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Kazuaki Kuroda, Yoshihide Kozai, Masa-katsu Fujimoto,
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Mark A. Barton, Nobuyuki Kanda, Yoshio Saito, Norihiko Kamikubota,
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Members of TAMA group

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INSTITUTE FOR COSMIC RAY RESEARCH
UNIVERSITY OF TOKYO
3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan

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Kazuaki Kuroda

Institute for Cosmic Ray Research, University of Tokyo, 3-2-1 Midoricho, Tanashi, Tokyo 188, Japan

Yoshihide Kozai[1], Masa-katsu Fujimoto[1], Masatake Ohashi[1], Ryutaro Takahashi[1], Toshitaka Yamazaki[1], Mark A. Barton[1], Nobuyuki Kanda[2], Yoshio Saito[3], Norihiko Kamikubota[3], Yujiro Ogawa[3], Toshikazu Suzuki[3], Nobuki Kawashima[4], Ei-ichi Mizuno[4], Kimio Tsubono[5], Keita Kawabe[5], Norikatsu Mio[6], Shigenori Moriwaki[6], Akito Araya[7], Kenichi Ueda[8], Kenichi Nakagawa[9], Takashi Nakamura[10] and Members of TAMA group

[1]*National Astronomical Observatory,* [2]*Institute for Cosmic Ray Research of the University of Tokyo,* [3]*National Laboratory for High Energy Physics,* [4]*The Institute of Space and Astronautical Science,* [5]*Faculty of Science of the University of Tokyo,* [6]*Faculty of Engineering of the University of Tokyo,* [7]*Earthquake Research Institute of the University of Tokyo,* [8]*Laser Science of the University of Electro-Communication,* [9]*Tokyo Institute of Polytechnics,* [10]*Yukawa Institute for Theoretical Physics of Kyoto University*

Abstract

TAMA is a five year project involving almost all gravity physics researchers in Japan. It adopts a Fabry-Perot type Michelson interferometer with premodulation and will be completed with recycling by March, 2000. The aim of this project is to develop advanced techniques needed for a future km-sized interferometer and to catch gravitational waves that may occur by chance within our local group of galaxies.

1 Overview of TAMA project

Members of the TAMA project had been developing prototype interferometric gravitational wave detectors for four years before starting TAMA, specifically the 20 m Fabry-Perot type interferometer at NAO (National Astronomical Observatory) and a 100 m delay-line type one at ISAS (The Institute of Space and Astronautical Science). We need a little more effort to attain the ultimate sensitivities in these detectors. After funding ended for these detectors, we started the TAMA project aiming to establish gravitational wave astronomy. In the lead up to TAMA, the 20 m Fabry-Perot detector at NAO has served as a work bench for the development of techniques necessary for a km-sized detector and the 100 m delay-line detector has provided information on the practicalities of an observational system. The main object of TAMA is to construct a 300 m baseline Fabry-Perot-Michelson interferometer at NAO, at Mitaka, a suburb of Tokyo. Needless to say, this interferometer will not be the final detector in Japan. After the end of funding for TAMA we plan to use the results towards a km-sized detector. Notwithstanding this long term plan, we are doing our best to attain the ultimate sensitivity with this 300 m base line system, incorporating new technologies from around the world, and we are hopeful of catching events occurring within the local group of galaxies including Andromeda.

TAMA started in the April of 1995 and will end in March of 2000. It is supported by seven organizations as listed in the author affiliation above and has a staff of about thirty people. Our schedule is to construct the body of the interferometer without implementing the recycling technique by the end of March, 1998. After this, the recycling mirror will be installed and the optical system will be changed appropriately. This improvement should be finished in two years. The budget of the first year was \$5M: \$3M for building with civil engineering and \$2M for part of the vacuum system and the R&D expenditure.

2 Interferometer design

2.1 Scientific object and targeted sensitivity

The scientific object is the detection of gravitational wave bursts produced in star collapses and coalescence of binary neutron stars. On average, supernovae are estimated to occur once every ten years and coalescences of binary nuetron stars every three centuries in galaxies such as ours. Simulations of the outcome of supernova explosion give no more than 0.6% of the total mass energy of the system as gravitational wave energy, so, the sensitivity should be 2.6×10^{-21} in h with S/N (signal to noise ratio) of 10 to catch supernova events in Andromeda which is 640kpc away. Although more than ten galaxies are counted in the "local group", of these, only five (LMC, SMC, M31, M33 and ours) are expected to produce supernova explosions of types II and Ib, those which might radiate gravitational waves as mentioned above. The estimated frequency is 2.5 per century.[1] Optimistic theory predicts the emission of gravitational wave in the form of a chirp during the coalescence of binary neutron stars, of a strength sufficient to be detected by a detector with a sensitivity of 3×10^{-21} with a S/N of 10 as far away as Andromeda. This sensitivity of 3×10^{-21} can be attained by a 300 m baseline system as shown below. Such coalescences are only expected in spiral galaxies such as ours and Andromeda, and thus the frequency does not exceed once per century. Since the Virgo cluster, which hold about four thousand galaxies, lies 10 times further away than Andromeda, we need to attain a sensitivity of 10^{-22} to probe it, and this is impossible with TAMA. Accordingly, putting emphasis on the development of techniques for future detectors, we nontheless anticipate to have a chance of catching events in the local group of galaxies.

Table 1: Important parameters of TAMA

Sensitivity	3×10^{-21} (BW 300 Hz at 300 Hz)
Interferometer	Recombined Fabry-Perot Michelson
Baseline length	300 m
Cavity finesse	516
Laser	10 W LD pumped Nd:YAG 1064 nm
Recycling gain	10
Vacuum pressure	10^{-6} Pa

Table 1 summarizes important parameters of TAMA.

2.2 Optical design

Fabry-Perot cavities are formed by flat near mirrors of 10 cm in diameter and 6 cm in thickness, and end mirrors of the same size but with a 450 m radius of curvature. The distances from the near mirrors to the beam splitter are different by 50 cm to allow pre-modulation with a frequency of 15.25 MHz. As shown in Fig. 1, pre-stabilized laser light is introduced with a mode matching telescope through appropriate adjusting mirrors to a 10 m ring mode cleaner. After the mode cleaner the light beam enters through a second mode-matching optical system into a recycling mirror. At present an optical circulator is planned to be inserted between the matching system and the recycling mirror. Optical alignment control is done by the method of wave front sensing, where light beams are picked off in front of near mirrors. The radius of curvature of the recycling mirror is 9 km. Commercial mirror manufacturers are unwilling to polish such a mirror so we decided to make it ourselves. This will be valuable experience for the future km-sized interferometer.

3 Design and development of key technologies for TAMA

Factors limiting the sensitivity are seismic isolation, suspension thermal noise, mirror internal thermal noise and laser shot noise. We have fairly concrete designs for a laser source with pre-stabilization and for an anti-vibration system and we have begun to design a practical suspension sytem. The following overviews of activities by all members of TAMA necessarily omit some of the many indispensable techniques that will be required for TAMA and its successor.

3.1 Laser

We have contracted with SONY corporation for making a LD pumped Nd:YAG laser source. Basically it is an injection-locked high-power laser with an input to change the laser frequency for stabilization. We have developed basic techniques for this stabilization.[2] An output of 10 W has been achieved and the integrated version of this laser will be delivered by the end of this June, 1996.

3.2 Optical pieces

The main mirrors except for the recycling one will be polished and coated by Japan Aviation Electronics Industry Ltd (JAE). A very low loss due to absorption and scattering, 6 ppm, was attained by the company and much better quality is expected. Such a coating can be achieved by refinements of sputtering technique. The recycling mirror will be coated by an IBS machine (Oxford) at NAO. As a first step towards this end we coated a 20 mm sample mirror and achieved a loss of 170 ppm, which is very promising.

3.3 Mode cleaner

Taking over the previous work,[3] a 4 m mode cleaner is being developed for the 20 m Fabry-Perot interferometer.[4] Since the phase modulator is placed before the mode cleaner, the FSR of the cleaner cavity should be made to coincide with that of the modulation. Any mismatch of these frequencies converts FM noise of the laser to AM noise. Although AM noise of high frequency is negligible compared with shot noise, that of frequency lower than 300 Hz is badly affected by vibration of the cavity mirrors. Since a similar effect is expected to occur in the 10 m ring mode cleaner for TAMA, optimization of the feedback loop is under study.

3.4 Alignment control system

To make the interferometer operate with power recycling, four degrees of freedom in the optical path have to be controlled: the sum and difference of the displacement of the main cavities, the length of the recycling cavity, and the difference of the near-mirror to beamsplitter distances. In addition to these, the five key optical elements should be held normal to the incident beam. Since each element has two degrees of freedom, ten degrees of freedom must be controlled. In total, the feedback system must control fourteen degrees of freedom. The main feedback loops will be closed by analog signals and those loops involving the end mirrors will be digitally closed. This control system is being designed.

3.5 Double pendulum system for suspension

The suspension system adopts an intermediate mass between the mirror and the suspension point, with motions of the intermediate mass being strongly suppressed by eddy current damping using permanent magnets, as originally developed by Tsubono *et al.*[5] Since this method is passive, it is easier to use than an active damping system. It has been tested using the direct recombination of the 3 m Fabry-Perot system by Kawabe *et al*[6] and by the direct recombination of the 20 m Fabry-Perot interferometer[4] at NAO. It introduces a strong magnetic field near the main mirror, which may induce noise from ambient magnetic fields, but the field can be reduced by shielding. In a preliminary test of this double pendulum system together with vertical isolation springs, many mechanical resonances appeared in the observational frequency range and degraded the performance of the suspension from the design level. However, since we cannot omit the function of mirror control from this suspension system, we will have to accept this degraded isolation at some level.

3.6 Anti-vibartion system

The suspension system is mounted on an isolation stack through an X-pendulum vibration isolation table. The stack consists of three legs, each containing three layers of rubber and heavy stainless blocks. We plan to cover the rubber with vacuum bellows. Since this type of stack is used in each of eight vacuum chambers, the total number of bellows amounts to 216. The air inside the bellows is evacuated before installation. The X-pendulum was invented by Barton and has been developed in ICRR.[7] The basic idea had been used in a field of geophysics as a tiltmeter but we were the first to apply it as a long period vibration isolation system.[8] The basic X-pendulum behaves as a pendulum of one degree of freedom. We extended this idea to two dimensions and designed a prototype system for TAMA with designed period of 10s. From results with a one-dimensional system, we expect a reduction ratio of 100 at 1 Hz.[9] Since this mechanism is made only of metal, it is suitable to be put into ultra-high vacuum system. The overall performance of the combined system with the X-pendulum on the isolation stack will be tested by this summer, 1996.

3.7 Control and data acquisition system

The data acquisition system covers a) data acquisition for interferometer signals with 20 kHz sampling rate, b) remote control, monitoring and data logging of interferometer components, and c) online pre-analysis for gravitational wave candidate signals.[10] An optical fiber will be installed for data transfer between the center and end chambers.

3.8 Vacuum chamber

The diameter of the vacuum tube, 11 m in length, is 40 cm and the diameter of the beam splitter chamber is 1.2 m. The chambers for the near mirrors, end mirrors and the end of the mode cleaner have a diameter of 1.0 m. The vacuum tubes are connected via bellows with metal gaskets. By the end of the 1995 financial year (March 1996), vacuum tubes of 150 m for one arm and chambers for the mode cleaner had been completed. Electro-Chemical Buffing and TiN coating for non-baking system[11] were studied and will be applied for TAMA.

3.9 Facility

The vacuum system will be placed in 3 m depth below ground at NAO. The arm sections of the vacuum tubes are enclosed by precast concrete box culverts connected with sealing material. Putting the tubes underground gives us several benefits such as stability of temperature, lower seismic noise and so on. The facility building was finished this March, 1996.

4 Development and research

4.1 High power laser

A laser power of 70 W has been attained using virtual point-source multipass-pump method[12] and 300 W is planned for the future. Radially mounted laser diodes emit light towards the center, where a Nd:YAG resonator rod is mounted along the axis. It lases in a single mode with a Gaussian power distribution. This is very promising for the future detector.

4.2 Thermal noise

Although thermal noise of the suspension pendulum is important around 100 Hz according to our structure damping model, the internal vibration modes of mirrors turn out to be even more important in the middle frequency range, where all the design sensitivity curves of existing projects have an optimum point. Preliminary experiments to measure Q of various internal modes of a sample mirror suspended by two wires as in the TAMA design show that there are a few modes with very poor Q (of the order of 1000) which decreases the estimated sensitivity by more than one order in the middle frequency range. Since mirrors are necessarily suspended by thin wires and are very likely controlled by magnets, much more research on this point is needed.

4.3 Recycling

A table top experiment of recycling using simple Michelson interferometer with suspended mirrors was conducted and a recycling gain of 60 was achieved. This is reported by Moriwaki in these proceedings. A new method to separate control signals clearly for recycling has been proposed and testing is planned.

5 Conclusion

The facility housing the vacuum chamber was completed this March, 1996. All of the vacuum system has been designed. Some parts have been ordered and the remainder will be finished by the year after next. The laser source will be delivered by this June. The seismic isolation system has been designed and its prototype has been partially tested. The suspension with control is being designed and the polishing and coating of the main mirrors have been ordered to be in time for the installation in 1997. Development of key techniques such as the mode cleaner, mirror coatings, mirror alignment and recycling are in progress. We are confident of achieving the object of TAMA.

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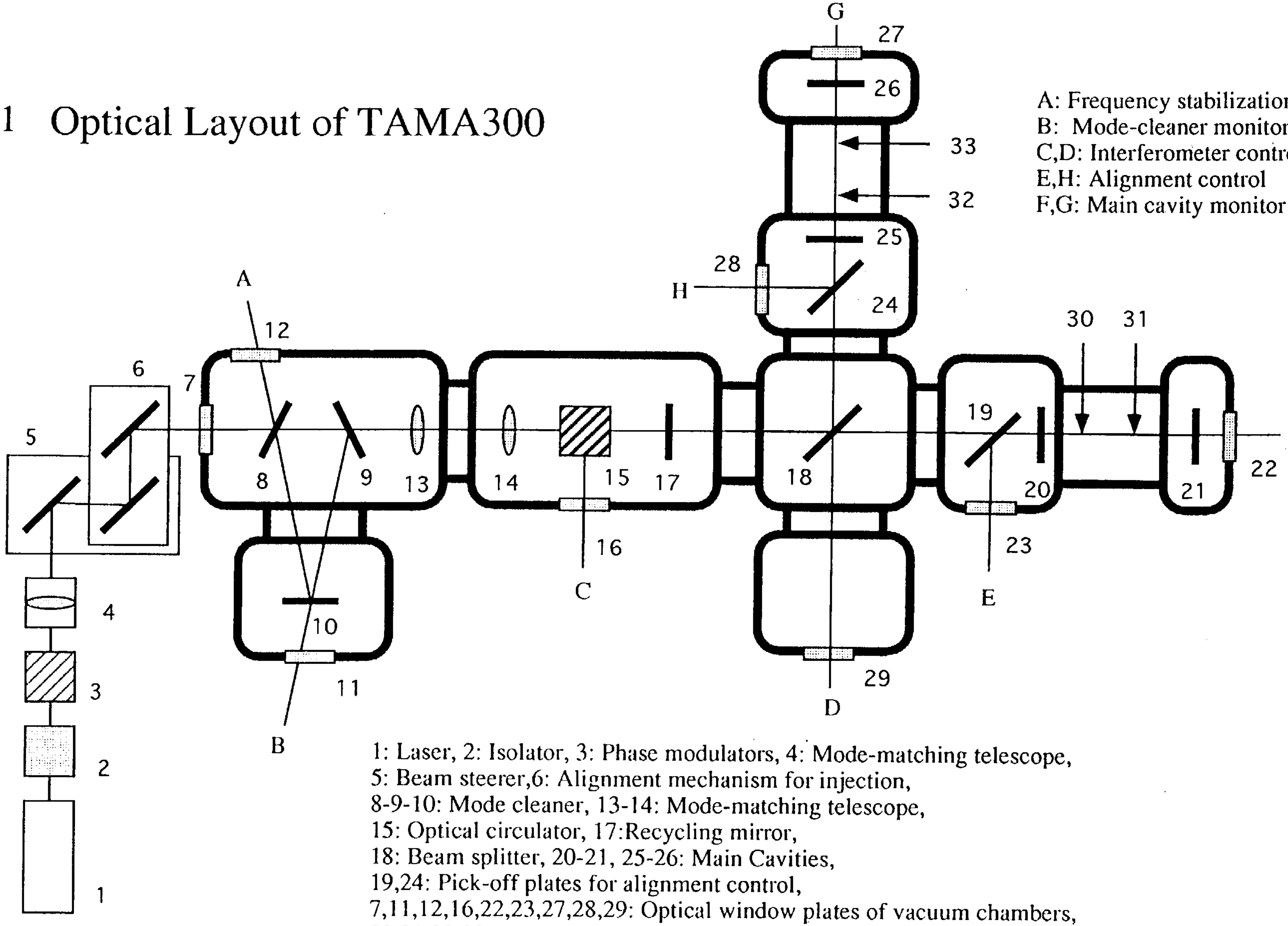
Fig. 1 Optical Layout of TAMA300



A: Frequency stabilization
B: Mode-cleaner monitor
C,D: Interferometer control
E,H: Alignment control
F,G: Main cavity monitor

1: Laser, 2: Isolator, 3: Phase modulators, 4: Mode-matching telescope,
5: Beam steerer,6: Alignment mechanism for injection,
8-9-10: Mode cleaner, 13-14: Mode-matching telescope,
15: Optical circulator, 17:Recycling mirror,
18: Beam splitter, 20-21, 25-26: Main Cavities,
19,24: Pick-off plates for alignment control,
7,11,12,16,22,23,27,28,29: Optical window plates of vacuum chambers,
30,31,32,33: Beam position sensors