The status of KAGRA underground cryogenic gravitational wave telescope

T. Akutsu[1], M. Ando[2], A. Araya[3], N. Aritomi[2], H. Asada[4], Y. Aso[5], S. Atsuta[6], K. Awai[7], M. A. Barton[1], K. Cannon[8], K. Craig[9], W. Creus[10], K. Doi[11], K. Eda[8], Y. Enomoto[2], R. Flaminio[1], Y. Fujii[1], M.-K. Fujimoto[1], T. Furuhata[11], S. Haino[12], K. Hasegawa[9], K. Hashino[11], K. Hayama[7], S. Hirobayashi[13], E. Hirose[9], B. H. Hsieh[9], Y. Inoue[10], K. Ioka[14], Y. Itoh[8], T. Kaji[15], T. Kajita[9], M. Kakizaki[11], M. Kamiizumi[7], S. Kambara[11], N. Kanda[15], S. Kanemura[16], M. Kaneyama[15], G. Kang[17], J. Kasuya[6], Y. Kataoka[6], N. Kawai[6], S. Kawamura[7], C. Kim[18], H. Kim[19], J. Kim[20], Y. Kim[21], N. Kimura[22], T. Kinugawa[9], S. Kirii[9], Y. Kitaoka[15], Y. Kojima[23], K. Kokeyama[7], K. Komori[2], K. Kotake[24], R. Kumar[22], H. Lee[21], H. Lee[20], Y. Liu[25], N. Luca[26], E. Majorana[26], S. Mano[27], M. Marchio[1], T. Matsui[28], F. Matsushima[11], Y. Michimura[2], O. Miyakawa[7], T. Miyamoto[9], A. Miyamoto[15], K. Miyo[7], S. Miyoki[7], W. Morii[29], S. Morisaki[8], Y. Moriwaki[11], T. Morozumi[9], M. Musha[30], S. Nagano[31], K. Nagano[9], K. Nakamura[1], T. Nakamura[32], H. Nakano[33], M. Nakano[9], K. Nakao[15], T. Narikawa[9], L. Nguyen Quynh[34], W.-T. Ni[35], T. Ochi[9], J. Oh[19], S. Oh[19], M. Ohashi[7], N. Ohishi[5], M. Ohkawa[36], K. Okutomi[37], K. Oohara[38], I. Pinto[39], N. Sago[40], M. Saijo[41], Y. Saito[7], K. Sakai[42], Y. Sakai[2], Y. Sasaki[43], M. Sasaki[14], S. Sato[44], T. Sato[45], Y. Sekiguchi[46], N. Seto[32], M. Shibata[14], T. Shimoda[2], H. Shinkai[47], A. Shoda[1], K. Somiya[6], E. Son[19], A. Suemasa[30], T. Suzuki[45], T. Suzuki[9], H. Tagoshi[9], H. Takahashi[43], R. Takahashi[1], A. Takamori[3], H. Takeda[2], H. Tanaka[9], K. Tanaka[15], T. Tanaka[32], D. Tatsumi[1], T. Tomaru[22], T. Tomura[7], F. Travasso[48], K. Tsubono[2], S. Tsuchida[15], N. Uchikata[9], T. Uchiyama[7], T. Uehara[49], S. Ueki[43], K. Ueno[50], T. Ushiba[9], M. H. P. M. van Putten[51], H. Vocca[48], S. Wada[2], T. Wakamatsu[38], T. Yamada[9], S. Yamamoto[47], T. Yamamoto[7], K. Yamamoto[11], A. Yamamoto[22], J. Yokoyama[8], T. Yokozawa[15], T. H. Yoon[52], H. Yuzurihara[15], S. Zeidler[1], Z.-H. Zhu[53] (KAGRA Collaboration)

[1] National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
[2] Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[3] Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan
[4] Department of Advanced Physics, Hirosaki University, Hirosaki, Aomori 036-8561, Japan
[5] National Astronomical Observatory of Japan, Hida, Gifu 506-1205, Japan
[6] Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan
[7] Institute for Cosmic Ray Research, University of Tokyo, Hida, Gifu 506-1205, Japan
[8] Research Center for the Early Universe, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[9] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

[10] Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan
[11] Department of Physics, University of Toyama, Toyama, Toyama 930-8555, Japan
[12] Institute of Physics, Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan
[13] Faculty of Engineering, University of Toyama, Toyama, Toyama 930-8555, Japan
[14] Yukawa Institute for Theoretical Physics, Kyoto University, Sakyo, Kyoto 606-8502, Japan
[15] Department of Physics, Osaka City University, Sumiyosi, Osaka 558-8585, Japan
[16] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[17] Korea Institute of Science and Technology Information, Yuseong, Daejeon 34141, Korea
[18] Korea Astronomy and Space Science Institute (KASI), Yuseong, Daejeon 34055, Korea
[19] National Institute for Mathematical Sciences, Daejeon 34047, Korea
[20] Department of Computer Simulation, Inje University, Gimhae, Gyeongsangnam 50834, Korea
[21] Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea
[22] High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
[23] Department of Physical Science, Hiroshima University, Higashihiroshima, Hiroshima 903-0213, Japan
[24] Department of Applied Physics, Fukuoka University, Jonan, Fukuoka 814-0180, Japan
[25] Department of Advanced Materials Science, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[26] Istituto Nazionale di Fisica Nucleare, Sapienza University, Roma 00185, Italy
[27] Department of Mathematical Analysis and Statistical Inference, The Institute of Statistical Mathematics, Tachikawa, Tokyo 190-8562, Japan
[28] School of Physics, Korea Institute for Advanced Study (KIAS), Seoul 02455, Korea
[29] Disaster Prevention Research Institute, The Kyoto University, Uji, Kyoto 611-0011, Japan
[30] Institute for Laser Science, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan
[31] The Applied Electromagnetic Research Institute, National Institute of Information and Communications Technology, Koganei, Tokyo 184-8795, Japan
[32] Department of Physics, Astronomy, Kyoto University, Sakyo, Kyoto 606-8502, Japan
[33] Faculty of Law, Ryukoku University, Fushimi, Kyoto 612-8577, Japan
[34] Hanoi National University of Education, Cau Giay, Hanoi, Vietnam
[35] Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
[36] Faculty of Engineering, Niigata University, Nishi, Niigata 950-2181, Japan
[37] The Graduate University for Advanced Studies, Mitaka, Tokyo 181-8588, Japan
[38] Department of Physics, Niigata University, Nishi, Niigata 950-2181, Japan
[39] Department of Engineering, University of Sannio, 82100 Benevento Italy
[40] Faculty of Arts and Science, Kyushu University, Nishi, Fukuoka 819-0395, Japan
[41] Research Institute for Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan
[42] Department of Information Science and Control Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
[43] Department of Information and Management Systems Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
[44] The Graduate School of Science and Engineering, Hosei University, Koganei, Tokyo 184-8584, Japan
[45] Department of Electrical and Electronic Engineering Faculty of Engineering, Niigata University, Nishi, Niigata 950-2181, Japan
[46] Faculty of Science, Toho University, Funabashi, Chiba 274-8510, Japan
[47] Department of Information Systems, Osaka Institute of Technology, Hirakata, Osaka 573-0196, Japan
[48] Istituto Nazionale di Fisica Nucleare, University of Perugia, Perugia 06123, Italy
[49] Department of Communications Engineering, National Defense Academy of Japan, Yokosuka, Kanagawa 239-8686, Japan
[50] Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA
[51] Department of Physics and Astronomy, Sejong University, Gwangjin, Seoul 143-747, Korea
[52] Department of Physics, Korea University, Seongbuk, Seoul 02841, Korea
[53] Department of Astronomy, Beijing Normal University, Beijing 100875, China

E-mail: `michimura@granite.phys.s.u-tokyo.ac.jp`

Abstract. KAGRA is the first km-class interferometric gravitational wave telescope constructed underground to reduce seismic noise, and the first telescope to use cryogenic cooling of test masses to reduce thermal noise. The construction of the infrastructure to house the interferometer in the tunnel, and the initial phase operation of the interferometer with a simple 3-km Michelson configuration have been completed. The first cryogenic operation is expected in 2018, and the observing runs with a full interferometer are expected in 2020s. The basic interferometer configuration and the current status of KAGRA are described.

1. Introduction

The direct detections of gravitational waves by Advanced LIGO in 2015 opened a completely new frontier in astronomy [1]. In 2017, Advanced Virgo [2] started simultaneous observing run with Advanced LIGO to extend the global network of advanced gravitational wave telesopes. Coincident detection of gravitational-waves at multiple sites helps sky localization and parameter estimation of the source [3].

KAGRA is another ground-based interferometric advanced gravitational wave telescope, which aims to further enhance the field of gravitational wave astronomy [4, 5]. Although the basic interferometer configuration is very similar to other telescopes, KAGRA uses two distinct strategies. Advanced LIGO and Advanced Virgo are constructed on the surface of the Earth, whereas KAGRA is constructed at an underground site in the Kamioka min to reduce seismic noise and gravity gradient noise [6]. Advanced LIGO and Advanced Virgo uses heavier and larger room temperature fused silica test masses to reduce thermal noise, whereas KAGRA uses sapphire test masses at 20 K to reduce thermal noise [7, 8]. Some concepts of future gravitational wave telescopes [9, 10] plans to incorporate underground construction and cryogenic cooling of test masses, and KAGRA is expected to pioneer technologies for the future.

The construction of the initial phase facility including the tunnel, vacuum system, cryostats, and clean booths was completed in November 2015. In March and April 2016, we have performed the first operation of a simplified 3-km Michelson interferometer at room temperature. Our next step is to operate the the cryogenic interferometer, and various installation works and tests are underway. In this article, we briefly describe the interferometer configuration and the current status of the KAGRA project.

2. Interferometer Configuration

KAGRA interferometer is a resonant sideband extraction (RSE) interferometer with 3-km Fabry-Pérot arm cavities formed by sapphire input test masses (ITMs) and end test masses (ETMs) at cryogenic temperatures (see Fig. 1). Other mirrors such as a beam splitter (BS), power recyling mirrors (PRM, PR2, PR3) and signal recycling mirrors (SRM, SR2, SR3) are room temperature fused silica mirrors. Power recycling cavity enhances the effective input power, and signal recycling cavity broaden the detector bandwidth by changing the spectral shape of the quantum noise. The interferometer is equipped with input and output mode cleaners (IMC and OMC) to reject higher-order spatial modes and unwanted frequency sidebands of the input and output beams. IMC is a triangular ring cavity formed by three suspended mirrors, and has a round-trip length of 53.3 m and finesse of 540. OMC is a bow-tie cavity formed by four mirrors monolithically fixed on a base plate, and has a round-trip length of 1.5 m and finesse of 780 [11].

We use 180 W continuous-wave laser source at a wavelength of 1064 nm. The laser frequency is pre-stabilized with respect to IMC length, and laser intensity is stabilized by the IMC transmitted power. The laser frequency is ultimately stabilized with respect to averaged length of the 3-km arm cavities. The designed power recycling gain is 10 and the arm cavity finesse is 1530. With input power to PRM of 78 W, the power inside the arm cavities reach 400 kW.

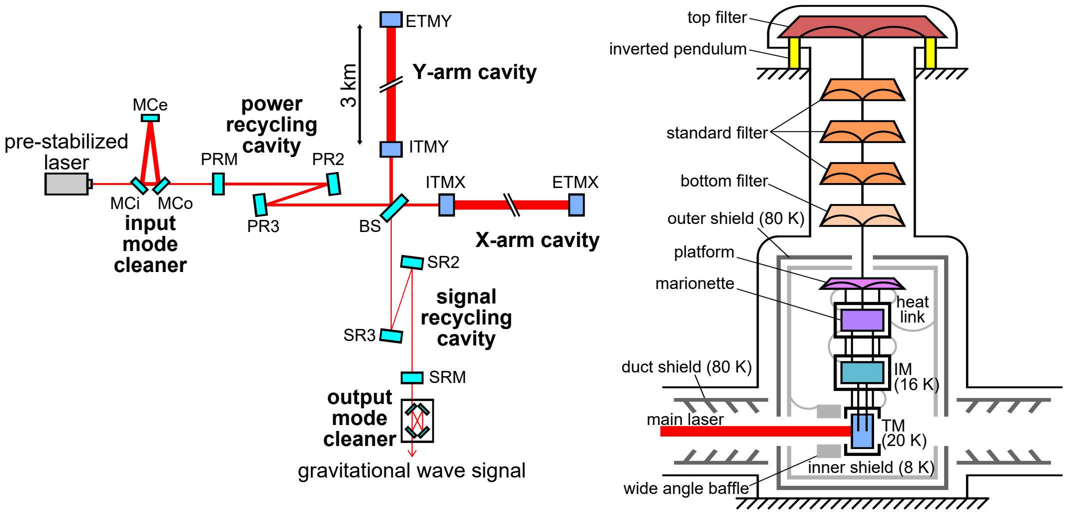

Figure 1. Schematic of the KAGRA interferometer (left) and cryogenic suspension system for sapphire test masses (right). Marionette, intermediate mass (IM) and test mass (TM) are surrounded by respective recoil masses for position and alignment control.

ITMs and ETMs are suspended by eight-stage pendulum suspended from a top geometric anti-spring filter on a inverted pendulum table for low frequency vertical and horizontal vibration isolation [12] (see Fig. 1). The last four stages of the pendulum is cooled down to cryogenic temperatures and called a cryogenic payload [13]. The heat generated by the main intra-cavity beam is extracted via sapphire fibers which suspend the test mass from the intermediate mass, and via high purity 6N aluminum heat links. The thermal conductivity of sapphire fiber is measured to be $\kappa \simeq 7.98 \times (T/1\ \mathrm{K})^{2.2}$ W/K/m at cryogenic temperatures, which is high enough to cool down the mirror to 20 K [14]. The cryogenic payload is surrounded by inner and outer shields which are cooled down to 8 K and 80 K, respectively, by low vibration pulse-tube cryocoolers [15]. The arm cavity also has different kinds of baffles and duct shields for absorbing stray light and thermal radiation from ducts at room temperature [16, 17].

Room temperature mirrors are suspended from simpler vibration isolation system. BS and signal recycling mirrors are each suspended by a four-stage pendulum from a top geometric anti-spring filter on a inverted pendulum table. Power recyling mirrors are each suspended by similar system, but by a triple-pendulum and has no inverted pendulum. IMC mirrors are suspended by a double pendulum fixed on vacuum compatible vibration isolation stacks. All the mirrors are installed in the vacuum chambers at 10^{-7} Pa to mitigate noise from residual gas. For details of the interferometer configuration and room temperature suspension system, see Refs. [4, 5] and Refs. [18, 19], respectively.

Along the KAGRA interferometer, environmental sensors such as thermo-hygrometers, barometers, seismometers, magnetometers, and microphones are placed to monitor and characterize environmental transient noises [20]. One of the most significant sensors is a 1.5-km laser strainmeter, which is placed along the X-arm. This strainmeter is fixed to the ground to monitor low-frequency ground motion, and has been operating since August 2016 [21].

3. iKAGRA Operation

The KAGRA project is split into two stages, initial phase (iKAGRA) and baseline phase (bKAGRA). iKAGRA was aimed to operate the 3-km underground interferometer for the first time, and bKAGRA aims to operate the full cryogenic RSE interferometer for observing runs.

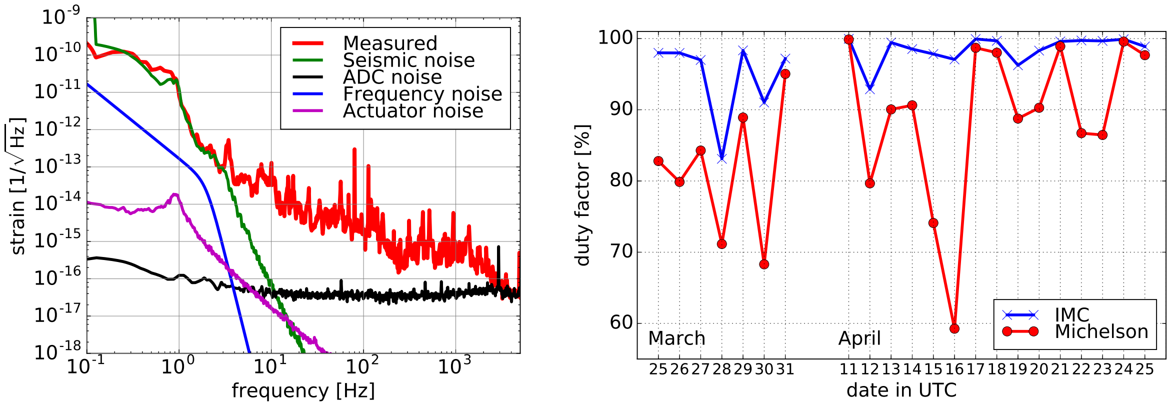

Figure 2. Strain sensitivity (left) and daily duty factor (right) of iKAGRA. Significant degradation in the duty factor on April 16 is due to an earthquake with a magnitute 7.3 which hit Kumamoto at 16:25 UTC.

In March and April 2016, we have operated the 3-km Michelson interferometer for the first time, with significantly simplified mirror suspension system. ETMs were room temperature fused silica mirrors suspended by a double pendulum, and only PR2, PR3 and BS were installed other than ETMs and IMC mirrors. All the mirrors were installed inside the vacuum chambers at air pressure, except for the IMC mirrors at 200 Pa. We used 2 W laser source and input power to the Michelson interferometer was 200 mW. With this iKAGRA operation, we have tested basic performance of the digital real-time interferometer control system and data acquisition, transfer and analysis pipelines.

The iKAGRA operation was done in two periods, from March 25 to 31 and from April 11 to 25. Between the March run and April run, we had a little commissioning break to improve the sensitivity and the stability of the interferometer. The strain sensitivity in March and April was $3 \times 10^{-15}\ /\sqrt{\text{Hz}}$ and $6 \times 10^{-16}\ /\sqrt{\text{Hz}}$ at 100 Hz, respectively. The duty cycle, the ratio of locked period to whole run period, in March and April was 80% and 89%, respectively. These improvements were done mainly by changing the lock scheme from mid-fringe lock to dark-fringe lock using frontal modulation technique, and by improving the actuator balancing of the ETMs.

The strain sensitivity was limited by the seismic noise below 3 Hz and analog-to-digital converter noise above 3 kHz (see Fig. 2). The limiting noise source in mid-frequencies is not completely understood, but acoustic noise coupling was proved to be very large because mirrors were installed at air pressure. After April run, some of the fans of the clean booths were turned off to show that sensitivity can be improved by reducing acoustic noise. The best sensitivity achived after the test run was $2 \times 10^{-16}\ /\sqrt{\text{Hz}}$ at 100 Hz. Details of the iKAGRA construction and operation will be discussed elsewhere.

4. Outlook

After completion of iKAGRA operation, we have quickly transitioned to bKAGRA phase. bKAGRA is split into 3 phases by project milestones, first operation of 3-km cryogenic Michelson interferometer (Phase 1), first operation of full cryogenic RSE interferometer (Phase 2), and start of observing runs (Phase 3). bKAGRA Phase 1 operation will be done with full suspension system by March 2018.

At the time of writing, we are currently installing the mirrors for bKAGRA Phase 1. PR2 and PR3 were installed, and PRM and BS are ready to be installed. Installation of the room temperature part of the ETMY suspension was completed, test assembly of the cryogenic part was also completed, and cooling test with a full suspension chain showed that the test mass can be cooled down to 12 K in 23 days, without any heatload from the laser beam. Assembly of ETMX suspension is also underway, and signal recycling mirrors and ITMs will be installed by the end of 2018. After installation of all the mirrors, we will start the commissioning of each arm and central dual-recycled Michelson iterferometer step by step. We are expecting the first full operation one year after the completion of the installation work, and observing runs are expected to start in early 2020s.

The sky position of many gravitational wave signals can be determined to below 10 deg^2 with coincident detection by Advanced LIGO, Advanced Virgo and KAGRA [3]. Contribution of KAGRA will be significant for multi-messenger astronomy and precision gravitational wave astronomy.

5. Summary

The major construction of KAGRA has been completed and the initial phase operation was performed. With initial phase operation of 3-km Michelson interferometer, we have tested the basic system from interferometer controls to data analysis pipelines as a gravitational wave telescope. We are now in the installation phase for the first cryogenic operation, and the observing runs with a full interferometer are expected in early 2020s. KAGRA joining the global network of advanced gravitational wave telescopes is important for sky localization and parameter estimation of the source. With underground and cryogenic technologies, KAGRA also paves the way to future gravitational wave telescopes.

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