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INTERNSHIP REPORT

A research on instrumental technologies to improve the sensitivity of laser interferometric gravitational wave detectors

Submitted by

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CONTENTS

ABSTRACT

Résumé en français :

TAMA300 est un ancien détecteur d'ondes gravitationnelles japonais qui permet dorénavant de tester les nouvelles technologies que l'on souhaite implémenter dans KAGRA. C'est à TAMA que l'on trouve la table de squeezing ayant pour but d'augmenter la sensibilité du détecteur en réduisant le bruit quantique. A TAMA est utilisé un Oscillateur Paramétrique Optique (OPO) qui est le composant générant le squeezing. Un nouvel OPO doit être réparé pour remplacer celui actuellement à TAMA. J'ai travaillé lors de ce stage à la préparation du montage optique pour vérifier que l'OPO soit réparé à l'Advanced Technology Center (ATC) et j'ai aussi assisté au début des réparations. En parallèle, j'ai aidé à réaligner toutes les cavités de TAMA. A cause de plusieurs problèmes tels que l'horloge cassée ou les problèmes sur le contrôle d'un des lasers à TAMA et un mauvais alignement de faisceau pour l'OPO, créant un comportement étrange à l'ATC, je n'ai pas pu mesurer de squeezing ou réparer complètement l'OPO. Néanmoins, j'ai appris le HTML, le CSS et le JavaScript pour créer un site pour mieux comprendre le fonctionnement de l'électronique à TAMA. Ainsi, on peut facilement trouver les informations principales des différents composants électronique et optiques en plus de mieux suivre les différentes connexions électroniques.

Mots clés : Détecteur d'ondes gravitationnelles, optique quantique, squeezing, squeezing dépendant de la fréquence, optique de précision, Oscillateur Paramétrique Optique (OPO).

English abstract :

TAMA300 is a former Japanese gravitational-wave detector, which is now being used to test new technologies to be implemented in KAGRA. TAMA is home to the squeezing table designed to increase the detector's sensitivity by reducing quantum noise. TAMA uses an Optical Parametric Oscillator (OPO), which is the component that generates the squeezing. A new OPO needs to be repaired to replace the one currently in TAMA. During this internship, I worked on the preparation of the optical assembly to ensure that the OPO would be repaired at the Advanced Technology Center (ATC), and I also attended the start of the repairs. At the same time, I helped realign all the TAMA cavities. Due to several problems such as the broken clock or problems with the control of one of the lasers in TAMA and a misalignment of the beam for the OPO, creating strange behavior at the ATC, I was not able to measure squeezing or completely repair the OPO. Nevertheless, I learned HTML, CSS and JavaScript to create a website to better understand how electronics work in TAMA. This way, you can easily find the main information on the various electronic and optical components, as well as better follow the various electronic connections.

Key words : gravitational wave detector, quantum optics, squeezing, frequency-dependant squeezing, precision optics, Optical Parametric Oscillator (OPO).

GLOSSARY

AOM : Acousto-Optic Modulator (AOM)

ATC : Advanced Technology Center

BHD : Balanced Homodyne Detector

EOM : Electro-Optic Modulator

FI : Faraday Isolator

GRMC : Green Mode Cleaner

HWP : Half-Wave Plate

IRMC : Infrared Mode Cleaner

JamMt : Just Another Mode Matching Tool

LIGO : Laser Interferometer Gravitational-wave Observatory

MMT : Mode Matching Telescope

MZ : Mach-Zehnder

NAOJ : National Astronomical Observatory of Japan

OPO : Optical Parametric Oscillator

PBS : Polarizing Beam Splitter

PDH : Pound-Drever-Hall

p-pol : p-polarization

PZT : Piezoelectric Transducer

QWP : Quarter-Wave Plate

SHG : Second Harmonic Generator

SQL : Standard Quantum Limit

s-pol : s-polarization

Chapter 1 : Introduction

1.1. Introduction to gravitational waves

In this first part of the chapter, I will first define what is a gravitational wave. Then, I will introduce the astronomical sources of gravitational waves, before explaining why these waves can be interesting and why we are looking to detect them.

1.1.1. Gravitational waves : definition

Acoustic waves propagate in the air, seismic waves in the ground and gravitational waves in space-time [1]. A gravitational wave is therefore an oscillation of space-time propagating at the speed of light, although unlike electromagnetic radiation, it is not visible to the naked eye or with conventional cameras used to observe the Universe. The existence of these waves, which compress and stretch everything in their path, was first predicted by Albert Einstein in 1916 when he wrote his article on general relativity [2, 3]. It was not until the 1960s that the race to detect gravitational waves was launched, following the construction of the first detector by Joseph Weber. Then, in the 70s, following the invention of the laser and the development of interferometry, scientists began to develop detectors based on Michelson interferometers [4].

1.1.2. Gravitational waves sources

Although we now know what a gravitational wave is, it is natural to wonder where this type of wave might come from. After all, it is not a type of wave that can be easily generated on Earth. To create gravitational waves, you need high-energy celestial events involving really massive objects [2, 5].

• **Collision or merger of two Black Holes**
A black hole is a celestial object so dense that its gravitational field attracts everything to it, even light. Once something crosses the black hole's event horizon, it can not escape it. There are 3 types of black hole: stellar, intermediate and supermassive. It is with these densest objects in the Universe that we can observe the largest number of gravitational waves [6,7]. It was following the merger of two black holes that gravitational waves were first detected on September 14, 2015. This first detection is called GW150914. It was made possible thanks to the collaboration between LIGO and VIRGO, two detectors that I will introduce in the section 1.2.3. [8].

• **Asymmetric supernova**
When a star at least five times the mass of the Sun reaches the end of its life, i.e. when it has used up all its fuel, it collapses on itself. The star's core, cooled by the lack of fuel, will reduce the star's internal pressure, which will then be compressed by the gravitational force surrounding it. This collapse is so fast and violent that it generates a large explosion known as a supernova. Following this explosion, the star becomes a cloud of dust, a neutron star or a black hole [9]. This violent explosion

can also be the source of gravitational waves if the star is asymmetric.

• **Binary neutron star system**

When two stars are close enough to each other to be bound by the force of gravitation, this system is called a binary star system or binary star. When the two stars are attracted to each other by the force of gravitation, they begin to rotate around their center of mass [10,11].

Currently, to be able to detect gravitational waves from this binary system, these stars must be neutron stars. These stars, which come from the end of the life of extremely massive stars, i.e. supernovae, are so dense that to compensate for the gravitational force, they are mainly composed of neutrons, hence their name ”neutron stars” [12].

• **Other astronomical sources**

There are other sources of gravitational waves, however, which are more difficult to detect, if not yet detected. For example, a sufficiently massive, asymmetric and rotating neutron star can emit gravitational waves. Scientists also believe that there are primordial gravitational waves originating from the Big Bang, which form something equivalent to the cosmic microwave background. However, these gravitational waves have not yet been detected. Detecting them would require even more sensitive detectors [13].

1.1.3. Why detecting gravitational waves ?

Most of these gravitational-wave-producing objects or celestial systems are difficult to observe. Although neutron stars can be observed using other means than gravitational waves, since they emit electromagnetic radiation, this is not the case for black holes, for example. Furthermore, electromagnetic radiation can be altered by gas clouds, dust clouds or even our own atmosphere if viewed from Earth. Gravitational waves, on the other hand, are difficult to detect because they interact little with matter, but are not altered by anything in their path. Seeking to detect gravitational waves can therefore enable us to observe these celestial objects without being altered by anything.

Moreover, by building sensitive enough detectors, we could observe primordial gravitational waves, those emitted just after the Big Bang. This would enable us to understand what happened at the beginning of our Universe, and thus to see further back in time than we already do with the cosmic microwave background.

1.2. Gravitational wave detection

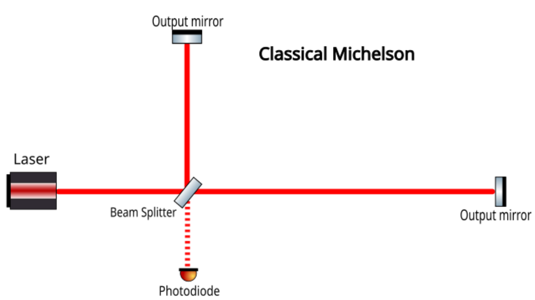
Now that we have defined what a gravitational wave is, where it comes from and, above all, why we want to observe it, let’s move on to the detection itself. I will start with a general presentation of how detectors work, and then move on to the various sources of noise that can disrupt and limit detection. Of course, I will give you a quick introduction to the different detectors before moving on to KAGRA and especially TAMA300, the Japanese detector I worked on.

1.2.1. General operation of a gravitational wave interferometer

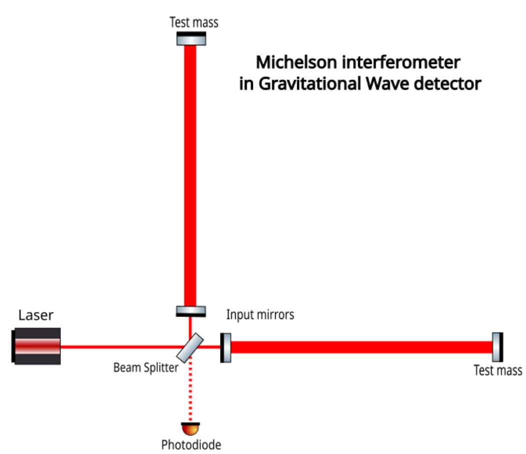
Since the 1970s, gravitational wave detectors have taken the form of Michelson interferometers (Figure 1.1a). In this interferometer, a beam of light - in this case, a 1064nm infrared laser beam - is directed onto a beam splitter. The beam is then split in two parts, one of it going through the beam splitter and then into a first arm, while the rest is reflected and sent into a second arm perpendicular to the first one. At the end of each of these arms is a mirror with a high-reflectivity coating, which sends the laser beam back to the beam splitter, where it gathers again. The principle is then to choose the length of the arms or modify it to see different interference fringes. In this way, the laser beam can be reconstituted (albeit with a slightly lower amplitude), or destructive interference can occur, causing the output light to be extinguished.

In a gravitational-wave detector, the Michelson is set to a dark fringe, making the slightest difference between the two laser beams before recombination easier to detect. It's also important to note that gravitational waves that can be detected by these detectors have a rather low frequency, in the audible range from a few Hz to several kHz. We therefore need the largest possible detectors to be sensitive to these low frequencies. This is why the arms of gravitational wave detectors measure several kilometers, for example 4km for LIGO, an American detector, or 3km for KAGRA, a Japanese detector.

To have truly sensitive detectors, we would have to build Michelson arms several hundred kilometers long. So, to increase the travel distance of the laser beams and thus the precision of these detectors, scientists came up with the idea of transforming the Michelson's arms into Fabry-Perot arm cavities. The purpose of the Fabry-Perot cavity is to increase the effective optical path in the arms by a given amount of round-trips. In this case, the laser will make several round trips (around 200 for LIGO) between the "end mirror" or "test mass" at the end of the arm and another mirror called the "input mirror" just after the beam splitter (Figure 1.1b). With these 200 round trips, the laser will travel almost 1600km in a detector "only" 4km long. The higher the reflectivity of the input mirror, the more round trips the laser beam will make, and the higher the sensitivity of the detector will be at detecting gravitational waves. We can also reduce the size of the Michelson arms if we use Fabry-Perot mirrors with higher finesse, i.e. allowing more round-trips for the laser.



(a) Classical Michelson interferometer.



(b) Michelson interferometer used in gravitational waves detection.

Figure 1.1: Michelson diagrams.

1.2.2. Noise sources that limit detection

As with any detector, it is important to consider the limits of our detection. These limits are caused by noises appearing on our measurements, and if the noise is too strong, it drowns out the information we are trying to obtain, i.e. detect a gravitational waves. Although there are many potential sources of noise, such as electronic noise, we're going to focus here on the main ones: seismic noise, Newtonian gravity noise, thermal noise and quantum noise.

- **Seismic noise**

The seismic noise limits the interferometer's sensitivity at frequencies below 40 Hz. This seismic noise can be classified in three different frequency bands. Seismic noise at frequencies below 1 mHz is caused by tidal deformation of the ground. Waves and large water mass movements cause seismic noise at frequencies between 0.1 Hz to 0.5 Hz. The last band is at frequencies above 1 Hz and comes from weather and human activity. To lessen this noise, we use a multiple-cascaded pendulum stages to isolate the test-masses [5,14].

- **Newtonian gravity noise**

The Newtonian gravity noise is a dominant source noise frequency range from 5 Hz to 15 Hz. It comes from seismic waves propagating through a medium, atmospheric disturbances like pressure, temperature and humidity, and objects moving at constant speed as cars on roads. We can not shield gravity field but we can choose a good location to reduce this noise. For example, it is possible to reduce it by building the interferometer underground and far from a big city [4,5].

- **Thermal Noise**

As test masses move, a part of the mechanical energy is converted to thermal energy which induces thermal noise. This noise includes thermorefractive noise, i.e. a change in the refraction index, thermally induced motion due to thermally excited modes of vibration and coating thermal noise. With good materials, we can have discrete vibrations outside the detection band so the thermally induced motion is no longer a source of noise in our measurements. To reduce the coating thermal noise and the thermorefractive noise, we can cool test masses and suspensions in a cryogenic cavity [4,5].

- **Quantum noise**

The quantum noise is divided in two parts : the quantum shot noise and the quantum radiation pressure noise. The laser beam can be considered as a stream of photons but this stream is not really constant. Even if photons are emitted at a defined frequency, it can happen that one photon is emitted too early or too late compared to the previous one. This difference is what we call quantum shot noise. To decrease this noise, we need to increase the laser's power (i.e. the number of emitted photons).

We then have the quantum radiation pressure noise. When the laser beam strikes an optical component such as test masses, each photon will apply a certain pressure. This pressure induces movement and therefore a noise from the optical component. To reduce this noise, we lower the laser's power. So we need to find a balance between the quantum shot noise and the quantum radiation pressure noise.

That also means that we are limited by a minimum error. This limit known as the Standard Quantum Limit (SQL), derives from the Heisenberg's Principle, which states that it is impossible to know precisely two complementary variables from photons. The only way to reduce this quantum noise below the SQL is to use quantum optics instead of classical optics [4,5,14].

1.2.3. The latest generation of detectors

From the USA with its two LIGO detectors to Japan with the KAGRA interferometer, via Germany with its GEO600 detector and Italy with Virgo interferometer, scientists around the world have been trying to build the most sensitive detector. As a result, each of these most famous interferometers used to detect gravitational waves have their own unique characteristics

• **GEO600**
Built near Hannover, Germany, this British-German detector is the smallest in this list with a 600m arm length. Even though, this interferometer is small, it is a reliable one and uses a state-of-the-art noise reduction technologies as triple pendulum suspension, thermal compensation or signal recycling. These technologies are used respectively to reduce seismic noise, thermal noise and reduce losses by increasing the input power recycling laser beam coming back to the laser. This detector also uses squeezed light to reduce quantum noise (explanation in section 1.2.4) [15].

• **Virgo**
The European Gravitational Observatory's detector, Virgo, was built in Italy, near Pisa. This ground-based interferometer with a 3km arm length uses different technologies than GEO600 to improve its sensitivity. Scientists built superattenuators, 10-meter-high towers that reduce seismic noise by a factor of 10^{12}. They use special materials with intrinsic low thermal noise. They also created a vacuum system in which the laser propagates. This system is the largest in the world, measuring 6800m long. It is used to limit light backscatter. To decrease the quantum noise, they also use frequency-dependant squeezed light [16].

• **LIGO**
There are two identical LIGO detectors (LIGO for Laser Interferometer Gravitational-wave Observatory) in the USA, one in Hanford and the other at Livingstone. These interferometers are the longest on this list with a 4km arm length (that is over 6.6 times the GEO600's length). These detectors also use special materials like Virgo to reduce thermal noise and power recycling like GEO600. The first gravitational wave detection was made by Virgo and LIGO [17].

• **KAGRA**
KAGRA, the Japanese detector with a 3km arm length, is striving to become more sensitive than LIGO, the currently most sensitive detector. To achieve this, scientists built this interferometer 200m underground to reduce seismic noise and Newtonian gravity noise. The interferometer uses sapphire mirrors that is different than other detectors. It also features a cryogenic cavity to control thermal noise at 20K i.e. -253°c. Finally, to reduce quantum noise, KAGRA will use frequency-dependant squeezed light [18].

1.2.4. TAMA300, old-generation detector

TAMA300, also known as TAMA, was built between 1995 and 1999 in Mitaka, Japan. This interferometer, with its 300 m-long arm, is the forerunner of today's Japanese KAGRA detector. In 1999, it was the most reliable gravitational wave detector. Today, this interferometer is no longer used to detect gravitational waves, even though it was the most sensitive detector 20 years ago, but it is still used to test and develop ways of improving detectors sensitivity. The most important source of noise limiting the sensitivity of detectors is quantum noise. To overcome this limitation and reduce noise at all frequencies, a team at NAOJ has demonstrated the feasibility of a technique known as frequency-dependent vacuum squeezing, at frequencies useful for gravitational wave detectors.

As I briefly explained in the section 1.2.2. about quantum noise, classical detection is limited by the standard quantum limit, because if we increase the laser frequency, we increase the quantum radiation pressure noise, but decrease the quantum shot noise. In the end, we have a kind of balance between these noises. But the limitation also depends on the frequency we want to detect. Simply put, if we want to detect something at lower frequencies, we are limited by quantum shot noise. If we reduce the uncertainty in the laser amplitude, we reduce the noise and increase sensitivity, but we also increase the uncertainty in the laser phase due to Heisenberg's principle. This is what we call "squeezed light". But the problem is that we only reduce the noise at low frequencies, whereas at higher frequencies, the noise becomes too great. That's why scientists have developed frequency-dependent squeezing. Thanks to this technique, detectors are now more sensitive to both low and high frequencies.

After demonstrating the feasibility of the frequency-dependant squeezing in early 2020, the NAOJ research team integrated this process into TAMA300, creating what is known as "TAMA squeezing table and filter cavity" [19, 20].

Chapter 2 : TAMA squeezing table and filter cavity

During this internship, I only worked on the TAMA squeezing, an important and complex part of this gravitational wave detector, which is supposed to be a prototype to be added to KAGRA. To better understand how this part of the detector works, I worked on its optics as well as its electronics.

2.1. Optical part of TAMA300

As TAMA300 is a kind of large Michelson with a Fabry-Perot in each arm, it uses a laser and therefore optical components. I have already explained this part in section 1.2.1, but before entering the Michelson, the laser must go through the squeezing table, which also uses a lot of optical components. In this section, therefore, I will start by introducing the important optical components. Next, I will present my work on a specific component known as the OPO. Finally, I will end this section by explaining how we started to realign everything inside this squeezing table and the filter cavity.

2.1.1. Optical setup

The TAMA300 squeezing uses 3 infrared lasers, one called "Main Laser" and the other two auxiliary lasers "AUX1" and "AUX2". All these lasers pass through a few important optical components: Second Harmonic Generator (SHG), Mach-Zehnder (MZ), Green Mode Cleaner (GRMC), Infrared Mode Cleaner (IRMC), Balanced Homodyne Detector (BHD) and Optical Parametric Oscillator (OPO). The main laser beam is split at the beginning: one part goes through the SHG, the MZ, the GRMC and then the OPO, and the other part passes through the IRMC and is used in the HMD. The two auxiliary lasers are used to control the OPO: AUX1 is used for coherent control and AUX2 for OPO length control.

• **Second Harmonic Generator (SHG)**
The principle of the second harmonic generator is a non-linear process. We send an infrared (IR) laser into a crystal ($\lambda_{IR} = 1064nm$), and the crystal sends back a green laser beam ($\lambda_{GR} = 532nm$). To explain how this works, we assume that we have a crystal with perfect performance. In this case, we send an energy $E = \frac{n_1 hc}{\lambda_1}$, where n is the number of photons, h is Planck's constant, c is the speed of light and λ_1 the wavelength of the input beam. Because it is perfect, the crystal returns the same energy, but with a different number of photons and a different wavelength. We therefore have $E = \frac{n_2 hc}{\lambda_2}$ where $\lambda_2 = \frac{\lambda_1}{2}$. So we have $n_2 = \frac{1}{2} \times n_1$. In our case, it's not perfect, so not all the IR beam is converted to green, and so we do not have the same energy between IR input and green output.

• **Mach-Zehnder (MZ)**
Here, the Mach-Zehnder consists in two mirrors and a large beam splitter used twice. This beam splitter divides the green laser beam obtained with the SHG in two parts. Like that, we can control each path's length and then control the laser's intensity at the MZ output.

• **Green and Infrared Mode Cleaners (GRMC and IRMC)**

The laser beam can be expressed as a linear combination of eigenmodes. These eigenmodes are electric field distributions that can propagate inside the cavity without the distribution changing shape. There are two types of modes: Hermite-Gaussian modes and Laguerre-Gaussian modes. I assume you already know what these modes are from what follows, but for more information, you can read section 2.4.3 of Yuhang Zhao's thesis [5] or the article by Dana Z. Anderson [21]. In our case, we only want the fundamental mode of the laser, also known as the "Gaussian mode", so as not to reduce our sensitivity due to the phase shift or frequency shift between these modes. To do this, we use mode cleaners that transmit only the Gaussian mode and reflect the other modes. In this way, we "clean" our laser of these parasitic modes.

• **Optical Parametric Oscillator (OPO)**

The OPO, like the SHG, uses a non-linear crystal, but it works in quite the opposite way. Whereas the SHG takes in two photons at frequency ω and outputs one photon at frequency 2ω, the OPO takes in one photon at frequency 2ω and outputs two photons at frequency ω. To achieve this, we precisely control the OPO using two auxiliary lasers, one to control the length of the OPO (with "AUX2") and the other to control its phase (with "AUX1"). The result is frequency-independent squeezed light. This squeezed light is then sent inside the filter cavity.

• **Balanced Homodyne Detector (BHD)**

We send the squeezed light and part of the light from the Main Laser, which will be used as a Local Oscillator (LO), to a beam splitter that is 50% transmitting. These two signal fields are mixed and the two outputs go to two photodiodes. Two different signals are then obtained, and the difference between them is calculated. This difference is proportional to the difference between the number of photons of the two outputs and also to the phase shift between the LO and the squeezed light. The BHD output is proportional to the magnitude of the LO.

2.1.2. Repair and replacement of the OPO

There are two different OPOs for TAMA: an old one and a new one. When I arrived at the National Astronomical Observatory of Japan (NAOJ) in April, the old OPO had not been working for a few months. The piezoelectric transducer (PZT) that controls the length of the OPO was broken. One of my activities during this internship was to witness its repair and check that everything was in order so that we could replace the old TAMA OPO with the new one. To carry out this repair, we used a clean room in the Advanced Technology Center (ATC) building at NAOJ.

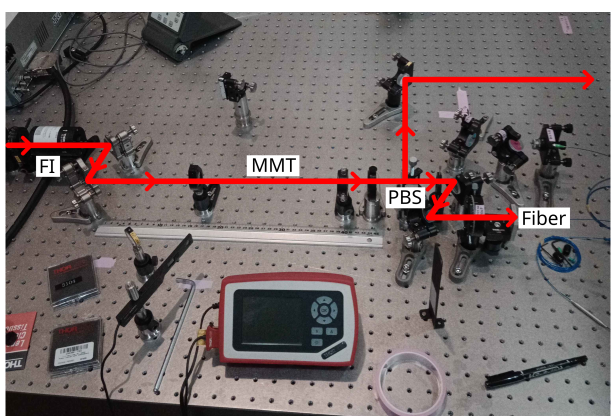
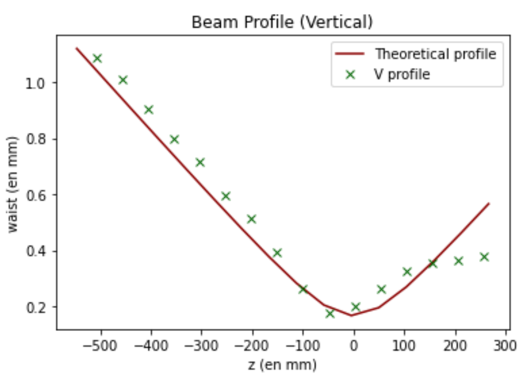
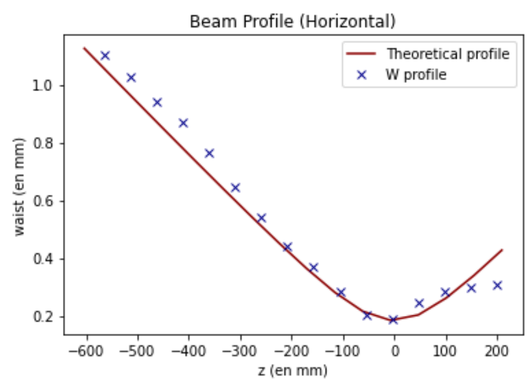


Figure 2.1: Photo of the setup already prepared in ATC

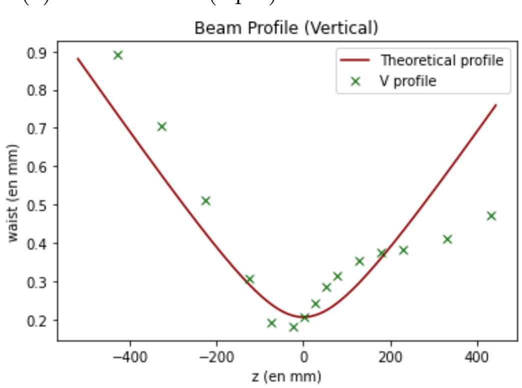
In this clean room, there was already a beam path on the table (Figure 2.1). The laser beam passed through a Half-Wave Plate (HWP) and a Quarter-Wave Plate (QWP) to achieve p-polarization (p-pol) inside a Faraday Isolator (FI). This isolator is used to protect the laser from backscattered light, which can degrade it. The laser then went through a mode-matching telescope (MMT) before entering a Polarizing Beam Splitter (PBS), which transmits the p-pol and reflects the s-polarization (s-pol). The p-pol was sent into a fiber and we wanted to use the s-pol to test the OPO. The first thing I had to do was check the beam profile in order to prepare the optical components needed on the s-pol path. I had to add an Acousto-Optic Modulator (AOM), an Electro-Optic Modulator (EOM) and a FI before a MMT for the OPO input. The beam profile on the s-pol was behaving strangely (Table A.1, Figure 2.2a and Figure 2.2b). To be sure that the problem was not with the way we measured, we did the beam profile on the p-pol but got the same behavior (Table A.2, Figure 2.2c and Figure 2.2d). We started to think about what could be the cause of this problem and the first idea was that it came from the FI if it was not from the laser.



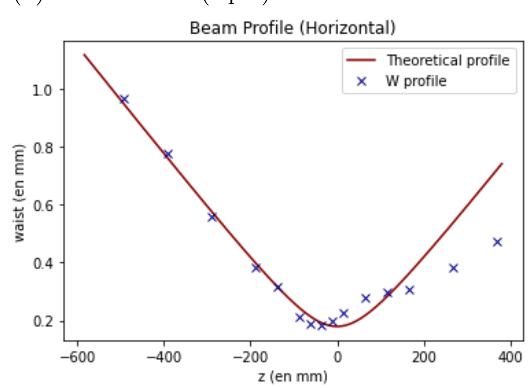
(a) Beam Profile (s-pol) for the vertical axis.



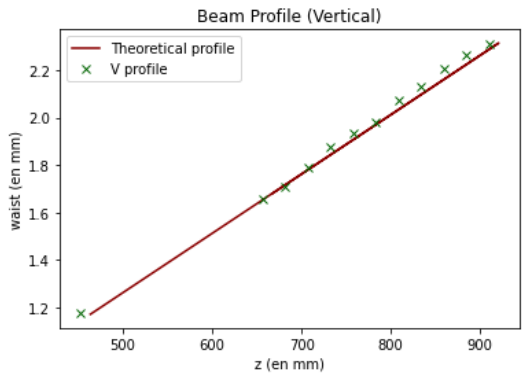
(b) Beam Profile (s-pol) for the horizontal axis.



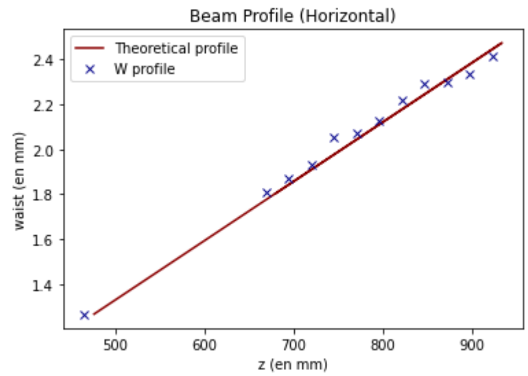
(c) Beam Profile (p-pol) for the vertical axis.



(d) Beam Profile (p-pol) for the horizontal axis.



(e) Beam Profile (laser) for the vertical axis.



(f) Beam Profile (laser) for the horizontal axis.

Figure 2.2: Beam profiles taken with the first Faraday Isolator (FI).

As there was little likelihood of the problem coming from the laser, I preferred to check by making a beam profile just after the laser output. Here, the profile was normal (Table A.3, Figure 2.2e and Figure 2.2f), so I started to change the FI. First I checked the input polarization, then placed the FI in the beam path. As this was a new FI, I had to adjust everything. We had placed it on a mount that was incompatible with it, so I could not adjust its position precisely. When I thought it was properly aligned, I did some more beam profiling, but I still had the same problem, even though it seemed to be a little better. Michael, a post-doc I worked with, checked my work and improved the alignment slightly, but nothing really changed. The next part we tried to check was the MMT between the FI and the PBS. This is where we found that the two lenses were not centered. After realigning it, I made another beam profile to find the beam size and prepare the beam path for the OPO again. When the beam path was ready on Just Another Mode Matching Tool (JamMT), I started to do it in the ATC (Figure 2.3). I set up the EOM and MMT for the OPO.

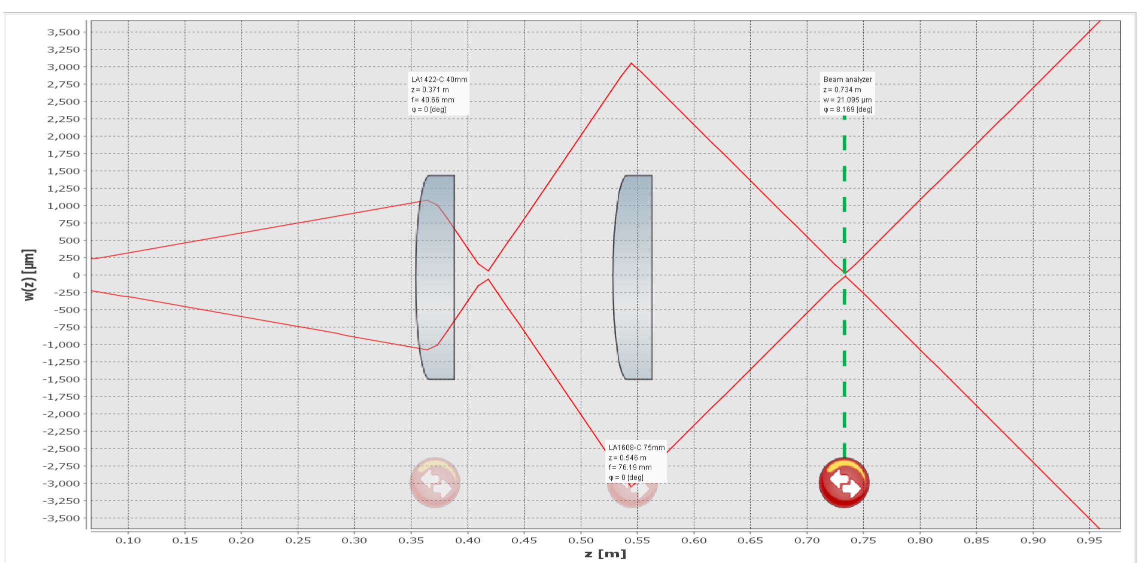
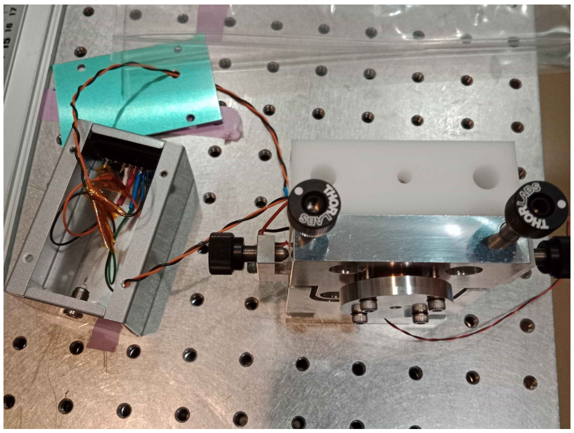


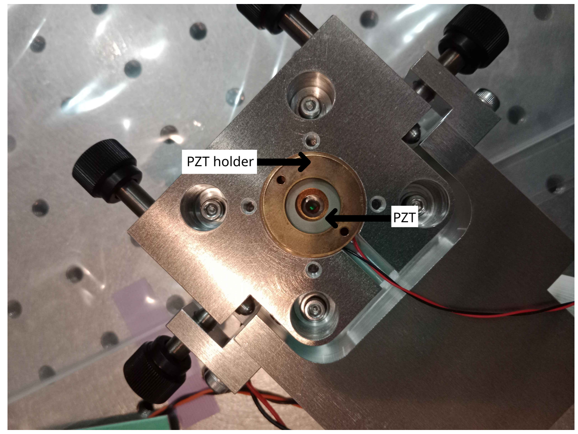
Figure 2.3: Mode Matching Telescope (MMT) for the Optical Parametric Oscillator (OPO) realised on Just Another Mode Matching Tool (JamMt).

The beam path is now almost fixed and we have to try and repair the broken OPO (Figure 2.4a).

We had to change the PZT which controls the length of the OPO. We unscrewed the input mirror and removed the broken PZT (Figure 2.4b). We replaced it with the new one, but we had a problem with the PZT holders in the OPO. I screwed the first one in too far and we couldn't remove it. Unfortunately, we didn't have enough time to repair the OPO because visitors arrived at NAOJ and had to use the ATC experiment table.



(a) Photo of the broken OPO.



(b) Photo of the PZT part in the broken OPO.

Figure 2.4: Photos of the broken OPO in ATC.

2.1.3. Optics alignment and cavity locking

At the same time as we were trying to repair the OPO with Michael, we were trying to recover the squeezing in the TAMA squeezing table with Marc, another post-doc I worked with (Figure 2.5). Before I arrived at NAOJ, all the electronics were reviewed because there was a problem and it had been a long time since the TAMA's filter cavity had been used. The first thing we checked in TAMA was the connection to make sure everything was connected. Meanwhile, we checked that we were receiving all the error signals from our LO.

In the process, we discovered that we were having problems with the DDS3, one of our electronic components. It was supposed to be sending a signal, but none of its outputs were working. On closer examination, we discovered that the problem was with the Clock. The signal was too weak for the DDS to use it to create the LO. We decided to check where the problem lay, and discovered that the crystal oscillator output was too weak. This gave us two solutions: change the crystal oscillator or add an amplifier. We chose the second option because it was the easiest and quickest to implement (Figure 2.6). After soldering the amplifier into the clock, we recovered the signals from the DDS3.

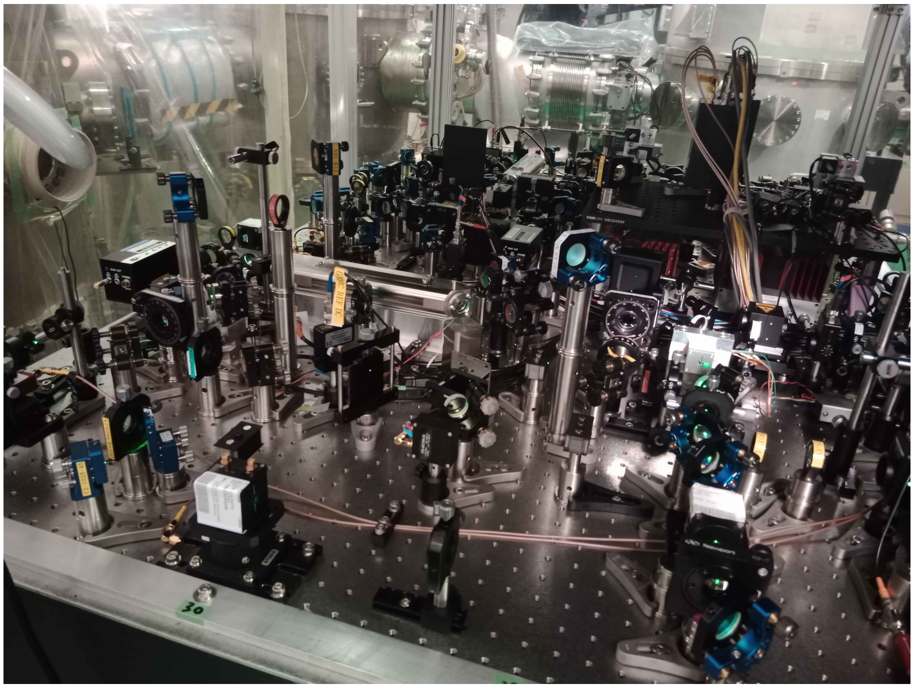


Figure 2.5: Photo of the Squeezing Table in TAMA300.

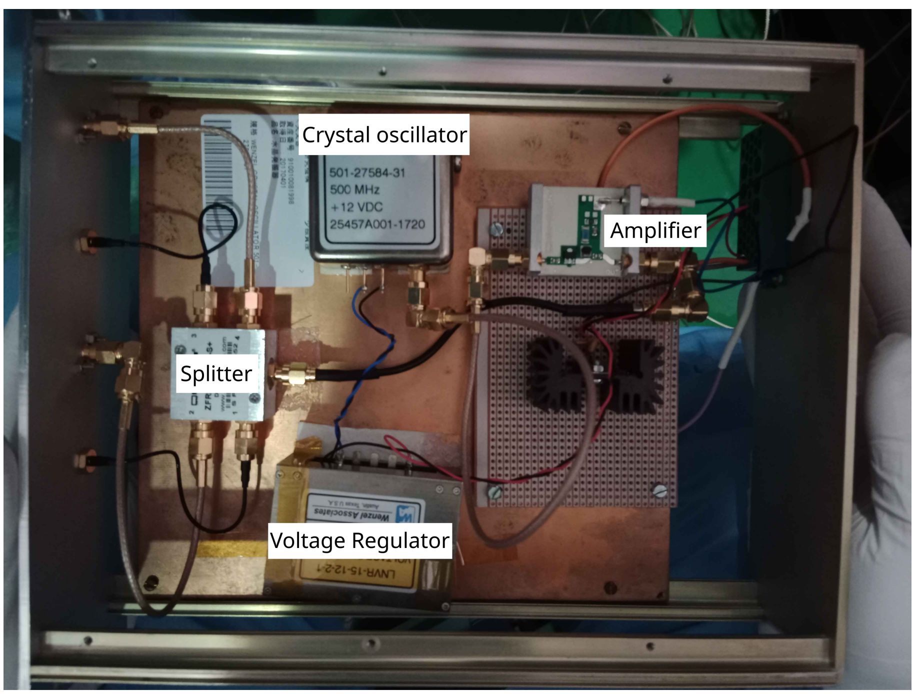
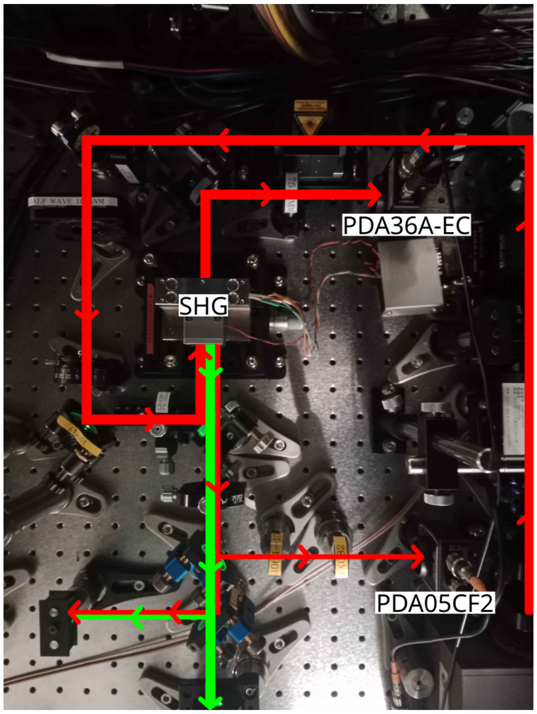
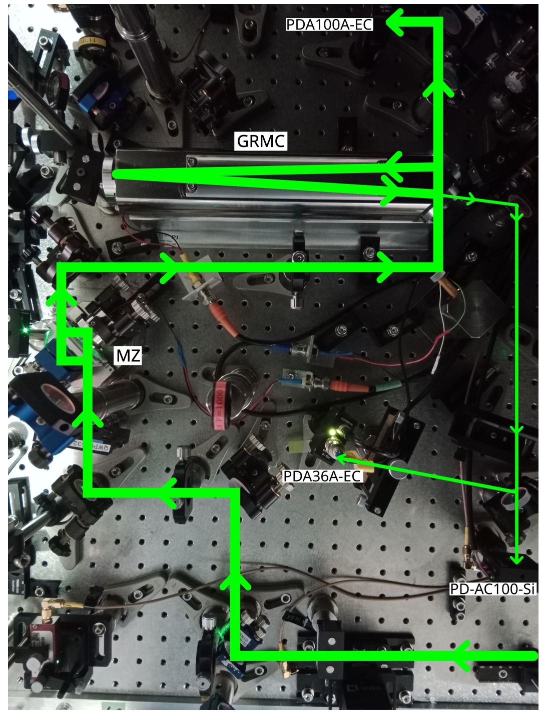


Figure 2.6: Photo of the Clock

When everything was rewired, we went back to aligning and locking each cavity. Locking means that we have a cavity tuned to the laser frequency, so that if this changes slightly, the cavity length adjusts itself. This is done using the Pound-Drever-Hall method explained in the section 2.2.1.. Marc showed me how to do it, and I did the SHG realignment while he did the IRMC realignment. The SHG was very important because it had problems before the cables and electronics were changed. We managed to recover 91% of the mode matching in the SHG, getting rid of all the problems present before my internship that were causing a loss of 30% of the mode matching (Figure 2.7a). Then we realigned the MZ and the GRMC. The purpose of the MZ here is to control the input power inside the GRMC and improve mode matching before the GRMC to limit optical losses (Figure 2.7b).



(a) Scheme of optical setup for Second Harmonic Generator (SHG).



(b) Scheme of optical setup fo Mach-Zehnder (MZ) and Green Mode Cleaner (GRMC).

Figure 2.7: Schemes of optical setup.

Having completed this, the next step was to prepare the PLL ML-PPOL and PLL ML-CC, the two control lasers for the OPO. With these PLLs, we control the two auxiliary lasers with the main laser. This is an important part because, once adjusted, these lasers go inside the OPO to control its length and phase coherence. We began by adjusting the PLL ML-PPOL, linked to the laser that controls the length of the OPO. After adjusting the polarization and realigning everything, we got a signal, but it seemed a little weaker than what we could get before. Even though it was a little weak, we could lock the cavity, so we kept this signal. Next, we tried to realign the PLL ML-CC connected to the laser that controls the phase coherence of the OPO. We proceeded in the same way as for the PLL ML-CC, but here we had a too weak signal to lock the cavity.

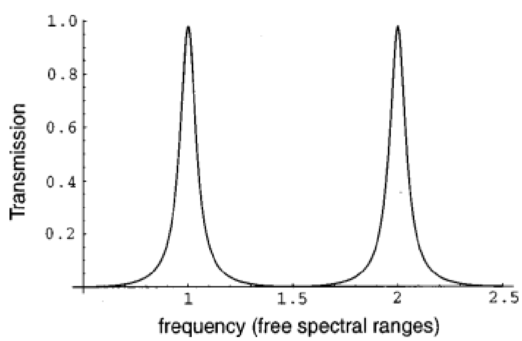
This weak signal problem could have come from alignment, perhaps caused by too great or too small a distance between the last lens and the fiber input coupler, perhaps because there was a problem with our photodiodes that we use to obtain the signal, or perhaps somewhere in the process inside the Servo, the central part that decides what to do during the locking process. With Michael, we investigated the possibility of a component problem by changing the power supply to one of the photodiodes in use. We also tried to check for maximum transmission. Michael finally found a problem with the input polarization. Once this had been modified, we recovered the PLL ML-CC lock.

2.2. Electronical part of TAMA300

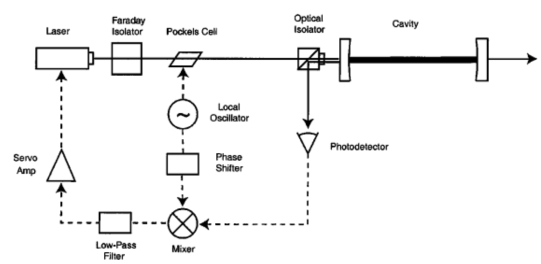
Another important and challenging part I worked on during this internship was the electronics of the TAMA300. First of all, I had to discover and understand each part, from the clock to the servos, from the mixer to the DDS. Then I drew up a schematic, which I modified to create an easy-to-understand, interactive diagram. Finally, I developed my idea and started a bigger project using HTML, CSS and JavaScript, three languages I did not know before coming to NAOJ for this internship.

2.2.1. Electronical setup

To have the best light squeezed vacuum states possible, it is important to have the best phase coherence and the lowest possible optical losses. To control laser phase, we use two auxiliary lasers (already explained in the section 2.1.1), and for optical losses, we try to limit them using Pound-Drever-Hall (PDH) locking. PDH locking is a method used to control the frequency of a laser as a function of the cavity length, or the cavity length as a function of the laser frequency (i.e. the least stable as a function of the most stable), in order to achieve the best transmission and the worst reflection at the cavity input (Figure 2.8a). The laser beam passes through a Pockels cell, which creates a sideband around the laser frequency. Next, we place a photodiode on either the transmission or reflection path (Figure 2.8b). If the cavity is well tuned and of the right length, transmission is total inside the cavity, and the photodiode shows a transmission maximum [22].



(a) Transmission of a cavity.



(b) Scheme of Pound-Drever-Hall locking setup.

Figure 2.8: Pound-Drever-Hall locking diagrams.

The sideband covers part of the transmitting frequency band, allowing us to see the evolution of transmission and thus to understand whether we need to increase or decrease the length of the cavity. We then electronically adjust this length to maximize transmission and minimize reflection. To do this, we need the photodiode signal, the LO - which also creates this sideband on the laser frequency - and some electronic components to process and analyze it all. Here, our first component is a Clock that we use for all our LOs. This Clock oscillates at 500 MHz and this signal is sent to the DDSs. The DDSs are connected to a computer and we select our reference values (or LOs), which are created in relation to the signal received from the Clock. This signal is then sent to the Mixer, sometimes amplified in the Radio-Frequency Amplifier (RF Ampli) beforehand. The same applies to the signal received from the photodiode. The Mixer then processes these signals and low-passes the result before sending it to the Servo. The Servo analyzes this signal and sends another signal to a PZT Amplifier. This signal sent to the PZT will be the signal used to modify the cavity length (Figure 2.9).

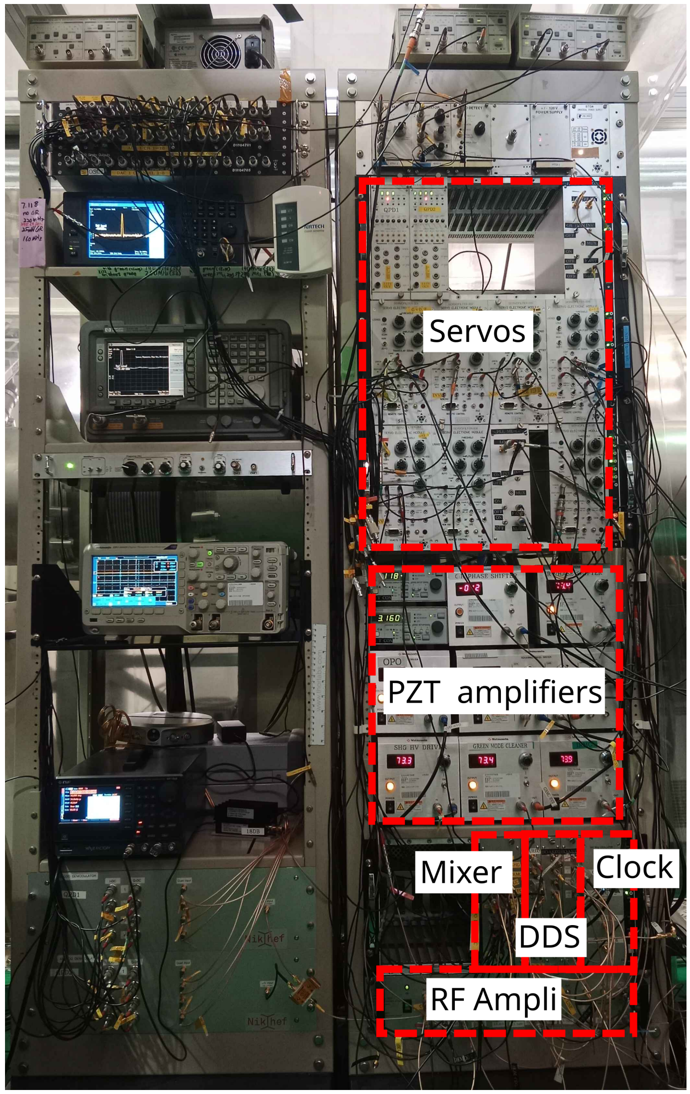


Figure 2.9: Photo of all TAMA electronic connections.

2.2.2. Intranet website

Because electronics are important at TAMA but really difficult (we use over fifty cables for the squeezing table alone), it was important to create an easy-to-understand diagram, and to do this I followed three steps. The first was to prepare a general diagram of all these connections. It took me a long time to check all the cables and write down where everything went. When that was done, all I had to do was turn everything I had written into a general scheme (Figure 2.10).

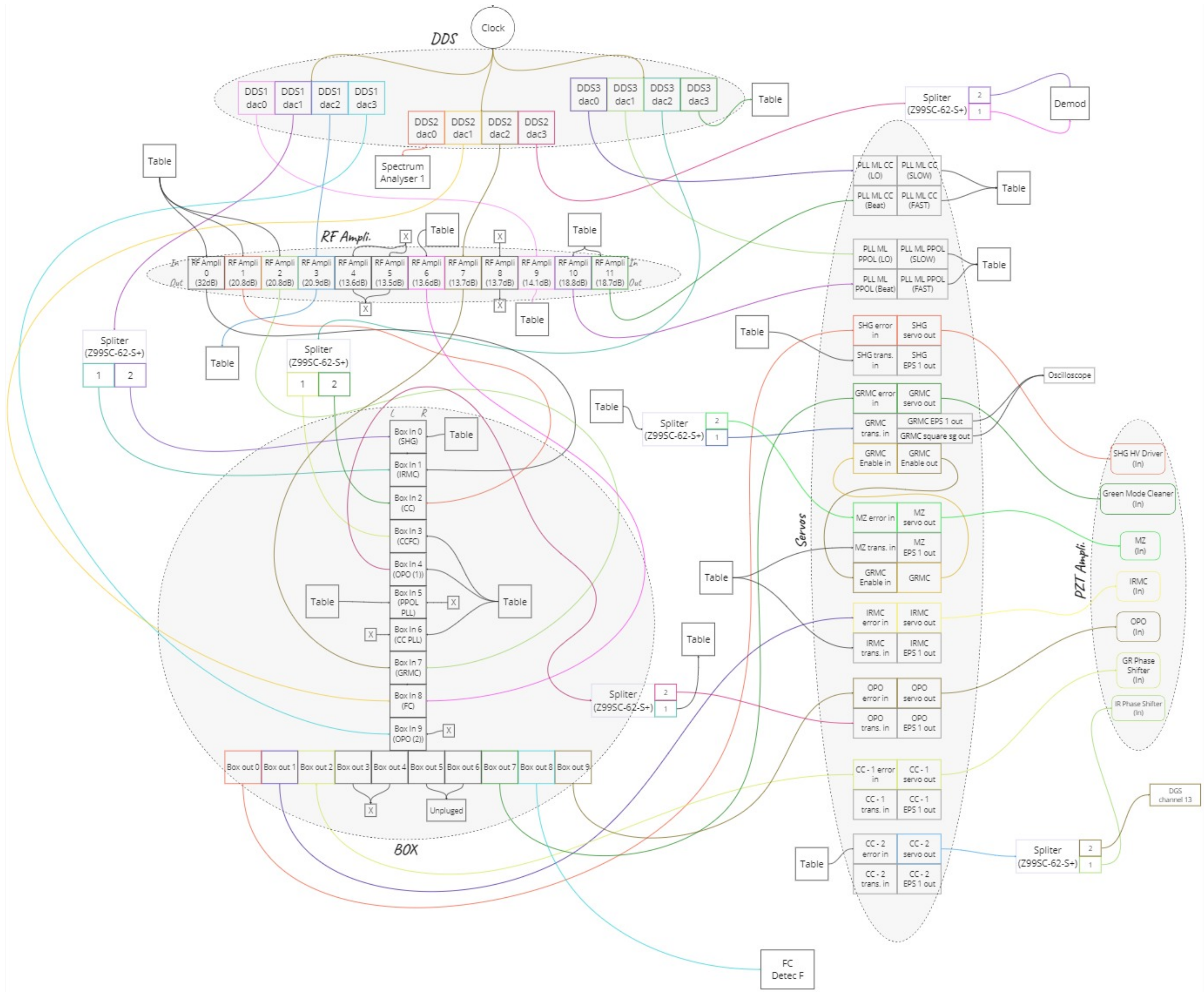


Figure 2.10: General scheme of TAMA300 electronics.

But because of all the cables, the schematic was too difficult to understand. So the next idea was to prepare smaller diagrams for each component, such as the DDS, mixer, RF amplifier or servos. This leads us to the second step: creating secondary schematics and discovering InkScape. To prepare the intranet website, I had to draw up some sort of schematics where all I had to do was specify the input, output and port name of the component. For example, there is only one input on each DDS, and it is always used by the Clock. Each DDS also has four outputs named "dac0" to "dac3". So, on a diagram, we can see the clock going to a DDS and for that DDS, we can have "dac0" going to channel 3 of the RF amp, "dac1" going to the mixer,... To prepare these diagrams, I discovered InkScape, a very useful software.

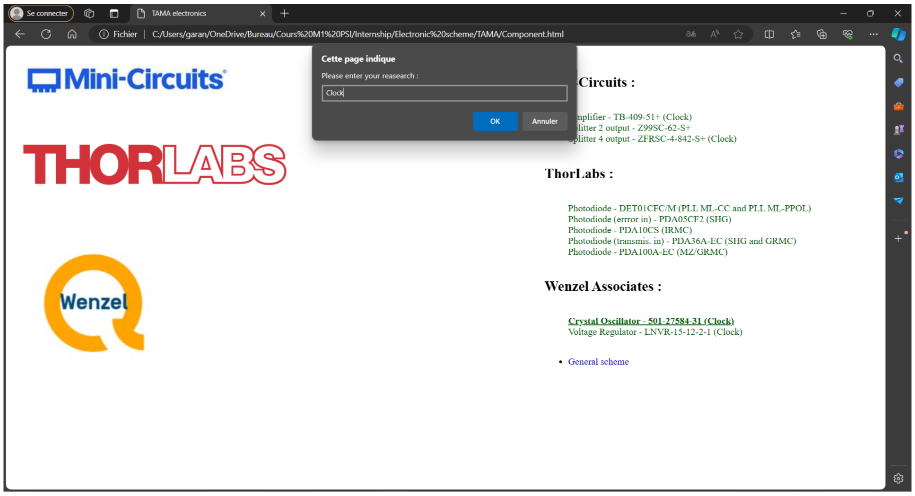
Having prepared everything, all that remained was to create HTML files, but as I did not know how HTML and CSS worked, I created my first two files with the help of ChatGPT. Thanks to this, I began to learn a few global functions and used them to create all the other files. Even though I did not know all the functions, I was able to create a functional website that seemed to work pretty well. I knew I could do better, but it was good enough to be acceptable and I was limited by my knowledge here. You can find an example of these HTML files in the section B.2 of Appendix B.

2.2.3. A better website

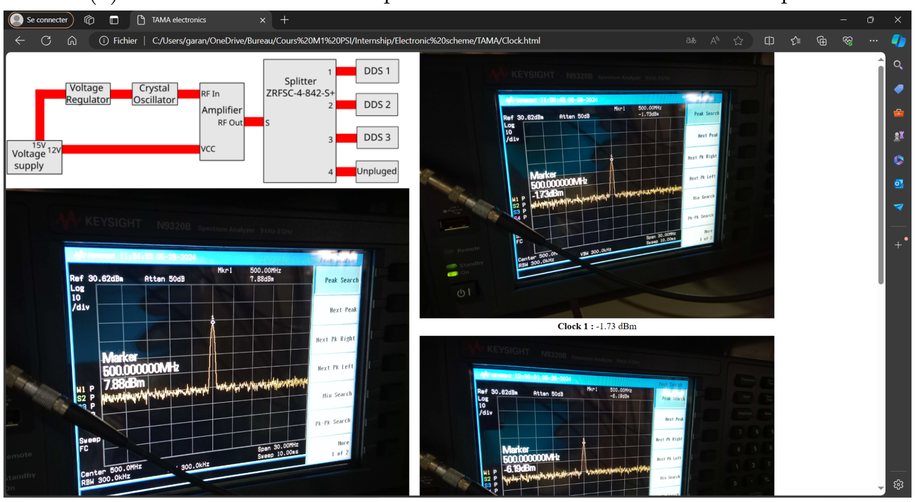
Although the website was working well, I thought I could improve it and make it more useful. To do something more useful, I suggested to Marc, who gave me the task of preparing the general scheme and even offered to do it in HTML, if I could add some sort of component catalog. When we had problems with the Clock, we had to find information on each component to understand where the problem lay. With this in mind, I wanted to add a components section to make it easier to find information on the website. I also wanted to add a link to the manufacturer's website for additional or more detailed information. With this idea approved by Marc, I decided to recreate the website to make something easier to modify, more useful and easier to understand in terms of code (HTML and CSS).

With this in mind, I decided to take an online course to learn more about HTML and CSS. To do this, I took a French course on OpenClassrooms and started to really learn HTML and CSS. This time, I created a CSS file called "style.css" in which I wrote all the CSS used for each HTML file. Although this seems like a big file that is hard to understand, it is better than having CSS in HTML files because many documents use the same properties that I only have to write once in the CSS file. Finally, I created a better website and added a components web page where you have a list of components (Figure 2.11a). You click on the component you need information on and a web page opens where you can find almost all the information and a link to the manufacturer's website for more detailed information. From the moment you open the first file to this web page, you don't need an internet connection, as everything is on the computer. The only time you need a WiFi connection is when you go to the manufacturer's website.

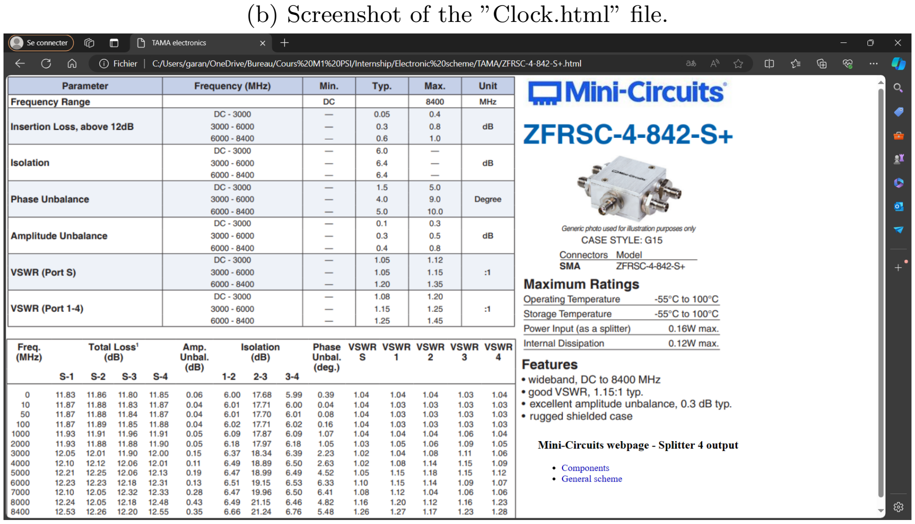
Finally, I also decided to follow the lessons on JavaScript to add another way of navigating the website other than clicking on text or areas. With this, if you already know what you want to see, just type "s" for "search". A search bar will open up and you can type in what you want to find out about (Figure 2.11a). I have created a text file to explain how to navigate and all the options you can enter. Finally, I have also added some reference values that we obtained when we repaired the clock with Marc (Figure 2.11b). We now have a complete, easy-to-use website where you can find all the information you need (Figure 2.11c). You can find an example of the new HTML file in B.2. in the Appendix B and download all the intranet website with [23].



(a) Screenshot of the "Component.html" file with research bar open.



(b) Screenshot of the "Clock.html" file.



(c) Screenshot of the "ZFRSC-4-842-S+.html" file (Splitter 4 output inside the Clock).

Figure 2.11: Screenshots of the new intranet website.

Chapter 3 : Conclusion

Despite all the work I did at NAOJ, I was unfortunately unable to attend the entire OPO repair. As we had problems with the beam path already defined in the ATC, it took us a long time to prepare everything for the OPO. I had to do a lot of beam profiling, and I also had to learn how to prepare a FI and align all the optical components. With these problems, my mistake with the PZT holder that I screwed too tightly into the OPO and the arrival of the visitors from Taiwan, we were unable to complete the repair of this OPO. So I won't be able to attend the next stage, which should be soldering the PZT before replacing the TAMA300's old OPO with this new one.

Even though we had not repaired the new OPO, I was supposed to see squeezing in TAMA, but again, I was out of luck. The clock problem wasn't the biggest one, as it only took a week to fix. The realignment of each cavity was quite interesting and difficult because of the precision required. I found this part very difficult and couldn't imagine doing something so precise before coming to NAOJ. Unfortunately, we had problems with the PLL ML-CC and although we got it back, the problem is now in the SHG cavity due to a power outage caused by a thunderstorm. Without more time, I won't be able to see the squeezinge even though I was supposed to get it during this internship.

To end this scientific conclusion on a high note, the easy-to-use electronic scheme is better than what I was asked to do. It works really well, it is easy to understand everything, you can find all the most important information and I have left lots of comments either on HTML, CSS or JavaScript files, or in a text file. The next thing to do to improve this website is to add reference values and error signals.

Finally, on a more personal note, this internship confirmed what I had discovered during my previous internship: it is sometimes difficult to adapt to the schedule. As research is about trying rather than applying, there are bound to be difficulties or problems to solve. I think that is what makes research so interesting and why I like it so much. Sometimes it's hard to overcome the difficulties, but once you do, it is really satisfying. I have also had the chance to learn about specific experiments, to discover KAGRA, to witness the repair of an important part of this gravitational wave detector and to take part in the preparations for another type of OPO at ATC with the Taiwanese visitors.

To conclude, I have been incredibly lucky to discover a lot, both from a scientific and a personal point of view. I learned a lot about gravitational-wave detectors, thanks in particular to Aso-san, Michael and Marc. I also took advantage of this internship to discover new computer languages. I let my curiosity guide me to KAGRA and ATC on the other type of OPO. Finally, I began to discover another culture, really different from the one we have in France, and I have completely fallen in love with it. I can not wait to go back to Japan.

Appendix A : Beam profile values

Distance to 0 (inches)	diameter W (profile value) (mm)	diameter V (profile value) (mm)	diameter W (gaussian value) (mm)	diameter V (gaussian value) (mm)	Gaussian correlation V (%)	Gaussian correlation W (%)
2	2.011	1.934	2.204	2.175	89.91	89.85
4	1.856	1.769	2.058	2.023	89.65	88.80
6	1.717	1.605	1.878	1.808	90.82	88.31
8	1.559	1.427	1.735	1.600	91.55	87.79
10	1.400	1.265	1.526	1.428	91.35	87.54
12	1.234	1.082	1.288	1.191	92.28	88.38
14	1.077	0.9060	1.080	1.024	90.43	87.04
16	0.9067	0.7316	0.8814	0.7908	92.23	86.85
18	0.7454	0.5447	0.7382	0.5278	94.95	90.28
20	0.5695	0.3984	0.5636	0.3550	90.10	90.54
22	0.4438	0.4096	0.4027	0.4027	94.47	83.66
24	0.4133	0.5021	0.3803	0.5281	95.46	90.39
26	0.4697	0.5859	0.4965	0.6509	92.35	92.60
28	0.5303	0.6535	0.5674	0.7124	92.95	94.87
30	0.5853	0.7054	0.5925	0.7290	92.67	93.85
32	0.6437	0.7882	0.6161	0.7610	92.34	92.68

Table A.1: Measured values for the s-polarization with the previous Faraday Isolator.

Distance to 0 (inches)	diameter W (profile value) (mm)	diameter V (profile value) (mm)	diameter W (gaussian value) (mm)	diameter V (gaussian value) (mm)	Gaussian correlation V (%)	Gaussian correlation W (%)
4	1.767	1.614	1.938	1.782	92.05	88.07
8	1.433	1.283	1.559	1.414	92.46	87.26
12	1.101	0.9192	1.115	1.024	91.30	87.48
16	0.7864	0.5973	0.7674	0.6165	94.87	83.74
18	0.6358	0.4354	0.6322	0.3853	90.10	96.57
20	0.4585	0.3826	0.4248	0.3632	93.00	83.09
21	0.4365	0.4254	0.3802	0.4146	94.85	86.51
22	0.4257	0.4794	0.3626	0.4866	96.39	90.39
23	0.4172	0.5308	0.3951	0.5676	94.72	90.94
24	0.4442	0.5715	0.4563	0.6310	92.99	91.76
26	0.5175	0.6430	0.5594	0.7071	93.32	93.82
28	0.5585	0.7121	0.5934	0.7494	93.54	93.30
30	0.6362	0.7894	0.6111	0.7665	93.00	92.98
34	0.8213	0.9882	0.7618	0.8217	86.62	91.21
38	1.077	1.205	0.9495	0.9444	84.29	88.91

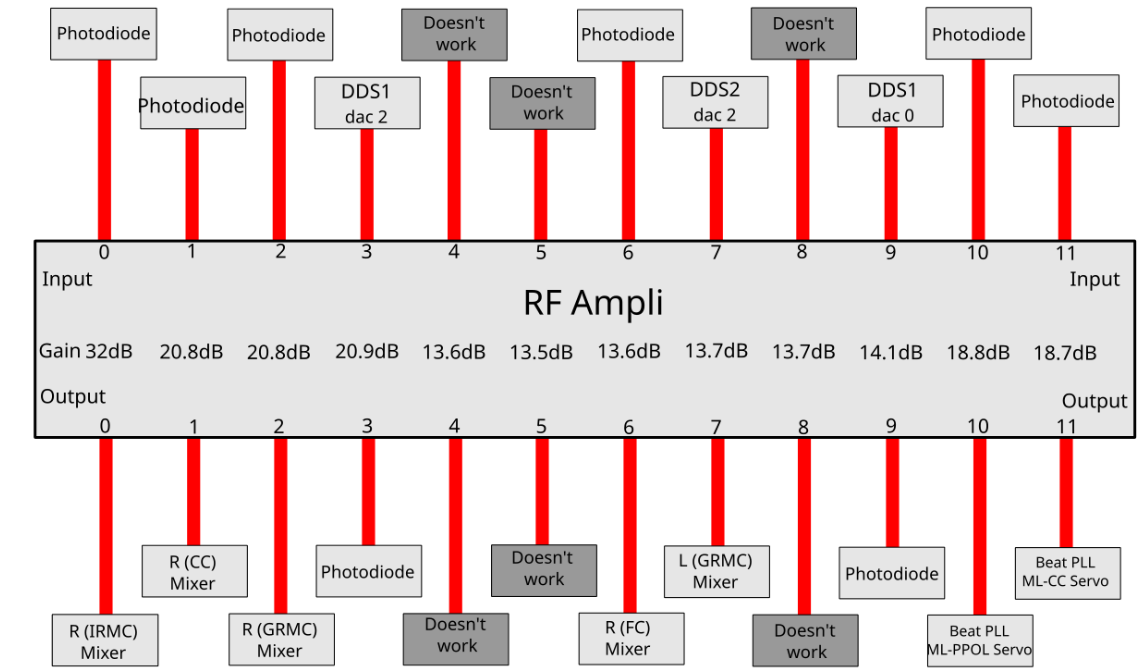
Table A.2: Measured values for the p-polarization with the previous Faraday Isolator.

Distance to 0 (inches)	diameter W (profile value) (mm)	diameter V (profile value) (mm)	diameter W (gaussian value) (mm)	diameter V (gaussian value) (mm)	Gaussian correlation V (%)	Gaussian correlation W (%)
-6	2.530	2.351	2.661	2.463	95.11	95.05
2	3.620	3.310	3.837	3.548	95.07	95.12
3	3.744	3.418	4.019	3.735	94.07	94.48
4	3.859	3.573	4.181	3.860	94.36	94.09
5	4.108	3.754	4.424	4.093	93.57	94.11
6	4.147	3.866	4.503	4.169	94.31	93.17
7	4.247	3.958	4.582	4.315	94.09	93.35
8	4.432	4.148	4.868	4.530	93.49	92.35
9	4.585	4.261	5.027	4.635	93.12	92.37
10	4.599	4.412	5.169	4.809	93.49	91.49
11	4.672	4.524	5.189	4.883	93.37	91.92
12	4.833	4.618	5.464	5.011	92.73	90.50

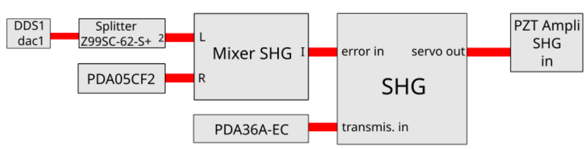
Table A.3: Measured values directly from the laser.

Appendix B : Additional information about the intranet website

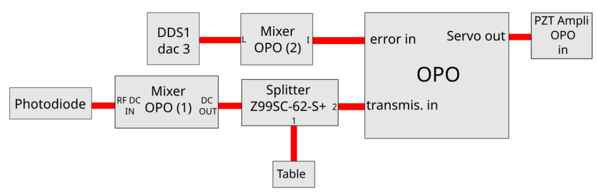
B.1. Secondary schemes



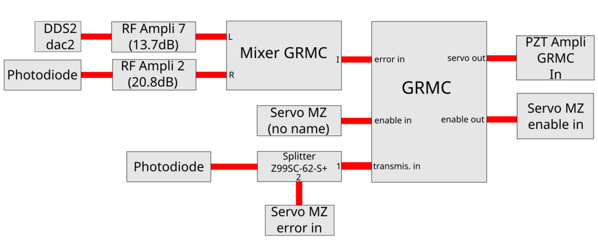
(a) RF Ampli scheme.



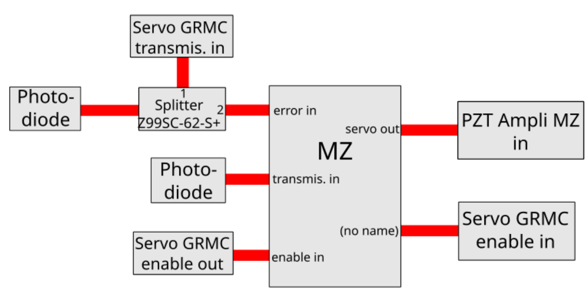
(b) SHG scheme.



(c) OPO scheme.



(d) GRMC scheme.



(e) Mach-Zehnder scheme.

Figure B.1: Example of some secondary schemes used in the intranet website.

B.2. Examples of HTML code used

Used code for the first version of the intranet website ("General scheme.html" file) :

```
<!DOCTYPE html>
<html lang="fr">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <title>TAMA Electronic scheme</title>
    <script src="navigation.js"></script>
    <style>
        .Text {
            position: absolute;
            color: rgb(255, 6, 6);
            font-size: 16px;
            font-family: Arial, sans-serif;
            font-weight: bold;
            text-decoration: underline;
            background-color: rgb(255, 255, 255);
            pointer-events: none;
        }

        #imageContainer {
            margin-right: 3px;
            position: absolute;
            top: 20px;
            left: 0px;
            width: 847px;
            height: 700px;
        }

        #imageContainer2 {
            margin-left: 3px;
            position: absolute;
            top: 20px;
            left: 900px;
            width: 439px;
            height: 700px;
        }

        #imageContainer img {
            width: 100%;
            height: 100%;
            display: block;
        }

        #imageContainer2 img {
            width: 100%;
            height: 100%;
            display: block;
```

```
}

.clickable-area {
    position: absolute;
    cursor: pointer;
    background-color: transparent;
    border:2px dashed black;
    border-radius: 75%;
}

.clickable-area a {
    display: block;
    width: 100%;
    height: 100%;
    text-decoration: none;
}

.clickable-text {
    position: absolute;
    color: rgb(0, 0, 0);
    font-size: 16px;
    font-family: Arial, sans-serif;
    font-weight: bold;
    text-decoration: underline;
    pointer-events: none;
}

#Back-link {
    position: absolute;
    top: 700px;

}

.back-link {
    margin-top: 20px;
    font-size: 18px;
    color: blue;
    text-decoration: underline;
    cursor: pointer;
}

.clickable-area2 {
    position: absolute;
    cursor: pointer;
    background-color: transparent;
    border:4px dashed rgb(255, 6, 6);
}

.clickable-area2 a {
    display: block;
    width: 100%;
    height: 100%;
```

```
            text-decoration: none;
        }

    </style>
</head>
<body>
    <div id="imageContainer">

        <img src="Scheme/Inkscape schemes/Scheme electronic filter cavity.jpg"
        alt="TAMA General electronics scheme">
        <!-- Link to DDS -->
        <div class="clickable-area" style="top: 31px; left: 148px; width: 375px; height: 71px;">
            <a href="DDS.html"></a> <!-- Link 1 -->
            <div class="clickable-text" style="top: 27px; left: 165px;">DDS</div>
        </div>

        <!-- Link to RF AMPLI -->
        <div class="clickable-area" style="top: 171px; left: 100px; width: 377px; height: 41px;">
            <a href="RF Ampli.html"></a> <!-- Link 2 -->
            <div class="clickable-text" style="top: 12px; left: 160px;">RF Ampli</div>
        </div>

        <!-- Link to MIXER -->
        <div class="clickable-area" style="top: 284px; left: 109px; width: 350px; height: 309px;">
            <a href="Mixer.html"></a> <!-- Link 3 -->
            <div class="clickable-text" style="top: 147px; left: 155px;">Mixer</div>
        </div>

        <!-- Link to SERVOS -->
        <div class="clickable-area" style="top: 82px; left: 570px; width: 121px; height: 584px;">
            <a href="Servos.html"></a> <!-- Link 4 -->
            <div class="clickable-text" style="top: 284px; left: 35px;">Servos</div>
        </div>

        <!-- Link to CLOCK -->
        <div class="clickable-area" style="top: 1px; left: 329px; width: 28px; height: 28px;">
            <a href="Clock.html"></a> <!-- Link 5 -->
            <div class="clickable-text" style="top: -14px; left: -7px;">Clock</div>
        </div>
    </div>

    <div id="imageContainer2">

        <!-- This is the photo from TAMA electronics -->
        <img src="Photos/Electronics.jpg" alt="TAMA Electronics photo">

        <!-- Link to SERVOS -->
        <div class="clickable-area2" style="top: 192px; left: 228px; width: 163px; height: 155px;">
            <a href="Servos.html"></a> <!-- Link 6 -->
            <div class="Text" style="top: 65px; left: 50px;">Servos</div>
        </div>
```

```
        <!-- Link to DDS -->
        <div class="clickable-area2" style="top: 532px; left: 330px; width: 34px; height: 85px;">
            <a href="DDS.html"></a> <!-- Link 7 -->
            <div class="Text" style="top: 30px; left: 0px;">DDS</div>
        </div>

        <!-- Link to MIXER -->
        <div class="clickable-area2" style="top: 532px; left: 303px; width: 19px; height: 85px;">
            <a href="Mixer.html"></a> <!-- Link 8 -->
            <div class="Text" style="top: 10px; left: -50px;">Mixer</div>
        </div>

        <!-- Link to CLOCK -->
        <div class="clickable-area2" style="top: 532px; left: 365px; width: 25px; height: 85px;">
            <a href="Clock.html"></a> <!-- Link 9 -->
            <div class="Text" style="top: 10px; left: 30px;">Clock</div>
        </div>

        <!-- Link to RF AMPLI -->
        <div class="clickable-area2" style="top: 622px; left: 240px; width: 165px; height: 42px;">
            <a href="RF Ampli.html"></a> <!-- Link 10 -->
            <div class="Text" style="top: 10px; left: 50px;">RF Ampli</div>
        </div>

    </div>

    <div id="Back-link" class="back-link">
        <a href="Component.html">Components</a>
    </div>
</body>
</html>
```

Used code for the second version of the intranet website (”General scheme.html” file) :

```
    <!DOCTYPE html>
<html>

    <!-- This part is just about some important information that are not on the pages when
         you open it.Here you open other files if needed and things like this. What you can
         see on the website is written in the <body> part. -->
    <head>

        <!-- The part just under is important to see approximately all the symbols and characters
        we can right on the page. -->
        <meta charset="UTF-8">

        <!-- This line is to set the page’s language. So here I wrote "en" for english. -->
        <html lang="en"></html>

        <!-- This is the title of the page, the name you see in the tab. -->
        <title>TAMA electronics</title>
```

```
    <!-- These 2 lines are to link this page to the JavaScript and CSS pages that I use
    for navigation and disposition on this website. -->
    <link href="Style.css" rel="stylesheet">
    <script src="navigation.js" defer></script>
</head>

<body>

    <!-- This part is about the first image. -->
    <div id="ImageContainer1GS" class="ImageContainer">

        <!-- With this line I open the image. -->
        <img src="Scheme/Inkscape schemes/Scheme electronic filter cavity.jpg"
        alt="TAMA General electronics scheme" title="TAMA General electronics scheme">

        <!-- In the following lines, you have all the clickable areas,
             files they are linked to and text associated. To change the
             shape of theses areas, you have to go in the CSS file. -->

        <!-- Link to DDS -->

        <!-- Little information : I had a problem here with the clickable-area and i
             finally found what was the problem and in case you need to change something,
             here is the problem. I could creat a zone where I wanted and with the exact
             shape that I wanted but when I was clicking on it, it didn't work. I finally
             understood (maybe it's obvious) that I used a <div> section with the
             class="clickable-area black-border" and the id used for each clickable area.
             Inside this <div>, I had the link with <a href="doc.html"></a>
             and the text that we couldn't click on. What I understood here is
             that the clickable-area needs to be applied to a <a> beacon because if
             it is in another beacon (here <div>), it can't find the link so it becomes a
             useless area. Be carefull if you change or add something like this. -->
        <a href="DDS.html" class="clickable-area black-border" id="AreaDDS1-GS">
            <div class="associated-text black-text" id="TextDDS1-GS">DDS</div>
        </a>

        <!-- Link to RF AMPLI -->
        <a href="RF Ampli.html" class="clickable-area black-border" id="AreaRF1-GS">
            <div class="associated-text black-text" id="TextRF1-GS">RF Ampli</div>
        </a>

        <!-- Link to MIXER -->
        <a href="Mixer.html" class="clickable-area black-border" id="AreaMixer1-GS">
            <div class="associated-text black-text" id="TextMixer1-GS">Mixer</div>
        </a>

        <!-- Link to SERVOS -->
        <a href="Servos.html" class="clickable-area black-border" id="AreaServo1-GS">
            <div class="associated-text black-text" id="TextServo1-GS">Servos</div>
        </a>

        <!-- Link to CLOCK -->
```

```
            <a href="Clock.html" class="clickable-area black-border" id="AreaClock1-GS">
                <div class="associated-text black-text" id="TextClock1-GS">Clock</div>
            </a>
        </div>



        <!-- This part is the same than the previous one but with the 2nd
             image, i.e. the photo. There are 2 differences : the shape of
             these clickable areas and the color used. Everything about the
             color for the text is in the class ".red-text" and for the border,
             you can find it in the class "red-border" in the Style.css file.-->
        <div id="ImageContainer2GS" class="ImageContainer">

            <!-- This is the photo from TAMA electronics -->
            <img src="Photos/Electronics.jpg" alt="TAMA Electronics photo">

            <!-- Link to SERVOS -->
            <a href="Servos.html" class="clickable-area red-border" id="AreaServo2-GS">
                <div class="associated-text red-text" id="TextServo2-GS">Servos</div>
            </a>

            <!-- Link to DDS -->
            <a href="DDS.html" class="clickable-area red-border" id="AreaDDS2-GS">
                <div class="associated-text red-text" id="TextDDS2-GS">DDS</div>
            </a>

            <!-- Link to MIXER -->
            <a href="Mixer.html" class="clickable-area red-border" id="AreaMixer2-GS">
                <div class="associated-text red-text" id="TextMixer2-GS">Mixer</div>
            </a>

            <!-- Link to CLOCK -->
            <a href="Clock.html" class="clickable-area red-border" id="AreaClock2-GS">
                <div class="associated-text red-text" id="TextClock2-GS">Clock</div>
            </a>

            <!-- Link to RF AMPLI -->
            <a href="RF Ampli.html" class="clickable-area red-border" id="AreaRF2-GS">
                <div class="associated-text red-text" id="TextRF2-GS">RF Ampli</div>
            </a>
        </div>

        <div id="LinkList-GS">
            <ul>
                <li><a href="Component.html">Components</a></li>
            </ul>
        </div>
    </body>
</html>
```

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