External Review of KAGRA Main Interferometer

KAGRA Main Interferometer Working Group

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Contents

Chapter 1

Overview

1.1 Definition and scope of the main interferometer subsystem

The main interferometer (MIF) is a subsystem which is responsible for converting gravitational waves into electronic signals on a photodetector. It includes two arm cavities, the power recycling cavity and the signal recycling cavity. The MIF subsystem also provides specifications for output mode cleaner, which will be manufactured by the input/output optics group.

The MIF team is also responsible for the development of the robust interferometer sensing and control schemes, both for length and alignment. The team will design the necessary electronic circuits, such as PDs, demodulation boards etc. The fabrication of the circuits is supposed to be out of scope of this subsystem, although we may end up doing it.

After the mirrors are installed in the vacuum system, the MIF team will be mostly responsible for the commissioning of the interferometer to achieve the target sensitivity as soon as possible.

Here is a list of the responsibilities of the MIF subsystem:

- Determine the optical parameters of the main interferometer.
- Determine the detailed optical layout of the main interferometer.
- Design robust length and alignment sensing schemes which do not contaminate the target sensitivity.
- Design a robust lock acquisition scheme.
- Perform the commissioning of the interferometer to achieve the target sensitivity.

1.2 Important interfaces

1.2.1 Mirror

Important interface items between the MIF and MIR are:

- Mirror reflectivities
- Acceptable optical loss
- Radius of curvatures
- Wedge angle

- AR surface reflectivities
- Reflectivities for green beams.

The latest mirror specifications are posted at [2].

1.2.2 Input/Output Optics

Important interface items between the MIF and IOO are:

- Laser power delivered to the PRM
- Laser noise requirements (intensity and frequency)
- Laser frequency stabilization servo topology
- RF modulation frequencies and depth
- Input mode matching (the beam parameter required at the PRM)
- Output mode cleaner requirements (RF SB and HOM rejection ratio)
- Detection bench design
- Green laser lock system design

1.2.3 Auxiliary Optics

Important interface items between the MIF and AOS are:

- Scattered light noise requirements
- Optical layout (handling of stray light beams)
- Optical levers
- Beam reducing telescopes

1.2.4 Vibration Isolation System

Important interface items between the MIF and VIS are:

- Displacement noise requirements for all the mirrors
- Movable range of the macroscopic mirror positions
- Actuator responses (for servo modeling)
- Local sensors (location, quantity, sensitivity)
- Mirror installation procedure for precise positioning of the mirrors

1.2.5 Analog Electronics Subsystem

At this moment, there is no active group working on AEL in KAGRA. Therefore, we plan to design the necessary circuits within the MIF team. Schematics will be prepared by the MIF. Then the printed circuit board (PCB) design, fabrication, component mounting and tests will be outsourced, most likely to outside companies.

1.2.6 Digital Subsystem

Important interface items between the MIF and DGS are:

- Number of ADC/DAC channels
- Front end circuits for ADC/DAC (whitening/dewhitening, AA/AI etc)
- Servo model implementation (done by MIF with the help of DGS).

1.2.7 Vacuum System

Important interface items between the MIF and VAC are:

- Optical layout (location of the chambers)
- Optical windows

1.3 Design phase

Not applicable.

Chapter 2

iKAGRA

2.1 Target specifications

The minimum goal of iKAGRA is to lock a Fabry-Perot Michelson interferometer. The duty factor and the sensitivity are not specified.

2.2 Final design

Details of the design are explained in the design document [1].

2.3 Schedule

We divide the iKAGRA development into 2 phases. The first phase is the tunnel excavation period, i.e. now. During this period, all the necessary hardware have to be delivered and ready to be installed. The task list and the plan are shown in Figure 2.1.

Once the tunnel is ready, the vacuum chambers and the mirror suspensions will be installed one by one. As the installation proceeds, we will start the commissioning of the interferometer from the available part, starting from the MC. This parallel strategy is shown in Figure 2.2. There is a risk of disturbances from the on going installation work make the commissioning very hard. In anyway, we will do our best to expedite the commissioning process.

2.4 Quality assurance

The quality of the MIF is the noise level and the stability of operation. We can only test those with the actual interferometer. The quality of MIF is assured[1] by carefully designing the interferometer and addressing any possible issues by thorough simulations. Careful planning and preparation of the commissioning work is another important action to reduce the risks.

2.5 Installation scenario

See section 2.3 of this document and chapter 8 of the design document [1].

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[1] Of course no one can **assure** the quality of a GW detector though.

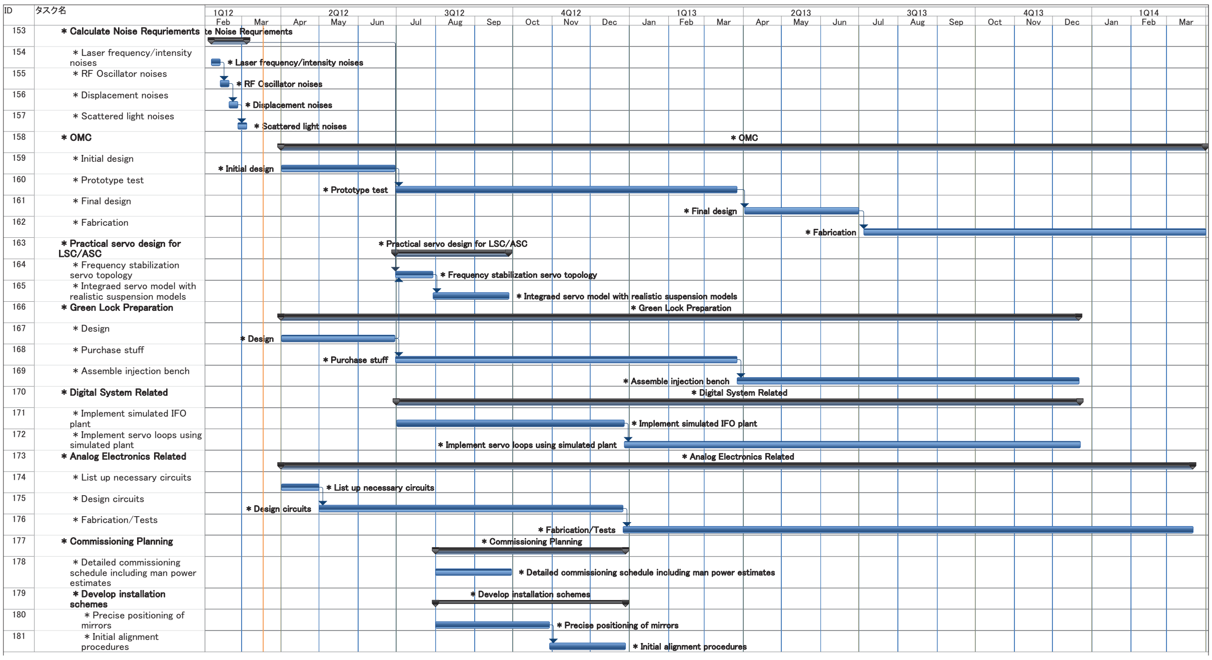

Figure 2.1: iKAGRA MIF schedule during the tunnel excavation period

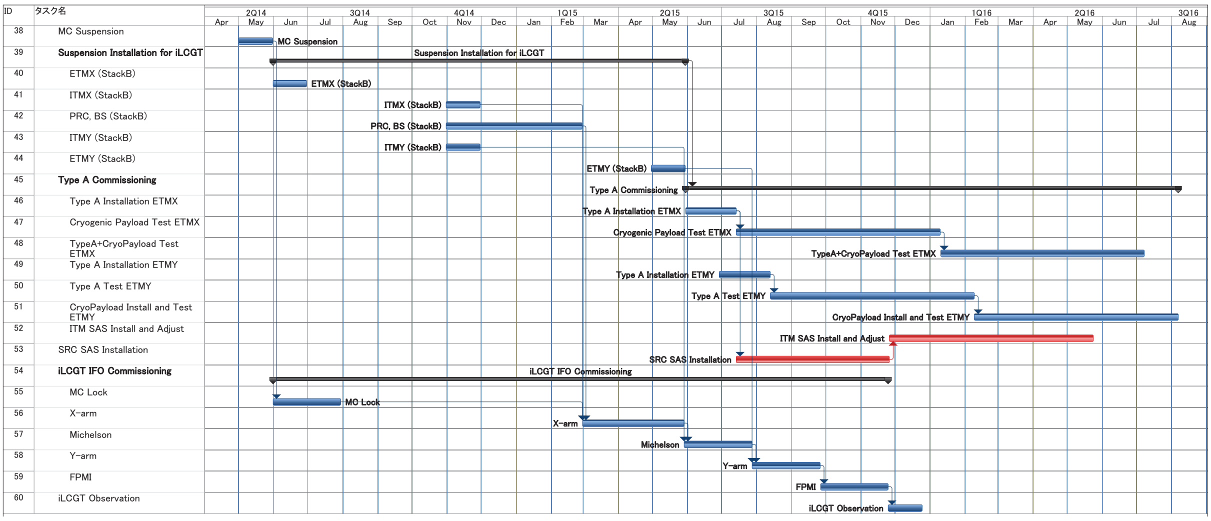

Figure 2.2: iKAGRA MIF commissioning schedule.

2.6 Risk management

Potential risks of iKAGRA are listed below. Tuples of numbers at the end of each item represents risk factors in the form (P,S,R), where P is the probability of the risk to become reality, S is the seriousness or impact of the problem, each in the scale of 0 to 3. R is the overall risk defined by P×S.

Large RMS motion of the mirrors: The suspensions used during the iKAGRA period are the payload part of the Type-B SAS with the upper part fixed. Since these suspensions are not designed to be used this way, the RMS motion of the mirrors may be too high. We will strongly damp the mirror motions to avoid this. Strong damping usually introduces extra noise in the observation band. However, we do not care much about noise in iKAGRA. Risk factors = (2, 3, 6).

Large laser frequency noise: At the beginning of iKAGRA commissioning, it is likely to happen that the laser frequency noise after the MC is still to high to lock the interferometer. We may have to spend some time to optimize the FSS. Risk factors = (2, 3, 6).

Commissioning takes too long: The commissioning schedule for iKAGRA is very tight. We need careful planning and preparation for the commissioning work to accomplish the goal, i.e. lock the FPMI, as soon as possible. Risk factors = (3, 3, 9).

Chapter 3

bKAGRA

3.1 Requirements

The bKAGRA interferometer has to meet the requirements listed below.

- The main interferometer has to be able to achieve the target sensitivities of bKAGRA shown in Figure 3.1 and 3.2. These target sensitivities are determined as a result of the optimization of the optical parameters given fundamental noise sources other than quantum noises. Details of the optimization work are described in [3].
- bKAGRA has two operation modes: BRSE and DRSE. The main interferer configuration should allow us to switch between the two modes within a reasonable amount of time.
- The control schemes of the KAGRA has to be robust enough to ensure stable operation of the interferometer in the environmental disturbances of Kamioka mine. The target duty cycle during the observation is more than 90%.

3.2 Preliminary design

The detailed design is explained in the MIF design document [1].

3.3 schedule

The commissioning plan for the bKAGRA interferometer is shown in Figure 3.3. After the short observational run of iKAGRA has finished, the PRM and the SRC are added to the interferometer. At this moment, the Type-A commissioning work will be still going on at the end stations. Therefore, we will start testing the Dual Recycled Michelson (DRMI) interferometer. The ITMs will be the fused silica ones. While the DRMI test is going on, we will replace the ETMs with the sapphire ones. For changing the ITMs to sapphire, we need a brief break in the interferometer commissioning. After the test masses are replaced, we restart the commissioning from PRMI[1] to the full RSE at room temperature. After some noise hunting of the room temperature RSE, we will cool down the mirrors to operate the full configuration bKAGRA interferometer.

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[1] Although the DRMI test was performed earlier, this time the ITMs are different. So we need this step to make sure the ITMs are in good shape.

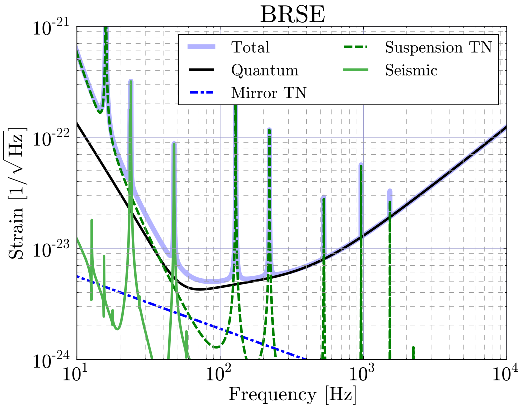


Figure 3.1: bKAGRA Target Sensitivity in the BRSE mode

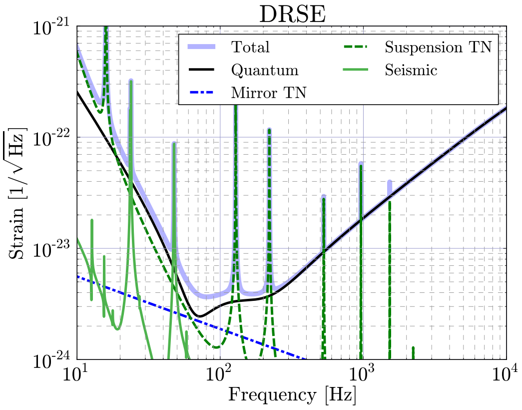
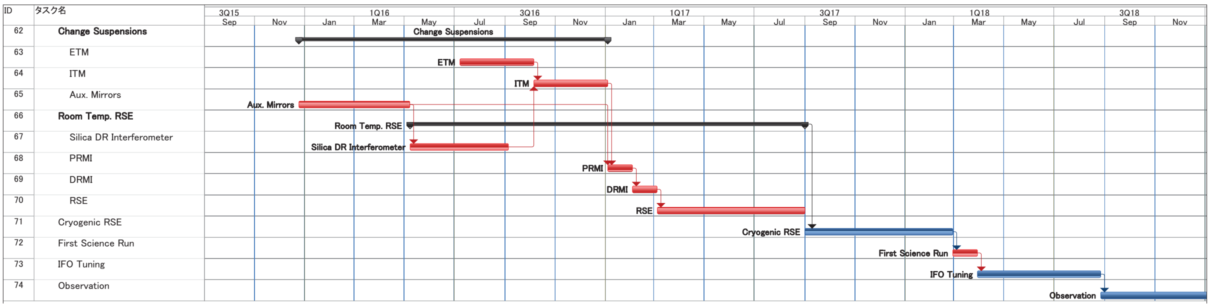


Figure 3.2: bKAGRA Target Sensitivity in the DRSE mode



ID	タスク名
62	**Change Suspensions**
63	ETM
64	ITM
65	Aux. Mirrors
66	**Room Temp. RSE**
67	Silica DR Interferometer
68	PRMI
69	DRMI
70	RSE
71	Cryogenic RSE
72	First Science Run
73	IFO Tuning
74	Observation

Figure 3.3: bKAGRA MIF commissioning schedule.

3.4 Prototype test

We plan to perform prototype tests of the OMC and the green laser injection bench. Details of the tests are still under discussion.

3.5 Quality assurance

The same as iKAGRA.

3.6 Installation scenario

See section 3.3 of this document and chapter 8 of the design document [1].

3.7 Risk management

Potential risks of bKAGRA are listed below. Tuples of numbers at the end of each item represents risk factors in the form (P,S,R), where P is the probability of the risk to become reality, S is the seriousness or impact of the problem, each in the scale of 0 to 3. R is the overall risk defined by P×S.

Large loss in the arm cavities: The losses in the arm cavities decrease the effective reflectivity, R_{FPMI}, of the Fabry-Perot Michelson for the carrier. The reflectivity of the PRM is chosen to be slightly lower than R_{FPMI} to make sure that the PRC is over coupled. If the loss is too large, the PRC becomes under-coupled. This will significantly reduce the CARM signal, making it impossible to achieve the required shot noise level. One solution to avoid this problem is to prepare an alternative PRM with smaller reflectivity. If we find that the losses are too large, we will replace the PRM with the alternative one. Risk factors = (2, 3, 6).

Small loss in the arm cavities: If the arm cavity loss is too small[2], the carrier light coming back to the REFL port will be larger. The double demodulation signals using the f3 sidebands will suffer the increase of shot noise by this. Therefore, we will use single demodulation signals during the observation. See section 3.4 of the design document [1]. Risk factors = (1, 1, 1).

Mismatch light at the AS port is too small: The DC carrier field at the AS port produced by the difference of the arm cavity reflectivities is called mis-match light. It is used to set the homodyne angle to the desired one. If the arm cavity mis-match is too small, we cannot use this method, i.e. we have to abandon the back action evasion. See section 3.2 of the design document [1] for details. Risk factors = (2, 2, 4).

Detuning associated side effects The detuning of the SRC is realized by adding a small offset to the error signal of SRCL. This will cause some unwanted side effects. First of all, the error signal for SRCL is not linear around the detuned operation point. It could generate some up- or down-conversion noises. See Appendix B of [1] for the detailed discussion. The conclusion is that the non-linear effect is not a problem. Secondly, the detuning converts the initially phase modulated f1 sideband into a mixuture of the PM and AM. This AM component produces large offsets in the error signals using the f1 sideband. This makes the requirement to the RF oscillator phase noise unrealistic. A possible solution is discussed in Appendix C of [1]. Risk factors = (3, 1, 3).

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[2] though unlikely to happen

ROC errors of the folding mirrors The folding part of the recycling cavities is a telescope. The mode shape inside is highly susceptible to the ROC of the folding mirrors, especially of the PR3 and SR3. The fabrication error in the ROC can be compensated by changing the distance between the PR3 and PR2 (or SR3 and SR2) [4]. The required amount of the length change is about 14 cm for 1% error. We either design the vacuum chambers to be relocatable, or require very stringent error tolerance for the ROC of the folding mirrors. We are currently pursuing both the approaches. Risk factors = (3, 2, 6).

Parametric Instability It was shown that the parametric instability is likely to happen in bKAGRA (see section 2.2.3 of [1]). The current plan is to damp the unstable mode with feedback to the mirror actuators. Risk factors = (3, 1, 3).

Lack of man power: Of course we are always short of man power :-(. The fix is easy: Hire more people ! Risk factors = (3, 3, 9).

Appendix A

Design changes that have been made with the suggestions in the 1st external review

- We plan to install at least two PDs with different gains at each signal extraction port.
- A preliminary ASC design is now included in the design document.
- The scattered light requirements have been calculated.

Appendix B

Items that have been reduced in cost

Nothing.

Appendix C

Human resources

Required man power for the interferometer development and commissioning.

- 2012 - 2013 (Tunnel excavation period)
  - Fully engaged post-doc: 2
  - Grad. students: 4
  - Electric engineer: 2
- 2014 - 2018 (Commissioning period)
  - Fully engaged post-doc: 5
  - Grad. students: 10
  - Electric engineer: 2

Appendix D

Terminology

Table D.1: Terminology

AC	Arm Cavity	
AM	Amplitude Modulation	
AS	Anti-symmetric port	
Auxiliary DOF		Length degrees of freedom other than DARM
Canonical DOF	Collective name of DARM, CARM, MICH, PRCL and SRCL	
CARM	Common Arm Length	
DARM	Differential Arm Length	
DOF	Degrees Of Freedom	
MC	Mode Cleaner	
MICH	Michelson Part	L shaped part of the interferometer formed by BS and two ITMs
MZ	Mach-Zehnder	
PM	Phase Modulation	
PD	Photo Diode/Detector	
POP	Pick-off in the Power Recycling Cavity	
POX	Pick-off at the ITMX	
POY	Pick-off at the ITMY	
QPD	Quadrant Photo Diode/Detector	
REFL	Reflection port	
RF SB	RF Sideband	
PRC	Power Recycling Cavity	
PRCL	Power Recycling Cavity Length	
SRC	Signal Recycling Cavity	
SRCL	Signal Recycling Cavity Length	

Bibliography

[1] MIF Design Document, JGW-T1200913

[2] http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/LCGT/subgroup/ifo/MIF/OptParam

[3] K. Somiya, Study report on the new LCGT setup with 22cm mirrors, JGW-T1100644

[4] K. Agatsuma, JGW-G1100553