TAMA300 project: Status

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and
the TAMA collaboration

TAMA300 project is in progress. Fabry-Perot Michelson interferometer with the 300 m arms was successfully locked in September,1998 for the first time. Here, alignment control system using wave-front-sensing method performed important role. The result of experiment in the 20 m prototype will make TAMA300's promise of power recycling gain of more than 10.

1 Overview

TAMA300, a medium scale antenna for gravitational waves, adopts a 300 m Fabry-Perot type Michelson interferometer with recycling[1]. It is located at Mitaka campus of NAO[a] in Tokyo. The aim of this project is to develop advanced techniques needed for a future km-sized interferometer and catch gravitational waves that may occur by chance within our local group of galaxies. Goal sensitivity is $h_{rms} = 3 \times 10^{-21}$ at 300 Hz (BW300 Hz). TAMA300 involves two 300 m-long vacuum ducts of 400 mm in diameter and eight vacuum chambers. The achieved vacuum pressure in the ducts is 1×10^{-6} Pa or less. Since the effective baking of such a large system is not easy in practice, we adopted an ECB (Electro-Chemical Buffing) technique instead of baking, so as to reduce the outgassing rate[2]. Vibration isolation of mirror is accomplished by a mirror suspension on the vibration isolated breadboard with three legs of three layers stack[3]. The mirror is suspended by double pendulums with flexible damping[4], naively isolation ratio of $(f/1\text{ Hz})^4$ is expected. Here f is frequency. Since the actual suspension has many mechanical resonances and cross coupling, 10^5 or a little more at 300 Hz, will be obtained. Therefore stack system charges vibration isolation ratio of about 10^3.

TAMA project started in 1995. The facilities in 1996, the vacuum system in 1997, are completed respectively. The vibration isolation system and the optics had been installed step by step from 1997, and partially experiments also started. Fig.1 shows phased task of installation schematically. Initial experiments of light source (Laser & Mode Cleaner) and main interferometer (progressing in Recombine I) were done independently. Since each experiment finished in February, 1999, these two parts have been connected. At present, task of Recombine II is going. Here not only status of development for the light source and main Fabry-Perot Michelson interferometer (FPMI) but also result of power recycling using the 20 m prototype are reported.

This project is organized by NAO, ICRR[b], The University of Tokyo, ILS[c], KEK[d], MUE[e], and YITP[f].

[a]National Astronomical Observatory
[b]The Institute for Cosmic Ray Research
[c]Institute for Laser Science
[d]High Energy Accelerator Research Organization
[e]Miyagi University of Education
[f]Yukawa Institute for Theoretical Physics

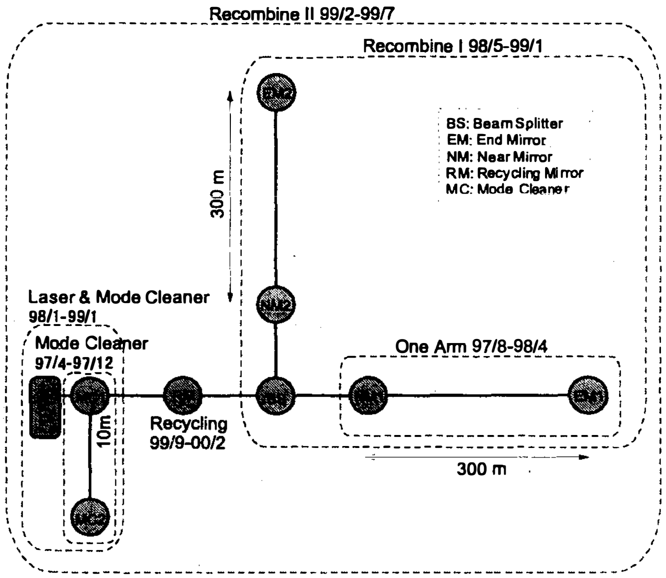

Figure 1: Schematic view of phased installation tasks.

2 Stabilized light source with the 10 m mode-cleaner

The light source consists of a 10 W injection-locked Nd:YAG laser and a 10 m ring type mode-cleaner. The laser was developed by SONY [5]. The light from 700 mW master laser [g] is injected to a slave laser, which consists of two Nd:YAG rods pumped by a fiber-coupled laser diode [h]. In order to lock the slave laser, a modulation frequency of 20 MHz is used.

The laser has frequency fluctuation of simply $3 \times 10^5 (1\,\mathrm{Hz}/f)\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ under free-running. Here f is frequency. It is stabilized by a servo system using the 10 m mode-cleaner as a frequency reference. Additional phase modulation frequency is 12 MHz to control this servo. Error signals are fed back to a thermal actuator for < 0.1 Hz, to a Piezo-elecric-transducer (PZT) for 0.1 Hz $\sim$ 30 kHz, and to an external Electro-optic-modulator (EOM) for 30 kHz $\sim$ 300-700 kHz. This servo is designed so that suppressing gain of more than 10^{10} is able to be achieved. Actual stability is limited by shot noise or electric noises. Fig.2 shows measured frequency fluctuation of the light source. $3 \times 10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz is obtained by S. Nagano. After the light source is connected to the main interferometer, a common mode error signal from the main interferometer also is fed back to the frequency stabilization servo. Since the frequency noises due to the light source fluctuation appear in the main interferometer as relative difference between the source and the interferometer, the frequency noise of about $10^{-6}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz is predicted. Then this servo loop (feed-around) has gain of about 10^2.

One more phase modulation is introduced in front of the mode-cleaner to control a main interferometer. It is necessary that the phase modulation sidebands of 15.25 MHz for operating the interferometer can pass through the mode-cleaner. Though the phase modulated sidebands cannot pass through a ring cavity in general, it is possible to do it by matching the free-spectrum-range (FSR) of the ring cavity to the modulation frequency. Since FSR is determined by an equation $FSR = c/2\ell$, the cavity length ℓ is 9.8 m. Here c is speed of light. Transmitted light has excess noises due to mismatching between FSR and cavity length. However this mechanism has been resolved by S. Telada and sidebands transmission without excess noises succeeded (see a report by him in this book).

[g] Lightwave Model 126
[h] SDL-3450-P6

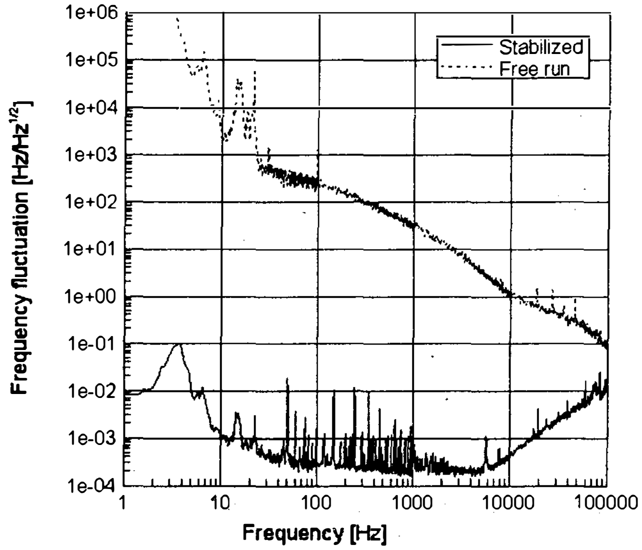

Figure 2: Measured frequency fluctuation of the light source.

Power transmission rate is important too. Power of least 3 W is required after the mode-cleaner. Though maximum power of the injection-locked laser is 10 W, reasonable power is 8 $\sim$ 9 W to keep long life-time. When the output power is 8.4 W, 6.5 W before the mode-cleaner and 3.5 W after it are achieved. Then the transmission rate is 54%.

3 Recombined interferometer with 300 m arms

The main interferometer is Michelson type. Each arm of the Michelson interferometer consist of 300 m length Fabry-Perot cavity. Mirror has diameter of 10 cm and thickness of 6 cm. Reflectivities are designed to 98.8% for front mirrors and 99.99% for end mirrors. In this case, finesse of cavity is 520. At first, length and alignment control of the Fabry-Perot cavity were demonstrated by K. Tochikubo, A. Sasaki and S. Taniguchi in 1997. Then the measured reflectivity of the cavity was about 90% and the finesse is 450. Since the pitch motion of mirrors is too large, not only misalignment of the cavity dose not satisfy the requirement angle of less than 5×10^{-7} rad but also the cavity is not stable without alignment control. Error signals of misalignment are acquired by wave-front-sensing (WFS) [6, 7]. When the alignment control is introduced, the rms fluctuation angle is reduced below 3.7×10^{-7} rad. More noteworthy is that the 300 m cavity was held the resonant condition for a several days. Actually, we observed absolute length of the cavity for this phase continuously [8].

The second step is recombination of two arms. Here I would like to focus attention on this phase, that we call Recombine I. Schematic setup of Recombine I is shown in Fig.3. Three error signals are necessary to control length between mirrors. The common length deviation between two arms, δL_+, are acquired from the symmetric port. This signal is fed back to the Laser as the frequency error. From the same port, the differential mode signal of the Michelson interferometer, $\delta \ell_-$, is acquired too. This signal is fed back to the beam-splitter (BS) in order to keep the anti-symmetric port dark. From the anti-symmetric port, the differential length deviation between two arms, δL_-, is acquired. This signal is divided, and fed back to two front mirrors with inverse sign each other. Alignment control is performed on each arm independently same as one arm experiment. M. Ando and S. Taniguchi demonstrated locking of FPMI with the 300 m arms successfully in September,1998 for the first time. Fig.4 shows lock acquisition status

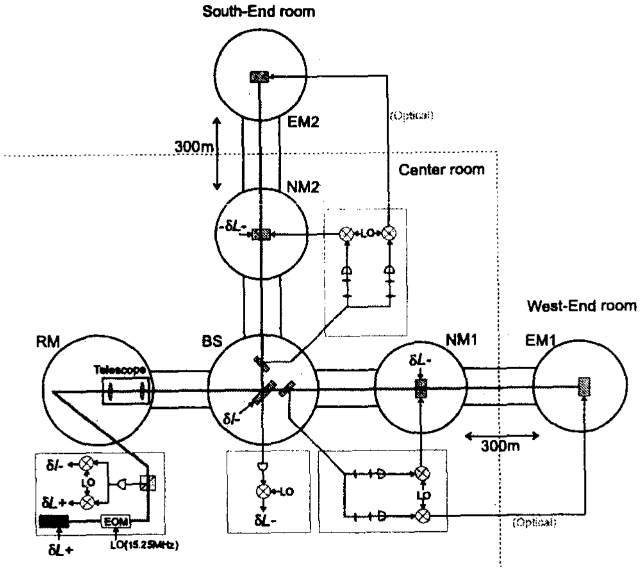

Figure 3: Schematic view of Recombine I.

of FPMI. At first, the inline arm is locked. After length servo on, transmission power of the arm is kept non-zero level but unstable. Additionally alignment control on, transmission light reaches at the maximum power (the top figure). Similarly the perpendicular arm is also locked (the middle figure). Finally Michelson interferometer is locked. 0 V on the anti-symmetric port shows dark fringe (the bottom figure). These locking are able to be kept for several hours.

4 Power recycling using the 20 m prototype

Power recycling gain of more than 10 is required for TAMA300. Power recycling on FPMI with suspended mirrors succeeded using the 3 m prototype at The University of Tokyo for the first time [9]. There recycling gain was 3. Recently S. Sato achieved gain of more than 10 using the 20 m prototype at NAO. Since expected reflectivity of the 20 m FPMI was 0.92 ± 0.02 for the carrier from various measurements, recycling mirrors with reflectivity of 0.70 and 0.91 were prepared.

In the case of using the recycling mirror with reflectivity of 0.70, recycling gain of 6 was obtained (Fig.5). However the gain had fluctuation of chiefly 8 Hz due to pitch motion of the suspended cavity mirrors. Alignment control to only one degree of freedom (the end mirror) using WFS method was engaged with length control. Then recycling gain became stable. Moreover the gain was increased by 25% after DC gain of servo was boosted. This recycling gain was kept over one hour.

In the case of high gain (reflectivity of 0.91), recycling gain shows about 12. Since the alignment control has not been tried yet, gain is not stable exactly. Locking time is very short (a few second). However with the alignment control, more stable operation is expected. This result will make TAMA300's promise of power recycling gain of more than 10.

5 Summary

Light source for TAMA300 is ready. High power (3.5 W after the mode-cleaner), sidebands transmission without excess noises, and good stabilization (3×10^{-4} Hz/$\sqrt{\text{Hz}}$ at 100 Hz) are achieved. Fabry-Perot Michelson interferometer with 300 m arms was successfully locked. Alignment con-

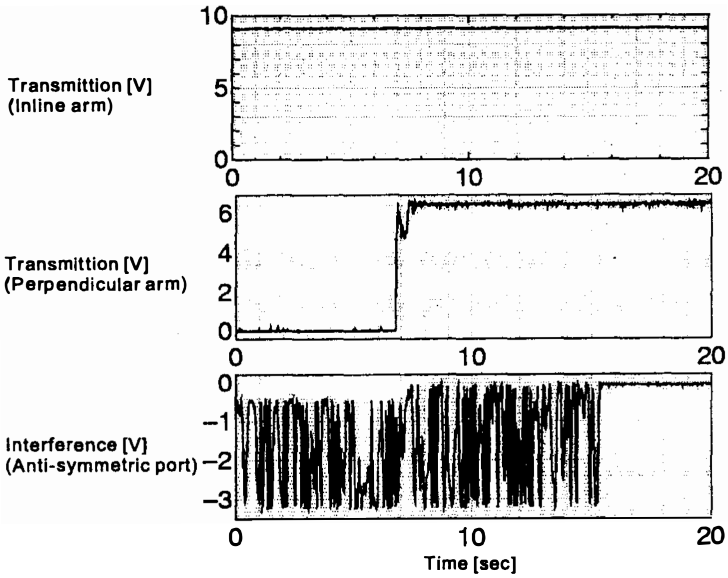

Figure 4: Lock acquisition status of FPMI.

trol is necessary for stable operation exactly. In the 20m prototype, power recycling gain of more than 10 was obtained.

In this summer (1999), first observation (phase I) is planed on TAMA300.

Acknowledgments

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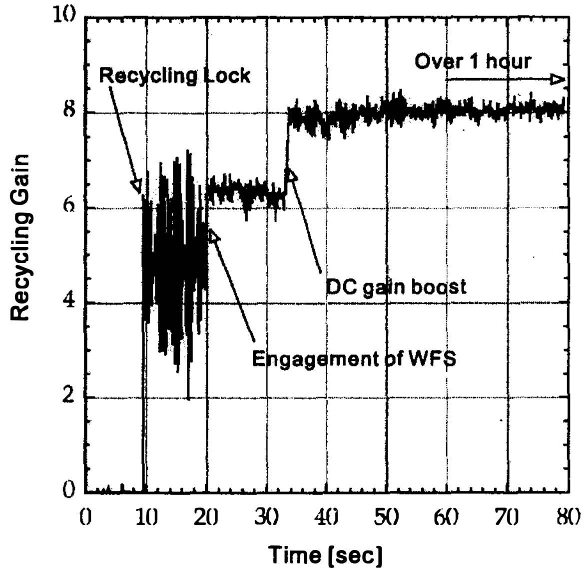

Figure 5: Recycling gain with WFS technique.