

CHAMELEON SEARCH IN CAST EXPERIMENT AT CERN

by

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ABSTRACT

CHAMELEON SEARCH IN CAST EXPERIMENT AT CERN

Chameleons are hypothetical particles that are proposed as a scalar field to account for the accelerated expansion of the universe, the so-called ‘dark energy problem’. They are proposed to be produced in the high magnetic field regions inside the Sun and they propagate through or reflect from a medium with the interaction strength depending on the ambient density. The models which characterize the interaction of the chameleons provide two interaction channels: direct coupling to matter dependent on the density and coupling to electromagnetic field by Primakoff effect. CAST Experiment probes the coupling of chameleons with matter with opto-mechanical KWISP detector which is based on Fabry-Perot and Michelson interferometers.

In this thesis, starting with an overview of the experimental search efforts of the CAST experiment, theoretical background of the dark energy and the chameleon mechanism will be provided. Then, the detection mechanism based on KWISP detector will be discussed and the versions of the detectors will be introduced. The analysis of the data which were taken on December 2016 will be explained in details and the results will be shown. In the end, results and plans for further improvement of the detector will be discussed.

ÖZET

CAST DENEYİNDE CHAMELEON ARAŞTIRMALARI

Chameleonlar, evrenin hızlanarak genişlemesinden sorumlu olduğu düşünülen karanlık enerji problemine yönelik ortaya atılan skaler alanlardan kaynaklı kuramsal parçacıklardır. Bu parçacıkların Güneş'in yüksek manyetik alana sahip iç bölgelerinde olduğu ve içinde yayıldıkları ortamla ortamın yoğunluğuna bağlı bir etkileşim gücüne sahip olduğu düşünülüyor. Chameleon'ların etkileşimini karakterize eden modeller iki farklı etkileşim kanalı öneriyorlar: yoğunluğa bağlı olarak doğrudan madde ile etkileşim ve Primakoff etkisi ile elektromanyetik alanlarla etkileşim. CAST deneyi chameleon'ların madde ile etkileşimlerini, Fabry-Perot ve Michelson girişimölçer tekniklerine dayalı optik-mekanik KWISP dedektörü ile araştırıyor.

Bu tezde, CAST deneyinin deneysel araştırmalarının genel bir özeti ile başlayarak, karanlık enerji ve chameleon mekanizmasının teorik temelleri gözden geçirilecek. Ardından, KWISP dedektörünün çalışma prensibi irdelenerek farklı uyarlamaları tanıtılacak. Aralık 2016'da alınan verilerin analizi detaylı olarak incelenip sonuçlar ortaya konacak. Son olarak, sonuçlardan yola çıkarak dedektörün geliştirilmesi için öneriler sunulacak.

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LIST OF SYMBOLS

a	Scaling factor
$\mathcal{A}$	Airy-function
B	Magnetic Field
c	The speed of light
c_k	Fourier coefficient
DC	Direct Current
F	Coefficient of finesse
$\mathcal{F}$	Finesse
$F^{\mu\nu}$	Electromagnetic field tensor
$\text{frq}_{\text{chopper}}$	Chopper frequency
g	Determinant of the metric tensor
G	Gravitational Constant
$g_{\alpha\gamma}$	Coupling constant of axions to photons
H	Hubble Parameter
I	Irradiance
k	Curvature Term
k_0	Wave number
k_y	Momentum in the y direction
$k_{x,\infty}$	Momentum in the x direction
$\mathcal{L}$	Lagrangian density for the axion-photon interaction
L_m	Matter field contribution to the Lagrangian density
m_a	Mass of the axion
m_c	Mass of the excitations of the chameleon field
m_{eff}	Effective mass
m_s	Mass of the excitations of static chameleon field
m_0	Mass of the excitations of the chameleon at the surface
M	Mass scale
M_{Pl}	Planck's mass

n	Chameleon model parameter
N	Noise
q	Momentum transfer in vacuum
P	Pressure
r	Reflection coefficient
r_c	Electric field reflectivity of the membrane
R	Ricci scalar
$R_\odot$	Solar radius
S	Action
S_d	Sensitivity of the detector
V	Potential
V_{eff}	Effective Potential
t	Transmission coefficient
x	Distance
z	Cosmological redshift
Z	Mass number of the buffer gas
α	Axion
β_m	Matter coupling constant
β_γ	Photon coupling constant
δ	Path difference
ϵ	Grazing angle
γ	Photon
$\hbar$	Planck's constant
λ	Wavelength
Λ	Cosmological Constant
ϕ	Chameleon field
ϕ_{min}	Minimum value of the chameleon field
ϕ_s	Static chameleon field
ϕ_0	Chameleon field at the surface
ρ	Density

ρ_m	Matter density
ω	Proportionality constant of the barotropic equation of state
ω_{cav}	Cavity frequency
Ω	Density parameter
θ	Incidence angle

LIST OF ACRONYMS/ABBREVIATIONS

ABRIXAS	A Broadband Imaging X-ray All-sky Survey
ADC	Analog-to-Digital Converter
CAST	Cern Axion Solar Telescope
CCD	Charged Coupled Device
CDM	Cold Dark Matter
CERN	Conseil Européen pour la Recherche Nucléaire
CM	Cavity Mirror
CMB	Cosmic Microwave Background
CP	Charge-Parity
DAC	Diigital-to-Analog Converter
DAQ	Data Acquisition
DC	Direct Current
DFT	Discrete Fourier Transform
EM	Electromagnetic Field
EOM	Electro-Optical Modulator
eV	Electron volt
EP	Equivalence Principle
FFT	Fast Fourier Transform
FP	Fabry-Perot
FPGA	Floating Point Gate Array
FRW	Friedman-Robertson-Walker
GeV	Giga electron volt
GR	General Relativity
INFN	Istituto Nazionale di Fisica Nucleare
InGrid	Integrated Grid
IR	Infra-red
ISR	Intersecting Storage Rings
LAN	Local Area Network

Λ CDM	Cold Dark Matter with Cosmological Constant
LHC	Large Hadron Collider
KSVZ	Kim-Shifman-Wainshtein-Zakharov
KWISP	Kinetic Weakly Interacting sub-eV Particle Detection
MI	Michelson Interferometer
Mpc	Mega parsec
PBS	Polarising Beam Splitter
PCB	Printed Circuit Board
PDH	Pound-Drever-Hall
PDR	Photo diode
PID	Proportional-Integral-Derivative
PS	Proton Synchrotron
RMS	Root Mean Square
QCD	Quantum Chromo Dynamics
SDD	Silicon Drift Detector
S/N	Signal-To-Noise Ratio
SM	Steering Mirror
SPS	Super Proton Synchrotron
TEM	Transverse Electric Field
TPC	Time Projection Chamber
WIMP	Weakly Interacting Massive Particles
WISP	Weakly Interacting sub-eV Particles
WWW	World Wide Web

1. INTRODUCTION

1.1. CERN

CERN (Conseil Européen pour la Recherche Nucléaire), European Organization for Nuclear Research is an international research organisation that hosts the biggest high energy physics laboratory in the world. It is situated at the Franco-Swiss border in Geneva, Switzerland. Established in 1954 by twelve founding members, it currently has 22 members (Belgium, Denmark, France, Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, Austria, Spain, Portugal, Finland, Poland, Hungary, Czech Republic, Slovakia, Bulgaria, Israel, Romania) and 6 associate member states (Serbia, Cyprus, Turkey, Pakistan, Ukraine, India). CERN provides technological infrastructure and an accelerator complex for particle physics experiments.

CERN's first accelerator was Synchrocyclotron and it provided beams for CERN's first experiments in particle and nuclear physics. Proton Synchrotron (PS) started its operations in 1959 and it provided beams up to 28 GeV. In parallel with the fixed target experiments, first colliding proton interactions were recorded with Intersecting Storage Rings (ISR), giving new insight into various processes. Super Proton Synchrotron (SPS) became operational in 1976 providing energies up to 450 GeV. Using the proton-antiproton collision data with SPS the discovery of W and Z bosons which mediate the weak interactions was announced in 1983. 27 km circumference Large Electron Positron Collider was built under Franco-Swiss border and its first beams circulated the ring in 1989. The World Wide Web (WWW) was also developed at CERN in 1990 by Tim Berners-Lee.

The main experiment at CERN is the LHC - Large Hadron Collider which collides protons and heavy ions. It is a circular collider placed 100 meters underground in a 27-km-circumference circular tunnel. Protons and heavy ions which are pre-accelerated in the sub-accelerator complex are injected into the tunnel and made to collide at 13

TeV center of mass energy. There are seven experiments on the LHC. The four main experiments are ALICE, ATLAS, CMS and LHCb. The other three smaller ones are LHC-forward, MoEDAL and TOTEM experiments. The first beam was circulated in the accelerator in August 2008. In July 2012, the announcement has been made for the discovery of the Higgs boson by ATLAS and CMS [1,2] which is a significant achievement for the particle physics community.

CERN also hosts significant number of non collider experiments such as CAST (CERN Axion Solar Telescope) searching for dark matter and dark energy particles, CLOUD (Cosmics Leaving Outdoor Droplets) searching for a possible link between galactic cosmic rays and cloud formation and ALPHA experiment which studies the difference between hydrogen and anti-hydrogen atoms. .

1.2. CAST

CERN Axion Solar Telescope is an helioscope experiment at CERN which searches for axions and other exotic particles. It was formally approved by CERN in 2000 and started to be built in 2001. The countries participating in the experiment are Canada, Croatia, Denmark, France, Germany, Greece, Italy, Russia, South Korea, Russia, Spain, Switzerland, Turkey and the USA.



Figure 1.1. CAST magnet in the experiment area at CERN. Image is taken from [3].

CAST uses a decommissioned LHC-dipole test magnet mounted on a moving platform that can track the Sun, see Figure 1.1. The magnet is 9.26 meters long and has two magnet bores with 43 mm aperture. It is cryogenically cooled to 1.7K by super-fluid helium and has a 9 Tesla magnetic field. The magnet platform can rotate ± 40 degrees horizontally and ± 8 degrees vertically. The movement is controlled by a designated slow control software [4].

The experiment aims to detect solar and relic axions as well as solar chameleons. In order to achieve this, it utilizes position sensitive micromegas detectors, imaging CCD cameras, an X-ray telescope and a opto-mechanical sensor attached on the magnet bore openings on both sides of the magnet.

It uses the principle of Primakoff conversion [5] of axions and chameleons into photons in high magnetic fields. The helioscope with its 9.2 meters length provides the necessary coherence length for axion-to-photon conversion. Refractive gases such as Helium can also be added to the magnetic pipes in order to increase the detection sensitivity and to scan different axion masses versus axion couplings.

The experiment also uses direct coupling of chameleons to matter for detection. Opto-mechanical force sensor is used to detect the 'radiation pressure' of the incoming chameleon flux.

1.3. Dark Matter and the Axion Particle

There is a missing 21 percent of the matter-energy density contribution for the content of the universe which contributes to the observed behaviours of the galaxy rotation curves [6], early universe structure formation [7] and cosmic microwave background [8]. The proposed matter is only observed so far through its gravitational effects, hence it is named as 'dark matter'. One of the most promising candidates for dark matter is the axion particle. Axions are thought to be produced early in the universe by the vacuum realignment mechanism and radiation from cosmic strings which leads to Cold Dark Matter and by thermal interactions leading to Hot Dark Matter [9, 10].

Axions have initially been proposed to solve the strong CP (Charge-Parity) problem [11, 12]. It is about the problem of why the angle θ parameter in QCD should be nearly zero ($\theta \lesssim 10^{-10}$) despite the presence of CP violation in Standard Model. Peccei-Quinn mechanism is proposed to solve this problem providing a possible explanation for the absence of measurable CP violating effects such as large neutron electric dipole moment [13–15]. Axion is the pseudo Nambu-Goldstone boson from Peccei-Quinn solution to the strong CP problem where θ is treated as a dynamical parameter. Due to their extremely weak interactions and significant abundance in the early universe, they are regarded as excellent candidates for dark matter.

One of the mechanisms that produces axions is the Primakoff process where photons in high electromagnetic field are converted into axions [5]. A promising candidate for such an axion source near the Earth is the Sun. Axions can be produced in the high temperature, high-EM-field plasma environment in the Sun by scattering in the Coulomb field of charged particles and then reach the Earth.

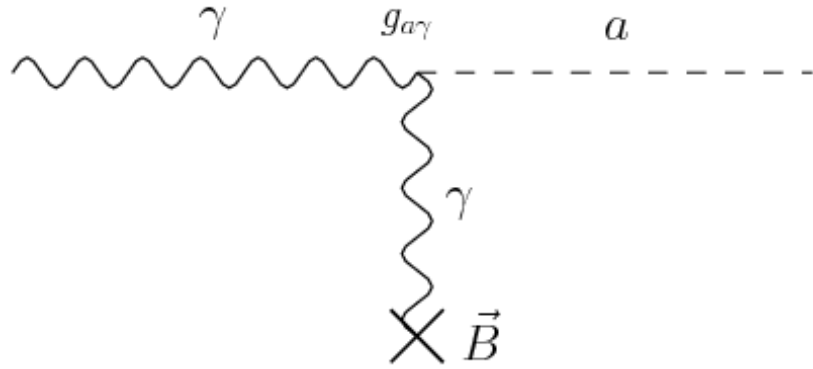


Figure 1.2. Feynman diagram describing the Primakoff process; conversion of a photon into an axion particle in a magnetic field, $\vec{B}$.

The detection principle for the incoming axions is to couple them with the virtual photons provided by the transverse field of a dipole magnet, hence converting them into photons that can be detected by detectors, see Figure 1.2. This principle is described by the Lagrangian density of the interaction:

$$\mathcal{L} = -\frac{1}{4}g_{a\gamma}F^{\mu\nu}\tilde{F}_{\mu\nu}a = g_{a\gamma}\vec{E} \cdot \vec{B}a$$

where $g_{a\gamma}$ is the axion-photon coupling, $F^{\mu\nu}$ is the EM field tensor, $\vec{E}$ is the electric and $\vec{B}$ is the magnetic field (with natural units $\hbar = c = 1$).

Axion to photon conversion probability is governed by the equation below and is proportional to the square of the transverse field strength and the length of the magnet.

$$P_{a \rightarrow \gamma} = \left(g_{a\gamma} B \frac{\sin qL/2}{q} \right)^2$$

where $q = m_a^2/2E$ is the $a \rightarrow \gamma$ momentum transfer in vacuum [16].

LHC dipole magnet with 9T magnetic field provides an opportunity to search for these elusive particles. CAST searches for axions through its vacuum configuration with a sensitivity for axions masses $m_a \lesssim 0.02$ eV. The coherence is lost beyond this mass in the magnet and is restored with pumping a low-Z buffer gas into the pipes matching the refractive mass of the photon to axion mass. This provides a way to scan different axion masses by incrementally changing the pressure of the gas in the magnet.

1.4. Dark Energy and the Chameleon Particle

Modern cosmology describes the universe by Λ CDM Model which incorporates General Relativity (GR), cosmological constant (Λ) and Cold Dark Matter (CDM). The expansion of the universe is found to be accelerating by using the supernova observations in 1998 [17, 18]. This has required a mechanism for such an acceleration reviving the discussion of cosmological constant. 70% percent of the matter-energy density is missing to account for the accelerated expansion of the universe and it is therefore named as “dark energy”.

Light scalar fields are proposed as the possible driving mechanisms for this accelerated expansion. However in order for these models to be also compatible with the General Relativity (GR) tests in the Solar System, they need to be screened. One of the solutions for this problem is the chameleon mechanism which renders an effective mass to the field depending on the local matter density. Gravitationally coupled scalar field

ϕ is introduced by modifying GR and this field provides the scalar particle chameleon which is a candidate particle for unknown dark energy. They couple to both matter β_m and photons β_γ .

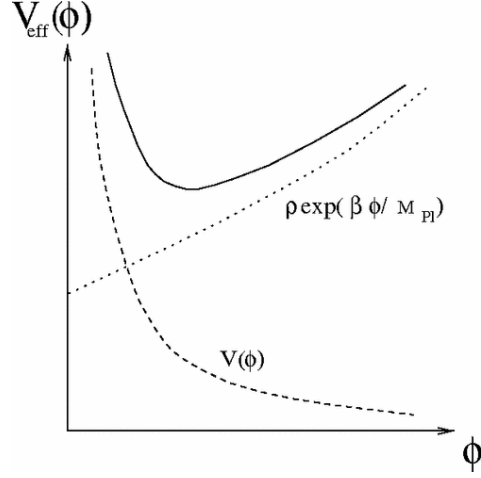


Figure 1.3. Chameleon effective potential V_{eff} (solid line) plotted as a sum of scalar potential $V(\phi)$ (dashed curve) and density dependent term (dotted curve) [19]

Chameleons can be produced in the Sun in its high magnetic fields. There are two regions of interest for this production: core of the Sun and the interior region called tachocline. Like axions, interacting with the nuclear Coulomb field of the plasma at the Solar core can give rise to chameleon particles. Alternatively, in the inner regions of the Sun about 0.7 Solar radius away from the core, high transverse magnetic field is produced due to shearing effects, giving rise to production of chameleons [20, 21]. This region is called tachocline. The spectrum of the solar chameleons is given in Figure 1.4 and mechanism of production is discussed in detail in [22, 23].

Chameleons can be detected by the Primakoff conversion in the high transverse magnetic fields produced in the dipole magnet of CAST. Particles coupling to virtual photons in the field convert into photons, which can be detected at the end of the tube by photon detectors. CAST uses SDD (silicon drift detector) and InGRID (Integrated Grid) micromegas detectors for such purpose.

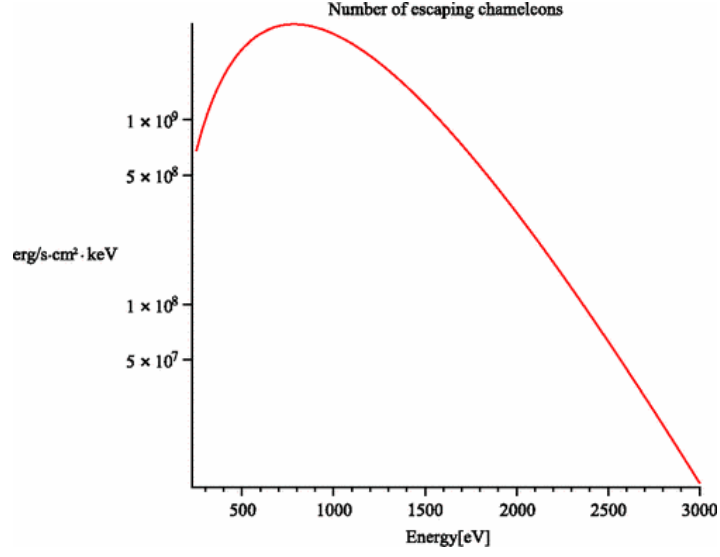


Figure 1.4. The energy spectrum of the emitted chameleons from the Sun. [23]

Chameleons can also be detected through their interaction with matter. They acquire an effective mass scaled with the local matter density ρ_m

$$m_{eff} = \rho_m^{\frac{n+2}{2(n+1)}} \quad (1.1)$$

where n is the model parameter (see Figure 1.3 for the plot of chameleon field.). When they reach a dense slab of material if they happen to have an effective mass bigger than their total energy, they get reflected. This reflection causes a momentum transfer, hence a force that can be sensed by a detector.

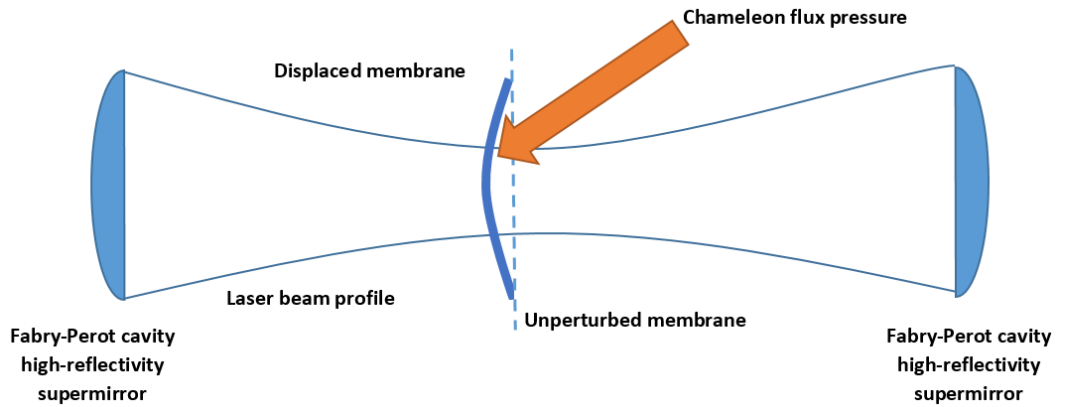


Figure 1.5. Schematic showing the detection mechanism of force detector KWISP to detect chameleon particles.

CAST uses a thick Si_3N_4 membrane and an optical Fabry-Perot (FP) resonator in order to sense the minute radiation pressure exerted by the reflected chameleons coming from the Sun with the KWISP (Kinetic Weakly Interacting sub-eV Particle-WISP Detection) detector (Figure 1.5). CAST magnet tracks the Sun while the chameleon beam from the Sun is focused on the membrane using the X-ray telescope using the grazing incidence. A membrane is placed in the Fabry-Perot cavity consisting of two high reflecting mirrors facing each other and an IR laser beam is locked to the cavity. The position of the membrane is such that it is at the node of the standing wave in the cavity. The chameleon flux is reflected from the membrane, disturbing the position of it and the change in the characteristic frequency of the wave is sensed by the electronic control software. This mechanism allows to sense tiny forces of the order of 10^{-14} N.

2. HISTORY OF AXION AND CHAMELEON SEARCH IN CAST

CAST helioscope took data for axion and chameleon searches between 2003 and 2015. It started with the “Vacuum Phase” during which the inside of the magnet was set to be in vacuum conditions. Afterwards, in order to scan different mass ranges, low-Z buffer gasses (^3He and ^4He) were pumped into the magnet bores to restore the coherence for different masses of axions by providing an effective mass to the photons. The details of and results from each phase are discussed in this chapter.

2.1. Phase I with Vacuum

CAST started its first data taking with vacuum conditions in the magnet. There were three X-ray detectors on the magnet; two Time Projection Chamber (TPC) detectors on the sunset side and micromegas and CCD detector on the sunrise side. The magnet was sensitive to axion masses up to 0.02 eV. Data were collected for tracking and background between 2003 and 2004. With the absence of a signal, upper bound was put to axion-photon coupling $g_{a\gamma} \lesssim 0.88 \times 10^{-11} \text{ GeV}^{-1}$ [24] (see Figure 2.1).

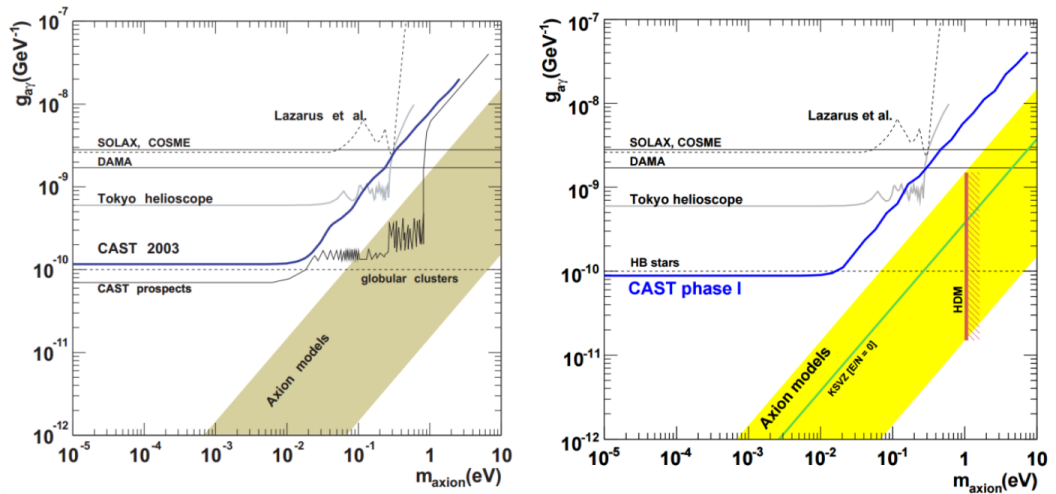


Figure 2.1. Exclusion plots showing the CAST’s first results on the left [24], and improved results on the right [25] with other experimental limits.

2.2. Phase II with ^4He

After the vacuum phase, CAST magnet was filled with ^4He buffer gas in order to scan different mass ranges for the axion, extending up to 0.4 eV. The limiting factor for these searches is the momentum difference between freely propagating photons and axions caused by the axion mass m_a . It limits the magnetic field volume over which the conversion is coherent. The search can be extended to larger m_a values by providing the photons with a refractive mass [26, 27]. TPCs were replaced with new generation Micromegas detectors, enhancing the detection capability. 300 hours of tracking data were taken between the end of 2005 and 2006.

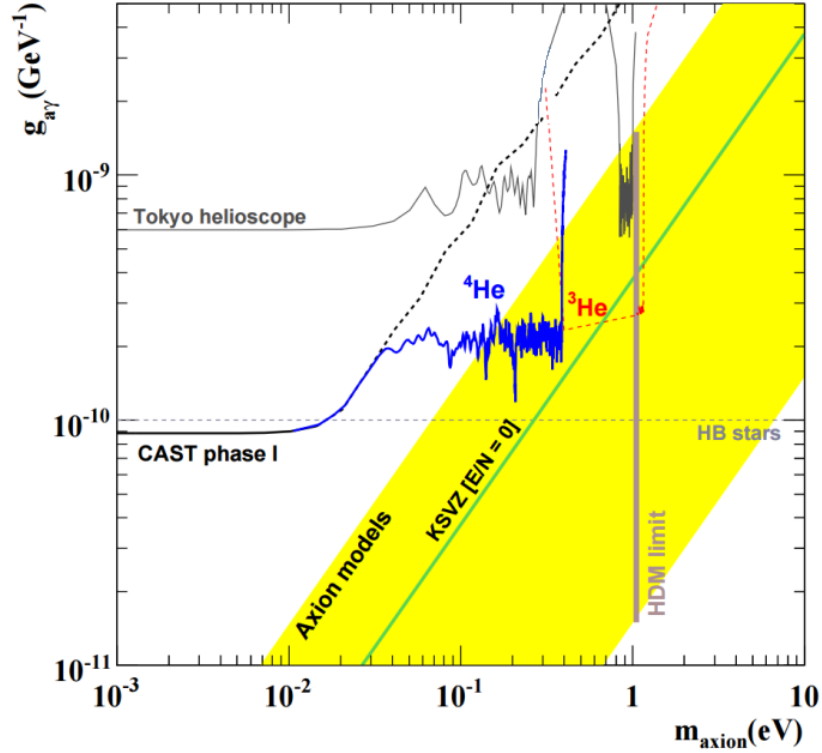


Figure 2.2. Results from [28] showing the CAST limit with ^4He Run with other experimental and observational limits. The yellow band represents typical theoretical models with $|E/N - 1.95| = 0.07 - 7$. The green solid line corresponds to KSVZ model (E and N are respectively electric and color anomaly of the axial current associated with the axion field, $E/N = 0$ for the KSVZ model [29, 30])

By changing the pressure of the buffer gas, one can scan an entire range of given axion mass values. Covering 160 pressure settings (0-13.4 mbar) it was possible to scan the mass range of 0.02 - 0.39 eV. As a result, mean upper limit for the axion-photon coupling was provided as $2.17 \times 10^{-10} \text{ GeV}^{-1}$ [26] where CAST reached the QCD axion band for the first time (see Figure 2.2).

2.3. Phase II with ^3He

In order to extend the mass scan range beyond 0.39 eV, the magnet bores were filled with ^3He buffer gas allowing to reach axion masses up to 1.15 eV. In the first part of data taking in 2008, the pressure was varied to scan the range $0.39 \lesssim m_a \lesssim 0.64 \text{ eV}$. The average lower limit coupling constant $g_{a\gamma}$ was found to be $2.27 \times 10^{-10} \text{ GeV}^{-1}$ [31]. In the second data taking period (2009-2011), 1100 hours of data were collected. The pressure was varied in 418 steps for effective axion mass range $0.64 \lesssim m_a \lesssim 1.17 \text{ eV}$. Average lower limit for the axion-photon coupling was reported as $3.3 \times 10^{-10} \text{ GeV}^{-1}$ [32]. The limit contour in the Figure 2.3 has high statistical fluctuations due to few hours of data for each specific mass point. This search range also coincides with current cosmic hot dark matter bound of $m_a \lesssim 0.9 \text{ eV}$.

2.4. Phase III with ^4He

In 2012, data were taken with ^4He buffer gas which provided a chance to revisit the theoretically motivated masses around 0.2 eV and 0.4 eV (KSVZ line crossing). On the sunset side, new micromegas detectors were installed with improved shielding, providing increased sensitivity and reduction in background levels. At each pressure setting, 7.5 hours of data per detector (5 solar tracking) were collected in order to reduce the statistical fluctuations on the resulting limit.

As a result, for the range $0.39 \lesssim m_a \lesssim 0.42 \text{ eV}$, the average limit on axion-photon coupling was found to be $g_{a\gamma} \lesssim 1.47 \times 10^{-11} \text{ GeV}^{-1}$ and for 0.2 eV $g_{a\gamma} \lesssim 1.40 \times 10^{-11} \text{ GeV}^{-1}$ [33].

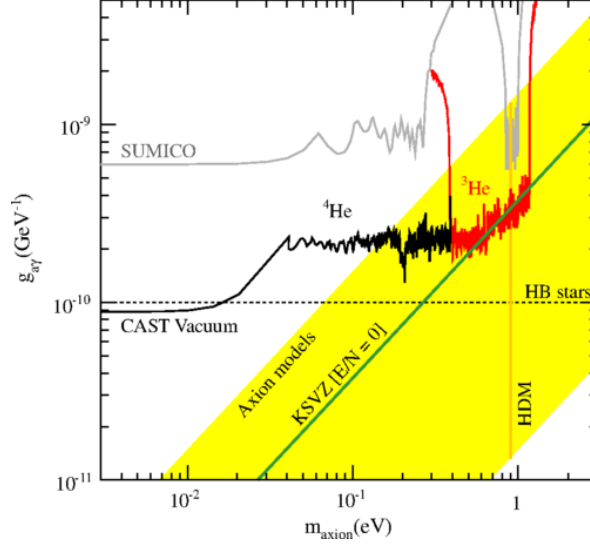


Figure 2.3. Exclusion regions in the $m_a - g_{a\gamma}$ plane achieved by CAST, previous results shown in black, and ^3He results in red. The yellow band represents typical theoretical models with $|E/N - 1.95| = 0.07 - 7$. The green solid line corresponds to $E/N = 0$ (the KSVZ model) [26].

2.5. Phase IV with Vacuum

Between 2013 - 2015, new sub-keV detectors (Ingrid and SDD) and a new XRT telescope were installed on the magnet. Background sensitivity was improved up to $10^{-6} \text{ keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. Data were taken with evacuated pipes. As a result, for axion masses $m_a \lesssim 0.02 \text{ eV}$, average axion-photon coupling was found to be $g_{a\gamma} \lesssim 0.66 \times 10^{-11} \text{ GeV}^{-1}$ [26].

2.6. Phase V - Chameleon Search

In addition to the search for axions, CAST has also a program to search for chameleon particles. Chameleons are thought to be produced in the tachocline region in the Sun at a distance of around $0.7 R_\odot$ from the center in high magnetic fields via Primakoff conversion of photons. They have nonlinear self interactions both with photons and matter given by interaction parameters β_γ and β_m respectively. They gain an effective mass which depends on the ambient mass(energy) density ρ . The parameter

space of the chameleons are characterized by three parameters, β_γ , β_m and dark energy model parameter n . Chameleons travel from Sun to the Earth with negligible loss of flux and arrive at the CAST magnet.

In 2013 CAST was reconfigured creating a vacuum line in the magnet. Similar to the axions, chameleons are expected to be converted into X-rays in the CAST magnet and be detected by the detectors at the ends of the magnet. The spectrum of the chameleon flux is estimated to have a peak around 600 eV, thus sub-keV sensitive X-ray SDD was installed on the sunrise side of the magnet.

Data were taken for a total of 108 hours (tracking and background). There was no excess over background which provide a limit for the chameleon coupling strength to photons $\beta_\gamma \lesssim 9.26 \times 10^{10}$ at 95% CL. Considering the various astrophysical parameters for the tachocline model, the limit $\beta_\gamma \lesssim 10^{11}$ was reported (see Figure 2.4) [34].

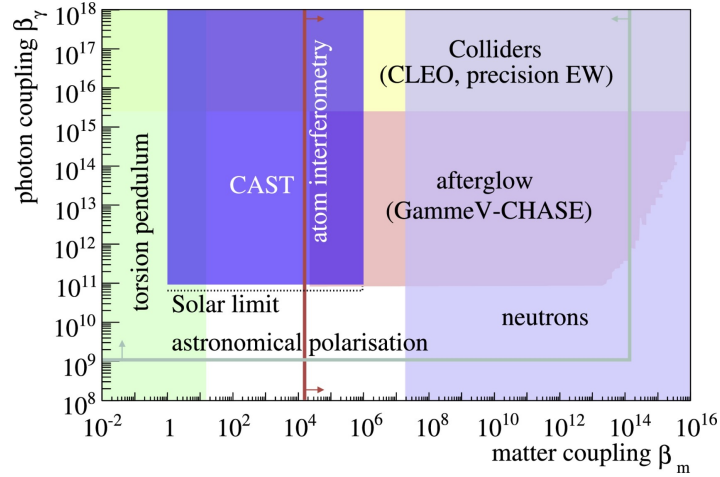


Figure 2.4. Exclusion plot for chameleons $\beta_\gamma - \beta_m$ plane achieved by CAST [34] and other experiments.

3. THEORY

In this chapter, the case for the the dark energy and the theory behind chameleon fields will be discussed. Starting with the Λ CDM model, Type Ia supernova observations and baryon acoustic oscillation measurements combining with the CMB which are considered as a significant evidence for the dark energy will be introduced. Then the chameleon field which has been proposed for dark energy will be discussed in detail. Finally, interaction of the chameleon field with matter and detection methods will be explained.

3.1. Λ CDM Cosmology

In modern cosmology the universe is defined as spatially homogeneous and isotropic on large scales. The matter-energy content is assumed to be distributed uniformly and independent of any direction on cosmological distance scales, on the order of 100 Megaparsec (Mpc) (1 Mpc $\sim$ 3,26 million light years). This assumption is verified by several observations of cosmic microwave background (CMB) and large scale structures to a high degree of precision [7, 8, 35].

The cosmological principle is encoded in the Friedman-Robertson-Walker (FRW) metric as:

$$ds^2 = -dt^2 + a(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right] \quad (3.1)$$

where ds is the line element, dt is cosmological time, r, θ, ϕ are spherical coordinates, $a(t)$ is the scale factor, a dimensionless parameter characterizing the expansion of the universe. k is the curvature term which can take values of 0, +1 and -1 which corresponds to flat, closed and open geometry for the universe respectively [36].

The physics of the universe in grand scales is based on Einstein's General Relativity which defines the relationship between the matter-energy content and the geometry

of the universe. The gravity is formulated by the Einstein-Hilbert Lagrangian:

$$\mathcal{L} = \frac{1}{16\pi G}(R + L_m)\sqrt{-g} \quad (3.2)$$

where R is the Ricci scalar, G is the Newton's constant, L_m represents the matter field and $g = |g_{\mu\nu}|$ is the determinant of the metric tensor.

Combining the symmetric FRW metric (3.1) and (3.2) gives the following result to Einstein's equations:

$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \quad (3.3)$$

$$\frac{\ddot{a}}{\dot{a}} = -\frac{4\pi G}{3}(\rho + 3P) \quad (3.4)$$

where dots represent time derivatives, H is the Hubble constant, ρ is the energy density of the universe and P is pressure. Energy-momentum tensor conservation leads to the continuity equation which relates the time evolution of the density with the pressure:

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = 0 \quad (3.5)$$

In order to solve for the equations (3.3), (3.4) and (3.5), we need an extra assumption regarding the relationship between P and ρ which is called the barotropic equation of state assumption where the proportionality of P and ρ is constant (ω).

$$P = \omega\rho \quad (3.6)$$

where ω takes values below for different constituents:

$$\omega = \begin{cases} 1/3, & \text{for radiation or relativistic matter} \\ 0, & \text{for dust} \\ 1, & \text{for stiff fluid} \\ -1, & \text{for cosmological constant.} \end{cases} \quad (3.7)$$

The density parameter Ω is defined by combining the different contributions from radiation, matter, and cosmological constant using (3.3):

$$1 + \frac{k}{a^2 H^2} = \Omega \quad (3.8)$$

where

$$\Omega = \Omega_R + \Omega_M + \Omega_\Lambda \quad (3.9)$$

Ω_R is the contribution from the radiation, dominated by the CMB, Ω_M is the matter contribution and Ω_Λ is the cosmological constant contribution. Density parameter determines the geometry of the universe since different values for Ω_M and Ω_Λ leads to different value for k . If $\Omega > 1$, then $k > 0$ and this gives a closed universe. If $\Omega < 1$, then $k < 0$ and this gives an open universe. For $\Omega = 1$, $k = 0$ at the critical value which gives a flat universe [37].

Different ω values for each of the constituents cause variable contributions throughout the evolution of the universe defined by epochs. Redshift parameter (z) is used to characterize the time and it is defined as:

$$1 + z \equiv a_0/a(t) \quad (3.10)$$

In the very early times, just after the Big Bang, the universe was hot and it was dominated by photons, electrons, neutrinos and other particles with high kinetic energies

($\omega = 1/3$). The universe cooled down and matter density started to dominate the radiation after $z = 3200$. Matter filled with dust contributed effectively no pressure for the expansion in this epoch $3200 \gtrsim z \gtrsim 1/2$ ($\omega = 0$). The dominant component of this epoch is defined as “Cold Dark Matter” (CDM) which consists of dark matter. The dark matter does not emit light and it is thought to be weakly interacting [36]. Although its effects are well characterized in terms of cosmological and astrophysical aspects, the nature of dark matter is still unknown. Weakly Interacting Massive Particles (WIMPs) and axions which are also searched by CAST Experiment are strong candidates for the dark matter.

After $z \sim 1/2$ the cosmological constant dominates the expansion of the universe with its negative pressure. This gives rise to the acceleration of the expansion. This accelerated expansion is proposed to be due to a new fundamental field which is called “dark energy” that induces a cosmological constant. Dark energy does not emit light and behaves as a transparent media that gravitates with an effective negative pressure [36]. Observations of Type Ia supernova and baryon acoustic oscillations in CMB provides evidence for such an accelerated expansion.

3.2. Type Ia supernova and acceleration of the universe

Distance to the objects in astronomy is an important parameter for models and measuring it is generally tricky. Sources with known intrinsic luminosities are used as ‘standard candles’ to infer the distance to the object from its observed brightness. One of the common used sources for this purpose are Type Ia supernovae. These supernovae are the explosion events of white dwarf stars coming to an instability at more or less the same mass value. This common mechanism for these events provide particular characteristic features such a similar peak brightness and intrinsic luminosities. Using the fact that they are very powerful explosions ($\approx 10^{44}$ Joules) and can be observed from very far distances, they provide a good tool to probe the conditions at distant times of the universe [38].

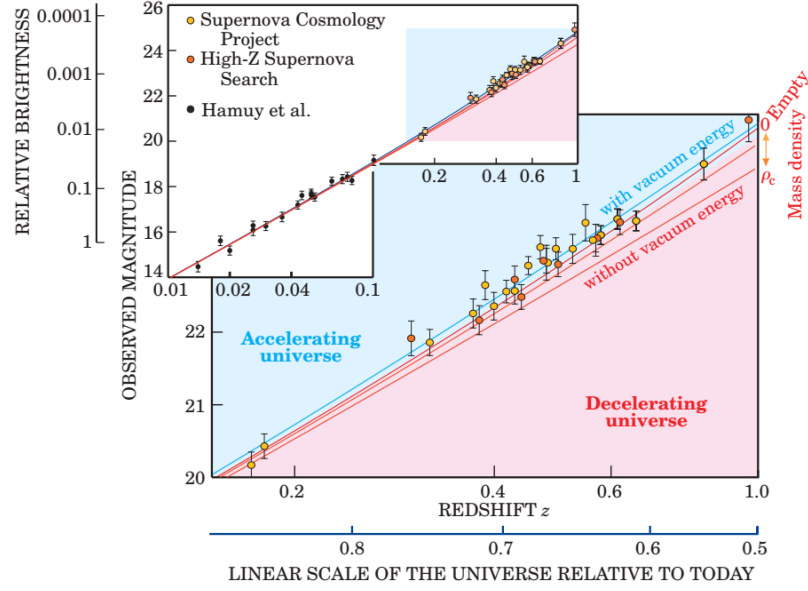


Figure 3.1. Type Ia supernova explosions are plotted with their distance (redshift z) and their observed brightness (upper left in full scale and beneath it the details). For distance supernovas (high z), the brightness is lower than expected due to the model without vacuum energy. High z supernovas have better fit with the model with vacuum energy [38].

Teams of astronomers have been observing Type Ia supernovae since the 1930s and trying to find the relation between the luminosity distance which is found from their peak brightness and redshift which is measured from their spectra. The relationship between these variables is known as the Hubble's Law. For nearby supernovae ($z < 0.1$) this relationship is linear. If the expansion rate of the universe changes over time, for large distances the relationship is expected to deviate from linearity. Two teams in 1998, Supernova Cosmology Project led by S. Perlmutter [17] and High- z Supernova Search team led by B. Schmidt and A. Riess [18] found out that distant Type Ia supernovae deviate from the relationship having fainter brightnesses than expected (see Figure 3.1). Since the relationship tells about the expansion and the matter-energy content of the universe, this result completely changes the expansion history. Fainter supernova indicates that larger light travel times, larger distances. This can only happen if the expansion of the universe accelerates, so that the light from a supernova from a distant galaxy reaches us in longer time than expected. S. Perlmutter, B.

Schmidt and A. Reiss received Nobel Prize for their discovery in 2011.

In accelerated universe, the universe was expanding more slowly in the past compared to now. The mechanism proposed to account for this accelerated expansion is the ‘dark energy’. The supernova observations indicate that the dark energy density is 70% while the matter density is 30% of the total energy-matter density of the universe.

3.3. Baryon Acoustic Oscillations and CMB

The universe was filled with high energy radiation and matter in a plasma state after the Big Bang. As the universe expands, both the radiation and the matter cools down and starts to form neutral hydrogen atoms in a period called recombination (approximately 380,000 years after the Big Bang). After this process the matter could no more absorb the thermal radiation so that the radiation becomes free, the universe becomes transparent. An afterglow of this event is the Cosmic Microwave Background (CMB) radiation which can be observed now in the microwave band and gives clues to the conditions about the early universe [37].

In early periods, the plasma containing baryonic matter and radiation contracts and expands due to gravitation and the resulting pressure which creates higher and lower density regions. These density variations lead to galaxy formation in the high density environments as the universe continues to expand. Contraction and expansion of the plasma create acoustic waves which leave imprints on the CMB radiation [39]. By measuring these density variations in the CMB and comparing the galaxy clustering tendencies in different times of the universe by observations, distances predicted by different models can be compared.

CMB and big galaxy surveys provide an opportunity to compare these distances. Spectrum of the correlation functions of the galaxies which measures the likelihood that two galaxies will be a distance apart and comparing it with the sound horizon from the CMB indicates that the expansion of the universe is accelerating [40].

3.4. Chameleon Mechanism

The simplest candidate for the dark energy component of the universe is the cosmological constant Λ which was introduced by Einstein. It was introduced to have a static universe in the framework of GR and its energy density remains constant in time. However, after the observations of expansion of the universe, Einstein abandoned this term in the Einstein equations. It was revived after the cosmic acceleration observations which were discussed in previous sections as an explanation for dark energy. From particle physics view, cosmological constant appears as vacuum energy density. If zero-point energies of all normal modes of some field is summed up, the vacuum energy is estimated to be 10^{120} times bigger than the observed value [41]. If the cosmological constant is the mechanism behind dark energy, this discrepancy should be explained.

There are also other alternative dark energy models which approach this problem by introducing new fields. In these kind of models, dark energy is generally modelled with a scalar field. For instance, these fields may couple with matter in the case of dilatons which arise in string theory. They should induce detectable effects due to their coupling to matter which can be measured on Earth. These effects, named as a ‘fifth force’ have not been observed yet. Furthermore, the proposed scalar fields have tight constraints due to tests of equivalence principle. So there needs to be a mechanism to screen the effects of such a scalar field in a high matter abundance environment such as the Solar System and also to evade the equivalence principle (EP) constraints. Chameleon field was put forward to provide this screening mechanism while acting as a quintessence, and having a negative pressure to drive the accelerated expansion of the universe.

The main idea of the mechanism is that the field can couple directly to baryons with gravitational strength and acquires mass proportional to the local matter density of the medium. In the case of high density environments such as the Earth and the Solar system, mass is large thus the effects of fifth force and EP violations are suppressed. In the cosmological case where the density is low, the mass of the field is also low.

Behaviour of the model is determined by the combination of a runaway potential and contributions that each depend on density [42].

$$V_{eff}(\phi) = V(\phi) + \sum_i e^{\beta_i \phi / M_{Pl}} \rho_i \quad (3.11)$$

The first part arises from the self-interactions which is generally described by a monotonically decreasing function. The second part which is in an exponential form arises from the conformal coupling to matter fields. These two parts are both monotonic functions of ϕ but their sum which gives an effective potential V_{eff} has a minimum at ϕ_c where

$$V_{,\phi}^{eff}(\phi_{min}) = 0 \quad (3.12)$$

The mass of the perturbations around the minimum is given by:

$$m_c^2 = V_{,\phi\phi}^{eff} \quad (3.13)$$

where $V_{,\phi}^{eff}$ and $m_c^2 = V_{,\phi\phi}^{eff}$ are the first and second derivative with respect to field ϕ . The effective potential, the value at the minimum and effective mass of the perturbations around this minimum all directly depend on the density (see Figure 3.2).

Action governing the dynamics is given by

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2}{2} R - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right\} - \int d^4x \sqrt{-g} \mathcal{L}_m(\psi_m^{(i)}, g_{\mu\nu}^{(i)}) \quad (3.14)$$

where $M_{Pl} = (8\pi G)^{-1/2}$ is the reduced Planck mass, g is the determinant of the metric tensor, R is the Ricci scalar and $\psi_m^{(i)}$ s are the matter fields (in natural units where $\hbar = c = 1$) [43].

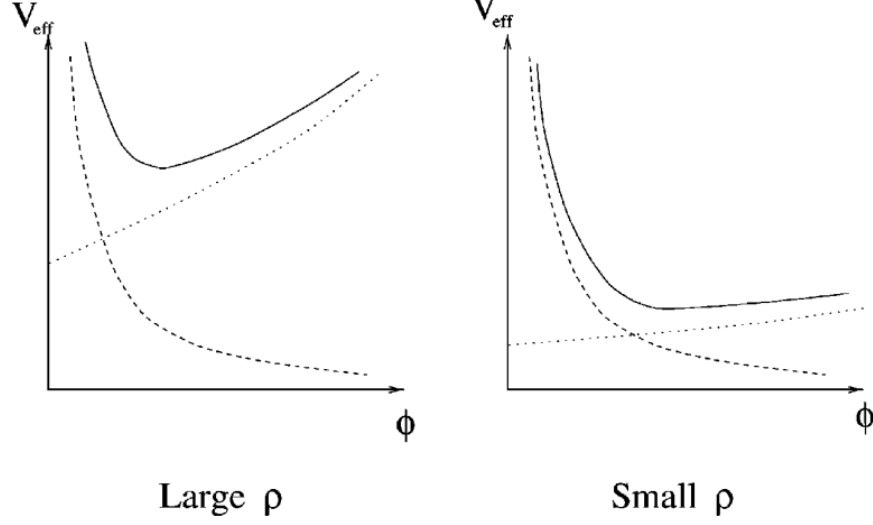


Figure 3.2. Two monotonic functions of $V(\phi)$ (dashed line), $\rho e^{(\beta\phi/M_{Pl})}$ (dotted line) and their sum (solid line) are plotted in both figures. On the left, for higher ρ , effective potential has higher minimum and also higher effective mass than on the right. The figure is adopted from [19].

The scalar field ϕ directly interacts with the matter with conformal coupling of the form $e^{\beta_m\phi/M_{Pl}}$

$$g_{\mu\nu}^{(i)} = e^{2\beta_i\phi/M_{Pl}} g_{\mu\nu} \quad (3.15)$$

and the potential is generally assumed to be a runaway potential with the following conditions:

$$\begin{array}{lll} \lim_{\phi \rightarrow \infty} V = 0 & \lim_{\phi \rightarrow \infty} \frac{V_{,\phi}}{V} = 0 & \lim_{\phi \rightarrow \infty} \frac{V_{,\phi\phi}}{V_{,\phi}} = 0 \\ \lim_{\phi \rightarrow 0} V = \infty & \lim_{\phi \rightarrow 0} \frac{V_{,\phi}}{V} = \infty & \lim_{\phi \rightarrow 0} \frac{V_{,\phi\phi}}{V_{,\phi}} = \infty \end{array}$$

The potential is chosen with the above conditions as:

$$V(\phi) = \frac{M^{4+n}}{\phi^n}, \quad n > 0 \quad (3.16)$$

where M is the mass scale and n is the model parameter. The equation of motion can be found by taking the variation of the action (3.14) with respect to the field ϕ :

$$\nabla^2 \phi = V_{,\phi} + \sum_i \frac{\beta_i}{M_{Pl}} \rho_i e^{\frac{\beta_i \phi}{M_{Pl}}} \quad (3.17)$$

From above, an effective potential can be defined as:

$$V_{eff} = V(\phi) + \sum_i \rho_i e^{\frac{\beta_i \phi}{M_{Pl}}} = \frac{M^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_{Pl}} \phi} \rho_m + e^{\frac{\beta_\gamma}{M_{Pl}} \phi} \rho_\gamma \quad (3.18)$$

V_{eff} has a minimum at ϕ_{min} and the minimum of the potential can be found by taking the derivative of (3.18) with respect to ϕ .

$$V_{,\phi}(\phi_{min}) + \sum_i \frac{\beta_i}{M_{Pl}} \rho_i e^{\frac{\beta_i \phi_{min}}{M_{Pl}}} = 0 \quad (3.19)$$

The value of the field at the minimum of the effective potential is given by

$$\phi_{min} = \left(\frac{n M^{4+n} M_{Pl}}{\beta_m \rho_m} \right)^{\frac{1}{n+1}} \quad \text{where } \rho_\gamma \ll \rho_m \quad (3.20)$$

The mass of the small perturbations around the minimum can be found by (3.12):

$$V_{,\phi\phi}^{eff} = n(n+1) \frac{M^{4+n}}{\phi^{n+2}} + \left(\frac{\beta_m}{M_{Pl}} \right)^2 e^{\frac{\beta_m}{M_{Pl}} \phi} \rho_m + \left(\frac{\beta_\gamma}{M_{Pl}} \right)^2 e^{\frac{\beta_\gamma}{M_{Pl}} \phi} \rho_\gamma \quad (3.21)$$

Assuming β_m/M_{Pl} , $\beta_\gamma/M_{Pl} \ll \phi^{-1}$ and ignoring the quadratic $\left(\frac{\beta_\gamma}{M_{Pl}} \right)^2$ terms, we get:

$$V_{,\phi\phi}^{eff} \approx n(n+1) \frac{M^{4+n}}{\phi^{n+2}} \quad (3.22)$$

Using the value of ϕ at minimum (3.20) gives:

$$m_{eff}^2 = (n+1) \frac{\beta_m \rho_m}{M_{Pl}} \frac{1}{\phi_{min}} \propto \rho_m^{\frac{n+2}{n+1}} \quad (3.23)$$

3.5. Chameleon Detection on Earth

The model for the chameleon mass is considered as follows [44]. Consider the chameleon field outside a thick planar slab of material with density $\rho(x) = \rho_m$ for $x < 0$ and $\rho(x) = 0$ for $x \geq 0$. The static field profile and the mass at $x \geq 0$ can be found by:

$$\phi_S = (1 + 1/n)\phi_{min}(\rho_m) \quad (3.24)$$

$$m_S^2 = n(n+1)\frac{\Lambda^{4+n}}{\phi_S^{n+2}} \quad (3.25)$$

$$\phi_0^2 = \phi_S \left(1 + \frac{(n+2)m_S x}{\sqrt{2n(n+1)}} \right)^{\frac{2}{n+2}} \quad (3.26)$$

$$m_0(x) = m_S \left(1 + \frac{(n+2)m_S x}{\sqrt{2n(n+1)}} \right)^{-1} \quad (3.27)$$

where ϕ_S and m_S represents the field and the mass on the surface of the slab at $x = 0$. Meanwhile at $x < 0$, ϕ_0 and m_0 approach $\phi_{min}(\rho_m)$ and $m(\phi_{min}(\rho_m))$ respectively over a length scale of order m_s^{-1} .

If the particle energy far from matter is ω , then the particle will be excluded from the region of space where $m_0 > \omega$. Thus an incident particle will reflect from the matter if $\omega < m(\phi_{min}(\rho_m))$ by the conservation of energy.

For the non-zero incidence angle cases it can be generalised by considering a plane of reflection, let's say $x - y$ plane. Since the equation 3.27 is independent of y , the particle momentum in y direction k_y is conserved. So the momentum in the x direction

at large x can be written as

$$k_{x,\infty} = (\omega^2 - k_y^2)^{1/2} \quad (3.28)$$

The particle will reflect if $m_0 > k_{x,\infty}$ at some x . Thus even a chameleon particle with $\omega \gg m_s$ can reflect at grazing incidence if $k_{x,\infty} < m(\phi_{\min}(\rho_m))$.

The chameleons produced in the inner layers of the Sun propagate through space unscathed, reaching the Earth's atmosphere. We treat the atmosphere as a thick planar slab with density $\rho_m = 1.2 \times 10^{-3} \text{ g/cm}^3$. Taking the x direction normal to the Earth's surface, the question is whether the chameleons will be transmitted through the atmosphere without reflection. Given an incident angle $\theta = \arccos k_{x,\infty}/\omega$, the requirement for transmission is $\omega > m(\phi_{\min}(\rho_m))/\cos \theta$. Chameleons at non-zero incident angles θ require greater energies for transmission. Figure 3.3 shows the chameleon effective mass in the atmosphere for different model parameters and also the minimum transmission energy ω for different incident angles.

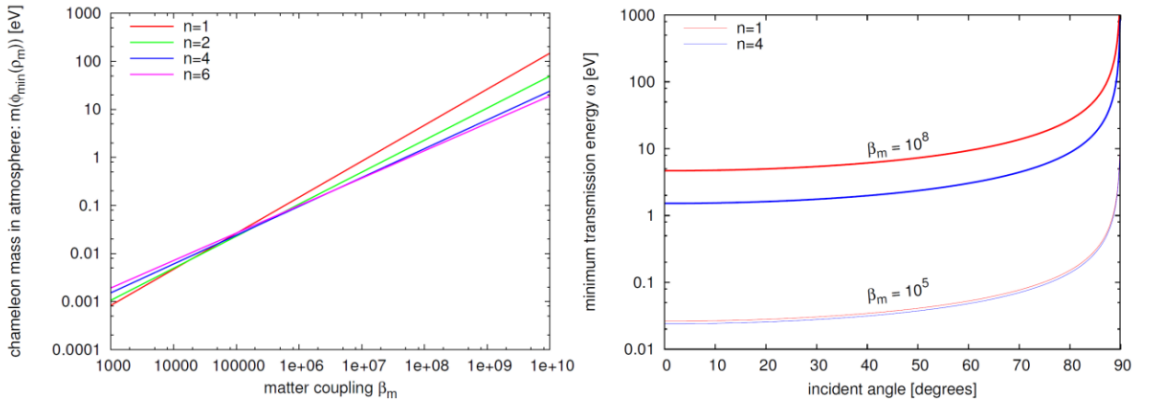


Figure 3.3. Chameleon effective mass in the atmosphere is plotted against different model parameters (left) and the minimum transmission energy in the atmosphere required for the chameleons is plotted against different incident angles (right). The

figure is taken from [44].

After going through the atmosphere, the chameleons arrive at the CAST magnet first encountering the X-ray telescope grazing mirrors (will be discussed in Chapter 4). It is expected that the chameleon beam is reflected from the surface of the grazing mirrors so that they will be focused on the membrane in the cavity. The density of the Ni-coated mirror is taken as $\rho_m \approx 10 \text{ g/cm}^3$. Let the grazing angle be $\epsilon = 90^\circ - \theta$, then the reflection condition $k_{x,\infty} < m(\phi_{\min}(\rho_m))$ becomes $w < m(\phi_{\min}(\rho_m))/\sin \epsilon$. The maximum focused energy for the chameleons is shown in Figure 3.4 for different model parameters. The peak of the solar chameleon spectrum of 600 eV is also indicated on the figure which requires around 0.5° grazing angle. As can be seen from the figure at a grazing angle of 0.5° particles with energies up to 2.5 keV will reflect from the surface. This means that chameleons with energies in the sub-keV range, such as those expected from the Sun's magnetized tachocline can be totally reflected by the mirrors of X-ray telescope.

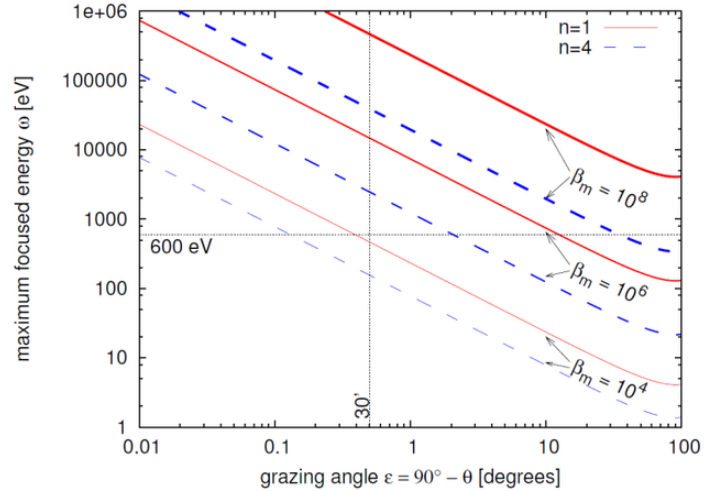


Figure 3.4. Maximum focused energy is plotted against the grazing angle ϵ for different model parameters β_m and n . The dotted horizontal lines indicate the value for the solar chameleon spectrum maximum of 600 eV. The chameleon will be focused by this mirror if $n = 4$ and $\beta_m = 10^6$, but will pass through the mirror if $n = 1$ and $\beta_m = 10^4$. The figure is taken from [44].

After the X-ray telescope mirrors, the chameleon beam hits the surface of the chopper mechanism with a grazing angle. It has a flat surface and is made from aluminum with density of 2.70 gr/cm^3 . The Figure 3.5 shows the maximum reflection

energy for this material for different model parameters. For the orientation of the chopper which is 5° with respect to the chameleon beam, it is possible for the chameleons to pass through the surface if $n = 4$ and $\beta_m = 10^6$, but they will reflect if $n=1$ and $\beta_m = 10^6$.

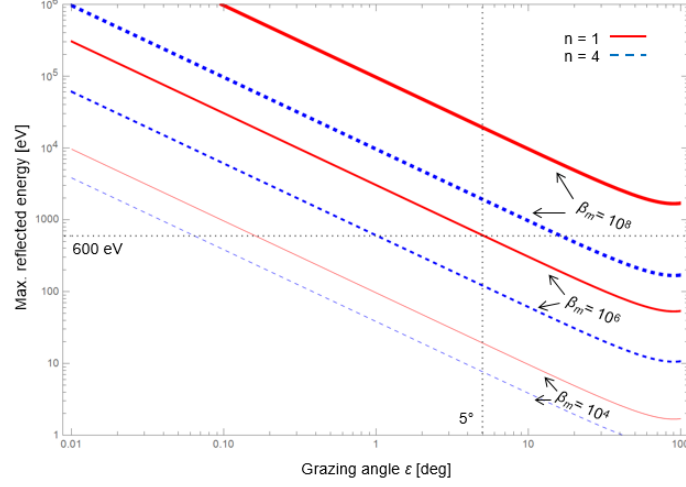


Figure 3.5. Maximum focused energy is plotted against the grazing angle ϵ for different model parameters β_m and n for $\rho_m \approx 2.70 \text{ gr/cm}^3$. The dotted horizontal and vertical lines indicate the value for the solar chameleon spectrum maximum of 600 eV and the orientation of the chopper mechanism which is 5° respectively. The figure is taken from [44].

Interaction of the chameleon beam with the membrane and the detection mechanism with interferometer techniques will be discussed in Chapter 5.

4. CAST EXPERIMENT SETUP

The main setup of CAST experiments involves the dipole magnet and appropriate detectors. Since the particles which are sought after originates from the Sun, there has to be a tracking mechanism attached so that the magnet and the detectors are oriented to the Sun during data taking. In this chapter, the CAST magnet, its control and tracking system will be briefly reviewed. Then the X-ray telescope attached to one of the bore openings of the magnet will be introduced.

4.1. CAST Magnet

CAST uses a decommissioned LHC dipole magnet for searching axions and chameleons from solar origin. It is directed to the Sun with a control system and it can track the Sun for a period of 1.5 hours, at sunrise and sunset. 9.26 meters-length CAST magnet is smaller in length than the standard LHC magnets which are 15 meters. It has two cold bores stretching parallel along the magnet with 42.5 mm apertures. The opening of these bores are used to install the detectors and the X-ray telescope.

Transverse magnetic fields of 9T can be reached within the magnet by supplying high currents of 13000 Amperes. This much current can be supplied by the superconducting wires which are kept at low temperature by liquid helium. The cooling is done by the cryogenic system and it is maintained by a designated team. In order to prevent possible quench (malfunctioning of the cryogenics) and monitor the pressure and temperature of the magnet, various sensors are positioned within the magnet and the cold bores. The temperature of the cold bores are kept at 1.8K in the superconducting state.

20 ton magnet is put on a moving platform that can support the weight and also move the magnet horizontally and vertically (Figure 4.1). The movement of the magnet is restricted only for $\pm 40^\circ$ horizontally and $\pm 8^\circ$ vertically. The movement is controlled by the tracking PC in the control room which sends the calculated angle

positions to the motors and it can also be controlled manually by motor switch box next to the magnet. The magnet position control is important because the magnet has to be directed to the Sun at a high precision, on the order of a degree for tracking. Thus, the position of the magnet is continuously checked by angle encoders and these values are stored for diagnostic and analysis purposes.

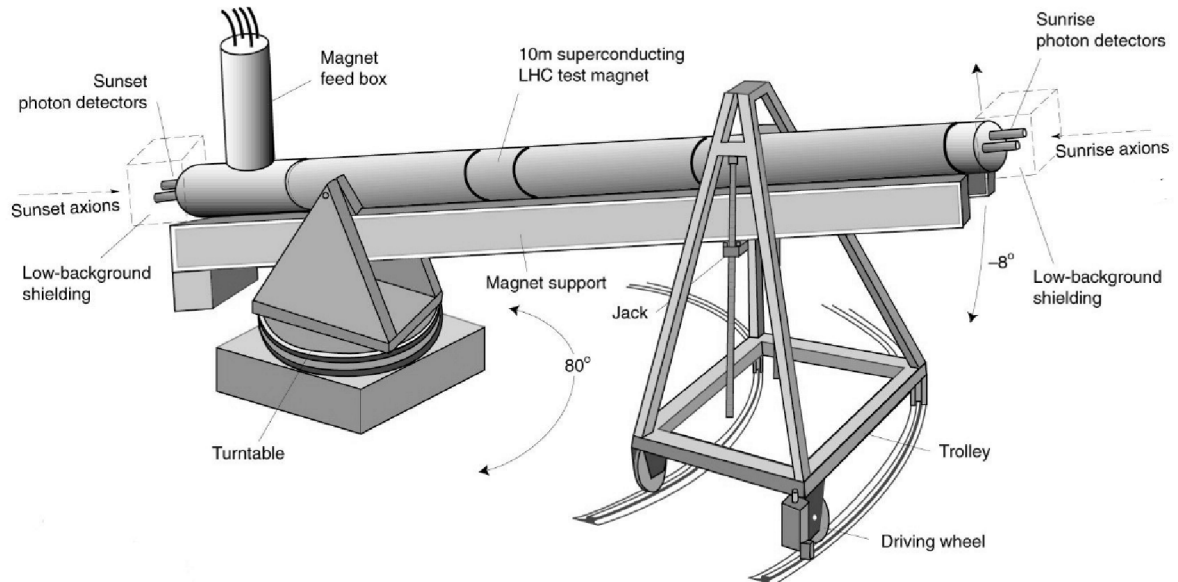


Figure 4.1. Schematic of the moving platform of the CAST magnet. The figure is taken from [45].

The positioning of the magnet is regularly checked with GRID measurements and sun filming. The GRID measurements are done every year with the help of CERN surveyors. They use reflecting devices which are positioned on the magnet and position of the magnet is checked by laser at different angle encoder values. The results are compared with a reference year data and it is made sure that the errors are small. In addition to this, the Sun is filmed with a camera two times a year to make sure that the magnet is looking to the right place. It is possible to do this through a small window in the experiment building and an external camera is put on the magnet and aligned parallel to the magnet axis. The images from the camera are analysed so that the alignment of the magnet is checked.

For the purpose of direct detection of chameleon particles using their matter coupling, the magnet is acting passively just to track the Sun and provide a path for

the chameleons to traverse and interact with the detectors behind the magnet. An X-ray telescope is put on the opening of one of the bores and KWISP detector is oriented with the other bore.

4.2. X-ray Telescope

CAST uses an X-ray Telescope which is attached to one of the bore openings behind the magnet. It is a Walter I type X-ray mirror (Figure 4.2) which is used for focusing the X-rays coming from the axion-to-photon, chameleon-to-photon beams, as well as chameleon beams directly onto a focal plane detector (Figure 4.3). These types of X-ray mirrors are common in the X-ray astronomy missions, e.g. Einstein, Exosat, Rosat, Chandra and XMM-Newton. The X-ray telescope of CAST is a spare module originally commissioned for the X-ray Mission ABRIXAS.

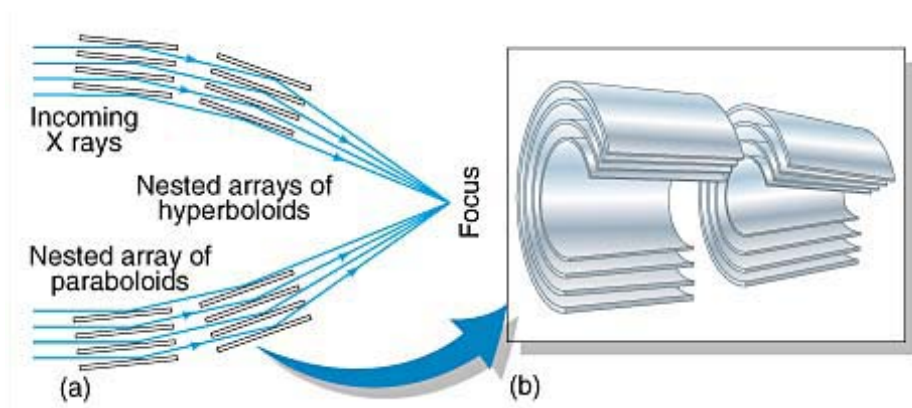


Figure 4.2. Combination of parabolic and hyperbolic mirrors are used to reflect the X-rays (a) and schematic of the mirror shells is depicted in (b). The figure is taken from [46]

The X-ray telescope has 27 nested gold coated and con focally arranged parabolic and hyperbolic nickel shells with a focal length of 1600 mm. The diameters of these shells range between 76-163 mm. It has six sectors of mirrors but since the aperture of the bores of CAST magnet is small with respect to the outer shell diameter, only one of the sector is used for imaging by mounting the telescope off axis. The details of the mirror system and performance of the telescope is discussed in detail in [47]. For

the purpose of this work, we are concerned with the reflecting surfaces of the mirrors so that chameleon beam coming to the surface gets effectively reflected and focused on the KWISP detector.

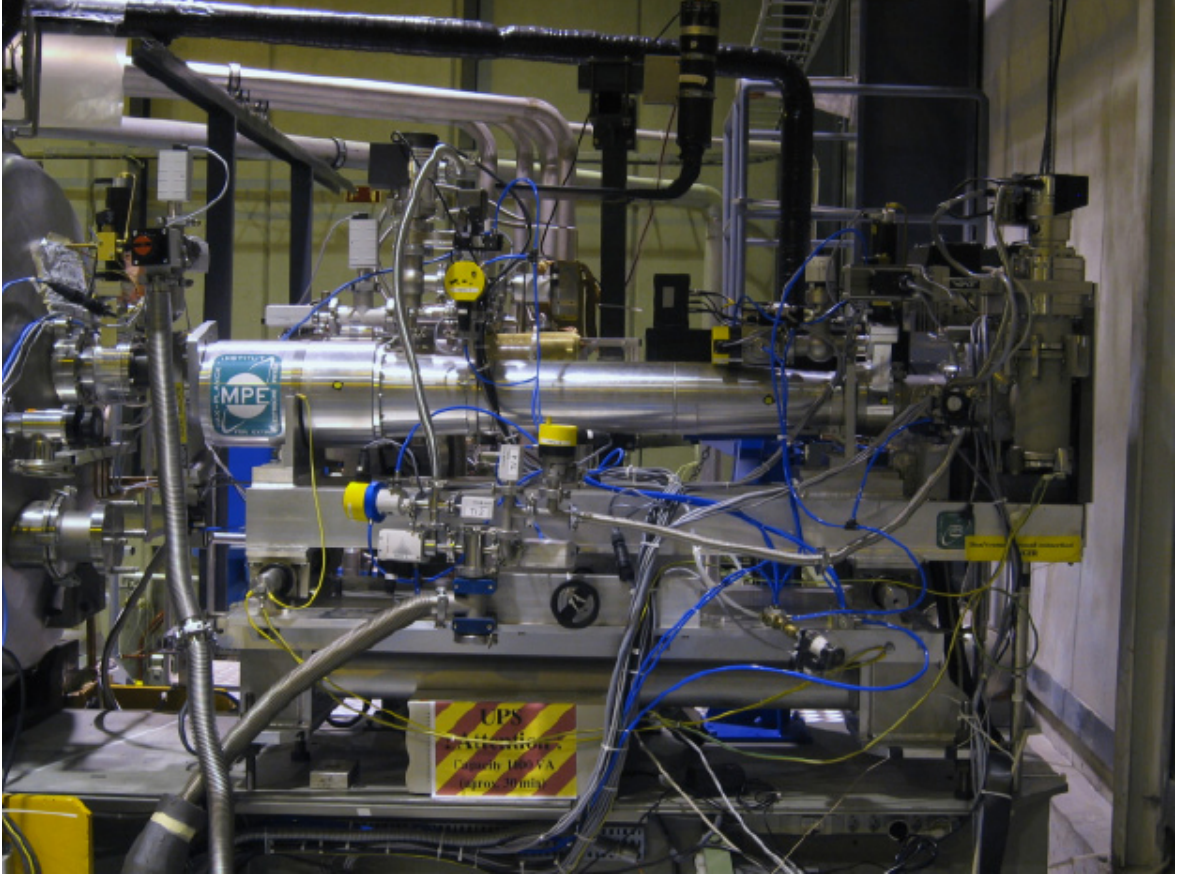


Figure 4.3. Side view of the X-ray telescope mounted on the magnet. The image is taken from [47].

As discussed in Chapter 3.6, the X-ray telescope's mirrors can be used to reflect the chameleon beams since for given density of the material of the telescope and a given grazing angle of 0.5° , particles with energies up to 2.5 keV can be reflected from the surface. It should be noted that mechanism of grazing reflection of chameleons is substantially different than the reflection of X-rays from the mirrors. The former is due to the chameleons reflecting due to interacting with the chameleon field whereas the latter is due to Compton scattering of photons with the mirror electrons [44].

5. KWISP DETECTOR

The interaction of chameleons with the matter has been described quantitatively in Chapter 2. The coupling between the chameleons and high density environments give rise to measurable effects which can be achieved with an appropriate detector. CAST experiment utilizes this concept by using an opto-mechanical detector called KWISP (Kinetic Weakly Interacting sub-eV Particle Detection) which was developed in collaboration with INFN Trieste, Italy. KWISP detection mechanism is based on optical Fabry-Perot and Michelson Interferometers and they will be described in this chapter. The concepts of these interferometers will be defined, then the KWISP setup will be discussed in detail covering the optics and lasers used, optical-electrical feedback mechanisms and electronic control and data acquisition (DAQ) systems. Three versions of the detectors will be introduced namely version 1 and version 1.5 with Michelson interferometer and version 2.0 with Fabry-Perot interferometer. The final setup of KWISP will be based on version 2.0 and the version 1.0 and 1.5 are built to accommodate it up to its completion. Therefore, firstly KWISP version 2.0 will be introduced and then 1.0 and 1.5 respectively.

5.1. Fabry-Perot Mechanism

Consider a light beam traversing a medium of refractive index n , encounter a thin slab of material with two parallel faces [48]. The part of the beam that enters the slab will be reflected multiple times as can be seen in Figure 5.1. At each reflection, a fraction of the beam leaves the slab, being refracted in accordance with Snell's law

The reflected rays leaving the medium can be focused at a point P via an optical lens and made to interfere with each other constructively or destructively. The interference pattern at point P depends on the path length differences and also the phase shifts due to reflections. The difference in optical length between two adjacent rays

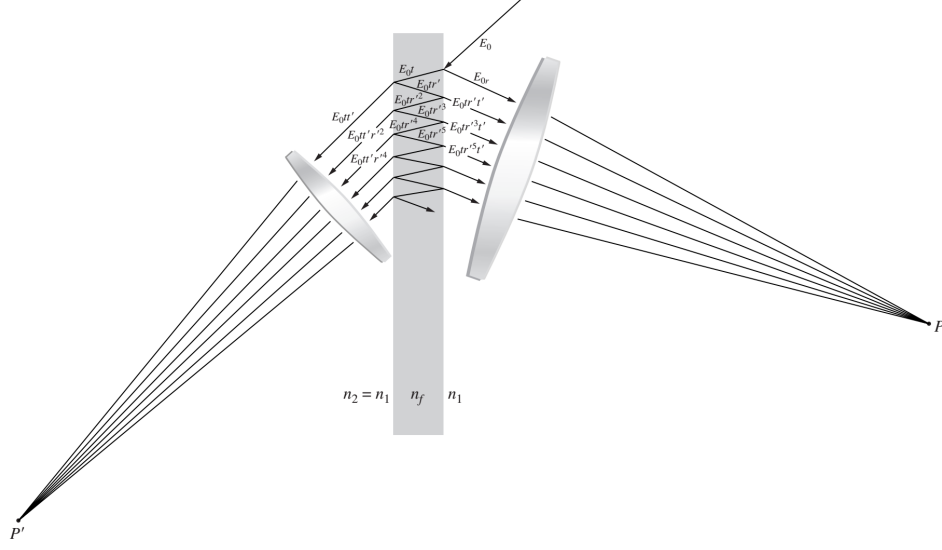


Figure 5.1. Large number of coherent beams are made to interfere via multiple reflection and refractions between the two mediums, in KWISP the medium interfaces are replaced by two mirrors [48].

leaving the medium is

$$\Lambda = 2n_f d \cos \theta_t \quad (5.1)$$

where θ_t is the angle of refraction n_f is the medium's index of refraction, and d is its thickness. The outgoing rays can then be described by the following equations:

$$\begin{aligned} \tilde{E}_{1r} &= E_o r e^{i\omega t} \\ \tilde{E}_{2r} &= E_o t r' t' e^{i(\omega t - \delta)} \\ \tilde{E}_{3r} &= E_o t r' {}^3 t' e^{i(\omega t - 2\delta)} \\ &\dots \\ \tilde{E}_{Nr} &= E_o t r' {}^{(2N-3)} t' e^{i(\omega t - (N-1)\delta)} \end{aligned} \quad (5.2)$$

where the reflection and transmission coefficients $r-t$ and $r' - t'$ are the reflection and transmission coefficients for traversing from n_1 to n_f and n_f to n_1 respectively. The terms $\delta, 2\delta, \dots, (N-1)\delta$ are the phase contributions arising from the path difference

between adjacent rays where $\delta = k_0\Lambda$ and k_0 is the wave number.. Additional phase differences arising from the different paths to point P are not considered. So the total electric field at point P is:

$$\tilde{E}_r = \tilde{E}_{1r} + \tilde{E}_{2r} + \tilde{E}_{3r} + \dots + \tilde{E}_{Nr} = E_0 e^{i\omega t} \left[\frac{r(1 - e^{i\delta})}{1 - r^2 e^{-i\delta}} \right] \quad (5.3)$$

The irradiance at point P is given by,

$$I_r = \tilde{E}_r \tilde{E}_r^* / 2 = I_i \frac{2r^2(1 - \cos \delta)}{(1 + r^4) - 2r^2 \cos \delta} \quad (5.4)$$

Similarly for transmitted waves we find the total electric field and the irradiance as

$$\tilde{E}_t = E_0 e^{i\omega t} \left[\frac{tt'}{1 - r^2 e^{-i\delta}} \right] \quad (5.5)$$

$$I_t = I_i \frac{(tt')^2}{(1 + r^4) - 2r^2 \cos \delta} \quad (5.6)$$

Using the identity $\cos \delta = 1 - 2 \sin^2 (\delta/2)$ and the fact that energy is not absorbed, i.e $tt' + r^2 = 1$, (5.4) and (5.6) becomes:

$$I_r = I_i \frac{[2r/(1 - r^2)]^2 \sin^2 (\delta/2)}{1 + [2r/(1 - r^2)]^2 \sin^2 (\delta/2)} \quad (5.7)$$

$$I_t = I_i \frac{1}{1 + [2r/(1 - r^2)]^2 \sin^2 (\delta/2)} \quad (5.8)$$

For $\delta = 2\pi m$, the transmitted beam is maximum ($I_t(max) = I_i$) and the reflected beam is minimum ($I_r = 0$). For $\delta = (2m + 1)\pi$ the transmitted flux becomes minimum and the reflected flux ($1 - I_t$) gets maximum and we have a maxima at the fringe pattern at P.

A new quantity called 'coefficient of finesse' F is defined:

$$F \equiv \left(\frac{2r}{1 - r^2} \right)^2 \quad (5.9)$$

The equations for the reflected and transmitted fluxes becomes

$$\frac{I_r}{I_i} = \frac{F \sin^2(\delta/2)}{1 + F \sin^2(\delta/2)} \quad (5.10)$$

$$\frac{I_t}{I_i} = \frac{1}{1 + F \sin^2(\delta/2)} \quad (5.11)$$

where I_i is the incident flux. $[1 + F \sin^2(\delta/2)]^{-1}$ is known as Airy function $\mathcal{A}(\theta)$ and

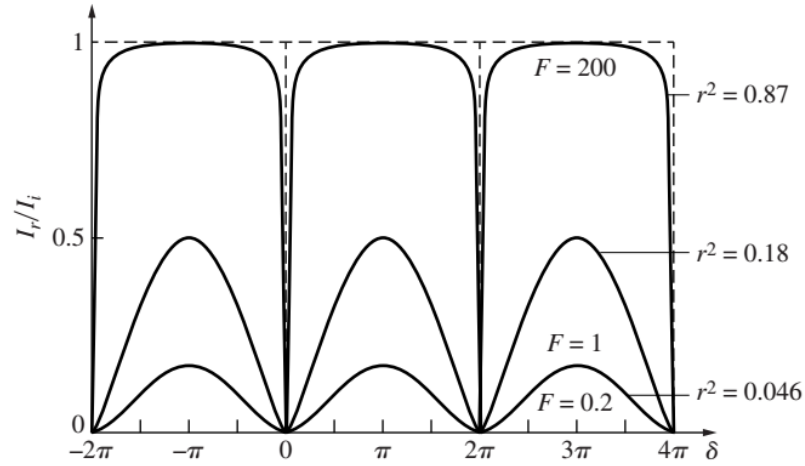


Figure 5.2. The reflected flux density $1 - \mathcal{A}(\theta)$ is plotted with δ for three different r values. $\delta = 2\pi m$ values correspond to sharp zero values for the reflected flux where

$$\delta = (2m + 1)\pi \text{ corresponds to maximum flux. [48]}$$

it represents the transmitted flux density distribution where $1 - \mathcal{A}(\theta)$ is the reflected flux density (see Figure 5.2).

5.2. Cavity Locking and Feedback Mechanism

The membrane is placed inside the cavity such that it is positioned at the node of the standing wave which is created when the cavity is at resonance. The displacement of the membrane shifts the cavity modes and the cavity frequencies gets detuned [49]. Change in the cavity frequency by a displacement of the membrane x is given by

$$\omega_{cav}(x) = \frac{c}{L} \cos^{-1} \left(|r_c| \cos \left(\frac{4\pi x}{\lambda} \right) \right) \quad (5.12)$$

where r_c is the electric-field reflectivity of the membrane [50].

FP cavity needs to be locked in with the laser in order to sense the effects of the change of the membrane displacements. This is achieved by electro-optic feedback system know as Pound-Drever-Hall (PDH) technique [51]. The feedback acts on the laser active medium which is generally a crystal-in our case Nd:YAG laser, so that the instantaneous distance between the cavity mirrors is always a half-integer multiple of the laser wavelength so that standing waves is created inside the cavity [22].

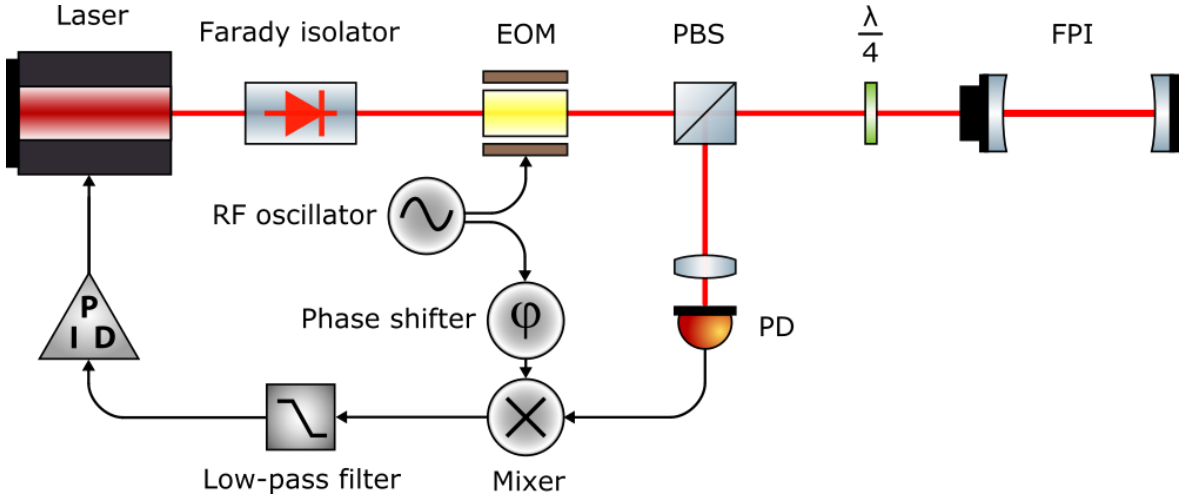


Figure 5.3. Schematic of PDH technique setup. The figure is taken from [52].

The frequency locking is achieved by the light reflected from the cavity which propagates backwards through the system up to the PBS which steers it to the photo diode (see Figure 5.3). The back-reflected light intensity is used for diagnostic purposes

and also as an input for electro-optic feedback system to keep the laser frequency continuously in resonance with the cavity. The system works by analysing the back-reflected beam to obtain a signal proportional to the instantaneous difference between the laser frequency and the cavity frequency. This difference is called the ‘error signal’ and it is fed back into the laser with amplification to control its frequency. The error signal contains the information of how the cavity frequency shifts and it is the signal from which membrane displacement is detected [53].

5.3. Michelson Interferometer

The other technique used for determining the change in position of the membrane is the Michelson Interferometer (MI). In MI, a beam of light from an extended source is divided into two parts of equal intensities by partial reflection and refraction. These beams travel in two mutually perpendicular directions and come together after reflections from plane mirrors. The beams overlap with each other and produce interference fringes (see Figure 5.4). The combined beam is detected with a sensor such as a photodiode so that the spectrum of the signal can be determined.

If the difference of the arm lengths is $d = d_1 - d_2$, then the constructive interference happens at,

$$2d \cos \theta = n\lambda \quad (5.13)$$

where λ is the wavelength of the beam and n is an integer and θ is the angular position of the fringe.

In the output, the circular fringes are created because of the constant equal inclination and they are called Haidinger Fringes [48]. The difference in the distance on the beam path between the dark and the light fringe corresponds to half of the wavelength of the sensing beam.

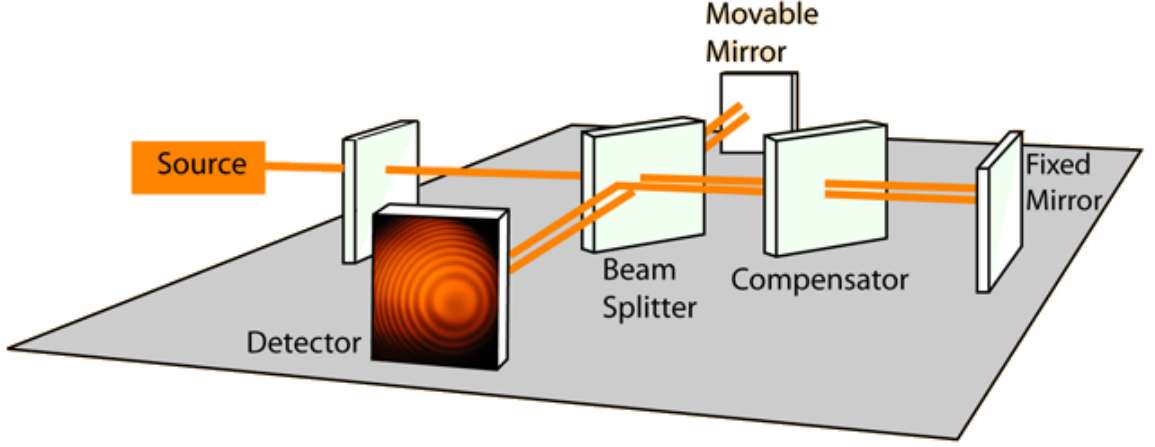


Figure 5.4. Schematic representation of the Michelson interferometer. The figure is taken from [54]

In the case of KWISP, one of the mirrors is replaced with the membrane and one of the cavity mirrors is used for the other mirror (see Figure 5.10 and Figure 5.14). The cavity mirror can move on its axis with piezo motors and is calibrated by moving a distance of half the wavelength ($\lambda/2$) of the sensing beam so that a transition from dark fringe to light fringe can be observed.

5.4. KWISP Setup version 2

KWISP detector utilizes the concept of multiple beam interference of the laser going inside the Fabry-Perot cavity in order to sense the displacement of the membrane from equilibrium position. The chameleon flux hitting the membrane exerts a force exciting the vibrational states and causes a displacement of the membrane from its equilibrium position.

The sensing laser beam is frequency locked to the cavity by active electro-optical feedback system which is called Pound-Drever-Hall (PDH) technique. A change in the membrane displacement from the initial position causes a shift in the cavity mode frequencies which is sensed in the feedback correction signal. The sensor converts this force signal into an electrical signal with a gain proportional to the finesse of Fabry-

Perot cavity.

The schematic of the complete setup of the KWISP version 2.0 can be seen in Figure 5.5 and the actual setup of the optical beam path is provided in Figure 5.6.

5.4.1. Optics and Laser

The operation of the KWISP detector is realised by a laser system supported with various optical elements which are put on the beam line. A brief description of the components used in the setup is provided in this section.

5.4.1.1. Lasers. Two lasers are used in the KWISP FP design, the sensing beam laser at 1064 nm wavelength and the pump beam laser at 532 nm wavelength.

Sensing beam is used for the frequency locking of the Fabry-Perot cavity with the electro-optic feedback mechanism. It encodes the error signal that is being used to keep the cavity at resonance. Alphalas Monopower 28 mW, 1064 nm ND:YAG laser is used for sensing beam.

In order to measure the sensitivity of the cavity a pump beam is used with another laser. Pump beam effectively acts as an external force to act on the membrane and causing it to displace. This is used for calibration and diagnostic purposes. The pump beam laser is an IR laser with 532 nm wavelength.

5.4.1.2. Electro-Optical Modulator (EOM). The laser beam needs to be modulated for the input of the feedback system and the EOM is used for this purpose. They operate on the principle of change in the refractive index of the material by applying a DC or low frequency electric field. The material in conventional EOMs are crystals and the refractive index of the crystal is a function of the local electric field. By changing the field in crystal, the phase of the laser light exiting the EOM can be controlled.

In our setup, EOM modulates the laser beam for the PDH technique and creates sideband carrier signal frequencies. The reflected light from the FP cavity is compared with the input signal and from the difference of these two an error signal is created to control the locking of laser to the cavity.

5.4.1.3. Polarising Beam Splitter (PBS). Polarising Beam Splitter is an optical device that splits the beam into two. It generally comes in the shape of a cube shape which is made from two triangular glass prisms with different refractive indexes n_1 and n_2 which are glued together at their base. The interface between the two prisms is oriented in such a way that when an unpolarized beam hits with a normal incidence to the surface, it hits the interface at a Brewster angle defined by

$$\theta_B = \arctan \frac{n_2}{n_1} \quad (5.14)$$

This results in the reflected and transmitted beams becoming perpendicular to each other, thus splitting the incoming beam into two perpendicularly polarised beams.

PBS is used in the setup with the combination of Faraday Isolator in order to prevent the back-reflected beam to go inside the laser cavity which can cause instabilities.

5.4.1.4. Faraday Isolator. Faraday Isolator is an optical device which transmits light in a certain direction while blocking light in opposite directions. They are used to protect against the back reflections in laser systems.

The working mechanism of a Faraday Isolator depends on the change of the polarisation of the incoming beams into the device. The plane of polarized light is rotated through an angle of 45° on passing through the device in one direction and then through further 45° on passing back in the opposite direction. The total rotation is thus 90° and the input polarizer then effectively rejects light returning through the device.

5.4.1.5. Half Wave Plate. Wave plate is an optical device which is used to change the polarization of the beam which is travelling through it as desired. The half wave plate is used to change the direction of the polarization of linearly polarized waves whereas quarter wave plates are used to change the linear polarization into circular.

Wave plates are made with birefringent materials whose refractive index depends on the polarization and propagation direction of light travelling through it. The change of phase is effected by three parameters: difference of the refractive indexes Δn , the thickness of the crystal L and the wavelength of the beam λ_0 given by the relation

$$\Delta\phi = \frac{2\pi\Delta nL}{\lambda_0} \quad (5.15)$$

For half wave plates $\Delta\phi = \pi$, thus it mirrors the wave's polarization vector through the plane formed by the vectors along the waveplate's fast axis and the propagation direction. In KWISP setup, half wave plate is used to match the polarization of the beams in order to pass PBSs in desired direction.

5.4.1.6. Matching Lenses. A combination of a divergent lens and of a convergent lens is used to adapt the curvature of the laser beam wavefronts to match the curvature of the cavity mirrors CM1 and CM2 at their respective positions, in order to maximise the light power coupled into the cavity at resonance.

5.4.1.7. Cavity Mirrors. There are two cavity mirrors placed inside the Fabry-Perot cavity. They are 1-inch diameter, 100 cm curvature radius, high reflectivity, multilayer dielectric mirrors made by ATFilms, Boulder, Co., USA. The mirror transmission coefficients are 5.0×10^{-5} and 0.50 at 1064 nm and 532 nm respectively. Each mirror is mounted on a two-axis, piezo actuated, tilted mount (Agilis series by Newport, USA), which is in turn fixed to the common base.

5.4.1.8. CCD Camera. CCD Camera is used to detect the change in the cavity modes for diagnostic purposes.

5.5. Alignment and Mechanism

The chamber containing the FP cavity, lasers and the optical devices are positioned on a Thorlab honeycomb optical bench which can be seen in Figure 5.6. Precise alignment of the setup was made with diagnostic tools such as IR power meter to measure the beam intensity in various places, IR-card to align the beam on optical surfaces, alignment disks to match the beam with the center of the mirrors. The procedure whose details are beyond the scope of this manuscript is very delicate and sensitive so that a typical application takes more than 20 manhours. The detailed treatment of the alignment and calibration of the detector can be found in [52, 53].

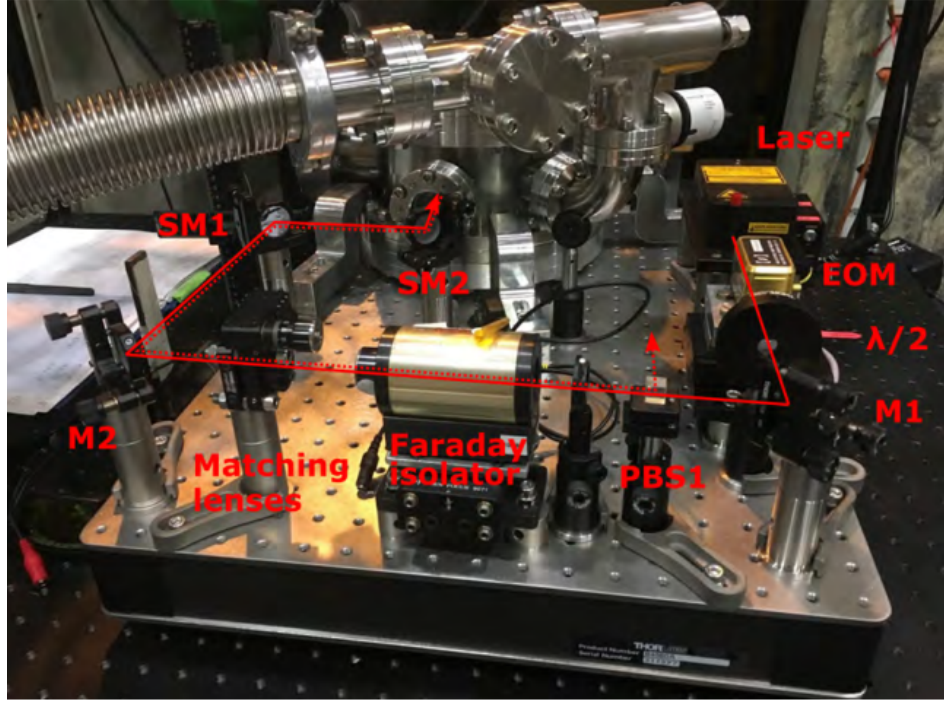


Figure 5.6. Optical beam path located outside the cavity. The labels on the figure is explained in Section 5.3. The figure is taken from [52].

Here the optical beam line starting from the sensing laser and reaching the inside of the cavity will be described. 1064 nm IR beam exiting the laser aperture arrives at the front of the EOM. The EOM is used for the modulation of the beam for the feedback system and it is adjusted to allow the maximum amount of light to exit from the output. Half wave plate is positioned after the EOM to adjust the polarization of the beam in order to pass directly from the PBS ahead. Then the beam arrives at the

Faraday Isolator and this creates a polarization difference between the forward going and the back-reflected beam. This prevents the back-reflected beam to go into the laser and cause instabilities in the laser cavity. Behind the Faraday Isolator two matching lenses are used to adjust the laser beam profile to match the cavity mirror curvature so that maximum amount of energy is supplied to the cavity. The configuration of the matching lenses were performed by the program GaussianBeam [55]. Then the beam is directed into the FP cavity by the steering mirrors M1, SM1 and SM2.

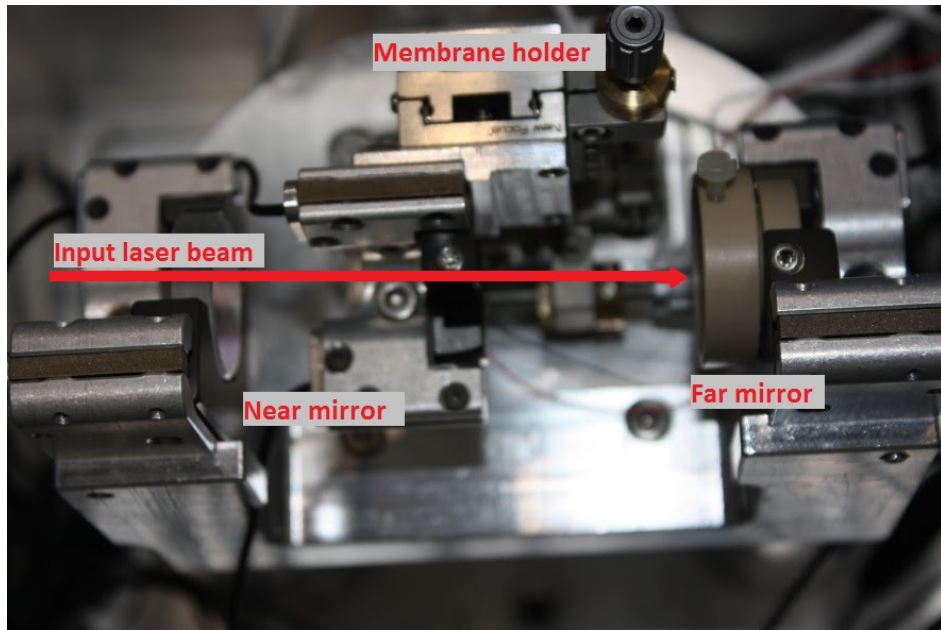


Figure 5.7. Inside the Fabry-Perot cavity.

The beam is aligned so that it passes just through the middle of the cavity mirror axis with the help of the alignment disks, IR camera and piezo motion controller that controls the cavity mirror holder. Near mirror CM1 and far mirror CM2 positions are adjusted to get the precise alignment. Inside of the cavity can be seen in Figure 5.7.

The back-reflected beam is traced on the beamline so that it is superposed on the forward going sensing beam and it is redirected with a steering mirror M3 into the reflection photodiode PDR to read the error signal.

After the alignment, the locking and resonance of the cavity is checked by giving a ramp signal to the piezo actuator of the far-mirror in the cavity and the transmission

spectrum and TEM mode image on the CCD are observed (see Figure 5.8).

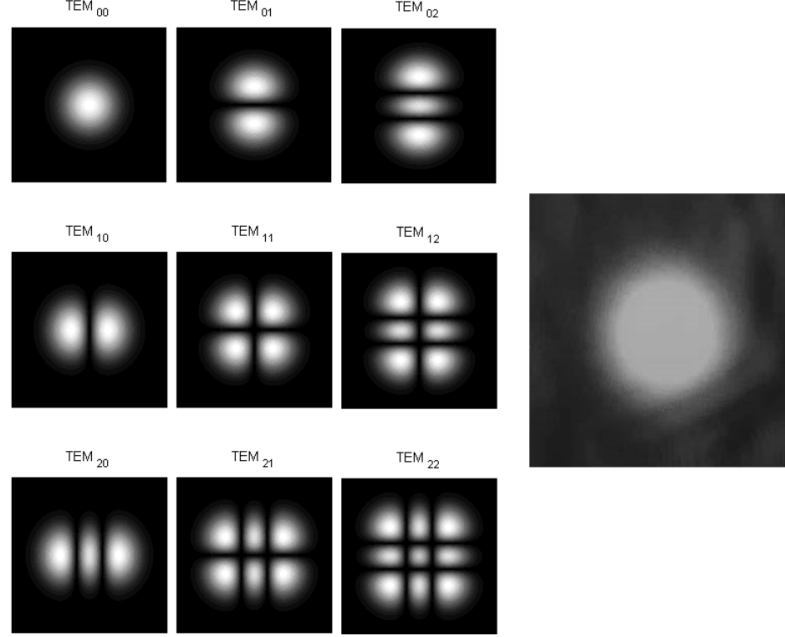


Figure 5.8. Theoretically derived TEM modes (left) and observed TEM_{00} mode (right).

If the lock is successful the peak in maximum transmission would be observed as in Figure 5.9. From these measurements and using the Fabry-Perot finesse calculations, the finesse $\mathcal{F}$ is found to be

$$\mathcal{F} \approx 2500 \quad (5.16)$$

which is a very low value compared to previous measurements of ~ 30000 [22]. The reason is thought to be misalignment or some problem with the laser.

As of the middle of 2017, due to a problem with the Alphalas laser, KWISP version 2.0 is not yet operational. The development is going on until it is provided in a working condition by the manufacturing company.

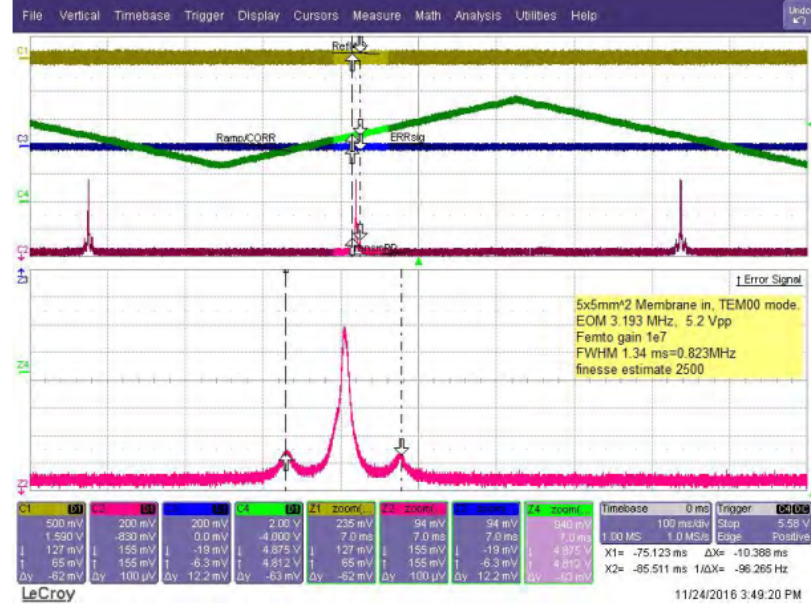


Figure 5.9. Oscilloscope output showing the triangular ramp signal given to the piezo actuator and by the resonance the peak in the transmission spectrum with the sidebands is observed.

5.6. KWISP Detector Version 1.0

KWISP version 1.0 is the first version used on beam in the CAST experiment searching for the chameleons. It is based on the Michelson interferometer principle which was discussed in Section 5.2. The two detector arms which are the cavity mirror and the Si_3N_4 membrane itself are placed inside the vacuum chamber which is placed in such a configuration that chameleon beam reaches the membrane inside the cavity at a grazing angle of 5° . An external input laser beam 5 mW CW laser at 532 nm is sent inside the chamber and the beam is split into two by the PBS. One part of the beam goes to the cavity mirror and the other part goes to the membrane (see Figure 5.10).

The flux of chameleons coming from the magnet passing through the XRT is modulated with a chopper. In this setup the chopper is constructed by combining two prisms end-to-end so that it gives 4 effective surface area where the chameleon beam

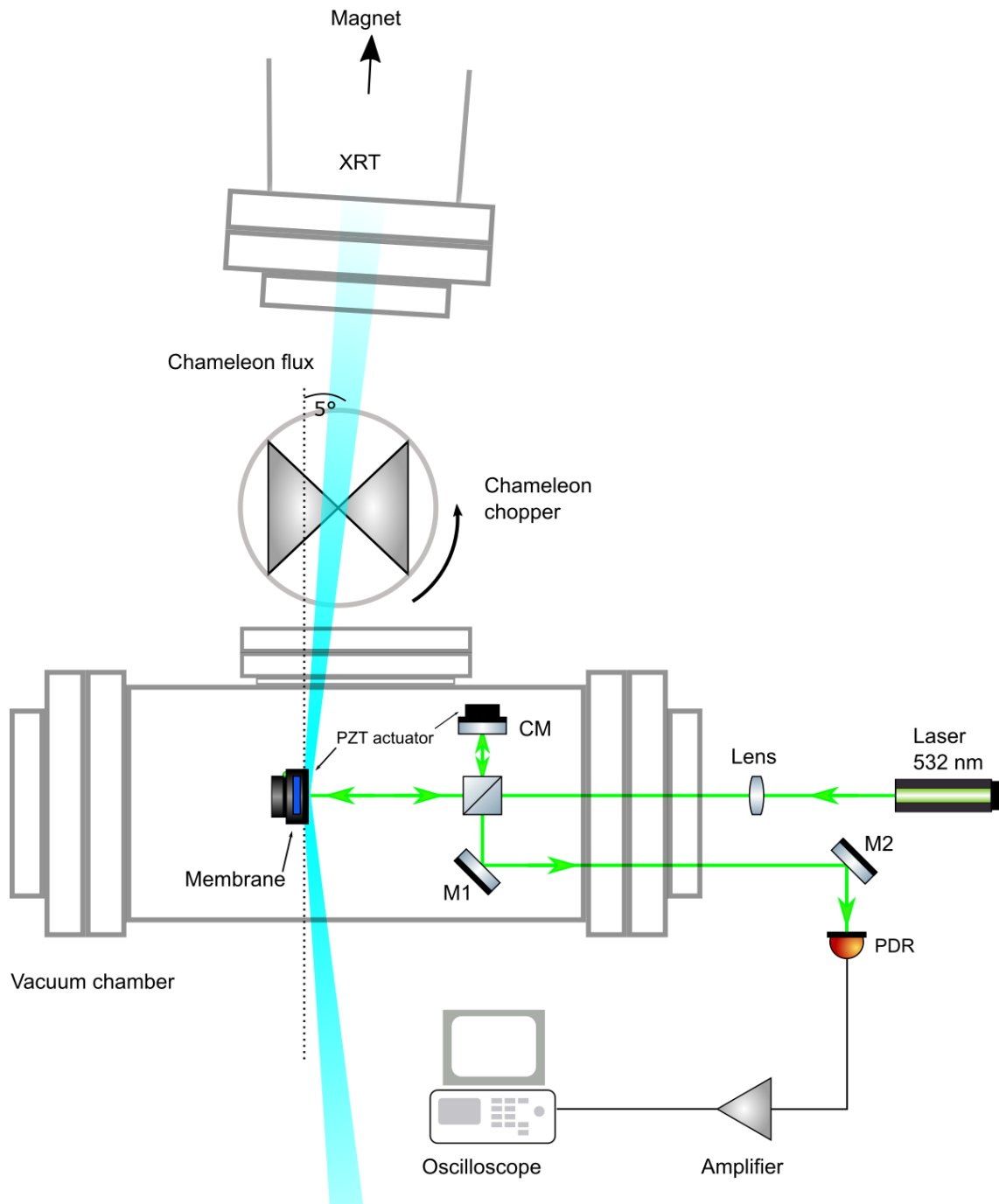


Figure 5.10. Schematic representation of the KWISP (version 1.0) detector. The figure was taken from [52].

is supposed to reflect from (see Figure 5.11). It rotates with a frequency of 24.4 Hz.

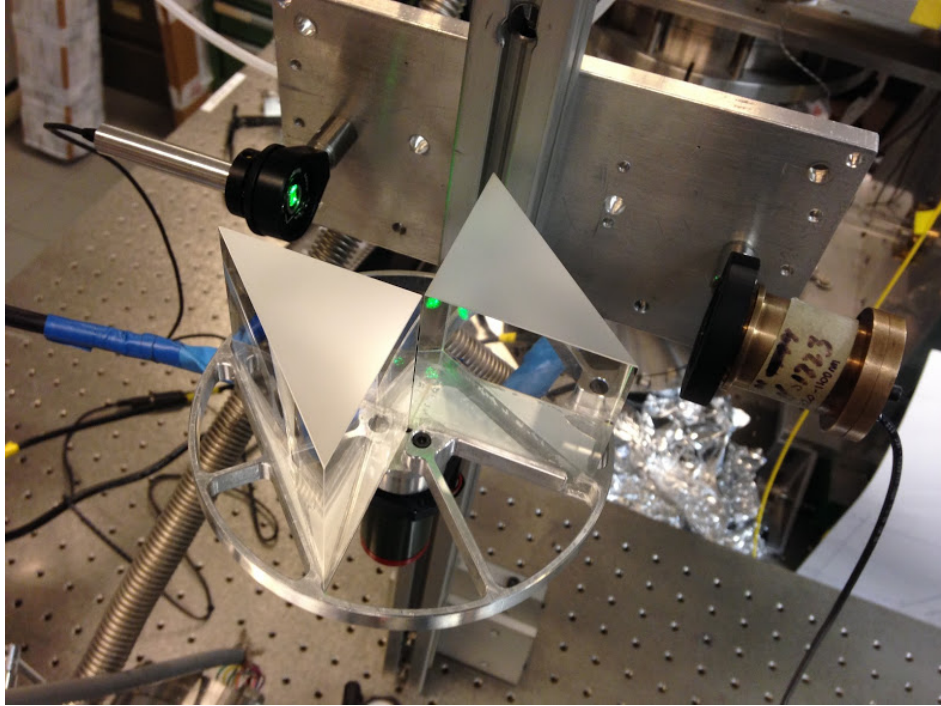


Figure 5.11. The chopper made by combining two prisms.

Figure 5.12 shows the optical setup of the interferometer. The reflected beam from the interferometer arms are combined again and steered out of the cavity by mirrors M1 and M2 where it is collected at the photodiode. The interference signal is amplified and is fed into the oscilloscope.

The calibration of the interferometer is done by manually moving the cavity mirror periodically by $\lambda/2$ so that in the interference pattern there is a transition from dark fringe to light fringe. From this operation the sensitivity of the setup has been estimated to be $S = 1.35 \times 10^{-13} \frac{N}{\sqrt{Hz}}$.

KWISP version 1.0 setup was used in April 2016 data taking during a period 7 days. 9000 seconds of Sun tracking and 121400 seconds of background data were collected by an automated data acquisition system based on the LabView program. The data consist of the interferometer signal and chopper trigger signal. The spectrum in Figure 5.13 shows no peaks for the chameleon signal.

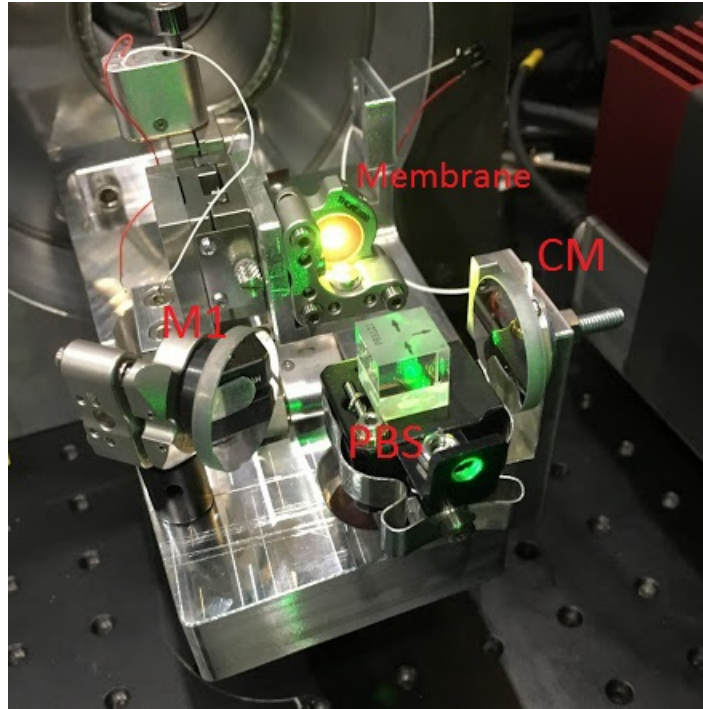


Figure 5.12. Optical setup of the KWISP version 1.0 detector

The chopper mechanism used for modulating the incoming chameleon beam is considered to be inefficient since it effectively chops the signal with its four surfaces but other times the beam passes through hence it has a very low duty-cycle. The incoming beam also reflects from the surfaces with different angles every time. This prevents to create a sharp peak in the interferometer spectrum. In order to bypass these problems a new chopper design is used in the upgraded detector which is called KWISP version 1.5.

5.7. KWISP Detector Version 1.5

Upgraded version of the detector called KWISP version 1.5 is also based on a Michelson interferometer where the two arms end in cavity mirror and the membrane (Figure 5.14). In this setup, the chopper design and the data acquisition system has been modified.

The principle is almost the same with the previous version but in this setup readout homodyne detection scheme is implemented. Homodyne detection is a method

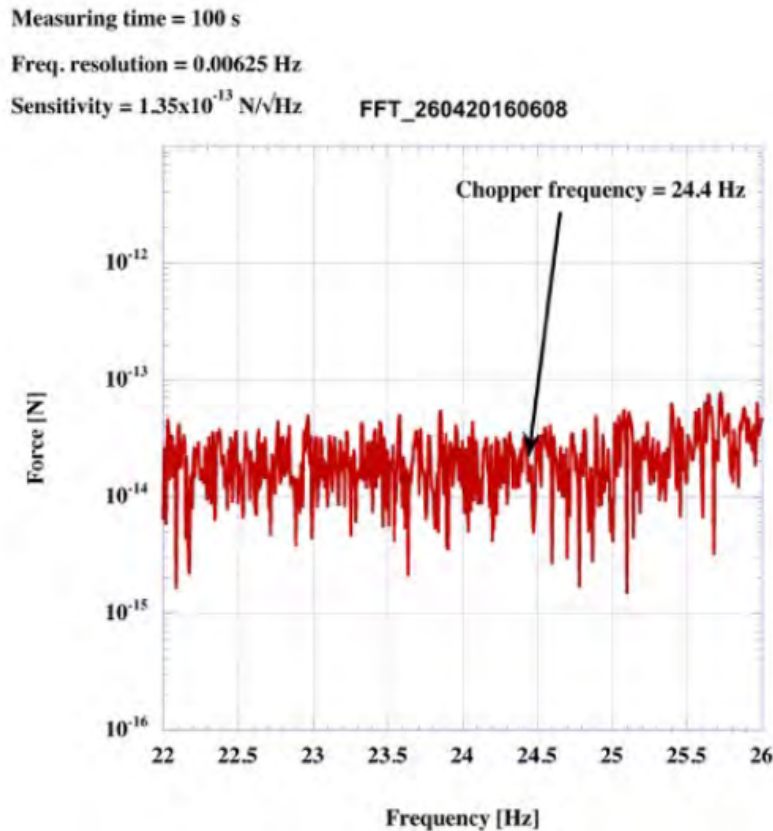


Figure 5.13. The signal spectrum sample (converted to force) of a 100 sec data; the chopper frequency of 24.4Hz is indicated in the plot where no peak that would indicate the presence of chameleons are observed. If there would be a signal, a peak would be observed at the operating frequency of the chopper itself.

of extracting information encoded as modulation of the phase and/or frequency of an oscillating system by comparing that signal with a standard oscillation that would be identical to the signal if it carried null information. Homodyne signifies a single frequency, in contrast to the dual frequencies employed in heterodyne techniques. On beam installation of the detector can be seen in Figure 5.15.

The laser beam from 532 nm 5 mW Firefly laser is sent through a half wave plate and inside to the vacuum chamber. The beam is divided into two by PBS, one part is 90% of the flux sent to the cavity mirror and 10% to the membrane. Quarter wave plates are put on each side and the beam hitting the membrane exits the chamber modulated while the beam from the cavity is kept unmodulated. They are directed to

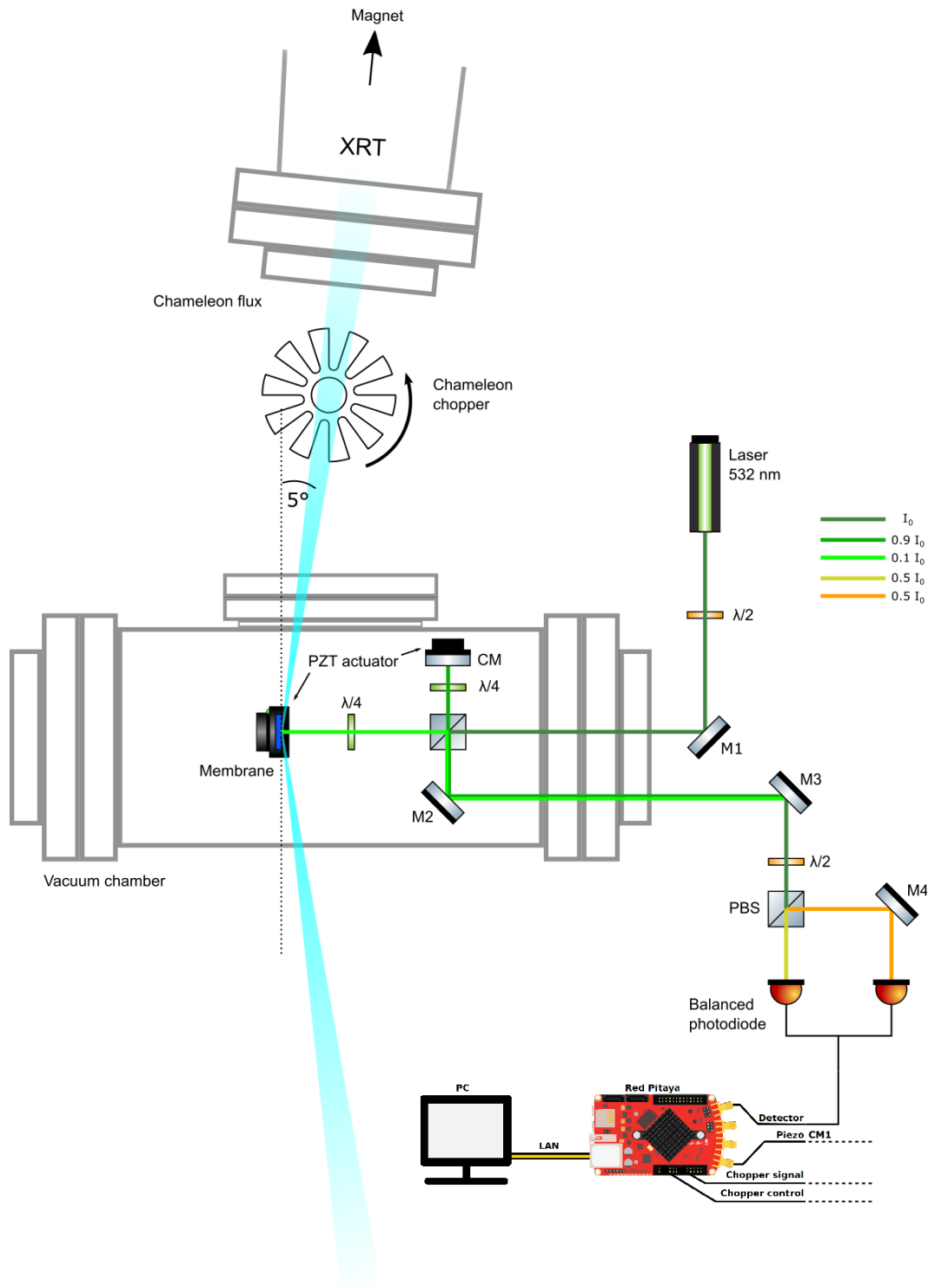


Figure 5.14. Schematic representation of the KWISP (version 1.5) detector. The figure was taken from [52].

the PBS and split into two. The two signals are subtracted from each other by the balanced photodiode to cancel out the noise and measure the small displacement of the membrane.

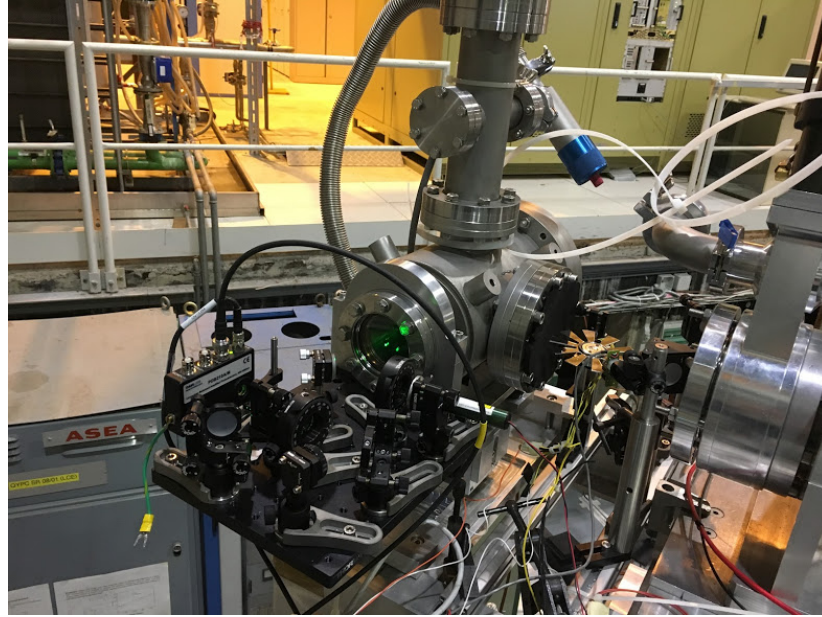


Figure 5.15. On beam installation of the KWISP version 1.5 detector.

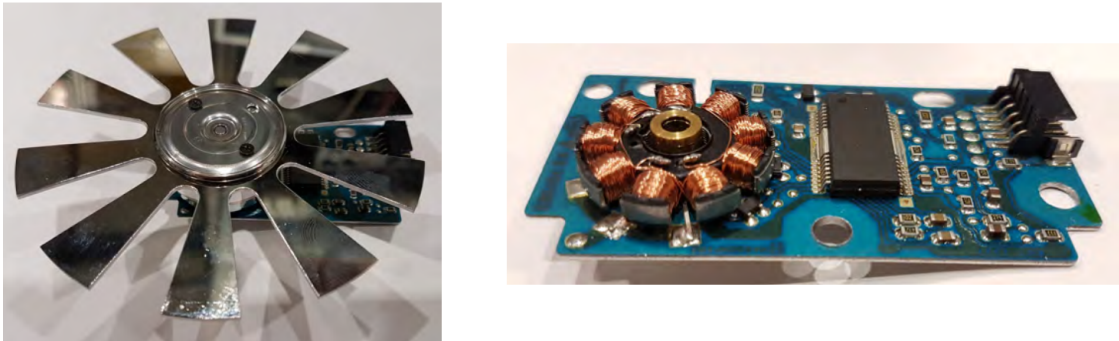


Figure 5.16. Chopper made from hard disk platter (left) and the motor and its driver PCB (right).

The chopper design has been changed to accommodate high duty cycle as well as equal reflection angle in each turn. For this purpose, at first 10 blade stainless steel wheel is used with a DC motor (Figure 5.16). It has been positioned on the chameleon beam line in front of the chamber (Figure 5.17). The maximum frequency achieved by this chopper design was around 300 Hz before it starts to shake significantly. This design was used during December 2016 data taking.

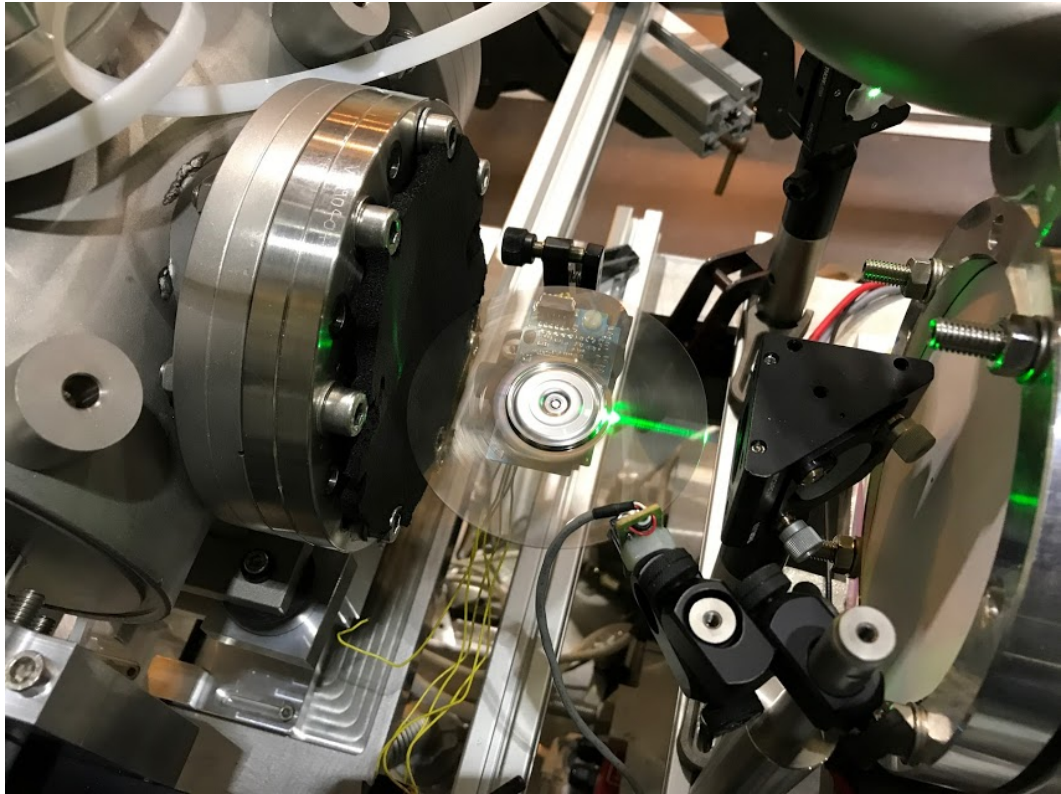


Figure 5.17. Rotating chopper placed horizontally at a grazing angle in front of the cavity.

Another design for the chopper is realised for the February 2017 data taking setup. It is manufactured from a used hard drive platter with 10 platters. This kind of material is chosen since the platters are required to have a low surface roughness on the order of a few Angstroms; they would be ideal for chameleon reflection. The material of the chopper is not known exactly since it has not been provided by the hard disk manufacturer but it was assumed to be aluminium. It is placed on a brushless DC motor which was taken from a laser printer and drivers are implemented on a PCB as seen in Figure 5.16.

The data acquisition is done by a FPGA (Field Programmable Gate Array) microcontroller which is called Red Pitaya (RP) (Figure 5.18) [56]. It has two 14 bit DAC (digital to analog converter) and two ADC (analog to digital converter) operating at 125 MS/s. It controls the chopper frequency as well as acts to lock the difference output of the balanced photodiode to zero. It also sends a calibration signal to the cavity

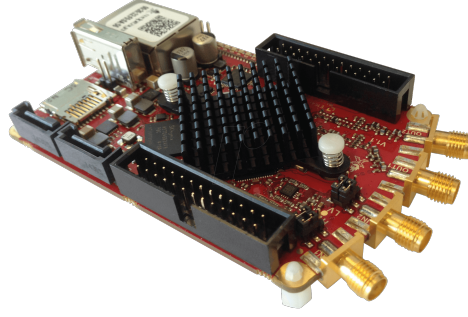


Figure 5.18. Red Pitaya FPGA board. The image is taken from [56].

mirror piezo actuator so that sensitivity is measured.

To estimate the sensitivity a ramp signal is sent to the mirror piezo actuator. The output of the oscilloscope is shown in Figure 5.19.

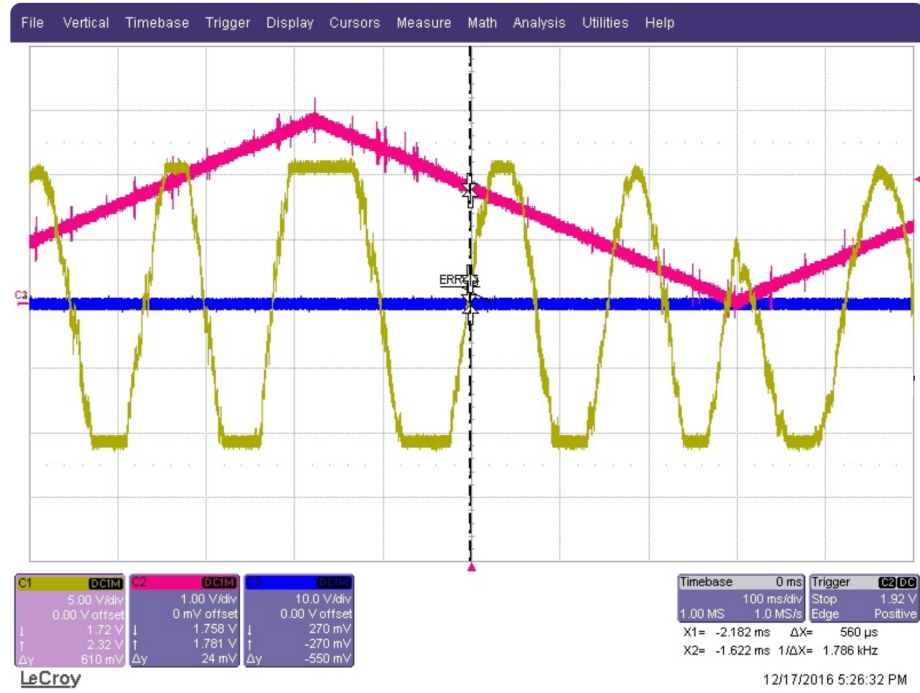


Figure 5.19. Oscilloscope output showing the ramp signal (red) and the corresponding output signal from the interferometer (yellow). The full swing of the output corresponds to $\lambda/2$ movement of the mirror.

The output swings between $\pm 10\text{V}$ corresponding to $\Delta V = 20\text{ V}$. This corresponds to a phase shift of π between the two inputs of the balanced photodiodes or to a

movement of $\lambda/2 = 532/2$ nm. If V_b is the amplitude of the background voltage observed in a time period T , the sensitivity is given by:

$$S_d = \frac{V_b}{\Delta V} \frac{\lambda}{2\pi} \sqrt{T} \quad (5.17)$$

Having the background of 4×10^{-3} V and $T = 10$ s,

$$S_d = \frac{4 \times 10^{-3}}{20} \times \frac{532 \text{ nm}}{2\pi} \sqrt{10 \text{ s}} = 5.3 \times 10^{-11} \text{ m}/\sqrt{\text{Hz}} \quad (5.18)$$

6. DATA AND ANALYSIS

KWISP detector has been collecting data since it became operational on the magnet since 2016. Periods of data taking were held with the detector versions which were discussed in Chapter 5 in detail. Configuration of each setup is modified with the feedback from the operations and subsequent data analysis to improve the performance and handle the problems encountered. In this chapter the data taking run which was carried on in December 2016 will be discussed. Fast Fourier Transform, main tool for the data analysis, will be introduced and the analysis procedure will be given in detail. In the end, preliminary results will be presented and avenues for future improvements will be discussed.

6.1. Data Acquisition

As mentioned in Section 5.7, the data from the KWISP detector were taken by the microcontroller Red Pitaya (RP). It is a single board computer equipped with an FPGA, two 14bit DACs and two 14bit ADCs at 125 MS/s. RP controls the readout from the balanced photodiode and piezo actuator of the mirror CM1. It also sets the frequency of the chopper and the acquired data is transferred to a PC via TCP over LAN and then stored on separate hard drives (Figure 6.1). The data acquisition software supports continuous acquisition up to 122 kS/s and burst acquisition up to 2 MS/s. Data are usually continuously acquired at 61 kS/s.

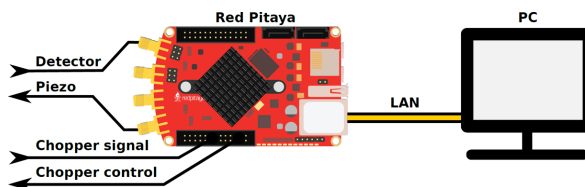


Figure 6.1. Red Pitaya FPGA board and its connection to the DAQ PC

An easy to use GUI written with Qt [57] (Figure 6.2) allows for full control of the acquisition process and parameters, such as the PID parameters and the chopper frequency.

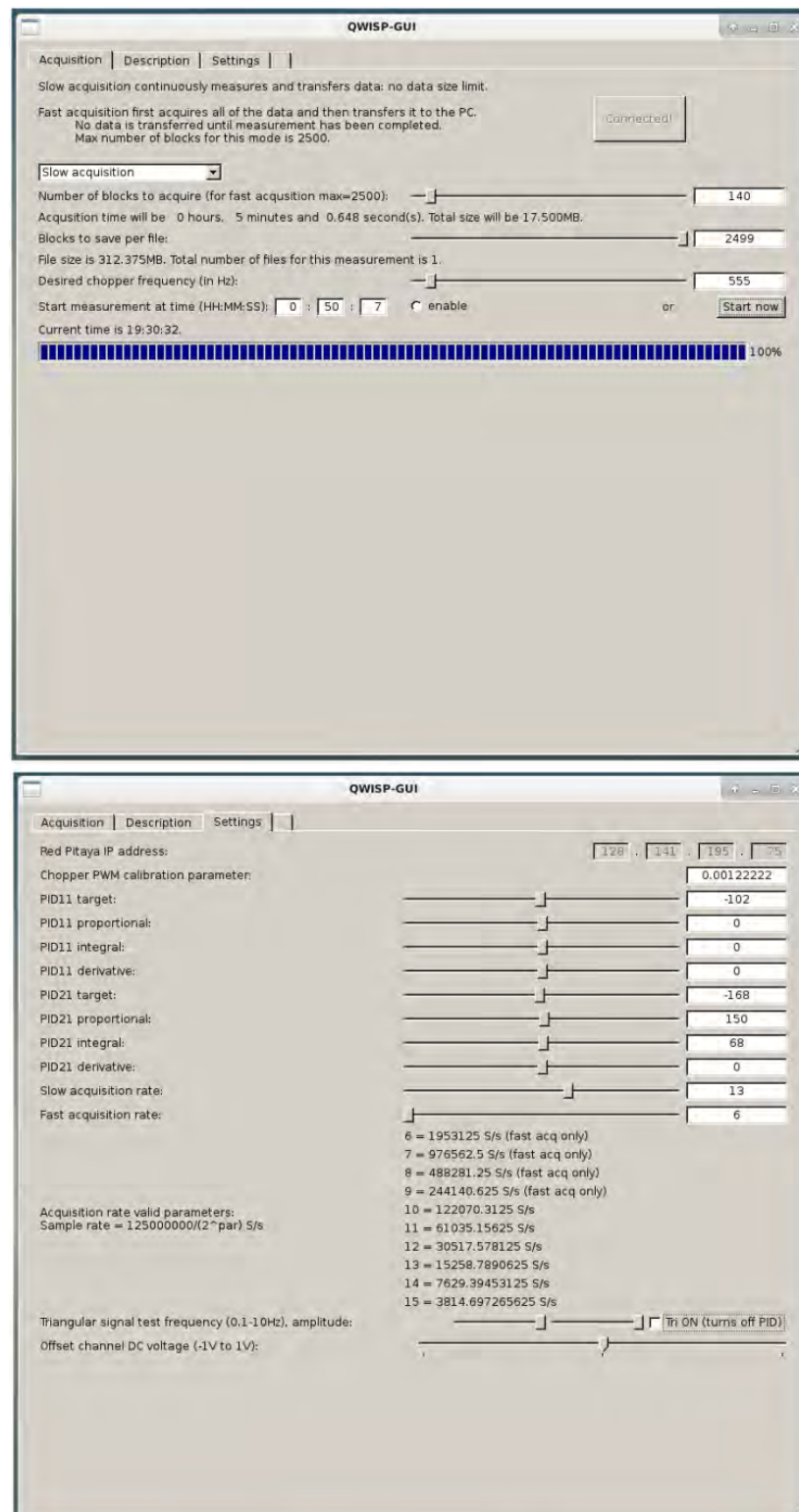


Figure 6.2. Graphical user interface of the data acquisition program

6.2. December 2016 Data

The data were collected in the 14-19 December 2016 run with tracking and background data. The data is acquired by the RP as a binary file. The file consists of two columns of data which corresponds to the error signal coming from the photo diode and the chopper signal.

The binary file is converted to the standard format with the proper conversion factors for the channel outputs. The Channel 1 (error signal) output swings between 0-1 V while the channel 2 (chopper signal) is between 0-20 V.

A sample plot of the data is shown in Figure 6.3 for 0.1 second interval.

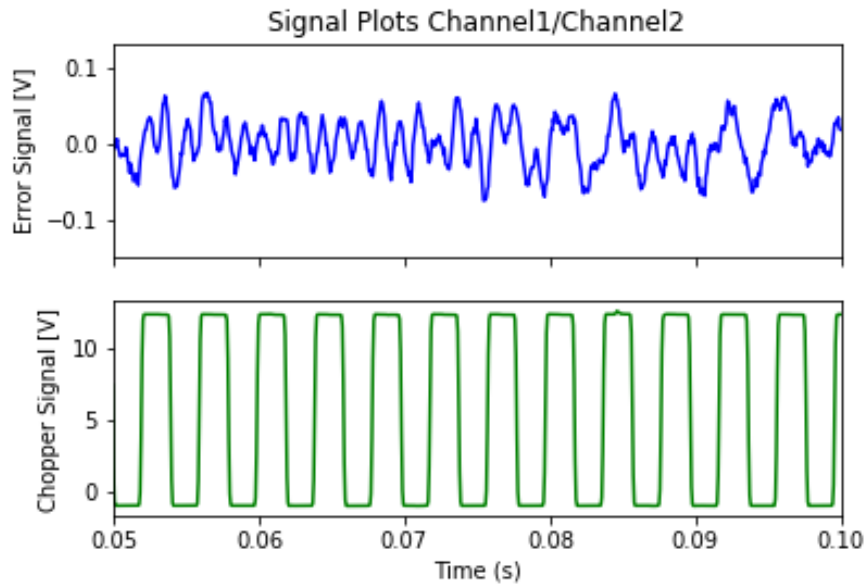


Figure 6.3. Data sample consisting of error (blue) and chopper signal (green)

The data is collected for each day of the run, one part for the tracking (1.5 hours) and one part for the background during the day for which the duration changes.

6.3. Fast Fourier Transform (FFT)

Functions can be represented in different domains by choosing appropriate basis elements. Typically functions which are defined in time or space domains can be decomposed so that their frequency components can be calculated. This kind of transformation is called Fourier Analysis and it is widely used in physics and applied mathematics. For our purpose, the time domain signal which we collect with the data acquisition software will be analysed so that different frequency components will be revealed in the data. Among these frequency components, a signal generated by time modulated chameleon flux hitting the membrane is sought after. Similarly, if the frequency components of a signal are known, the signal can be constructed by combining the components with the proper basis.

In order to develop the method, let's consider the case of finite-discrete time domain signals with N data points [58]. Assuming we know the frequency domain coefficients c_k of a discrete signal f , which is sampled at equal intervals of $x = 0, \frac{2\pi}{N}, \frac{4\pi}{N}, \dots, \frac{(N-1)\pi}{N}$, we can construct the function as

$$f(x) = \sum_{k=0}^{N-1} c_k e^{ikx} \quad (6.1)$$

We can write the components of the function f (denoted as y_i), in terms of coefficients c_k , using $w = e^{2\pi i/N}$ as

$$\begin{aligned} y_0 &= c_0 + c_1 + c_2 + c_3 \\ y_1 &= c_0 + wc_1 + \omega^2 c_2 + \dots + w^{N-1} c_{N-1} \\ y_2 &= c_0 + w^2 c_1 + \omega^4 c_2 + \dots + w^{2(N-1)} c_{N-1} \\ &\vdots \\ y_{N-1} &= c_0 + w^{N-1} c_1 + w^{2(N-1)} c_2 + \dots + w^{(N-1)^2} c_{N-1} \end{aligned} \quad (6.2)$$

The coefficients of this transformation can be written in the matrix form as

$$\begin{pmatrix} y_0 \\ \vdots \\ \vdots \\ \vdots \\ y_{N-1} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & \dots & 1 \\ 1 & w & w^2 & \dots & w^{N-1} \\ 1 & w^2 & w^4 & \dots & w^{2(N-1)} \\ \vdots & & & & \\ 1 & w^{N-1} & w^{2(N-1)} & \dots & w^{(N-1)^2} \end{pmatrix} \begin{pmatrix} c_0 \\ \vdots \\ \vdots \\ \vdots \\ c_{N-1} \end{pmatrix} \quad (6.3)$$

or equivalently $y = \tilde{F}c$. The $N \times N$ matrix $\tilde{F}$ is called the inverse-Discrete Fourier (iDFT) matrix since it operates on the Fourier coefficients and gives back the function components. The inverse of the iDFT is labelled as F and is called the DFT matrix. It operates on the function components and gives the corresponding Fourier coefficients. The relation between $\tilde{F}$ and F is given by

$$F\tilde{F} = \tilde{F}F = NI \quad \text{or} \quad F^{-1} = \frac{1}{N}\tilde{F} \quad (6.4)$$

where I is the $N \times N$ identity matrix.

In algorithmic sense, the DFT operation which involves multiplying with a $N \times N$ matrix takes $\mathcal{O}(N^2)$ time. An efficient algorithm was proposed by Cooley and Tukey [59] which computes the DFT in $\mathcal{O}(N \log N)$ time. This algorithm is called the Fast Fourier Transform (FFT). It computes such transformations by factorizing the DFT matrix into a product of sparse factors. The main idea of the FFT algorithm is to group the coefficients into two groups, even and odd and then dividing the transformation of length N into two pieces which are of length $N/2$ [60].

In our numerical calculations, functions from Python programming language's Discrete Fourier Transform "numpy.fft" package is used [61].

6.4. Analysis Procedure

The data analysis was done with a code written in Python programming language. The aim of the code is to read the data files and take the FFT of both the error signal and chopper signal. In order to quantify a chameleon signal, S/N ratio is defined and computed for each 10 seconds of interval. 10 seconds interval is chosen since the chopper is seen to be stable in at least that amount of time.

Step by step procedure of the algorithm is given below:

- (i) Read the data file line by line and get the error signal (Channel 1) and chopper signal (Channel 2).
- (ii) Divide each signal into equal chunks of period 10 seconds each.
- (iii) Take the FFT of the error and chopper signal for each chunk.
- (iv) Find the peaks in the FFT spectrum of the chopper signal and pick the frequency which has the maximum amplitude; set it to $\text{frq}_{\text{chopper}}$.
- (v) Look at the FFT spectrum of the error signal and find the amplitude corresponding to $\text{frq}_{\text{chopper}}$, set it to the value S (signal).
- (vi) Take a window of defined size n around $\text{frq}_{\text{chopper}}$ in the error signal, say $n = 4$, and compute the average within this window and define it as noise N .
- (vii) Define the signal-to-noise ration (S/N) by (v) and (vi).
- (viii) Define the RMS signal-to-noise ratio by calculating the signal and noise by taking RMS rather than average.
- (ix) Repeat this procedure for each chunk and combine the S/N values and plot them.

6.5. Results

After reading the data from the files, the analysis algorithm is applied which has been described in the Section 6.4.

The plots for the 17th December 2016 are shown below. The two plots are from the morning tracking and they cover 1800 seconds each (Figure 6.4 and Figure 6.5).

- Blue plot: Signal-to-noise ratio calculated using (vii) in Section 6.4
- Green plot: RMS signal-to-noise ratio calculated using (viii) in Section 6.4
- Red plot: The chopper frequency

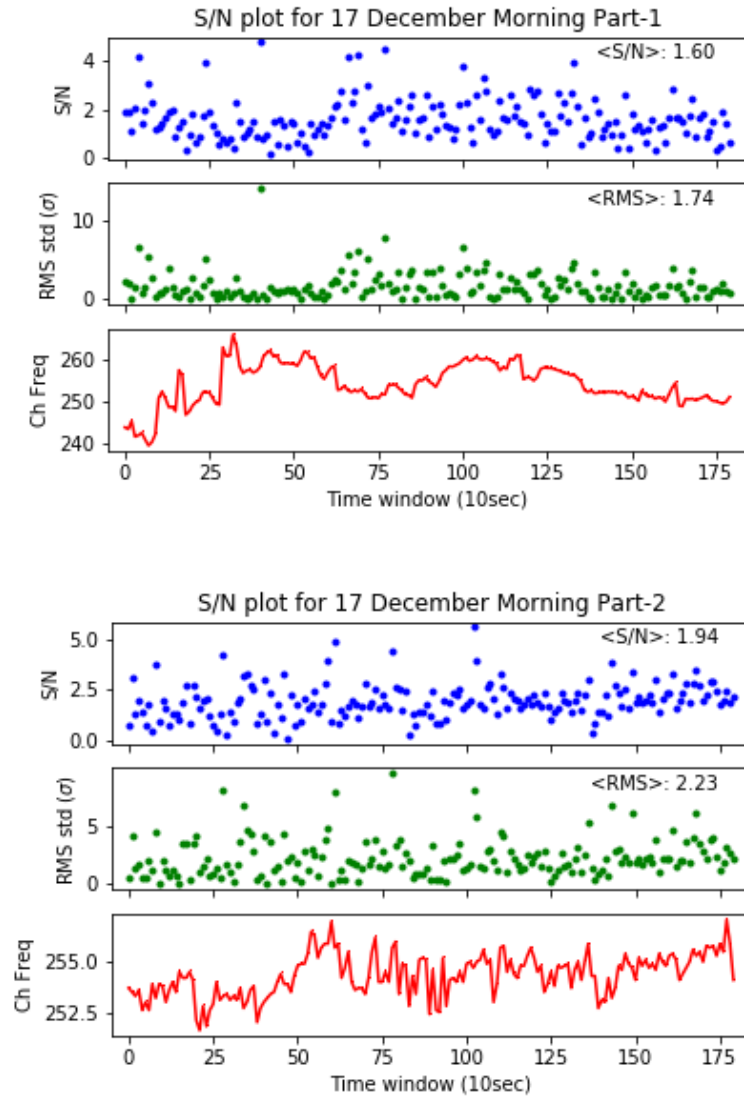


Figure 6.4. Signal to noise ratio and chopper frequency plots for 10 sec intervals of data taking while tracking

The plots show no significant signal in the tracking data with low S/N ratios.

The chopper frequency is unstable and changes on the order of 10 seconds interval. This unpredictable behaviour of the chopper becomes an obstacle to determine the reference signal for searching in the error signal.

The background S/N plots are also similar to the tracking plots. The two plots in Figure 6.5 are from the evening background data covering 1400 seconds each.

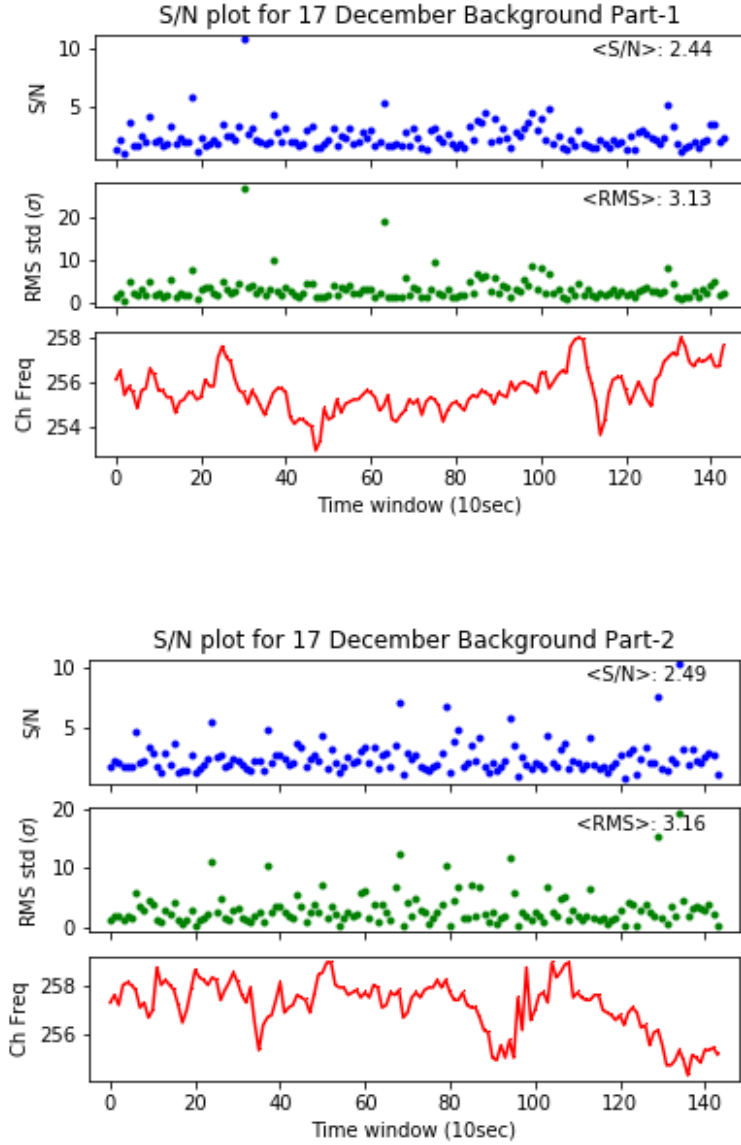


Figure 6.5. Signal to noise ratio and chopper frequency plots for 10 sec intervals of background.

If the data is inspected in detail, when each 10 seconds chunks of data is considered, there is significant peak around the chopper frequency both in the tracking and background data. The plots in Figure 6.6 and Figure 6.7 show the spectrum of both the error signal and the chopper signal together in 10 second interval of tracking and background data which were taken on 17th December 2016. The frequency resolution

is 0.1 Hz and the amplitudes in both plots are normalized.

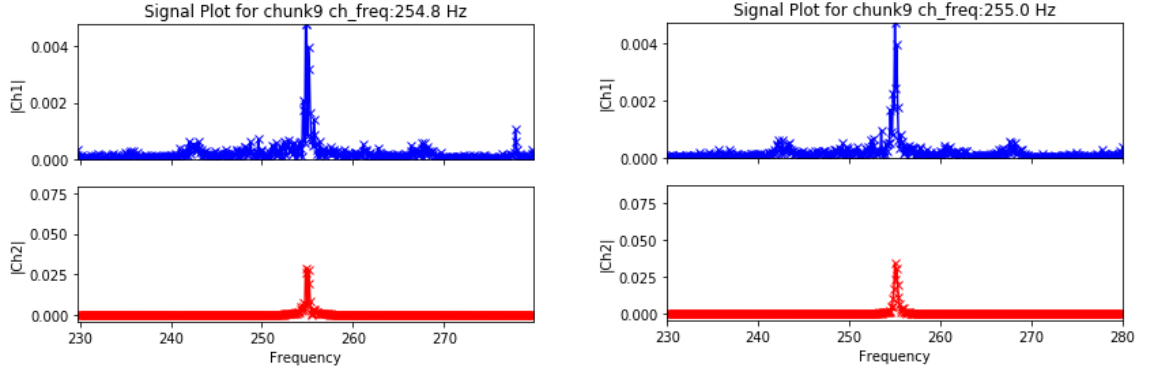


Figure 6.6. FFT plots for the error (blue) and chopper (red) signals in tracking; error signal showing a peak around the chopper frequency

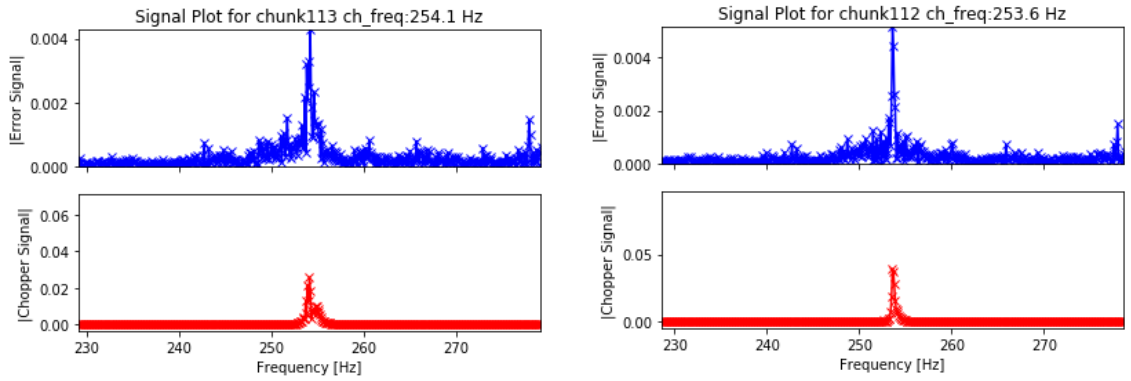


Figure 6.7. FFT plots for the error (blue) and chopper (red) signals in background data; error signal showing a peak around the chopper frequency

6.6. Discussion

Looking at the spectrum of the error signal and chopper signal, we can deduce the following:

- The chopper frequency is only stable on the order of 10 seconds and it oscillates around some mean value in irregular fashion. Thus, the reference frequency is always changing with time (Figure 6.4 and Figure 6.5).

- By looking at the FFT plots of each interval (Figure 6.6 and Figure 6.7), a coinciding peak at both spectra can be found. The peak of the error signal spectrum is at the same frequency of the chopper. The spectra are broad due to experimental errors but the coincidence is significant.
- The peak coincidences occur both at the tracking data when the magnet is tracking the Sun and the background data when it is stationary.
- The fact that the peak is also seen at the background eliminates the case that it is a signal coming from the chameleons.

The frequency component seen in the error signal at the chopper frequency must be due to an interfering effect where the source of it is yet undetermined. A possible cause can be due to acoustic noise generated by the turning chopper with the blades 'chopping' the air. Another possibility, the vibrations from the chopper mechanism might couple to the detector system since both of them are standing on the same board. The experiment area is also a very noisy place, considering the low and high frequency noises of the generators and various electric systems might also contribute to the observed signal. Lastly, the DAQ system controlled with the Red Pitaya might be interfering with the signal itself.

In order to find out the cause of the spurious signal and eliminate it, different methods are being implemented. One of the proposal is to decouple the chopper mechanism from the board so that it does not have any direct mechanical connection to the detector. Furthermore, in order to eliminate the possible noise generation while chopping the air, an isolating cover is proposed to be built around the chopper. Acoustic noise measurements are planned to be made with acoustic measuring devices at various places. Different chopper frequencies will also be set for data taking to see whether the problem still persists at different frequencies. The detector itself can also be covered with an isolating material so that it would be decoupled from the environment itself.

7. CONCLUSION

CAST experiment at CERN has been searching for dark matter candidate axions since 2003 and it has recently started to search for dark energy candidate chameleons. These searches have made use of the coupling of the mentioned hypothetical particles to the electromagnetic field through the Primakoff effect. More recently, CAST has broadened its search efforts by attempting direct detection of chameleon particles via their coupling to matter.

Towards this end, KWISP detectors which are based on Fabry-Perot and Michelson interferometers have been built, tested and run by the CAST experiment. The aim is to sense the tiny forces that are exerted by the chameleon flux coming from the Sun. A dielectric membrane is used as a sensing device which reflects the chameleon beams impinging on its surface at a grazing angle. Laser and an optical setup were used to detect the change in the displacement of the membrane.

In this work, data which were collected with KWISP in December 2016 were analysed using the Fast Fourier Transform. The spectrum of the error signal which was generated using the interference pattern coming from the detector and the spectrum of the chopper signal used as modulation reference signal were compared and signal to noise ratios were calculated. A matching signal has been observed at the chopper frequency both in the tracking and also in the background data. This behaviour is likely to be due to coupling of the chopper and the environment to the setup by means of mechanical noise. Noise measurements and noise cancellation modifications are being planned for further inspection.

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