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TRITIUM: Design, Construction and Commissioning of an In-Water Tritium Detector

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*Dedicated to
my family*

Sometimes it is the people no one imagines anything
of who do the things that no one can imagine.

"Alan Turing"

I

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Abstract

Tritium is one of the most abundantly emitted radioisotopes by nuclear facilities and, specifically, by nuclear power plants. Large amounts of tritium are normally produced in the water of their cooling system, which are finally emitted to the environment. Due to the fact that large releases of tritium could be dangerous for human health and for the environment, there exist several regulations around the world which try to control this radioactive emissions in each country, like the Directive Europeen 2013/51/Euratom, which establishes the tritium limit for drinking water in Europe to 100 Bq/L, or the U. S. Environmental Protection Agency, in United States, that limits tritium in drinking water to 20 nCi/L.

Due to the low energy of electrons emitted in the tritium decay, very sensitive detectors are needed for measuring them like LSC. The issue with LSC is that it is an off-line method and the measurement process can take 2 days or more, a time too long to detect a problem in the NPP.

Detectors based on solid scintillators are a promissing idea for building a tritium detector that works in quasi-real time. This type of detectors is developed so far succesfully but without achieving the required sensitivity of the legal limits.

The results of the TRITIUM project are presented in this thesis. In the framework of this project a quasi-real time monitor for low tritium

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activities in water have been developed. This monitor is based on a tritium detector that contains several detection cells which are read in parallel, several active vetos and a passive shielding for reducing the natural radioactive background and an ultrapure water system to prepare the sample before being measured. Each detection cell is made up of hundreds of scintillating fibers read out by PMTs or SiPM arrays.

The final objective of this monitor will be the radiological protection around the nuclear power plant. This monitor will provide an alarm in case of an unexpected tritium release that exceeds the legal limits established in Europe. The final idea will be to include this monitor in the early alarm system of Extremadura consisting of several detectors the objective of which is to control the impact of Nuclear Power Plants to the environment.

Keywords: Tritium, Tritiated water, Real-time monitor, Nuclear Power Plant, Environmental Safety, Radiosecurity.

Nomenclature and Acronyms

Acronyms:

<i>ALARA</i>	— As Low As Reasonably Achievable
<i>APD</i>	— Avalanche Photodiode
<i>BIXS</i>	— Beta Induced X-ray Spectrometry
<i>BWR</i>	— Boiled Water Reactor
<i>CCD</i>	— Charge-Coupled Device
<i>CDF</i>	— Dose Conversion Factor
<i>CE</i>	— Collection Efficiency
<i>CL</i>	— Collection Efficiency
<i>CNRS</i>	— Le Centre National de la Recherche Scientifique, France
<i>CSN</i>	— Nuclear Safety Council
<i>C_t</i>	— Terminal Capacitance of the SiPM
<i>DAQ</i>	— Data Acquisition System
<i>DRIM</i>	— Detecção da Radiação e Laboratório Imagem Médica laboratoire (Laboratory for Radiation Detection and Medical Imaging)
<i>EEC</i>	— European Economic Community
<i>EPA</i>	— Environmental Protection Agency
<i>EU</i>	— European Union
<i>EURATOM</i>	— European Atomic Energy Community
<i>FF</i>	— Fill Factor of a SiPM
<i>G – APD</i>	— Geiger Avalanche Photodiode

X

GCR	— Gas-Cooled Reactor
GL	— Guideline Level
G_{PMT}	— Gain of the PMT
G_{SiPM}	— Gain of the SiPM
$HPGe$	— High Purity Germanium Detector
HV	— High Voltage
HWR	— Heavy Water Reactor
$IAEA$	— International Atomic Energy Agency
IC	— Ionization Chamber
$ICRP$	— International Commission on Radiological Protection
$ICRU$	— International Commission of Radioactivity Units and Measurements
I_{DC}	— Intensity of the PMT due to the dark current
I_{PMT}	— Intensity of the PMT when photons are detected
ISR	— International Society of Radiology
$LARUEX$	— Laboratorio de Radiactividad Ambiental of the University of Extremadura (Environmental Radioactivity Laboratory of the University of Extremadura)
LDL	— Lower Detection Limit
LED	— Light-Emitting diode
LSC	— Liquid Scintillation Counting
LWR	— Liquid Water Reactor
$MAPD$	— Micro-Pixel Avalanche Photodiode
MDA	— Minimum Detectable Activity
$MPPC$	— Multi-Pixel Photon Counter
$MRS - ADP$	— Metal-Resistor-Semiconductor Avalanche Photodiode
NA	— Numerical Apertures
NPP	— Nuclear Power Plants
P_{av}	— Avalanche probability in a SiPM
PCB	— Printed Circuit Board
PDE	— Photodetection Efficiency of the SiPM
$PHWR$	— Pressurized Heavy Water Reactor

<i>PMMA</i>	— Polymethyl Methacrylates
<i>PMT</i>	— PhotoMultiplier Tube
<i>POF</i>	— Region of interest
<i>PVC</i>	— Polyvinylchloride
<i>PWR</i>	— Pressurized Water Reactor
<i>q</i>	— Annual Volume of drinking water consumed
<i>QE</i>	— Quantum Efficiency
<i>quasi-real</i>	— Less than 10 minuts
<i>RDL</i>	— Reference Dose Level
<i>REA</i>	— Network of automatic stations
<i>REM</i>	— Network of sampling stations
<i>ROI</i>	— Region of interest
<i>R_q</i>	— Quenching resistance of the SiPM
<i>S</i>	— Energy loss by the particle per unit of path length
<i>SDD</i>	— Silicon Drift Detector
<i>SiPM</i>	— Silicon PhotoMultiplier
<i>SSPM</i>	— Solid State PhotoMultiplier
<i>STP</i>	— Standard Temperature and Pressure conditions
<i>UDL</i>	— Upper Detection Limit
<i>UN</i>	— United Nations
<i>UNSCEAR</i>	— United Nations Scientific Committee on the Effects of Atomic Radiation
<i>U.S.</i>	— United States
<i>USA</i>	— United States of America
<i>U.S.DOE</i>	— United States Department of Energy
<i>U.S.EIA</i>	— United States Energy Information Administration
<i>U.S.EPA</i>	— United States Environmental Protection Agency
<i>V_{BD}</i>	— Breakdown Voltage of the SiPM
<i>V_{bias}</i>	— Supply Voltage of the SiPM
<i>V_O</i>	— Potencial difference between the n and p layers of the SiPM
<i>V_{OV}</i>	— Over voltage of the SiPM

WHO	— World Health Organization
ΔTV_{op}	— Temperature Coefficient (mV/ $^{\circ}C$)
δ	— Multiplication factor of a PMT dynode

Atomic and nuclear symbols

A_m	— Activity Measured
$^{10}_{\text{B}}$	— Boron
c	— Speed of the light in the vacuum
$^{12}_{\text{C}}$	— Carbon
$^{14}_{\text{C}}$	— Carbon isotope
$^{60}_{\text{Co}}$	— Cobalt
$^{137}_{\text{Cs}}$	— Cesium
$^2_{\text{D}}$	— Deuterium (Non-Radiative Hydrogen Isotope)
D_2O	— Heavy Water
e^-	— Electron
E_b	— Binding energy of the electron in a specific material
E_e	— Energy of the electron
$E_\gamma = h\nu$	— Energy of the photon
F_{sci}	— Active surface of the Plastic Scintillator
$^1_{\text{H}}$	— Hydrogen
$^2_{\text{H}}$	— Deuterium (Non-Radiative Hydrogen Isotope)
$^3_{\text{H}}$	— Tritium (Radiative hydrogen Isotope)
$^3_{\text{He}}$	— Isotope of the Helium (Non-radiative, 1 neutrons)
HT	— Air tritium molecule
HTO	— Water tritium molecule
H_2O	— Usual Water
$^{40}_{\text{K}}$	— Potassium
$^6_{\text{Li}}$	— Lithium Isotope
$^7_{\text{Li}}$	— Lithium
mip	— Minimum Ionizing Particle

m_0	— Rest mass of a electron
n	— Free Neutron
$^{14}_7\text{N}$	— Nitrogen
NaI(Tl)	— Thallium doped Sodium Iodide
$^{16}_8\text{O}$	— Oxygen
OBT	— Organic tritium molecule
q_e	— Electron Charge
Q_β	— Energy released in a radioactive decay
$^{222}_{86}\text{Ra}$	— Radon
S	— Specific Energy Lost
S_{ij}	— Single states of energy levels of electrons in scintillator
$^{90}_{38}\text{Sr}$	— Strontium
^3_1T	— Tritium (Radiactive hydrogen Isotope)
$T_{1/2}$	— Half-life Time of a Radioactive Element
T_{ij}	— Triple states of energy levels of electrons in scintillator
Z	— Atomic number
α	— Alpha Decay
β	— Beta Decay
γ	— Photon
ε_{det}	— Specific Detector Efficiency
η_{det}	— Intrinsic Detector Efficiency
λ	— Wavelength
λ_p	— Maximum wavelength of the associated spectrum
σ	— Cross Section of a radioactive process
σ^{rel}	— Relative uncertainty
σ_{si}	— Sistematically Component of the Uncertainty
σ_{st}	— Stadistical Component of the Uncertainty
σ_T	— Total Uncertainty of the Measurement
$\bar{\nu}_e$	— Electron Antineutrino

Units:

A	— Ampere (C/s).
Bq	— Becquerel, Nuclear Decay Number per Second
Bq/L	— Becquerel per Liter
C	— Coulomb.
Ci	— Curies
Ci/L	— Curies por Liter
Ci/yr	— Curies per year
F	— Farads
g CO ₂ /kWh	— Grams of CO ₂ per Kilowatt Hour
h	— Hour
kcps	— Kilo Counts per Second
L	— Liter
m	— meter
mrem	— Millirem
STP	— Standard Temperature (0°C = 273K) and Pressure (1 atm)
Sv/cm	— Sievert per Centimeter
T	— Temperature (°C).
V	— Voltage.
W	— Watt
yr	— Year

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Chapter 1

Introduction

1.1 Tritium and Nuclear Energy

Radioactivity has been present in the Universe since its inception. It was an important element of the Big Bang¹, which occurred about $14 \cdot 10^9$ years ago. It was also present during the formation of the earth, $4.5 \cdot 10^9$ years ago, which explains why the different layers that make up the earth contain radioactive elements.

Therefore, humanity has been exposed to radioactivity since its origin, whether present in the Earth's crust or in the universe (external natural irradiation). Even the human being himself is radioactive as radioactive elements are contained in the human body such us ${}^3\text{H}$, ${}^{14}\text{C}$ or ${}^{40}\text{K}$, introduced into the body through food or water ingestion or air inhalation (internal natural irradiation). The annual average of the radioactive dose received by the population is presented in Figure 1.1 and Table 1.1.

¹The Big Bang is the most acceptable hypothesis that explains the formation of the universe and its development over time so far.

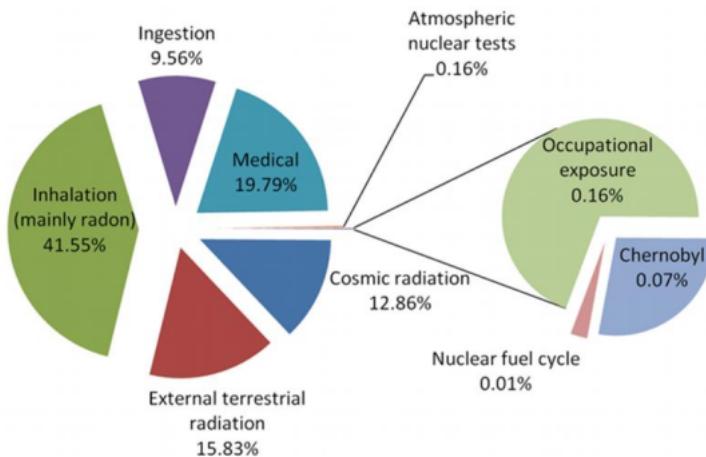


Figure 1.1 – Annual average distribution of the radioactive dose received by the population [IAE21].

As it can be seen in Figure 1.1, most of the radioactive dose received by the population is due to both, internal and external natural radioactivity, the effective dose² of which is estimated in 2.42 mSv/yr shown in Table 1.1.

Since the discovery of radioactivity, made by Hènri Becquerel in

²The effective dose is the radioactive dose absorbed by the population, taking into account the different radiosensitivity of each organ or tissue.

Radiation source	Eff. dose (mSv/yr)	Typical range (mSv/yr)
Cosmic (external)	0.39	0.3 – 1.0
terrestrial (external)	0.48	0.3 – 0.6
Inhalation (internal)	1.26	0.2 – 10
Ingestion(internal)	0.29	0.2 – 0.8
Total	2.42	1 – 12.4

Table 1.1: Annual average distribution of the effective dose received by the population due to natural radioactive [UNS21, CSN21a].

1896, a lot of technology based on nuclear concepts has been developed and applied to several fields such as energy production, research, medicine, industry, etc. Due to the introduction of radioactivity in the society, various anthropogenic radioactive sources have appeared in the environment, resulting in increased levels of radioactive elements. It can be noticed in Figure 1.1 that the most important part of the artificial radiation received by humans comes from medical practices. As our knowledge about radioactivity and our measurement techniques advance, the harmful effects of radioactivity were observed and characterized. Because of that, it is important to control the level of radioactive background to which the population is exposed and to ensure that these levels are kept below of a safe limit. To accomplish this task, several organizations were created to forward recommendations in radiological protection to the different organizations and governments of the world:

1. A definition of concepts and units was necessary to quantify the negative effects of radioactivity and, for that, the International Commission of Radiological Units and Measurements, ICRU [ICR21b], was created during the first international conference of radiology held in London, in 1925.
2. The International Commission on Radiological Protection, ICRP [ICR21a], was created in 1928 by the International Society of Radiology, ISR [ISR21]. The ICRP aims to make recommendations and to provide guidance on different aspects of protection against radioactivity. The ICRP does not have the legal capacity to enforce its recommendations, but these are widely included in the legislation of most countries.
3. The United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR [UNS21], was created in 1955, with the goal of estimating and reporting the levels and effects of ionizing radiation on the population and the environment. These estimates are taken

into account by governments around the world to establish their safety standards.

4. The International Atomic Energy Agency, IAEA [IAE21], was created in 1957 to promote the peaceful use of nuclear energy and to avoid its use for military purpose such as nuclear weapons. Although IAEA is an independent agency, it must report to the United Nations, (UN) [UN21].
5. At the level of the European Union (EU), the European Atomic Energy Community (EURATOM) was created in 1957, which is an international organization established by the EURATOM treaty. Its objective is to coordinate research programs for the peaceful use of nuclear energy and the sharing of knowledge, infrastructure and funding of nuclear energy.
6. In Spain, the Nuclear Safety Council (CSN) was created in 1980 [CSN21a]. The CSN is the only institution in Spain in matter of nuclear safety and radiological protection and its objective is to reduce to the maximum the radioactivity of anthropogenic origins in the environment. For this task, the CSN has created various networks consisting of several detectors of radioactivity that are in charge of controlling the levels of radioactivity in the environment and checking the impact of radioactivity facilities. Two of the most important networks are the network of automatic stations (REA) and the network of sampling stations (REM):
 - (a) The network of automatic stations [CSN21b], REA for its acronym in Spanish, shown in Figure 1.2a, consists of several gamma detectors³ distributed in Spain that measure the radioactive dose in real time. The REA is employed for the instantaneous detection of radiological problems and the application of quick response.

³Detectors that only measure gamma radioactivity



(a) Measured points of the REA [CSN21b]. The white box is the daily average of the gamma dose and the green box is the monthly average of the gamma dose.



(b) Measured points of the REM [CSN21c]. Blue dots are located around nuclear facilities. Green dots are uniformly distributed in Spain.

Figure 1.2 – Networks of automatic and sampling stations managed by the spanish CSN.

- (b) The network of sampling stations [CSN21c], REM for its acronym in Spanish, shown in Figure 1.2b, consists of several strategic points in Spain where samples are taken and transported to a laboratory to be measured. About twenty Spanish laboratories integrate this network, the objective of which is to characterize the concentration and evolution of various radioisotopes present in the radioactive background of Spain and to quantify the impact of radioactive facilities on the environment.

There are other networks that measure different parameters such as the concentration of ^{222}Ra in the air. The measurements of all the networks are adapted to the EUROTAM treaty [Dir21].

The goal of this thesis and the *TRITIUM* project is to develop a monitor capable of automatically measuring low levels of tritium in water

in quasi-real time⁴. This monitor is intended to be finally included in the REA.

Tritium is one of the radioactive isotopes routinely measured in REM tests and it is detected through the low-energy electrons produced in tritium beta decay, mainly through the liquid scintillation counter technique (LSC). Due to the limitations of the current methods, which will be described in section 2.1, the *TRITIUM* project is created, the objective of which is to build a tritium detector based on scintillating fibers in contact with the sample (water). The photons produced in these scintillating fibers are read out using photosensors, either photomultiplier tubes (PMTs) or silicon photomultipliers (SiPMs).

The *TRITIUM* collaboration is an international group consisting of a consortium of 6 different European institutions of 3 different countries: Portugal, France and Spain. The final emplacement of the *TRITIUM* monitor is the Arrocampo dam, Extremadura, Spain, the water of which is used for the cooling system of the Almaraz nuclear power plant (NPP). This detector will be installed 4 km downstream from the Almaraz Nuclear Power Plant.

The monitor will be used to ensure that the tritium levels of the Arrocampo dam water are below of the legal limit specified in the EURATOM treaty [Dir21], which is 100 Bq/L and, indirectly, it will be used to verify the correct operation of the Almaraz NPP since its malfunctioning may produce an increase of tritium activity released.

Tritium is one of the most abundantly produced radioisotope in a NPP, as it was verified in the United States Department of Energy complex, (U.S. DOE) [Berb, Bera] and in several research facilities in China [Hou18] and places around them (ground water, surface water and process waste

⁴Quasi-real time is an approximation of real-time measurements. It means a relatively small time, like ten minutes.

water).

Tritium is produced in the water used for nuclear reactor cooling system of some NPPs by neutron capture of deuterium, existing in the heavy water (D_2O), semi-heavy water (HDO) or deuterium created by neutron capture in usual water (H_2O). All these processes have a large probability to happen due to the huge neutron flux in a nuclear reactor, of the order of $10^{14} \text{ n cm}^{-2}\text{s}^{-1}$ [?]. This tritium is finally released partially or totally to the environment in a quantity that depends on the reactor type as it is shown in Table 1.2. The most common form in which tritium is released to the environment is HTO [Hou18].

Reactor type	Gaseous discharge (GBq/y)	Liquid discharge (GBq/y)
PWR	$3.70 \cdot 10^3$	$2.59 \cdot 10^4$
BWR	$1.85 \cdot 10^3$	$3.70 \cdot 10^3$
HWR	$7.40 \cdot 10^5$	$1.85 \cdot 10^5$
GCR	$7.40 \cdot 10^3$	$1.11 \cdot 10^4$

Table 1.2: Emission of tritium per year from different types of nuclear reactors. Pressurized Water Reactor (PWR), Boiled Water Reactor (BWR), Heavy Water Reactor (HWR) and Gas-Cooled Reactor (GCR) [Hou18].

NPPs are operational since more than 60 years and, nowadays, they are essential for providing a large part of the electric power used in the world (more than 20% in Spain [dE19] and more than a 10% in the world [AIde14]). Although the Spanish government is planning to progressively shut down all NPP there are other countries like China [Pre16] or United States, USA [New19], that promote their use. NPPs are a profitable investment since they are one of the cheapest source of energy production. Their energy production rate is stable as this doesn't depend on meteorological parameters. Moreover, NPPs do not emit greenhouse gases. Although there are alternative energy sources which are being developed quickly (photovoltaic, wind, tidal energy, etc.), even other concepts of energy production and saving (local production, solar roofs, energy efficiency,

smart cities, etc.), today they are not developed enough to fully cover the population needs. On the other hand, NPPs still have some problems such as the contamination of fresh water from uranium mining, the nuclear waste produced, the nuclear proliferation or the risk of radioactive contamination from accidents as happened in the past: Chernobyl, Fukushima and Three Mile Island [Ass20].

In any case, world nuclear energy production is not going to be stopped in the next decade. In fact, the United States Energy Information Administration (U.S. EIA) expects an increase of nuclear energy production [Cap20]. Therefore the development of different types of alarm systems is a good investment. Safety is not a negotiable aspect and there must be safeguards that warn us of any malfunction of a nuclear power plant. In addition, it is important to highlight that the developed monitor could be used to check the correct operation of a nuclear power plant, but this is not our objective. Our objective is to ensure that the levels of tritium in the analyzed water are below the Spanish legal limit. It means that this monitor could be used in many different places with radioactive facilities like the future fusion power plants⁵, nuclear research facilities⁶ or tracking the pathway of tritium discharges to ground water [AS00].

1.2 Tritium Properties and Radiological Hazards

Tritium is the only radioactive isotope of hydrogen present in the environment. It was produced for the first time in 1934 in neutron capture of deuterium by Ernest Rutherford, Mark Oliphant and Paul Harteck [MLO34] and it was isolated in 1939 by Luis Walter Alvarez and Robert Cornog

⁵The International Thermonuclear Experimental Reactor, ITER, will need up to several tens of kilograms of tritium to function, which correspond to various TBq of tritium.

⁶Tritium is one of the main emissions from these sites [Fer19], [(BN)].

[Alv39], who checked that tritium is a radioactive element.

Tritium is naturally produced in the environment through the interaction of cosmic rays and gaseous elements of the upper atmosphere like nitrogen ($^{14}\text{N}(\text{n}, ^3\text{H})^{12}\text{C}$) [USDoEW16] and oxygen ($^{16}\text{O}(\text{n}, ^3\text{H})^{14}\text{N}$) [Hai14]. Around 99% of cosmogenic tritium forms water (HTO) and reaches the Earth's surface as rain with an estimated production rate of $4 \cdot 10^6 \text{ Ci/yr}$ ($1.48 \cdot 10^8 \text{ GBq/yr}$), producing a tritium concentration of $0.6 - 1.2 \text{ Bq/L}$ in precipitation [Hou18, USDoEW16].

Tritium can be produced artificially in the environment from different anthropogenic sources [Hou18, USDoEW16]. There is a large amount of tritium which was produced in military nuclear test explosions between 1945 and 1975, with an estimated total production of $8 \cdot 10^9 \text{ Ci}$ ($2.96 \cdot 10^{11} \text{ GBq}$), a part of which remains to the date. In these nuclear explosions, tritium was produced mainly from the nuclear reactions $^{14}\text{N}(\text{n}, ^3\text{H})^{12}\text{C}$ and $^2\text{H}(\text{n}, \gamma)^3\text{H}$. Tritium is produced by commercial producers of radioluminescent and neutron generator devices ($1 \cdot 10^6 \text{ Ci/yr}$), nuclear power and defense industries (around $2 \cdot 10^6 \text{ Ci/yr}$) and several research facilities and nuclear reactors for energy production ($2 \cdot 10^6 \text{ Ci/GWyr}$). The production cross sections of the relevant process are shown in Table 1.3.

Source	Origin	Nuclear reaction	Cross section (b)
^2H	Water coolant	$^2\text{H}(\text{n}, \gamma)^3\text{H}$	$5.2 \cdot 10^{-4}$
^3He	Helium coolant	$^3\text{He}(\text{n}, \text{p})^2\text{H}$	5330
^6Li	Moderator	$^6\text{Li}(\text{n}, \alpha)^3\text{H}$	940
^{10}B	Moderator, control rods	$^{10}_5\text{B}(\text{n}, 2\alpha)^3\text{H}$	3835

Table 1.3: Most common nuclear reactions of artificial tritium production [Hou18].

Tritium levels in the water of the environment, excluding anthropogenic radioactive sources, are between 1 and 4 Bq/L, larger than the

expected due to the cosmogenic background levels ($0.6 - 1.2 \text{ Bq/L}$) [Cal10]. This can be attributed to nuclear weapons tests. Tritium levels in rivers around a NPP are between 1 and 10 Bq/L and even between 20 and 50 Bq/L at the water discharge site of NPPs [Cal10], where the produced tritium is partially or totally released into the environment, mainly in the HTO water form.

The effect of NPP on tritium levels can be observed in the REM data, for example for the case of Cofrentes. Cofrentes is the closest nuclear power plant to Valencia. The tritium level is measured in three different places along the Jucar river, marked on the map shown in Figure 1.3. The first place, P1, is located in the river, 6 km upstream from the NPP, the second place, P2, is located 1 km downstream and the third place, P3, is located 5 km downstream. The level of tritium measured in these three locations is shown as a function of the time in Figures 1.4a, 1.4b and 1.4c respectively.

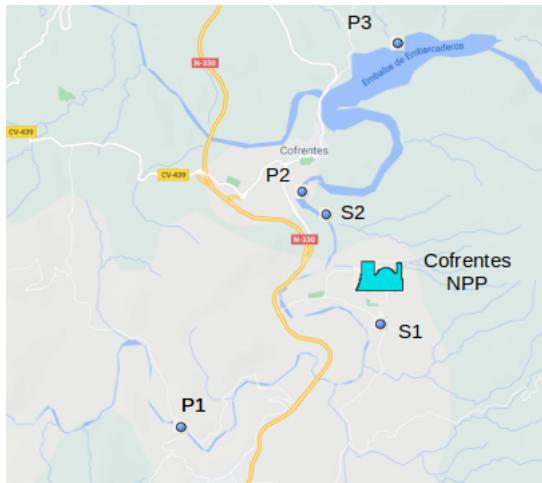
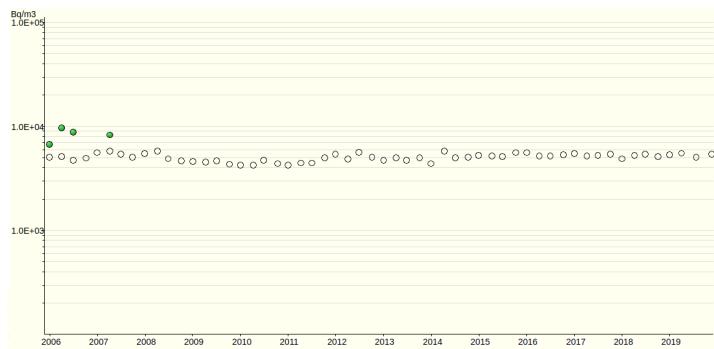
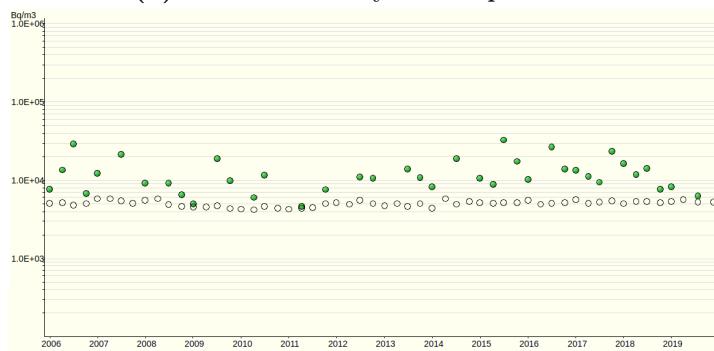


Figure 1.3 – Tritium sampling locations around Cofrentes NPP.

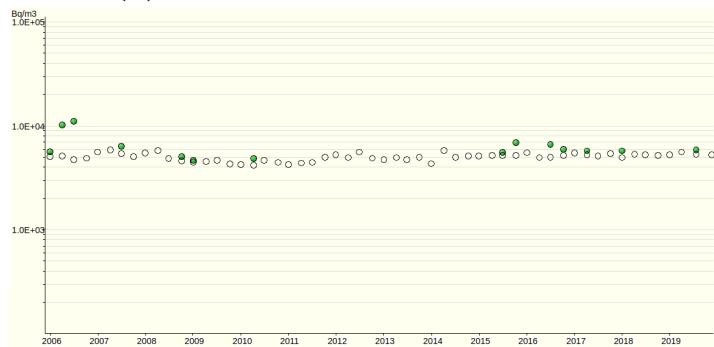
In these figures, the detection limit and the measured activity is plotted by white and green dots, respectively. The measured activity is only displayed when this is larger than the corresponding detection limit.



(a) Tritium activity 6 km upstream.

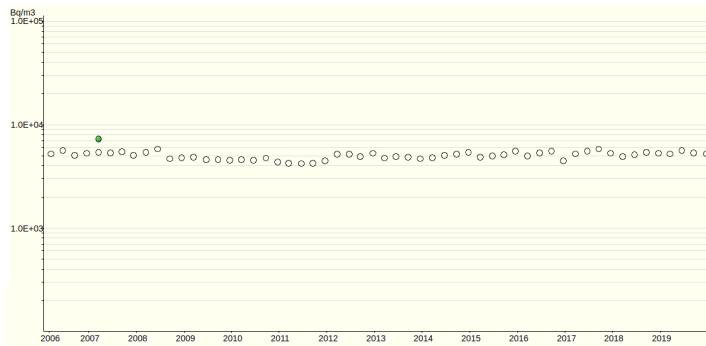


(b) Tritium activity 1 km downstream.

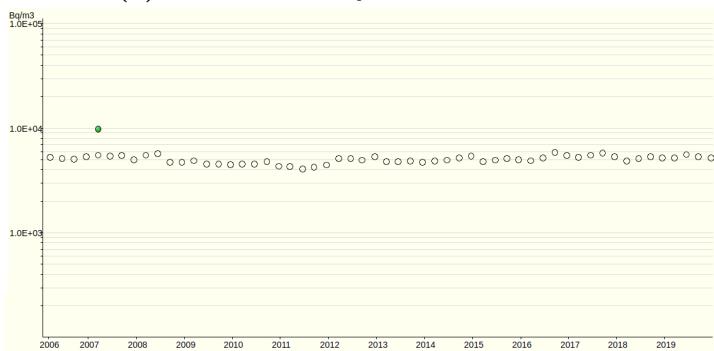


(c) Tritium activity 5 km downstream.

Figure 1.4 – Tritium activity levels in surface water around Cofrentes NPP from January 2006 to November 2019. The white points are the detection limit and the green points are the measured activity, when this is above the detection limit [CSN21c].



(a) Tritium activity 1 km before NPP.



(b) Tritium activity 1 km after NPP.

Figure 1.5 – Tritium activity levels in groundwater around Cofrentes NPP from January 2006 to November 2019 [CSN21c].

The tritium level in the river increases due to the discharge of the NPP and it is diluted again after 4 km downstream, as can be seen from these data. Two additional measurements of the tritium level in groundwater are included, points S1 and S2 on the map in Figure 1.3, located 1 km before and 1 km after the NPP. Both tritium levels are shown in Figures 1.5a and 1.5b, respectively, where it can be observed that they are below the detection limit.

It is important to note that, although environmental tritium level is affected by NPP, these levels are below the maximum allowed limit. The maximum level of tritium measured since of January 2, 2006 is around

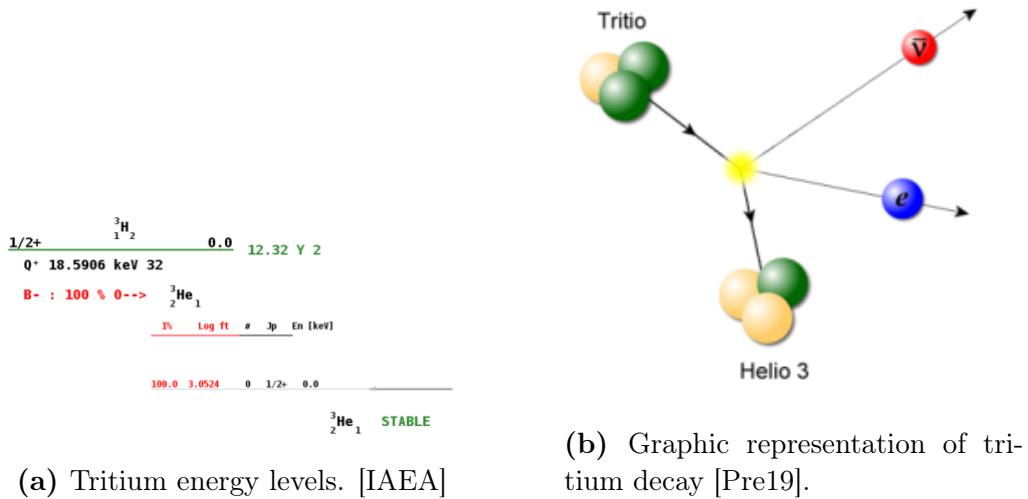


Figure 1.6 – Tritium decay.

32 Bq/L, below the maximum allowed limit in Europe, 100 Bq/L.

Tritium is a radioactive element with a half-life time of $T_{1/2} = 12.32$ years. It has one proton and two neutrons and decays exclusively through β radiation. Tritium decays 100% directly to the ground state of the ^3_2He isotope of helium, which is a stable nuclei, through the process,



In Figure 1.6, the scheme of tritium energy levels is shown. In this decay it is not possible to detect the neutrino because of its extremely weak interaction with matter ($\sigma \propto 10^{-44} \text{ cm}^2$ [Her07]) and, since ^3He has a much larger mass than electrons and neutrinos, by conservation of energy and momentum, the energy is taken by the daughter nucleus is very small. Therefore, the detection of tritium is through its decay electron.

The energy released in the tritium decay is $Q_\beta = 18.6 \text{ keV}$, shared between the decay products. Therefore, the energy spectrum of the decay

electrons is a continuum with a maximum value of 18.6 keV, as shown in Figure 1.7. This energy spectrum has an average energy of 5.7 keV and the most likely energy is slightly below, around 4.5 keV.

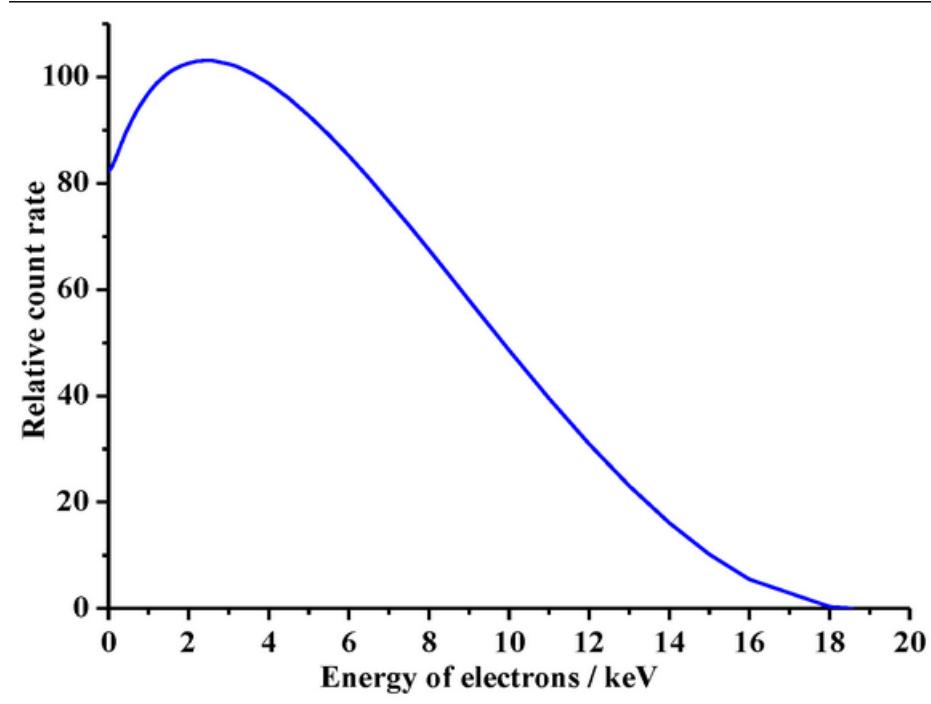


Figure 1.7 – Energy spectrum of tritium electrons [Lin20].

The released energy in tritium decay, is very low. In fact, it is the radioactive isotope with the lowest energy released in β decay [USDoEW16]. Consequently, the β particle is emitted has a very short mean free path, given in Table 1.4.

This short mean free path is a major issue in tritium detection, as it makes more difficult the electron detection, which requires a highly sensitive detector. It also means that tritium electrons have a low penetration in our body and they are easily stopped by clothes or laboratory gloves, resulting in a low radiological hazard of external tritium. Nevertheless, the danger of tritium increases when this is ingested or inhaled since it binds and perform

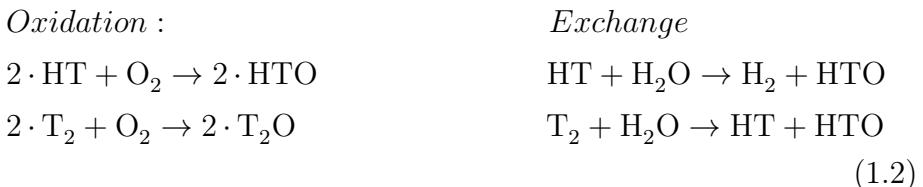
Material	P. Depth (5.7 keV)	P. Depth (18.6 keV)
${}^3_1\text{H}_2$	0.26 cm	3.2 cm
Air	0.036 cm	0.45 cm
Water, soft tissue (solid matter with a density of $1 \text{ g} \cdot \text{cm}^{-3}$)	$0.42 \mu\text{m}$	$5.2 \mu\text{m}$

Table 1.4: Penetration depth for decay electron of mean (5, 7 keV) and maximum (18, 6 keV) energies in different media (tritium gas and air at standard conditions of temperature (273 K) and pressure (1 atm), STP, and water) [Bla].

the same chemical reactions as hydrogen, sometimes with higher rate if the tritium concentration is high enough to catalyze the reaction.

Tritium can be absorbed in our body in three different forms, gaseous tritium (mainly HT), tritiated water (mainly HTO) and organically bound tritium (called OBT).

1. Gaseous tritium, which is normally found mixed in the air, is the least harmful since less than a $3 - 5 \cdot 10^{-3}\%$ is absorbed by the human body, which is negligible [USDoEW16]. However, it can be transformed into tritiated water, more harmful from a radiobiological point of view [USDoEW16], through the oxidation and exchange reactions by equations 1.2:



2. Tritiated water, which is normally found in drinking water and food,

has a larger impact since the 99% of it is absorbed [USDoEW16]. Its biological life-time corresponds to the water cycle in the body, around 9.5 days ($\pm 50\%$), during which tritium remains in our body [USDoEW16, Cal10, Mas]. As in the case of water, the biological life-time of tritiated water can vary due to various external parameters such as temperature, humidity, drinking habits, etc. or reduced with the use of diuretics [USDoEW16].

3. Organically bound tritium, normally found in food, generally forms a covalent bond with a carbon. It corresponds to 5 – 10 % of tritium absorbed in the body. Although it is less absorbed in the body than tritiated water, it can be more dangerous since it has a longer biological life time. The biological life-time of this tritium compound depends on the affinity of the organic molecule to the different biological tissues and it can vary from tens to hundreds of days (larger than the ICRP estimate) [Cal10, Mas, PF81, Mar72].

There are many studies showing that tritium in living matter can cause the same effects than X-rays or γ rays, which are mutations, tumors, cancer, genetic effects, reproductive effects, etc [Str93, Ryt]. In fact, the consequences of tritium radiation may be worse than a similar γ radiations since its biological efficiency⁷ is two or three times larger [Str93].

In summary, tritium is a naturally occurring radioactive element that can affect health if it is excessively released. Because of that, each country has developed a legislation, described in section 1.3, to manage the release of tritium and ensure that its levels in the environment are safe for health.

⁷The biological efficiency is used to quantify the damage produced in the living cells due to an external radiation.

1.3 Current Legislation

Due to the radiological risk of tritium, described above, it is important that the current legislation limits the release of tritium to the environment ensuring that the levels are below a safe value for health.

The guidelines to limit the radioactive elements in drinking water for many countries. They are based on the radiation protection methodology developed by the ICRP [ICoRP91] and the recommendations of the world health organization (WHO) [WHO04]. The objective of the international radiation methodology is to protect people and the environment from the negative effects of ionizing radiations but allowing beneficial activities that involve a reasonable radiation exposure. It is based on three main points, which are:

1. The justification: The benefit from radiological exposure must outweigh the detriment to health that it causes.
2. The ALARA principle ("As Low As Reasonably Achievable"): The radiological exposure must be kept as low as possible considering social and economic factors.
3. The dose limitation: Limit that must never be exceeded.

While the ICRP recommends a maximum dose of 1 mSv/yr, excluding the natural background and medical interventions, the WHO is more conservative, recommending a maximum dose of 0.1 mSv/yr, which correspond to less than 5% of the annual dose due to background radiation, 2.42 mSv/year.

The guideline reference level of each radionuclide in drinking water,

GL, is usually calculated from these recommendations using the equation,

$$GL(\text{Bq/L}) = \frac{RDL}{DCF \cdot q} \quad (1.3)$$

where RDL is the reference dose level, DCF is the dose conversion factor (the normal used value for tritium is $1.8 \cdot 10^{-11}$ Sv/Bq, provided by ICRP [ICoRP96]) and q is an estimation of the annual volume of drinking water consumed (normally assumed two liters per day, 730 L/yr).

The GL calculated for tritium in drinking water according to the ICRP and WHO recommendations is 76, 103 Bq/L and 7, 610 Bq/L respectively. It means that tritiated water with activities below these values is considered not harmful for health.

Based on these recommendations, each country has created organizations in charge of developing its own legislation on radionuclide limits. In Spain, the responsible organization of this task is the CSN. Most of the countries in the world implement the RDL of 0.1 mSv/yr recommended by the WHO. The legal limit for tritium in drinking water in this case is 7, 610 Bq/L but it is often approximated in different ways. Some countries like Switzerland [Dfdl06] or some organizations like the WHO [WHO04] take this value as 10, 000 Bq/L. Others like some countries of Canada, such as Ontario and Québec, truncate this value to the first number 7, 000 Bq/L [otE94, Que16]. There are other countries like Russia which use the much more accurate approximation value of 7, 700 Bq/L [ICfS07]. There are other countries like Australia that prefer to implement the RDL of 1 mSv/yr, recommended by the ICRP, the legal limit of which is 76, 103 Bq/L [AG21]. Other countries like Finland are based in the ICRP recommendations and use only half of this value, 0.5 mSv/yr, rounded to a legal limit of 30, 000 Bq/L for tritium in drinking water [NEA93].

There are two different exceptions to these recommendations:

1. Most of the USA states like California use a RDL of 4 mrem (0.04 mSv), which corresponds to a legal limit of 20 nCi/L (740 Bq/L) [OoEHHA07]. This value was proposed by the United States Environmental Protection Agency (US EPA) as a result of an analysis performed [USEPA76].
2. Most of the EU countries, such as France, Germany or Spain, impose an GL of 100 Bq/L, which is one of the most restrictive limit in the world [Idredsn17, BfS05, CdSN13]. This value arise from the consideration that it is an indicator of the presence of other radionuclides more dangerous than tritium. These limits are fixed by the EURATOM Council Directive [EAEC13].

All limits mentioned in this section are summarized in table 1.5.

Country/Agency	Legal limit of tritium in water (Bq/L)
ICRP	76, 103
WHO	10, 000
Switzerland	10, 000
Canada	7, 000
Russia	7, 700
Australia	76, 103
Finland	30, 000
United States	740
European Union	100

Table 1.5: Legal limit of tritium in drinking water established in each country.

1.4 This Thesis

This thesis is divided into nine different chapters that structure the information as follows:

Chapter 1 provides a brief introduction to tritium detection, reports some important properties of tritium, and discusses the current legislation that limits tritium levels in many countries around the world. **Chapter 2** describes the State-of-the-Art of tritium detection and shortly introduces the TRITIUM project. **Chapter 3** outlines the different parts of the TRITIUM monitor, which are the ultrapure water system, the background rejection system (consisting of the lead shielding and the active veto) and the tritium detector. **Chapter 4** reports the calibrations of the different parts of the TRITIUM monitor and specify the developments aimed at improving the efficiency of tritium detection. **Chapter 5** details the geometrical configuration of the different prototypes built in the TRITIUM project and **Chapter 7** reports the measurements carried out. **Chapter 6** details the Monte Carlo simulations performed, the result of which are shown in **Chapter 8**. Finally, **Chapter 9** summarizes the most important results achieved in this work.

Chapter 2

Tritium Detection Systems

2.1 State-of-the-Art

Measurement of tritium activity is one of the routine environmental controls that are carried out in the vicinity of nuclear research facilities and nuclear power plants during their energy production lifetime. Consequently, this measurement is carried out with different available technologies under development to improve the state of the art of tritium detection. The most employed techniques are summarized in Table 2.1.

Nowadays, the most used technique for measuring tritium in water is liquid scintillator counting (LSC). This technique consists of mixing a liquid sample (some milliliters for environmental measurements or less for higher activities) with liquid scintillator. This mixture is usually made in a ratio of 50:50 but it depends on the detection system and on the activity of the samples [AH99, Hof92a]. In this technique, the β particles emitted from the sample excite the molecular energy levels of the liquid scintillator which promptly decays emitting several photons with a well-known energy (fluorescence), usually in the visible spectrum. Finally, these photons are detected

	LSC	IC	Calorimetry	BIXS
Measured quantity	Scintillation photons	Ionization current	heat	X-rays
LDL	$\sim \text{Bq}$	$10 - 100 \text{ kBq}$	$\sim \text{GBq}$	$\sim \text{MBq}$
Sample form	Liquid	Gas, vapor	All	All

Table 2.1: State-of-the-art of tritium detection by different techniques. This table shows the measured quantity, low detection level (LDL) and the sample form for four different techniques, liquid scintillator counting (LSC), ionization chamber (IC), calorimetry and beta induced X-ray spectrometry (BIXS).

with photosensors, which convert the optical signal into a measurable electrical charge. The liquid scintillator technique has a very good detection sensitivity for low activity levels of tritiated water ($< 1 \text{ Bq/L}$) [Pal07] but it has the problems of long measurement time (up to 2 days) and of producing chemical waste, since liquid scintillator contains toluene which is toxic. In addition, this technique requires special staff for sampling, chain-of-custody and lab analysis which require economical and time resources. In order to avoid this problem some unsuccessful efforts have been made in order to build a monitor of tritium with LSC [Sig94].

The ionization chamber (IC) consists of a gas chamber (sample) which contains electrodes that collect the ionization current that is produced due to the β radiation. It is a simple and fast system, but it has the problem of high Low Detection Limit ($> 10 \text{ kBq}$) and of requiring the samples to be in a state of gas or steam [Khe02, ZC13].

The calorimetry method is based on the measurement of the heat generated in the detection medium (normally platinum) [CGA17, BD13]. The problem with this technique is that it has a high LDL, of the order of a GBq, and requires long measurement time, 2 days or more.

The Beta Induced X-ray Spectrometry (BIXS) is based on the

measurement of the bremsstrahlung radiation produced by the tritium decay electrons, using a NaI(Tl) crystal coupled to a PMT [Mat07, Mat08] or Silicon Drift Detector (SDD) [Nie15]. The problem with this technique is its high LDL, of the order of MBq.

There are additional methods for tritium detection, although they are less employed or less developed, each one with its own advantages and limitations. For example, the Avalanche PhotoDiode (APD) cannot be used in contact with water [Sha97], the mass spectrometry which needs to store the sample several months before taking the measurement [JB10] and the Cavity ring spectroscopy requires a special optical configuration that is not possible outside a laboratory [Bra15].

All the above techniques are offline methods that need long time for sample collection, shipment to the laboratory and activity measurement. Therefore, they cannot be used for in-situ monitoring of tritium in water. The liquid scintillation technique is the only one with sufficiently small LDL to fulfill the requirement of 100 Bq/L of tritium in the water samples, established by the EURATOM directive.

The purpose of the TRITIUM project is to develop an alternative method, based on solid scintillators, that allows to accomplish the requirements of in-situ monitoring of levels as low as 100 Bq/L in quasi-real time. There are several studies with solid scintillators so far:

1. The study done by M. Muramatsu, A. Koyano and N. Tokunaga in 1967 who used a scintillator plate read out by two PMTs in coincidence [Mur67].
2. The study carried out by the A. A. Moghissi, H. L. Kelley, C. R. Phillips and J. E. Regnier in 1969 that used one hundred plastic fibers coated with anthracene powder and read out by two PMTs in coincidence [Mog69].

3. The study performed by R. V. Osborne in 1969 that used sixty stacked scintillator plates read out by two PMTs in coincidences [Osb70].
4. The study done by A. N. Singh, M. Ratnakaran and K. G. Vohra in 1985, that used a scintillator sponge read out by PMTs in electronic coincidence [Sin85, MR00].
5. The study carried out by K. J. Hofstetter and H. T. Wilson in 1991, that tested different shapes of scintillator plastics like several sizes of beads, fibers, etc. The better result obtained for solid plastic scintillator was a tritium detection efficiency, ε_{det} , of the order of $10^{-3}(\frac{cps}{kBq/L})$ [Hof92b, Hof].

Study	$\varepsilon_{det}(\frac{cps \cdot 10^{-3}}{kBq/L})$	F_{sci} (cm ²)	$\eta_{det}(\frac{cps \cdot 10^{-6}}{kBq/L \cdot cm^2})$	LDL (kBq/L)
Muramatsu	0.39	123	3.13	370
Moghissi	4.50	> 424.1	< 10.6	37
Osborne	12	3000	4	37
Singh	41	3000	13.7	< 37
Hofstetter	2.22	~ 100	< 22.2	25

Table 2.2: Efficiencies of different scintillator detectors for tritiated water detection. This table shows the efficiency of the detector (ε_{det}), its active surface (F_{sci}), its specific efficiency ($\eta_{det} = \varepsilon_{det}/F_{sci}$), defined as its efficiency normalized to its active surface, and its low detection-level (LDL) for each study listed above.

The results of these experiments are summarized in Table 2.2. As can be seen in the first column, the intrinsic detector efficiency, ε_{det} , is very different in these experiments. As one of the most important factors that affect the efficiency is the active surface of the plastic scintillator, F_{sci} , which varies largely with the detector type, the specific detector efficiency (third column) is used in order to compare these detectors, which is the intrinsic detector efficiency normalized to its active surface. It can be checked that

these specific efficiencies are quite similar. The specific efficiency obtained by Moghissi for scintillating fibers is sufficiently high to justify our choice of scintillating fibers as a detection medium. Finally, as can be seen in the last column, the LDL in all these experiments are of the order of a few tens of kBq/L. Thus, to develop a detector with much lower LDL is essential to comply with the EURATOM directive of 100 Bq/L of tritium in water for human consumption.

2.2 The TRITIUM Project

As a conclusion of section 2.1, the current techniques cannot be used for tritium monitoring in quasi-real time since they have either a high LDL or they work in off-line method.

To overcome these limitations the *Tritium* project [Pro21], with the title of "Design, construction and commissioning of automatic stations for quasi-real time monitoring of low radioactive levels of tritium in water", was proposed.

The *Tritium* collaboration is a international group consisting of a consortium of 6 different European institutions of 3 different countries: The University of Aveiro, in Portugal, The University of Bordeaux and the National Center for Scientific Research, CNRS (Section Aquitaine-Limousin), in France and the University of Extremadura, *Junta de Extremadura* and University of Valencia, in Spain.

This project was funded by the Interreg Sudoe program of the European Economical Community, EEC, in the 2016 call with the reference number SOE1/P4/EO214. The purpose of this project is the development of a tritium monitor in quasi-real time. This monitor consists of a ultrapure water system, which prepares the water sample before introducing it in the



(a) Arrocampo dam and Almaraz Nuclear Power Plant.



(b) Tagus river along Spain and Portugal.

Figure 2.1 – Arrocampo dam, Almaraz NPP and Tagus river.

detector for tritium measurement, a cosmic veto and a passive shielding, which reduces the natural radioactive background of our tritium detector, and several electronic modules which control the different parts of the monitor, analyze the tritium measurement and send an alarm if the configured limit (100 Bq/L) is exceeded.

A crucial problem is to distinguish tritium signals from the background because tritium events has low energy (\sim keV) and fall in an energy range of the spectrum where there is significant background. To reduce the background counts of TRITIUM monitor, coincidence techniques are employed.

The TRITIUM monitor will be installed in the Arrocampo dam, Almaraz, Spain, where the Almaraz NPP releases the water from the secondary cooling circuit, displayed in Figure 2.1. This NPP has two nuclear reactors of PWR type. Arrocampo dam is located near the Tagus river, shown in Figure 2.1b, which is the longest river in Spain, with a length of 1007 km. This river, shown in Figure 2.1a, rises in Aragon (Spain) and flows into the Atlantic Ocean, Lisbon (Portugal). The water of this river is used for agriculture and drinking water by both, Spanish and Portuguese people. Therefore the international cooperation in order to maintain the quality of the Tagus river water is very important.

Each institution has concentrated its efforts in the development of a different part of this project:

1. The Extremadura group has developed and installed the ultrapure water system to produce water with very low conductivity, $\sigma \approx 10 \mu\text{Sv}/\text{cm}$ (two orders of magnitude less than sample before the cleaning process, $1000 \mu\text{Sv}/\text{cm}$). This cleaning process is very important for two reasons. On the one hand, for maintaining our detector very clean, which is a critical point. On the other hand, to reduce the natural background since several natural radioactive isotopes present in this water (except tritium) are removed such as ^{222}Rn , ^{40}K or ^{137}Cs . This system is explained in section 3.3.
2. The French group has developed the passive shielding for the detector. The shielding is made of ultra radiopure lead with very low intrinsic activity in order to reduce the external natural background of the system. This shielding is presented in section 3.4.1.
3. The Portuguese and Spanish groups have collaborated for designing, developing and building four different prototypes of tritium detector and active vetos for removing cosmic events. These prototypes and vetos are explained in chapter 5 and section 3.4.2 respectively. They have also carried out simulations of this system. The environment chosen to develop these simulations is the package GEANT4 [Col21a], consisting of an extensive C++ library with which the geometry of our detector, the relevant physical processes, etc. were specified. This simulation are explained in chapter 6.

The important characteristics of the TRITIUM detector must have are:

1. *Compact.* This is an important point because in the place where this detector is installed the useful space to be used is very limited.

2. *Thin active volume and large active area.* The mean free path of the β particle of tritium decay is very short so thin detector active volumes are needed. In practice, active thickness beyond the mean free path of the tritium electrons only contribute to background. In addition, as reported in section 2.1, the efficiency of this type of detector scales with the active area, so it is crucial to design the detector with the largest possible active area.
3. *High efficiency to tritium.* As the tritium activities to be measured are very low, it is very important to detect the maximum possible number of tritium events.
4. *High specificity to tritium.* The monitor has to be able to distinguish the tritium signal from the signal due to other radioactive elements present in the sample.
5. *Quasi-real time response.* It is important that the system work in quasi-real time in order to detect any anomalous tritium release as fast as possible.
6. *Rugged system.* The final goal of the project is to install an automatical system working during a number of years requiring only scarce intervention of specialized people. Therefore, a rugged monitor is required.

In order to get the measurement in quasi-real time, it is needed to work *in situ*, that is, in the same place that the water sample is taken. Working *in situ* has some advantages such as: 1) Faster and cheaper maintenance, since the sampling process, chain of custody, etc. are eliminated, 2) More frequent measurements are carried out and 3) Safer monitoring since personal exposure dose is reduced, 4) Changes in activity levels can be detected quickly.

Chapter 3

Design Principles of the Tritium Monitor

3.1 Detector System Overview

The objective of the TRITIUM project is the design, development, construction and commissioning of an automatic station for real-time monitoring of low levels of tritium in water. To achieve this aim, the TRITIUM group has developed a monitor consisting of several parts, listed below:

1. The TRITIUM detector, described in chapter 5, is based on several modules read in parallel. Each module consists of hundreds of scintillating fibers, section 3.2.2, which are in contact with the water sample measured, read by two coincident photosensors, section 3.2.3. The photosensors considered are photomultiplier tubes (PMT) (section 3.2.3) and silicon photomultipliers (SiPM) (section 3.2.3).
2. The ultrapure water system (section 3.3) that prepares the water sample before measurement. This system removes all the organic parti-

cles dissolved and all the particles with a diameter greater than $1 \mu\text{m}$ without affecting the tritium content of the sample. This system is important for two reasons: First, because the mean free path of tritium in water is very short, 5 or $6 \mu\text{m}$, so it is essential to avoid deposition of particles onto the fibers since this would prevent the tritium decay electrons from reaching the fibers. Second, particles dissolved in water may contain radioactive isotopes like ^{40}K , which would increase the background. As the water sample has few tritium counters, to reduce the background is a crucial matter.

3. The background rejection system (section 3.4), that has two different parts. The first one is a passive shield (section 3.4.1), consisting of a lead castle inside of which the TRITIUM detector is located. This castle is employed to eliminate natural radioactive background and cosmic rays with energies up to 200 MeV/nucleon . The second part is an active veto (section 3.4.2), consisting of two plastic scintillation plates located inside of a passive shielding, above and below the TRITIUM detector and read by photosensors. The goal of this active veto is to remove the remaining high energy events ($> 200 \text{ MeV}$), cosmic rays that can travel through the passive shielding and contribute to background. Contrary to low energy cosmics rays, high energy cosmic rays are difficult to stop. The technique employed to eliminate their contribution consists of reading the TRITIUM detector in anti-coincidence with the active veto.
4. A monitoring electronic system sends an alarm if the signal limit of the tritium level, 100 Bq/s , is exceeded.

The different parts of the TRITIUM monitor were subjected to tests to verify their correct operation before installing them in the Arrocampo dam. The final goal is to include TRITIUM in the network of automatic stations, REA (section 1.1).

3.2 TRITIUM Detector

As discussed in section 2.1, the TRITIUM consists in a chain of three main elements:

1. The scintillator, that detects the tritium event. Ionizing radiation hits this material and deposits kinetic energy through ionization and excitation processes. Part of the absorbed energy is converted into photons, mostly in the visible range¹. The produced photons carry information about the particle detected, like its energy, type, etc.
2. The photosensor, that detects the photons produced in the scintillator. The most common photosensors in nuclear physics are PMTs and SiPMs. They detect the photons produced in the scintillator and transform them in electrons with a multiplication factor of around 10^6 . These electrons form a electronic pulse than gives information of the detected photons.
3. The electronic system, which is the part of the scintillator detector in charge of processesing and analyzing (first analogically and later digitally) the electrical pulse given by the photosensor. The output of the electronic system is the useful information about the events detected such as number and energy spectrum.

In Figure 3.1 a scheme of a scintillation detector is shown. There, the scintillator detects ionizing radiation and produces photons that are guided by the reflector and the light guide to the photosensor. Some of the photons that reach the sensitive part of the photosensors are converted and multiplied, forming an electronic pulse. The output signal of the photosensor (electronic pulse) is processed and analyzed by the corresponding electronics.

¹The visible range is made up by photons with a wavelength between 380 nm and 750 nm

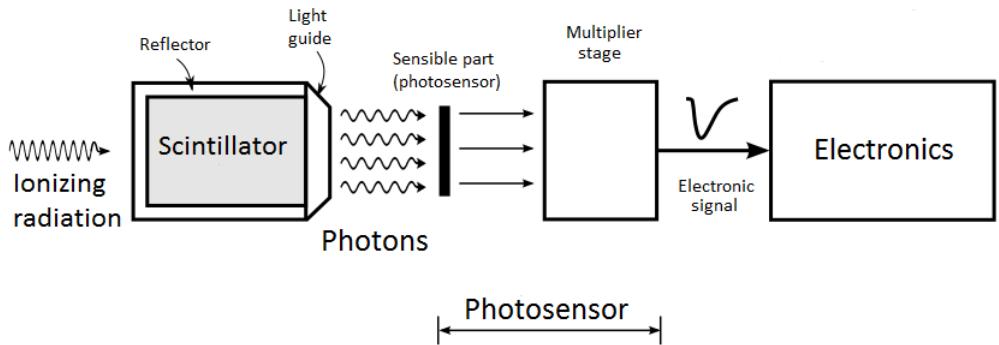


Figure 3.1 – Scheme of the scintillator detector.

3.2.1 Interaction of Fast Electrons and Photons with Matter

This section describes the interaction of particles with matter, focusing on the particles and energy range relevant for this thesis, electrons ($0 - 18$ keV) and photons in the visible range (approx. $380 - 750$ nm).

Electrons have charge, so their interaction with matter is mainly with the orbital atomic electrons through the Coulomb force. The electron trajectory is much more tortuous than heavier particles because the mass of both interacting particles is equal. Furthermore, for the same reason, these electrons lose a significant amount of energy in each collision. The specific energy loss is defined as $S = -\frac{dE}{dx}$ which gives the energy loss suffered by the particle per unit of path length. In the case of electrons, this total energy loss has two main contributions, the collisions (elastic and inelastic) and radiative processes (bremsstrahlung), which are roughly proportional [Kno99, Leo94]:

$$\frac{dE}{dx} \approx \left(\frac{dE}{dx} \right)_c + \left(\frac{dE}{dx} \right)_{br}; \quad \frac{\left(\frac{dE}{dx} \right)_{br}}{\left(\frac{dE}{dx} \right)_c} \approx \frac{EZ}{700} \quad (3.1)$$

where E is the energy of the electron in MeV and Z is the atomic number of the absorbing material. Due to this energy loss, the electrons can only penetrate a material as far as they go before losing their total kinetic energy. This distance is known as range and, in the case of tritium electrons, its value is quoted in Table 1.4.

As photons do not have charge, their possible interactions with matter are photoelectric effect, Compton effect, coherent scattering and pair production and the probability of each process, displayed in Figure 3.2, depends on the energy of the photon, $E_\gamma = h\nu$, and on the atomic number of the material, Z . The only relevant photons for this thesis are in the visible range, between 400 and 700 nm, that corresponds to energies of the order of the eV. Therefore, pair production process does not play any role since this requires a photon energy equal or more than 1.022 MeV.

The photoelectric effect occurs when a photon interacts with an orbital electron in the material, losing all its energy. This energy is absorbed by the electron that is released from the atom (ionization). The energy of the resulting electron, E_e , is [Kno99, Leo94]:

$$E_e = E_\gamma - E_b \quad (3.2)$$

where E_b is the binding energy of the electron in this material. The probability of this effect depends on the number of available electrons in matter through the variable Z , and the energy of the electron according to the expression [Kno99]:

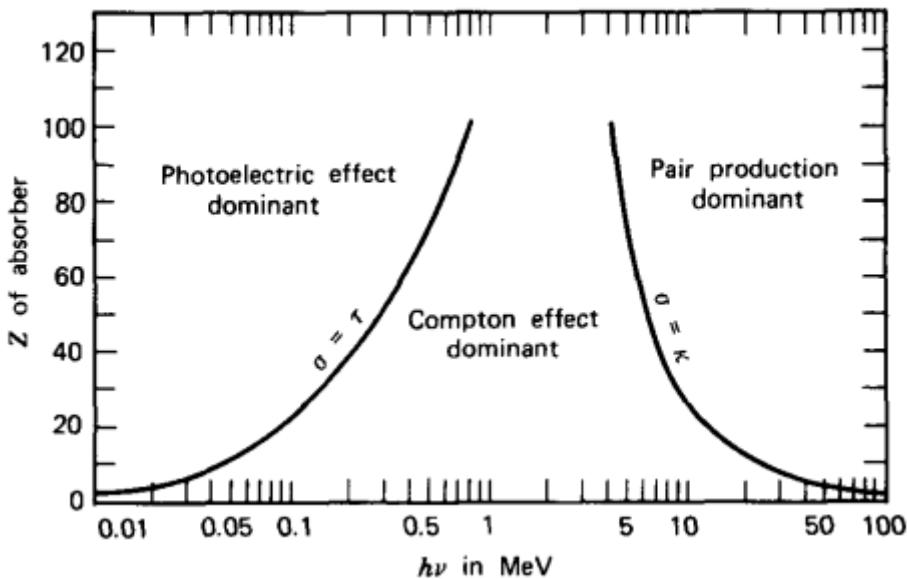


Figure 3.2 – Domain regions of the three most probable types of interactions of gamma rays with matter. The lines show the values of Z and $\hbar\nu$ where the two neighboring effects are equally likely [Kno99].

$$(Pr)_{Ph-eff} \approx \frac{Z^n}{E_\gamma^{3.5}} \quad (3.3)$$

Thus, the photoelectric effect is most probable for elements with high atomic number. This is the reason why this type of elements are the best insulators against gamma radiation and why the passive shielding of TRITIUM monitor consists of lead bricks ($Z = 82$) (section 3.4.1).

The Compton effect occurs when a photon interacts with an orbital electron of the material, transferring part of its energy to the electron, which is released, scattered at an angle θ with respect to the original direction. If the electron binding energy is neglected, the energy transferred to it, E_e , is

given by [Kno99, Leo94]:

$$E_e = \frac{\frac{E_\gamma^2}{m_o c^2} (1 - \cos\theta)}{1 + \frac{E_\gamma^2}{m_o c^2} (1 - \cos\theta)} \quad (3.4)$$

where m_0 is the rest mass of the electron and c is the speed of the light in the vacuum. The probability of the Compton effect is proportional to the atomic number (available electrons in the matter), Z , and decreases with the energy of the photon. As it can be seen in Figure 3.2, for photon energies in the visible spectrum (of the order of eV), the Compton effect is only likely for very light materials, ($Z < 4$). For heavier materials the photoelectric effect is the dominant effect.

Finally, for coherent scattering, the atom is neither excited nor ionized and the photon conserve all its energy in the collision. Coherent scattering is more probable for photons with low energies and materials with high atomic numbers and, as it will be shown in section 3.2.2, it explains why the produced photons are guided along scintillating fibers.

3.2.2 Plastic Scintillators

Scintillators are widely employed for radiation detection in nuclear physics. Scintillators convert kinetic energy of the incoming particles into light² which can be detected and quantified. Light emission is produced due to the photon de-excitation of scintillating atoms.

Light production is linear in a wide energy range of incoming particles. Scintillators should have good optical properties, such as being transparent to the wavelength of their own emission and having a refractive

²The light is made up of photons in the visible energy range.

index as close as possible to that of glass for optimizing optical coupling with photosensors. Photon emission in scintillators is a statistical process, which means that identical events emmit a different number of photons that follows a Poisson statistics.

Scintillators can be organic and inorganic. Inorganic scintillators normally have a higher atomic number and density, so their light output is higher. For these reasons they are better for gamma-ray spectroscopy. Organic scintillators are generally faster and they are commonly used for beta spectroscopy and neutron detection. This section is focussed on organic scintillators since they are the ones used in the TRITIUM project.

Organic scintillators are based on a scintillator material dissolved in a base solvent, normally aromatic hydrocarbons as $C_{18}H_{14}$, $C_{24}H_{22}N_2O$ or $C_{15}H_{11}NO$ with an average atomic number between 3,5 and 5. The scintillator molecules of organic scintillators have a π -electron structure. The energy levels of their electrons are commonly illustrated with a Jablonsky diagram, shown in Figure 3.3. This diagram shows the fundamental singlet state, S_{0i} , where the valence electrons are, the excited singlet states, S_{jk} , and the excited triplet states, T_{lm} . The energy difference between S_1 and S_0 states is around 3 or 4 eV (the visible range). As it is shown in the figure, each energy state is splitted in close sublevels separated around 0.15 eV. This fine energy structure is due to excitations of molecular vibrational modes tagged by the second index of the energy states. As the energy levels and sublevels have an energy larger than the termal energy, 0.025 eV, non-excited electrons are in the ground state S_{00} at STP³.

When a particle deposits its kinetic energy in a scintillator, the valence electrons are exited to higher singlet energetic states very fast (times of the order of picoseconds) and are quickly de-excited to the first singlet excited state, S_{10} , through non-radiative processes known as internal conversion. These electrons can de-excite to the fundamental single state, S_{00} ,

³Standard temperature and pressure conditions

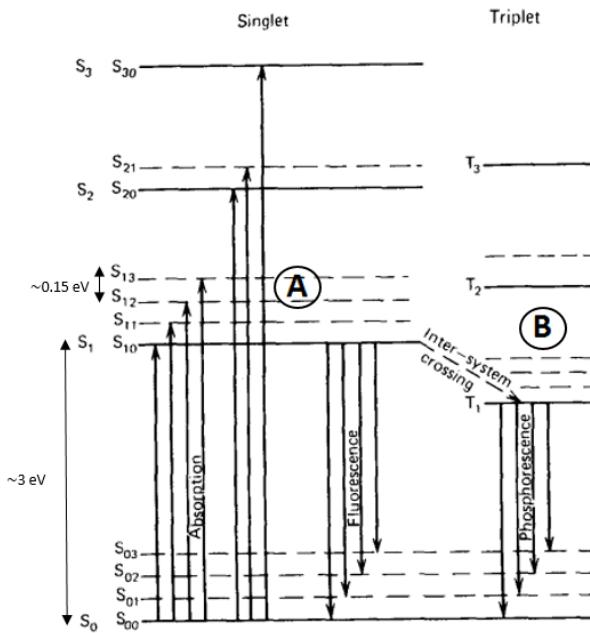


Figure 3.3 – Jablonsky diagram [Kno99].

through three different physical mechanisms:

1. Prompt fluorescence (process A in Figure 3.3), where the electron in the S_{10} energy level is de-excited to some sublevel of the ground state S_{0i} , emitting a photon. This process happens immediately after the excitation of the scintillator molecules (around tens of nanoseconds after excitation). Each scintillator has a characteristic emission spectrum that defines its response due to the fluorescence mechanism.

Organic scintillators are practically transparent to their own fluorescence emission because there exist a quenching effect in each de-excitation process by which all emitted photons by the scintillator have less energy than the excitation energy. This effect is called Stokes shift and it is represented in Figure 3.4.

The intensity of the fluorescence emission in an organic scintillator

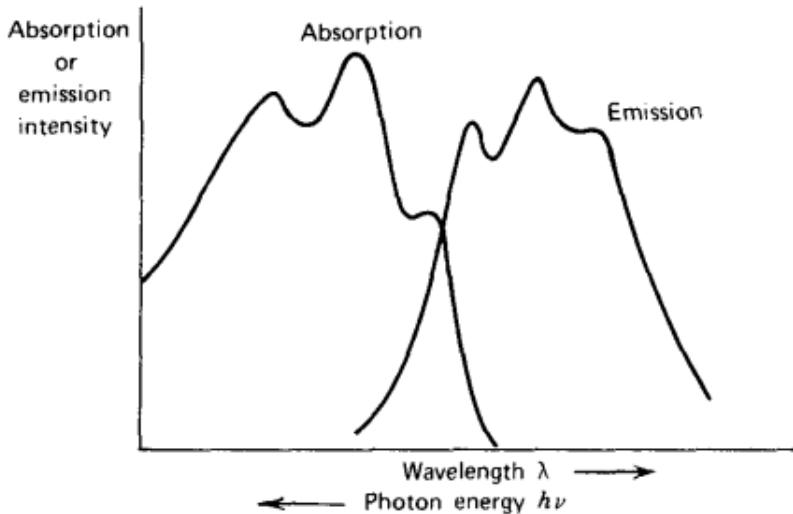


Figure 3.4 – Stokes shift [Kno99].

versus time is the combination of two exponential functions, one associated with the lifetime of the level, τ (on the order of nanoseconds), and the other associated with the energetic level population, τ_1 (on the order of picoseconds) [Kno99].

$$I = I_0 (e^{t/\tau} - e^{t/\tau_1}) \quad (3.5)$$

2. Phosphorescence, where the electron that is in the first single excited state cross to a triple excited state (process B in Figure 3.3) with a process called "intersystem crossing". This is a metastable state with a longer lifetime than phosphorescence. This process happens around 10^{-3} seconds after scintillator excitation.
3. Delayed fluorescence, which occurs when an electron is in a triple excited state but its transition to the ground state is forbidden. In this case, the electron interacts with another electron in a similar state, falling to the first singlet state and quickly de-exciting to the ground state.



This emission has the same emission spectrum as immediate fluorescence, but with a longer lifetime.

As the prompt fluorescence light produces the scintillator signal, the detector design should optimize its detection and reduce other possible physical mechanisms. One of the most important parameters is the scintillation yield⁴, defined as the number of photons emitted per unit of absorbed energy. This yield depends on the type of particle and on other mechanisms that do not produce prompt fluorescence, like phosphorescence, delayed fluorescence, or even internal conversion. The scintillator yield is normally quoted by the manufacturer for mips⁵.

Plastic scintillators are easy to machine to any desired shape. The chosen shape for TRITIUM detector is the fiber, specifically, commercial fibers BCF-12 from Saint-Gobain Crystals Inc [Cer05]. This type of fiber was chosen as the result of a comparative study [Cam17] among some of the best-known commercial manufacturers. The BCF-12 fibers consist of scintillating polystyrene with the possibility of surrounding it by a cladding of polymethylmethacrylate (PMMA) (smaller refractive index than core in order to achieve a critical angle) or a multicladding (second cladding) with even smaller refractive index.

When a particle deposits all or part of its kinetic energy, some photons are produced in the fiber core as a result of the scintillating process. The number of photons produced depend on the scintillation efficiency and its value is around 2.4% for the fibers used (BCF-12), which means that a scintillation yield of about 8000 photons will be produced per MeV for

⁴The scintillation yield is a way of expressing the efficiency of the scintillator in converting the energy deposited by the particle into photons.

⁵The MIP, Minimum Ionized Particles, is a particle that has the speed that generate minimum ionization, that's, for example, electrons with 500 keV or more

a mip. For instance, for tritium electrons, these fibers release a maximum of around 148 photons (when a tritium electron has the maximum energy, 18.6 keV), or less as electrons of these energies are not mips. The emission spectrum of the fibers employed in this work, is shown in Figure 3.5.

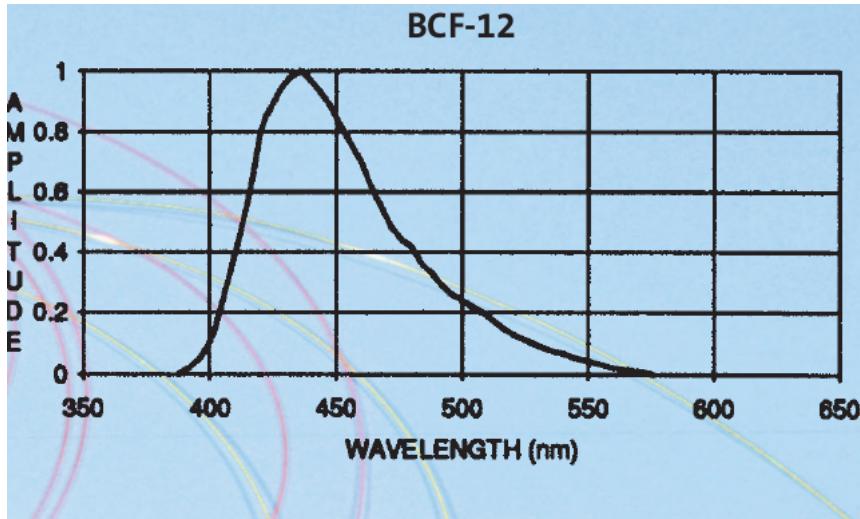


Figure 3.5 – Emission spectrum of BCF-12 fibers of Saint-Gobain [Cer05].

The scintillation light is guided to the sensitive part of the photosensor. A single photon produces a signal with some probability, called the quantum efficiency. Fibers (and scintillators in general) use the optical property of Snell's law [Bor19] to guide their photons to the desired part (ends of the fibers). The guiding mechanism is based on the interface created between the core and the surrounding material. When a photon hits this interface, it is refracted (and therefore lost) following the Snell equation, 3.7 [Bor19].

$$n_0 \sin(\theta_0) = n_1 \sin(\theta_1) \longrightarrow \theta_c = \arcsin\left(\frac{n_1}{n_0}\right) \quad (3.7)$$

If the surrounding material has a lower refractive index than the core of the fiber, there exist a critical angle, θ_c , beyond which photons will be totally

reflected and therefore kept within the fiber as illustrated in Figure 3.6.

The trapping efficiency or photon collection efficiency is defined as the efficiency of the scintillator to guide photons. For BCF-12 fibers with optical clad this efficiency is between 3.44% and 7% per meter of fiber (depending on where the event is detected and is minimum near the fiber axis and maximum near the core-clad interface). For unclad fibers BCF-12 surrounded by water, the trapping efficiency is larger than for cladded fibers. Therefore, from the maximum of 148 photons initially created by a tritium decay electron with the maximum energy, only 41 photons (for maximum trapping efficiency) are guided along the 25 cm fiber length of the TRITIUM detector. Thus, the output signal is very weak and is in the range of the spectrum where electronic noise is already significant. As described in the following chapters, a great effort was made to minimize electronic noise by different techniques. In Figure 3.6 the light collection in a fiber is illustrated.

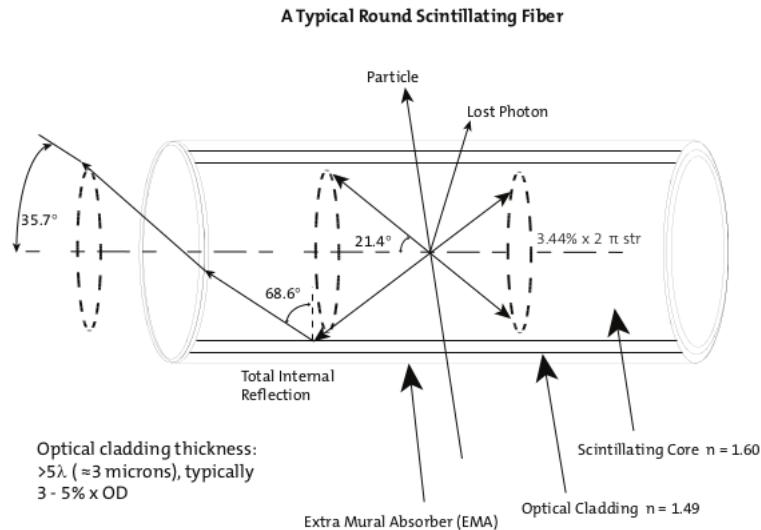


Figure 3.6 – Photon collection in a single clad fiber [Cer05].

The cladding material is useful for protecting the core surface from dirt or aggressive external agents that may reduce the light collection but at

the cost of increasing the critical angle with its corresponding loss of light. Three different cases are shown in Table 3.1, where the cladding effect is illustrated.

Material	Refractive index	critical angle (°)
Air	1	42.98
Water	1.33	62.47
Cladding of PMMA	1.49	76.26

Table 3.1: Critical angles associated to different interfaces created with polystyrene, $n_0 = 1.6$, and other materials.

In the practice, it is difficult to achieve a perfect air-core or water-core interface, and this affects light collection. As commercial claddings are thicker (30 μm) than the mean free path of tritium decay electrons in water (around 5 μm) cladded fibers is not an option for the TRITIUM detector. Hence, special attention is needed for achieving a water-core interface good enough. To achieve this goal a special protocol was developed in the ICMOL laboratory for preparing fibers for tritium detection, detailed and tested in section 4.1.4. The most important parameters of scintillating fibers of TRITIUM are given in Table 3.2.

3.2.3 Light Detection in Photosensors

The scintillating photons created in the core of the fiber and guided to its end are detected by photosensors. Photosensors have a sensitive part that is optimized to detect photons in a range of energy (usually in the visible range) with a certain probability, called quantum efficiency. The photosensors produce an electronic signal that carries information about the detected photons such as their number, detection time, etc. There are many available photosensors that rely on various physical processes, such as photoelectron multiplier tubes (PMTs), silicon photoelectron multipliers

Property	Value
Core material	Polystyrene
Core refractive index	1.60
Density (g/cm ³)	1.05
Cladding material	Acrylic (PMMA)
Cladding refractive index	1.49
Cladding thickness (μm)	30
Numerical aperture	0.58
Trapping efficiency	3.44% minimum
No. of H atoms per cc (core)	$4.82 \cdot 10^{22}$
No. of C atoms per cc (core)	$4.85 \cdot 10^{22}$
No. of electrons per cc (core)	$3.4 \cdot 10^{23}$
Radiation lenght (cm)	42
Emission peak (nm)	435 (Blue)
Decay Time, (ns)	3.2
1/e Length (m)	2.7
Scintillator yield (# γ /MeV)	~ 8000
Operating Temperature	-20°C to 50°C

Table 3.2: Properties of BCF-12 fibers from Saint-Gobain Inc. [Cer05].

(SiPM) or charge-coupled devices (CCD).

The optimization of the efficiency of a scintillation detector is essential. To do so, the emission spectrum of the scintillator (Figure 3.5 for the fibers used) must overlap as much as possible with the detection efficiency spectrum of the photosensor chosen. The detection efficiency spectrum gives the probability of detecting photons as a function of wavelength. The efficiency of a detector is proportional to the product of both, the emission and the detection efficiency spectra, and this is largest when both spectra match.

The proposal of TRITIUM is to use SiPM arrays because they are very fast (of the order of ns) and have a high photodetection efficiency of about 50%, a high gain (multiplication factor of 10^6) and need a low voltage supply. The most important reason of this choice is that SiPM arrays are able to detect a single photon with high efficiency, which is a fundamental aspect due to the low amount of photons generated by tritium decay. The PMTs, which are the conventional choice, were also tested because they have lower dark count rate than SiPM and similar properties like gain and timing.

Photoelectron Multiplier Tubes (PMTs)

Photoelectron multiplier tubes are employed as photosensors in nuclear physics since decades. They detect the scintillating photons that reach its sensitive part, the photocathode, and produce an electronic signal, large enough to be easily measured. In Figure 3.7 a schematic drawing of a PMT is given. This consists of a vacuum tube that has a glass window through which photons can penetrate. The electrons created in the photocathode travel in vacuum.

The signal production has two phases:

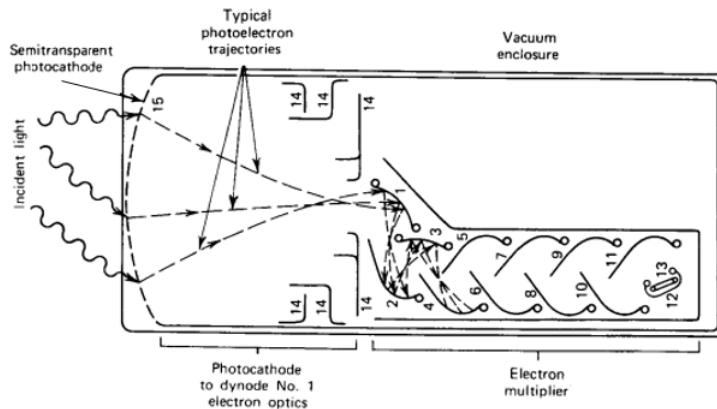


Figure 3.7 – Scheme of a PMT [Kno99].

1. In the photocathode, photons are converted in photoelectrons through photoelectric effect. The photocathode consists of a thin layer, of the order of nanometers, deposited on the inner surface of the PMT window. The material of the photocathode is chosen to optimize the probability of producing photoelectric effect with the scintillating photons. The PMTs used in the TRITIUM experiment are the model R8520-406 from Hammatsu [K.K19] and the material of their photocathode is Bialkali⁶.

The response of the PMT for long wavelengths is inhibited, mainly because photon energy is not enough to produce a photoelectric effect or the emitted photoelectron does not have enough energy to overcome the material-work function. The response of the PMT at short wavelengths is inhibited due to absorption in the window material, quartz in our case. Thus, the response of the PMT has a strong dependence on the energy of the photon. The quantum efficiency (QE) spectrum, shown in Figure 3.8 for the PMT used in TRITIUM, is defined as the ratio of the number of photoelectrons produced at the cathode of the PMT and the number of photons reaching it.

⁶The bialkali material is based on the elements ^{121}Sb , ^{85}Rb and ^{132}Cs

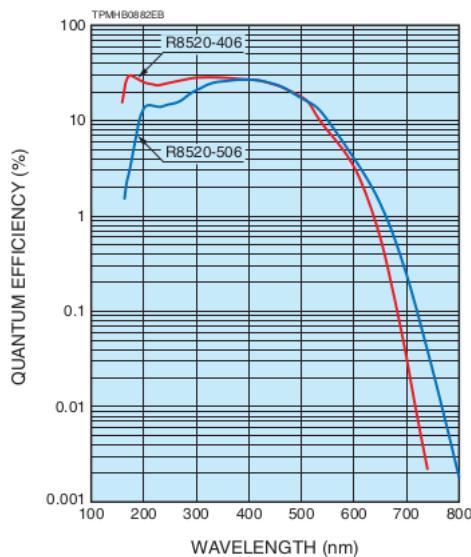


Figure 3.8 – Quantum efficiency spectrum for the PMT used (R8520-406) [K.K19].

The maximum values of the PMT quantum efficiency is usually between 20% and 30% [Kno99] (a little bit less than 30% for the PMTs employed by us). The emission spectrum of the scintillating fibers used, Figure 3.5, matches the quantum efficiency spectrum of the PMTs used, Figure 3.8, and the positions of both peaks are very close, 435 nm and 420 nm for fibers and PMT respectively.

2. As the number of photoelectrons produced in the photocathode is very small, an electron multiplication stage is employed to obtain an electronic signal of sufficient size to be processed by the electronic system. The amplification stage is based on three elements, focusing electrodes, dynodes and anode, which are metallic plates with a shape and position designed to optimize the collection and multiplication of electrons. A high voltage (HV) is applied to the PMT which is distributed between all this elements, including the photocathode, with the help of an electronic circuit. A positive HV, grounded in the ph-

tocathode, is convenient for measuring PMT currents, and a negative HV, grounded in the anode, gives a faster response. The commercial electronic circuits of Hamamatsu are shown in Figure 3.9.

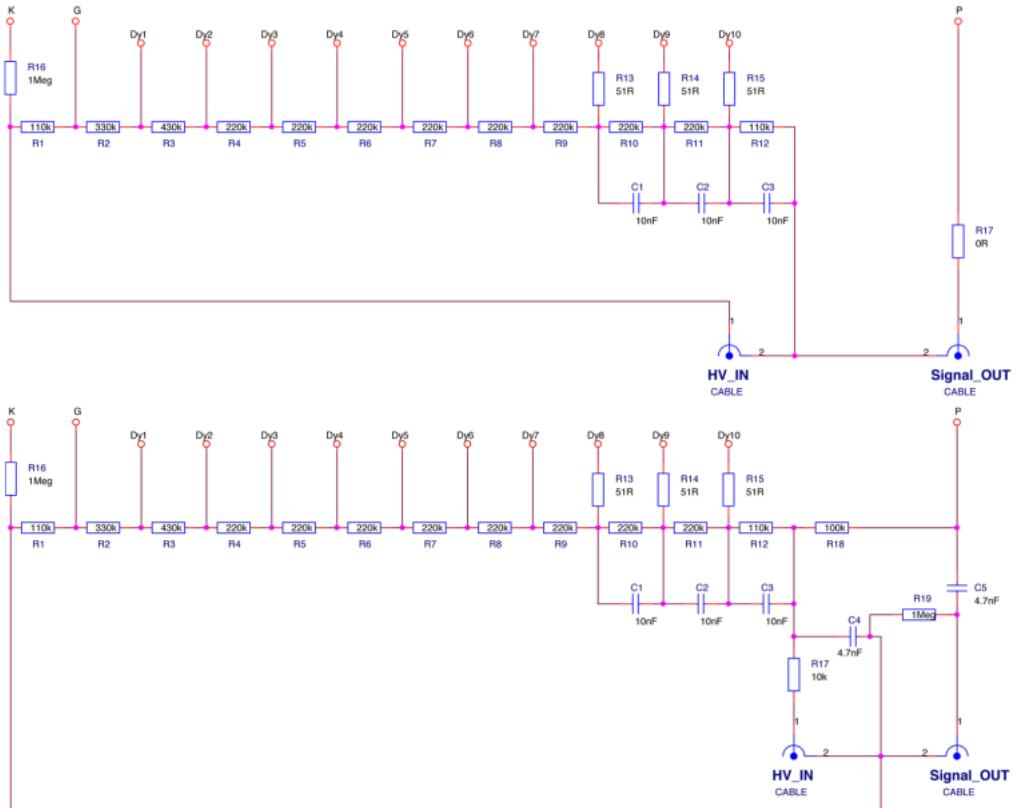


Figure 3.9 – Hamamatsu commercial voltage divider electronic circuit. Upper circuit with negative supply and lower circuit with positive supply [K.K19].

Focusing electrodes guide the photoelectrons to the first dynode. They have a collection efficiency (CE) defined as the ratio of the number of photoelectrons reaching the first dynode and the number of photoelectrons leaving the photocathode. This value is around 80%. The dynodes achieve the electron multiplication. A voltage difference between adjacent dynodes accelerates the electrons and produce their

multiplication. The multiplication factor of each dynode, δ , is usually around 5 and is strongly dependent on the HV. If all dynodes have the same gain, the overall gain of a PMT with N dynodes is [Kno99]:

$$G_{PMT} = CE \cdot \delta^N \quad (3.8)$$

that gives an overall gain of a PMT of the order of 10^6 , strongly dependent on the applied HV.

The multiplication stage adds an uncertainty to the measurement. Working without gain allows us to count the number of photons that reach the PMT. This can be done by short-circuiting all the dynodes and the anode and collecting the signal directly from the photocathode. This special setup was used for fiber characterization, described in section 4.1.3.

The output pulse of a PMT has a width of the order of tens of nanoseconds. The multiplication process can be described as a Poisson statistical process. For each electron in the first dynode, G_{PMT} new electrons are created with a variance of $\sqrt{G_{PMT}}$.

The output signal of a PMT is linear with the number of photons that reach its sensitive part up to a saturation limit, at which the linearity is lost. This limit depends on the PMT characteristics.

The photocathode may emit electrons in absence of any scintillation light. This signal, called dark current, I_{DC} , can arise due to thermoionic emission. For the PMTs employed in this work, this value is around 2 nA according to their data sheet.

The characterization of the PMTs for dark current, gain versus HV and quantum efficiency, was done at IFIC in the framework of NEXT experiment [Pé10].

Silicon Photoelectron Multiplier Array (SiPMs array)

The Silicon Photomultiplier (SiPM) is a kind of photosensor, based on semiconductor materials, developed in recent years. SiPMs are replacing progressively conventional PMTs in many experiments and applications. They achieve outstanding photon-counting capabilities with higher photodetection efficiency than PMT and similar gain. SiPMs have convenient characteristics as insensitiveness to magnetic fields, low operating voltage and compactness. The main problem with the SiPMs is their high dark count rate (between 100 kHz and 1 MHz).

SiPMs are formed by a matrix of APDs connected in parallel which are photodiodes operating in Geiger mode. APDs, the scheme of which is shown in Figure 3.10, are based on p-n junctions⁷ made with special techniques to achieve a good contact between both surfaces.

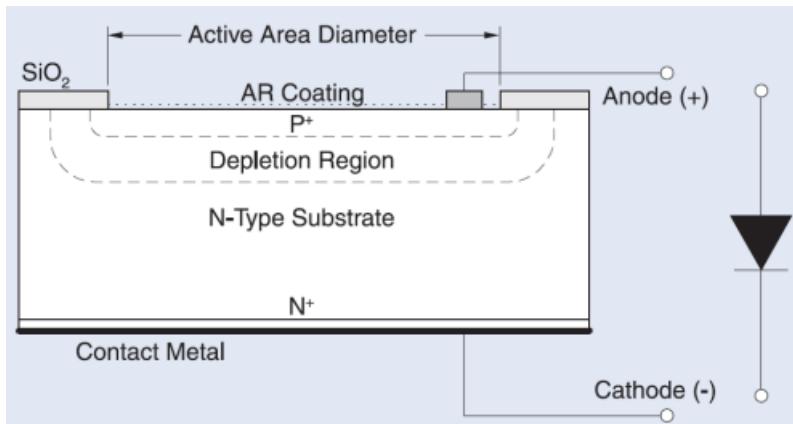


Figure 3.10 – Scheme of a APD and electrical symbol used [Opt].

The voltage at which the SiPM starts operating in Geiger mode is called the breakdown voltage, V_{BD} . At lower voltages, SiPMs work in

⁷A p-n junction is a junction of a p+ and n+ layer, which are a tetravalent material doped with a trivalent or pentavalent material respectively, creating sublevels in the forbidden energy gap.

proportional mode in which the signal of the pixel is proportional to the energy deposited but their gain is lower than in Geiger mode. The experimental measurement of the breakdown voltage, described in section 4.2, is an important measurement to characterize a SiPM, since many properties of SiPMs depend on the overvoltage, V_{ov} . The overvoltage is the voltage applied to the SiPM above their own breakdown voltage and this is expressed as:

$$V_{bias} = V_{BD} + V_{OV} \quad (3.9)$$

These APDs, called pixels when they are part of a SiPM, are connected in parallel and the sum of all of them is read. The output signal of an individual pixel is quite similar regardless of the energy deposited, with some difference because of the uncertainty due to the SiPM manufacturing process and the statistical nature of the detection process. Therefore, the energy deposited in each APD is not known but the charge of the output signal when n pixels are simultaneously fired is n times the charge of a single pixel, as can be checked in Figure 3.11. Due to this property, considering that each pixel only detects one photon, the number of detected photons is linearly proportional to the value of the output signal. Hence, after a correct calibration of SiPMs, described in section 4.2, the linearity of the SiPM output signal versus the deposited energy of tritium events is recovered.

The size of a SiPM pixel should be very small⁸ to make sure that, for low enough photon fluxes, only one photon is detected in each pixel. If the photon flux is high (typically several thousand of photons per event) more than one photon will impinge on the same pixel, but the output signal would be that of one detected photon. This effect, known as saturation, produces a loss of linearity of the output signal. However, this effect is not important for the TRITIUM detector since its scintillating signals are far

⁸Pixel sizes for commercial SiPMs are 25, 50 or 75 μm [Div16a], [Div16c], [Div16d]

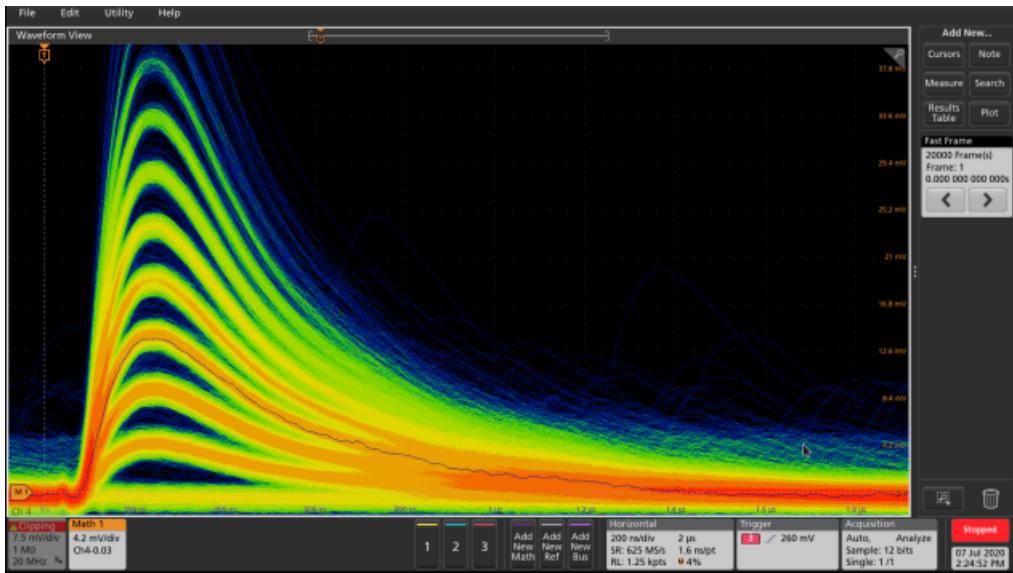


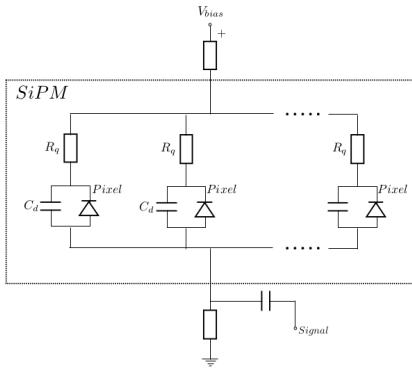
Figure 3.11 – SiPM output pulses displayed on oscilloscope, model MSO44X from Tektronix [Tek21]. To easily observe several heights of these pulses, associated with a different number of SiPM pixels fired at the same time, the persistence function of the oscilloscope is used.

from producing so many photons.

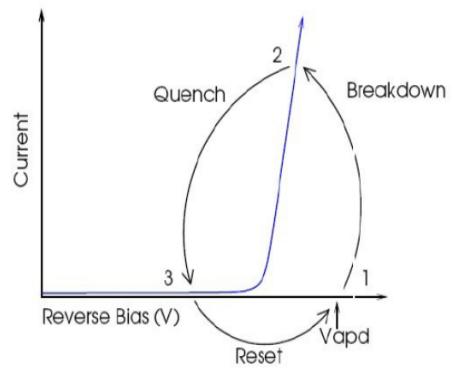
The SiPM can be modeled as an electric circuit, shown in figure 3.12a, in which, due to the charge distribution in the depletion zone, a capacitance is induced by the SiPM. This looks like a reverse diode in parallel with a capacitor of capacitance C_d . When the pixel detects a photon, the capacitor is discharged, creating an output current (electronic pulse).

In addition, each pixel of a SiPM has a quenching resistance⁹ in series, R_q , that stops the current produced when this pixel is fired. When the discharge is produced, a current flows through the resistance, reducing the reverse voltage seen by the diode below the breakdown voltage. Then, the current that flows through the diode is stopped and the voltage seen by

⁹The typical value of this quenching resistance for commercial SiPMs is around 500 kΩ



(a) Photon Detection Efficiency, PDE.



(b) Output current of a SiPM.

Figure 3.12 – (Left) Electronic scheme of a SiPM and (right) output current of a SiPM as a function of the reverse voltage. It is seem that the quenching mechanism is essential for working with SiPMs [sl17].

the diode is reset to the bias voltage. This pixel is ready to detect a new photon again. This behaviour is schematically shown in Figure 3.12b.

The recovery of the bias voltage seen by the SiPM after photon detection is characteristic of a RC circuit, described by the equation:

$$V_{bias}(t) = V(t_0) \left(1 - e^{-t/\tau}\right) \quad (3.10)$$

where τ is the recovery time constant of the system, given by $\tau = C_d \times R_q$. In section 4.2 the capacitance C_d and the quenching resistance R_q are experimentally measured and the recovery time constant extrapolated from both.

SiPM gain (typically of the order of 10^6) is defined as the charge produced when a single pixel is fired. This can be measured experimentally from its Single Photon Spectrum, SPS, which is the spectrum obtained when the SiPM output signal is integrated (charge) and histogrammed. The experimental measurement of the SPS and the calculation of the gain

is presented in section 4.2. It has to be taken into account that the SiPM gain is highly dependent on temperature, which cannot be controlled with sufficient sensitivity (less than 1°C) in the final emplacement of the TRITIUM monitor. Therefore, a gain stabilization method was developed to compensate for the temperature effect. This method is detailed in section 4.2.

An important parameter for the SiPM used in the TRITIUM project is the photon detection efficiency, PDE. This is defined as the probability of recording the electrical pulse produced by a photon that hit the SiPM. The PDE of a SiPM consists of a product of three different parameters, the fill factor (FF), which is the ratio between the active area of the SiPM and the total area, the quantum efficiency for photoelectron conversion (QE), which is the probability that a incident photon generate an electron-hole pair, and the probability that the generated electron or hole produces an avalanche, P_{av} .

$$PDE = FF \times QE \times P_{av} \quad (3.11)$$

Like PMTs, sometimes the SiPM produces pulses that are unrelated with any incident photon. The current due to these pulses is called the dark current rate. It depends on temperature. At temperatures around 25°C, these pulses are mainly produced by the thermal generation, i.e., when a free electron or hole start an avalanche. The dark current signal is identical to the signal produced by a single photon, so they cannot be discriminated. Therefore, it is very important to determine the importance of the dark current on the tritium signal.

Electrons contained in an avalanche of a SiPM pixel emit secondary optical photons¹⁰. These optical photons can reach other pixels, producing

¹⁰Around 20 secondary optical photons are emitted in each SiPM output pulse with gains of the order of 10^6 [Spi97]

new avalanches. This effect, called optical crosstalk, produces signals that are larger than those corresponding to single photons, producing erroneous information about the number of photons detected. The probability of producing an optical crosstalk event depends on the number of electrons produced in the avalanche (gain) and, therefore, on the temperature and the overvoltage. This probability at the recommended overvoltage and temperatures around 25°C is typically less than 10%.

The PED, dark count rate and crosstalk are not experimentaly measured yet since a different setup, shown in reference [Yah13], is needed. These parameters will be measured for the SiPM model used in the final version of TRITIUM monitor.

Due to imperfections existing in the cristal lattice of a SiPM, called traps, an electron of an avalanche can be captured and released after a characteristic time, τ_t . If this characteristic time is longer than the time used to recover the charge of the pixel, typically 3τ , this electron can trigger a new avalanche which will be seen as a new event. This events, called afterpulses, are often emitted around 1 μs after SiPM output pulses. The afterpulse probability was not measured since it is not interesting for the TRITIUM project. The reason is that the TRITIUM detector uses the SiPM as a counter (without integrating the signal). In addition, time coincidences are made using time windows of 10 ns. At this level, the afterpulse probability is negligible since it normally happen 1 μs after the SiPM output pulse.

The initial SiPM cadidate for TRITIUM project and the one which was characterized is the model S13360-1375 from Hamamatsu Photonics [Div16b] because this model has interesting characteristics and properties, shown in Table 3.3. This model was mainly choosen due to its large pixel size, 75 μm , which implies a high PDE and a high gain, both important parameters for the TRITIUM project due to the low activity to be detected and to the small signals produced by tritium events. High PDE and high gain are achieved at the cost of reducing the dinamic range, which is not an

issue due to the small signals generated by tritium events.

Parameter	S13360-1375	S13360-6075
Series	S13360	S13360
Model	1375	16075
Pixel Pitch (μm)	75	75
Effective photosensitive area (mm^2)	1.3×1.3	6.0×6.0
Number of pixels	285	6400
Fill factor	82%	82%
Refractive index of windows material	1.55	1.55
Operating temperature range ($^\circ\text{C}$)	$[-20, 60]$	$[-20, 60]$
Spectral response range, λ (nm)	[320, 900]	[320, 900]
Peak sensitivity wavelength, λ_p (nm)	450	450
PhotoDetection Efficiency, PDE, $\lambda = \lambda_p$ (%)	50	50
Dark counts, Typical/Maximum (kcps)	90/270	2000/6000
Terminal capacitance, C_t (pF)	60	1280
Gain, M,	$4 \cdot 10^6$	$4 \cdot 10^6$
Breakdown Voltage, V_{BD} (V)	50.97	53
Cross talk probability(%)	7	7
Temperature coefficient ΔTV_{op} (mV/ $^\circ\text{C}$)	54	54

Table 3.3: Characteristics of SiPM S13360-1375 and S13360-6075 from Hamamatsu Photonics [Div16b].

These parameters quoted in Table 3.3, provided by Hamamatsu photonics, are only an approximation for a given element. They can vary significantly even for SiPMs of the same model, so they must be measured for each SiPM used. The measurement of some important characteristics for the TRITIUM project is reported in section 4.2.

This SiPM was also chosen because, as it can be observed in Figure 3.13, its maximum PDE is reached at $\lambda_{p,SiPM} = 450$ nm, which is very close to the peak of the emission spectrum of the scintillating fibers used, $\lambda_{p,fiber} = 435$ nm.

This SiPM was later replaced by the more performant model S13360-

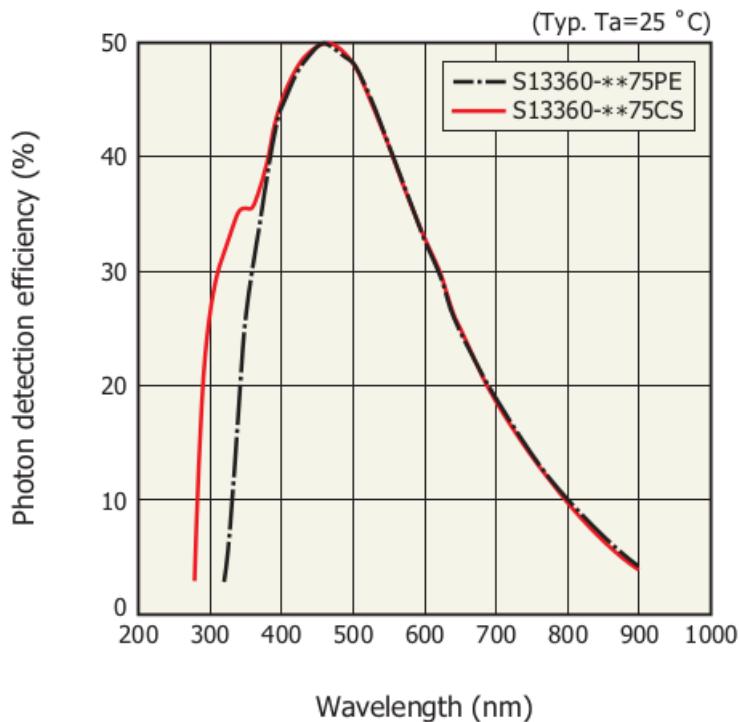


Figure 3.13 – Photon detection efficiency (PDE) spectrum for SiPM S13360-**75 models [Div16b].

6075 from Hamamatsu Photonics [Div16d], whose properties are also listed in Table 3.3. The only difference between both models is their active area ($6 \times 6 \text{ mm}^2$) that allow to read more scintillating fibers with the second model. This improvement is achieved at the price of a higher dark count rate (typically 2 Mcps). In addition, commercial matrices are available, with a total area of $24 \times 24 \text{ mm}^2$.

Although TRITIUM detector uses whole SiPM matrices, the characterization has been carried out at the level of a single SiPM to learn about the values of the SiPM parameters and to test the gain control method. A new experimental setup, detailed in appendix A, is already prepared to perform a complete characterization of the SiPM model S13360-6075.

Comparison of photosensors considered

The photosensors employed in TRITIUM are both, PMT and SiPM. Each kind of photosensor has its advantages and disadvantages, so both were tested to decide the most suitable. The output signal of both photosensors is proportional to the number of incident photons in our range of luminosity and they have a similar gain (of the order of 10^6). Both properties are essential to detect tritium events and to obtain a large enough signal to be measured and recorded. Both photosensors have fast output signals, with a rise time of the order of nanoseconds, and a wide spectral sensitivity (200 – 800 ns for PMT and 300 – 900 ns for SiPM). The supply voltage necessary to work with SiPM, of the order of tens of volts, is much lower than that of PMTs, which require a high voltage, of the order of a thousand volts. The electron detection efficiency at 420 nm, achieved with SiPM is higher, around 50%, than with PMT, about 30%. A large efficiency is essential because the number of photons produced in a tritium event is rather low. Furthermore PMTs, as they consist of a vacuum tube, are more bulky and fragile than SiPMs, which are compact and robust. This is an advantage for the SiPMs because the TRITIUM detector should work during years. Fur-

thermore, PMTs are rather more expensive, than SiPMs. In addition, PMTs are affected by magnetic fields, contrary to SiPMs that work correctly in magnetic field up to 7 Tesla. Moreover, due to their high uniformity, SiPMs are capable of measuring the exact number of photoelectrons detected and even of resolving a single photoelectron, which is not possible with PMTs due to their gain uncertainty.

However, the dark current of PMTs is much lower (a few counts per second) than that of SiPMs, that have a dark current between 0.1 and 1 Mcps¹¹, depending on their size, and this happens with SiPMs almost entirely at the level of a single photoelectron. This prevents to separate tritium decay signals from background in the singel photon-detection zone. Another inconvenient of SiPMs is their large crosstalk and afterpulses that need to be corrected. An additional drawback of SiPMs is that their response depends strongly on temperature. As the TRITIUM detector will be installed in an environment with significant temperature variations, this problem is solved by developing a stabilization method of the SiPM gain.

3.2.4 Electronic Readout

The electronic system is in charge of reading, processing and analyzing the output signal of photosensors and providing output information about tritium detection. This electronic system depends on the type of output information that is desired and on the detector configuration used.

Electronics for PMTs

PMTs were used in TRITIUM experiment for two main objectives. On the one hand, to know the amount of incident photons that reach the PMT

¹¹Mega counts per second, 10^6c/s

photocathode, which is important to characterize fibers, and, on the other hand, to know the energy of events, which allows us to discriminate events according to their origin, obtaining an energy spectrum of triggered events.

To know the amount of photons that reach the photocathode, the PMT should work without internal gain since it introduces a large uncertainty in the measurement. For that end, the electron multiplication stage (shown in section 3.2.3) should not be employed. This was achieved with the help of a PCB, shown in Figure 3.14, designed, built and tested for this purpose.

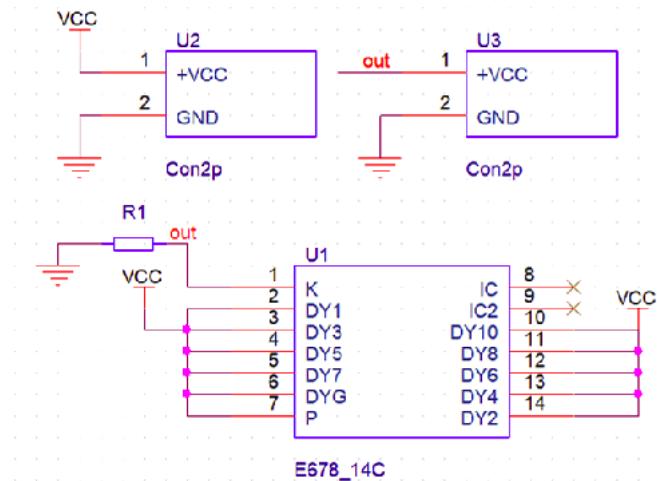


Figure 3.14 – Electronic scheme of the voltage divider circuit used for working with PMTs without internal gain).

This PCB short-circuits the dynodes and reads the signal directly from the photocathode. This PCB was designed to be supplied with a positive voltage smaller than the usual running voltage because this voltage is only needed to create a voltage difference between the photocathode and the first dinode. As the electrons are not multiplied, the output pulse of the photosensor is very small (currents of the order of tens of nanoamperes) and a special readout system is needed. The chosen system is Keithley 6487 Pi-

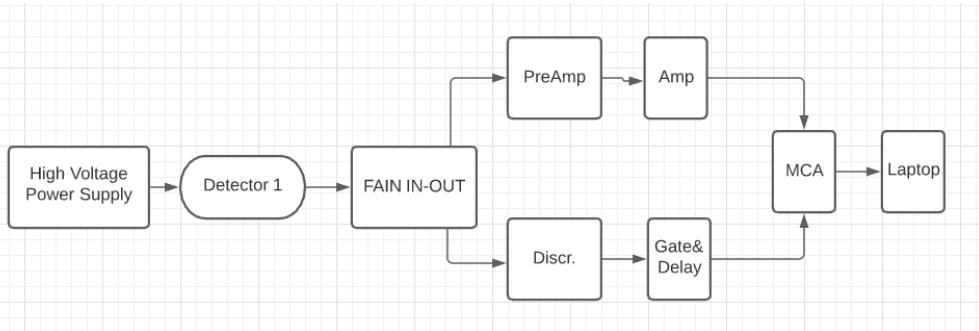
coammeter/Voltage Source [KEI], a commercial system from Keithley. This system has some useful options such as automatic baseline correction, the ability to read currents of the order of picoamperes and the possibility of carrying out mathematical operation on the signal, such as the average of N measurements with the associated statistical error, where N is programmable by the user ($N = 100$ in all our studies). Finally, the number of photons reaching the photocathode is calculated from,

$$N^o \gamma / \text{sec} = \frac{(I_{PMT} - I_{DC})}{q_e \cdot QE \cdot CE} \quad (3.12)$$

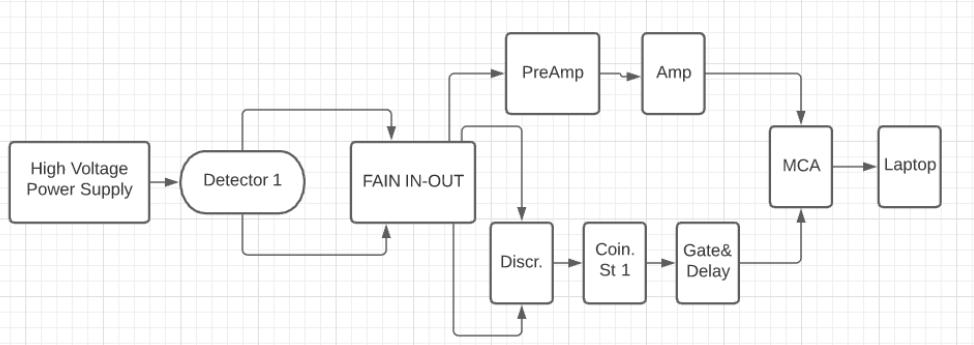
where I_{PMT} is the output current of the PMT when it detects photons and I_{DC} is the dark current. This equation takes into account the quantum efficiency of the PMT, which is close to 30%, and the capture efficiency in the dynodes, equal to 1 since the signal is read directly from the photocathode. In addition, it is assumed that each detected photon only generates one electron, the charge of which is q_e . To determine the energy of the events, the gain of the PMT has to be restored by removing the short-circuit of the electron multiplication stage. The number of PMTs used simultaneously was one, two or four, depending on the measurement. A simplified scheme of the electronic chain employed in each case is shown in Figures 3.15a, 3.15b and 3.15c, based on various NIM modules¹².

The PMTs were supplied in all the cases by TC 952 High Voltage Supply from Tennelec [Cam], which has four channels. If two or more configurations are needed, a second voltage supply HV Power Supply N 1130-4 from Wenzel Elektronik company [Ele] with 4 additional channels, was employed. As it can be seen in the figures, there are two different lines followed by the PMT output signals, the amplification line, used to create an energy spectrum, and the time coincidence line, used to make time coincidences. Therefore, an analogic FAN IN-OUT module was used to

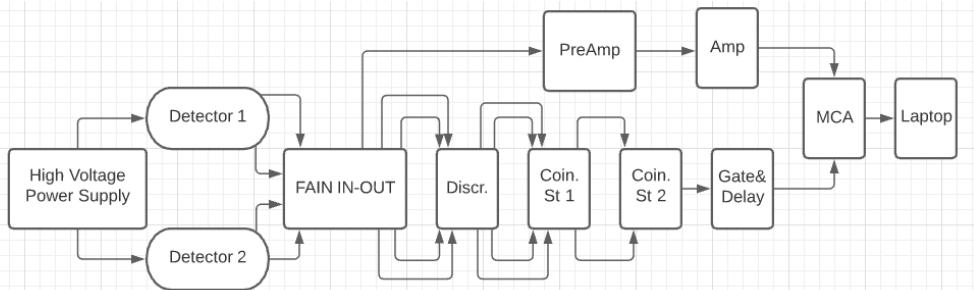
¹²The Nuclear Instrumentation Module (NIM) is a standard specification convention for electrical and mechanical parameters defined in electronic modules used in experimental nuclear and particle physics.



(a) Electronic scheme employed when only one PMTs was used in time coincidence.



(b) Electronic scheme employed when two PMTs were used in time coincidence.



(c) Electronic scheme employed when four PMTs were used in time coincidence.

Figure 3.15 – Schemes of the different electronic for measuring with PMTs.

duplicate the input signal. The module employed was the Quad linear FAN IN-OUT MODEL 740 from Philips Scintific [Sci], which has four channels. One output signal was used as the input for the amplification part and the second output was used as input for the time coincidence electronics.

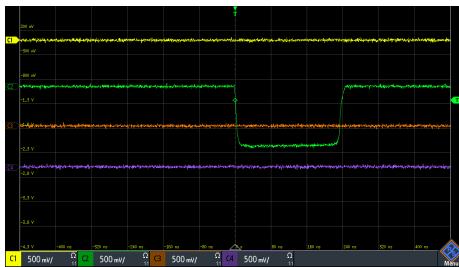
1. The amplification line, which is the same for the three configurations, provides the energy information and is based on two steps;
 - (a) The output signal is integrated by a preamplifier, which gives an output signal with a height proportional to the charge of the input pulse. This signal has a long tail¹³ produced by the preamplifier capacitance. The preamplifier used was "MODEL 9326 FAST PREAMP" from ORTEC [ORTd].
 - (b) The output signal from the preamplifier is lead to the amplifier which gives a gaussian shaped output signal. The amplifier modules were 575A and 671 from ORTEC [ORTb, ORTc]. An example of the output signal for 575A module is shown in Figure 3.17, green color.
2. The time coincidence line contains the time information and gives the gate that triggers coincident signals of both PMTs. This line consists of the following branches,
 - (a) The output signal of the FAN IN-OUT module of each PMT is introduced into a discriminator module that gives a logic signal of -1.2 V height and of 240 ns width when a given threshold is exceeded. The discriminators employed are Octuple Constant-Fraction Discriminator CF8000 module from ORTEC [ORTe] and 4 channels discriminator model 84 from CAEN [CAEa].

¹³The length of the tail is, $\tau = RC$, where R is the input resistance and C is the capacitance used. It is the typical output signal in RC circuits.

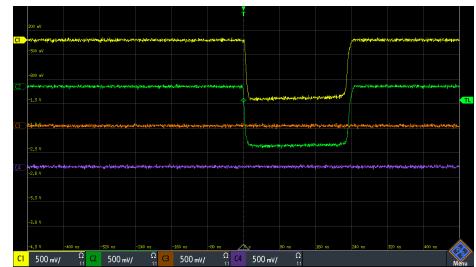
- (b) Time coincidences are required to ensure that detected events come from the scintillating fibers and to remove external light and dark current. The two logic signals given by the discriminator from the two PMTs that read a detector are introduced in a coincidence module which generates an output signal of -1.4 V height and of 20 ns width, when both inputs are in time coincidence. The modules used were Coincidence Unit Model 465 from LeCroy [LeC] and Coincidence Type N6234 from CERN-NP [CERb].
- (c) Time coincidence of two different detectors (4 PMTs, configuration 3.15c) was also studied, which is useful to remove background due to hard cosmic radiation. To do so, a coincidence step similar to the previous one must be applied. The two single detector coincidence signal are checked for coincidence.

Some examples are shown in Figure 3.16 for time coincidences of two detectors (4 PMTs). There, four logical signals are shown, two of them (channel one and two, yellow and green respectively) come from two PMTs reading the first detector and the other two signals (channels three and four, color orange and violet respectively) come from PMTs reading the second detector.

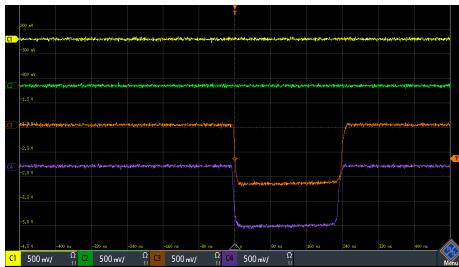
- i. In Figure 3.16a only one PMT (channel two) detected an event. It means that the event is likely not produced in the scintillator. In this case, no output signal is generated.
 - ii. In Figures 3.16b and 3.16c two PMT signals of one of the detectors are generated but the other detector gives no signal. This event is discarded.
 - iii. In Figure 3.16d the four signals are generated and, consequently, the output signal is generated and the event is recorded.
- (d) The logical output signal, is introduced in the Gate and Delay Generator, model 416A of the company ORTEC [ORTa], which



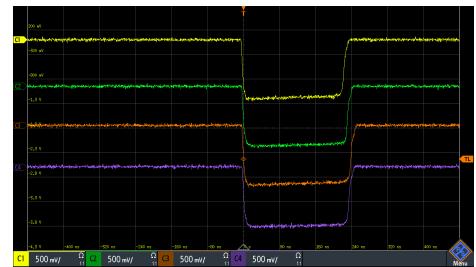
(a) Event detected in only one PMT, one detector.



(b) Event detected in two PMTs, one detector.



(c) Event detected in two PMTs, other detector.



(d) Event detected in all PMTs, both detector.

Figure 3.16 – Different possibilities when time coincidences with PMTs are done.

gives a positive logical signal, called time windows, shown in Figure 3.17, orange color, with a height of 8 V and width of $2 \mu\text{s}$. This module is used to delay the time windows until it overlaps with the energy signal as it is shown in Figure 3.17, orange signal.

As a final output of the electronics, a logical and analogical signals are obtained, shown in Figure 3.17, which are recorded by the MCA 8000D, Pocket MCA from AMPTEK [Amp]. The analogical signal has information about the energy of the event and this is the signal which information is saved for later analysis. The logic signal (output from the Gate and Delay Generator module) indicates when the amplified signal must be saved.



Figure 3.17 – Signal amplified and logical gate (input signals of MCA).

Electronical system for SiPMs

The SiPMs in the TRITIUM experiment are arranged in matrices of 4×4 . The electronic system chosen to process and analyze the output signals of

the SiPM arrays is PETsys [PET], displayed in Figure 3.18, which is a commercial system prepared to work with SiPM matrices from Hamamatsu. PETsys provides time and energy digitalization, including the charge integrations QDCs¹⁴ and TDCs¹⁵, resulting in a complete acquisition and digitization system capable of working with up to 1024 SiPM. This system consists of a basic board to which 16 different SiPM matrices can be connected with up to 64 SiPM per matrix. This number of channels is needed in the TRITIUM project because, as shown in section 5.3, the TRITIUM monitor consists of a large number of SiPM matrices with 16 channels per matrix.



Figure 3.18 – Different parts of PETSYS system [PET].

Although the capacity provided by PETSYS should be enough for the requirements of the TRITIUM project, TRITIUM is a modular detector with scalable sensitivity. This means that, if an improvement of TRITIUM

¹⁴charge-to-digital converter

¹⁵time-to-digital converter

limits is needed to improve its sensitivity or to further reduce the background, more photosensors would be needed. Therefore, the electronics should be able to increase its capacity in a scalable way. This requirement is fulfilled by PETSYS since it has an additional module, called Clock and Trigger, to which up to sixteen different PETSYS basic boards can be connected. These sixteen PETsys basic boards are read in parallel, giving a total system capacity of reading 256 SiPM matrices (16384 SiPMs¹⁶).

PETSYS software is based on C++ and Python scripts to drive the main tasks required, such as time coincidence options between SiPM (or even SiPM matrices) or energy discrimination. This software is open source, giving the possibility to modify the current scripts or to develop others with additional functions. PETsys has a time resolution better than 30 ps which is one of the best time resolutions of commercial systems available and its price is around 10€/ channel, which is cheaper than similar electronic systems.

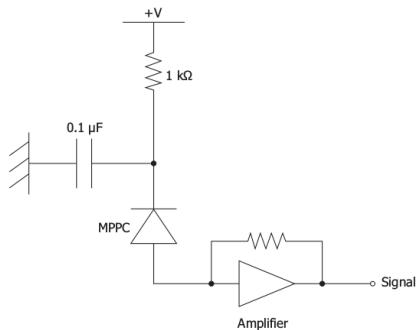
As reported in section 4.2, the SiPM matrix temperature is an important parameter. The PETsys system has the ability to monitor the temperature of the SiPM matrices and ASICS employed to control them. Temperature monitoring is important to ensure the correct functioning of both, photosensors and system. PETsys has the possibility of developing new scripts to implement the stabilization method of the SiPM gain reported in section 4.2.

Some characterization measurements were carried out using the PETSYS system to ensure that the system works properly but the SiPM characterization was carried out at the level of a single channel (individual SiPM). The reason is that the output information of PETSYS is already integrated and digitized, so it does not allow the SiPM to be calibrated. Therefore, to characterize a SiPM, a different electronic system was used

¹⁶ $1024 \cdot 16 = 16384$



(a)



(b)

Figure 3.19 – a) Electronic board used to provide the SiPM bias voltage and to read the SiPM output signal. b) Electronical scheme in which this PCB is based.

to read up to eight different SiPMs. This system consists of a PCB¹⁷ that provides the SiPM bias voltage and reads the SiPM output signal. An example of the electronic scheme (provided by Hamamatsu) in which this PCB is based is shown in Figure 3.19.

The PCB was feed at ± 6 V using the voltage source ISOTECH, model IPS-4303 [IT] and the SiPM was feed using the electrometer KETHLEY, model 6517B [Keh], that achieves a resolution of 1 mV, low enough to ensure that this voltage variations does not affect the SiPM gain. The output signal of this PCB is connected to an oscilloscope, model WwaveRunner 625Zi from TELEDYNE LECROY [LEC17] that records the data which were subsequently analized by ROOT¹⁸ scripts.

¹⁷PCB, Printed Circuit Board

¹⁸ROOT is a framework for data processing, based on C ++ and object-oriented technology, developed at CERN and widely used in nuclear and particle physics.

3.3 Ultrapure Water System

3.3.1 Introduction to the Ultrapure Water System

The objective of the ultrapure water system is to purify the water sample before the measurement. This system is important for two reasons:

1. The mean free path of tritium electrons in water is around $5 \mu\text{m}$ and even less in solid materials like organic material. Tritium decay electrons have to reach the fiber to be detected and, consequently, the detector must be kept very clean. If the analyzed water sample contains particles that may be deposited on the fibers, a layer of matter could be formed, preventing tritium decay electrons from reaching the fibers and reducing drastically the tritium detection efficiency.
2. The tritium monitor does not have any spectrometric capabilities that could be used to distinguish other radioactive elements from tritium. That means that, any radioactive event in the analyzed water sample would be counted as a tritium event.

The ultrapure water system was designed to remove all particles up to a diameter of $1 \mu\text{m}$ and organic matter, which means that tritium is the only radioactive particle that passes through it.

In summary, the ultrapure water system is used to keep our detector clean, ensuring the stability of its detection efficiency and to eliminate all radioactive particles other than tritium.

3.3.2 Design of the Ultrapure Water System

The requirements of the ultrapure water system are:

1. A high degree of purification of the processed water sample, reducing its conductivity by approximately two orders of magnitude (from $1000 \mu\text{S}/\text{cm}$ to $10 \mu\text{S}/\text{cm}$)
2. Low maintenance (low cost and low manpower)
3. To manage probes and valves by software.

The LARUEX laboratory in Extremadura, one of the six collaborators of the TRITIUM experiment, has designed, developed and built the ultrapure water system, a scheme of which is shown in Figure 3.20.

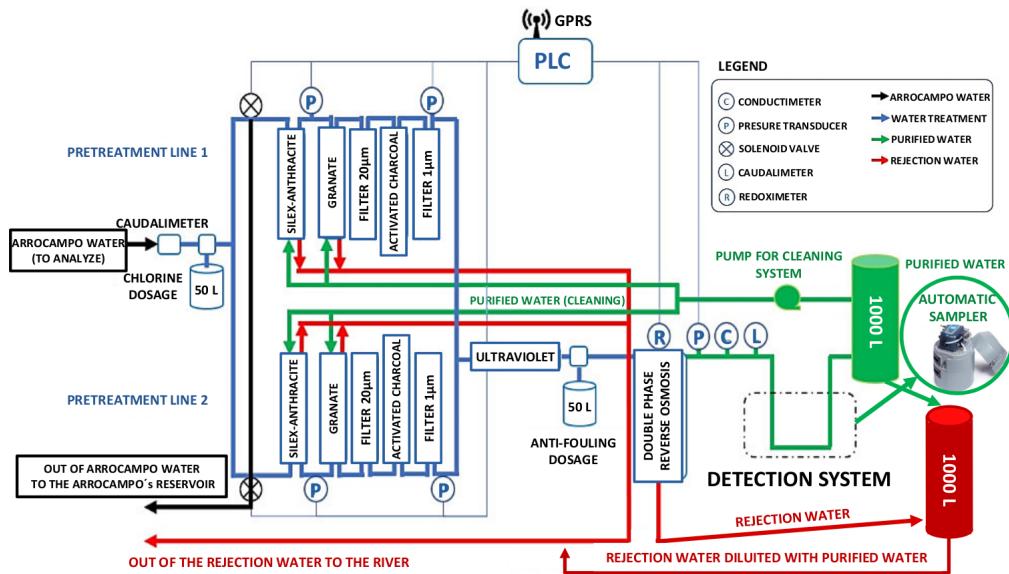


Figure 3.20 – Scheme of water purification system.

This system is installed in the Arrocampo dam and consists of four different stages:

1. The raw water from the Tagus river passes through two different filters, the first made of silex-anthracite and the second of garnet, with which

a rough filtering is made (the largest particles are eliminated). This system has two parallel lines and implements self-cleaning by injecting ultrapure water in the opposite direction.

2. The outlet water sample of the first stage, called fine filtration stage, passes through a $20\ \mu\text{m}$ filter (formed by a synthetic mesh) and activated charcoal filters (one per line) that remove chlorine and iron particles.
3. The outlet water of the second stage passes through a super-fine filtering consisting of a $1\ \mu\text{m}$ filter, formed of a dense polypropylene mesh and UV lamps. The first filter removes all the particles up to diameters of $1\ \mu\text{m}$ and the UV lamps remove the organic matter present in the sample.
4. Finally, the water is introduced in the last stage, double-phase reverse osmosis, that reduces the conductivity of the water to about $5\ \mu\text{S}/\text{cm}$. It was verified that a conductivity of $10\ \mu\text{S}/\text{cm}$ is achieved with only one module of reverse osmosis, enough for the needed conditions. Therefore, only one module of reverse osmosis is used, reducing the power consumption of the system.

As a result of the purification process, besides the ultrapure water that is introduced into the TRITIUM detector, a rejection water is produced, which contains the particles extracted from the ultrapure water that results in conductivities greater than the original water.

The ultrapure water system is able to process up to $0.850\ \text{m}^3/\text{h}$ with a single line operating or $1.480\ \text{m}^3/\text{h}$ with both, greatly outperforming the requirements of the tritium detector.

The software used for remote controlling the ultrapure water system is Siemens PLC, that gives information such as the state of the valves,

the reading of pressure probes and the amount of water production in real time.

The appendix B contains several pictures of different parts of this system, installed in Arrocampo dam.

3.4 Background Rejection System of the TRITIUM Monitor

The aim of the background rejection system is to reduce the TRITIUM radioactive background. The TRITIUM project follows the ALARA principle for the tritium activity measurement, that is, to measure tritium activity "as low as reasonably achievable". The detection limit of tritium activity is set by the uncertainty in the activity of the radioactive background, since tritium activities below this uncertainty cannot be distinguished from the background. Therefore, the background uncertainty must be reduced as much as possible. The total uncertainty is the quadratic sum of all the different uncertainties related to the measurement, i. e., the statistical uncertainty¹⁹, σ_{st} , the systematic uncertainty²⁰, σ_{si} , etc. The background rejection system of TRITIUM monitor minimizes the statistical component. Because of the Poissonian nature of the process, the statistical uncertainty is given by the square root of the measured activity, A_m , which can be reduced by minimizing detected background events.

$$\sigma_T^2 = \sigma_{st}^2 + \sigma_{si}^2; \quad \sigma_{st;bak} = \sqrt{A_{m;bak}} \quad (3.13)$$

The background of TRITIUM is due to natural radioactivity and

¹⁹Uncertainty due to the statistical nature of the radioactivity process

²⁰uncertainty due to the manufacture of the detectors

has two different sources. On the one hand, radioactive elements that are present in the crust of the Earth, mainly ^{40}K and elements from the four different natural radioactive series, shown in Table 3.4. On the other hand, the cosmic ray radiation. The primary cosmic radiation is composed of high-energy particles, mainly protons and α particles, but, after interacting with the Earth's atmosphere, they generate a shower mainly composed by muons, electrons, photons and neutrons.

Mass Num.	Series	Prim. el.	Half life (y)	Final isotope
4n	Thorium	^{232}Th	$1.41 \cdot 10^{10}$	^{208}Pb
4n+1	Neptunium	^{237}Np	$2.14 \cdot 10^6$	^{209}Pb
4n+2	Uranium-Radium	^{238}U	$4.51 \cdot 10^9$	^{206}Pb
4n+3	Uranium-Actinium	^{235}U	$7.18 \cdot 10^8$	^{204}Pb

Table 3.4: Classification of natural radioactive series [The96, Eva96].

Cosmic radiation depends on several parameter like the longitude, latitude, latitude and the solar activity cycle. The spatial distribution of cosmic rays, mainly muons, follows a $\cos^2(\theta)$ distribution with the zenith angle.

To remove the background two different techniques are employed for the weak and the hard radiation,

1. The weak radiation, which is any radiation with energy below 200 MeV/nucleon, is stopped by a lead castle, described in section 3.4.1,
2. The hard radiation, that is any radiation of energy greater than 200 MeV/nucleon, is much more difficult to stop and the technique employed is a cosmic veto in anti-coincidence with the TRITIUM detector, reported in section 3.4.2.

3.4.1 Passive Shield (Lead)

Weak radiation is suppressed by a lead shielding inside which the TRITIUM detector is placed. This lead shielding is effective for particle energies below 200 MeV/nucleon, originating from the Earth's natural radioactivity and the weak component of cosmic radiation. This lead shielding consists of 158 lead bricks of ultra-low intrinsic radioactivity, 25 mm thick. They are chevron shaped, as shown in Figure 3.21a, specially designed for a perfect fit and easy assembly. As can be seen in Figures 3.21b and 3.21c, these lead bricks are arranged in two layers with a total thickness of 50 mm. The junction of the inner layer lead bricks is shielded by a lead brick of the outer layer to avoid any leak of radiation.

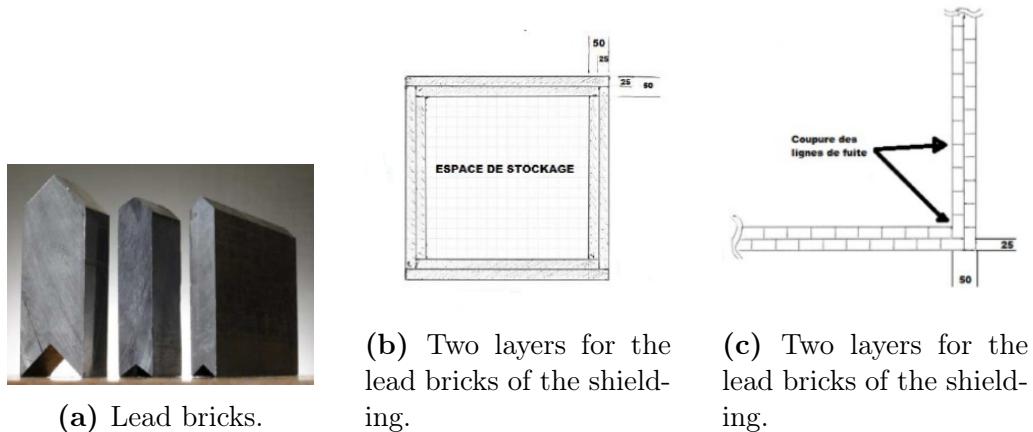
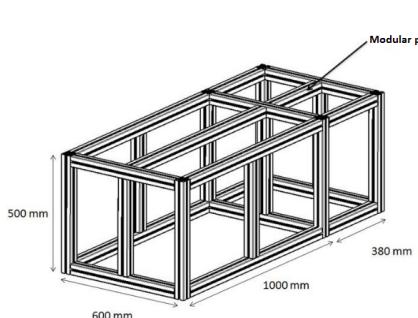


Figure 3.21 – Lead Bricks and their arrangement in the lead shielding.

A special aluminum structure, shown in Figure 3.22, was designed by mechanical engineering department of CENBG to support the total weight of the lead bricks, 2.4 tons.

The internal room of the lead shielding is divided in two parts, as exhibited in Figure 3.21. The larger one has internal dimensions of $90.5 \times 41 \times 51 \text{ cm}^3$ and is used to place the TRITIUM detector. The smaller one, of dimensions of $33 \times 41 \times 51 \text{ cm}^3$, contains the DAQ system. The



(a) Aluminium structure scheme.



(b) Aluminium structure of TRITIUM monitor.

Figure 3.22 – Lead Bricks and their arrangement in the lead shielding.

external dimensions of the lead shielding are $148 \times 60 \times 70$ cm³ and it weighs 2.5 tons.

3.4.2 Active Shield (Cosmic Veto)

As hard radiation cannot be stopped by a moderate lead thickness cosmic vetos are employed, which consist of at least two complementary detectors in coincidence that reject events simultaneously detected in both of them. As shown in Figure 3.23, the two complementary detectors are placed one above and the other below the TIRTIUM detector. The distance between both detectors, 34.2 cm for our latest prototype developed, is set by the TRITIUM prototype to be placed inside.

A hard cosmic event crossing simultaneously both cosmic detectors is schematically sketched in figure 3.24a. Each cosmic detector has two photosensors, so the electronic configuration given in Figure 3.15c is used to make time coincidences. The TRITIUM detector is read out in anti-coincidence with the cosmic veto to reject the hard cosmic events from the tritium measurement. Random coincidences from two different hard cosmic events, one in each detector, as drawn in Figure 3.24b, are negligible. The

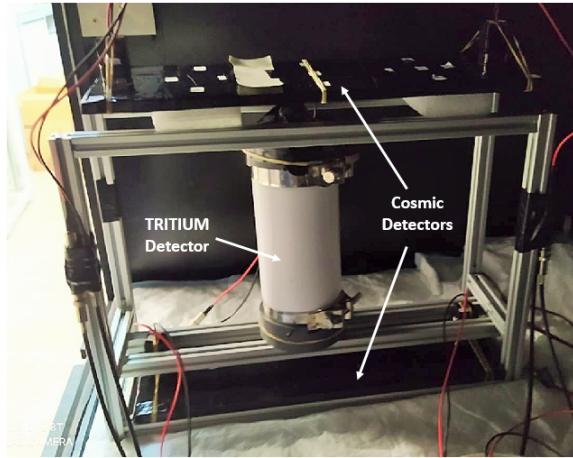
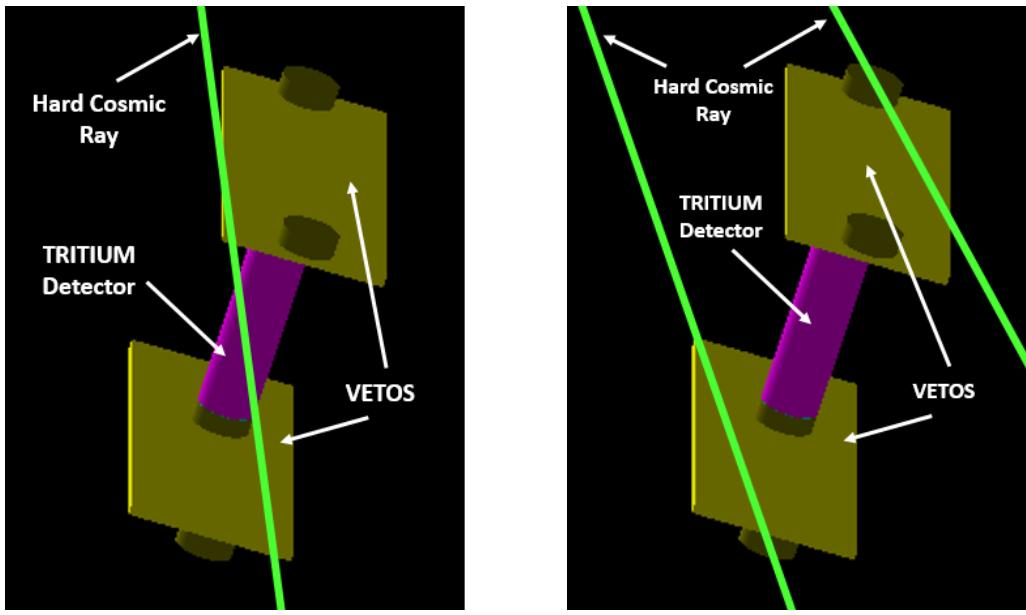


Figure 3.23 – Cosmic veto and Tritium-IFIC 2 prototype in an aluminum mechanical structure developed by IFIC’s mechanical engineering department.

expected hard cosmic rate at sea level for muons is $7 \times 10^{-3} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ [ea20, SAG01], as shown in the plot of Figure 3.25. As time coincidences are triggered by logical gates of about 10 ns, the probability of recording two different hard cosmic events in temporal coincidence is less than 10^{-9} which is negligible.

The vetos are made of a plastic scintillator block from Epic-Crystal [Cry20]. Its properties are given in Table 3.5 and its energy emission spectrum is displayed in Figure 3.26.

The energy spectrum has a peak very close to that of the scintillating fibers used, so the same photosensors are used to read them out. The dimensions of the scintillator block are $45 \times 171 \text{ cm}^2$. They are wrapped by three different layers, teflon, aluminum and black tape, exhibited in Figure 3.27. These layers prevent external photons from reaching the scintillator plastic and avoid photons generated by the scintillator plastic from escaping before reaching the photosensor. Two $2.5 \times 2.5 \text{ cm}^2$ windows are made on the wrapping to allow reading by the photosensors.



(a) Real hard cosmic event.

(b) Fake hard cosmic event.

Figure 3.24 – Hard cosmic events detected with the cosmic veto of TRIUM: a) Real coincidence, b) Fake coincidence.

As mentioned above, the expected hard cosmic rate at sea level is $7 \times 10^{-3} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. Taking into account that the solid angle of our detectors is $\omega = 0.5434$, calculated by integrating the solid angle of one scintillator on the other, and that the area of the veto is 765 cm^2 , the expected hard cosmic rate on our cosmic vetos should be 2,909 event/s. This is an important result which is used in section 4.4 to determine the efficiency of the cosmic veto.

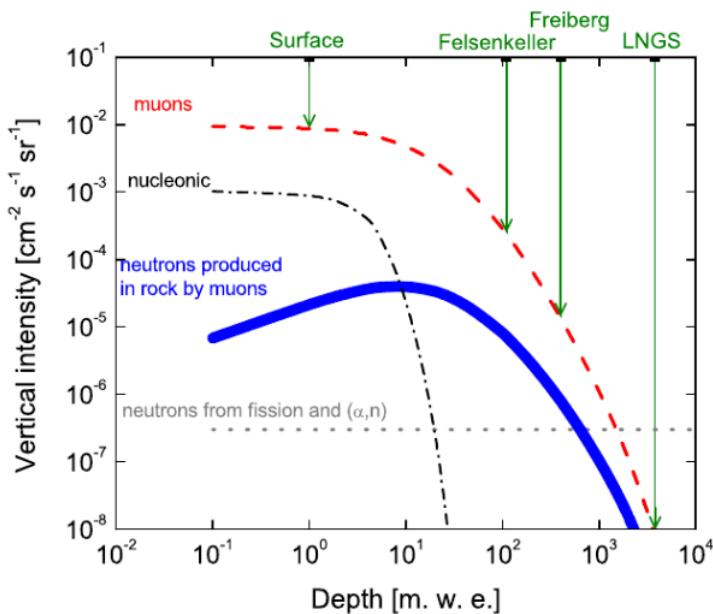


Figure 3.25 – Hard cosmic muon rate [Szu15].

Property	Value
Base material	Polystyrene
Growth method	Polymeric
Density (g/cm ³)	1.05
Refractive index	1.58
Soften temperature (°)	75-80
Light output (Anthracene)	50-60%
H/C ratio	1.1
Emission peak (nm)	415 (Blue)
Decay Time, (ns)	2.4
Hygroscopic	No

Table 3.5: Properties of plastic scintillators from Epic-Crystals [Cry20].

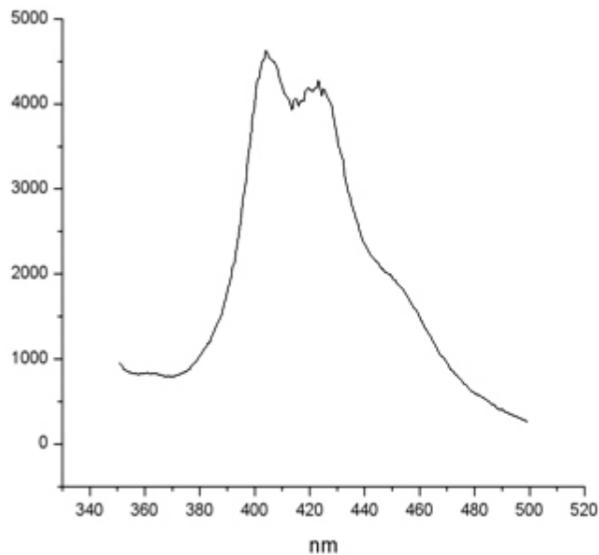
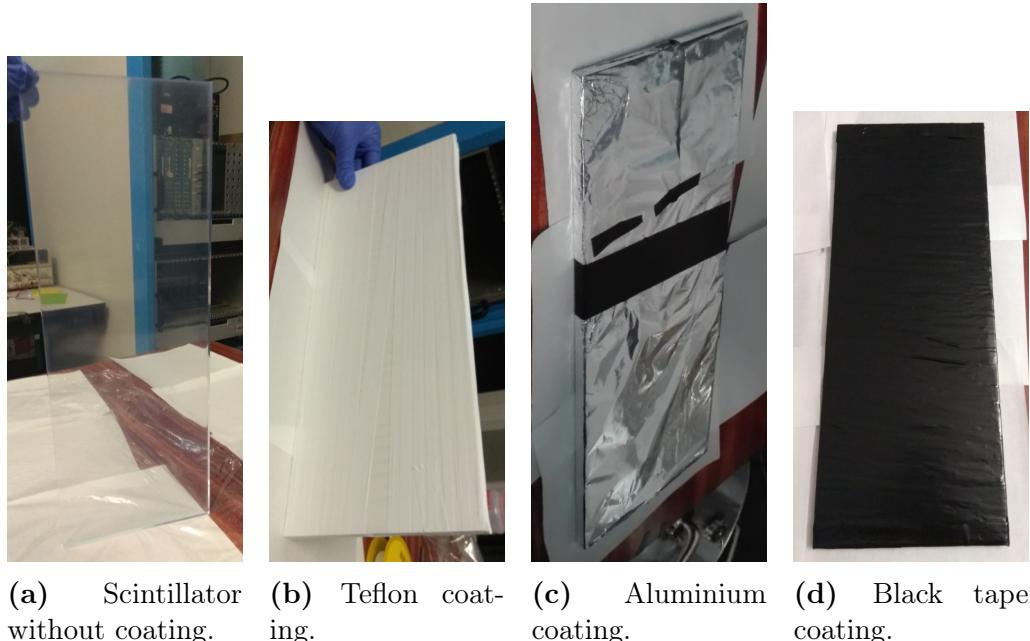


Figure 3.26 – Emission energy spectrum of the plastic scintillation used for the cosmic vetos [Cry20].



(a) Scintillator without coating. (b) Teflon coating. (c) Aluminium coating. (d) Black tape coating.

Figure 3.27 – Different layers used to wrap the cosmic veto detectors.

Chapter 4

Research & Development on Detector Design and Components

This chapter describes the characterization of the different parts of the TRITIUM monitor, including scintillating fibers, SiPMs, the ultrapure water system and the background rejection system. This characterization is crucial to understand the behaviour of the different parts and the results of the monitor. Furthermore, several developments were made to improve fundamental parameters of the TRITIUM monitor components to enhance their tritium sensitivity. All these studies were carried out inside a special light-tight box, called black box, to ensure that the detected photons come from the sources used, either LEDs or scintillators. In addition, as the energy response of plastic scintillators has a rather large uncertainty, most of the energy spectra are shown in ADC¹ channels, which are linearly proportional to energy.

¹ADC units are the internal units, called channels, in which an analog signal is digitized after an Analog-to-Digital Converter. The ADC units are proportional to the energy and the number of available channels depends on the bits used in its digitization.

4.1 Characterization and R&D on Scintillating Fibers

This section reports experimental measurements of the scintillating fiber parameters relevant for tritium detection, such as collection efficiency and conditioning uncertainty. Error bars are included in all graphs displayed but they are too small to be visible. Thousands of scintillating fibers are used in the TRITIUM detector which were prepared and conditioned prior to characterization studies or tritium detection. Therefore, various mechanical and electronical devices were developed to automatically prepare large number of fibers simultaneously.

4.1.1 Scintillating Fiber Conditioning Process.

The first step in TRITIUM desing was to choose the fiber length at which the signal of tritium events is optimized. On the one hand, long fibers are suitable because the efficiency of TRITIUM detector is proporcional to the fiber length, but, on the other hand, in long fibers, scintillating photons are reflected on the fiber walls many times before reaching the photosensors, that produce a deterioration in the tritium signal. To determine the optimal fiber length, several simulations, described in section 6.2.3, were carried out using Geant4 [Col21a], a particle and nuclear physics simulation package based on C++. It was concluded that it is preferable to employ relatively short fibers. The fiber length for the TRITIUM prototypes developed in Valencia, was 20 cm, which was also the length used for most of the experiments carried out in the framework of the TRITIUM experiment. As Saint-Gobain commercial fibers are 1 meter long, an effective scintillator cutting technique had to be developed with strict requirements on the cutting quality of the fiber ends since this greatly affects the transmission of photons and, consequently, the efficiency of TRITIUM monitor. This cut

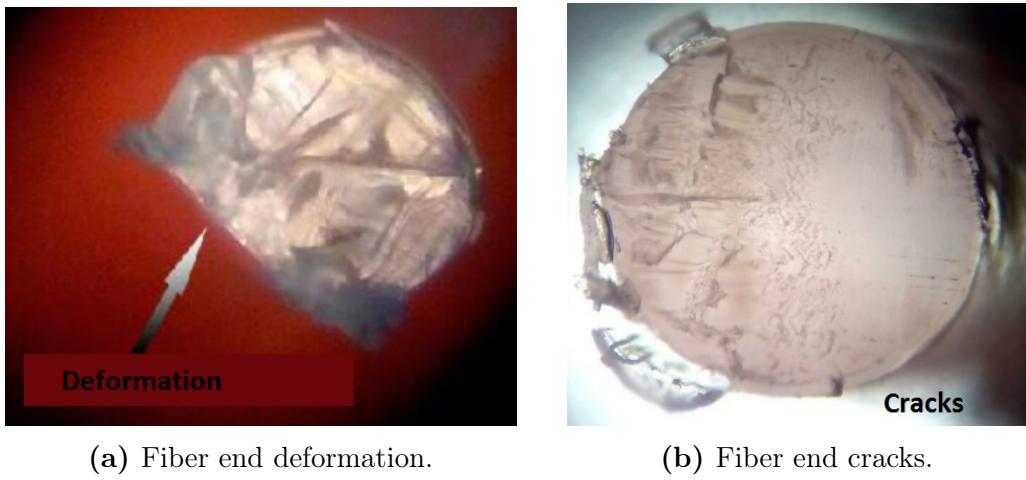


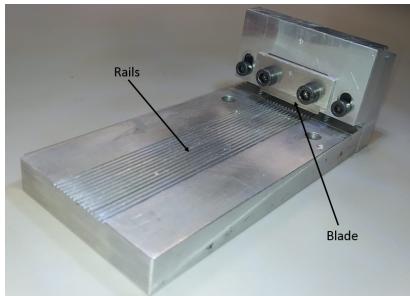
Figure 4.1 – Unsuccessful results of using commercial techniques to cut fibers.

must be perpendicular to the fiber and with very low uncertainty in the cutting position to achieve a good coupling of the fiber to the surface of the photosensor. It is also important that the fiber integrity be preserved, without cracks or deformations that contribute to the loss of photons. Cutting the end faces of polymer fibers is a current challenge. There are many different techniques such as milling, laser cutting, focused-ion-beam, blade cutting, etc. The blade cleaving technique was chosen for TRITIUM experiment because of its mechanical simplicity.

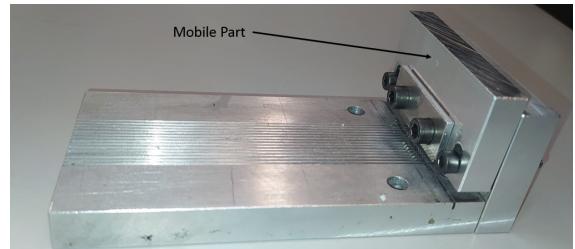
Many commercial devices based on blade cleaving, such as the one provided by Thorlabs with a diamond tipped blade [Inc06] or others similar to guillotine designed for industrial fiber optics [fo], were tested in an extensive study with unsuccessful results [Cam17]. As it can be seen in Figures 4.1, Commercial techniques produce deformations, cracks and imperfections so they do not fulfill the requirements previously imposed.

The microscope model PB 4161 from EUROMEX and the Digital Microscope from Jiusion were used to check the results in the fiber ends.

Because commercial devices do not work for our scintillating fibers, a cutting device, shown in Figure 4.2, was designed, built and tested.



(a) TRITIUM cutting device.



(b) TRITIUM cutting device.



(c) Additional piece of the TRITIUM cutting device.

Figure 4.2 – Cutting device developed in the TRITIUM experiment and additional part to set accurately the length of cut fibers.

This device consists of fourteen rails to which fibers are held and a thin blade, attached to a mobile piece, which is used to cut them. The perpendicular cut, which is one of the requirements, can be ensured since the moving piece, to which the blade is attached, is set perpendicular to the fibers. The blade used is a typical commercial razor blade, of 0.1 mm thickness, which is the thickness that gave the best results. The blade was adjusted with 5° tilt, with respect to the horizontal axis since it was found in several studies that this helps to obtain a less aggressive and cleaner cut [SR15, Law06]. As it can be seen in Figure 4.3a, with this cutting device fiber ends without breaks or deformation were obtained. An additional parameter that could in principle affect the cutting quality of the fiber ends is the temperature of both, fiber and blade. A study was carried out in

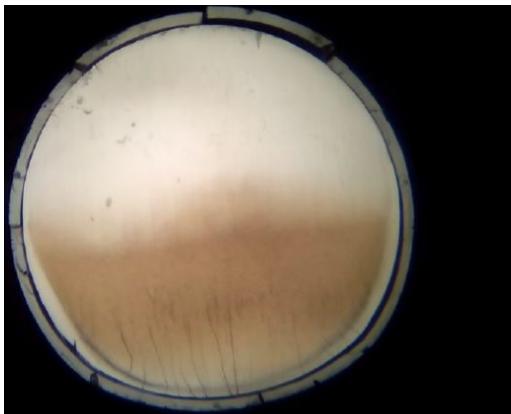
which both were subject to different temperatures from room temperature to 110 degrees. No significant conclusions were obtained [Cam17]. Thus, the cutting process was carried out at room temperature to make the cutting process easier.

To set the fiber length, which is the last requirement, an additional piece was designed and built, shown in Figure 4.2c. With the help of this piece, an uncertainty of less than 1 millimeter in the fiber length was achieved. With this cutting device all the requirements imposed were fulfilled, obtaining fibers with optimal light transmission. The quality fiber end after cutting is shown in Figure 4.3a. The slightly darkened zone at the bottom of the fiber is an inavoidable effect of the cutting process and, to reduce this effect, a polishing process developed by Thorlabs was applied [Inc06]. It consists on rubbing the fibbers during two minuts with five different polishing papers, with a decreasing grain size, 30 μm , 20 μm , 12 μm , 5 μm and 0.3 μm , describing on the the paper a shape of an 8 (approximately 120 movements). The result obtained after polishing is shown in Figure 4.3b, where it can be noted that the darkened zone has completely disappeared and the fiber end is completely clear without any damage or imperfection. Therefore, both tasks, cutting and polishing, are necessary.

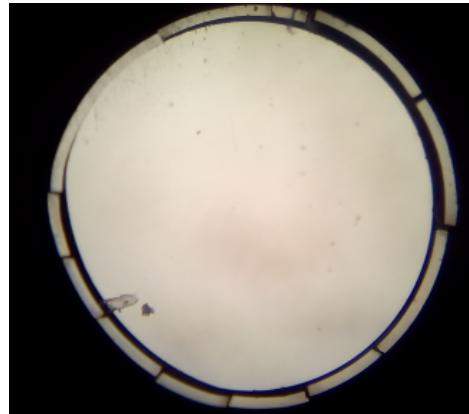
4.1.2 Automatic Polishing Machine for Scintillating Fibers

As mentioned above, tens of thousands of fibers had to be prepared and conditioned for the TRITIUM monitor², section 5.3. Although this number of fibers was not a problem for cutting, which is very fast process, the polishing process is quite time consuming. It takes more than ten minutes to polish each fiber, that would result in an unaffordable amount of time to prepare the needed quantity of fibers. Therefore, an automatic polishing

²Tritium prototype will be a module of TRITIUM monitor, based on dozens of modules.



(a) Fiber end after cutting with Tritium device.



(b) Fiber end after cutting and polishing.

Figure 4.3 – Result of the polishing process. a) Fiber end after cutting b) Fiber end after cutting and polishing with Thorlabs technique.

machine for scintillating fibers was designed, built and tested. This polishing machine is able to polish up to one hundred scintillating fibers at the same time and automatically. Furthermore, it is easily scalable to larger number of fibers.

This automatic polishing machine, displayed in Figure 4.4, consists of two parts: 1) A polishing table, where the fibers are polished 2) The electronics, based on Arduino technology, that operates the movement of the polishing table:

1. The polishing table, shown in Figure 4.5a, is divided in two parts: the static part, where the fibers are fixed, and the movable part, where the polishing papers are fixed. It was decided to set the polishing papers on the movable part because they are lighter and less fragile than fibers.

The static part consists of a piece, shown in Figure 4.5a, built with a 3D printer and locked to the system by four vertical screws. There

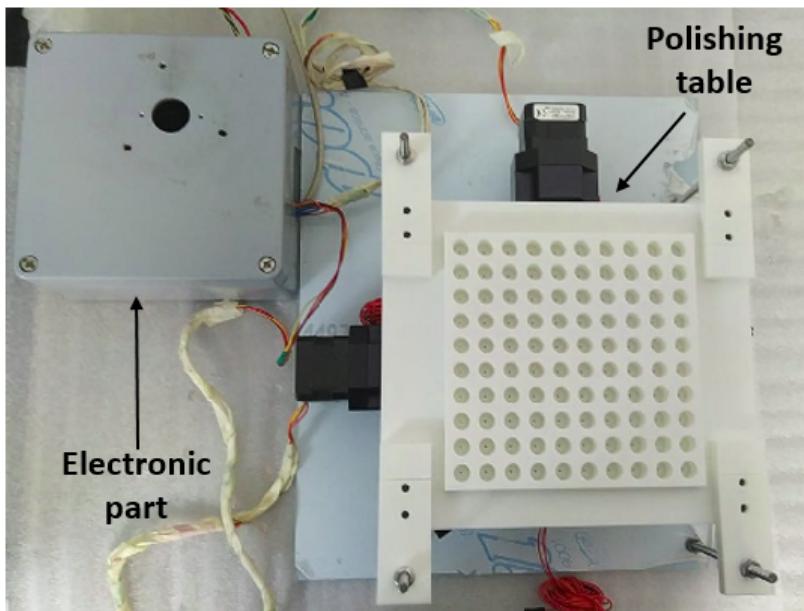


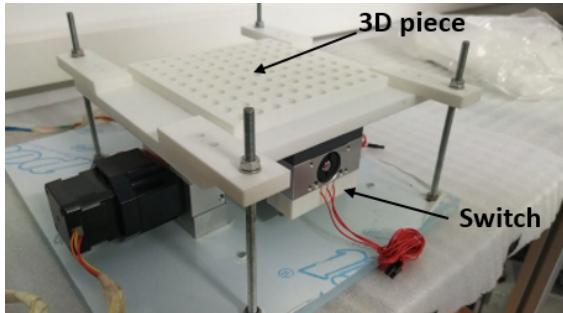
Figure 4.4 – Polishing machine developed in TRITIUM experiment.

are two nuts on each screw used to set the relative height and the inclination of fibers to the polishing papers. This piece contains one hundred holes in which the fibers are placed.

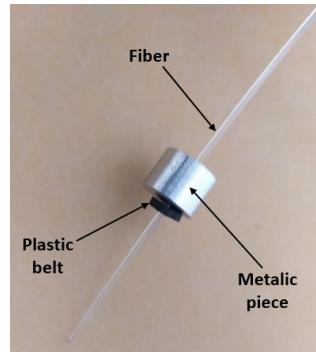
As the fibers are too light (0.16 g) to make the necessary pressure on the polishing paper, a plastic belt and a piece of metal with a weight of around 1.5 g, shown in Figure 4.5b, were employed to increase their contact pressure (similar to the connectors used in the Thorlabs polishing process).

The movable part consists of a flat PMMA plate of $18 \times 18 \text{ cm}^2$ to which the polishing paper is attached. This part is locked to two horizontal screws, perpendicular to each other that are used to set its position in the XY plane (horizontal plane), as shown in Figure 4.5c.

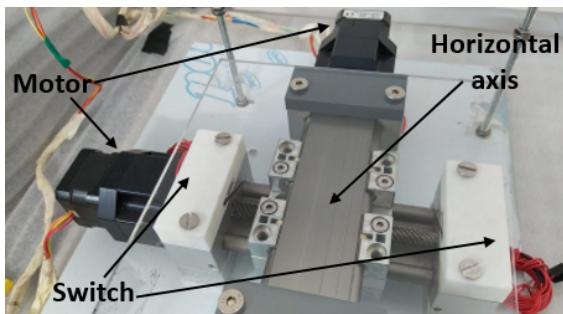
The polishing system contains several switches, mounted on a piece made with the help of a 3D printer, shown in Figures 4.5a, 4.5c and 4.5d, which are used to find the origin of coordinates when the system



(a) Polishing table.



(b) Fiber with metal piece.



(c) Horizontal screws and PMMA plate.



(d) Piece to hold switches.

Figure 4.5 – Polishing table of the polishing machine.

is reinitiated and to stop the movable part when the end of the path is reached.

2. The electronics which controls the automatic movement of the polishing paper, shown in Figure 4.6, is based on Arduino technology.

This electronics consists of two stepper motors, model NEMA ST4209S1404-A [Nan], which move the horizontal screws on which the polishing paper is attached. These motors are controlled by an Arduino UNO [ARD] that uses a CNC shield [OSO17] in which two different drivers are connected to control the stepper motors, one driver for each stepper motor.

Drivers are controllers that allow to manage stepper motors in a simple way. It is very important to choose the correct controller for the system because the controller limits the supply power to the motors, avoiding burning of the motors in the worst case. Instead of using the Pololu A4988 drivers [All12], which is one of the most widely used drivers, the first choice was the DRV8825 driver [Ins14]. DRV8825 allows to power the motor with higher voltage and intensities (45 V and 2.5 A) than A4988 (35 V and 2 A). Also, the DRV8825 controller includes a new microstepping mode (1/32) compared to the A4988 (1/16) with which we get more accurate and smooth movements. Finally the drivers were replaced by the TMC2208 [Cir19], much less noisy since it includes the *StealthChop* function with which the noise is practically eliminated. Furthermore, this controller is much more accurate owing to its a microstepping mode of 1/256. The voltage and current used to power the motors are 35 V and 2 A which are sufficient for the whole system since the current of the motors is limited to 1.33 A. The excess current will be transformed into heat that has to be dissipated from the system. Overheating of the drivers may cause loss of steps, producing wrong movements or even destroying the driver. Therefore, a cooling system is needed to ensure the correct operation of the polishing system. The cooling system, shown in Figure 4.6, consists of a copper piece³ in contact with both controllers and a fan, used to prevent heat accumulation inside the electronics box. The cooling power can be improved by using a PELTIER cell.

This polishing machine is controlled by a Raspberry Pi computer board using the Universal G-code Sender software (a grafical interface based on the GRBL package). There are several useful pre-programmed functions such as "HOME" with which the system, using the switches, finds its origin of coordinate every time the system is turned on. The software also has the possibility of loading a file containing the G-code to be executed. In the

³The copper is one of the best thermal conductor at STP

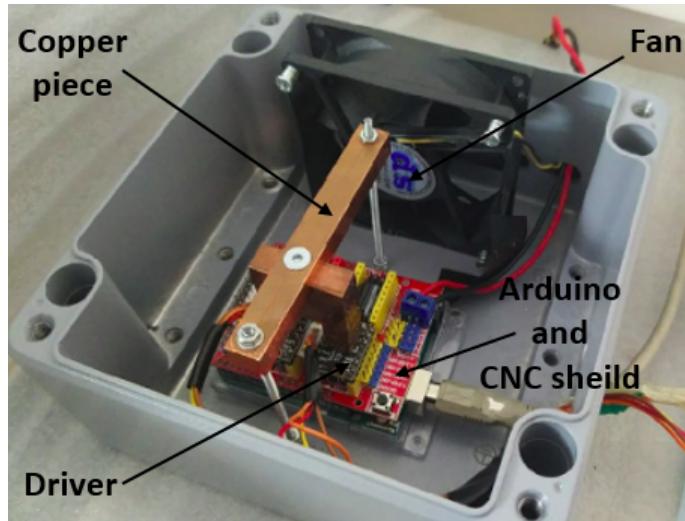


Figure 4.6 – Electronic system of Polishing machine.

TRITIUM project, the 120 movements required for each polishing paper are loaded in this way. This machine was tested with twenty fibers of 15 cm length arranged in a bundle. The fibers were fixed to the structure shown in Figure 4.7 and two PMTs located at the bundle ends, read in coincidence as described in section 3.2.4, Figure 3.15b, monitored the light transmission of the fibers.

The light transmission was measured before and after polishing. These measurements were carried out using two radioactive sources, a ^{60}Co gamma source of 715 Bq activity, and a ^{90}Sr beta source of 17.8 kBq activity. The energy spectra recorded for both radioactive sources are exhibited in Figure 4.8. The sources were placed in the middle of the fiber bundle, at 7.5 cm from each PMT.

As it can be seen in Figure 4.8, both energy spectra are shifted to the right after polishing, which means that the detected events have more energy (more photons per event reach the PMTs). This energy increase was more than 40% ($(42 \pm 4.6)\%$ for gamma source and $(49 \pm 8.4)\%$ for beta

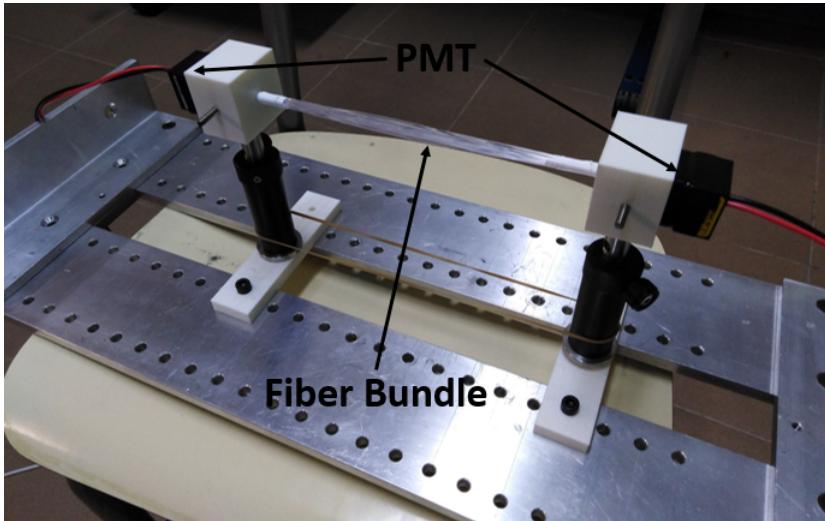


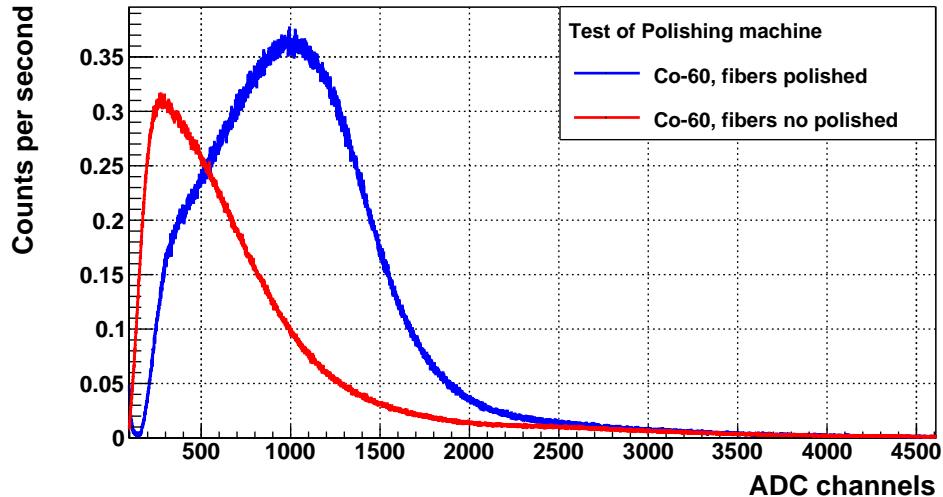
Figure 4.7 – Setup used to test the effect of the polishing machine.

source) with respect the unpolished fibers. In summary, with the polishing machine, the photon collection efficiency of the fibers was improved (mainly due to the improvement of the interface between fibers and PMTs). It is very important to achieve a high detection efficiency as the expected number of photons per tritium event is quite low.

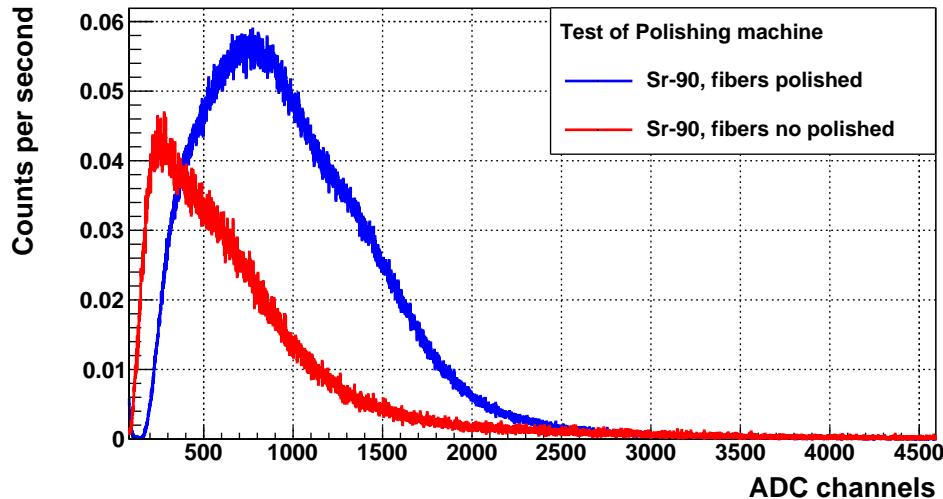
4.1.3 Characterization of Scintillating Fibers

This section describes the characterization of uncladded BCF-12 fibers from Saint-Gobain, which are the fibers selected for the TRITIUM experiment. These fibers are compared to single clad and multiclad BCF-12 fibers to quantify the influence of the clad in the relevant parameters of the scintillating fibers.

Although commercial clads are too thick for the TRITIUM experiment, a low thickness clad could be developed. For example, clads with a thickness of the order of tens of nanometers could be achieved by elec-



(a) Energy spectrum recorded for the Co-60 source.



(b) Energy spectrum recorded for the Sr-90 source.

Figure 4.8 – Energy spectra recorded with polished and unpolished fibers.

trodeposition techniques. The difference between these three types of fibers is that uncladded fibers only consist of a polystyrene core with a refractive index of 1.60 whereas single clad fibers have an acrylic clad (PMMA) of 30 μm thickness and a refractive index of 1.49 and, multiclad fibers have a second fluor-acrylic clad of 10 μm thickness and a refractive index of 1.42.

This characterization was carried out for a single scintillating fiber. The parameters measured for each fiber type were the fiber collection efficiency and the uncertainty of the fiber response due to the conditioning process. The magnitude employed for the characterization was the rate of photons reaching the active area of the photosensor. To measure this magnitude, a calibrated R8520-06SEL PMT of 29.76% quantum efficiency at the working wavelength measured by Hamamatsu was employed. The PCB described in section 3.2.4 was used to switch the PMT internal gain off and the PMT output current was measured by a Keithley 6487 picoammeter/voltage source. The photon rate was obtained from the current measurement using the equation 3.12 with $QE = 0.2976$ and $CE = 1$. A simplified scheme of the setup is shown in Figure 4.9.

This setup consists of an optical structure in which a LED and a PMT are separated a user set distance from each other. A LED435-03 from Roithner LaserTechnik GmbH [Gmb10], simulated the fiber scintillating light. The emission spectrum of the LED, given in Figure 4.10, was experimentaly measured by a spectrometer and fitted to a Gaussian function. The LED emission peak is at 433.9 nm with a FWHM of 18.4 nm. The fiber was placed between the LED and the PMT. The length of the fiber was 20 cm. Optical grease [Cera] was used for optimal coupling between the fiber and the PMT. Two collimators were used to ensure that only photons detected from the LED were detected in the PMT. Two FH-ST⁴ connectors from RoHS company [], were used to fasten the fiber to the system.

⁴FH-ST is a quick assembly connector for 1 mm POF, Plastic Optical Fiber

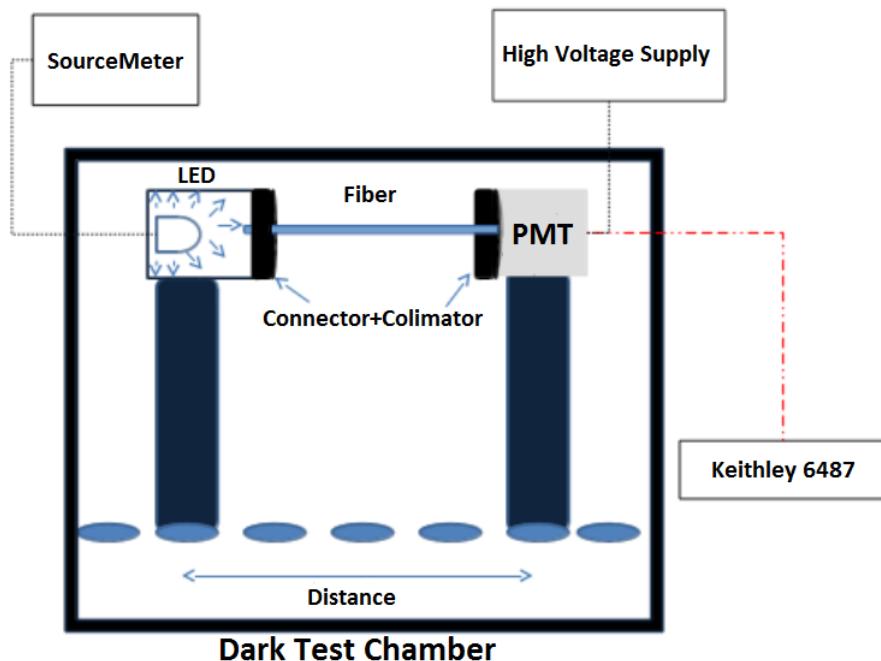


Figure 4.9 – Setup used for fiber characterization.

Preparation of the Characterization System.

Before characterizing a fiber several tasks had to be performed to check that the black box is light-tight enough and that the PMT response is linear.

A light leak in the black box would produce a background larger than the signal. To check the light-tightness of the black box a uncladded fiber of 20 cm length was arranged in the setup. The LED was fed with four different intensities (0.05 mA, 0.1 mA, 0.15 mA and 0.2 mA) and the PMT response was measured with and without a special black blanket from Thorlabs [Thoa], that prevents external photons to reach the system. This test was repeated for three different fibers and the mean and standard deviation of the light output were calculated.

The difference of the PMT responses in both cases is plotted in

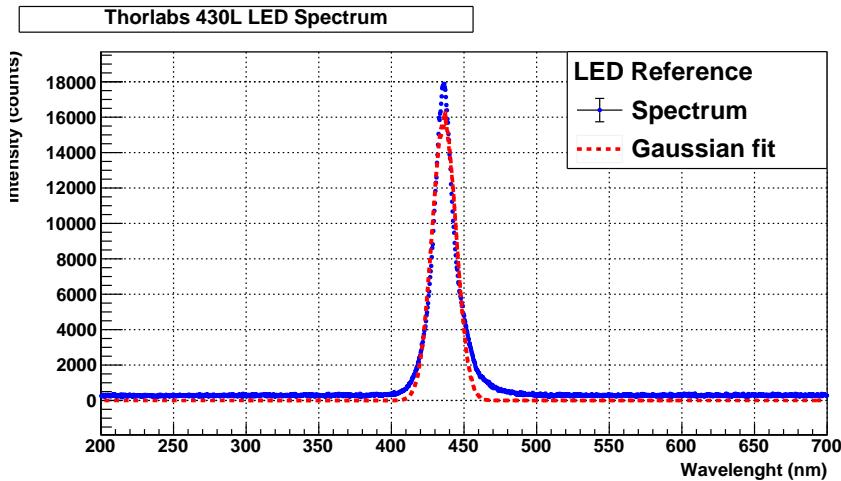


Figure 4.10 – Emission spectrum measured for the LED model 435-03 from Roithner LaserTechnik GmbH Company.

Figure 4.11 as a function of the LED intensity. As it can be seen in this figure, there are no statistically relevant differences between covered and uncovered fibers. Therefore, the light tightness of the black box is sufficient for this study.

The optimal voltage of the PCB without the PMT internal gain was obtained by finding the voltage plateau at which the electron collection efficiency in the first dynode was practically 100%. With no fibers in the setup, the LED was fed at 1 mA intensity and the PMT output current was measured for different PMT supply voltages, between 0 and 500 V. The number of photons detected by the PMT is plotted in Figure 4.12. As it can be seen, the plateau starts at voltages higher than 150 V. The chosen voltage for the characterization was 250 V.

Finally, the linearity of the PMT was verified. The LED was powered with intensities ranging from 0 to 10 mA (LED linearity range) to check that the LED emission light does not saturate. The linearity was tested in the of the number of photons range expected for a tritium event

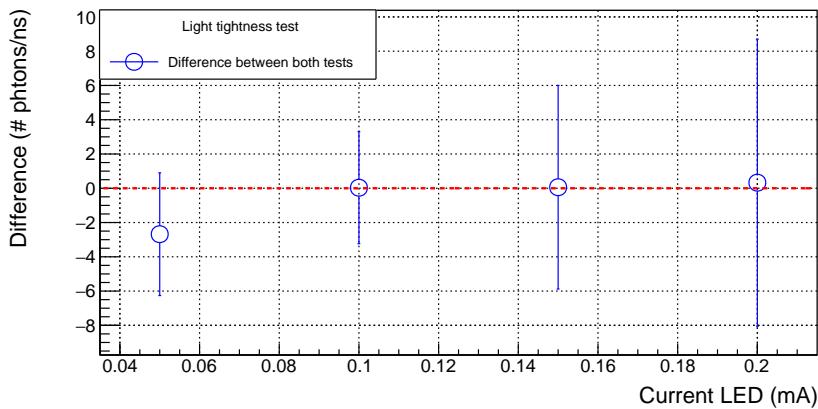


Figure 4.11 – Difference between the results obtained in both tests carried out to check the light-tight quality of the system.

(a few tens of photons per tritium event, which gives tens of photons per nanosecond) and in the range around two thousand five hundred photons per nanosecond. To test the linearity of the PMT in the range of tritium events, the setup described above was used without any fiber but with one of the connectors and the collimators kept to make sure that the active area of the PMT is the same as in the characterization study. To test the linearity of the PMT in the range of more than a thousand photons per nanosecond, the remaining connector was removed in order to increase the photons that reach the photosensor but the collimator was also kept. The results for both intensity ranges are shown in Figures 4.13. As it can be seen, the PMT output current is linear in both intensity ranges.

Results of the Characterization of Scintillating Fibers

The conditioning process, consisting of cutting and polishing the fibers, is an individual task that generates a small dispersion in the response of each individual fiber, σ_{con} . This uncertainty is present in the tritium measure-

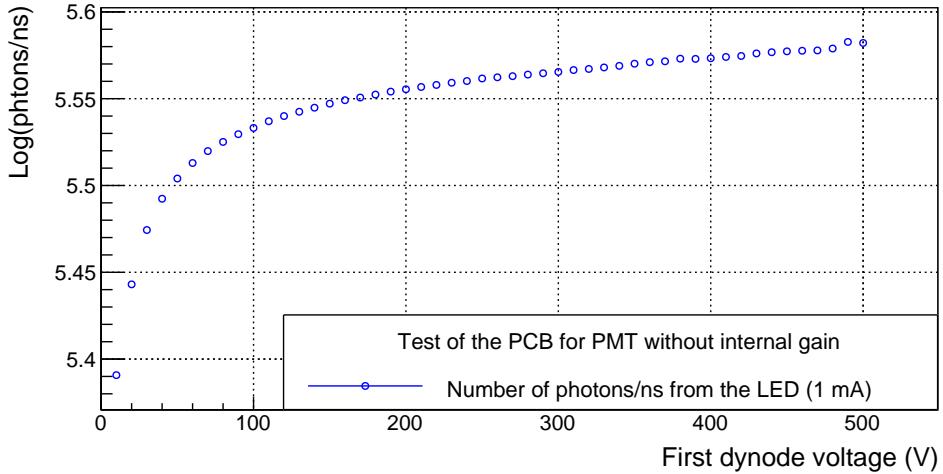


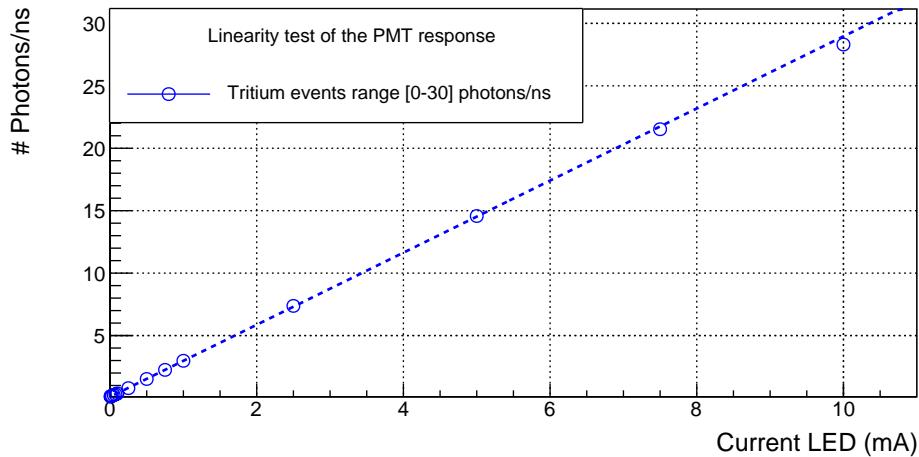
Figure 4.12 – Response of the PMT as a function of its high voltage using the designed PCB with which no internal gain of the PMT is obtained.

ment by the monitor. To measure this uncertainty, it has to be taken into account that the position of the connectors that lock the fiber in the experimental setup produce an additional uncertainty, σ_{pos} , in the measurement. Since both uncertainties are independent, the total uncertainty is given by:

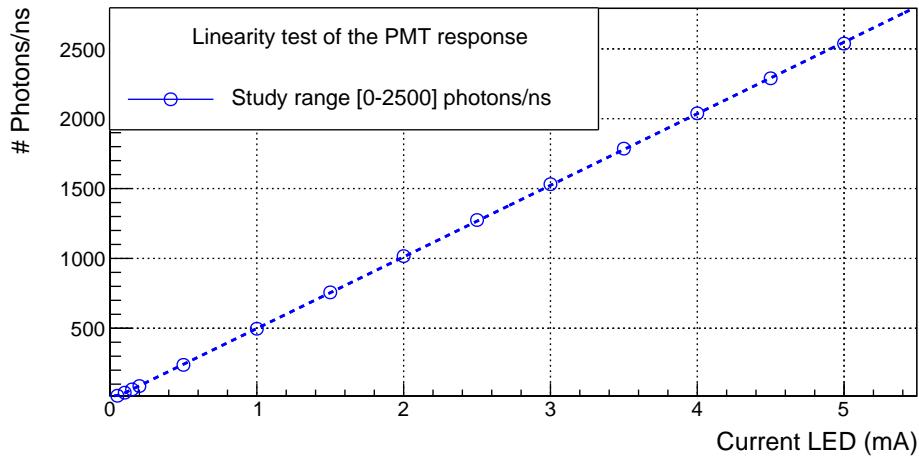
$$\sigma_t = \sqrt{\sigma_{pos}^2 + \sigma_{con}^2} \quad (4.1)$$

The uncertainty due to the fiber position has to be quantified to extract the conditioning uncertainty from the total uncertainty. Two different experiments were designed, the first giving only the uncertainty in the fiber position ($\sigma_t = \sigma_{pos}$), and the second to obtain the total uncertainty. The conditioning uncertainty is given by,

$$\sigma_{con} = \sqrt{\sigma_{tot}^2 - \sigma_{pos}^2} \quad (4.2)$$



- (a) Response of the PMT in the intensity range of tritium events. Error bars are smaller than the point size.



- (b) Response of the PMT in the range 0 – 2500 photons/ns. Error bars are smaller than the point size.

Figure 4.13 – Linearity tests of the PMT response.

The test designed to measure σ_{pos} consisted of preparing one fiber of each type (uncladded, single clad and multiclad) by the conditioning process reported above. Each fiber was locked in the setup, and measurements by feeding the LED with an intensity of 0.1 mA are made. These measurements were repeated ten times with a given fiber. The mean, \bar{x} , and the standard deviation of the measurements for each fiber type are shown in Table 4.1 where the relative standard deviation, σ_{pos}^{rel} , defined by equation 4.3, is also included.

$$\sigma_{pos}^{rel} = \frac{\sigma_{pos}}{\bar{x}} \quad (4.3)$$

Fiber type	Mean (photons/ns)	σ_{pos} (photons/ns)	σ_{pos}^{rel} (%)
Uncladded	524.09 ± 0.01	17.65	3.37
Single Clad	1071.70 ± 0.01	9.07	0.85
Multiclad	949.93 ± 0.03	9.91	1.04

Table 4.1: Mean and standard deviation (due to fiber position in the setup) of photons per nanosecond that reach the PMT for 0.1 mA LED intensity.

As it can be noticed, the clad reduces the position uncertainty, which means that it improves the uniformity of the fiber response. It was also found that the clad significantly improves the light collection efficiency of the fibers. The reason could be that photons are mainly collected in the core of the fiber and the interface of core is better defined for single-clad and multi-clad fibers than for uncladded fibers. In the latter case, the interface is provided by the environment (air or water in the case of TRITIUM). External conditions, as dirt, may produce noticeable interface fluctuations. It is also seen in the table that a second clad slightly reduce the collection efficiency. The reason could be that a second clad layer reduces the radius of the fiber core proportionally. Concerning the error of the measurement, the error of the Keithley device was three orders of magnitude smaller than the standard deviation of the measurement and was neglected.

To determinate the whole uncertainty, ten different samples of each fiber type were prepared and each fiber was measured under the same conditions as above. This measurement was done for four different LED emission intensities (0.05, 0.1, 0.15 and 0.2 mA). The results for uncladded fibers are plotted in Figure 4.14, where it can be seen that, although each fiber shows a very linear trend with the number of collected photons, a dispersion in the fiber response is clearly seen. Similar results were obtained for single clad and multiclads fibers, displayed in figures 4.15a and 4.15b, respectively.

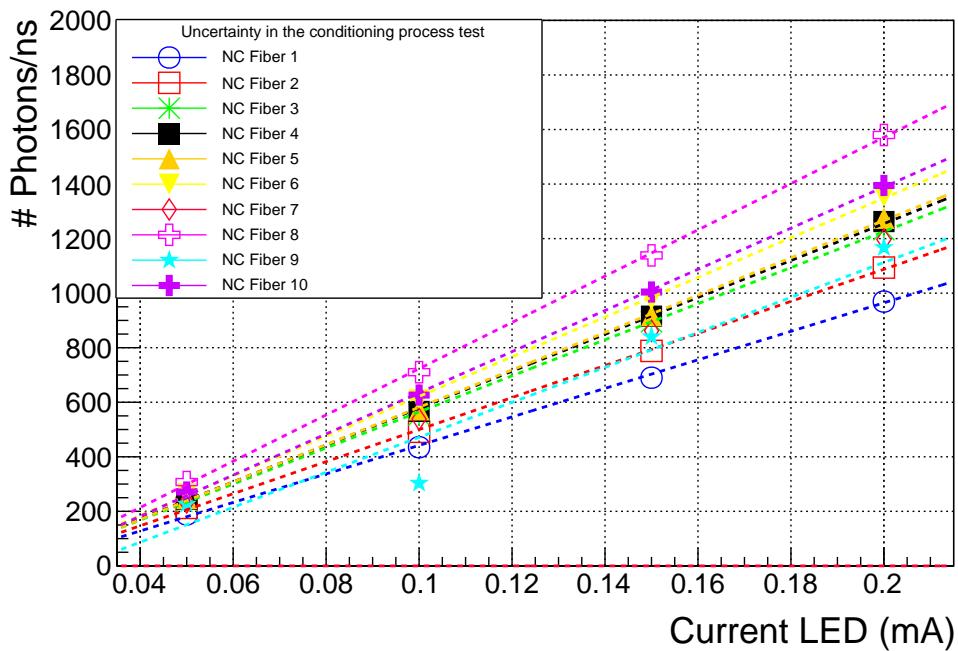
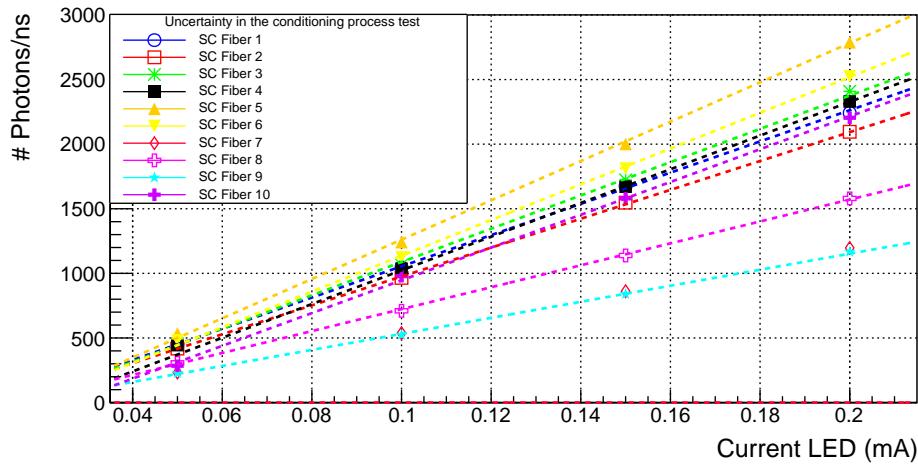
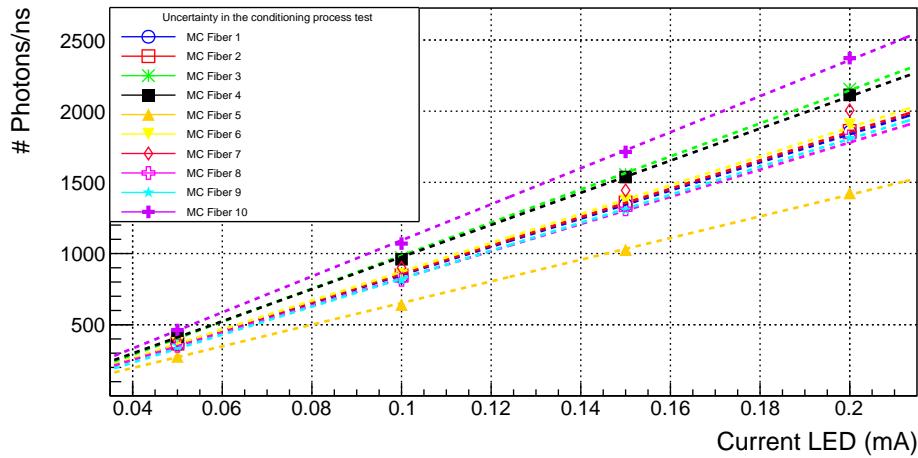


Figure 4.14 – Number of photons/ns reaching the PMT for Uncladded fibers.

The average number of collected photons versus LED intensity and the relative standard deviation for each type of fiber are given in Tables 4.2 and 4.3 respectively and are plotted in Figure 4.16, where they can be compared.



(a) Number of photons/ns reaching the PMT for single clad fibers.



(b) Number of photons/ns reaching the PMT for multi-clad fibers.

Figure 4.15 – Number of photons/ns reaching the PMT for ten samples of each fiber type.

Led Int. (mA)	Uncladded	Single Clad	MultiClad
0.05	245 ± 11	384 ± 33	377 ± 15
0.1	572 ± 26	923 ± 74	871 ± 35
0.15	915 ± 39	1485 ± 120	1397 ± 55
0.2	1267 ± 55	2054 ± 166	1933 ± 76

Table 4.2: Number of collected photons versus LED intensity for the different type of fibers.

Led Int. (mA)	Uncladded	Single Clad	MultiClad
0.05	4.38	8.66	3.97
0.1	4.59	8.02	3.97
0.15	4.34	8.07	3.95
0.2	4.36	8.10	3.93
Mean	4.42	8.21	3.96

Table 4.3: Relative standard deviation, $\sigma_t(\%)$, versus LED intensity for the different fiber types.

As it can be noticed in Figures 4.14 and 4.15 the fiber response is quite linear and single clad and multiclad fibers have stronger signals than uncladded fibers, which means that the clad has a significant effect on the fiber collection efficiency. It can also be remarked in Table 4.3 that the relative standard deviation, σ_{pos}^{rel} , does not vary with the LED intensity.

An average of the relative standard deviation caused by the fiber positioning and conditioning is given in Table 4.4. As it can be noticed, the smallest relative standard deviation due to the conditioning process was found for uncladded fibers, which means that the damage from this process occurs mainly in the fiber clad, as illustrated in Figure 4.3. It was checked under microscope that this damage only occurs at the end of the fiber. Also, the largest relative standard deviation in this process is measured for single clad fibers, which means that the second clad increases the resistance of the

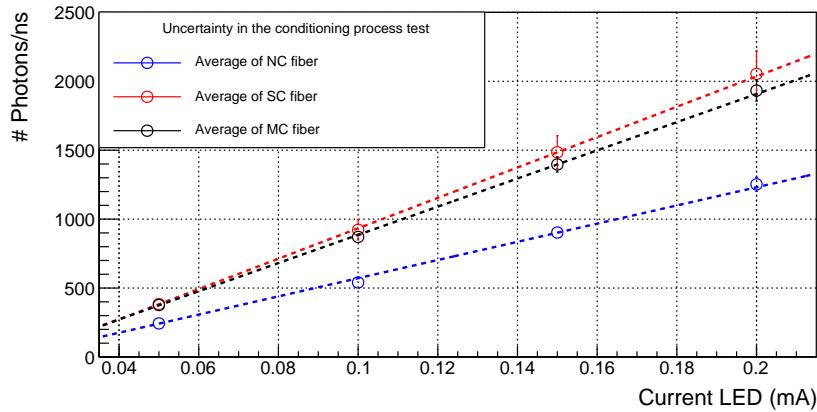


Figure 4.16 – Average number of photons versus LED current for 10 samples of each fiber type (uncladded, single clad and multi-clad fibers).

fiber to the conditioning process.

Fiber type	σ_t (%)	σ_{pos} (%)	σ_{con} (%)
Uncladded	4.42	3.37	2.86
Single Clad	8.21	2.17	7.92
Multiclad	3.96	1.04	3.82

Table 4.4: Relative standard deviations (σ_t , σ_{pos} and σ_{con}) measured in this test.

In summary, this study shows that the use of a fiber clad improves the photon collection efficiency. The relative statistical deviation due to the fiber conditioning process was quantified for the different fiber types. It was found that the damage by the conditioning process is produced mainly in the fiber clad. Thus, if a method to build a clad for fibers is developed, it should be applied after the fiber conditioning process.

Finally, the measurement of the photon collection efficiency for each type of fiber is shown. To measure the collection efficiency, CE_{100} , ten

different samples 10 cm length were prepared for each fiber type. Similar measurements, summarized in Table 4.5, were carreid out.

Led Int. (mA)	Uncladded (γ/ns)	Single-clad (γ/ns)	Multi-clad (γ/ns)
0.05	318 ± 61	550 ± 71	480 ± 84
0.1	736 ± 143	1270 ± 164	1111 ± 193
0.15	1184 ± 232	1984 ± 231	1777 ± 307
0.2	1645 ± 324	2507 ± 208	2338 ± 350

Table 4.5: Number of the collected photons versus LED intensity for 10 different fibers of 10 cm length.

The collection efficiency of 10 cm fiber length, CE_{10} , was calculated by comparing these tests to those performed for a fiber length of 20 cm. The collection efficiency to CE_{100} was calculated from CE_{10} by assuming a linear dependence on length.

Fiber type	CE_{10} (%)	CE_{100} (%)
UnCladded	76 ± 8	7.6 ± 0.8
Single Clad	78 ± 6	7.8 ± 0.6
Multiclad	83 ± 7	8.3 ± 0.7

Table 4.6: Collection efficiencies CE_{10} and CE_{100} .

The collection efficiency, CE_{100} , given by the manufacturer Saint-Gobain is in the range 3.44% – 7% [Cer05]. Our measurements, given in Table 4.6, are close but slightly higher than the manufacturer values which could be attributed to our use of collimated photons.

4.1.4 Cleaning Process for Scintillating Fibers

The tritium events only produce a few photons in the fibers, so it is very important to detect as many photons as possible. As it was demostrated

in the fiber characterization study, the quality of the interface between the core of unclad fibers and the environment (tritiated water in the case of TRITIUM detector) affects conspicuously the photon collection efficiency. To improve the quality of the interface, a fiber cleaning process was included, aiming to remove external particles deposited on the fibers, such as dust and fat that worsen the photon collection efficiency. Through this cleaning process, the wetting property of the fibers, illustrated in Figure 4.17, is improved, preventing air molecules from attaching to the fiber and achieving a uniform water clad around the fibers, which results in an improvement of their collection efficiency.

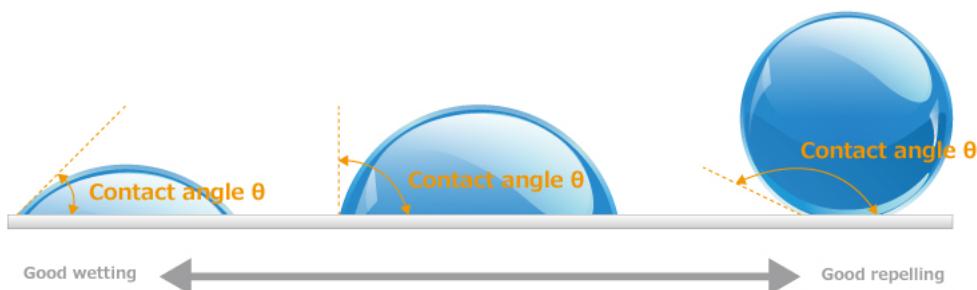


Figure 4.17 – Wetting property produced by the cleaning process. [comb]

This cleaning process was developed and carried out in the clean room of ICMOL laboratory⁵. It consists of filling three different glass beakers, one with alkaline soap, another with millipore water⁶ and the last one with isopropanol. First, the fibers are rubbed for 5 minutes with alkaline soap and then placed in the first beaker for sonication for 3 minutes. Then, the fibers are cleaned with a constant flow of water for 5 minutes and they are placed in the second beaker for sonication for another 3 minutes. Third, the fibers are placed in the third beaker for sonication for another

⁵ICMOL, Institute of Molecular Science, is a research institute located in the Science Park of the University of Valencia.

⁶The millipore water is water in which all the ions were removed, producing a very low conductivity of it-self, on the order of $10 \mu\text{Sv}/\text{cm}^2$

3 minutes. Finally the fibers are dried with an N₂ air gun and introduced inside of the prototype.

The improvement in fiber response was verified using a bundle of twenty fibers of 15 cm length that was prepared with the conditioning process described. This bundle of fibers was arranged in the setup described in section 4.1.2, Figure 4.7, and several energy spectra were taken using different radioactive sources. Then, these fibers were cleaned with the fiber cleaning process and spectra were measured again. Two radioactive sources were used in this study, a ⁹⁰Sr beta source, already used in the polishing machine test, and a ¹³⁷Cs gamma source, of 500 Bq activity. The results are plotted in Figure 4.18. A shift of the spectrum to higher energies can be noticed for the cleaning fibers. This improvement was quantified by a parameter F defined as,

$$F = \frac{A_C - A_{NC}}{A_C} \quad (4.4)$$

where A_C and A_{NC} are the integrals of the energy spectra measured after and before the cleaning process, respectively.

The value of F obtained is about 21% for both radioactive sources. Nevertheless, it should be taken into account that F was measured in air and the result could differ in water.

4.2 Characterization of SiPM

This section details the characterization of the SiPM S13360-1375 model, which was the first chosen as TRITIUM monitor photosensor. This characterization is incomplete since some important SiPM parameters for the TRITIUM monitor, which are PDE, dark count rate and crosstalk probability, were not measured. A complete characterization is already underway for the

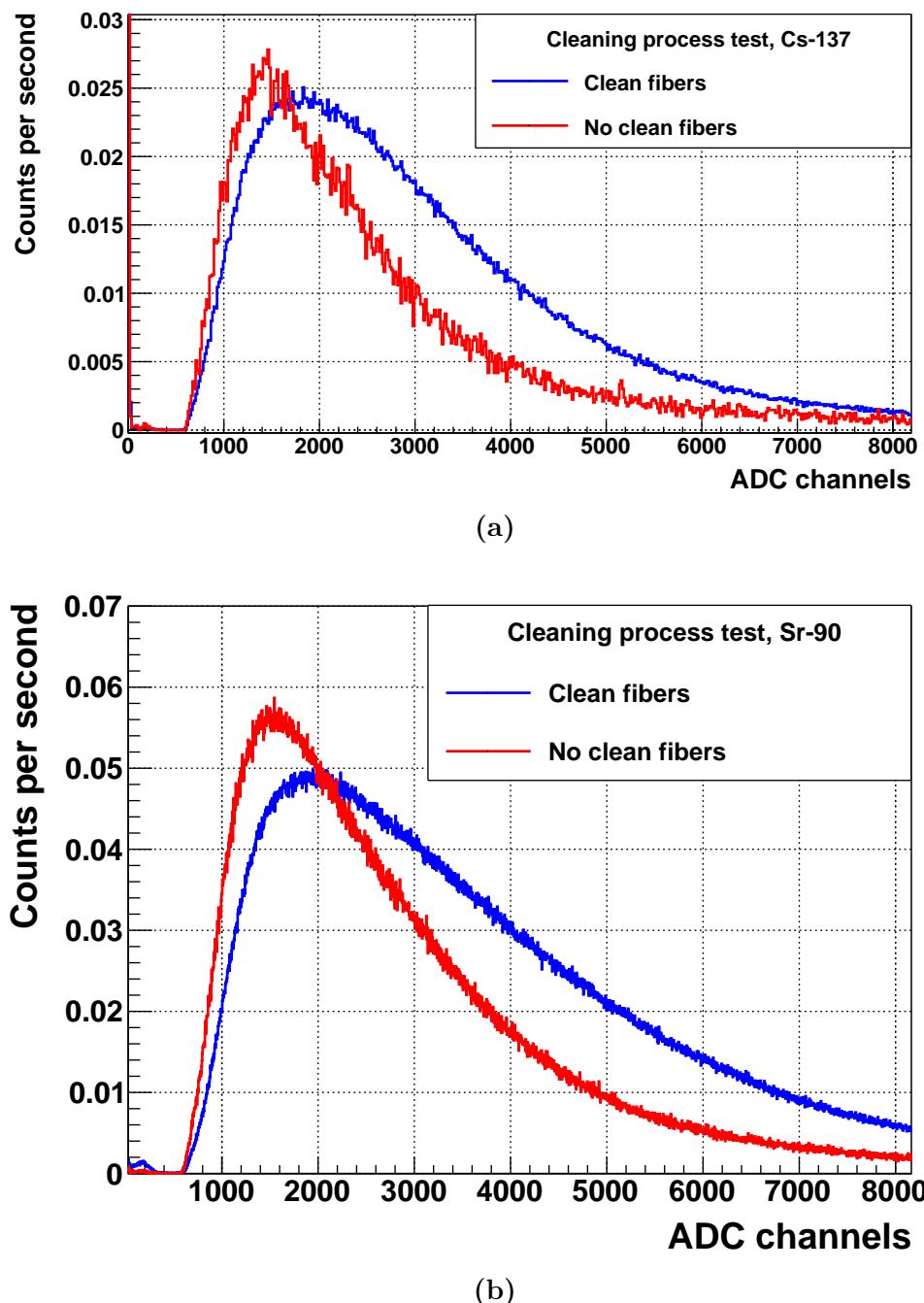


Figure 4.18 – Energy spectra obtained before and after the cleaning process using a radioactive source of a) ^{137}Cs and b) ^{90}Sr .

S13360-6075 model, the latest proposal for the TRITIUM detector, where the relevant parameters, given in section 3.2.3, will be experimentaly determined using the experimental setup, described in appendix A. The SiPM characterization is carried out inside of a climatic chamber, model CCM 81 from DYCOMETAL [DYC]. This climatic chamber allows to control the temperature and humidity with a precision of 0.1°C and 0.1% respectively. In addition, this chamber is a Faraday cage. A special black blanket [Thoa] was used to prevent external photons from reaching the SiPM.

First, the quenching resistance and the breakdown voltage of the SiPM were obtained from the measurement of the current-voltage curves of the SiPM with the bias voltage applied in forward and reverse direction, respectively. This measurement was done without the amplification of the electronic board to achieve a better precision in the dark. The output current of the SiPM was directly measured using the Keithley 6487 Picoammeter/Voltage Source [KEI]. The LabView sofware was used to take the data. The measured parameters are plotted as a function of the bias voltage in Figure 4.19.

As can be seen, when the bias voltage is applied in forward direction, Figure 4.19a, the output current of the SiPM does not flow until the potential difference between the n and p layers is reached, which is approximately $V_0 = 0.7$ V for silicon photosensors, close to the value experimentally obtained, $V_0 = 0.5$ V. When the current start to flow, the intensity is linear with the applied voltage. The equivalent resistance, R_{eq} , was determined from,

$$I = \frac{1}{R_{eq}}V; \quad \frac{1}{R_{eq}} = \sum_{i=1}^N \frac{1}{R_{qi}} = \frac{N}{R_q} \quad (4.5)$$

and R_{iq} are the quenching resistance of each pixel of the SiPM in parallel which have the same value, R_q . A value of $R_q = 511.39 \pm 0.74$ k Ω was obtained, which is in agreement with the typical values given by Hamamatsu.

The breakdown voltage, V_{BD} , was obtained from the reverse bias

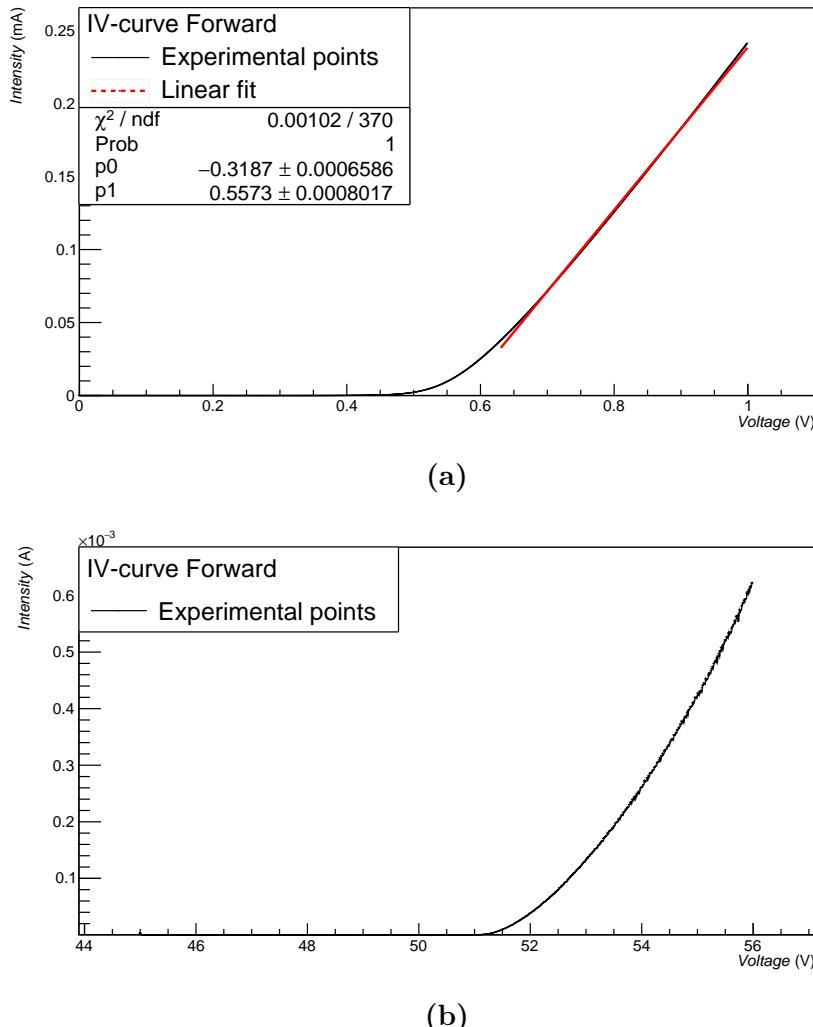


Figure 4.19 – I-V curves measured for the SiPM S13360-1375 model with the bias voltage applied in a) forward direction b) reverse direction. Measurements taken at $T = 25^\circ\text{C}$ and humidity $H = 45\%$.

voltage plot. This is the points at which the output current of SiPM start to flow, which can be calculated from the maximum of the function

$$f = \frac{1}{I} \frac{dI}{dV} \quad (4.6)$$

The value obtained, $V_{BD} = 51.02$ V, is in agreement with the value provided by Hamamatsu, Table 3.3.

To measure the SiPM gain, G_{SiPM} , the electronic board described in section 3.2.4 with an amplification factor of $F_{amp} = 170$ was used. An incoherent light source, LED435-03 from Toithner LaserTechnik GmbH [Gmb10], described in section 4.1.3, was used to illuminate the SiPM with a low enough flux of $\lambda = 435$ nm photons. The SiPM output signal shows various well-defined pulse heights, shown in Figure 4.20, corresponding to the number of pixels simultaneously fired. The single photon spectrum, SPS is plotted in Figure 4.20. This spectrum was obtained by integrating and histogramming the SiPM output pulses with time windows wide enough to contain the full charge of the pulse. The time windows used in these measurements was $t_w = 500$ ns. The light source gave a trigger signal for the measurement, green line in Fig 4.20.

The well-separated peaks in the SPS spectrum correspond to the charge produced by a different number of fired pixels. The first peak in the spectrum is the pedestal, which is the charge measured when no pixel is fired. This peak is caused by the electronic noise of the system. The second peak corresponds to one fired pixel and so on. The SiPM gain, G_{SiPM} , can be obtained from the SPS spectrum from the equation,

$$G = \frac{\overline{\Delta Q}(V \cdot s)}{F_{amp}(V/A) \times e^-(C)} \quad (4.7)$$

where e^- is the electron charge and $\overline{\Delta Q}$ is the average peak distance in the SPS spectrum, corresponding to the charge released by a fired pixel.

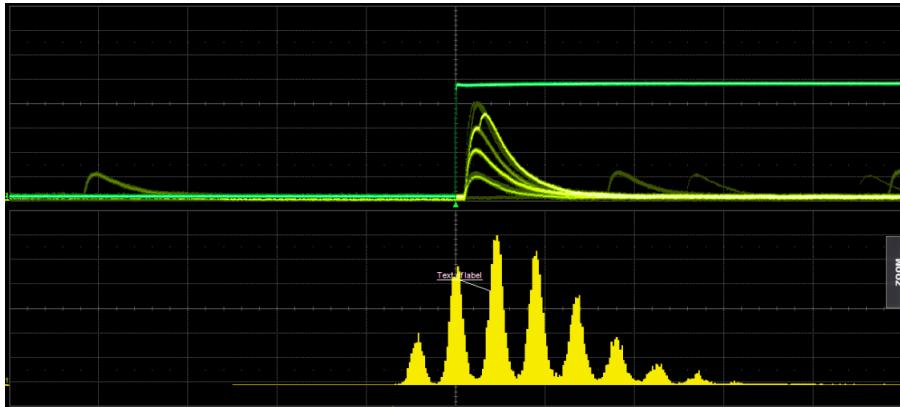


Figure 4.20 – Above: Trigger signal (green) and SiPM output pulses (yellow). Bottom: SPS spectrum obtained by integrating and histogramming the SiPM output pulses. This measurement was done at 25°C , $V_{bias} = 53.98$ and humidity of $H = 60\%$.

To obtain the value of $\overline{\Delta Q}$ a macro was written in ROOT [Col21b]. This macro finds and extract the background, which is crucial in some cases like high temperatures or high bias voltages. After that, this macro find all peaks in the SPS spectrum and fits each one to a Gaussian function, shown in Figure 4.21a. The value and error of the charge produced by multiple fired pixels are obtained from the centroid and the sigma of the different fitted Gaussian functions. The obtained charges are fitted to the number of fired pixels, Figure 4.21b.

Up to 10 simultaneously fired pixels were obtained with a relative uncertainty of the charge measurement of less than 2%. The slope of the straight line in Figure 4.21b corresponds to $\overline{\Delta Q}$.

The value obtained for the SiPM gain is $G_{SiPM} = 4,11 \cdot 10^6$, very close to the value provided by Hamamatsu, Table 3.3.

A stabilization method for the SiPM gain was implemented. This is necessary for the TRITIUM project since the temperature in the final location of the tritium detector cannot be controlled with enough sensitivity

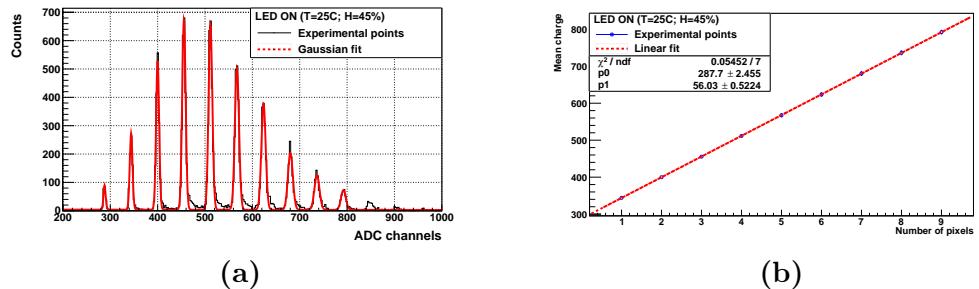


Figure 4.21 – ROOT analysis performed to obtain the SiPM gain. a) Fit of the SPS spectrum to various Gaussian functions. b) Charge of successive number of pixels as a function of the number of pixels fired. Error bars are within point size. This experience was carried out at $T = 25^\circ\text{C}$, $V_{bias} = 53.98$ V and humidity of $H = 45\%$.

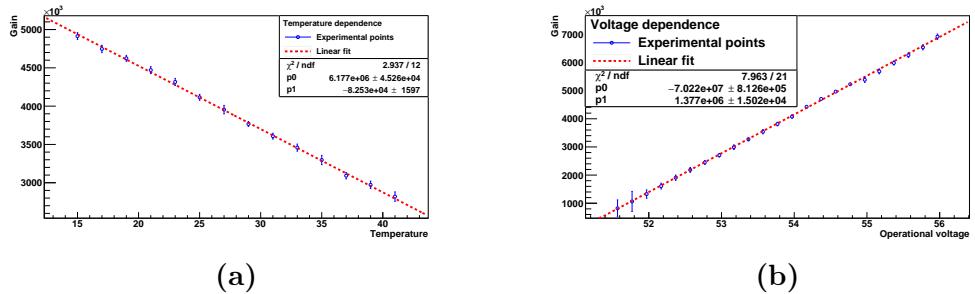


Figure 4.22 – Dependence of the SiPM gain with the a) Temperature b) Bias voltage.

to avoid variations of the SiPM gain. This method consists of compensating for variations in the SiPM gain caused by variations of temperature by controlled variations of the bias voltage. For this task, first, the dependence of the SiPM gain with the temperature and bias voltage was measured. The SiPM gain was measured at several temperatures from 15°C to 41°C in steps of 2°C , which is expected to be the temperature range in the final location. The bias voltage was $V_{bias} = V_{BD} + 3$. The SiPM gain was measured at several overvoltages from 1 V to 5 V in steps of 0.2 V. The temperature was $T = 25^\circ\text{C}$. Both measurements are shown in Figure 4.22.

As can be seen, an excellent linear trend is obtained for both cases. The parameters of the linear fit obtained are,

$$\begin{aligned} G_{SiPM} &= a \cdot T + b; & G_{SiPM} &= c \cdot V_{bias} + d \\ a &= (-82.53 \pm 1.59) \cdot 10^3; & c &= (137.72 \pm 1.50) \cdot 10^4 \\ b &= (617.65 \pm 4.53) \cdot 10^4; & d &= (-762.16 \pm 8.13) \cdot 10^5 \end{aligned}$$

In addition, the breakdown voltage, V_{BD} , and the terminal capacitance, C_t , can be obtained from the linear fit of the SiPM gain as a function of the bias voltage, V_{bias} . Both parameters can be obtained from the definition of the SiPM gain and taking into account that the charge produced in a pixel is proportional to the capacitance of the pixel and the difference voltage in the SiPM, V_{OV} ,

$$G_{SiPM} = \frac{Q_{pixel}}{e^-} = C_d \frac{V_{bias} - V_{BD}}{e^-} = c \cdot V_{bias} + d \quad (4.8)$$

where C_d is the pixel capacitance.

From the linear fit obtained in Figure 4.22b, a value of $V_{BD} = 50.98 \pm 0.59$ V and $C_d = 220.63 \pm 2.41$ fF are obtained. The terminal capacitance of the SiPM can be calculated assuming all pixels in parallel, $C_t = N_p \times C_d = 62.88 \pm 0.69$ pF. Both parameters, the breakdown voltage and the terminal capacitance, agree with the values provided by Hamamatsu, Table 3.3.

Finally, the value of the bias voltage to be applied to compensate for the variation in the SiPM gain due to a variation of the temperature can be obtained by applying variations to linear relations:

$$\begin{aligned} G_{SiPM} &= a \cdot T + b \longrightarrow \partial G_{SiPM} = a \partial T \\ G_{SiPM} &= c \cdot V_{bias} + d \longrightarrow \partial G_{SiPM} = c \partial V_{bias} \end{aligned}$$

Therefore, the total variation of the SiPM gain, which is produced by the variation of both parameters, must be cancel:

$$\begin{aligned}\partial G_{SiPM,tot} &= \partial G_{SiPM}(T) + \partial G_{SiPM}(V_{bias}) = 0 \\ \partial G_{SiPM}(V_{bias}) &= -\partial G_{SiPM}(T) \longrightarrow c\partial V_{bias} = -a\partial T \\ \partial V_{bias} &= -\frac{a}{c}\partial T = e\partial T\end{aligned}$$

where the parameter $e = 59.93 \pm 1.33 \text{ mV/}^\circ\text{C}$ is the ratio of a and c and agrees with the value of the temperature coefficient provided by Hamamatsu, Table 3.3. Finally, integrating this expression, we obtain:

$$\int_{V_i}^{V_f} \partial V_{bias} = e \int_{T_i}^{T_f} \partial T \longrightarrow \Delta V_{bias} = e\Delta T \quad (4.9)$$

This equation gives the variation of the voltage, ΔV_{bias} , that keeps the SiPM gain when there is a variation, ΔT , of the temperature. More relevant is to know the bias voltage, V_{bias} to be applied as a function of the temperature, T . For this, it is necessary a reference situation. In our case, the reference situation considered is $V_i = V_{ref} = V_{BD} + 3 \text{ V} = 53.98 \text{ V}$ and $T_i = T_{ref} = 24^\circ\text{C}$, at which the gain is $4.2 \cdot 10^6$ (experimentally measured). Thus, we get:

$$(V_{bias} - V_{ref}) = e(T - T_{ref})$$

$$V_{bias}(\text{V}) = 59.9 \cdot 10^{-3} \cdot T(\text{ }^\circ\text{C}) + 52.54 \quad (4.10)$$

Finally, the stabilization method of the SiPM gain developed was tested. The temperature was varied from 21°C to 29°C and the bias voltage was modified according to the equation 4.10. The value of the SiPM gain obtained is shown in Figure 4.23 as a function of the temperature.

A red dotted line is included, indicating the value of the SiPM gain to be kept. The SiPM gain is maintained fairly well by this method.

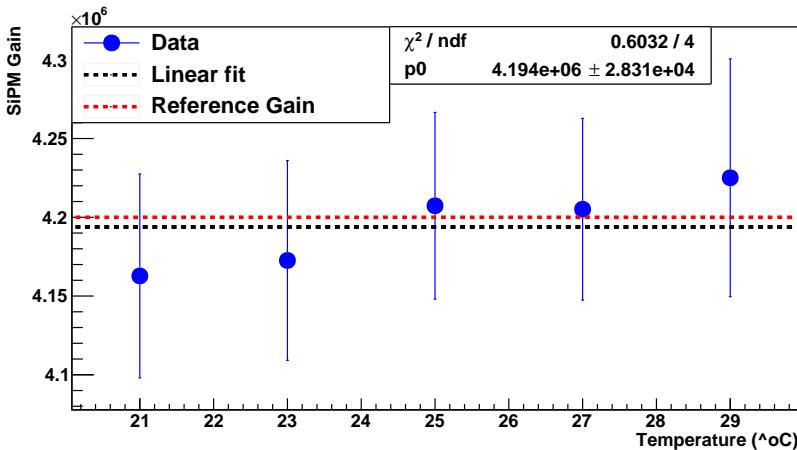


Figure 4.23 – SiPM gain as a function of the temperature with the stabilization method.

4.3 Characterization of the Ultrapure Water System

This section describes the characterization of the ultrapure water system, that guarantees that the quality of the water sample fulfills the requirements of the TRITIUM detector. There are three different requirements that this ultrapure water system must satisfy,

1. A quite low conductivity⁷ of the water, around $10 \mu\text{Sv}/\text{cm}$, to avoid that external particles dissolved in the water be deposited on the fibers, drastically reducing the detector efficiency.
2. The radioactive particles (other than tritium isotope) from the water sample should be removed because tritium cannot be separated from other radioactive isotopes.

⁷Conductivity is the ability of a material to conduct electrical current. In liquids, conductivity is related to the presence of salts (presence of positive and negative ions)

3. The tritium activity should not be affected by the water purification process.

To verify that these requirements are fulfilled, a characterization of the water sample for both, raw water and purified water, was done. This characterization consisted of measuring the water sample conductivity and the activity of the different radioactive element present in the sample. The turbidity and the chemical components of the water sample were also measured. The sample of the raw water was taken at 40 meters from the ultrapure water system and two meters deep in the river since it is the place where the samples used in TRITIUM monitor will be taken. Variations of up to 25% in the tritium activity was measured between both points (due to the diffusion of tritium along the river). The chemical composition of the water was measured by a physico-chemical analysis, shown in Table 4.7, before the ultra-purification process. The water sample contains a number of components, that must be removed to prevent their deposition on the scintillating fibers of the detector.

Chemical components	Concentration (mg/L)
CO ₃ H ⁻	154
Mg	46
Ca	105
NO ₃ ⁻	16
Cl ⁻	196
NO ₂ ⁻	0.03
K	11
Na	173
SO ₄ ⁻	217
Dry Residue	1029

Table 4.7: Chemical components and turbidity measured in the raw water sample.

The water turbidity⁸ was measured using the Hanna Hi 9829 portable multiparameter system from Hanna Instruments [Ins], obtaining a value of 29 NTU, much higher than the WHO recommended limit of 5 NTU for drinking water. The water conductivity was also measured for both, raw and purified water, using the same system. The results of the conductivity measurements, together with the measurement of the rejected water, described in section 3.3.2, are presented in Table 4.8. As it can be seen in the first column, the raw water sample has high values of conductivity, due to its content of ions, shown in Table 4.7. It can be noticed in the second column of the table that the conductivity of pure water was reduced by almost two orders of magnitude, to values close to 10 $\mu\text{Sv}/\text{cm}$, fulfilling the requirement. In the third column, it can be remarked that the rejected water conductivity is higher than that of raw water, because this water contains the removed ions from the purified water.

Date	Raw ($\mu\text{Sv}/\text{cm}$)	Pure ($\mu\text{Sv}/\text{cm}$)	Reject ($\mu\text{Sv}/\text{cm}$)
1/8/18	970	11.85	1442
7/8/18	958	11.8	1632
14/8/18	966	12.04	1725
22/8/18	980	12.54	1702
28/8/18	987	9.9	1692
5/9/18	1009	12.02	1645

Table 4.8: Measurements of the conductivity for several samples of water.

The gamma radioactive elements present in both, raw and purified water, were identified and their activities measured by a HPGe, high purity germanium detector. A gamma analysis was carried out to determine the emitters with long enough lifetime to be measured. The radioactive isotopes found in the raw water sample with measurable activities were ^{40}K and ^{226}Ra which were absent in the purified water.

⁸The turbidity of water is the loss of transparency due to dissolved particles, normally measured in Nephelometric Units of Turbidity, NTU, as the intensity of scattered light at 90 degrees.

The tritium activity was measured by liquid scintillation counting (LSC) to check if the ultra-purification process had modified it. The raw water was filtered at 0.45 microns to remove any particles that could cause the extinction of the scintillation signal. Table 4.9 show several measurements of the tritium activity for different water samples before and after purification. As seen in the table, tritium activity is not affected by the purification process.

Date	Raw (Bq/L)	Pure (Bq/L)
7/8/18	24 ± 3	26 ± 4
11/12/19	13.2 ± 2.1	13.85 ± 2.2
15/01/20	30.6 ± 4.2	30 ± 4

Table 4.9: Measurements of the tritium activity for several samples of both, raw and purified water.

4.4 Characterization of the TRITIUM Cosmic Veto

This last section reports on the characterization of the active shield (cosmic veto), which was carried out using PMTs as photosensors. Measurements of the cosmic veto using SiPM arrays has already started and their replacement will be as soon as possible.

The quality of the veto wrapping, shown in Figure 3.27, was checked. This study was done at the level of one detector so the configuration of the electronics is the one given in Figure 3.15b. The surface of the veto was divided in 9 parts, shown in Figure 4.24, in which a gamma source was placed.

Two different tests were made for this task:

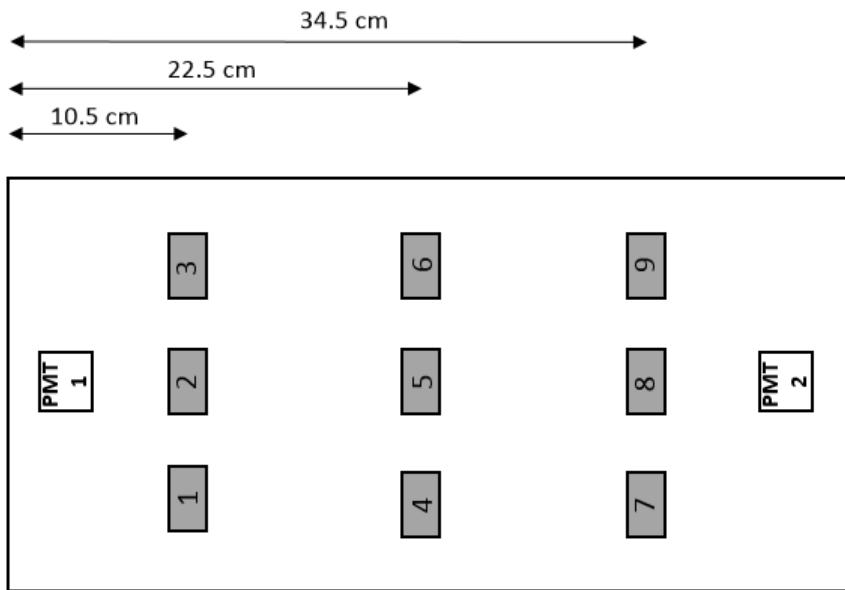


Figure 4.24 – Reference points used for veto mapping.

1. The improvement of the veto signal due to wrapping. A ^{137}Cs source was placed at point 2 and a energy spectrum was measured with the veto before wrapping. Next, the measurement was repeated after wrapping. The spectra obtained are shown in Figure 4.25.

The spectrum of the wrapping veto is shifted to the right, which means that more photons are collected per event. No improvement was obtained in the number of events detected, only in the collection efficiency.

2. The spatial uniformity of the signal in the wrapped veto was evaluated. For this task, a mapping was carried out, which consisted of placing a ^{60}Co source at each point and measuring the number of events detected in the same time window. This test was done for two different veto modules and the energy spectrum obtained was integrated. The count rates obtained are plotted in Figure 4.26. It can be observed that the veto signal has a uniform response on its whole surface, giving a fairly

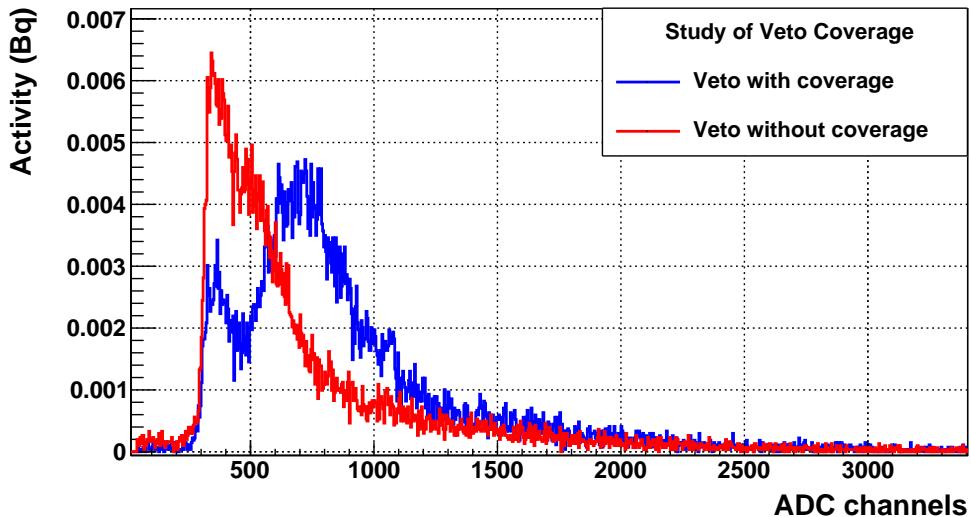


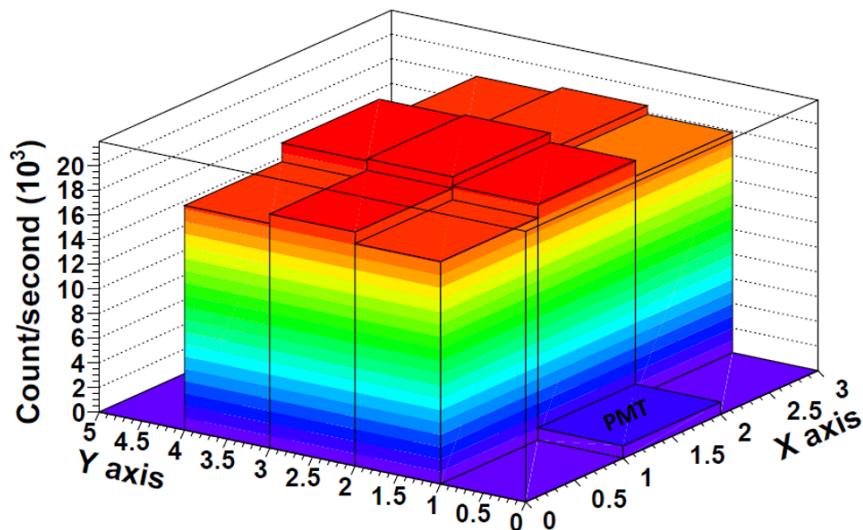
Figure 4.25 – Measurement of a radioactive source ^{137}Cs with the TRI-TIUM cosmic detector with and without wrapping.

similar counting rate in all the points measured.

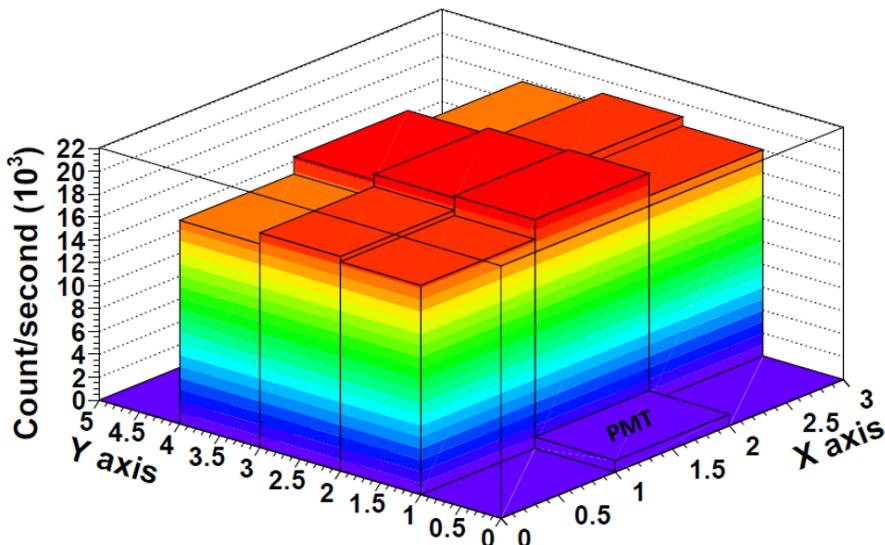
Next, both vetos in time coincidence was studied, so the configuration of the used electronics was that of Figure 3.15c. The goal was to find the conditions in which the detection of cosmic events is optimized. This optimization consists of, on the one hand, finding the minimum high voltage of PMTs for which their efficiency is stable, and, on the other hand, finding the maximum threshold of the discriminator⁹ before starting to loss cosmic events. For higher voltages and a smaller thresholds, a plateau of the counting rate should be obtained.

The counting rate was measured for several high voltages at fixed threshold and for several thresholds at fixed high voltage, plotted in Figure 4.27. To find the optimal conditions, the amplification line of the electron-

⁹The threshold is the voltage value that the PMT output signals must exceed to contribute to the cosmic detection



(a) Mapping of the first TRITIUM cosmic detector.



(b) Mapping of the second TRITIUM cosmic detector.

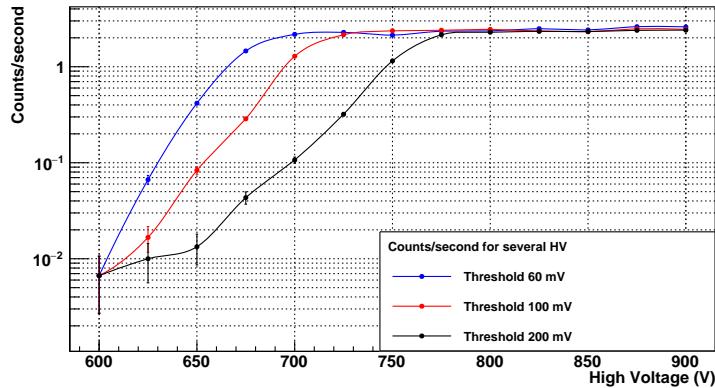
Figure 4.26 – Bidimensional graph of the count rate (Mapping) measured with two different TRITIUM cosmic detectors using a radioactive source of ^{60}Co .

ics was eliminated and the output signal of the coincidence module was connected to a CAEN Quad Scaler And Preset Counter-Timer module, N. 1145, [coma]. The counting rate was measured in a time window of 300 s. In Figure 4.27a, the counting rate at several high voltages for three different thresholds, 60 mV, 100 mV and 200 mV is plotted. As it can be observed, there is a minimum high voltage for each threshold, 700 V, 730 V and 780 V respectively, at which the plateau start. This minimum voltage is higher when the value of the threshold increases, as it should. Analogously, the counting rate for several thresholds and fixed high voltage was measured for three different high voltages, 750 V, 800 V and 850 V, plotted in Figure 4.27b. There is a maximum threshold for every high voltage used, 140 mV, 270 mV and 450 mV respectively, at which the plateau ends. This maximum threshold increases with high voltage, as it should. The voltage chosen was 800 V since it is on the plateau for the three thresholds and the threshold chosen was 200 mV which is on the plateau for the selected high voltage.

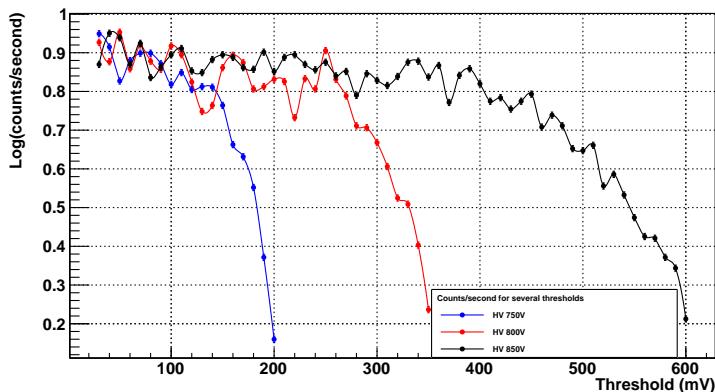
With this setting, the energy spectrum of cosmic events was measured, shown in Figure 4.28.

As expected, this energy spectrum fits well to a Landau function. The cosmic ray rate determined from the area of this spectrum is 2,5 event/s. The expected cosmic rate, calculated in section 3.4.2, is 2,9 event/s, so the efficiency of the active veto developed in TRITIUM experiment for cosmic event detection is 85%, which is a usual value for the efficiency of plastic detectors to mips.

Finally the detected cosmic ray rate versus the distance between the two cosmic veto was obtained. The energy spectrum was measured for five different distances, namely 10 cm, 20 cm, 36 cm, 40 cm and 50 cm. The spectra are plotted in Figure 4.29a. The energy spectrum in Figure 4.28 was also included. As it is expected, the counting rate decreases with the distance but the spectrum shape remains the same. The integrated spectra as a function of distance, plotted in Figure 4.29b, was fitted to a second



(a) Counting rate as a function of high voltage for three different thresholds in semilogarithmic scale.



(b) Counting rate as a function of threshold for three different high voltage in semilogarithmic scale.

Figure 4.27 – Counting rate as a function of high voltage for fixed thresholds and as a function of thresholds for fixed high voltage.

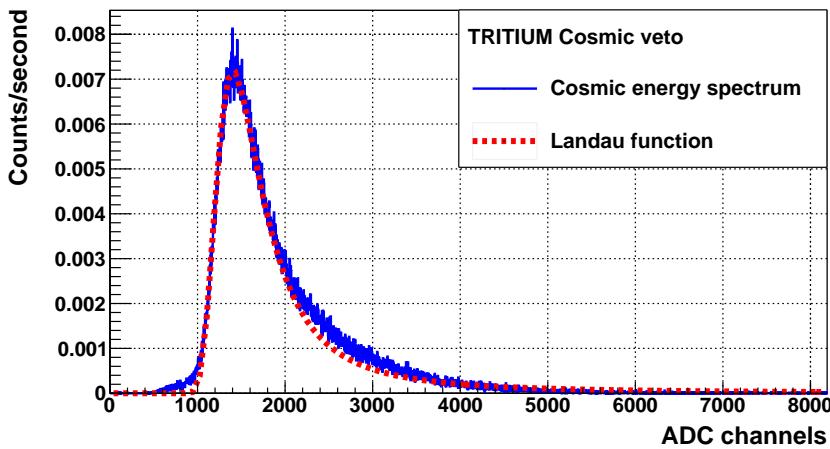
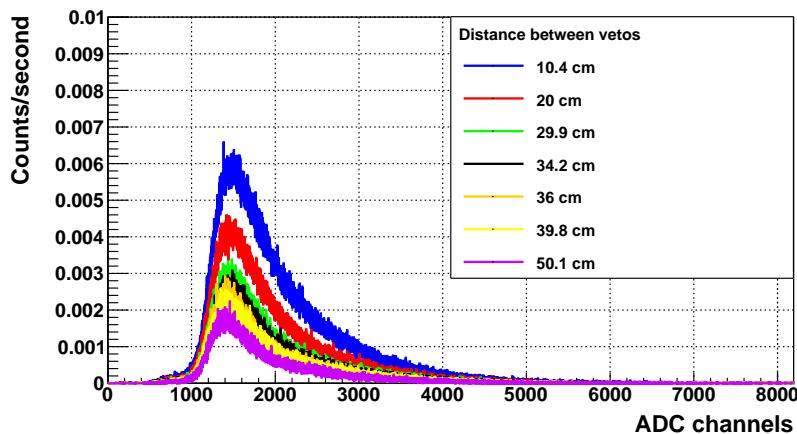
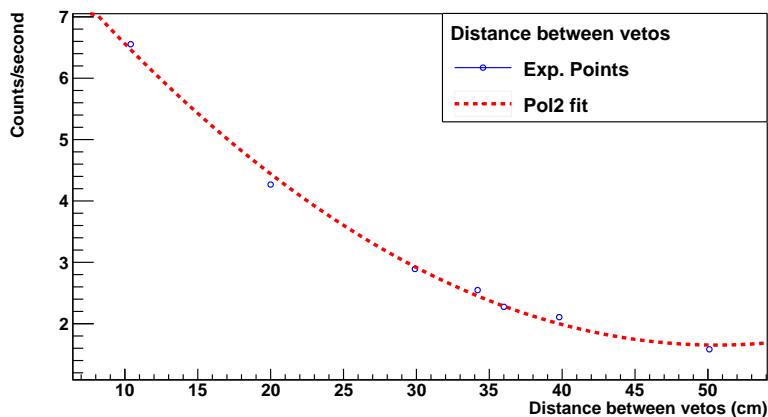


Figure 4.28 – Energy spectrum measured with the cosmic veto.

degree polynomial which allows to estimate the cosmic rate for a given veto distance.



(a) Energy spectrum of the cosmic veto for several distance.



(b) Fit of the cosmic veto rate versus distance to a second degree polynomial.

Figure 4.29 – Measurement of the cosmic veto for several distances between the two scintillators.

Chapter 5

TRITIUM Monitor Prototypes

This chapter describes the different prototypes that was developed in the framework of the TRITIUM experiment, which are TRITIUM-IFIC 0, TRITIUM-IFIC 1, TRITIUM Aveiro 0 and TRITIUM-IFIC 2, listed in chronological order of their construction.

The first two prototypes built, TRITIUM-IFIC 0 and TRITIUM-IFIC 1, are preliminary prototypes used to learn about tritium detection and to detect and solve problems in their designs.

The other two prototypes built, TRITIUM-Aveiro 0 and TRITIUM-IFIC 2, are prototypes with a well-defined design in which no problems were found. They were built to check more subtle effects.

Each prototype was designed and built in the laboratories of the university (IFIC, Valencia or Aveiro, Portugal) and it was filled with tritiated water following a protocol specially developed for this task. Several water tightness and filling tests were carried out in each prototype to guarantee its radiosecurity.

Lastly, the final monitor of TRITIUM detector will be explained.

It is based on modular detection units for easy scalability, where each module is the chosen prototype (the one with the best results).

5.1 Preliminary IFIC prototypes, TRITIUM-IFIC 0 and TRITIUM-IFIC 1

Two preliminary prototypes, TRITIUM-IFIC 0 and TRITIUM-IFIC 1, are shown in this section, which were designed, developed and built at the IFIC workshop.

These prototypes were thought to be a small scale of the final TRITIUM detector module and they were used to learn about tritium detection, to detect possible problems in their designs and to verify the improvements applied to them.

5.1.1 TRITIUM-IFIC 0

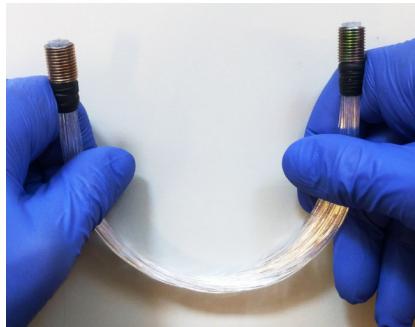
The TRITIUM-IFIC 0 prototype was the first prototype developed in TRITIUM experiment and it was used to check the feasibility of the technology proposed by TRITIUM, that's, to verify that it is possible to detect tritium in water using scintillating fibers.

Due to the problems that arise when liquid radioactive sources are used, the design of this first prototype paid special attention to radiation safety, rather than in detecting tritium efficiency.

TRITIUM-IFIC 0 consists of bundle of 35 fibers, shown in Figure 5.1, with a length of 20 cm, which were cut and polished with the techniques explained in section 4.1.1. This bundle has a metallic pieze located in both ends, shown in Figure 5.1a, which are used to fix it to the prototype.



(a) Metallic piece of the fiber bundle.



(b) Fiber bundle in a position similar to the prototype.



(c) Bundle of fibers in a straight position.

Figure 5.1 – Bundle of 35 fibers, the length of which is 20 cm, used in TRITIUM-IFIC 0 prototype.

This bundle is placed inside of a vessel, whose material is PVC¹ since it is a safe material widely used. This vessel, shown in Figure 5.2, was designed in a U-shape to improve the radiological safety, although this shape worsen the efficiency of tritium detection.

As can be seen in Figure 5.2, a piece of methacrylate and steel was designed and built to hold the detector. Two calibrated PMTs were optically coupled directly to the fiber bundle ends using optical grease [Cera].

The employed PMTs were the model R8520-460 from Hamamatsu company [K.K19], whose reference number are ZB2771 and ZB2773, and the electronic circuit, shown in figure 3.9, was used to distributed the high voltage between the dynodes. The employed high voltage was -800 V, at which their gain are $1.26 \cdot 10^6$ and $1.01 \cdot 10^6$ and their quantum efficiency are 29.76% and 28.66% respectively. Their signals were processed and analyzed

¹Polyvinyl Chloride, PVC

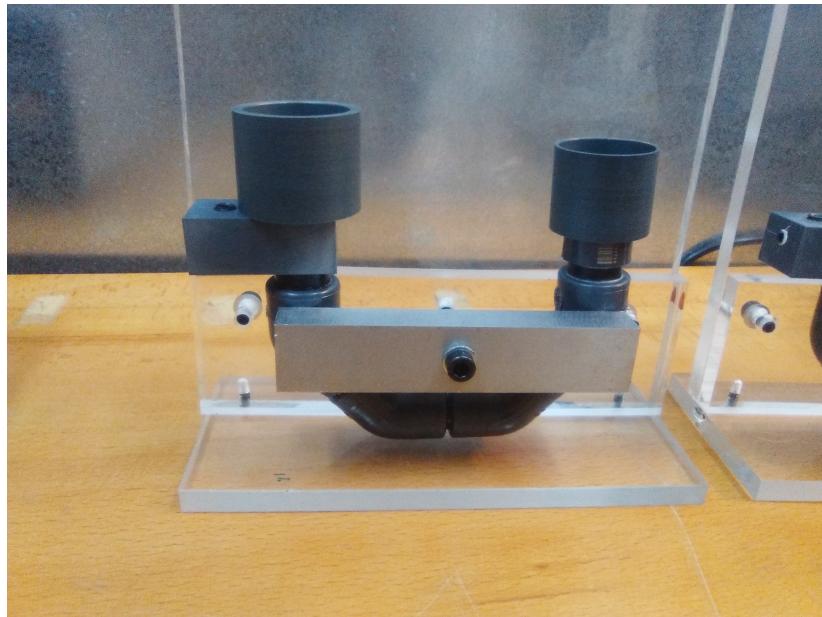


Figure 5.2 – TRITIUM-IFIC 0 Prototype.

using the electronic configuration shown in Figure 3.15b.

Two identical prototypes were built and filled following the same protocol but using different liquid solutions. The first prototype, called TRITIUM-IFIC 0 Background, was filled only with ultrapure water (39 mL, uncertainty of 0.05%) and it was used to measure the radioactive background of the detector whereas the other prototype, called TRITIUM-IFIC 0 Signal, was filled with a radioactive liquid source of tritium, the preparation of which is explained in the appendix C. The specific activity of the liquid source employed was 99.696 kBq/L (uncertainty of 2.24%) and the volume used to fill this prototype was the same, 39 mL (uncertainty of 0.05%). Therefore, the total activity of this tritiated water sample is approximately 3.888 ± 0.087 kBq.

This second prototype was used to measure the signal of the detector (tritium + background) and the measured tritium activity can be

known by extracting the background (measurement of TRITIUM-IFIC 0 Background) to the signal (measurement of TRITIUM-IFIC 0 Signal).

A statistically significant amount of time coincident events was not found in both PMTs, so the measurement of time coincidence was not possible.

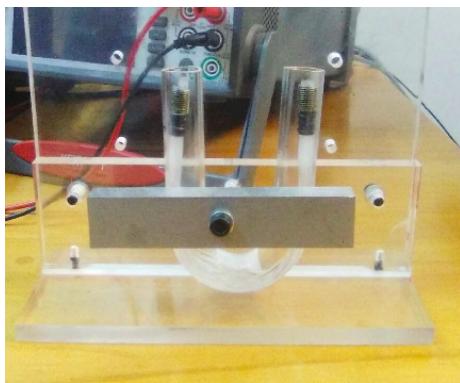
The loss of photons could be caused for several reasons, such as an excessive curvature in the fiber bundle due to the U-shape of PVC vessel, causing that too many photons escape from the fibers, or the poor quality of the tritiated water-fiber interface (the cleaning process explained in section 4.1.4 was motivated by this result).

To avoid this problem and obtain some results with this prototype, a measurement was performed with a single PMT. For this task, the electronic configuration shown in Figure 3.15a was used. The results of these measurements are shown in section 7.1.1, where they are discussed.

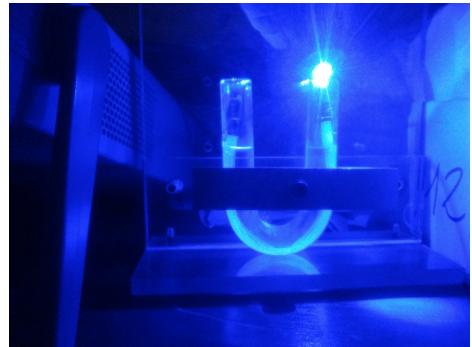
In addition, a test was carried out to find an explanation for why it was not possible to obtain a measurement with both PMTs in time coincidence. To do so, a transparent PMMA vessel, shown in Figure 5.3a, was built in a similar shape to that of the TRITIUM-IFIC 0 prototype vessel to check the effect of the fiber bundle curve.

The LED described in section 4.1.3 was used to verify the reduction in photocollection efficiency of the fiber bundle due to this curve.

As can be seen visually in Figure 5.3b, a large percentage of the photons are lost due to the curve, which can be easily solved by using a straight fiber arrangement in next prototypes.



(a) PMMA vessel.



(b) Test performed to check the lost photons.

Figure 5.3 – PMMA vessel used to check photon loss due to fiber bundle curve.

5.1.2 TRITIUM-IFIC 1

The next prototype, TRITIUM-IFIC 1, was intended to overcome the problems and limitations found in the previous one, TRITIUM-IFIC 0, section 5.1.1. To do so, some improvements were applied on it:

1. The fiber bundle is arranged straight to optimize the photon collection efficiency of the fibers.
2. A special fiber cleaning protocol, explained in section 4.1.4, was applied on the fibers. It was used to improve the interfaces between fiber and tritiated water, creating a better wetting property of the fiber, which will improve the photon collection efficiency of the scintillating fibers.
3. Teflon vessel was using in the Tritium prototypes to reduce the effect of the small photon collection efficiency of the fibers, measured in section 4.1.3, which is an innerent characteristic of the fiber which cannot be changed.

Teflon is an interesting material for its optical properties, specifically its reflection factor, which is very close to 100% at the working wavelength. It means that the photons that escape from the fiber will hit the Teflon walls and go back to the scintillating fiber.

The TRITIUM-IFIC 1 prototype consists of 64 scintillating fibers, with a length of 20 cm, that are arranged in a straight position using a teflon structure, shown in Figure 5.4. The fibers are fixed in an $8 \cdot 8$ square matrix.

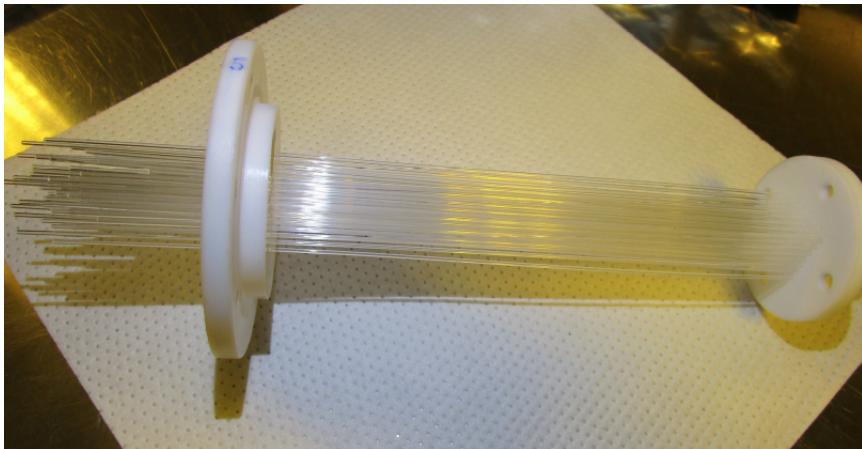


Figure 5.4 – Teflon structure used to arrange the fibers of TRITIUM-IFIC 1 prototype in a matrix of $8 \cdot 8$.

A new teflon vessel was designed and built, shown in Figure 5.5. It has a cylindrical hole whose internal diameter and length are 48 mm and 200 mm respectively, where the fiber structure will be placed.

In addition to cutting and polishing the scintillating fibers, a cleaning process, described in section 4.1.4, was applied to them to achieve a better tritiated water-fiber interface.

A piece of PVC was used to fix the photosensor on the prototype and prevent the photosensor from being affected by external light. A general

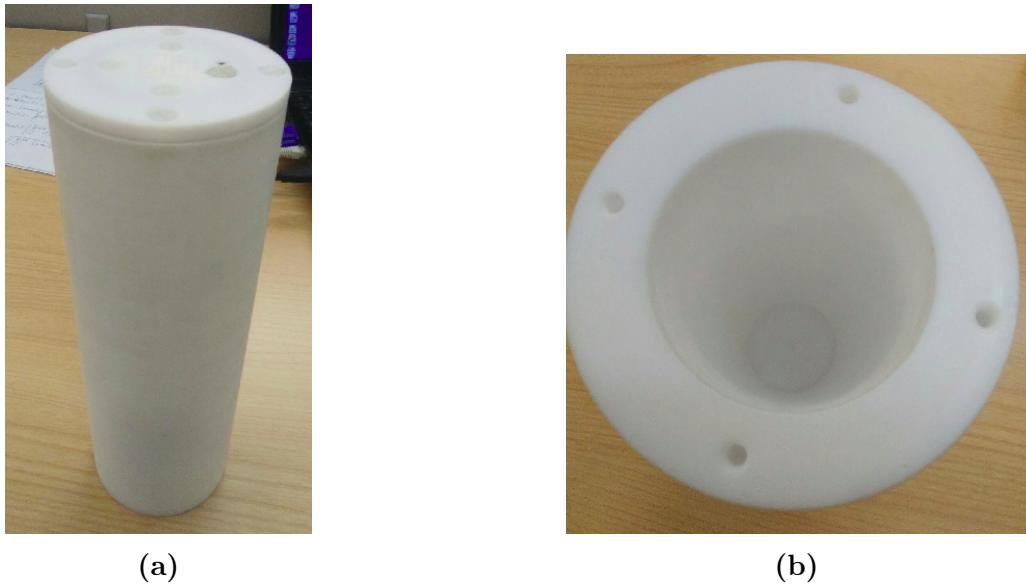


Figure 5.5 – Teflon vessel of TRITIUM-IFIC 1 prototype.

view of this prototype is shown in Figure 5.6, which, for radioactivity safety reasons, will be read using only one PMT.

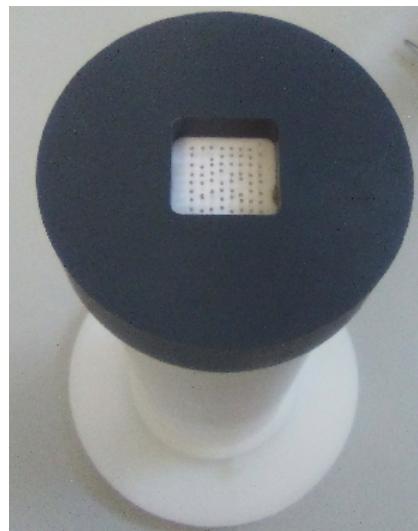
The PMT used was the model R8520-460, from Hamamatsu Photonics company [K.K19] and it was coupled directly to the fiber bundle using optical grease [Cera]. The electronic circuit, shown in Figure 3.9, was used to distributed the high voltage between the dynodes. The employed high voltage was -800 V, at which, its quantum efficiency is 28.66%.

The signal from this PMT was processed and analyzed using the same electronic configuration as that used for the TRITIUM-IFIC 0 prototype, shown in Figure 3.15a.

Unlike the previous prototype, only one TRITIUM-IFIC 1 was built. First, it was filled with ultrapure water (118 mL, uncertainty of 0.05%) and several background measurements were taken over a week. Then, it was emptied and refilled with 118 mL (uncertainty of 0.05%) of



(a)



(b)

Figure 5.6 – A general view of TRITIUM-IFIC 1 prototype.

the radioactive liquid source of tritiated water with the same activity as the one used in TRITIUM-IFIC 0 prototype, 99.696 kBq/L.

The results of these measurements are shown in section 7.1.2, where they are discussed and compared with the result obtained with the previous prototype, TRITIUM-IFIC 0.

5.2 Latest TRITIUM Prototypes

This section shows the last prototypes, TRITIUM-Aveiro 0 and TRITIUM-IFIC 2, in which the problems previously found are solved and a well-defined design is developed for them.

A different design was employed in both prototypes so that they can safely allow the reading of a large number of fibers arranged in a straight position with two photosensors in time coincidence.

Particular attention to tritium detection efficiency was paid in these prototypes, which is the reason why they use many more fibers than the preliminary prototypes and time coincidences are made on the photosensors.

Furthermore, the activity of the radioactive liquid source of tritium, which is used to fill these prototypes, is much lower than previous prototypes since the interesting parameter to be measured is their low detection level, LDL.

The design of both prototypes is very similar and their objective is to test the subtle effects caused by the little difference, such as the diameter of the fibers used, and to choose the one with the best results which will be included in the final design of the TRITIUM monitor.

5.2.1 TRITIUM-Aveiro 0

The third prototype built and the first thought to be the final version of the TRITIUM detector module was TRITIUM-Aveiro 0, shown in Figure 5.7, which was designed and built in the workshop of the University of Aveiro.

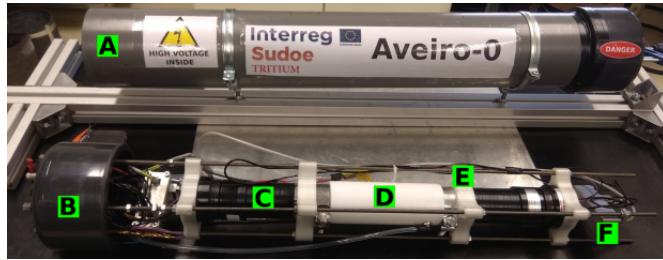


Figure 5.7 – TRITIUM-Aveiro prototype.

It consists of a teflon vessel (D of Figure 5.7), shown in Figure 5.8, which has an internal cylindrical hole the diameter and length of which are 43 mm and 18 cm respectively.



Figure 5.8 – Teflon structure and fiber bundle used in TRITIUM-Aveiro 0 prototype.

This vessel contains 360 uncladded scintillating fibers with a length of 180 mm. The model of the used fibers is BCF-10 from Saint-Gobain company [Cer01], which have practically the same characteristics than the

others used up to now (BCF-12 fibers) and their most important difference is their diameter, which is the double, 2 mm.

A larger diameter could be interesting because it facilitates the flow of water around the fibers, reducing the problems related to surface tension and ensuring that the entire active volume of the fibers is used for tritium detection. In addition, it increase the resistance of the fibers, which is very important since the water is flow around them. However, it could be detrimental since this worsens the signal-to-background ratio. The detector active volume for 2 mm fibers in the same space is smaller, producing a smaller tritium signal and the part of the fibers where no tritium events reach (they only contribute to the background) is larger, producing a larger background. As a result, a worse signal-to-background ratio will be achieved.

In order to quantify the importance of the fiber diameter effect, the measurements were compared with similar measurements performed with TRITIUM-IFIC 2 prototype, shown in section 5.2.2, based on a similar configuration with 1 mm fibers (BCF-12 model).

The amount of fibers used in TRITIUM-Aveiro 0 prototype is the maximum which allows the water to flow around the fibers. It has to be taken into account that it was not possible to use a structure to fix the fibers due to the large amount of them, so they will remain free inside of the teflon vessel.

These fibers were cut with the fiber cutting device developed by TRITIUM but they were neither polished nor cleaned. The reason for this is that the automatic polishing machine was not yet developed and it was not feasible to polish 360 fibers by hand. In fact, the automatic polishing machine was motivated by the amount of fibers used in the last prototypes.

To ensure the radiosecurity of this prototype, the teflon vessel is totally closed and a water inlet/outlet were installed in it to allow a constant

water flux through it. Two PMMA windows was used to read the fibers, whose thick is 10 mm, which was located at both ends of the fiber bundle and two clamps are used to press the Teflon walls against the PMMA windows to ensure the water tightness of the prototype. PMMA was chosen for its optical properties, especially its transmission coefficient, which is more than 95% for the working wavelength.

Two PMTs (C of Figure 5.7) are used to read this prototype in time coincidence, which are powered at -1500 V, at which the quantum efficiency is 26%. They are fixed to both fiber bundle ends of the prototype using two pieces (E of Figure 5.7) which was designed and built with a 3D printer. Both PMTs are optically coupled to the PMMA windows using optical grease [Cera].

The PMTs used are the model R2154-02 2" from Hamamatsu company [K.K10], whose characteristics, specially its gain and efficiency, are quite similar to the PMTs used in the other prototypes.

All these different parts, together with the electronic system (F of Figure 5.7), is arranged in a structure, shown in Figure 5.7, which is based on several nuts located on four long stainless-steel screws. This screws are fixed to an external PVC structure, A and B of Figure 5.7, which is used to protect the prototype from physical damage and provide a light-tight operation environment. This PVC structure is equiped with several high voltage power, low voltage power and signals feed-through connectors.

Only one prototype was built, which was designed to be installed in the Arrocampo dam and an electronic chain, based on several PCBs, was specially designed, developed, built and tested to process and analyze the signals of this system, shown in appendix D.

Two interfaces were developed, one to control the power supply to the PMTs, shown in Figure 5.9a, and the other to control the different options of the electronic reading chain, such as thresholds and measured

counts, shown in Figure 5.9b.

First some measurements were taken in the laboratory, which were used to characterize the detector. For this task it was firstly filled with ultra-pure water, which was used to measure the background of the detector, and then, with a radioactive liquid tritium solution with an activity of 30 kBq/L, which were used to measure the efficiency and the low detection level, LDL, of the prototype. The volume of ultrapure water and tritium solution used in TRITIUM-Aveiro 0 prototype is 58 mL. Later, it was installed in the arrocampo dam to test its functionality and to begin with the tritium level monitoring. The laboratory and Arrocampo measurements, both, are shown in section 7.1.3 and 7.2 respectively, where they are discussed and compared with the measurements of the previous prototypes.

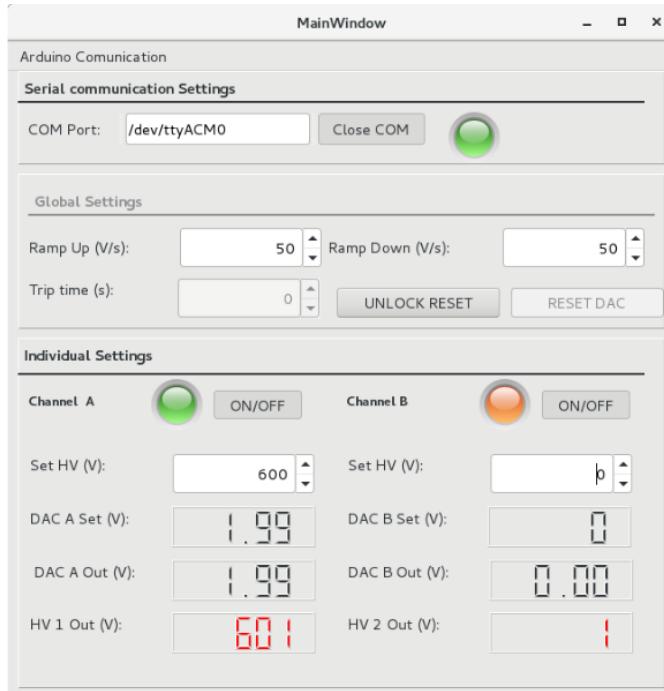
5.2.2 Advanced IFIC prototype, Tritium-IFIC 2

The last prototype developed in TRITIUM experiment and the second thought to be the final version of the TRITIUM detector module was TRITIUM-IFIC 2, which is shown in Figure 5.10, A.

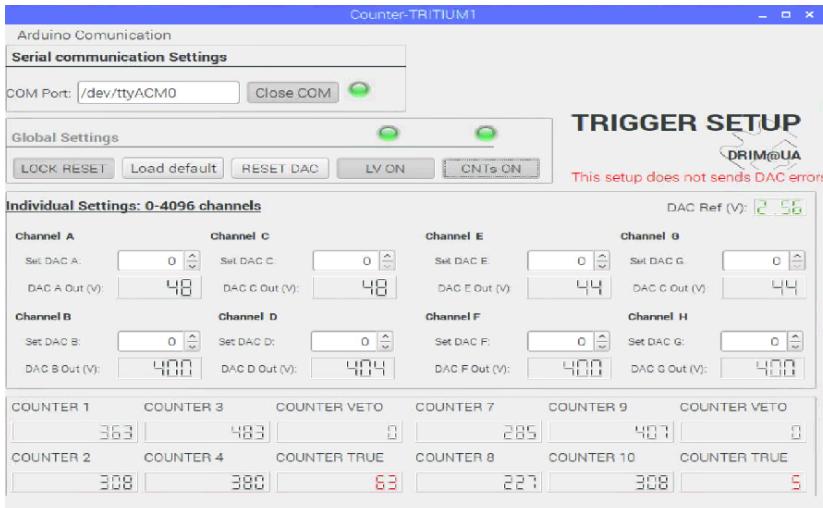
This prototype was designed and built in the IFIC workshop and it consists of a cylindrical teflon vessel, shown in Figure 5.11, the shape of which is similar to the one used in TRITIUM-Aveiro 0 prototype. The internal length and diameter of the teflon vessel are 210 mm and 36 mm respectively.

This prototype contains 800 unclad scintillating fibers, BCF-12 model, with a length of 200 mm. As can be seen, a larger number of scintillating fibers than the TRITIUM-Aveiro 0 prototype are used which are arranged in less volume.

The fibers used are cut, polished and cleaned with the conditioning



(a) Graphical user interface to manage the power supply voltage of PMTs.



(b) Graphical user interface used to manage the counter system.

Figure 5.9 – Graphical User Interface developed to control the TRITIUM-Aveiro prototype.

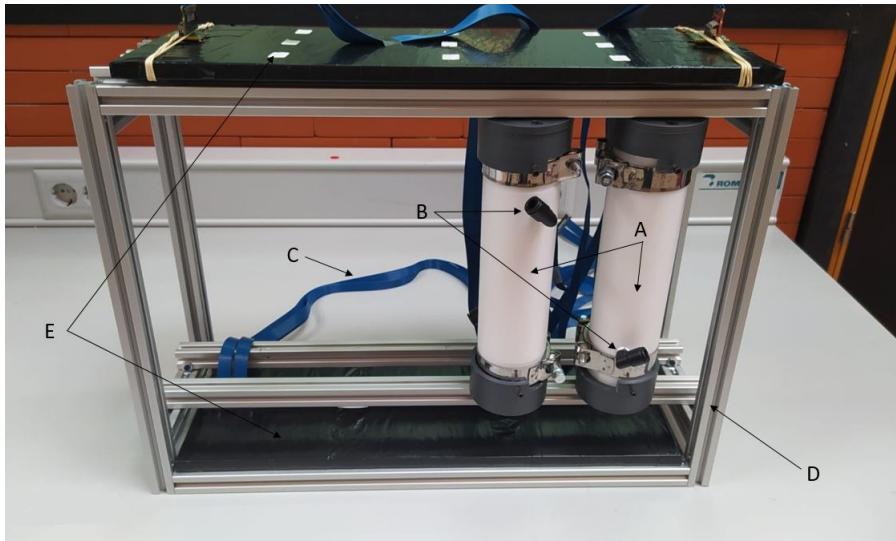


Figure 5.10 – TRITIUM-IFIC 2 prototype.

processes previously shown in section 4.1 since, during the construction of the prototype, the development of the automatic polishing machine was completed.

These fibers are freely arranged, with a density that allows water to flow through the fibers and two PMMA windows, located at the ends of the fiber bundle, were used to read this system, similar to the TRITIUM-Aveiro 0 prototype.

The width of the PMMA optical windows used is 5 mm, which is sufficient to guarantee radiosecurity since the detector works at very low water pressure. Two clamps are used to ensure the watertightness of the prototype, similar to the TRITIUM-Aveiro 0 prototype. PMMA was chosen for its optical properties, especially its transmission coefficient, which was measured for visible light range in the ICMOL laboratories, shown in Figure 5.12.

As can be seen, its transmission coefficient is approximately 95%



(a) TRITIUM-IFIC 2 vessel.



(b) TRITIUM-IFIC 2 vessel with PVC caps.

Figure 5.11 – TRITIUM-IFIC 2 teflon vessel.

for the working wavelength (435 nm). Slightly better transmission coefficients can be achieved with other materials such as quartz or sapphire but they are much more expensive.

A water inlet/outlet was installed in the teflon vessel, shown in Figure 5.10, B, and Figure 5.11, to allow a constant water flux through it, similar to the TRITIUM-Aveiro 0 prototype.

For the first laboratory measurements, two PMTs were used, model R8520-460 from the Hamamatsu Photonics company [K.K19], which is useful to understand the results and compare them with the results obtained with the previous prototypes. However, measurements with SiPM arrays have already started the output signal of which is connected to PETSYS system through flat wires as can be seen in Figure 5.10, C.

The PETSYS system will be employed to readout the SiPMs used

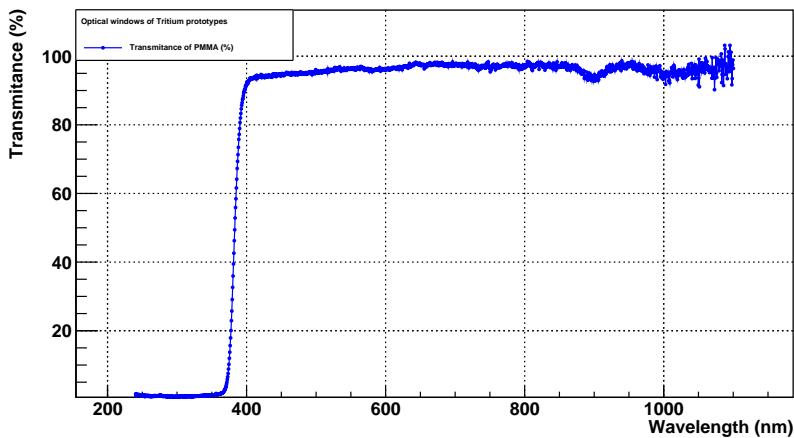


Figure 5.12 – Transmission spectrum of light (in the visible range) in a piece of PMMA of 5 mm thickness measured in the ICMOL laboratory.

in the TRITIUM-IFIC 2 prototype that will be installed in Arrocampo dam. Therefore, it is not necessary to develop a electronics chain to process and analyze the PMT signals of this prototype.

Like the TRITIUM-Aveiro 0 prototype, although PETSYS has a graphical user interface, shown in Figure 5.13, which allows controlling all the different options such as the voltage with which the SiPM arrays is fed, the thresholds used, the measurement obtained, etc., normally it will be controlled remotely via computer terminal.

Two PVC caps, located at both ends of the prototype, Figure 5.11b, were used to work with the SiPMs in a light-tight environment and an aluminum structure, shown in Figure 5.10, was designed and built, which is able to house up to 10 TRITIUM-IFIC 2 modules and two cosmic vetos, shown in Figure 5.10, E.

The available space of the lead shielding, explained in section 3.4.1 is enough to accommodate up to 5 structures like the one shown in Figure 5.10. It means that the final TRITIUM module has the capacity to con-

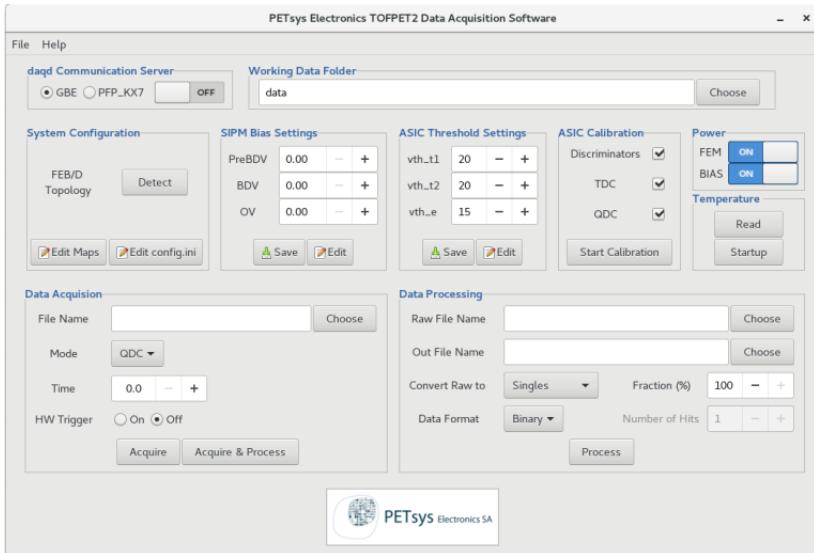


Figure 5.13 – Graphical User Interface (GUI) of PETSYS.

tains 50 TRITIUM-IFIC 2 modules and 5 different cosmic vetos. As the sensibility of the TRITIUM monitor scales with the number of TRITIUM modules used, the results obtained with the TRITIUM monitor should improve the results obtained with the TRITIUM-IFIC 2 prototype by a factor of N, where N is the number of cells used.

Two identical TRITIUM-IFIC 2 prototypes were built, similar to the TRITIUM-IFIC 0 prototype, one of them was filled with ultrapure water and used to measure the background and the other was filled with a radioactive liquid source of tritium and used to measure the signal. The volume used in both cases was 82 mL (uncertainty of 0.05%).

The activity of the tritium source used for this prototype is 10 kBq/L (uncertainty of 2.24%), which was prepared by diluting a sample of tritiated water explained in appendix C with ultrapure water until the desired activity was achieved.

The results of this prototype is shown in section 7.1.4, where they

are compared with the results of the previous prototypes and, specially, with TRITIUM-Aveiro 0 prototype.

5.3 Modular TRITIUM Detector for In-Situ Tritium Monitoring

Lastly, this section presents the final TRITIUM monitor, a schematic design of which is shown in Figure 5.14.

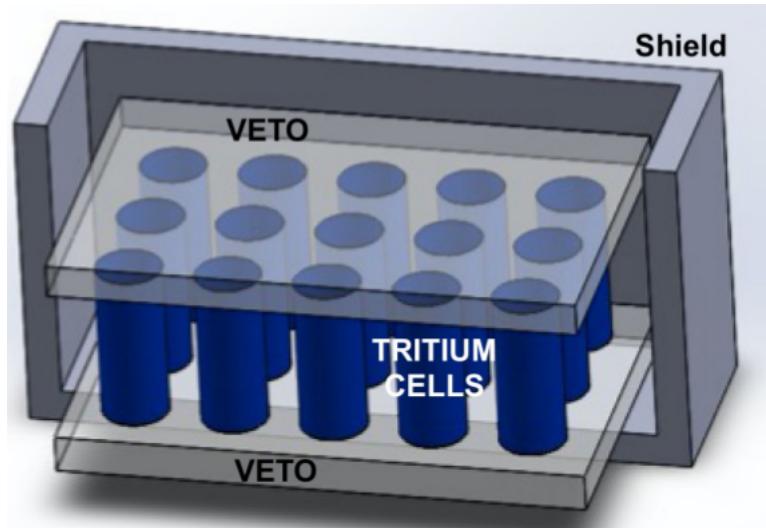


Figure 5.14 – A schematic design of the TRITIUM detector.

It consists of several TRITIUM modules, shown in Figure 5.14, which are read in parallel. Each module will be the prototypes that achieves better results, TRITIUM-Aveiro 0 (section 5.2.1) or TRITIUM-IFIC 2 (section 5.2.2).

These modules are isolated from environmental radioactivity using three different techniques.

1. First, an external lead shielding, explained in section 3.4.1, a part of which is shown in Figure 5.14. This is used to stop the environmental radioactivity which increase the radioactive background measurement of the TRITIUM monitor (radioactive events with energies below 200 MeV).
2. Second, several active vetos, explained in section 3.4.2 and characterized in section 4.4, which is also exhibited in Figure 5.14, placed below and above the TRITIUM modules. These active vetos are read in anticoincidence to eliminate the effect of the high energy events of the background, mainly cosmic events with energies above 200 MeV, on the TRITIUM measurement.
3. Finally, the radioactive elements present in the water samples, introduced into TRITIUM modules to be measured, are eliminated using an ultrapure water system, shown in section 3.3 and appendix B and characterized in section 4.3.

The ultrapure water system, the lead shielding and a TRITIUM-Aveiro 0 prototype are installed and currently in operation at the Arrocampo dam. This entire system was used to successfully monitor the tritium levels in Arrocampo dam during three months. Furthermore, two additional TRITIUM-Aveiro 0 prototypes and four active vetos are currently under manufacturing to be installed, which are measured in parallel with the current prototype installed.

The RaspberryPi, in which the counter electronic system of TRITIUM-Aveiro prototype is based, has some counting limitations if multiple modules are used. To overcome this problem, it must be replaced with an FPGA-based counter board to ensure reliable counting.

At the same time, three TRITIUM-IFIC 2 prototypes and an active veto have already been built, the installation of which at the Arrocampo

dam was delayed due to the coronavirus pandemic restrictions imposed in Spain. They will be installed as soon as possible.

One of the most important points of the TRITIUM detector is its modular design, with which scalability can be achieved to reach the required sensitivity, 100 Bq/L. It means that if this sensitivity target is not reached with the three modules to be installed, this will be improved simply by installing a few additional modules.

The only scalability restriction is the available space, which is fixed by the lead shield already built and installed (it is also fixed by the available space in the house where the lead shield is installed). Taking into account the currently available space, five different structures designed for TRITIUM-IFIC 2, one of which is shown in Figure 5.15, can be used, where ten different modules (grey) and an active veto (black) can be accommodated in any of them.

It means that up to 50 TRITIUM-IFIC 2 modules can be used in parallel, reducing the tritium sensitivity measured for TRITIUM-IFIC 2 prototype by a factor of fifty. In light of the results obtained with these prototypes, it is not expected to use more than one structure like the one shown in Figure 5.15 (ten modules) to reach the target sensitivity.

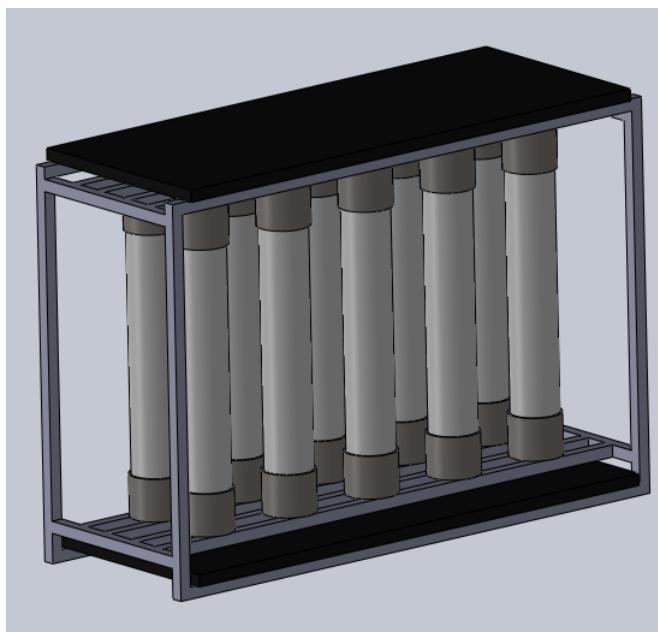


Figure 5.15 – A TRITIUM detector design based on the TRITIUM-IFIC 2 prototype.

Chapter 6

Simulations

This chapter details the Monte Carlo simulations that were performed in the TRITIUM experiment. Their goal were to choose the best design for the TRITIUM detector, understand its behavior and find its limitaitons. The simulation environment used for this task is Geant4 [Col21a, Ago03].

6.1 Geant4 Environment

Geant4 is a software toolkit for the simulation of the passage of particles through matter. It is a package developed at CERN that is based on object-oriented technology implemented in the C ++ programming language.

This includes the definition of all the different aspects of the simulation process such as detector geometry, materials used, particles of interest, pyhisics processes that handle particle and matter interactions, response of sensitive detectors, generation, storage and analysis of event data and visualization.

Geant4 simulates particle-by-particle physics. It means that the tritium events are initialized one by one, whose energy, moment, position, etc. are determined. Then, the propagation of each tritium event and its interaction with the scintillator is simulated, in which optical photons are created. The propagation of these optical photons are also simulated one by one and the simulation ends when all tritium events have been simulated and all created optical photons have been absorbed by either the sensitive detector or other materials present in the simulation.

A physics list used for these simulations is Livermore, G4EmLivermorePhysics, which is specially designed to work with low energy particles. This list includes the most important electromagnetic process at low energies such as Bremsstrahlung, Coulomb scattering, atomic de-excitation (fluorescence) and other related effects.

The materials used in these simulations were water (to simulate the tritiated water source), PMMA (to simulate the optical windows of the prototype), polystyrene (to simulate the core of scintillating fibers), teflon (to simulate the prototype vessel), silicone (to simulate the optical grease), silicate glass (to simulate the optical windows of the PMTs) and bialkali (to simulate the photocathode material of the PMT).

The properties of water, teflon, polystyrene were taken from the Geant4 NIST database and the other materials were built by specifying their atoms. Optical properties was added to these materials:

1. First, the spectrum of the refractive index and the light attenuation were added to the water which was obtained from the reference [Bui94]. Furthermore, an electron emission, uniformly distributed in the volume, was added to the water, the energy of which IS calculated using the tritium energy spectrum. This emission of electrons simulates the disintegration of the dissolved tritium particles in the water sample. The used data was obtained from the reference [Mer15].

2. Second, the spectrums of the refractive index, the light attenuation and the photon emission were added to the polystyrene, which was obtained from the data sheet of scintillating fibers, [Cer05]. Also the scintillation yield and the decay time was included.
3. Third, the quantum efficiency spectrum was included to the photocathode material of the PMTs, the data of which was obtained from their data sheet, [K.K19] and a refraction index of 1.46 was used for the optical grease, also obtained from its data sheet, [Cera].
4. Finally, the optical data for the remaining materials, PMMA windows, teflon and silicate glass, were taken from the reference [Arg11].

It is important to note that the simulations shown in this thesis are focused on the Tritium-IFIC 2 prototype since these were the simulations I was primarily working on, but a similar simulation was performed for the Tritium-Aveiro prototype, some of their most important results are also presented. In addition, other smaller simulations are shown used to choose the best design of the TRITIUM detector.

6.2 Description of the Simulations Performed

Several simulations was designed and run during the life of the TRITIUM project to quantify how different values of interesting parameters affect to the tritium measurement and to understand the behaviour of the different TRITIUM prototype built which are shown in the following sections.

6.2.1 Tritiated Water Source

First of all the shape of the simulated tritiated water source was optimized.

The mean free path of tritium electrons in water are only around $5 \mu\text{m}$, so there are many electrons that don't reach the scintillating fibers. These are electrons that don't provide useful information and only contribute to being time consuming and reducing available computing resources.

To optimize the simulation, the dimensions of the simulated tritium source was studied. The goal of this study was to minimizes the tritium events that do not reach the scintillating fibers, avoiding missing the tritium events.

A simulation test was performed to ensure that the tritium source is simulated correctly. This test consists of a scintillating fiber 20 cm long and 2 mm in diameter and a surrounding tritiated water source of the same length and 0.5 mm thick, 100 times greater than the mean free path of tritium electrons.

The dimensions of the fiber are not important in this study since only the energy deposition of tritium electrons in the fiber were simulated. That is, this simulation doesn't include the following steps such as photon generation, propagation of these photons, etc. in which the shape of the scintillating fiber becomes important.

The results of this simulation are shown in section 8.1.1, where they are discussed.

6.2.2 Energy Deposition and Light Output of Scintillating Fibers

The scintillation yield provided by the manufacturer, 8000 phot./MeV, only works for Minimum Ionizing Particles (MIP). As tritium electron energies are far from being MIP particles, the output light generated by the scintillating fibers was studied. For this task, the energy deposition of tritium

electrons in scintillating fibers and their subsequent emission of scintillation photons was added to the simulation.

When particles that are not MIP are detected in plastic scintillators a light quenching effect affect to the proportionality between the output light per unit of path length, $\frac{dL}{dx}$, and the energy deposited per unit of path length, $\frac{dE}{dx}$, through the so-called Birks coefficient, following equation [Bir51].

$$\frac{dL}{dx} = S \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}} \quad (6.1)$$

where S is the scintillation yield, provided by the manufacturer. A value of $k_B = 0.126 \text{ mm/MeV}$ was considered for the Birk's coefficient which is the one used for scintillators based on polystyrene [Lev11]. The effect of this correction is shown and discussed in section 8.1.2.

6.2.3 Fiber Length Optimization

Another test was performed to find the fiber length that optimizes the tritium detection efficiency. Two different lengths of the scintillating fiber were considered in this study, 1 m and 25 cm.

As the active area of the detector is related with its tritium detection efficiency, the advantage to use a longer fibers is that larger active areas can be achieved with a less number of cells, considerably reducing the number of used photosensors and, as a consequence, the price of the TRITIUM monitor. However, smaller length of scintillating fibers reduce de photon absorption produced in the fibers, increasing the tritium detection efficiency for the same active area.

For this task, the Tritium-Aveiro prototype was simulated, consisting of a similar design of TRITIUM-IFIC 2 prototype but using 360

scintillating fibers of 2 mm diameter and readout by two different photo-sensors, model R2154-02 2" from Hamamatsu company [K.K10]. All optical properties mentioned in section 6.1 were included in this study.

The results of this study are shown in section 8.1.3, where they are discussed. It must be taken into account that the result of this study is also applicable to the design of the TRITIUM-IFIC 2 prototype.

6.2.4 Fiber Diameter Effect

A third test was carried out to check the effect of the fiber diameter in the tritium measurement. For this test, the same simulation explained in section 6.2.3 was used, where a fiber length of 20 cm was choseen. Two different diameters were taken into account in this study, 1 mm and 2 mm, which are the commercial options given by Saint-Gobain company.

It doesn't have sense to test it with the tritium source since its efficiency will scale with the active surface of the scintillating fiber. However, an interesting study can be performed to check how the fiber diameter affect to the cosmic detection in the fiber. It is an important result as the background-signal ratio is mainly affected by the cosmic ray events.

For this task, the tritiated water source was replaced by a cosmic ray source, which was generated using the CRY library¹ [(NA], [Hag07]. The CRY library is a package based on objected-oriented technology and implemented in the C++ programming language. This library is used to generate cosmic-ray shower distributions for different particles (muons, neutrons, protons, electrons, photons and pions) with several options that can be varied like several altitude.

The cosmic sources shape used in this simulation is a horizontal

¹CRY library, Cosmic-Ray Shower library

square of $1 \cdot 1 \text{ m}^2$ located at a height of 35 cm (above the detector) with the typical distribution of cosmic particles at sea level.

The result of this simulation are shown in section 8.1.4, where they are discussed.

6.2.5 Simulation of the Tritium-IFIC 2 Prototype

The Tritium-IFIC 2 prototype simulation was the last simulation developed in the TRITIUM experiment and this was the one I mainly focused on. It consists of 800 equispaced fibers distributed in sixteen different circles with increasing radius, which are shown in Figure 6.1. The fibers simulated has a diameter of 1 mm and the optical properties, mentioned in section 6.1, was included.

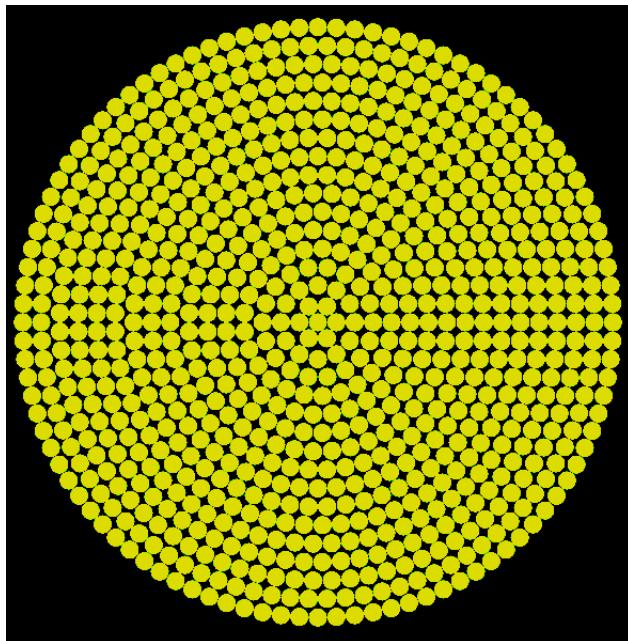


Figure 6.1 – Distribution of the scintillating fibers in the simualtion of Tritium-IFIC 2 prototype.

The tritiated water source used consists of a tritiated water volume with a thickness of $5 \mu\text{m}$ around each scintillating fiber.

Scintillator fibers are located inside of a teflon vessel, which was simulated with the dimensions mentioned in section 5.2.2. Two PMMA windows with a thickness of 5 mm were simulated and located in both fiber ends and a optical grease layer with a thickness of 0.5 mm was included in each PMMA windows.

Finally, two PMTs, model R8520-460 from Hamamatsu company [K.K19], were simulated in both ends.

The optical properties used for the tritiated water, teflon vessel, PMMA windows and the optical grease, mentioned in section 6.1, are included in this simulation.

The simulation of TRITIUM-IFIC 2 is shown in Figure 6.2 in which can be appreciated the PMTs (black), the optical grease (blue), PMMA windows (white), tritiated water (green) and scintillating fibers (yellow). In this image, the Teflon container was not drawn to allow its interior to be seen and several volumes of tritiated water were also not included to allow several scintillation fibers to be seen.

As can be seen in this figure, the used PMTs don't cover the entire active area formed by the scintillating fiber bundle. It's not a problem for the Tritium detector since its final version will not include this photosensors. The final version of Tritium-IFIC 2 prototype will use SiPM arrays and the PMTs model used in the Tritium-Aveiro 0 prototype are circular PMTs with which the full active area is covered.

The simulation of the Tritium-Aveiro 0 prototype is similar to this since the design of both detectors are quite similar. There are two main difference between both simulated prototypes:

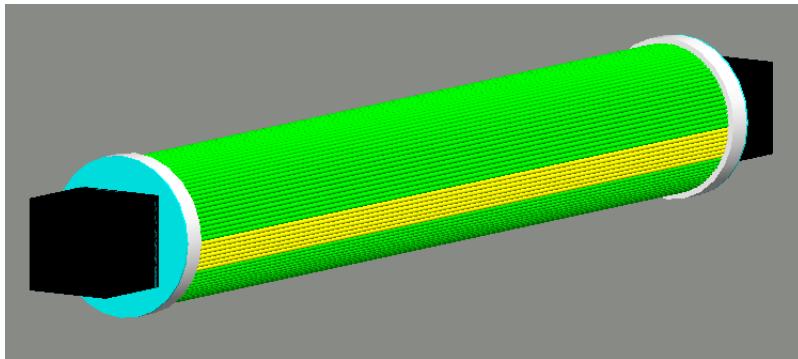


Figure 6.2 – Simualtion of Tritium-IFIC 2 prototype. PMTs (black), the optical grease (blue), PMMA windows (white), tritiated water (green) and scintillating fibers (yellow).

1. The diameter of the fibers used, which is 1 mm for Tritium-IFIC 2 prototype and 2 mm for Tritium-Aveiro 0 prototype. As the internal volume of the teflon vessel is filled, this difference imply a difference number of the scintillating fibers used, causing a difference in the signal-background ratio.
2. The photosensors used since, although both are PMTs, the model of the used PMTs is different and it cause a different active area readout, affecting to the tritium detection efficiency.

The results obtained with the simulation of the TRITIUM-IFIC 2 prototype are shown in section 8.2.1, where they are discussed.

6.2.6 Simulation of the Lead Shielding and Cosmic Veto

Finally the lead shielding and active vetos, detailed in section 6.2.5, were included in the simulation of the Tritium-IFIC 2 prototype. The objective of these simulations was to quantify the reduction of cosmic events detected by the prototype, demonstrating its usefulness.

For this task, similar to that done in section 6.2.4, the tritium source was replaced by the cosmic events source, which was simulated through the CRY library.

As can be seen in Figures 3.24a and 3.24b, two plastic scintillators were simulated with the dimensions mentioned in section 3.4.2 and located above and below of the Tritium-IFIC 2 prototype simulated.

The optical properties included to this plastic scintillators are the refractive index, the light attenuation spectrum and energy emission spectrum, the values of which were obtained from their data sheet provided by the manufacturer [Cry20].

As shown in this figure, two PMTs, model R8520-460 from Hamamatsu company, were simulated to read each plastic scintillator, similar to that presented in section 3.4.2.

Finally, a lead shielding was simulated, whose properties were taken from the Geant4 NIST database. The dimensions of the simulated lead shielding were $60 \cdot 60 \cdot 70$ cm³, which is the minimum needed to accommodate an active veto and Tritium detector module inside. The length of the simulated lead castle, 60 cm, is smaller than real dimension, 148 cm. The reason for this is that only one tritium detector module was simulated, so the dimension of the lead shielding can be reduced to optimize simulation time and computing resources.

The results of these simulation are shown in section 8.2.2, where they are discussed.

Chapter 7

TRITIUM Monitor Results and Discussion

This chapter shows and discusses the experimental results obtained with the different prototypes developed in the TRITIUM experiment. This is divided into two sections, according to the place where they were carried out. The first section shows the measurements obtained at the University Laboratories, where external atmospheric conditions, such as temperature, can be better controlled. The second section shows the measurements obtained at the Arrocampo dam, the final TRITIUM monitor emplacement, where the control of external atmospheric conditions is less precise.

7.1 Results from Laboratory Measurements

This section shows, compares and discusses the experimental results obtained with the different prototypes developed in the TRITIUM experiment during their installation in the laboratory. The facilities used for this task

were the Nuclear Radiation Laboratory, at the IFIC, Valencia, the DRIM¹, at the University of Aveiro, and the LARUEX² laboratory in Extremadura.

7.1.1 Experimental Results of TRITIUM-IFIC 0 Prototype

This section shows the measurements obtained with the TRITIUM-IFIC 0 prototype during its installation in the Nuclear Radiation Laboratory at IFIC, the design of which was explained in section 5.1.1.

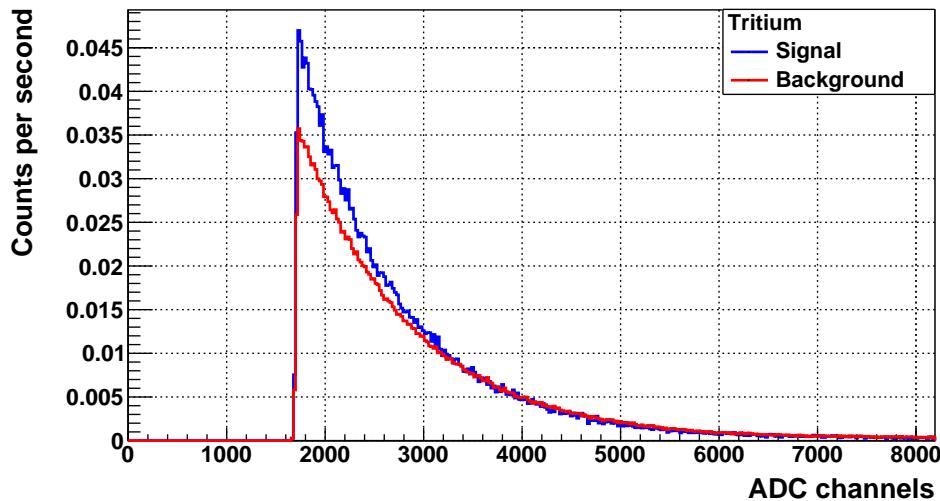
As stated in section 5.1.1, a statistically significant number of events was not obtained when the prototype was read with two PMTs in time coincidence. To overcome this problem, a single PMT measurement was taken using the electronic chain configuration shown in figure 3.15a. The energy spectra were measured for both, the signal and background prototypes, which are shown in Figure 7.1a. As it was mentioned in section 5.1.1, the signal prototype was filled with a tritiated water solution with an activity of 99.696 kBq/L and the background prototype was filled with ultrapure water.

In this figure, a difference between both energy spectra is clearly visible, which correspond to the energy spectrum of tritium, Figure 7.1b. The number of counts per second obtained for these three spectra is shown in Table 7.1, where the Tritium counts are obtained from the difference of the signal and background counts.

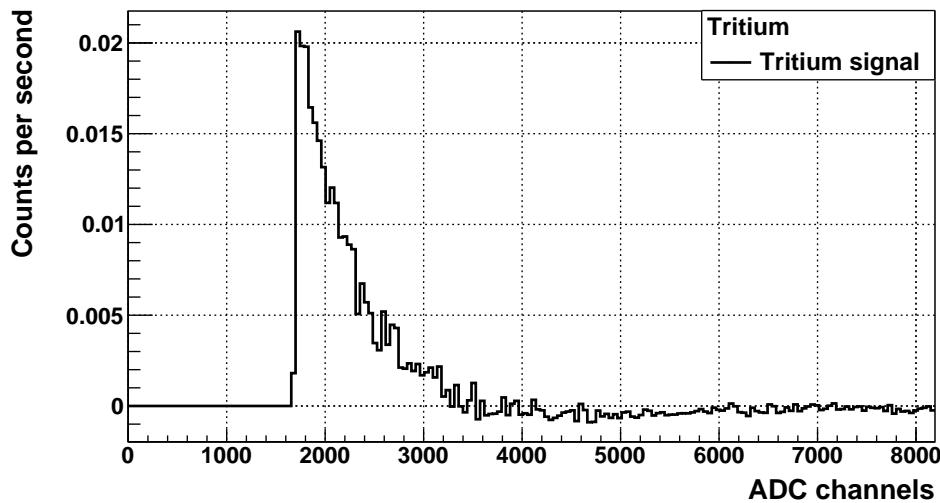
The tritium detection efficiency obtained for this prototype is $(2.11 \pm 0.85) \cdot 10^{-3} \frac{\text{c/s}}{\text{kBq/L}}$, which is calculated from the quotient of both, the tritium

¹DRIM, Deteção da Radiação e Laboratorio Imagem Médica laboratoire (Laboratory for Radiation Detection and Medical Imaging)

²LARUEX, Laboratorio de Radiactividad Ambiental de la Universidad de Extremadura (Environmental Radioactivity Laboratory of the University of Extremadura)



(a) Signal and background energy spectra.



(b) Tritium energy spectrum.

Figure 7.1 – Energy spectra experimentally measured with TRITIUM-IFIC 0 prototype.

Spectrum	Counts/second
Signal prototype	2.27 ± 0.06
Background prototype	2.06 ± 0.06
Tritium counts	0.21 ± 0.085

Table 7.1: Counts per second obtained with TRITIUM-IFIC 0 prototype.

counts per second measured and the specific activity of the tritium liquid source used.

Comparing with the detectors developed so far by other experiments, Table 2.2 the efficiency obtained is of the order of the detectors the worst results, obtained by Moghissi and Muramatsu.

As we explained in section 2.1, the efficiency of scintillating detectors scales with the active area of the scintillator used. Therefore, to compare the efficiency with other detectors and with other prototypes developed in TRITIUM experiment, the specific efficiency of this prototype is calculated by normalizing to the scintillator area, the value of which is $(9.59 \pm 3.88) \cdot 10^{-6} \frac{\text{c/s}}{\text{kBq/L cm}^2}$.

As can be seen comparing with the Table 2.2, the specific efficiency is a little bit larger than the detectors with the worsen specific efficiency developed up to now, Muramatsu and Moghissi. This fact can be explained with the loss of photons produced in the curve of the fiber bunch, discussed and experimentally demonstrated in section 5.1.1.

7.1.2 Experimental Results of TRITIUM-IFIC 1 Prototype

This section shows the results obtained with the TRITIUM-IFIC 1 prototype during its installation in the Nuclear Radiation Laboratory at IFIC. Its design is explained in section 5.1.2, which includes several improvements, such as a teflon vesel and new straight arrangement of scintillating fibers, which were found to be a problems in the previous prototype, reducing its efficiency.

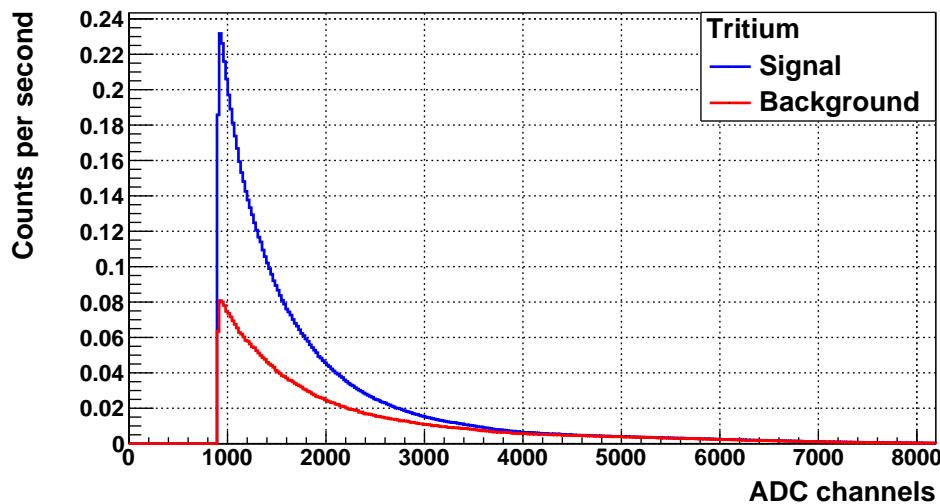
The energy spectra of both, signal and background, were measured with TRITIUM-IFIC 1 prototype, which is shown in Figure 7.2a. As it was mentioned in section 5.1.2, to mesure the signal, the prototype was filled with a tritiated water solution with an activity of 99.696 kBq/L and, to measure the background, the prototype was filled with ultrapure water.

As can be see, the difference between both energy spectra is clearly visible, which corresponds to the tritium energy spectrum, Figura 7.2b. Furthermore, compared to the energy spectra obtained with the previous prototype, Figure 7.1a, the difference between both is larger, which implies that the tritium detection efficiency of this prototype was improved.

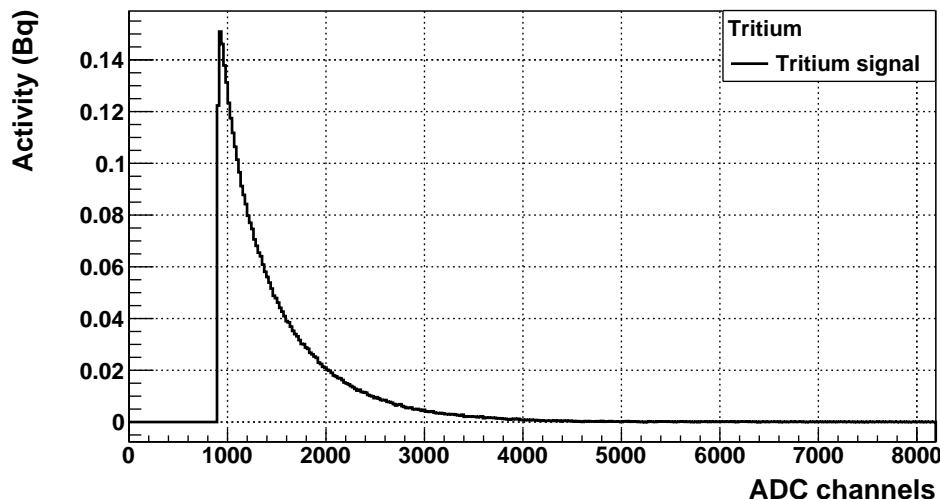
This efficiency improvement can be quantified using similar calculations than the previous section. The number of counts per second measured for these three signals are shown in Table 7.2, where the tritium counts was obtained from the difference of signal and background.

Spectrum	Counts/second
Signal prototype	7.82 ± 0.11
Background prototype	3.99 ± 0.08
Tritium counts	3.83 ± 0.13

Table 7.2: Counts per second obtained with TRITIUM-IFIC 1 prototype.



(a) Signal and background energy spectra.



(b) Tritium energy spectrum.

Figure 7.2 – Energy spectra experimentally measured with TRITIUM-IFIC 1 prototype.

The tritium detection efficiency obtained for TRITIUM-IFIC 1 is $(3.84 \pm 0.16) \cdot 10^{-2} \frac{\text{c/s}}{\text{kBq/L}}$, which is calculated using the same quotient explained in the previous section. As can be seen, the efficiency obtained for this prototype is larger than that obtained for the previous prototype, TRITIUM-IFIC 0. It is an expected result since this prototype uses a larger active area. The specific efficiency is calculated to eliminate the effect this different between both prototypes and quantify the improvement in the efficiency due to modifications in the design. The specific efficiency obtained is $(9.56 \pm 0.40) \cdot 10^{-5} \frac{\text{c/s}}{\text{kBq/L cm}^2}$.

Therefore it was verified that the specific efficiency of this prototype was improved by a factor of ten due to the modifications applied to its design which confirms and quantifies the usefulness of these modifications. Furthermore, compared with scintillating detectors developed in other experiments, table 2.2, on the one hand, the efficiency of this prototype is very close to the best result, obtained for Singh, and, on the other hand, the specific efficiency, which is the most relevant value to compare, is almost 5 times larger than the best results, obtained for Hofstetter.

It must be taken into account that in the first two prototypes the Low Detection Level, LDL, was not studied, since their objective was to improve its design and find the problems that reduced their efficiency. In fact, it can be seen in Figure 7.2 that the activity used is further to be the LDL of the TRITIUM-IFIC 1 prototype. The LDL was only studied in the final prototypes.

7.1.3 Experimental Results of TRITIUM-Aveiro 0 prototype

This section shows the results obtained with the TRITIUM-Aveiro 0 prototype during its installation in Aveiro and Extremadura laboratories. The

design of this prototype is shown in section 5.2.1.

This prototype was first installed in the DRIM laboratory, at the University of Aveiro, where the first measurements were taken. These measurements were used to find and solve the problems, learn about low energy detection and develop a functional scintillation prototype for TRITIUM.

First, the energy distribution of a single photon was measured from the self-emission of PMTs (dark current). To avoid the environmental light detection, the TRITIUM-Aveiro prototype was removed and the measurement was carried out only with the PMTs, the windows of which were covered with black caps. The output signals of the PMTs were digitalized, shaped and pulse-height measured by a CAEN V1724 digitalizer [CAEb].

The single-photon energy distribution of both PMTs is shown in Figure 7.3 in which a gaussian function was fitted. Due to the electrical noise of the PMT, an extrapolation (dashed line) was needed to be applied.

As can be seen, the distribution obtained with PMT1 deviates from the Gaussian function due to the higher noise in the low energy channels. This fact indicates that it could be interesting to use PMT with very low background for future prototypes.

As DRIM laboratory was not equipped to work with liquid radioactive source such as tritiated water, the first measurements were taken with a ^{55}Fe radioactive source since the energy of its γ emission, 5.9 keV, is very close to the energy of tritium electrons. To do so, the TRITIUM-Aveiro 0 prototype was coupled to both PMTs using optical grease and, due to its low mean free path in solid materials, the radioactive source was placed inside the teflon vessel. This prototype was not filled with water because of the presence of the radioactive source. This measurement is shown in Figure 7.4.

A shift to the right side is observed for the PMT2 data, which is

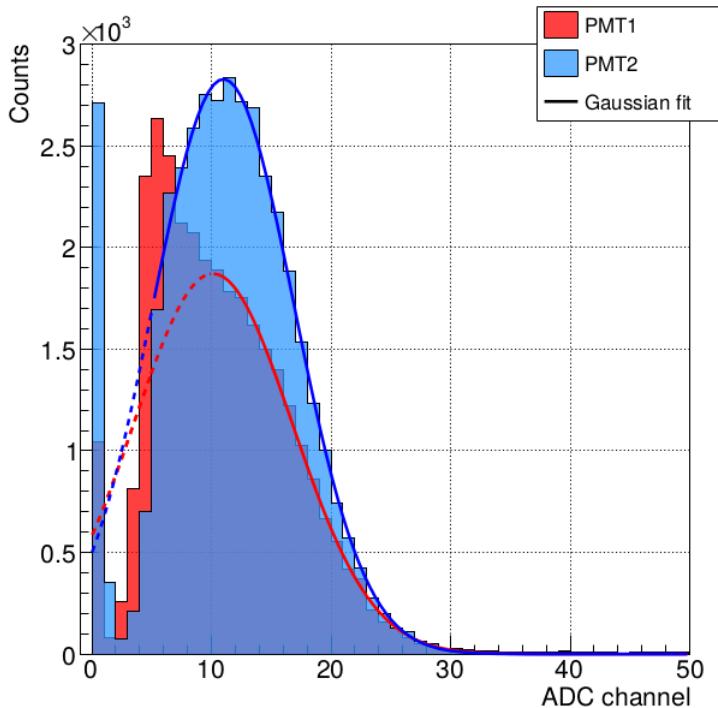


Figure 7.3 – The single-photon energy distribution of both PMTs used in the TRITIUM-Aveiro 0 prototype and their sum [CA].

produced because this PMT has a higher gain and the radioactive source was placed closer to it, reducing the attenuation of the photons.

Lastly, a passive shield test was performed in the DRIM laboratory to quantify the attenuation of the background produced by lead. To do so, the ^{55}Fe radioactive source was removed and the electronical chain explained in appendix D was used in counting mode for this test.

The measurements, shown in Figure 7.5, were carried out in three different situations. The first, region A, in which the measurement was performed without using any lead foil, the second, region B, in which lead foil with a thickness of 2.5 mm was used and the third, region C, in which another lead foil layer with the same thickness (total thickness of 5 mm)

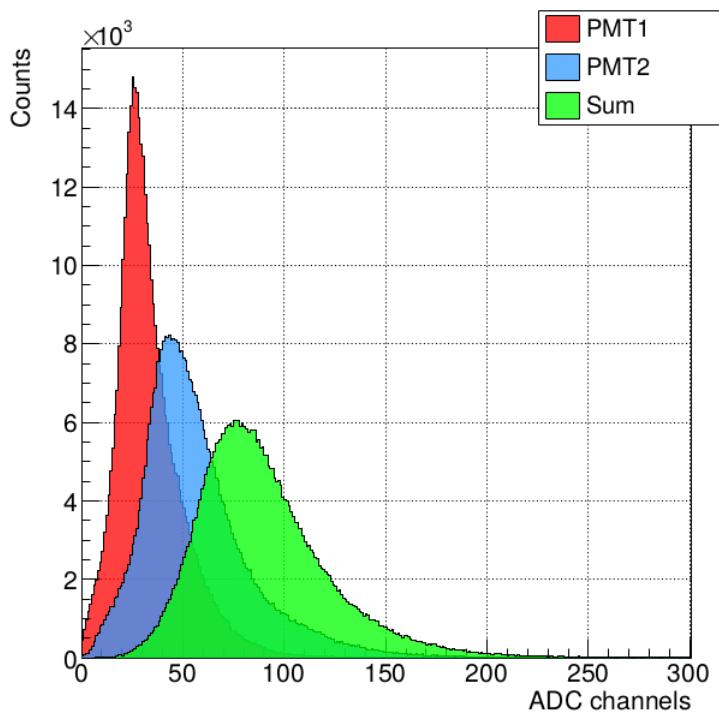


Figure 7.4 – Measurement of a ^{55}Fe radioactive source with the TRITIUM-Aveiro 0 prototype [CA].

was used.

As can be seen, in the region A, the average of the data adquired during 2.5 days is $3.5 \cdot 10^3$ counts/min (58 counts/sec). In the region B a reduction of more than two times was observed, measuring an average of $1.6 \cdot 10^3$ counts/min (26 counts/sec). In the region C a reduction of about 4 times relatively to the region A is observed, measuring an average of $0.9 \cdot 10^3$ counts/min (15 counts/sec).

The DRIM laboratory was not equipped to work with a liquid radioactive source such as tritiated water, so this prototype was installed in the LARUEX laboratory, at the University of Extremadura to finalize with the characterization measurements.

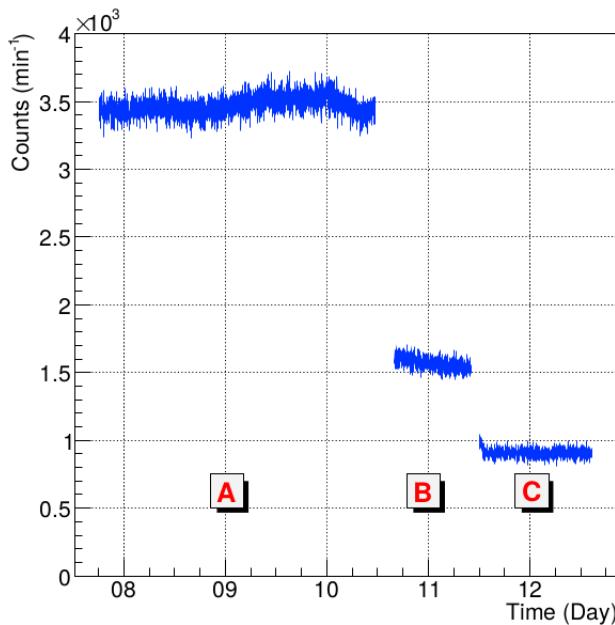
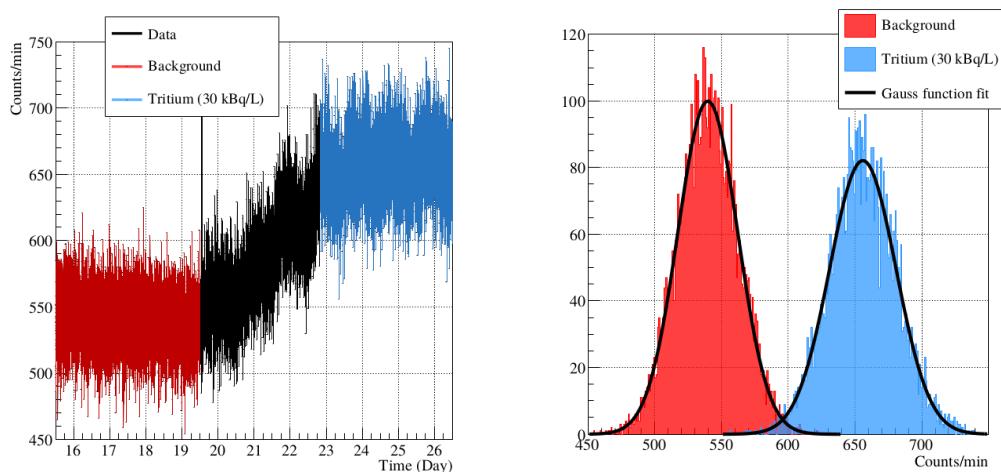


Figure 7.5 – Measurement of the background with TRITIUM-Aveiro 0 prototype covered with different thicknesses of lead [CA].

First, the background of the prototype was measured during 4 days. For this task, the prototype was filled with ultrapure water and covered with lead bricks with a thickness of XXX. The time of each measurement is 1 minut and the data is shown in Figure 7.6a and 7.6b in which a gaussian fit was done.

As a result of the gaussian fit, an average (N_B) of 540 counts/min and standard deviation (σ_{Nb}) of 22.61 counts/min was obtained. To calculate the Minimum Detectable Activity (MDA), the detection limit concepts developed by Lloyd A. Currie [Cur68] was applied. With this concepts, the minimum net counts with the probability of a false-negative less than a 5%, N_D , and minimum net currents with the probability of a false-positive less than a 5%, L_C , called critical level, are calculated using the equations:



(a) Counts per minut measured as a function of time.

(b) Distribution of the acquired data.

Figure 7.6 – Measurements of the background and tritium liquid source (with an activity of 29.8 kBq/L) performed with the TRITIUM-Aveiro 0 prototype and integrated during a minute [CA].

$$L_C = 2\kappa\sigma_{Nb} = 53 \text{ counts/min} \quad (7.1)$$

$$N_D = \kappa^2 + 2L_C = 108 \text{ counts/min} \quad (7.2)$$

Both values refer to the net counts per minute after background subtraction, so, L'_C and N'_D referred to the detector signal (before background subtraction) are 593 and 648 counts/min respectively.

To find the MDA associated to this N'_D , tritiated water was slowly added so that the tritium water activity increased continuously up to an average of 656 ± 0.43 counts/min. Then, the activity of this solution was measured with a Quantulus system, obtaining a MDA of 29.8 kBq/L.

The tritium detection efficiency can be calculated from the quotient of the net tritium counts per second measured, 1.93 ± 0.58 counts/sec,

and the activity of the tritium source used. The efficiency obtained is $(6.49 \pm 1.94) \cdot 10^{-2} \frac{\text{c/s}}{\text{kBq/L}}$. The value obtained with TRITIUM-Aveiro 0 prototype is larger than the efficiency reported by other similar experiments, Table 2.2. This is also larger than the efficiency obtained with previous TRITIUM prototypes, an expected result since the active area of this prototype is on order of magnitude larger.

The specific efficiency is calculated to compare with other scintillating detectors, the value of which is $(1.59 \pm 0.48) \cdot 10^{-5} \frac{\text{c/s}}{\text{kBq/L cm}^2}$. Comparing with the specific efficiency obtained with scintillating detectors developed in other experiments, Table 2.2, the value obtained for TRITIUM-Aveiro 0 prototype is close the largest specific efficiency, obtained by Hofstetter. However this prototype has a worsen specific efficiency than other prototypes developed in TRITIUM experiment such us TRITIUM-IFIC 1. A possible reason is that the fibers used in this prototype are not polished or cleaned. Therefore, the importance of the fiber polishing and cleaning process is again exhibited.

It can also be noted that the efficiency uncertainties obtained for this prototype are greater than those obtained in the previous TRITIUM prototypes. The reason of that is a difference in the measurement time. The measurement time used for the TRITIUM-Aveiro prototype is 1 minute, while that used for the previous prototypes is 10 minutes. Smaller uncertainties are achieved in the measured counts and, therefore, in the efficiency when longer measurements are taken.

Finally, as lower uncertainties in the measured counts allow a lower MDA to be achieved, longer measurements are studied to quantify the reduction of the MDA of this prototype. For this task, groups of 60 successive measurements are integrated, resulting in several measurements of 60 minutes. The acquired data is shown in Figure 7.7, where it can be checked a smaller relative uncertainty than the values for 1 minute.

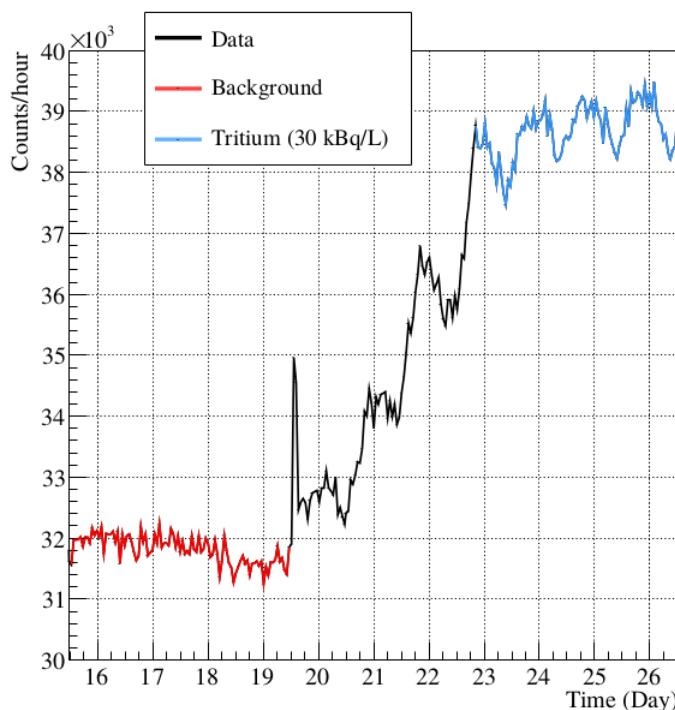


Figure 7.7 – Measurements of the background and tritium liquid source (with an activity of 29.8 kBq/L) performed with the TRITIUM-Aveiro 0 prototype and integrated during an hour [CA].

In this case, the average and uncertainty of the measured background data are $3.186 \cdot 10^4$ and 228 counts per hour respectively. Using the equations 7.1 and 7.2, the values of $L_C = 530$ and $N_D = 1043$ counts per hour are obtained respectively. Assuming linearity between the measured counts for the background and the tritiated water, $3.872 \cdot 10^4$ counts per hour, this N_D corresponds of a MDA of 4.53 kBq/L.

A diarly oscilation is clearly observed in the Figure 7.7, showing that the measurements are affected by external light. This oscilation begins on the 19th day, where the water closed circuit pump was installed, so it is likely that the light leak is produced through this system.

7.1.4 Experimental Results of TRITIUM-IFIC 2 prototype

This section shows the results of the lastest prototype developed in the TRITIUM experiment, TRITIUM-IFIC 2, during its installation in the Nuclear Radiation Laboratory at IFIC. The design of this prototype is shown in section 5.2.2.

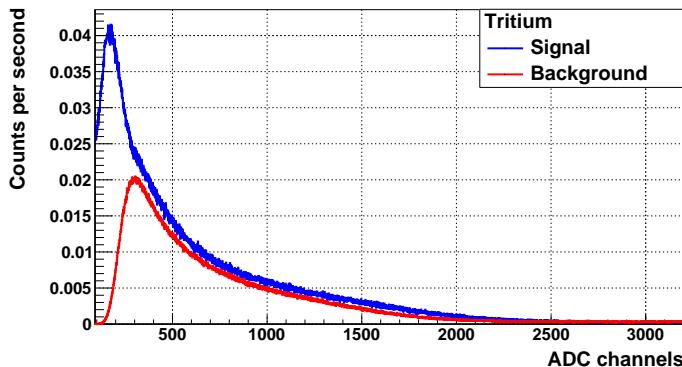
The energy spectra of the signal and background prototypes were measured, which are shown in Figure 7.8a. As it was mentioned in section 5.2.2, the signal prototype was filled with a tritiated water solution with an activity of 10 kBq/L and the background prototype was filled with ultrapure water.

A difference between both signals is clearly visible, which corresponds to the energy spectrum of tritium, Figure 7.8b. The number of counts per second obtained for these three spectra is shown in Table 7.3, where the Tritium counts are obtained from the difference of the signal and backgorund counts.

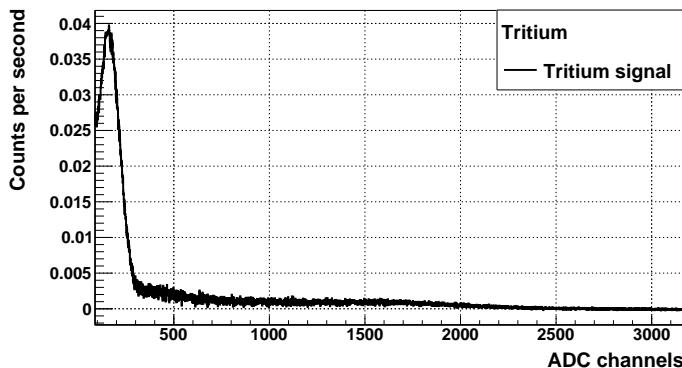
Spectrum	Counts/second
Signal prototype	19.05 ± 0.18
Background prototype	11.54 ± 0.14
Tritium counts	7.11 ± 0.23

Table 7.3: Counts per second obtained with TRITIUM-IFIC 1 prototype.

The tritium detection efficiency obtained for this prototype is $(7.11 \pm 0.28) \cdot 10^{-1} \frac{\text{c/s}}{\text{kBq/L}}$, calculated from the quotient of both, the counts per second measured and the specific activity o the tritium liquid source used. This efficiency is larger than all scintillating detectors developed so far, including the prototypes developed in TRITIUM experiment, Table 2.2 and sections 7.1.1, 7.1.2 and 7.1.3. It is an expected result since the active area used in



(a) Signal and background energy spectra.



(b) Tritium energy spectrum.

Figure 7.8 – Energy spectra experimentally measured with TRITIUM-IFIC 2 prototype.

this prototype is larger than those used in others.

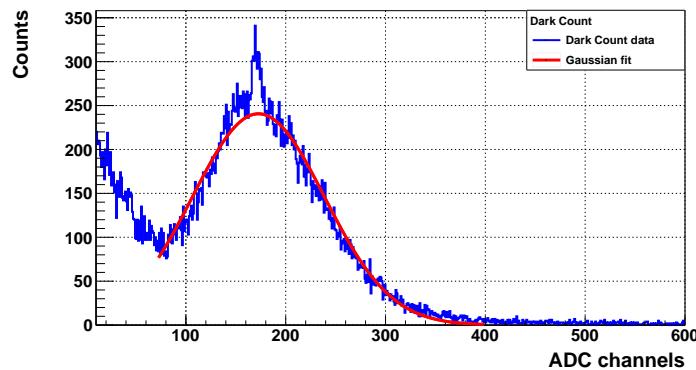
To remove the effect of different active area, the specific efficiency is measured, obtaining a value of $(1.59 \pm 0.48) \cdot 10^{-5} \frac{\text{c/s}}{\text{kBq/L cm}^2}$ for this prototype. Again, it can be observed that this prototype has the largest specific efficiency obtained so far with a scintillating detector used for tritium detection.

Therefore, as it has demonstrated, the intrinsic and specific efficiency obtained so far for scintillating detectors used for tritium detection has been exceeded with the last TRITIUM prototype, TRITIUM-IFIC 2.

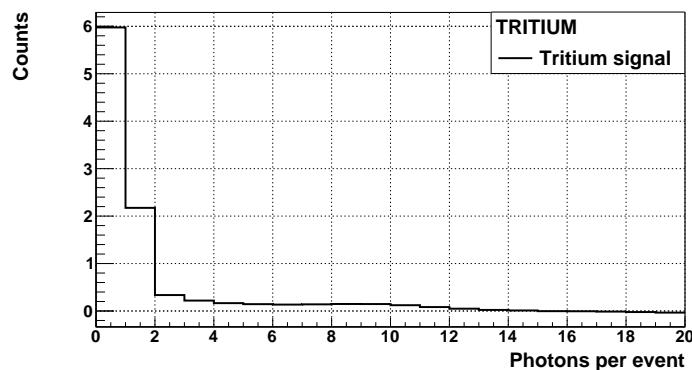
As discussed in chapter 4, the energy spectrum is shown in ADC units, proportional to energy, since it is difficult, even impossible, to do an energy calibration for a plastic scintillator due to its large uncertainty in the number of photons produced per event. Nevertheless, a detector calibration can be performed to express the results in units of photons detected per event. It was carried out using the single-photon distribution of the used PMTs, which was obtained from their self-emissions. Similar to the TRITIUM-Aveiro 0 prototype, the PMT used to read this prototype was decoupled to the prototype and covered with a special black blanket to ensure that external photons did not reach the PMT. The output signal of the PMT was analyzed using the electronical chain shown in Figure 3.15a. The distribution measured is shown in Figure 7.9a, in which a gaussian function was fitted.

As can be seen, the mean and uncertainty of the signal produced for a single photon detected with the PMT used are 172.71 and 66.19 (in ADC units) respectively. Therefore, the tritium signal, Figure 7.8b, can be expressed in number of photons detected per event, Figure 7.9b, by simply dividing this spectrum by the mean measured for the single-photon distribution.

As can be seen, a maximum of 15 photons are generated per tritium



(a) Single photon distribution.



(b) Tritium energy spectrum.

Figure 7.9 – Tritium measurement with TRITIUM-IFIC 2 prototype and expressed in photons detected per event.

event, which is in accordance with the expected result taking in to account the efficiencies involved.

Finally, a monitoring of both prototypes, signal and background, were carried out for several months, the measurements of which are shown in Figure 7.10.

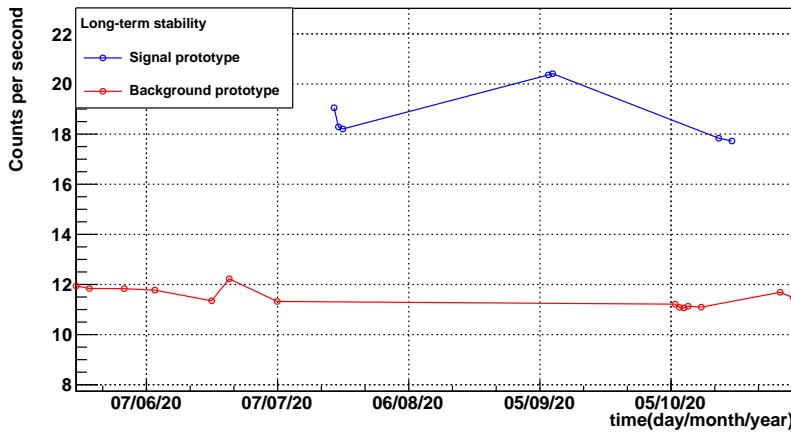


Figure 7.10 – Monitoring of the signal and background prototypes for several months.

As can be seen, the signal of both was not reduced, ensuring the maintainance of the detector efficiency during 3 months for the signal and 6 months for the background. Furthermore, it can be verified that the tritium activity used, 10 kBq/L, is not the LDL of the TRITIUM-IFIC 2 prototype since both measurements, signal and background, are clearly separated along the time.

ESTUDIAR EL LDL DEL DETECTOR CON LAS MEDIDAS TOMADAS!!!

INCLUIR QUE NO SE HA CONSEGUIDO MEDIR 1kBq/L!!!

7.2 Results from Measurements at Arrocampo Dam

This section shows the measurements obtained with the TRITIUM-Aveiro 0 prototypes during their installation in the Arrocampo dam, which has been the only prototype installed in Arrocampo dam so far. This prototype was installed and working there for more than four months, from March 27, 2019 to August 18, 2019, during which time this prototype was taking background measurements. The data acquired during this time are shown in the figure 7.11, the measurement time of which is 60 minutes.

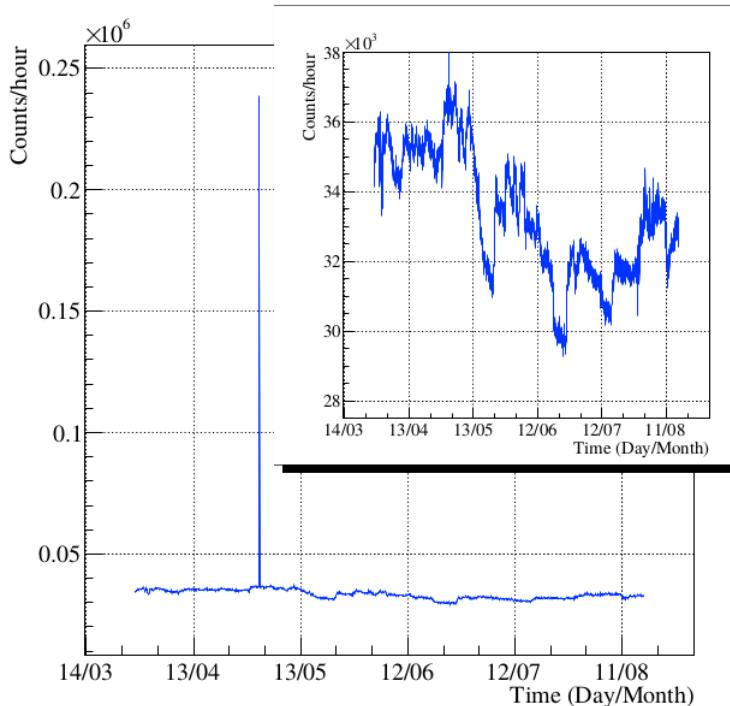


Figure 7.11 – Background measured with the TRITIUM-Aveiro 0 prototype during its installation in Arrocampo dam [CA].

This data shows good stability in the working months, measuring

a mean value of around 9.31 counts per second. A large peak is observed on May 2, 2019, caused by an opening of the roof of the lead shield to access the prototype. In the small box of the figure, the data is zoomed for a better visualization. The MDA measured in Arrocampo dam for 60 minute integration counting data is 6 times larger than that calculated in section 7.1.3. This variations can be caused by electric noise induced by the electric pumps of the water purification system and instabilities observed in the electronic boards.

A cosmic veto currently under development is planned to be installed and used in anti-coincidence along with two additional prototypes.

Furthermore, three TRITIUM-IFIC 2 prototypes and a cosmic veto, explained in section 5.2.2 and 3.4.2 respectively, are also planned to be installed in Arrocampo dam as soon as possible.

Chapter 8

Results of the TRITIUM Simulations

This chapter shows the results obtained in the simulations described in chapter 6, which is divided in two different sections. The first section contains the results of several simulations used to improve the design of the TRITIUM detector while the second exhibits the results obtained for the simulation of a full TRITIUM monitor based on an active veto read in anticoincidence with several TRITIUM-IFIC 2 prototypes. As shown throughout the different sections of this chapter, several tests were carried out to verify the correct simulation of the different steps such as the simulated tritium source, the energy deposition in the fibers and the production of photons in them.

8.1 Optimization of the TRITIUM Monitor Design

Several simulations were performed during the design of the TRITIUM detector, which were used to quantify the effect of some modifications and to choose those that optimize the tritium detection. The characteristics studied are the diameter and length of the scintillating fibers. As the tritium electrons has a very low mean free path, the shape of the simulated tritium source was also studied to reduce the consuming time and computing resources.

8.1.1 Optimization of the Tritiated Water Source

This section show and discuss the results obtained with the simulation described in section 6.2.1, the objective of which is to find the radial thick of the simulated tritium source that reduce the consuming time and computing resources used in the simulations.

First, the initial energy of the simulated tritium events are verified. For this task, the energy distribution of the simulated tritium electrons is obtained, shown in figure 8.1a, and compared with that obtained in the reference [Mer15]. As can be checked, there is a good agreement between both.

In addition, a spectrum of the initial energy of tritium electrons that are capable of reaching the fiber and depositing energy are shown in Figure 8.1b, red histogram, which is compared to the energy distribution of all simulated tritium events, blue histogram. A shift to the right side in the red histogram is observed, creating a peak centred at 10 keV. This shift occurs mainly because the lower energy tritium electrons don't have enough energy to reach the fiber and overcome the water-fiber interface, producing

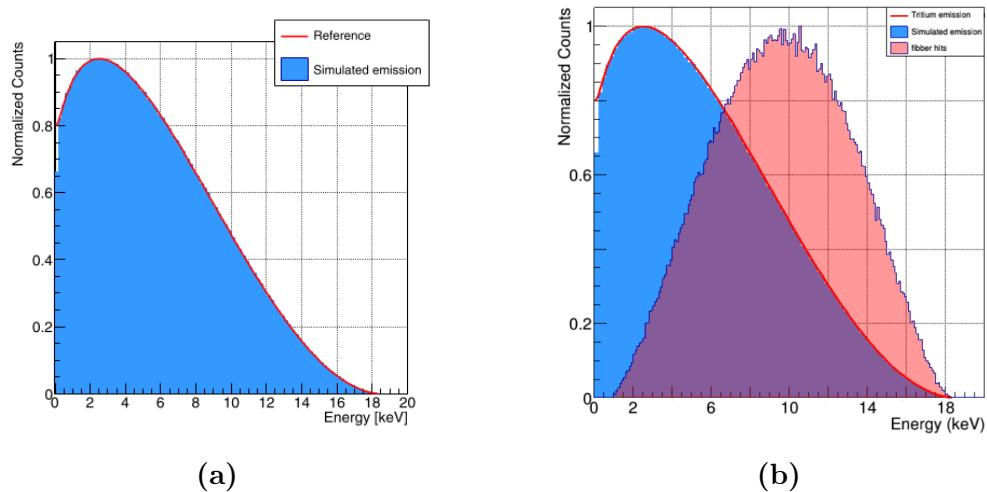


Figure 8.1 – Energy distribution of a) simulated tritium decays b) Initial energy of tritium decays that reach the scintillating fibers (red histogram) compared the all simulated tritium events (blue histogram) [Aze20].

a non-detected tritium event.

Regarding the radial thickness of the tritiated water source, Figure 8.2a shows a transversal cut of the 2 mm scintillating fiber, yellow, the simulated tritium source 0.5 mm thick around the fiber, green, and the tritium decays the electrons of which has deposited their energy in the scintillating fiber, red dots. Furthermore, the distribution of the radial distance between the position where tritium decays take place and the surface of the scintillating fiber are shown in figure 8.2b.

As can be seen in both figures, most of the tritium decays that are detected occur in close proximity to the scintillating fiber. A zoom is applied in the inset box of the Figure 8.2b for better viewing. The chosen thickness of the simulated tritium source is $5 \mu\text{m}$ since the 99.4% of the events that are able to deposit energy in fibers are produced at least of this distance.

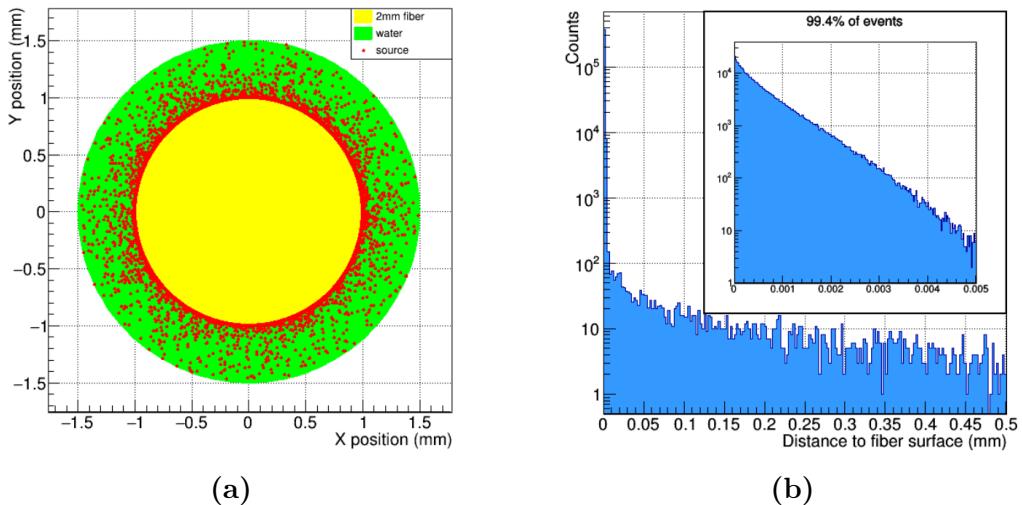


Figure 8.2 – a) Transversal cut of simulated scintillating fiber (yellow) and tritium source (green) with various tritium decays (red dots) b) Distribution of the radial distance between the position where the tritium decay takes place and the surface of the scintillating fiber [Aze20].

8.1.2 Simulation of the Output Light of Scintillating Fibers

As tritium electrons are far from being a MIP particles, a quenching effect is produced in the output light generated by scintillating fibers, following the Birks law (equation 6.1). This quenching effect produces a reduction in the photons emitted by the scintillating fibers. The objective of this section is to quantify the significance of this effect and how it affects to the tritium detection.

First, a verification test of the energy deposition of tritium electron on scintillating fibers is carried out. In Figure 8.3 the initial energy of simulated tritium electrons that has reach the scintillating fibers, blue histogram, is compared with their energy deposited in scintillating fibers, red histogram.

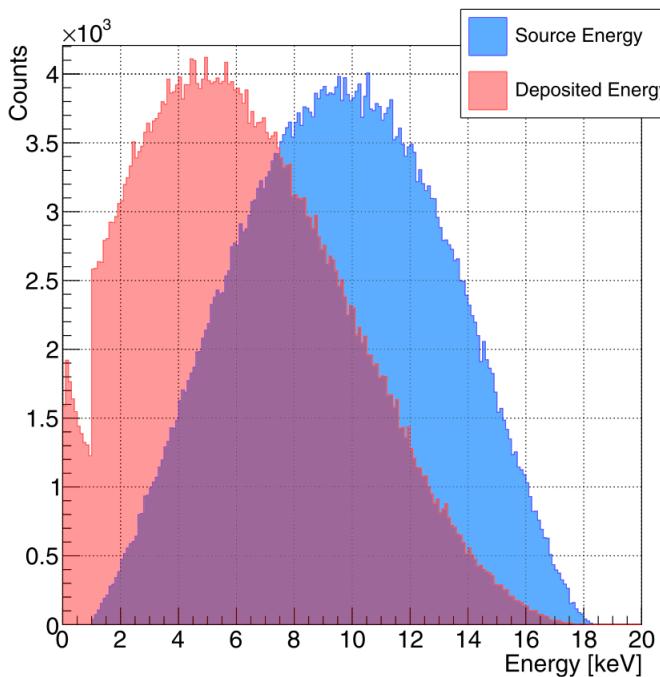


Figure 8.3 – Distribution of the initial energy of tritium events that has reach the scintillating fibers, blue histogram, and the energy deposited, red histogram [Aze20].

A shift to the left side of the spectrum (smaller energies) is observed between the blue histogram, with a peak around 10 keV, and the red histogram, with a peak around 5 keV. This displacement is mainly caused by the loss of energy of tritium electrons in the water. A cut of around 1 keV is observed in both energy distributions, produced by the default energy threshold of 990 eV that exist in the G4EmLivermorePhysics physics list.

Figure 8.4 shows two distributions of number of photons produced in scintillating fibers by tritium events, one in which the quenching effect has not been considered ($k_B = 0$), red histogram, and other in which the Birks coefficient has been applied ($k_B = 0.126 \text{ mm/MeV}$), blue histogram.

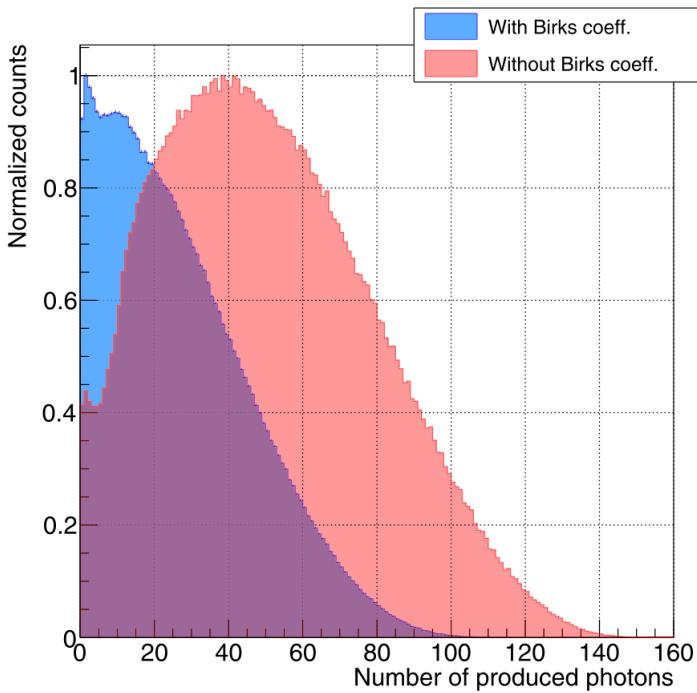


Figure 8.4 – Energy distribution of photons produced by the scintillating fiber when the birks coefficient is not considered, red histogram, and when this is considered, blue histogram [Aze20].

As expected, a distribution with a peak of around 40 photons per tritium event and a maximum of around 150 photons is obtained when the quenching effect was not considered. A significantly reduction of the output light is observed when the Birks coefficient is taken into account, producing a distribution with a peak centred around 10 photons and a maximum of 110 photons. The quenching effect is also observable in Figure 8.5, where the number of produced photons as a function of the energy deposited in the fiber is displayed in a bidimensional plot.

In this figure, in addition to a reduction of number of photons produced per energy deposited, a broader distribution is obtained when the Birks coefficient is considered, showing an increasement of the fluctuations

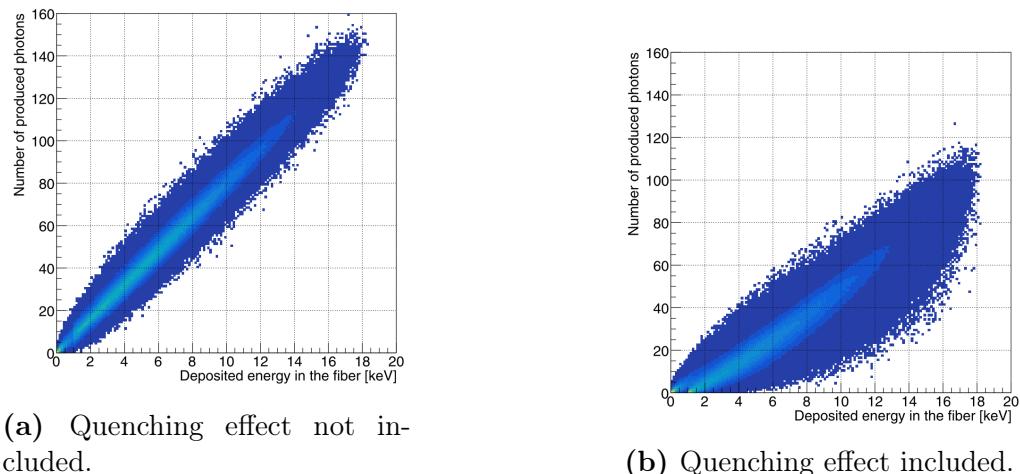


Figure 8.5 – Number of photons produced in front of the energy deposited in the scintillating fibers when a) the birks coefficient is not considered ($k_B = 0$) b) the Birks coefficient is considered ($k_B = 0.126 \text{ mm/MeV}$) [Aze20].

of energy deposition.

8.1.3 Optimization of the Scintillating Fiber Length

A study was carried out to choose the length of scintillating fibers that optimize the tritium detection efficiency. For this task, the complete TRITIUM-Aveiro 0 prototype was simulated, in which the photon propagation was included.

First, the propagation of photons in scintillating fibers was studied. The blue distribution of Figure 8.6 shows the number of photons produced in the fiber per tritium event that reaches them and the red distribution shows the same information but only for those events detected for both photosensors in time coincidence.

It can be seen that tritium events that produce a high number of

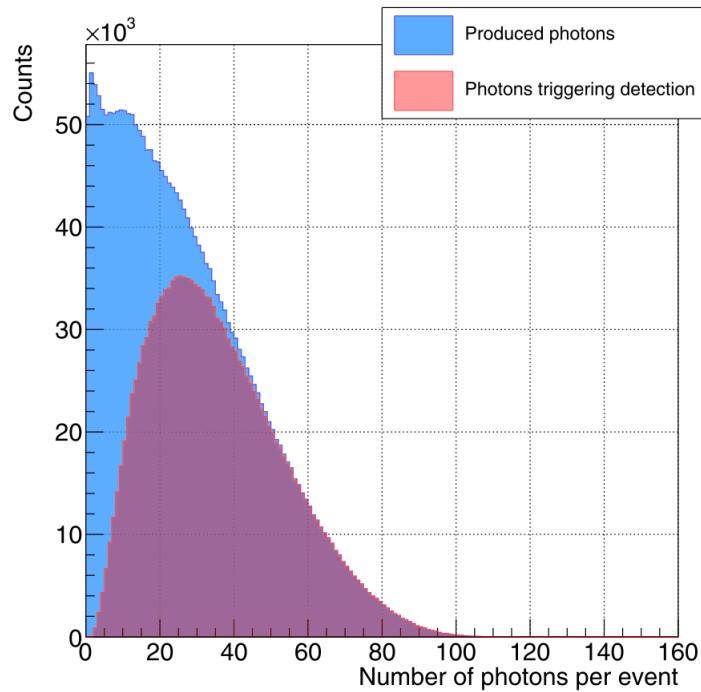


Figure 8.6 – Number of photons produced in the fiber per tritium event for all tritium events that reach the fiber (blue histogram) and only for tritium events the photons of which are detected by photosensors (red histogram) [Aze20].

photons are practically always detected but most of the events with fewer photons produced in the fibers are not detected, producing a peak centred of around 25 photons.

Regarding the fiber length study, two different lengths were compared, 1 m and 0.20 m, and two different tritium source activity were used, 0.5 kBq/L and 2.5 kBq/L. As detected tritium counts is proportional to the active area, 5 detectors were simulated for the case of 0.20 m fiber length to normalize the study to the same active area. The counts, which were integrated over 60 min and taken over a week, are shown in Figure 8.7.

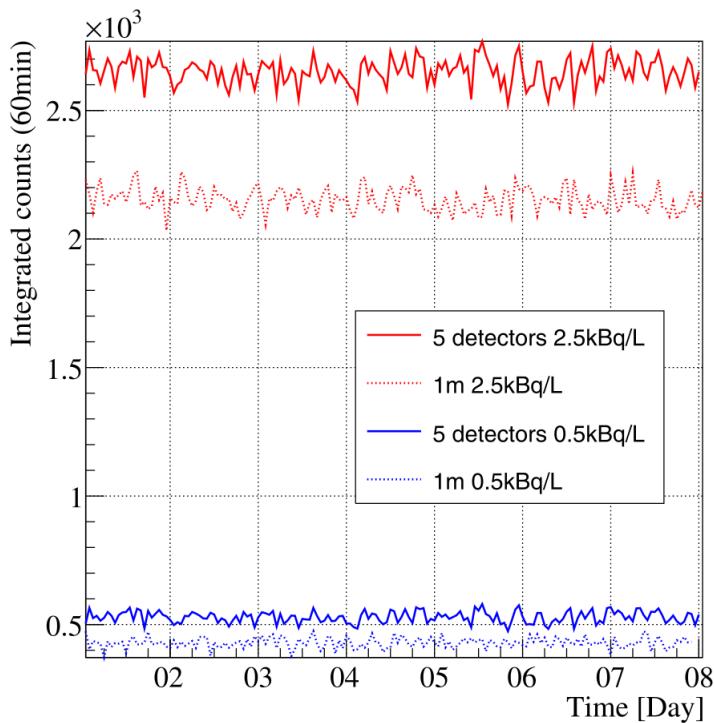


Figure 8.7 – Counts integrated over 60 min, normalized to the same active area and taken over a week for a fiber length of 1 m, dashed lines, and 20 cm, solid lines and two different activities, 0.5 kBq/L, blue lines, and 2.5 kBq/L, red lines [Aze20].

A larger signal is seen for shorter fiber lengths in both cases, producing a increase in tritium detection efficiency of approximately 25%, principally caused by a lower absorption of photons in shorter scintillating fibers and the leakage of some photons due to a non-perfect photon collection in the fiber.

8.1.4 Optimization Scintillating Fiber Diameter

This study quantifies the effect of the scintillating fiber diameter on the detection of cosmic ray events. The energy deposited in the scintillating fiber by a cosmic ray event is proportional to the active volume crossed, which is larger for 2 mm fibers. Therefore, the cosmic ray signal obtained for a measured cosmic event will be larger for a detector based on 2 mm diameter. The objective of this study is to find the design with which a lower background is obtained in the region of interest of tritium detection, ROI (up to 18 keV).

The distribution of energy deposited in scintillating fibers by cosmic ray events are shown in figure 8.8 for both cases, 1 mm and 2 mm fibers.

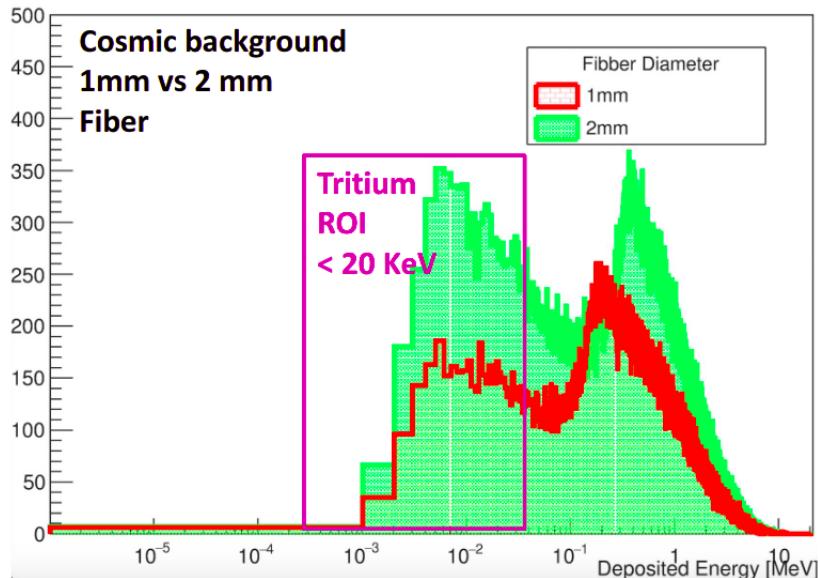


Figure 8.8 – Comparison of the energy deposition of cosmic ray events in scintillating fibers of 1 mm and 2 mm in diameter.

As can be seen in the figure, a smaller background is measured for fiber diameters of 1 mm, which reduces the low detection level LDL of

the detector. There are other reasons that favor the use of 2 mm fibers, such as their greater resistance and an improvement to the passage of water through them, so an experimental test is needed to choose the best design.

8.1.5 Effect of the PMMA windows

In the first prototypes, TRITIUM-IFIC 0 and TRITIUM-IFIC-1, the fibers were directly coupled to the photosensor, so the detected photons were only those guided by fibers. However, in the last prototypes, TRITIUM-Aveiro 0 and TRITIUM-IFIC 2, two PMMA windows are used, which allows the detection of photons guided by fiber and photons that come from the water medium.

To quantify the importance of this effect, the TRITIUM-Aveiro 0 prototype was simulated and the distribution of the number of photons that reach the PMMA per tritium event are shown in Figure 8.9. Fiber-guided photons are shown in a red distribution, while those traveling in the water medium are represented in the blue histogram.

It can be seen that the tritium signal obtained from the water is as important as that obtained from the fibers, contributing half of a signal. Therefore, an improvement in tritium detection efficiency is achieved using PMMA windows.

8.2 Simulation Results of TRITIUM Monitor

This section shows the results obtained in the simulation of the TRITIUM monitor, consisting of a study of the tritium detection with various TRITIUM-IFIC 2 prototypes in parallel, section 8.2.1, and a study of the effect of the background rejection system, section 8.2.2.

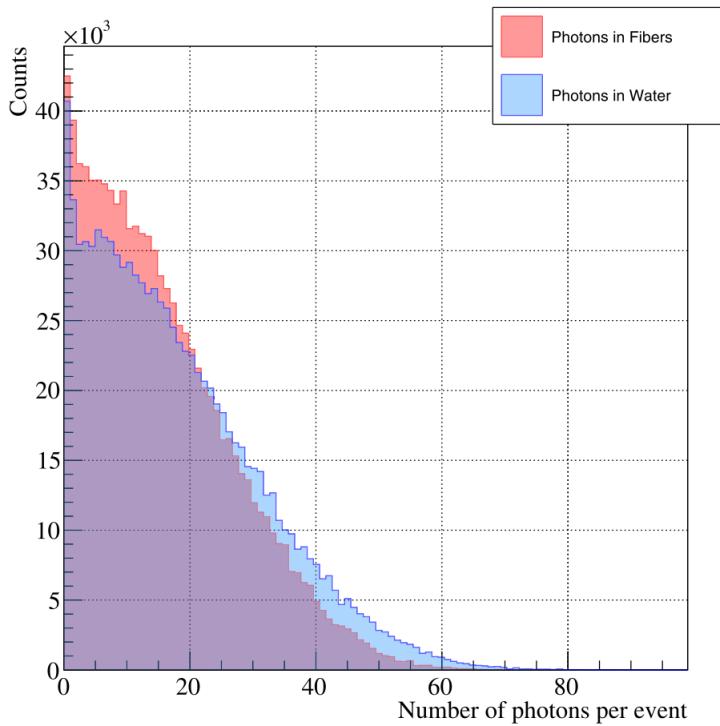


Figure 8.9 – Distribution of photons reaching PMMA windows. The red histogram includes those guided by fibers and the blue histogram includes those traveling in the water medium [Aze20].

8.2.1 Simulation Results of TRITIUM-IFIC 2

This section shows the results obtained with the simulation of the TRITIUM-IFIC 2 prototype, which was used for two different objectives. On the one hand, these simulations were carried out to find the Low Detection Limit, LDL, of this prototype for tritiated water activity, which is an important parameter to know the limitation of the prototype. On the other hand, these simulations serve to study the activity resolution of the prototype and how it can be improved through various parameters such as the increasement of the integration counting count time of the measurement or the number of prototypes read in parallel.

The detection of a tritium event by the TRITIUM-IFIC 2 prototype is shown in Figure 8.10, in which, the path followed by the photons created in scintillating fibers are represented by green lines which end in red dots when it is absorbed in the fiber or the water and blue dots when it is absorbed in the PMTs (detected). The fiber that has detected the tritium electron is clearly identified and the photons out of this are those that has not been collected due to the critical angle. Blue dots are obtained in both PMTs for this event, indicating that this is detected on time coincidence.

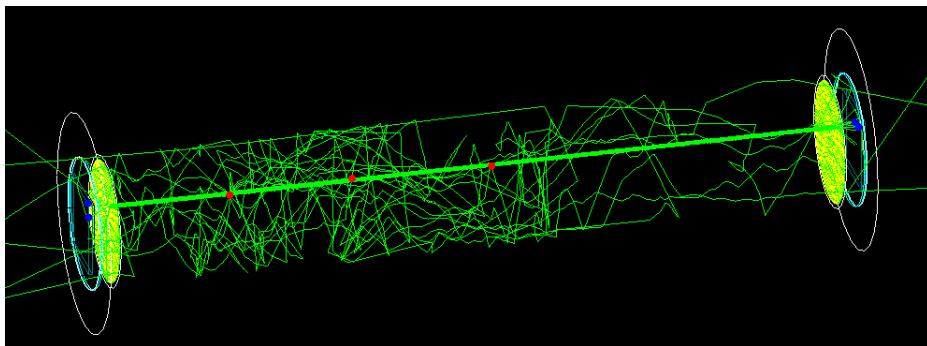


Figure 8.10 – Tritium electron detected in the simulated TRITIUM-IFIC 2 prototype. The path of the optical photons is represented by green lines and the position in which it is absorbed is represented by red and blue dots (absorbed in water or PMT, respectively).

Several variables were used as tests in each simulation to verify the different steps of the simulation such as the production of tritium events, the energy deposition in scintillating fibers and their subsequent photon emission, spatial distribution of generated events, detected events, etc.

The distribution of the number of photons detected by both PMTs per tritium event was obtained for the simulated TRITIUM-IFIC 2 prototype, shown in Figure 8.11.

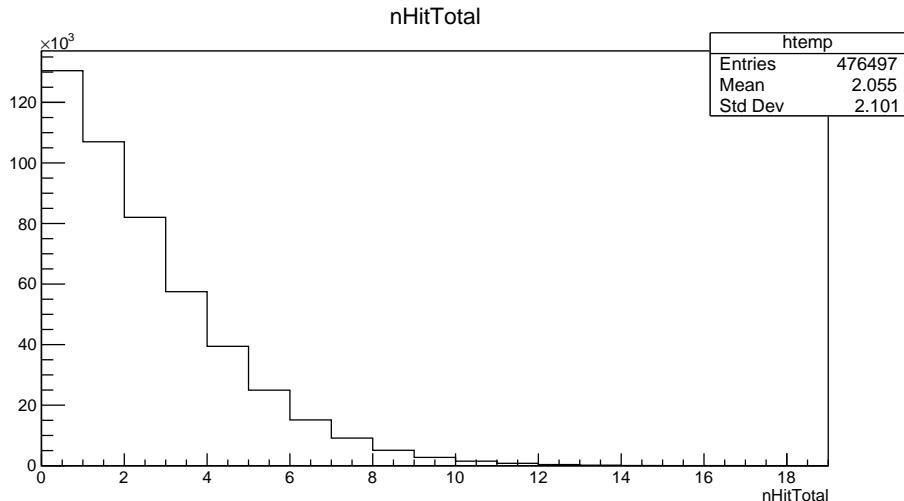
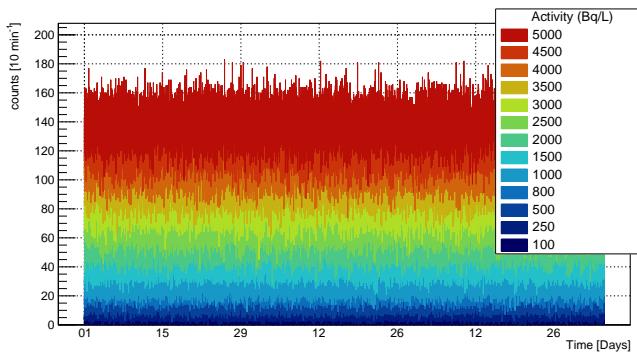


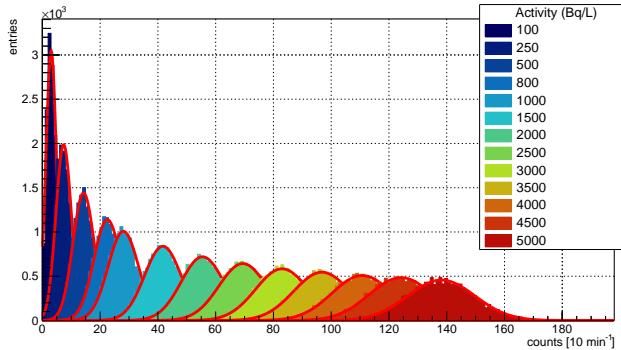
Figure 8.11 – Photons detected by both PMTs per tritium event in the simulated TRITIUM-IFIC 2 prototype.

A maximum of 17 photons is obtained for the TRITIUM-IFIC 2 prototype simulations, which are in agreement with the maximum of 15 photons experimentaly measured by the experimental experience, Figure 7.9b. This confirms that the value used in the simulations for the Birks coefficient, $k_B = 0.136 \text{ mm/MeV}$, is adequate. The experimentally obtained distribution are a bit small between 3 and 8 photons, probably due to imperfections of the prototype which are impossible to simulate.

Various activities were simulated from 100 Bq/L to 5 kBq/L for three months of simulated data taking and an integration counting time of



(a) Counts as a function of the time.



(b) Distribution.

Figure 8.12 – Tritium counts detected with a simulated TRITIUM-IFIC 2 prototype using a integration counting time of 10 min a) as a function of the time b) distribution of them.

10 min was used.

The measurements obtained are presented in Figure 8.12a as a function of time, which are histogramed in Figure 8.12b.

Difference of 250 Bq/L is not distinguished due to the overlapping of sevarial distributions. To reduce the width of the distribution obtained for each activity, the statistics must be increased, which can be done in two different ways, increasing the integration counting time or increasing the

number of prototype read in parallel.

To check the effect due to an increasement of the integration counting time similar distributions are obtained for three increasing integration counting times (10 min, 30 min and 60 min), which are shown in Figure 8.13.

The effect of increasing the integration counting time is clearly visible in this figure, reducing the relative distribution width and improving the activity resolution of the TRITIUM monitor. Difference as low as 250 Bq/L are clearly distiguised using only one detector and an integration counting time of 60 min, which we can still consider a quasi-real time measurement. Similarly, this distributions are shown in Figure 8.14 for 10 min of integration counting time, in which three increasing number of prototypes were read in parallel (1, 5 and 10).

Again the reduction of the distribution width is clearly visible in these figures, improving the activity resolution of the detector. In this case, differences of 250 Bq/L are clearly distinguished using a integration counting time of 10 min and measuring with 5 TRITIUM-IFIC 2 prototypes.

The effect on the resolution, defined as the equation 8.1, is also studied as a function of both TRITIUM monitor characteristics, integration counting time and number of used prototypes, and shown in Figure 8.15.

$$\text{Resolution}(\%) = \frac{\text{FWHM}}{\text{centroid}} \cdot 100 \quad (8.1)$$

A growing improvement can be observed in both cases and, as can be verified with the lines in the figure, the resolution of both cases fit to the expected behavior of the inverse of the root of accounts.

Therefore, both characteristics must be balanced based on the requirements and financial budget of the experiment. The activity difference,

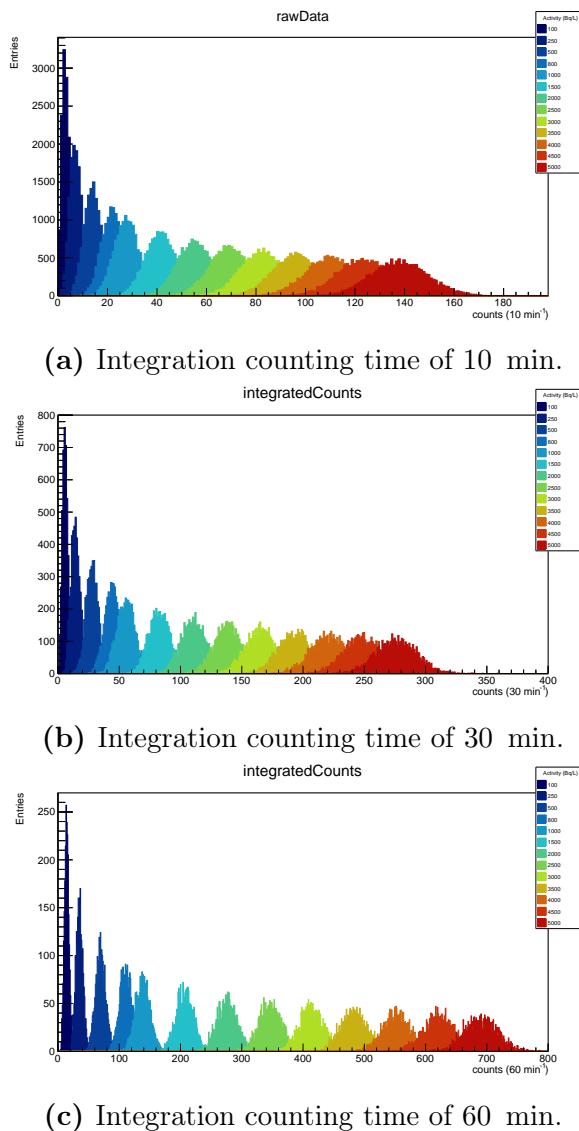


Figure 8.13 – The distribution of the tritium counts detected with a simulated TRITIUM-IFIC 2 prototype for three different integration counting time, a) 10 min b) 30 min and c) 60 min.

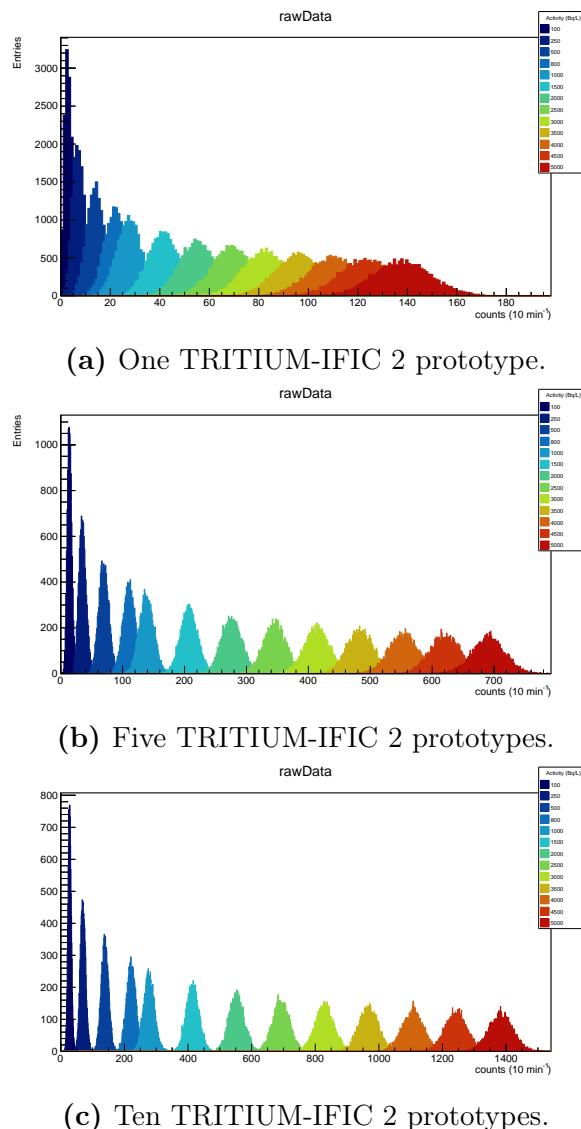


Figure 8.14 – The distribution of the tritium counts detected with several simulated TRITIUM-IFIC 2 prototypes a) 1, b) 5 and c) 10 for an integration counting time of 10 min.

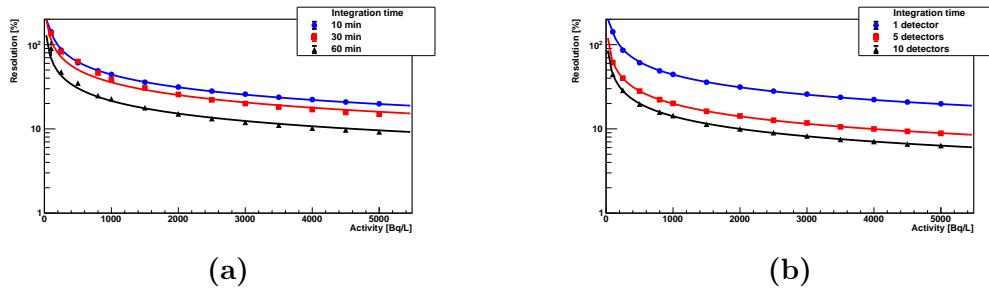


Figure 8.15 – Resolution of the TRITIUM-IFIC 2 prototype as a function of the a) integration counting time b) number of prototypes.

the distribution peaks of which are clearly distinguished for each different case of integration counting time and number of detectors used, is summarized in Table 8.1.

# of Detectors	10 min	30 min	60 min
1	< 1000 Bq/L	500 Bq/L	200 Bq/L
5	200 Bq/L	150 Bq/L	100 Bq/L
10	150 Bq/L	100 Bq/L	≈ 50 Bq/L

Table 8.1: Difference in activity that can be clearly distinguished for various cases of the TRITIUM-IFIC 2 prototype based on different integration counting times and different number of prototypes.

The decision made in the TRITIUM experiment is to install 3 different TRITIUM-IFIC 2 prototypes, with which differences of 250 Bq/L are expected to be distinguished using an integration counting time of 30 min. These prototypes are expected to be installed in Arrocampo dam as soon as possible. Two other TRITIUM-Aveiro 0 prototypes are being built and will be installed soon, along the one currently installed.

8.2.2 Simulation Results of Background Rejection System

Finally, this section shows the results obtained with the simulation of a TRITIUM-IFIC 2 prototype when the background rejection system, detailed in section 6.2.6, is included. These simulations quantify the effect on the tritium measurement of both parts of the background rejection system, lead shield and cosmic veto.

Similar to the simulations used for the study of the TRITIUM-IFIC 2 prototype, analogous variables were used as tests, which were systematically verified, to ensure that all the steps of the simulations were carried out correctly.

Three different simulations were carried out to independently quantify how the tritium detection is affected due to both, the lead shield and the cosmic veto. The first simulation consists of a TRITIUM-IFIC 2 prototype and the cosmic ray source, in the second simulation a lead shield was added and for the third simulation, the cosmic veto was also included.

The cosmic events detected by the TRITIUM-IFIC 2 prototype are reduced around 5.5 times when a lead shielding with walls of 5 cm is included. This reduction is mainly caused due to the stop of the weak cosmic radiation (energy lower than 200 MeV). It has to be taken into account that the natural backgrounds of the place are not included in this simulation. This radioactive background will be also stopped by the lead shielding, so the expected reduction of the radioactive background due to the passive veto is even better.

Regarding to the cosmic events that pass through the lead shield and reach the TRITIUM IFIC 2 prototype, which are the hard cosmic radiation, a percentage of around 10% is detected with the cosmic veto and, therefore, removed to the tritium measurement.

Therefore, the usefulness of both parties of the background rejection system, lead shield and active veto, has been demonstrated by quantifying their effect.

Chapter 9

Conclusions and Prospects

This chapter contains a brief summary of the most important achievements reached in this work and highlights the main conclusions obtained.

The design of a tritium detector capable of measuring low tritium activities in quasi-real time is mandatory since this is one of the first sign of a malfunctioning of a nuclear facility, such us nuclear power plants, future nuclear fusion reactors and laboratories of high energy physics.

The goal of the TRITIUM project is to design, build, install and commission a tritium monitor that will measure tritium activities as low as 100 Bq/L (legal limit imposed for European Council Directive 2013/51/EU-RATOM for drinking water consumption) in quasi-real time (1 hour or less).

The TRITIUM monitor developed in the TRITIUM project has different parts, which are detailed in this thesis. The different parts, which was characterized indendently, are an ultrapure water system, which prepares the water sample before the measurement, a tritium detector, consisting of scintillating fibers readout by photosensors (PMTs or SiPM arrays), and a passive and active shielding, which is used to reduce de radioactive

background measured by the tritium detector.

First, the components of the tritium monitor, which are scintillating fibers and SiPM, were characterized and some improvements were studied.

- On the one hand, a characterization of the photon collection efficiency of the BCF-12 unclad scintillating fibers was performed, which was compared with single clad and multiclads fibers to check the importance of the clad.

In addition, a conditioning process of scintillating fiber was developed, tested and implemented, consisting of cutting, polishing and cleaning them, the objective of which is to increase the tritium detection efficiency. Due to the large number of scintillating fibers used, it was necessary to develop an automatic polishing machine, based on arduino technology, which is capable of polishing up to one hundred scintillating fibers at the same time. The improvement in photon collection efficiency due to the polishing and cleaning process was quantified in more than 40% and 21%, respectively.

- On the other hand, a characterization of the SiPM used (Hamamatsu model S13360-6075) was carried out at the level of a single SiPM. In this characterization several interesting parameters such as quenching resistance, terminal capacitance, internal gain of SiPM, breakdown voltage, temperature coefficient, etc. were experimentally measured.

Due to the strong dependence of the SiPM internal gain on temperature, a stabilization method for the SiPM gain was developed and experimentally tested. The objective of this mechanism is to compensate for temperature variations with variations in the operating voltage of the SiPM, maintaining the internal gain of the SiPM during its operation.

Second, a characterization of the ultrapure water system was carried out, in which it was checked that the imposed requirements were fullfilled. The requirements are to prepare water samples with very low conductivity (of the order of about $10 \mu\text{Sv}/\text{cm}^2$) in which the organic matter and all particles up to 1 mm diameters is removed without affecting the tritium levels.

Third, a characterization of the active veto was carried out in which several interesting parameters were experimentally measured.

- First, the quality of the coverage of the plastic scintillator, consisting of a layer of teflon, aluminium and black tape, was tested and quantified, obtaining an improvement in the uniformity and quality of the photon collection efficiency.
- Second, the high voltage and threshold that optimize the detection of hard cosmic rays ($> 200 \text{ MeV}$) was experimentally found.
- Third, a hard cosmic events was experimentaly measured with the active veto developed, obtaining an energy spectrum with a shape similar to a Landau functions, as it is expected, and an efficiency of hard cosmic rays detection of 85%. In addition, the relationship between the number of the hard cosmic rays measured and the distance between both plastic scintillators of the active veto was obtained, allowing this distance to be changed without the need to perform a new calibration of the active veto.

This background rejection system, consisting of a lead shielding and an active veto, is essencial to achieve the activity goal of 100 Bq/L .

Fourth, four different prototypes of the tritium detector have been developed. The first two prototypes, TRITIUM-IFIC 0 and TRITIUM-IFIC 1, was used to detect potencial problems that affect to the tritium

measurement as well as to test several improvement in the detector design. The last two prototypes, TRITIUM-Aveiro and TRITIUM-IFIC 2, are two different designs to be used in the final tritium cell of the TRITIUM monitor. Each design has its own advantages and disadvantages and the one with the best results will be used as a final design of the TRITIUM cell.

With the different prototypes, an increasing sensitivity has been achieved, showing the effect of the applied improvements. The best tritium detection efficiency was obtained with the lastest prototype developed, TRITIUM-IFIC 2, with which the State-Of-The-Art of tritium detection has been overcomed. The most important results of each prototype developed in TRITIUM project are presented in Table 9.1, in which the results obtained with other experiments are also included.

Study	$\varepsilon_{det} (\frac{cps \cdot 10^{-3}}{kBq/L})$	F_{sci} (cm ²)	$\eta_{det} (\frac{cps \cdot 10^{-6}}{kBq/L \cdot cm^2})$	LDL (kBq/L)
Muramatsu	0.39	123	3.13	370
Moghissi	4.50	> 424.1	< 10.6	37
Osborne	12	3000	4	37
Singh	41	3000	13.7	< 37
Hofstetter	2.22	~ 100	< 22.2	25
T-IFIC 0	2.11 ± 0.85	219.91	9.59 ± 3.87	100*
T-IFIC 1	38.42 ± 1.61	402.12	95.55 ± 4.01	100*
T-Aveiro 0	64.87 ± 19.41	4071.50	15.93 ± 4.77	29.8
T-IFIC 2	711.03 ± 27.77	5026.55	141.45 ± 5.52	10*

Table 9.1: Results of scintillator detector developed for several experiments (including the TRITIUM project) for tritiated water detection. This table shows the efficiency of the detector (ε_{det}), its active surface (F_{sci}), its specific efficiency ($\eta_{det} = \varepsilon_{det}/F_{sci}$), defined as its efficiency normalized to its active surface, and its low detection-level (LDL) for each study listed above. The "*" symbol indicates that this is the specified activity that the detector can distinguish from the background, but it is not its LDL.

As can be seen in the table, the specific efficiency of the latest prototype, TRITIUM-IFIC 2, is almost an order of magnitud better than

the best result obtained in other experiments (Hofstetter). Special attention need to be paid for the specific efficiency obtained for the TRITIUM-Aveiro prototype, which is smaller than the expected. A possible reason is because the used fibers was not polished nor cleaned, reducing the tritium events detected. It could be interesting to develop a new TRITIUM-Aveiro prototype, the fibers of which are prepared with the conditioning process detailed in sections 4.1.1 and 4.1.4 to decide which tritium cell design optimizes the tritium detection.

A low detection level, LDL, of 29.8 kBq/L has been measured for the TRITIUM-Aveiro prototype using 1 minutes of integration time, slightly improving the State-Of-The-Art. It is expected to be improved up to 5 kBq/L by increasing the integration time up to 1 hour, which is still considered quasi-real time.

A better result was obtained for the TRITIUM-IFIC 2 prototype, being able to clearly measure an activity of 10 kBq/L, improving the best results obtained in other experiments. However this is not the LDL of the prototype. To measure this, it is necessary to take many more measurements and apply the same mathematical method used for the TRITIUM-Aveiro prototype.

Nevertheless the low detection level achieved with this prototypes is further from being the goal of the TRITIUM project, 100 Bq/L. This is not a problem since the TRITIUM monitor will consists of several TRITIUM cells readout in parallel, becoming the TRITIUM monitor in a scalable detector. It means that more tritium cells can be used, readed in parallel, to improve the results obtained. The activity goal is expected to be achieved using three different cells of TRITIUM-IFIC 2 read in anti-coincidence with an active veto.

In summary, two different prototypes has been developed in the TRITIUM project with which it is possible to measure low activities of tri-

tiated water in quasi-real time, improving the specific efficiency and the low detection level of the activity currently achieved with other experiments. In addition, the stability of the tritium detection efficiency of both prototypes has been verified during several months.

Currently, the lead shielding, the ultrapure water system and a TRITIUM-Aveiro 0 prototype are installed in Arrocampo dam, near to Almaraz Nuclear Power Plant. Two additional TRITIUM-Aveiro 0 prototypes and an active veto are planned to be installed as soon as possible. In addition, three prototypes of TRITIUM-IFIC 2 and an active veto are ready to be installed too, the installation of which has been delayed due to the coronavirus pandemic.

Finally several Monte Carlo simulation has been developed using Geant4. These simulations were used for three different tasks:

- First, several simulations were carried out to study the different steps of the simulation, such as the energy deposition of tritium electrons on scintillating fibers (spectrum peaked of around 5 keV), the number of photons produced by the fibers (spectrum peaked of around 10 photons) or which of these are detected by the photosensors in time coincidence (spectrum peaked of around 25 photons). They were also used to quantify the importance of the reduction of the scintillating fiber signals because tritium electrons are not MIP particles (Birks effect).
- Second, these simulations were used to test different tritium detector designs, such as different fiber lengths or fiber diameters, and choosing the one with the best results, that is, the one that optimizes the tritium detection efficiency.
- Third, these simulations were used to verify the results obtained with the last two TRITIUM prototype, such as the spectrum of the number of photons obtained per tritium event, ensuring that this prototype

works correctly. They were also used to find the sensibility of each different prototype and how the integration time and the number of cells used can improve to the tritium detection of the TRITIUM monitor.

Appendices

Appendix A

Electronic Readout for characterization the SiPM 13360-6075 Model

This appendix shows the electronic system designed to perform a complete characterization of the SiPM S13360-6075 model. This consists on three different PCBs¹, shown in Figure A.1:

1. The first PCB, shown in Figure A.1a, is used to organize the SiPMs and sensor temperature. This PCB place up to 8 different SiPMs and a temperature sensor and arrange their output signals on two HDMI connections. This PCB is placed inside a special black box, from Thorlabs company [Thob], that has a high degree of light tightness. This black box has a small hole of 1 mm diameter, prepared to introduce an optical fiber² to illuminate SiPMs with an incoherent light source. The light source utilized is a LED, model 430L from Thorlabs com-

¹PCB, Printed Circuit Board

²The optical fiber used is BCF-98 from Saint-Gobain company [Cer21]

pany [Tho18], which gives an spectrum shown in Figure A.1d. The spectrum was experimentaly measured with a spectrometer and fitted to a Gaussian function. It can be seen that the emission peak of this LED is placed at 436.3 with a FWHM³ of 19.1 nm. With the help of this LED the light emission of the fibers used in TRITIUM experiment is simulated to calibrate the SiPMs at the working wavelength.

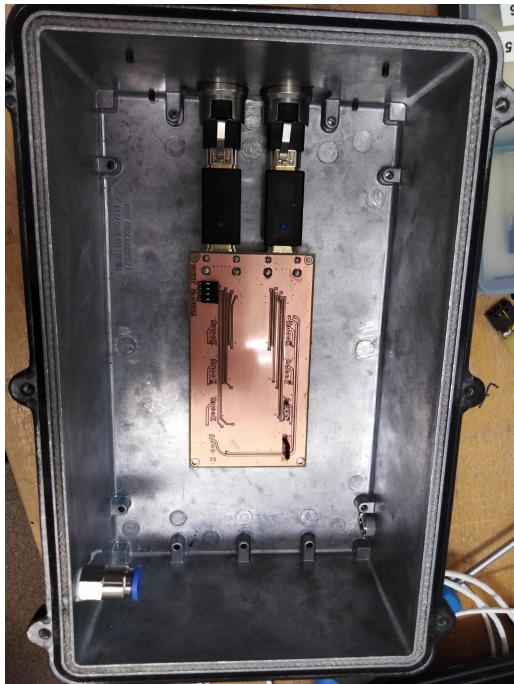
2. The second PCB, shown in Figure A.1b, sums the different signals of the SiPMs and amplify them by a factor $G = 4187.5$ or $G = 10761.88$, depending on the input resistance of the oscilloscope, 50Ω or $1 M\Omega$, respectively. This PCB uses a differential amplification that reduce the electronic noise of the system and is connected to the first PCB through two HDMI feedthroughs.
3. The third PCB, shown in Figure A.1c, rearranges all the different input and output signals in an HDMI connection to avoid crosstalk between different signals. This PCB is connected to the second PCB through a HDMI feedthrough.

The input signals are the supply voltage of the SiPMs and the supply voltage of the PCBs (± 6 V) and the output signals are the temperature sensor signal and the summed signal of all SiPMs.

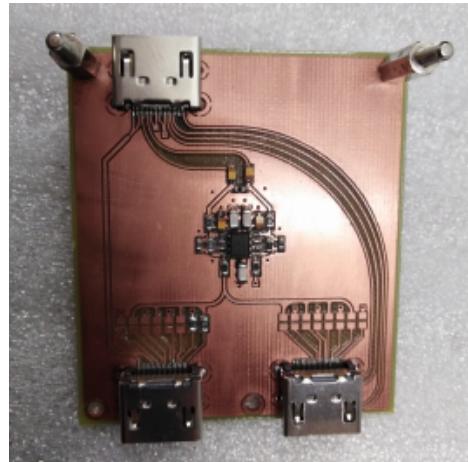
The output signal of the third PCB is connected to an oscilloscope, model MSO44X from Tektronix [Tek21], that records the data which are subsequently analized by ROOT⁴.

³The FWHM parameter, Full Width at Half Maximum, of a Gaussian fit can be calculated from its sigma using the equation: $\text{FWHM} = 2.35 \cdot \sigma$

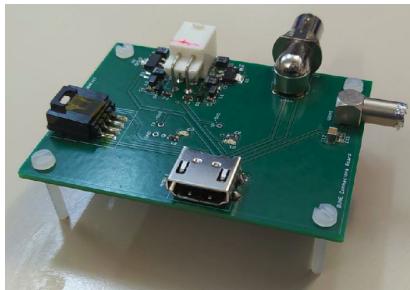
⁴ROOT is a framework for data processing, based on C ++ and object-oriented technology, developed at CERN and widely used in nuclear and particle physics.



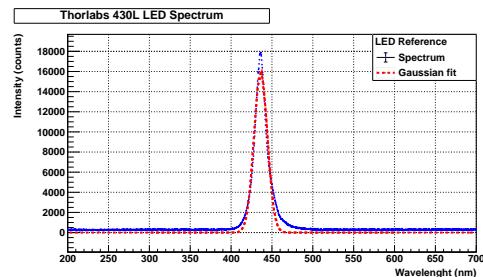
(a) PCB 1 used to arrange 8 SiPMs and black box.



(b) PCB 2 used to sum and amplify the output signals of SiPMs.



(c) PCB 3 used to rearrange the different signals of the system.



(d) Emission spectrum of the LED.

Figure A.1 – Three PCBs used for the SiPM characterization and LED emission spectrum.

Appendix B

Ultrapure Water System

This appendix shows several photos of the ultrapure water system in the same order that the water flows through them.

First of all, the complete scheme of the ultrapure water system is shown in Figure B.1:

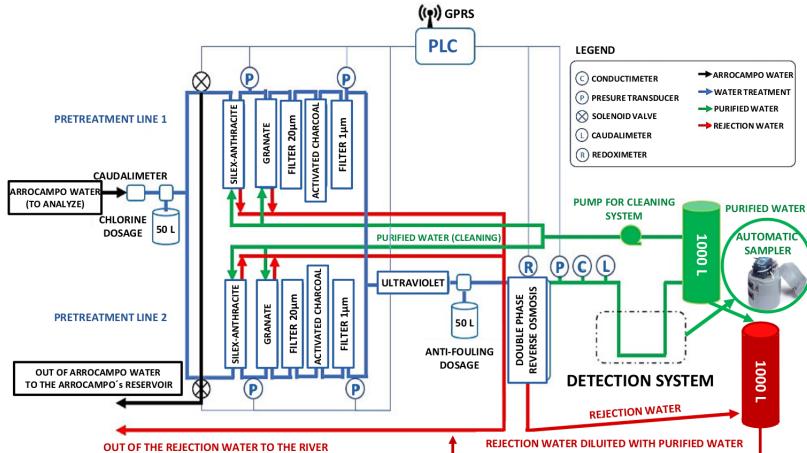


Figure B.1 – Scheme of the ultrapure water system.

The Gross filtering stage, made up of Silex-Antracite and Granate

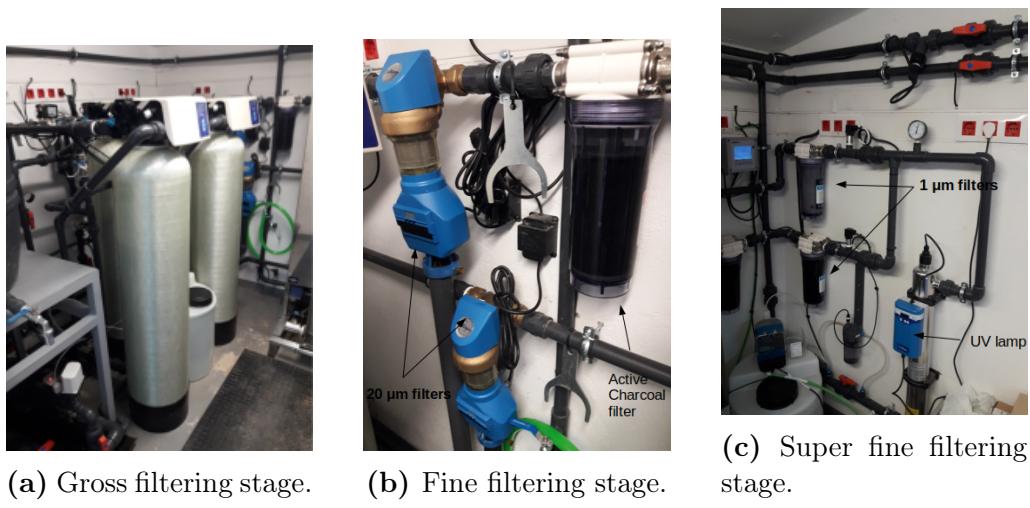


Figure B.2 – Different stages of filtration of the ultrapure water system.

filters, the fine filtering stage, consisting of $20\text{ }\mu\text{m}$ filter and active carbon filter and the superfine filtering, composed of the $1\text{ }\mu\text{m}$ filter and the UV lamps, are shown in Figure B.2.

The double phase reverse osmosis is exhibited in Figure B.3a and the containers in which we store the ultrapure water and the reject water after treatment is displayed in Figure B.3b.

The Siemens PLC, software used to control the ultrapure water system, is shown in Figure B.4.

Finally, the complete system of the ultrapure water system is displayed in Figure B.5

Just as a curiosity, the three types of water (raw water, rejection water and ultrapure water) are exhibited in Figure B.6, where it can be visually checked the difference in the turbidity of each type of water.



(a) Doble phase reverse osmosis stage.



(b) Storage containers of reject and ultrapure water.

Figure B.3 – Doble phase reverse osmosis stage and containers used to store the outlet water of the ultrapure water system.



(a)



(b)



(c)

Figure B.4 – Siemens PLC, software for remote control of ultrapure water system.



Figure B.5 – General photo of the complete ultrapure water system.

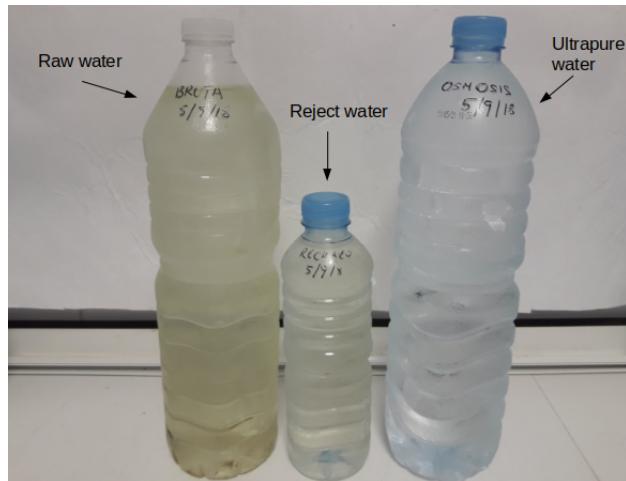


Figure B.6 – Raw water, reject water and ultrapure water obtained with this system.

Appendix C

Preparation of Liquid Radioactive Source of Tritium

To prepare this radioactive liquid source, 1.86 g (uncertainty of 0.05%) of tritium was purchased from the Germany company PTB¹, which has a serial number of 2005 – 1442 and reference number of PTB-6.11 – 285/03.2017 [PTB]

The activity of this tritium source is 26,8 MBq/g (uncertainty of 2.24%), reference data of 1 of January of 2017, and it was dissolved in 500 mL (uncertainty of 0.05%) of ultrapure water, giving 500 ml of tritium water, to which we will call standard solution, with an activity of 100.096 kBq/g (uncertainty of 2.24%), that's, 99.696 kBq/L (uncertainty of 2.24%), which was measured with the TRI-CARB 2810 system, based on liquid scintillation readout by PMT.

¹Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Germany

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Appendix D

Electronic System of TRITIUM-Aveiro 0 prototype

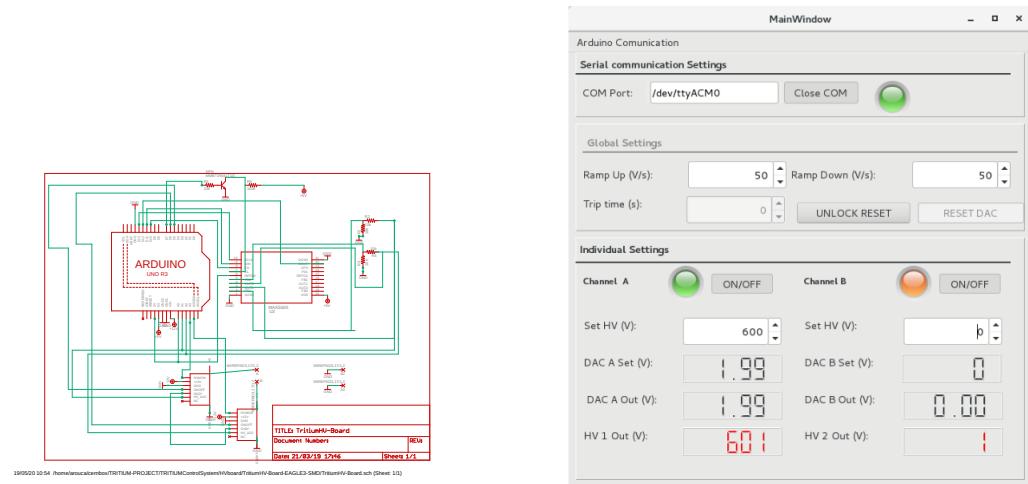
The electronic system used in TRITIUM-Aveiro 0 prototype consists of several PCB and can be divided into two parts:

1. A PCB, whose electronic scheme is shown in Figure D.1, was designed to power the PMTs with a negative high voltage. It consists of several high voltage power supply, model C11152-01 from Hamamatsu company [K.K15], one for each PMT used, which is controled by a DAC¹, model MAX5500 from Maxim Integrated company [Int09]. An Arduino Mega is used for the DAC communication and cross-checking the output values and it is connected to a Raspberry Pi to control the system.

A graphical interface, shown Figure D.1b, has been developed to manage the different options of this system in a comfortable way.

2. A electronical chain consisting of several PCBs was used to process

¹DAC, Digital-to-analog converter



(a) Electronic scheme of the PCB.

(b) Graphical user interface.

Figure D.1 – Electronic scheme of the PCB designed to power the PMTs of Aveiro prototype and the graphical user interface developed to control it.

and analyze the system signals, whose simplified electronic scheme is shown in Figure D.2.

It consists of three different lines, two of them are used for the PMT signals of the prototype and the remaining line is used for doing anti-coincidence with an active veto.

To test this electronic chain a plastic scintillation with dimensions of $10 \cdot 10 \cdot 1 \text{ cm}^3$ was used to simulate a veto signal but four different vetos are being developed, based on a rectangular plastic scintillations of Saint-Gobain company [SG], whose dimensions are $50 \text{ cm} \cdot 30 \cdot 2 \text{ cm}^3$ with a PMT coupled, model R2154-02 2" from Hamamatsu company [K.K10]. The output signal of these PMTs will be input in a OR stage, whose response will be introduced in the veto line shown previously in Figure D.2. As a result, each plastic scintillator will be read in anticoincidence with tritium-Aveiro prototype.

Both lines, used to process and analyze the PMT signals of the prototype, are equal and they are used to operate in time coincidence.

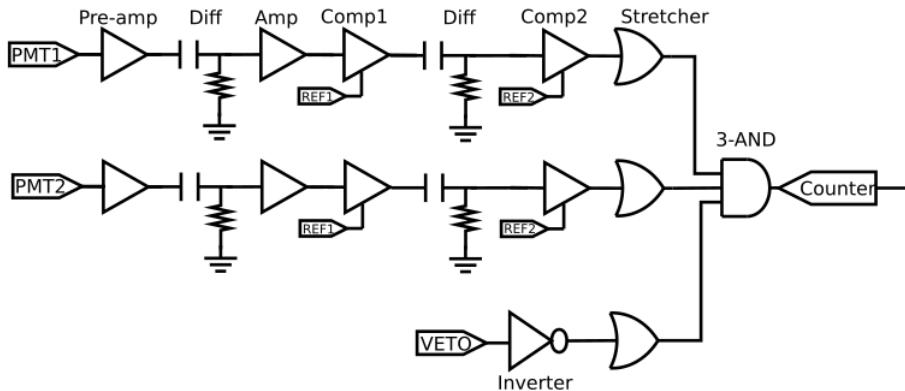


Figure D.2 – Simplified electronic scheme used to process and analyze the signal of TRITIUM-Aveiro 0 prototype.

First, each PMT signal is introduced in a preamplifier model CR111 from CREMAT Inc. company [Inc], which is used to shape and preamplify the signal. To reduce electronic noise and signal loss, both preamplifiers are connected as close as possible to the PMTs and they are located inside of aluminum boxes which act like a Faraday cage.

Each preamplifier is followed by a differentiation stage, which is used to reduce the time width of the signal, and amplification stages, used to amplify the signal. The amplification used is the model OPA656 from Texas Instruments [Ins15].

Then, a fast comparator, model LT111 from Linear Technology company [Tec], is used to set a threshold which will be used to remove the PMT signals whose amplitude are below this value (dark counts of the PMT). A MAX5500 DAC is used to configure the thresholds.

The time width of the preamplifier output signal is too large, $200 \mu\text{s}$, with which too many false coincidence will be registered. To solve this problem a second differentiation stage is included and a second comparator are added to produce a 5V square signal again.

Finally a tunable pulse stretcher based on an OR gate, model SN74AHC1

from Texas Instruments company [Ins17], is used to set the time width of each signal at 100 ns, with which the time coincidence windows of our adquisition system is 200 ns, narrow enough to have a negligible false coincidence rate.

In the remaining line, used for the veto signal, an inverter is used in the first stage. With it, the signal will always be in the high level, 5 V, except when a cosmic particle is detected, in which case the signal will be in the low level, 0 V. Then, another stretcher is used to create a signal with the same time width than the others, 100 ns.

Lastly, these three signals are introduced into a 3-input AND gate, model SN74LVC1G11 from Texas Instruments company [Ins16], to perform a logic level comparison. With this last stage we achieve a temporal coincidence of both PMT signals of the prototype and anti-coincidence of them with the veto signal. The output signal of this last stage is simply connected to a pulse counter.

A GPIO pins of a Raspberry Pi is used to communication with the system, control it and configure the different threshold levels. A graphical user interface, which is shown in Figure D.3, was developed to manage the counter system in a comfortable way.

In addition to count, which is the option normally used in our detector, this electronic system include a voltage follower circuit connected to the preamplifier output signal which can be used to obtain a energy spectrum of each PMT of the prototype.

It is important to note that, although this system has a graphical user interface that allows comfortable control of the system, the usual way in which it is controlled is remotely through the computer terminal.

In Figure D.4 two screenshots are shown to demostrate two different situations of this system. There, we have four different signals. The yellow and cyan signal are input signals of the AND-Gate, which come from the PMT signals of the prototype. The pink signal is the third remaining input signal of the AND-Gate, which come from the PMT

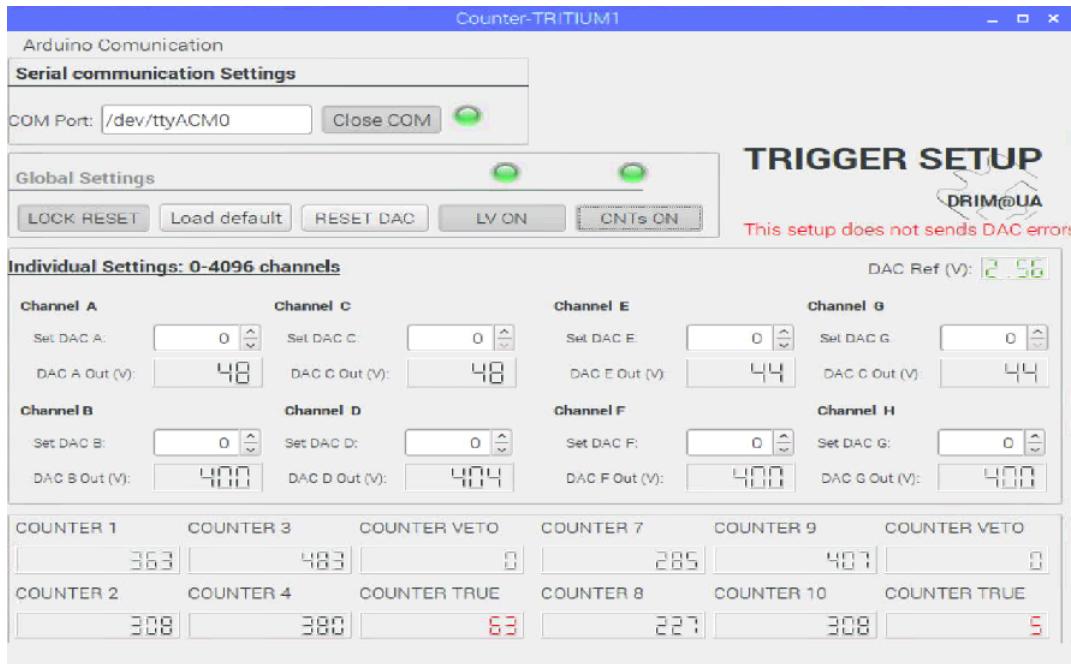
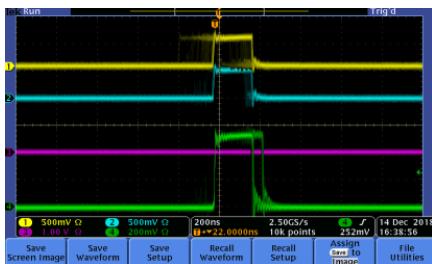


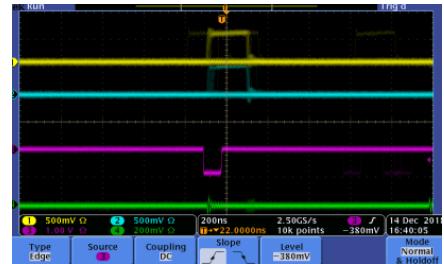
Figure D.3 – Graphical user interface used to manage the counter system.

signal of the veto. The last signal, green, is the output signal of the AND-Gate.

As can be seen, in Figure D.4a both PMTs of the prototype have detect a time coincident event, which has not been detected for the veto, so this event is counted. In Figure D.4b, a time coincidence event has been observed in the three PMTs, which means that it is a cosmic event, so this event is not counted.



(a) Event accepted by the electronic system.



(b) Event rejected by the electronic system.

Figure D.4 – Two different situations of the electronic chain response. A.- Event accepted since veto has not detected it. B.- Event rejected since veto has detected it.

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