismic attenuation system, so upper floors and pits to connect the upper and ground floors are also excavated above the chambers for the test mass.

Delivery of vacuum chambers and ducts for KAGRA is scheduled to start in August of 2014. In the iKAGRA phase, 23 chambers will be installed; 19 on the base floor and 4 on the upper. Each 3-km long arm duct is assembled from 12-m long ducts at the site. The inner surface of each vacuum duct is finished by electro-chemical buffing (ECB) method to reduce outgassing, so that the interferometer can be operated in vacuum of $\sim 10^{-7}$ Pa.

3.3. Research and development for bKAGRA

A cryogenic payload, the most challenging part in the KAGRA project, should support a sapphire test mass satisfying both low temperature and seismic noise. A conceptual design of this system is that the suspension wire from the upper floor at the room temperature comes downward via several pendulum stages to the cryogenic payload through an aperture on the top of the double inner shields, in which a sapphire test mass is suspended by sapphire wires or rods (Figure 3). Polishing of sapphire pathfinders (test pieces of substrates) produce satisfactory results so far, but the value of bulk absorption is a concern [10]. Mechanical loss of the coating on a sapphire is also investigated, and the result will be published later.

To conduct heat from a sapphire mirror, it is supported by sapphire wires from an upper stage (intermediate mass). Measurements show that heat conductivities of test pieces of sapphire fibers are more than 5000 W/m/K at 20 K, which is a promising result that they can be used as wires for the cryogenic payload [11].

The entire 3-km arm is not cooled, so a sapphire mirror will be exposed to the 300 K radiation from the room temperature parts. In order to reduce the entering radiation, two cryogenic duct shields of 5-m long each are installed on either sides of the sapphire mirror (Figure 3); they are also cooled to temperatures around 80 K and are designed to have an array of funnels inside to absorb or reflect this radiations [12].
4. Summary

KAGRA is a Japanese large-scale cryogenic gravitational-wave telescope under construction at the Kamioka mine in Gifu prefecture, Japan. Unlike the other terrestrial advanced interferometers, the KAGRA interferometer is not a simple upgrade of previous one, and started with building a tunnel to make the underground site. The tunnel was finally completed at the end of March 2014. The first engineering run is planned at the end of 2015 with the initial configuration of the interferometer. The upgrade of the interferometer will start from the beginning of 2016 to reach the designed sensitivity of KAGRA.

Acknowledgments

The authors are grateful for support from the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program A, Advanced Research Networks, and Grant-in-Aid for Specially Promoted Research of the KAGRA project.

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