# The cryogenic challenge: status of the KAGRA project

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**Abstract**. The KAGRA project is building a gravitational wave detector inside the Kamioka mine (Japan). The detector is based on a laser interferometer with arms 3 km in length. In addition to its underground location the detector will be characterized by its mirrors made of sapphire and operated at cryogenic temperature. This paper describes the status of the construction at the site and gives an overview of the developments ongoing to prepare the cryogenic operation.

## 1. Introduction to KAGRA

KAGRA is a gravitational wave detector based on laser Michelson interferometer with arms 3 km in length and aiming at the direct detection of gravitational wave in the frequency band comprised between 10 Hz and a few kHz. The goal is the detection of gravitational waves emitted by astrophysical sources such as the coalescence of binaries made of neutron stars and black holes, the explosion of supernovae, the spinning and instabilities of neutron stars in the galaxy, the relic waves from the Big Bang as well as many others very energetic events undergoing in the Universe. Their detection will not only allow to probe the gravitational force in a regime inaccessible on Earth and in the solar system but also provide a new mean to observe the Universe [1].

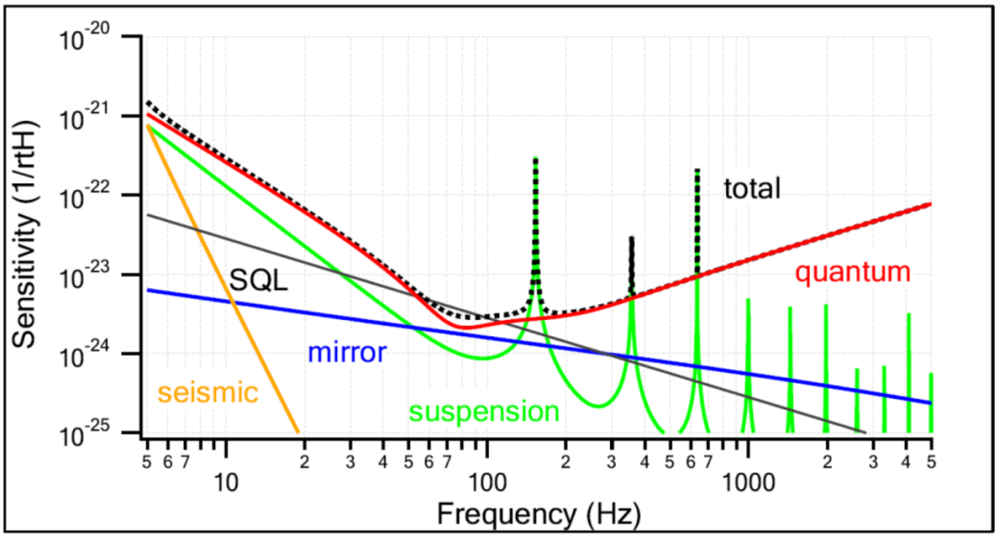


Figure 1. The KAGRA sensitivity for two different configuration of the signal recycling cavity

The KAGRA detector [2] is currently being built underground in the Kamioka mine. The site is located in the Gifu prefecture of Japan. The main features of the KAGRA design compared to other similar detectors (Virgo [3], LIGO [4], GEO[5]) is its location underground and the operation of the interferometer mirrors at cryogenic temperature. The interferometer optical configuration will be more traditional with Fabry-Perot cavities in the interferometer arms to amplify the gravitational wave effect and the use of power and signal recycling to decrease the quantum noise limitation. For the vibration isolation KAGRA will use 12 m long chains of pendulums and springs to isolate the main mirrors from the ground vibrations. The target detector sensitivity is the one shown in Figure 1 and should allow to detect the coalescence of a binary made of two neutron stars up to distances of about 150 Mpc. The overall plan foresees two phases. In a first step a simplified version of the detector (called iKAGRA) consisting of a 3 km long Michelson interferometer (without Fabry-Perot nor recycling cavities) will be operated at room temperature. Then the full interferometer (called bKAGRA) with all the components and the cryogenic mirrors will be installed and operated. The present plan is to complete the first step by the end of 2015 and the second step in 2018.

## 2. Status of construction

The project was approved in 2010 but, due to the big earthquake in 2011, construction could start only in 2012. The 3 km tunnels excavation including the central large hall as well as the smaller terminal halls was completed in March 2014 [6]. The excavation included the construction of four rooms above the main halls and four shafts to host the long vibration isolations systems.

After the excavation was completed the vacuum systems installation started. This includes the 3 km long vacuum tubes as well the four cryostats and all other vacuum chambers to host the interferometer mirrors. The installation was completed in the spring of 2015 despite the difficulties with the water leaking into the tunnels and the halls through the roofs and the floors. During the snow melting season the amount of water through the tunnels was more than 1000 t/h. Thanks to the 0.3% slope built in the tunnels, it was possible to avoid the flooding of the arms but additional works were required to mitigate the water issue. Nevertheless it was possible to install all the vacuum system required for iKAGRA. In addition all the clean-booths were installed around the vacuum chambers to allow installing the suspension and the mirrors in a cleaner environment.

In parallel the facility inside the cavern was completed with the construction of the clean room for the laser and the room for hosting the electronics and control system racks. Infrastructure works were done also at the exterior. In particular a building was realized outside to host the control room and some office space. The network was installed in the tunnel so to control the equipment inside the tunnel from the control room.

Thanks to the installation of the first clean booths, after the water issue was solved, it was possible to resume the installation of the equipment inside the vacuum systems. At the time of writing the first vibration isolation systems for the input mode-cleaner are being installed. In parallel the 2W laser for iKAGRA and the input optics on the laser bench were installed in the laser room. The next step will consist in sending the laser light into the input mode-cleaner and start the commissioning of the input optics system. Even if the planning is extremely tight the KAGRA project is working hard to complete the installation of the iKAGRA interferometer by the end of the year and have a one month engineering run at the beginning of 2016.

## 3. Preparation of bKAGRA

The final configuration of the KAGRA interferometer is called bKAGRA. Its optical configuration [7] will be similar to that of Advanced LIGO [4] and Advanced Virgo [3] i.e. the so called dual recycling Michelson interferometer with Fabry-Perot cavity in the arms. As in Advanced LIGO, KAGRA will use folded recycling cavities to avoid the cavities degeneracy [8] for the laser frequency sidebands. The main difference will be the Fabry-Perot cavity finesse which will be higher in KAGRA (1500 compared to 450 in LIGO and Virgo) in order to reduce the laser power inside the power recycling

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cavity and so the power inside the input mirror substrates. This allows reducing the heat to be extracted to cool down the mirrors. The laser power will be around 180 W. Assuming 80 W entering the recycling cavity and a recycling gain of 10, the power stored in the Fabry-Perot arms will be around 400 kW resulting in a shot noise similar to the one of other advanced detectors.

The high power laser is under development. The current design uses two 40 W fiber laser amplifiers coherently added to obtain an 80 W beam. A power very close to 80 W was achieved and work is ongoing to stabilize its frequency and power. This beam is further amplified passing through three solid state laser amplifiers in series to obtain 180 W. A power of 210 W was achieved but work is still to be done to improve the beam shape before the development of the stabilization system can start.

The vibration isolation system will be based on a chain of pendulums and springs made of maraging steel combined in a design similar to the one used in Virgo [9] and TAMA [10]. All the main interferometer mirrors will be suspended using this type of vibration isolation with the number of filters depending on the vibration isolation required. The so called Type A vibration isolation composed of a low frequency pre-isolator, a series of five seismic filters will be used to suspend the Fabry-Perot cavities mirrors [11]. Each mirror is part of a payload including the mirror itself as well as all the additional suspending and recoil masses required to control its position. The total height being 15 m it has been decided to hang these vibration isolation systems from the second floor of the cavern and having it reaching the main experimental area thought a shafts connecting the two floors. A shorter vibration isolation system including only two filters after the pre-isolator (so called Type B) will be used to suspend the beam splitter and the signal recycling mirrors while a further simplified vibration isolation (Type Bp) without pre-isolator will be used for the recycling mirrors. Finally a simpler double pendulum assembled over bench itself sustained by three stacks of masses and springs will be used for the input and output optics components. A complete Type B was recently installed for test at TAMA to check the installation procedure (see Figure 2) [12].

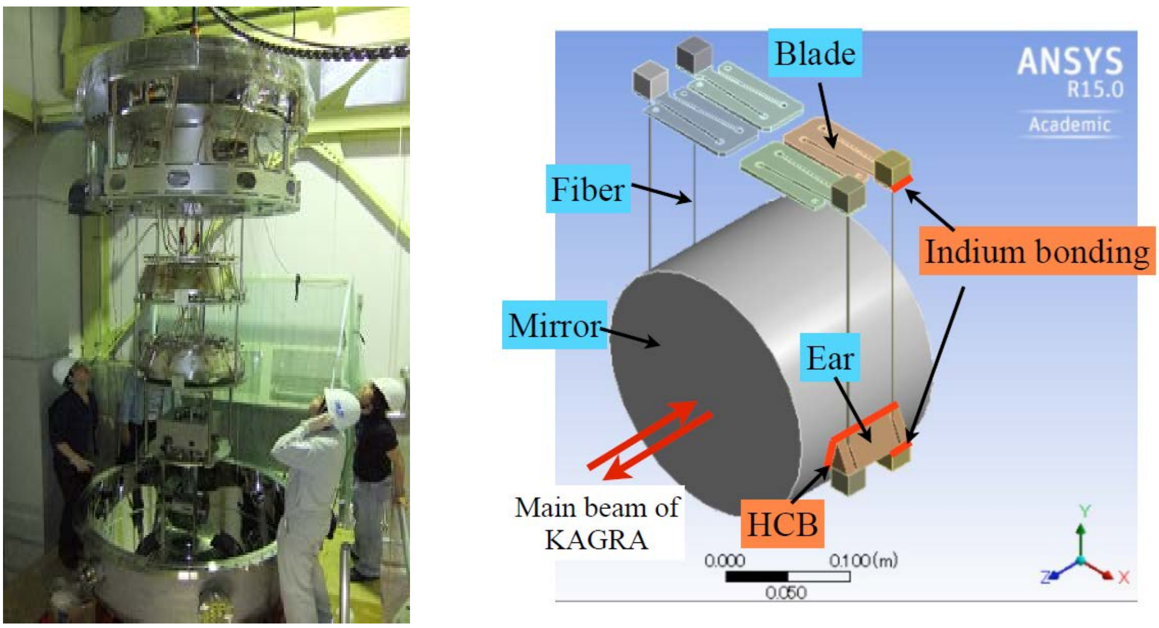


Figure 2. Test of the vibration isolation at NAOJ (left) and design of the sapphire suspension (right). HCB stays for hydroxide catalysis bonding.

The mirrors are divided into two categories. On one side the mirrors working at room temperature (including all those required for iKAGRA). These are made of silica and their production is progressing according to the schedule. On the other side the sapphire mirrors that have to be operated at cryogenic temperature. For the latter some R&D is still ongoing. The polishing on a test sample has shown that it is possible to achieve flatness rms below 1 nm as it is the case for fused silica substrates [13]. The most critical parameter is the absorption in the sapphire which is about a factor of two larger than expected (ranging from 40 ppm/cm up to 90 ppm/cm in the first two crystals received). The quality of the second two being worst, attempts are ongoing to find better crystals. If the absorption is not decreased the laser power inside the arms will have to be lowered (unless the heat extracted from the input mirrors is increased).

## 4. The cryogenic challenge

The cryogenic operation of the bKAGRA interferometer represents the main challenge of the project. Several aspects have to be considered. If the sapphire crystal absorption stays within the goal value of 30 ppm/cm, then 0.4 W will have to be extracted from each of the arm input mirrors. In order to do so the cryostat design includes two inner shields: an outer one at 80 K and an inner one at 8 K [14]. Four cryo-coolers will be used. The first stages of the cryo-coolers are devoted to the cooling of the outer shield. Two of the cryo-cooler second stages cool the inner shield and the other two cool the mirror payload itself. This design should allow to extract the amount of power deposited by the laser in the mirrors and cool down the mirror to 20 K provided a sufficiently heat conduction path is made between the mirror and the cryo-coolers. The temperature of 20 K has been chosen since at this temperature the sapphire used for the mirror substrate and the fibers has high quality factor. In addition two 5 m long cryogenic ducts allow the laser beam to enter the cryostat and while reducing the 300 K radiation input to the mirror by a factor of a thousand compared to the input one would have from the tube in the absence of the ducts [15].

The design of the cryogenic sapphire suspension (see Figure 2, [16]) is primarily driven by the need to cool down the mirror while keeping its thermal noise as low as possible. This is a complex system of requirements since, while the thermal noise requires to go for a monolithic suspensions all made of sapphire with the fibers suspending the mirror as thin as possible, the cryogenic requirement pushes for fibers as thick as possible. The compromise has been made to choose fibers made of sapphire 35 cm long and 1.6 mm in diameter with a nail head at both ends [17]. The lower fiber heads are attached to sapphire prisms (called ears) themselves attached to the side of the mirrors by hydroxide catalysis bonding (HCB). On their upper end the fiber heads are bonded to sapphire springs attached to the suspension upper stage (so called intermediate mass). On the ends the heads are bonded by means of a thin Indium intermediate layer. Extensive studies were performed to verify the strength, thermal conductivity and mechanical quality factor of the bondings. The mechanical quality factors of the fibers alone (not bonded to the mirror) has been measured finding values as high as $10^7$ at 20 K [16] which allow reaching the thermal noise requirements. The thermal conductivity of these fibers was studied also finding values larger than 5500 W/m/K [17] and so sufficient to extract the heat provided the diameter of 1.6 mm is used. A complete prototype of the monolithic sapphire payload is currently being built [18].

The cooling time is also an important parameter since the mirrors will have to be heated up and cooled down once a year to remove the water deposited on the optical surface due to adsorption. Radiation cooling will allow to reach 150 K. Below 150 K the efficiency of radiation cooling becomes insufficient and appropriate heat links will ensure the cooling down. Moreover it is planned to coat all the payload (with the exception of the mirror, of course) with diamond like carbon (DLC). According to the simulations this solution allows increasing the radiation cooling efficiency and thus to reduce the total cooling time from nearly two months to 39 days. Experimental tests done with a half size prototype of the payload coated with DLC confirmed the validity of the simulation [15].

The heat links are a potential path for the transmission of the cryostat vibrations. This is one of the main challenge whenever cryostats are used in conjunction with an apparatus requiring a very low level of vibrations. To study this effect the cryostat vibration have been measured at the factory and combined with the expected seismic noise at the site (which is considerably lower than the one at the factory). The estimate of the cryostat vibrations is then used as input in a mechanical model of the heat links combined with a model of the suspended payload to estimate the mirror vibrations. The simulations show that even if the heat links are connected to the recoil mass of the intermediate mass, and so not directly connected to the mirror, several of the cryostat vibration peaks can limit the interferometer displacement noise. The model shows that this effect can be reduced below the noise requirement if the heat links go through another mass seismically isolated independently from the main mirror. The effect of this mass is to short circuit the heat links vibrations [19]. New vibration measurements are being done on the cryostats installed underground in the cavern to verify the validity of the previous results.

## 5. Data analysis preparation and perspectives

In order to prepare the scientific exploitation of KAGRA, the project is currently developing the data analysis pipelines.

A library including the tools for the data access and the data processing, called KAGRA Algorithmic Library (KAGALI) is being developed to this purpose. In parallel data analysis pipelines to be used for the search of coalescing binaries, burst event and continuous waves are being developed. In addition to a traditional matched filtering approach, the development of the coalescing binary search includes also the development of a low latency pipeline for on line search and of an algorithm based on a Bayesian approach for the estimate of the parameter of the selected events. In the case of continuous wave search a pipeline is being developed to search for signals from known pulsars using the resampling technique and GPGPU (General-Purpose computing on Graphics Processing Units). The search of burst events is being prepared by developing a pipeline based on a combination algorithms able to run both off-line and on-line.

In parallel the KAGRA project has established a collaboration with astronomers working on different type of astronomical observatories in order to prepare for the electro-magnetic follow up of candidates GW events. This collaboration, specifically funded by a grant-in-aid from the Japanese Society for the Promotion of Sciences, includes astronomers working with optical and infrared telescopes as well as radio telescope and x-ray/g-ray detectors. Last but not least the KAGRA project is preparing the joint data analysis with LIGO and Virgo. To this purpose a Memorandum of Understanding was put in place already. The final goal will be to jointly analyze the data from the three projects in order to pinpoint candidate GW sources in the sky with a precision of a few degrees and open the era of gravitational wave astronomy. Such a pointing precision will allow following up the event with other observatories and the start of a full multi-messenger astronomy including the gravitational wave sky.

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