

Testing silicon photomultipliers with vacuum-ultraviolet light for nEXO.

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Abstract

In this thesis, an optical cryostat was developed to support SiPM testing infrastructure for the next-generation double beta decay experiment nEXO. The optical cryostat uses two orthogonal linear rails to position vacuum-ultraviolet (VUV) light sources over a custom large-area viewport. Light is projected into the cryostat through the viewport, and onto SiPMs that have been cooled to 165 K, which is the temperature of liquid xenon (LXe). The optical cryostat was used to characterize SiPMs using dynamic and static measurements, and to study ionization damage of cryogenic SiPMs from VUV light. A current-voltage multiplexer was developed to simplify bulk-testing of cryogenic SiPMs, allowing up to 105 SiPMs to be tested with a single Arduino module. This work informs validation protocols of nEXO's photosensors. The nEXO photodetection system uses $\sim 4.5 \text{ m}^2$ of silicon photomultipliers (SiPMs) to detect the vacuum-ultraviolet (VUV) scintillation light from LXe. The individual SiPMs for the nEXO photodetection system are $\sim 1 \text{ cm}^2$ in area, so efficient methods are required to test $\sim 45,000$ SiPMs prior to assembling the detector.

nEXO is next-generation neutrinoless double beta decay experiment based on a monolithic single-phase time-projection chamber using 5 tonnes of LXe, enriched to $\sim 90\%$ in Xe-136. Neutrinoless double beta decay is a hypothetical nuclear decay that would necessarily imply a neutrino-antineutrino transition. An observation of neutrinoless double beta decay would represent new physics in the form of a Majorana mass term and lepton number violation.

Résumé

Dans cette thèse, un cryostat optique a été développé pour soutenir l'infrastructure de test des SiPM pour l'expérience de désintégration double bêta de nouvelle génération nEXO. Le cryostat optique utilise deux rails linéaires orthogonaux pour positionner des sources de lumière dans le vide et l'ultraviolet (VUV) au-dessus d'une fenêtre de visualisation personnalisée à grande surface. La lumière est projetée dans le cryostat à travers la fenêtre de visualisation et sur des SiPMs qui ont été refroidis à 165 K, qui est la température du LXe. Le cryostat optique a été utilisé pour caractériser les SiPMs à l'aide de mesures dynamiques et statiques, et pour étudier les dommages d'ionisation des SiPMs cryogéniques causés par la lumière VUV. Un multiplexeur courant-tension a été développé pour simplifier les tests en masse des SiPMs cryogéniques, permettant de tester jusqu'à 105 SiPMs avec un seul module Arduino. Ces travaux alimentent les protocoles de validation des photodétecteurs de nEXO. Le système de photodétection nEXO utilise 4,5 m² de photomultiplicateurs au silicium (SiPMs) pour détecter la lumière de scintillation dans le vide et l'ultraviolet (VUV) provenant du LXe. Les SiPMs individuels du système de photodétection de nEXO ont une surface de $\sim 1 \text{ cm}^2$, des méthodes efficaces sont donc nécessaires pour tester $\sim 45\,000$ photomultiplicateurs avant d'assembler le détecteur.

nEXO est une expérience de désintégration double bêta sans neutrino de nouvelle génération, basée sur une chambre de projection temporelle monolithique monophasée utilisant 5 tonnes de LXe, enrichi à $\sim 90\%$ en Xe-136. La désintégration double bêta sans neutrino est une désintégration nucléaire hypothétique qui impliquerait nécessairement une transition neutrino-antineutrino. Une observation de la désintégration double bêta sans neutrino représenterait une nouvelle physique sous la forme d'un terme de masse de Majorana et d'une violation du nombre de leptons.

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Contribution of the Author

This statement is to certify that the works presented in this document are original and my own, with any contributions acknowledged herein. I designed and tested the optical cryostat. The linear rail system was developed by Soud Al Kharusi, Megan Cvitan, Chloe Gingras, Thomas McElroy, and Xiao Shang, and the xenon scintillation light source was developed by Sebastian Eppelt. Otherwise, I developed and tested the vacuum-ultraviolet optical system. The data acquisition system for dynamic measurements with the VX2740 digitizer was developed by David Gallacher. The IV multiplexer was designed by Eamon Egan. The control program for the Keysight Electrometer was developed by Marc-Andre Leclerc. All the measurements and analysis presented in Sections 4, 5, and 6 were completed by me.

Lucas Darroch

Contents

1	Introduction	2
2	Neutrinos	4
2.1	The Standard Model of Particle Physics	4
2.2	Neutrino Interactions	4
2.3	Neutrino Oscillations	7
2.4	Neutrino Mass	9
2.5	Neutrinoless Double Beta Decay	12
2.6	Experimental Searches for Neutrinoless Double Beta Decay	13
3	nEXO	18
3.1	EXO-200	18
3.2	nEXO and the Search for $0\nu\beta\beta$ in LXe	23
3.3	The nEXO Photodetection System	27
4	An Optical Cryostat for Testing SiPMs with Vacuum-Ultraviolet Light	32
4.1	Introduction	32
4.2	Cryostat Design	34
4.2.1	Vacuum Chamber	35
4.2.2	Cryostat	36
4.2.3	Cold Plate	39
4.3	VUV Optical System	40
4.3.1	VUV Viewport	40
4.3.2	Linear Rail System	42
4.3.3	Dark Box	43
4.3.4	VUV Light Sources	44
4.4	Measurements	45

4.4.1	Temperature Stability	47
4.4.2	SiPM Measurements	47
5	Ionization Damage of SiPMs from Vacuum-Ultraviolet Light	58
5.1	Introduction	58
5.2	Experimental Setup	59
5.3	Method	61
5.4	Results	66
6	An IV Multiplexer for Automated Testing of Cryogenic SiPMs	73
6.1	Introduction	73
6.2	Design	75
6.2.1	Minimizing Leakage Current	75
6.2.2	Control	77
6.2.3	Device Connectivity	78
6.3	IV-MUX Performance in Vacuum	79
6.3.1	Hardware Setup	79
6.3.2	Measurements	80
6.4	IV and Dynamic Response	81
6.4.1	Hardware Setup	81
6.4.2	Measurements	83
7	Conclusions	92
8	Bibliography	95

List of Figures

2-1	The fundamental particles in the Standard Model of Particle Physics.	5
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2-2	Feynman diagrams of charged current interactions.	6
2-3	Feynman diagrams of neutral current and charged current scattering interactions.	7
2-4	The normal and inverted mass hierarchies for neutrinos [16].	10
2-5	Fermion masses grouped by each generation [11].	13
2-6	Feynman diagrams of double beta-decay and neutrinoless double beta-decay.	14
2-7	The expected electron energy from $\beta\beta$ and $0\nu\beta\beta$ given a relative rate of 10^2	16
3-1	The EXO-200 detector. Figure reproduced reproduced from [44].	20
3-2	Data from an external source calibration with EXO-200. Figure reproduced from [9].	21
3-3	Analysis of the energy spectrum from the complete EXO-200 dataset. Figure reproduced from [31].	22
3-4	A computer rendering of the nEXO cryostat, and the detector installation. Figure reproduced from [9].	25
3-5	A section view of the nEXO TPC. Figure reproduced from [9].	26
3-6	The simulated response of nEXO for 10 years of detector livetime. Figure reproduced from [51].	27
3-7	The projected sensitivity and 3σ discovery potential of nEXO to $0\nu\beta\beta$, and the discovery significance from 10 years of detector livetime. Figure reproduced from [51].	28
3-8	The nEXO photodetector.	31
4-1	Photograph of the Environmental Test Stand cryostat and a computer rendering of a sectioned view.	35
4-2	The custom cold finger flange used to control the cryostat power level.	38
4-3	A photograph of the ETS cold plate.	39
4-4	The Environmental Test Stand optical system.	41
4-5	The custom CaF_2 viewport used for VUV light transmission into the cryostat.	42

4-6	The 172 nm xenon scintillation lamp and the Hamamatsu L11035 xenon flash lamp.	45
4-7	A Hamamatsu VUV4 mini tile mounted onto a custom evaluation PCB, designed for developing additional readout electronics for use with the ETS. . .	46
4-8	The temperature stability of the Environmental Test Stand cryostat.	48
4-9	The IV response for ten SiPMs from the Hamamatsu mini-tile.	49
4-10	A sectioned computer rendering of the scintillation light source illuminating the SiPM mini tile inside of the ETS.	50
4-11	The charge spectrum of a SiPM under xenon scintillation light from the decay of ^{252}Cf	51
4-12	The SPAD capacitance for nine SiPMs from the Hamamatsu mini tile was measured from 163 K to 253 K in increments of 10 K.	52
4-13	The breakdown voltage of ten SiPMs from the mini tile was measured using the IV method from 165 K to 295 K.	53
4-14	The normalised relative spectral irradiance from the xenon flash lamp, with and without 172 nm bandpass filters.	54
4-15	The photodiode current as a function of source position while scanning the beam linearly across the device in both the x- and y-directions.	55
4-16	The light map from raster scanning a beam with radius of $w_x = 1.95$ mm and $w_y = 1.03$ mm across the photodiode, superimposed on a photograph of the photodiode.	57
5-1	The interior of the dark box atop the Environmental Test Stand cryostat. . .	60
5-2	The charge spectrum for both the trigger SiPM and a SiPM on the mini-tile.	62
5-3	The light map of the xenon flash lamp with a single 172 nm bandpass filter, recorded by rastering the flash lamp over the photodiode.	65
5-4	The fission-vetoed charge spectrum of SiPM 8 from the mini-tile at 48 V. . .	66

5-5	The SPE charge, mean number of detections, and the average extra charge as a function of bias voltage and overvoltage for SiPM 8 from the mini-tile. . .	67
5-6	The relative change of the PDE from the baseline measurement to the measurement after a vacuum-ultraviolet light exposure.	68
5-7	The average relative change of the PDE, average extra charge, and the SPE charge.	69
5-8	Secondary pulse distribution for SiPM 8 at 48 V, after a VUV exposure. . .	70
5-9	The DCR as a function of overvoltage after annealing and after irradiation. .	71
5-10	The DCR as a function of time since irradiating the SiPMs.	72
6-1	A annotated photograph of the IV Multiplexer.	76
6-2	A simplified circuit diagram showing the IV Multiplexer.	77
6-3	Hamamatsu SiPMs used for testing the IV Multiplexer.	80
6-4	A comparison of IV measurements using both modes of the IV Multiplexer. .	82
6-5	A schematic of the experimental setup and a simplified electrical diagram. .	84
6-6	The voltage dependence of the dark count rate, measured for all quads of the Hamamatsu VUV4 SiPM.	86
6-7	The voltage dependence of the SPE charge, measured for all quads of the Hamamatsu VUV4 SiPM.	87
6-8	The voltage dependence of the ECF, measured for all quads of the Hamamatsu VUV4 SiPM.	89
6-9	The dark current for each of the quads from the Hamamatsu VUV4 SiPM, as determined by both dynamic and static measurements.	90
6-10	The effective dark count rate for each quadrant of the Hamamatsu VUV4 SiPM, calculated through different methods.	91

List of Tables

2-1	A survey of completed, ongoing, and proposed experiments searching for	
	$0\nu\beta\beta$ [25]	17

List of Acronyms

EXO	Enriched Xenon Observatory
LXe	Liquid xenon
Xe	Xenon
SiPM	Silicon photomultiplier
VUV	Vacuum-ultraviolet light
SM	Standard Model of Particle Physics
EM	Electromagnetic
SNO	Sudbury Neutrino Observatory
PMT	Photomultiplier tube
PMNS	Pontecorvo-Maki-Nakagawa-Sakata
KATRIN	KARlsruhe TRItium Neutrino
$0\nu\beta\beta$	Neutrinoless double beta decay
$\beta\beta$	Double beta decay
TPC	Time-projection chamber
WIPP	Waste Isolation Pilot Plant
LAAPD	Large area avalanche photodiode
SS	Single-site
MS	Multi-site
DNN	Deep neutral network

MC	Monte Carlo
SPAD	Single photon avalanche diode
PTE	Photon transport efficiency
PDE	Photodetection efficiency
2s3p	2-series, 3-parallel
SPE	Single photoelectron
DCR	Dark count rate
ETS	Environmental Test Stand
LN	Liquid nitrogen
MLI	Multi-layer insulation
CF	ConFlat
VCR	Vacuum coupling radiation
SMP	Subminiature push-on
RTD	Resistance temperature detectors
PID	Proportional–integral–derivative
SHV	Safe high voltage
RT	Room temperature
PCB	Printed circuit board
DAQ	Data acquisition system
FWHM	Full-width-half-maximum

IV	Current-voltage
IV-MUX	IV multiplexer
DPST	Dual pole single throw
SMA	Subminiature type A
TTL	Transistor-transistor logic
SLA	Stereolithography
SCPI	Standard Commands for Programmable Instruments
USB	Universal serial bus
UART	universal asynchronous receiver/transmitter
ECF	Excess charge factor
LED	Light emitting diode
NIEL	Non-ionizing energy loss
PKA	Primary knock-on atom
IEL	Ionization energy loss
e-h	Electron-hole
UV	Ultraviolet

1 Introduction

The discovery of neutrino oscillations implies that neutrinos have mass [1–5]. The existence of massive neutrinos raises the question of the mechanism behind their mass generation. The most general Lagrangian for the neutrino mass should include a Dirac and Majorana mass term. If neutrinos have a Majorana mass term, then they are Majorana particles, and there is a direct coupling between particle and antiparticle neutrino states [6, 7]. Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical nuclear decay that would necessarily imply a neutrino-antineutrino coupling. An observation of $0\nu\beta\beta$ would represent new physics in the form of a Majorana mass term and lepton number violation [8].

nEXO is a detector in development by the Enriched Xenon Observatory (EXO) to search for $0\nu\beta\beta$ in ^{136}Xe [9]. The general design of the detector is a 5000 kg monolithic single-phase liquid xenon (LXe) time-projection chamber (TPC), where the xenon is enriched to 90% in ^{136}Xe . The nEXO photodetector will use 4.5 m^2 of silicon photomultipliers (SiPMs) to detect the vacuum-ultraviolet (VUV) scintillation light from LXe. The SiPMs used by nEXO are $\sim 1\text{ cm}^2$ in area, and will be ganged into groups of six, comprising a single channel. The six-device channel will be arranged into tile modules that are assembled onto long staves, which are then placed around the inner walls of the TPC vessel. Efficient methods are required to test $\sim 45,000$ SiPMs before assembling the detector, and long-term stability studies are required to ensure performance is maintained throughout the expected ten year lifetime of the detector.

The nEXO group at McGill University is supporting the development of the nEXO photodetector through SiPM testing infrastructure. An optically transparent cryostat for testing SiPMs with VUV light was built to develop methods for SiPM mass testing, to test nEXO tiles, and to provide long-term stability studies of SiPMs. Exposure to VUV light in cryogenic environments can lead to ionization damage, affecting the longevity and reliability of SiPMs. The optical cryostat was used to study the effects of ionization damage from VUV light on cryogenic SiPMs. Current-voltage (IV) measurements offer a simple method to characterize

SiPMs. An IV multiplexer was developed to facilitate rapid testing and characterization of SiPMs using IV measurements.

The document is organized as follows. A review of neutrino physics is presented in Chapter 2, and the nEXO detector and its technologies are described in Chapter 3. The design of the optical cryostat and commissioning studies are presented in Chapter 4. A study on the effects of ionization damage from VUV light on SiPMs is presented in Chapter 5. The IV multiplexer hardware and characterization tests using SiPMs is presented in Chapter 6. The thesis work is summarized and concluded in Chapter 7.

2 Neutrinos

2.1 The Standard Model of Particle Physics

The Standard Model of Particle Physics (SM) is a scientific theory that uses quantum field theories to describe matter and its interactions at a fundamental level. In the SM, particles correspond to excitations of underlying quantum fields. Particles exist in a superposition over all time-like trajectories between points of interaction, known as vertices. It is at these vertices where the fields interact and particle exchange occurs. The outcomes of these exchanges are governed by local conservation laws, which reflect the symmetries embedded in the SM. The SM incorporates three fundamental forces: the electromagnetic (EM) force, the weak force, and the strong nuclear force. These forces are described by gauge fields that mediate interactions between fermion fields. Each force is associated with a symmetry group - $U(1)$ for the EM force, $SU(2)$ for the weak force, and $SU(3)$ for the strong force - and the corresponding gauge bosons (photons, W and Z bosons, and gluons) act as force carriers. Fermion fields, which are sometimes called matter fields, can be broadly classified by type (lepton or quark) and generation (first, second, or third). Each generation of leptons (and quarks) comes in pairs: the electron and electron neutrino, the muon and the muon neutrino, and the tau and the tau neutrino, which results in six flavors of leptons, and six flavors of quarks (up/down, charm/strange, top/bottom). Figure 2-1 shows the SM particles, grouped by type, generation, and spin. Heavy particles decay into lighter particles, and so the generations of particles are defined by their mass. All stable particles are of the first-generation, as they are the least massive.

2.2 Neutrino Interactions

The neutrino is an electrically neutral particle that interacts with matter only through the weak force and gravity. An interesting feature of the weak force is that the interactions are mediated by the exchange of massive gauge bosons, and as a consequence, result in a

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.2730 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.20 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.70 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$\approx 0.5110 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1776.93 \text{ MeV}/c^2$	$\approx 91.1880 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 0.8 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.3692 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS VECTOR BOSONS
					SCALAR BOSONS

Figure 2-1: The fundamental particles in the SM. The leptons and quarks (fermions) are organized in the left column, by their generation, and the bosons are in the right column. The gauge bosons mediate force exchange and the scalar higgs provides mass. Image reproduced from [10].

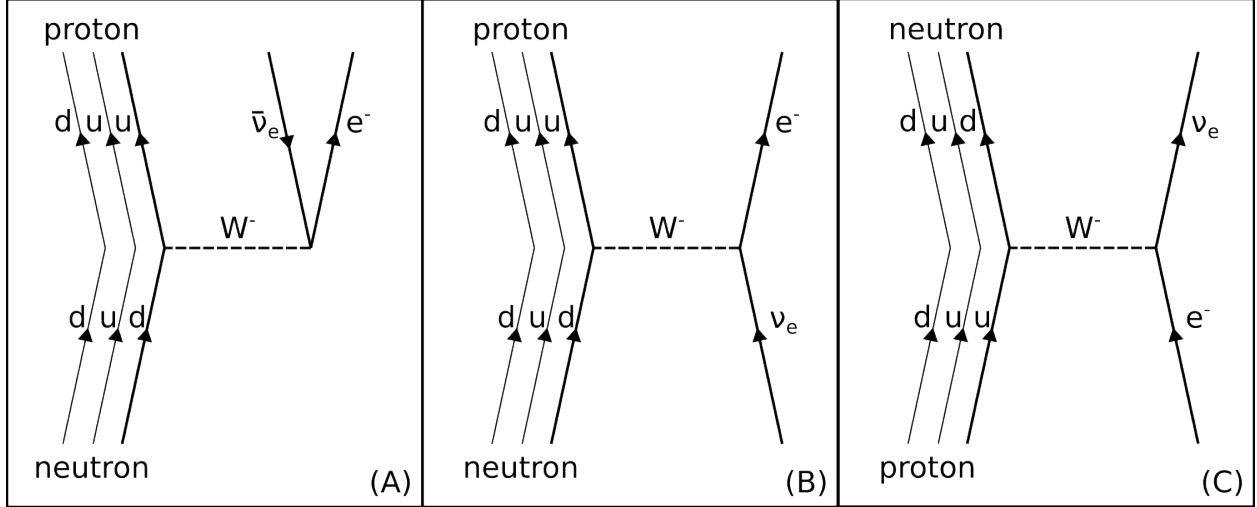


Figure 2-2: Feynman diagrams of charged current interactions. (A) Beta-decay, where a neutron decays into a proton through a down-up flavor change and the emission of an electron and an electron anti-neutrino through the mediator W^- . (B) Inverse beta-decay, where an electron neutrino interacts with a neutron, inducing decay into a proton through a down-up flavor change and the emission of an electron. (C) Electron-capture, where an electron is captured by a proton, inducing a transformation into a neutron through a up-down flavor change and the emission of an electron neutrino.

short range force that is far weaker than the EM or strong force. The relatively low strength of weak interactions means that neutrinos can pass through a significant amount of matter before interacting, which poses challenges for experimental detection. There are two types of weak interactions: charged current interactions and neutral current interactions. In charged current interactions, a neutrino interacts with its corresponding charged lepton through a flavor change. Figure 2-2 shows a Feynman diagram of several charged current interactions involving neutrinos. In neutral current interactions, a neutrino interacts with another particle without changing its flavor. Neutrinos produced in charged current interactions can induce further charged current interactions with leptons of the same generation. This observation motivates the lepton pairing in each generation because of a conserved quantity: lepton flavor number. An important property of neutrinos is their chirality, as weak interactions have an inherently chiral structure: only left-handed neutrinos and right-handed anti-neutrinos participate in weak interactions [11].

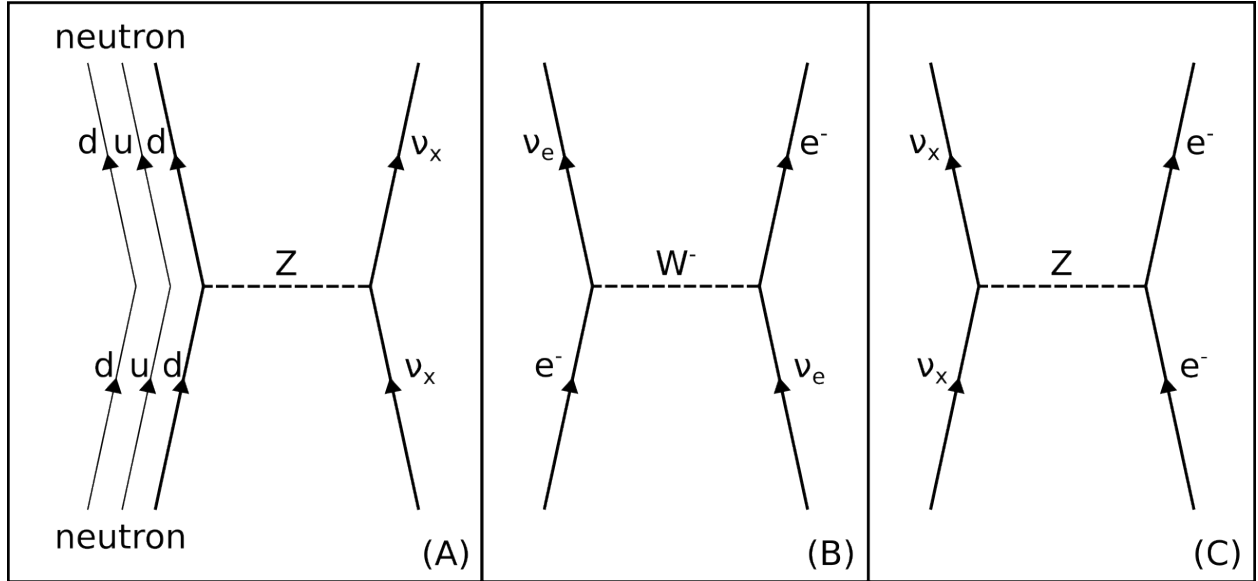


Figure 2-3: Feynman diagrams of neutral current and charged current scattering interactions. (A) Neutron-neutrino scattering, where a neutrino scatters off a neutron through the mediator Z . (B) electron neutrino neutral current scattering, through the mediator Z . (C) electron neutrino charged current scattering, through the mediator W^- .

2.3 Neutrino Oscillations

The Homestake experiment used a neutrino detector designed to measure the solar neutrino flux [12]. The detector was a large tank of perchloroethylene deployed 1500 m underground at the Homestake mine in Lead, South Dakota. Perchloroethylene is rich in chlorine, which has a high natural abundance, $\sim 24\%$, of ^{37}Cl . When an electron neutrino interacts with ^{37}Cl , the nucleus undergoes inverse beta-decay, transforming it to ^{37}Ar . After a period of exposure, ^{37}Ar was removed from the tank to observe the decay of ^{37}Ar back to ^{37}Cl through electron capture. The decay was observed using a small gas proportional counter after aspirating the argon from the tank using helium gas. Stellar dynamic models predicted a specific flux of electron neutrinos emanating from the Sun's fusion process. The experiment measured a total neutrino capture rate per ^{37}Cl atom $\leq 3 \times 10^{-36}\text{s}^{-1}$, which was at least a factor of two lower than what was predicted by the accepted solar dynamic models at the time ($6.2 \times 10^{-36}\text{s}^{-1}$). The discrepancy between theory and experiment would be a long-standing problem in particle physics, known as the solar neutrino problem.

To solve the solar neutrino problem, a detector was developed that would be sensitive to all neutrino flavors. The Sudbury Neutrino Observatory (SNO) experiment was a water Cherenkov detector underground at the Creighton mine near Sudbury, Ontario. The unique feature of SNO was that it was filled with ultrapure heavy water (D_2O), rather than light water. The neutron found in the deuteron has a high cross section for interactions with all flavors of neutrinos, compared to electron neutrino interactions in light water. Figure 2-3 shows a Feynman diagram of neutral current and charged current scattering interactions. Inverse beta decay and electron neutrino scattering both produce a relativistic electron that generates Cherenkov light in heavy water. Neutral current interactions with the deuteron, however, dissociate the deuteron and produce a free neutron. The free neutron thermalizes in the heavy water and is captured by another deuteron, which emits a gamma ray. The emitted gamma ray is likely to Compton scatter, subsequently producing Cherenkov light through a relativistic electron [13]. The heavy water was contained within a spherical acrylic vessel that was surrounded by a geodesic sphere populated with photomultiplier tubes (PMTs). PMT timing and hit patterns from Cherenkov light were used to reconstruct events inside of the heavy water. The sum of the neutrino flux for all neutrino flavors was consistent with the predicted solar neutrino flux, demonstrating that the electron neutrino had changed its flavor state while travelling from the Sun to Earth¹ [2]. The transition between neutrino flavor states is known as a neutrino oscillation, which requires neutrinos to have mass. Neutrino oscillations are modelled using the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [3–5], which expresses the neutrino flavor states ($\nu_\alpha; e, \mu, \tau$) as a superposition of the mass states ($\nu_i; i = 1, 2, 3$):

¹Evidence of neutrino oscillations from atmospheric neutrinos was first observed by the Super-Kamiokande experiment [1].

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}, \quad (1)$$

where ν_1 , ν_2 , and ν_3 are the neutrino mass states, and $U_{\alpha i}$ are the entries of the PMNS matrix. When a pure flavor state is created at a charged current interaction vertex, it can be expressed as a superposition of mass states through Equation 1. The mass states are eigenstates of the free-particle Hamiltonian, and as the superposition propagates, each mass eigenstate gains a phase factor $\exp(-iE_i t)$. Neutrinos are ultra-relativistic particles, so $E_i \approx p + m_i^2/2p$, and the probability for a neutrino to transition from flavor state α to β after propagating some distance L is [14]

$$P(\nu_\alpha \rightarrow \nu_\beta; L) = \left| \sum_i U_{\beta i} \exp\left(-i\frac{\Delta m_{ij}^2 L}{2p}\right) U_{\alpha i}^* \right|^2. \quad (2)$$

2.4 Neutrino Mass

The transition probability between flavor states depends on the entries of the PMNS matrix and the mass-squared differences, $\Delta m_{ij}^2 = m_i^2 - m_j^2$. Neutrino oscillation experiments cannot tell us the absolute mass scale of neutrinos; however, they provide information on the relative mass scale of neutrinos. Oscillation experiments have constrained the relative neutrino mass into two hierarchies: normal, $m_3 > m_2 > m_1$, and inverted, $m_2 > m_1 > m_3$. In either case, the lightest neutrino mass is unconstrained. If the lightest neutrino mass is ~ 0.1 eV, then the mass spectrum is quasi-degenerate, and $m_1 \sim m_2 \sim m_3$ [15]. Figure 2-4 depicts the neutrino mass ordering for normal and inverted mass hierarchy, and the fraction of each flavor state contained in each mass eigenstate [16].

Modern experiments to determine the neutrino mass are done using beta-decay, double

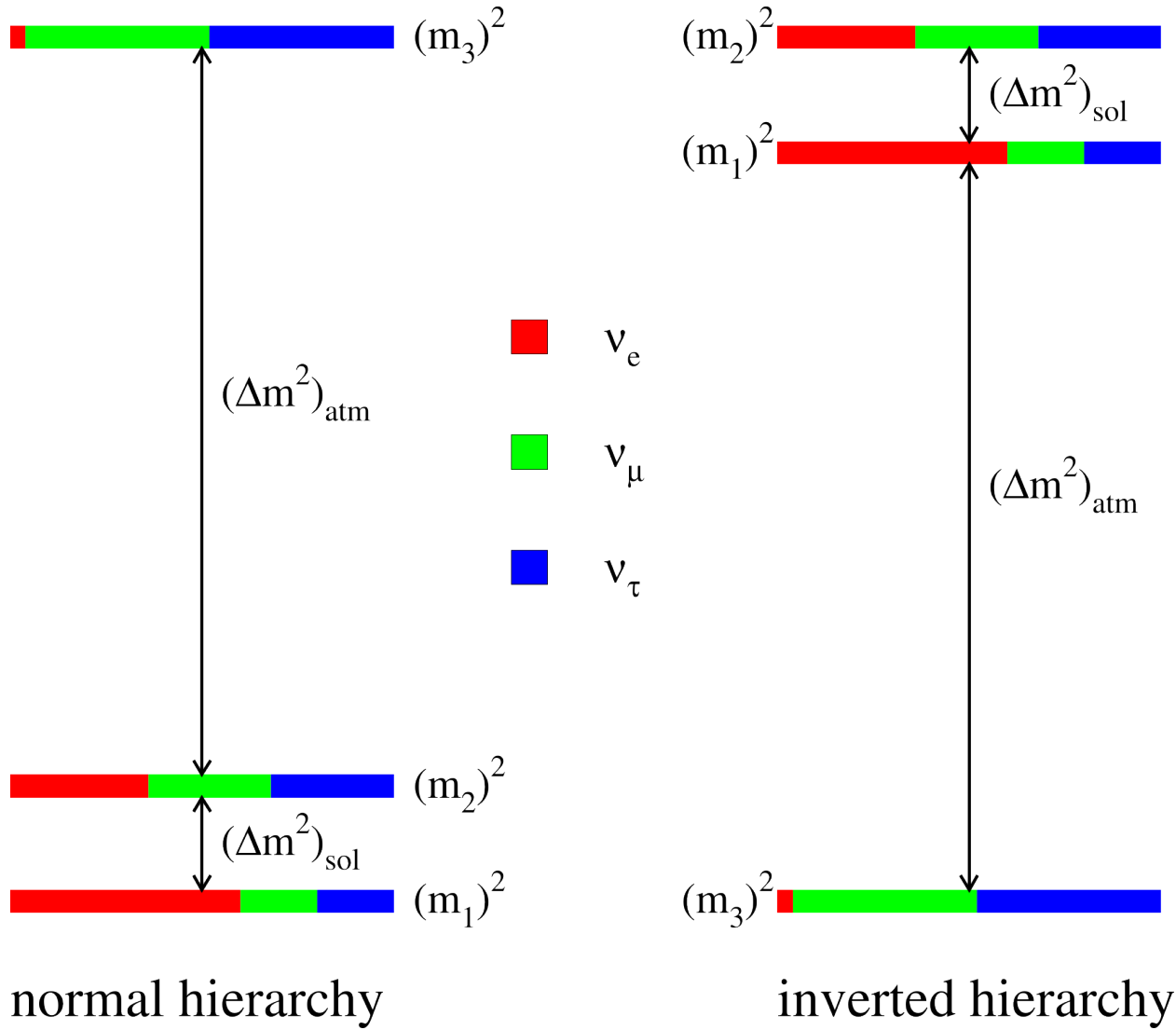


Figure 2-4: The normal (left) and inverted (right) mass hierarchies for neutrinos. The color represents the fraction of each flavor state contained in the mass eigenstates. Figure reproduced from [16].

beta-decay, and cosmological measurements. The Planck collaboration has reported a (model dependent) limit on the sum of the neutrino masses, $\sum_i m_i < 0.12$ eV, through analysis of the cosmic microwave background [17]. More recently, the KArllsruhe TRItium Neutrino (KATRIN) collaboration has reported a limit on the mass of the electron neutrino, $m_\beta < 0.45$ eV, through analysis of the beta-decay spectrum of tritium [18]. KATRIN is an ongoing experiment that has a projected sensitivity of $m_\beta < 0.3$ eV.

Questions regarding the neutrino mass are not limited to its scale and hierarchy. A mechanism is required to generate the neutrino mass, and that has not been discovered. The simplest extension to the SM would be to generate neutrino masses through the Higgs mechanism, similar to the up-quark. In that case, the gauge invariant Dirac mass term for the neutrino is

$$\mathcal{L}_\nu = -m_D (\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R), \quad (3)$$

where $\nu_{L/R}$ are the left- and right-handed chiral neutrino fields, $m_D = \frac{g_\nu v}{\sqrt{2}}$, is the Dirac mass, g_ν is the neutrino coupling to the Higgs field, and v is the vacuum expectation value of the Higgs field [11]. Equation 3 includes right-handed chiral neutrino states, which are excluded in all SM processes, i.e., a Dirac mass requires the existence of *sterile* neutrino states that do not participate in weak interactions. Another mass term arises for Majorana fermions, which are solutions to the Dirac equation that are invariant under charge conjugation. Assuming Majorana fermions, the Majorana mass of the neutrino can be written as

$$\mathcal{L}_M = -\frac{1}{2}M (\nu_R^c \bar{\nu}_R + \bar{\nu}_R \nu_R^c), \quad (4)$$

where M is the Majorana mass, $\nu_R^c = \hat{C}\hat{P}\nu_R$ is a left handed anti neutrino, $\hat{C}$ is the charge conjugation operator, and $\hat{P}$ is the parity operator. The most general Lagrangian that includes right-handed chiral neutrinos will include both a Dirac and Majorana mass term. The Lagrangian can be written as

$$\mathcal{L} = -\frac{1}{2} \begin{bmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{bmatrix} \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \begin{bmatrix} \nu_L^c \\ \nu_R \end{bmatrix}. \quad (5)$$

An interesting feature of Equation 5 is that when $M \gg m_D$, the eigenvalues are M and m_D^2/M , which correspond to heavy and light neutrino states, respectively. This result is the so-called seesaw mechanism, which seeks to explain the relative smallness of the neutrino mass compared to the other fermions [19], as shown in Figure 2-5. In the type-I seesaw model hypothesis, the Dirac mass of the neutrino is of similar magnitude to the other fermions, and the Majorana mass is sufficiently large so that the light neutrino state has a mass consistent with kinematic measurements. There are several seesaw models [20] and, more generally, many models for a Majorana mass term [21]. The seesaw mechanism is an attractive hypothesis to describe the relative smallness of the neutrino mass, however, to date there is no experimental evidence for Majorana neutrinos. A method to search for Majorana neutrinos relies on the direct coupling between particle and antiparticle neutrino states, as shown in Equation 4. A positive signal of a neutrino-antineutrino transition would imply that neutrinos are Majorana particles, i.e., the SM Lagrangian would include Equation 5.

2.5 Neutrinoless Double Beta Decay

Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical nuclear decay that would necessarily imply a neutrino-antineutrino transition. An observation of $0\nu\beta\beta$ would represent new physics in the form of a Majorana mass term and lepton number violation [8]. $0\nu\beta\beta$ is a rare form of double beta decay ($\beta\beta$) where the same neutrino acts as the emitted antineutrino and the absorbed neutrino for two different nuclei through a neutrino-antineutrino transition. $\beta\beta$ is itself a rare decay that occurs when single beta decay is forbidden due to a decrease in binding energy and $\beta\beta$ results in an increase. The effective Majorana mass of the neutrino can be parameterized as

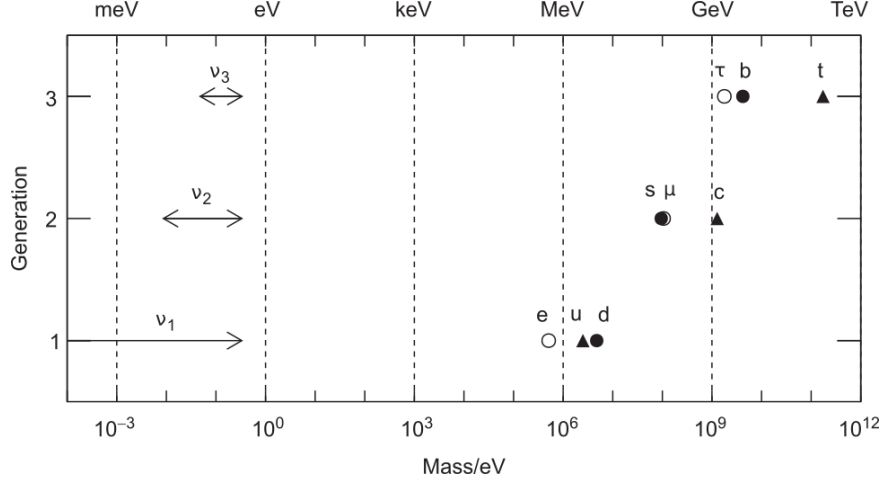


Figure 2-5: Fermion masses grouped by each generation, assuming a normal mass hierarchy for the neutrino. With the exception of neutrinos, fermions of each generation have a similar mass scale. The neutrino masses are ~ 6 orders of magnitude smaller than the other fermions, indicating either a small coupling between the neutrino and the Higgs, or some unknown mechanism for neutrino mass generation. Under the seesaw mechanism hypothesis, the relative smallness of the neutrino masses would be caused by a mixing of a Dirac mass term and a Majorana mass term, where the Dirac mass term is scaled similarly to the other fermions in each generation. Figure reproduced from [11].

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|, \quad (6)$$

and in the case of light Majorana exchange, the half-life is

$$T_{1/2}^{0\nu} = (G |\mathcal{M}|^2 \langle m_{\beta\beta} \rangle^2)^{-1} \approx 10^{27-28} \left(\frac{0.01 \text{ eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \text{ years}. \quad (7)$$

In Equation 7, G is a phase space factor, $\mathcal{M}$ is the nuclear matrix element, and the scale 0.01 eV is chosen for convenience, given the scale of the effective Majorana mass that can be probed in modern $0\nu\beta\beta$ experiments [22]. For a discussion on heavy Majorana exchange, see the reference [21].

2.6 Experimental Searches for Neutrinoless Double Beta Decay

The difficulty in probing rare processes like $0\nu\beta\beta$ lies in controlling the background well enough to detect a signal. Achieving such low backgrounds has required significant improve-

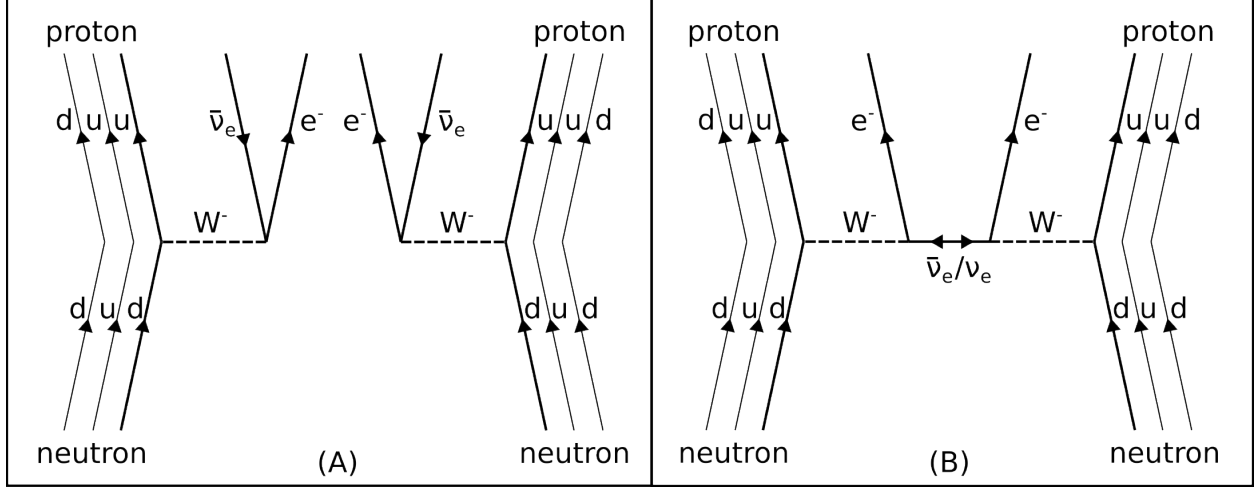


Figure 2-6: Feynman diagrams of $\beta\beta$ and $0\nu\beta\beta$. (A) $2\nu\beta\beta$, a SM process where two neutrons decay simultaneously, emitting two electrons and two electron neutrinos. (B) $0\nu\beta\beta$, a hypothetical nuclear decay where the two neutrinos annihilate due to a particle-antiparticle transition.

ments in detector design and radioactive background control. In $0\nu\beta\beta$, the energy is carried entirely by the electrons and the recoiling nucleus, and since the nuclear recoil is small, the electrons carry kinetic energy equal to the Q-value of the decay. Figure 2-6 shows a Feynman diagram of $0\nu\beta\beta$ and $\beta\beta$. If background events can be controlled well enough, a $0\nu\beta\beta$ signal can be measured by counting excess events at the Q-value of the decay. For radioactive nuclei with half-life $T_{1/2}$, the number of decays after some time t is $N = N_0 \left(1 - \left(\frac{1}{2}\right)^{t/T_{1/2}}\right)$, where $N_0 = N_A \epsilon a M / W$, and N_A is Avagadro's number, ϵ is the detection efficiency, a is the relative abundance of the decaying isotope, M is the total mass, and W is the molar mass. If the event is rare, then the number of decays after some time t can be approximated by

$$N = \log(2) \frac{N_A}{W} \left(\frac{\epsilon a M t}{T_{1/2}} \right). \quad (8)$$

Equation 8 shows that without any backgrounds, the half-life sensitivity $T_{1/2} \propto \epsilon a M t$. In the presence of backgrounds, a signal-to-noise ratio must be specified to quantify the half-life. If the number of counts is equal to the fluctuations in the background, $\sqrt{N_B} = \sqrt{M t B \Delta E}$, where N_B is the number of background counts, B is the background index, in units of

counts/(kg·keV·yr), and ΔE is the detector's energy resolution at the Q-value, then the half-life sensitivity is

$$T_{1/2} = \log(2) \frac{N_A}{W} \left(\epsilon a \sqrt{\frac{Mt}{B\Delta E}} \right), \quad (9)$$

and $T_{1/2} \propto \epsilon a \sqrt{\frac{Mt}{B\Delta E}}$ [23]. Thus, $0\nu\beta\beta$ experiments aim to achieve measurements that are background free to maximize the half-life sensitivity. Equation 9 was derived using Poisson background counts, however, the background counts in a $0\nu\beta\beta$ detector will generally depend on its technology.

Experimental searches for $0\nu\beta\beta$ amount to counting excess events at the Q-value of the decay. Figure 2-7 shows a plot of the electron energy spectrum, normalised by the Q-value of the decay, for $\beta\beta$ and $0\nu\beta\beta$ given a relative rate of 10^2 , and 10^6 in the inlay. Of the candidate isotopes for $0\nu\beta\beta$, only some are suitable for use in a detector. Equation 9 can inform us how to best select candidate isotopes. The observation time is constrained for practical concerns, and the overall detection efficiency is of order unity. The relative abundance of the candidate isotope can significantly impact the cost of the experiment, which excludes certain isotopes for pragmatic considerations. The detector mass, resolution, and background index can vary greatly. Optimizing for mass, resolution, and background index will significantly limit the candidate isotopes and technologies available for building a $0\nu\beta\beta$ detector. Table 2-1 shows a survey of completed, ongoing, and proposed experiments searching for $0\nu\beta\beta$, and their respective isotope of interest, decay half-life limits, and effective Majorana mass [25].

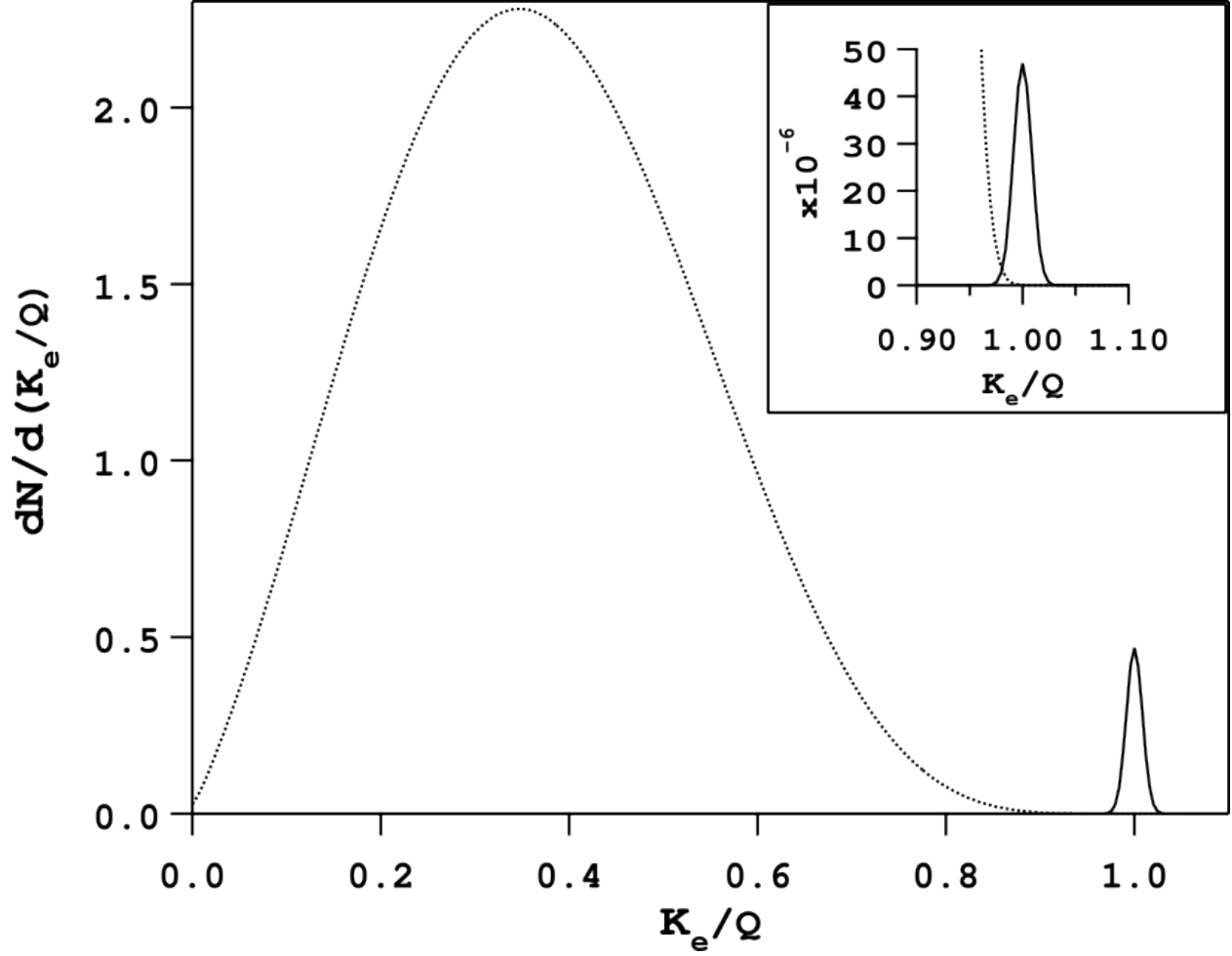


Figure 2-7: The summed electron energy spectrum from $\beta\beta$ and $0\nu\beta\beta$ for a relative rate of 10^2 , and 10^6 in the inlay. The $0\nu\beta\beta$ spectrum is broadened by the resolution of the detector. $\beta\beta$ becomes a background to $0\nu\beta\beta$ when the relative rate of the two processes is sufficiently large compared to the resolution of the detector. Figure reproduced from [24].

Experiment	Status	Isotope	$T_{1/2}^{0\nu}$ (years)	$m_{\beta\beta}$ (meV)
GERDA [26]	completed	^{76}Ge	1.8×10^{26}	79-180
MAJORANA [27]	completed	^{76}Ge	8.5×10^{25}	113-269
LEGEND-200 [28]	taking data	^{76}Ge	1.5×10^{27}	34-78
LEGEND-1000 [28]	proposed	^{76}Ge	8.5×10^{28}	9-21
CDEX-200 ν [29]	proposed	^{76}Ge	3.3×10^{27}	18-43
KamLAND-Zen [30]	taking data	^{136}Xe	2.3×10^{26}	36-156
EXO-200 [31]	completed	^{136}Xe	3.5×10^{25}	93-286
nEXO [32]	proposed	^{136}Xe	1.3×10^{28}	6.1-27
NEXT-100 [33, 34]	construction	^{136}Xe	6.0×10^{25}	80-130
CUORE [35]	taking data	^{130}Te	2.2×10^{25}	90-305
SNO+ [36]	construction	^{130}Te	2.1×10^{26}	37-89
AmoRE-II [37]	proposed	^{100}Mo	5.0×10^{26}	17-29
CUPID-Mo [38]	completed	^{100}Mo	1.8×10^{24}	280-490
CUPID [39]	proposed	^{100}Mo	1.5×10^{27}	10-17
CUPID-0 [40]	completed	^{82}Se	4.6×10^{24}	263-545
SuperNEMO-D [41]	construction	^{82}Se	4.0×10^{24}	260-500
CANDLES-III [42]	taking data	^{48}Ca	5.6×10^{22}	2900-1600

Table 2-1: A table of completed, ongoing and proposed $0\nu\beta\beta$ experiments. The range of $m_{\beta\beta}$ is reported by that experiment and their choice of nuclear matrix elements. Table reproduced from [25].

3 nEXO

The Enriched Xenon Observatory (EXO) is searching for $0\nu\beta\beta$ in the isotope ^{136}Xe using a single-phase liquid xenon (LXe) technology. The feasibility of this approach was demonstrated with the EXO-200 detector, which was operational from 2011 to 2018. This detector discovered the allowed $2\nu\beta\beta$ decay mode in ^{136}Xe [43] and the power to identify and suppress backgrounds based on their multiplicity. Based on the success of EXO-200, a successor experiment is being developed called nEXO. The nEXO detector will be a monolithic single-phase time-projection chamber (TPC) that will search for $0\nu\beta\beta$ in 5 tonnes of LXe, enriched to $\sim 90\%$ in the isotope ^{136}Xe using centrifuges.

3.1 EXO-200

EXO-200 was a single-phase LXe TPC that contained 200 kg of Xe enriched to 80% in ^{136}Xe . The detector consisted of two TPC halves, divided by a shared optically transparent cathode. Figure 3-1 shows a computer rendering of the EXO-200 detector clean room (left) and a schematic of the detector (right) [44, 45]. The detector was installed 660 m underground inside a mine drift at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico. The installation was made from a series of five modular cleanrooms with stringent decontamination procedures between adjacent modules, leading to a class 1000 cleanroom at the detector module. The detector module was surrounded by a cosmic ray veto counter made from plastic scintillator panels, covering five sides. Inside the cleanroom, the copper cryostat was surrounded by lead blocks to shield the interior from gamma radiation. The detector was sealed within the cryostat and maintained at 167 K by immersing it in HFE-7000 refrigerant. The TPC vessel was constructed using specially selected low background copper that had minimal exposure to cosmic radiation. The walls of the detector were optimally designed 1.37 mm thick to minimize backgrounds from the copper vessel while also mechanically supporting a 35 kPa pressure differential between the xenon and the refrigerant. The inside of

the detector was divided into two twin TPCs by an optically transparent cathode wire plane that spanned the middle section. Each end of the TPC had a shielding wire plane and a charge collection wire plane, offset by 6 mm and angled at 60°. The charge collection plane was at virtual ground and the shielding plane was biased to ensure electron transparency. Charge collection signals from the collection plane and induction signals from the shielding plane were combined to reconstruct a projection of the two-dimensional charge cloud from ionizing radiation inside the LXe. Field shaping rings were used along the interior walls of the TPC to ensure a uniform field strength. Each field shaping ring was separated by a 900 M Ω resistor, which was made from thick-film conductive paste adhered to a sapphire substrate. High-voltage was supplied through a delivery conduit welded to the body of the TPC using a solid-core RG217 cable that was connected to a spring-loaded copper receptacle, embedded in a Teflon block. The HV delivery conduit was welded to the outer hatch of the cryostat, about 1.5 m away from the TPC, where it was terminated with a warm seal using a Swagelok compression fitting around the polyethylene dielectric of the cable, which created a He-tight seal. A plane of large area avalanche photodiodes (LAAPD) was installed on either end of the TPC, behind the anode wires. The LAAPDs detect scintillation light from the initial flash of scintillation inside the LXe, which was then used as a start-time for reconstructing the position of the charge cloud, through its drift time. The ionization signal from the drifting charge cloud was attenuated by reactions with electronegative impurities as it drifted inside the detector. The attenuation was corrected by regularly calibrating the average electron lifetime inside the detector. Vacuum-ultraviolet (VUV) reflective Teflon was used to line the interior of the field shaping rings and at either end of the TPC, behind the LAAPD plane, to increase photon transparency. The signal wire plane and LAAPD plane were connected with adhesive-free photo etched polyimide flexible copper clad laminate that was sealed into a copper feedthrough using epoxy. After assembly, bulkheads were welded to either end of the TPC, sealing the detector.

The TPC was filled with liquid xenon enriched to 80.6% in ^{136}Xe [46]. When a double

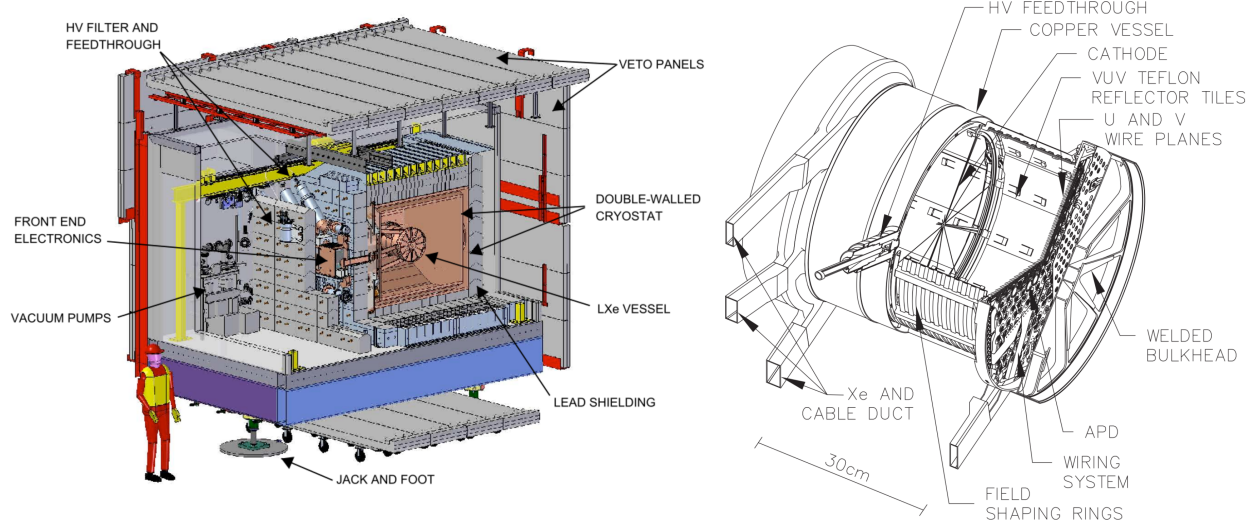


Figure 3-1: Left: A sectioned view of a computer rendering of the EXO-200 detector, which was located inside an amorphous salt mine drift 660 m underground at the Waste Isolation Pilot Plant in Carlsbad, New Mexico. Right: A schematic of the EXO-200 detector. See text for a detailed description. Figures reproduced from [44].

beta-decay occurs, a charge cloud is created by knock-on electrons from the primary beta rays. Both knock-on electrons and xenon ions can excite other xenon atoms, and these excited xenon atoms can form an excimer, which releases a 175 nm photon when it dissociates [47]. The scintillation occurs almost instantly, and the remaining charge was drifted away under the effect of an electric field. Ionization and scintillation are anticorrelated in xenon under an electric field, which means a rotated energy spectrum has improved resolution over the summed energy spectrum [48, 49]. The rotation angle θ is defined by $\tan \theta = E_{scint}/E_{ion}$, and is inversely proportional to the field strength. Figure 3-2 shows data from an external source calibration from EXO-200. A ^{228}Th source was deployed outside the TPC, positioned midway along its length at the location of the cathode plane. The energy calibration used the 2615 keV gamma line from ^{208}Tl decay, a decay product of ^{228}Th , to deposit a known amount of energy inside the TPC, which was also used to determine the average electron lifetime through the drift time.

Figure 3-3 shows a plot of the energy spectrum near the Q-value of $0\nu\beta\beta$ in ^{136}Xe from the complete EXO-200 dataset, collected across two operational phases (Phase-I/II). The single-

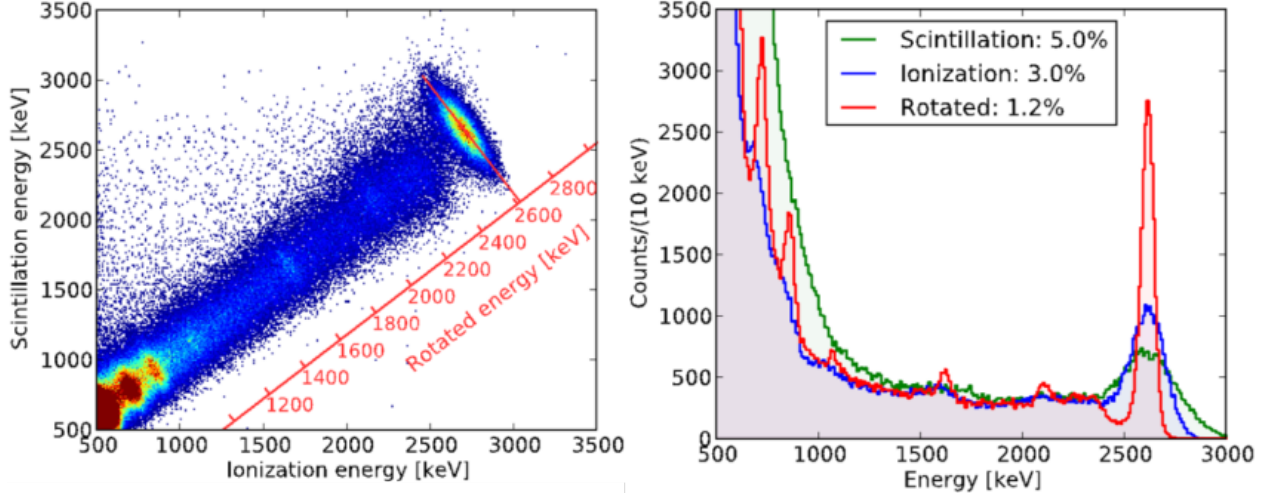


Figure 3-2: Data from an external source calibration with EXO-200. Left: a 2D histogram of the scintillation and ionization energy. A third axes, the rotated energy scale, is inlaid. Right: the projection of the scintillation, ionization, and rotated energy spectrum onto their respective axes. See text for a more detailed description. Figure reproduced from [9].

site (SS) and multi-site (MS) spectra are defined by the topology of energy deposition, which was used to discriminate candidate $\beta\beta$ events (SS) from gamma rays (MS), since gamma rays are likely to Compton scatter. A deep neural network (DNN) discriminator is used to differentiate SS from MS events using data from the charge collection wires. The data was blinded $\pm 2\sigma$ from the Q-value, and later fit using a Monte Carlo (MC) based background model. Maximum likelihood fits were performed to the data, and no statistically significant $0\nu\beta\beta$ signal was observed, resulting in a combined (Phase-I and -II) half-life $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ years, and an upper limit on the effective Majorana mass $\langle m_{\beta\beta} \rangle < (93 - 286)$ meV [31].

EXO-200 was a pilot project to prove the feasibility of a single-phase LXe TPC for measuring $0\nu\beta\beta^2$. LXe has several properties that make it attractive for use in a $0\nu\beta\beta$ detector. These properties and the associated technologies used by nEXO are discussed in the following section.

²One of the goals of EXO-200 was to confirm/deny the positive signal of $0\nu\beta\beta$ reported by the Heidelberg-Moscow double-beta decay experiment [50].

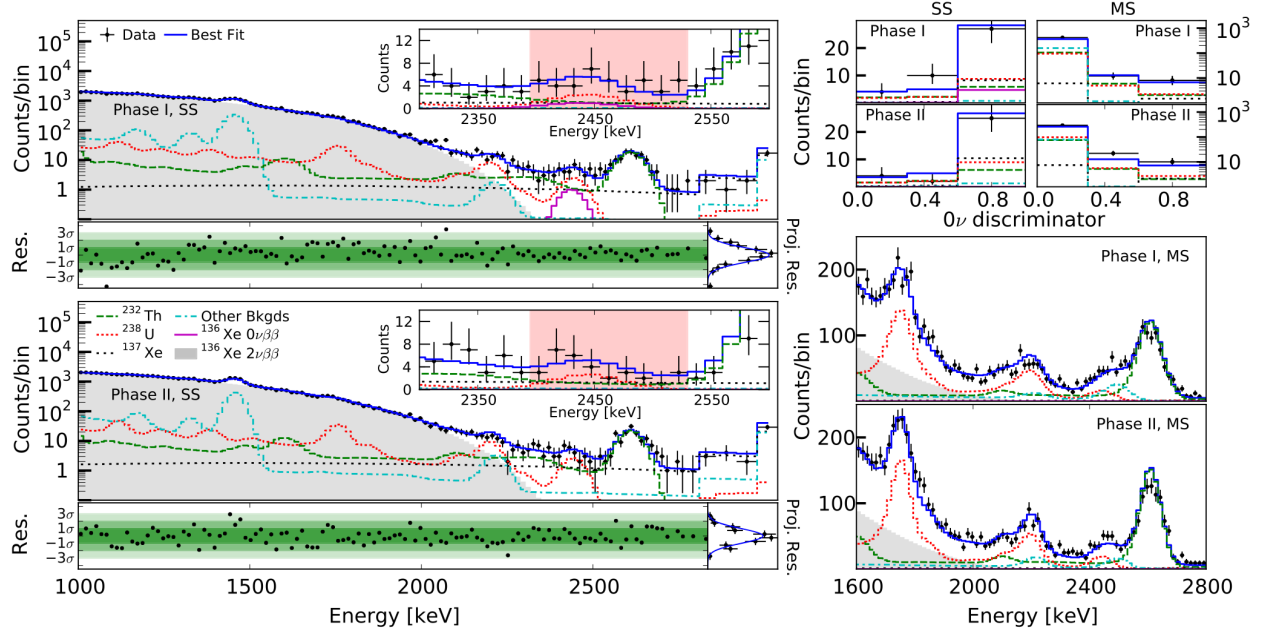


Figure 3-3: Analysis of the SS and MS energy spectrum from the complete EXO-200 dataset. A zoomed-in section around the $0\nu\beta\beta$ Q-value is shown in the inset of the SS plots, and the blinded data $\pm 2\sigma$ from the decay Q-value is highlighted in red. The left panels show the SS energy spectrum, and the lower-right panels show the MS energy spectrum. The results of a DNN discriminator used to differentiate single-site from multi-site are shown in the top right panel. Figure reproduced from [31].

3.2 nEXO and the Search for $0\nu\beta\beta$ in LXe

nEXO builds on the success of EXO-200 with its research and development efforts, which are detailed in a pre-conceptual design report [9] and discussed herein. LXe technology is inherently scalable for a $0\nu\beta\beta$ search because it is a dense noble gas that acts as both the source and detector medium inside the TPC. These factors have the effect that when the detector increases in volume, the background contribution at its center decreases. The three dominant backgrounds for a $0\nu\beta\beta$ search in LXe come from the gamma line at 2448 keV from ^{214}Bi , the gamma line at 2615 keV from ^{208}Tl , and the beta-decay of cosmogenically active ^{137}Xe with a Q-value of 4173 keV. The majority of gamma radiation originates from long-lived and naturally occurring ^{238}U and ^{232}Th inside the copper vessel, and other detector components, which decay to ^{214}Bi and ^{208}Tl , respectively. The attenuation length of 2400 keV gammas in LXe is 8.7 cm, which suggests a region free from external gammas is possible when the diameter of the detector is much larger than the attenuation length. For nEXO, the diameter and length of the TPC vessel are 127.7 cm, which maximizes the ratio of volume to surface area. The center of the TPC is 14.7 attenuation lengths from the TPC walls, and the uniform drift region, which contains 3281 kg of LXe, is 1 attenuation length from the TPC walls [51]. A significant internal background comes from cosmogenically produced ^{137}Xe . ^{137}Xe is produced when muons interacting with materials in the detector and the surrounding environment create spallation neutrons that are captured on ^{136}Xe . nEXO is planned to be located in the Creighton mine at SNOLAB, in Sudbury, Ontario. SNOLAB, 2 km below the Canadian shield, has an overburden of 6010 m of water equivalent shielding, which is nearly 4 times that of WIPP [52]. This additional overburden will significantly reduce the effect of cosmogenic production of ^{137}Xe .

A challenge in LXe detectors is that ^{222}Rn will leach into the system and mix with the LXe. ^{222}Rn has a gamma line at 2448 keV from the decay of ^{214}Bi , which contributes an internal background to the signal. Most internal backgrounds, other than ^{137}Xe , are prevented because the LXe will be continuously purified through an evaporator/getter, then

recondensed and bled back into the detector. However, the amount of ^{222}Rn present in the detector will increase as the detector becomes larger because the detector requires more plumbing, which increases the surface area of the recirculation system. For nEXO, the effects of radon emanation are mitigated by two strategies: screening materials for radon emanation, and removal of radon using an in-line trap. Additionally, daughters from the ^{222}Rn decay chain can be tagged using a Bi-Po veto, which uses space-correlated alpha and beta-decays, with an estimated design efficiency of 40%. Another challenge in scaling the size of the detector is that it generally increases the copper mass of the TPC vessel, which contributes about 3/4 of the total backgrounds at the region of interest. As discussed above, scaling the detector creates a background free region in the inner most volume through self-shielding and is significantly more beneficial than reducing the amount of ^{238}U and ^{232}Th in the TPC vessel for mitigating external backgrounds. However, the nEXO design takes two additional steps to mitigate additional ^{238}U and ^{232}Th when scaling the detector. The first is to replace tensioned anode wires with solid-state charge collection tiles, which reduces the strength requirement of the vessel and therefore the mass contribution from ribs or other mechanical support structures on the copper vessel. The second is by electroforming the copper underground at SNOLAB, which reduces cosmogenic activation and can be done with much higher purity than traditional techniques.

Figure 3-4 shows a computer rendering of the nEXO cryostat, and the detector installation in the Cryopit at SNOLAB. In the conceptual design, the TPC is suspended vertically from the top of an inner cryostat vessel and immersed in HFE refrigerant, likely HFE-7200. The inner cryostat is suspended from an outer cryostat with a carbon structure. The outer vessel is evacuated to moderate vacuum, around 10^{-5} mbar, and lined with superinsulation. The cryostat is suspended using a support structure that is attached to a free-standing platform above the outer detector, which is filled with 1.5 ktonne of ultra-pure water. The outer detector is a water tank that is instrumented with photomultiplier tubes on the inward facing surface that are used to detect and veto cosmic rays. Access to the detector is through the

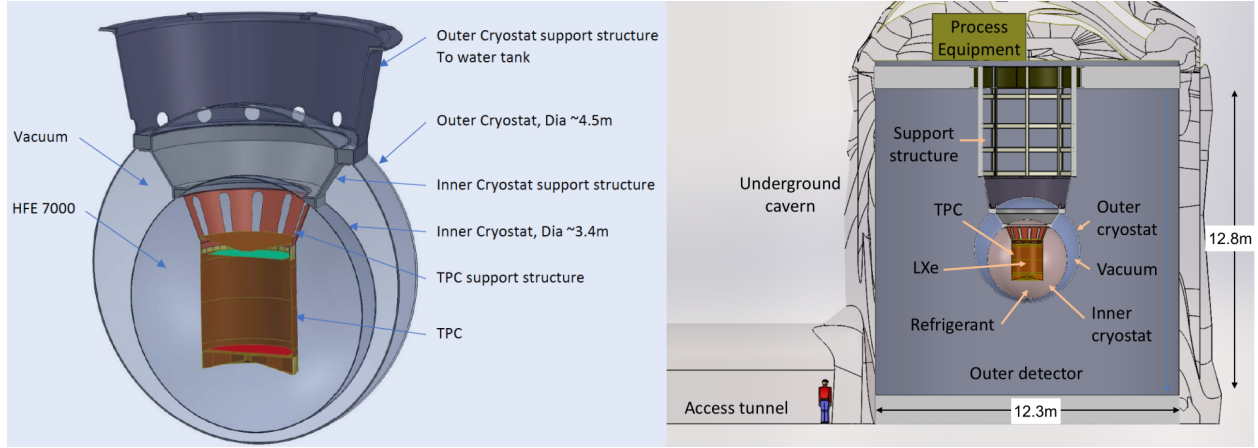


Figure 3-4: A computer rendering of the nEXO cryostat (left), and the detector installation (right). Figure reproduced from [9].

top access tunnel and bottom access doors, where various process equipment is located. The outer detector is adjacent to a lower access tunnel where various support infrastructure is held.

Figure 3-5 shows a sectioned view of the nEXO TPC. The inside of the TPC vessel is a right-angled cylinder with equal diameter and length. The ends of the TPC are structurally reinforced to increase the mechanical strength of the vessel. The fundamental principle of the nEXO detector is the same as the EXO-200 detector, however there are a few alterations. Notably, the TPC uses a single drift volume so that radioactive wires are kept away from the innermost volume of the TPC. The longer drift distance in EXO-200 demands improved xenon purity so that a longer electron lifetime can be achieved. In nEXO, compared to EXO-200, the tensioned wires are replaced by fused-silica charge collection tiles [53, 54], the cathode is replaced by a tensioned copper sheet, and the LAAPDs are replaced with silicon photomultipliers (SiPMs) [55]. The cathode is a thin sheet of copper foil that is about $125\text{ }\mu\text{m}$ thick, aluminized and coated with VUV reflective MgF_2 to prevent oxidization. The cathode is offset by 7.5 cm from the TPC base, and the field shaping rings are offset 2 cm from the copper sheet and from adjacent field shaping rings. Fifty-eight field shaping rings are used to ensure a uniform field strength from the cathode to the anode. The anode is made from modular fused silica charge collection tiles that are glued to a copper backbone, offset 1.9 cm

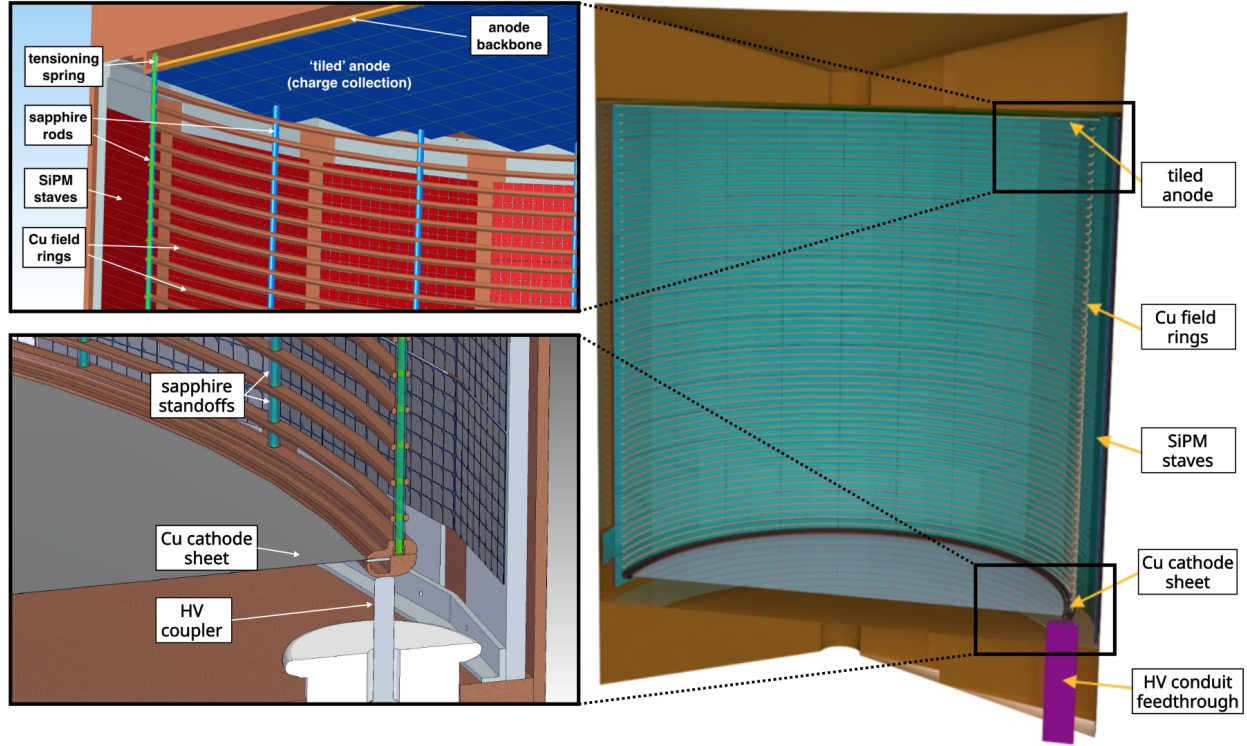


Figure 3-5: A section view of the nEXO TPC (right) with zoomed views of the anode (top-left), cathode (bottom-left), and SiPM staves (top/bottom-left). Figure reproduced from [9].

from the top of the TPC. The anode, cathode, and field shaping rings are connected using 24 sapphire rods, and spaced using 1.6 cm amorphous silicon cylindrical spacers. The electric field is graded by metalization of the amorphous silicon spacers, possibly with palladium. A high-voltage conduit is welded to the TPC vessel and used in a similar fashion as in EXO-200, described above, where the outer jacket is removed and a seal is made around the dielectric material. Arrays of SiPMs are assembled onto 24 long copper staves that are installed on the TPC inner surface, behind the field shaping rings. Both the charge tiles and SiPM staves have in-LXe front-end electronics, and digitized signals are sent outside of the TPC to a data-acquisition system on the free-standing platform.

The sensitivity of nEXO to $0\nu\beta\beta$ was projected for 10 years of nEXO livetime using detailed MC simulations of the detector and background contributions in the energy range from 1000 to 3500 keV [51]. Figure 3-6 shows the simulated detector response with respect to

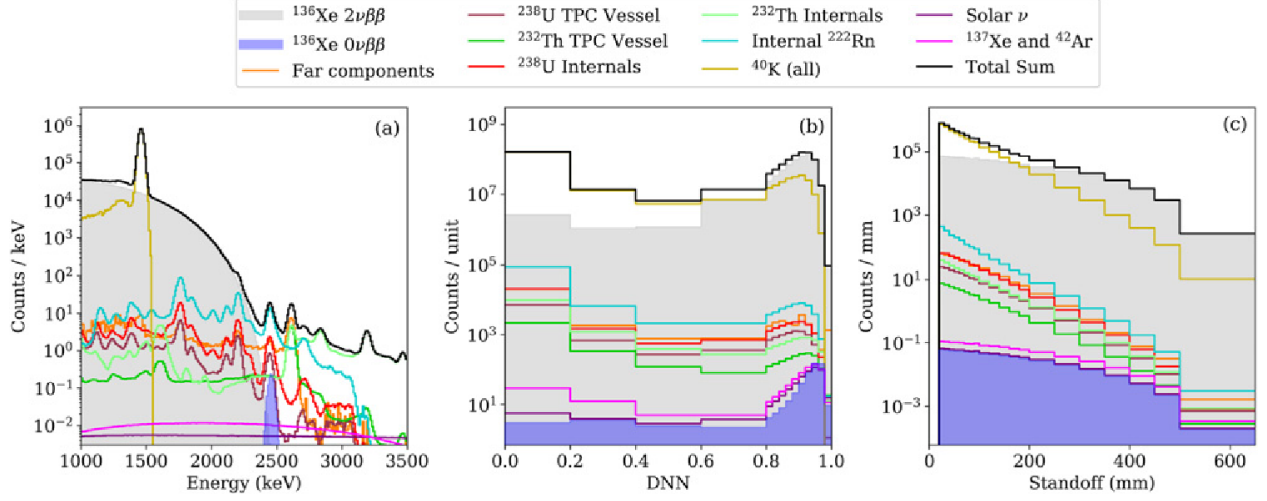


Figure 3-6: The simulated response of nEXO for 10 years of detector livetime. The single-site event energy (left), topology (center), and standoff distance (right) are simultaneously optimized to determine the probability for a $0\nu\beta\beta$ event. Figure reproduced from [51].

energy, a DNN discriminator selecting for event topology, and the distance from the energy deposition to the closest surface. Events within a 2 cm standoff distance to the closest surface were cut. A toy model of all the contributing probability density functions was used to determine the likelihood for the energy deposition event to be a background event. Figure 3-7 shows a plot of the 90% confidence level sensitivity and 3σ discovery potential for nEXO as a function of livetime, and the expected discovery significance as a function of $0\nu\beta\beta$ half-life, respectively. If no signal is discovered after 10 years of nEXO livetime, the median expected exclusion for nEXO is $T_{1/2}^{0\nu} > 1.35 \times 10^{28}$ years at 90% confidence level. The median 3σ discovery potential is $T_{1/2}^{0\nu} > 0.74 \times 10^{28}$ years. The 5σ discovery potential is $T_{1/2}^{0\nu} > 0.38 \times 10^{28}$ years, and $T_{1/2}^{0\nu} = 10^{28}$ years has a 2.4σ discovery potential.

3.3 The nEXO Photodetection System

The nEXO photodetection system uses 4.5 m^2 of SiPMs to detect the scintillation light from LXe. SiPMs are used instead of LAAPDs in nEXO for several reasons. SiPMs are square and can be more tightly packed than round LAAPDs, which is the preferred form-factor for optimum device performance and manufacturing. Additionally, LAAPDs have a large dead space

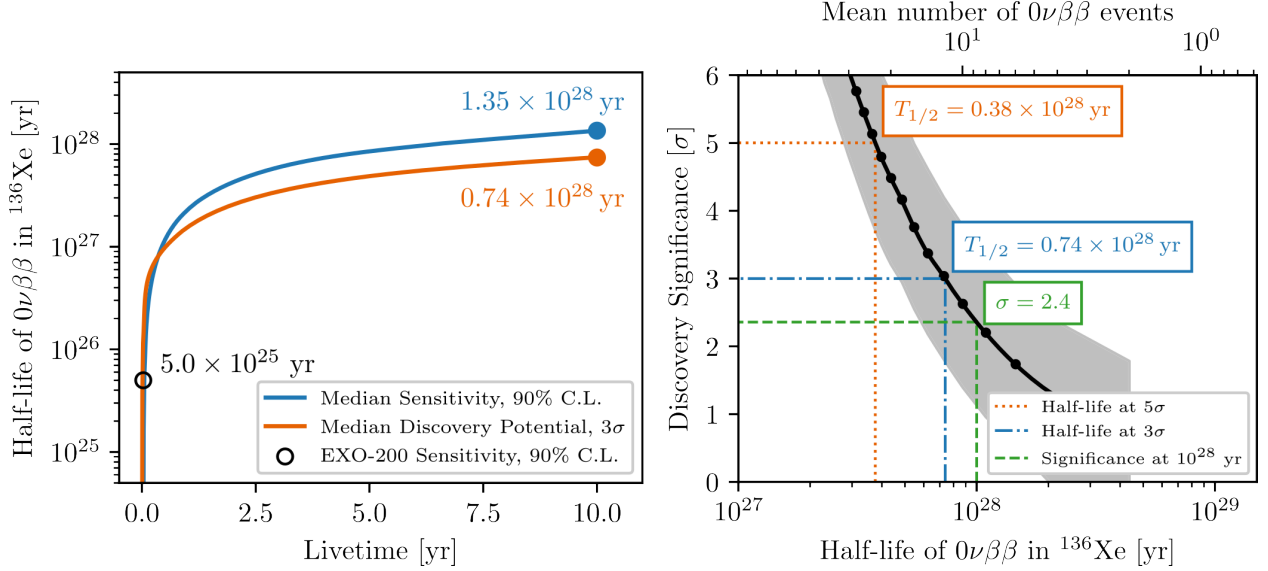


Figure 3-7: Left: the projected sensitivity and 3σ discovery potential of nEXO to $0\nu\beta\beta$. Right: the discovery significance after 10 years of detector livetime as a function of $T_{1/2}^{0\nu}$. Figure reproduced from [51].

around the photosensitive area for the detector package. SiPMs are simpler in construction and thinner than LAAPDs, which reduces the total mass, and thereby the background contribution from a given photosensitive area. One of the most significant improvements is the ratio of the gain to capacitance of the device: LAAPDs have a large capacitance (1 pF/mm^2) and a gain of about 100 [56], whereas SiPMs have a larger capacitance (42 pF/mm^2), but a much larger gain around 10^6 [57].

SiPMs are an array of single-photon avalanche diodes (SPADs) read in parallel as an analog sum. When a photon is absorbed by a SPAD, an electron transitions from the valence band to the conduction band, and is accelerated under the influence of an internal electric field across its p-n junction. Both the electrons and holes multiply through impact ionization, which produces a runaway process that is not affected by the initial number of electron-hole pairs produced in the SPAD. When the avalanche process builds sufficient current, a voltage drop across a resistor reduces the electric field sufficiently that the runaway process is quenched, and the SPAD resets. The relatively large gain-to-capacitance ratio of SiPMs allows the detection of single photons with a resolution better than 10%, which

makes the electronic noise contribution negligible. The most significant noise contribution comes from fluctuations in the scintillation signal. Fluctuations in the scintillation signal are dominated by the photon transport efficiency (PTE), which is the probability of a photon reaching the detector, and the photodetection efficiency (PDE), which is the probability of an incident photon being detected. nEXO requires an overall light detection efficiency of $> 3\%$ to achieve a energy resolution $> 1\%$. The PTE is improved by maximizing the photosensitive area and by using VUV reflective materials inside the detector. The xenon purity requirements prevent the usage of VUV reflective Teflon, such as with EXO-200. When possible, materials inside the detector will be aluminized and coated with VUV reflective MgF_2 , including the cathode, charge collection tiles, and field shaping rings. Research and development is underway to determine coatings for the amorphous silicon spacers that will reach a compromise between VUV reflectivity and resistivity.

Fluctuations in the signal also arise from the dark noise and correlated noise of SiPMs. Dark noise is a process where an electron in a SPAD thermally transitions from the valence band to the conduction band, and triggers an avalanche. For cryogenic SiPMs, the dark noise is naturally suppressed, and a coincident dark avalanche does not significantly contribute to nEXO's signal fluctuation for a $1 \mu\text{s}$ event window. Correlated noise is a process where additional avalanches accompany a initiating avalanche. Correlated noise can be broadly classified as afterpulsing and cross-talk. Afterpulsing occurs in cryogenic SiPMs when a charge carrier becomes trapped by some lattice defect during an avalanche. The trapped charge carrier is in a quasi-stable state, and if it can remain trapped until the SPAD begins to recharge, then it can initiate a partial or full avalanche when it is subsequently released. Cross-talk is a process where a charge carrier crosses a p-n junction and releases a photon after recombination. The released photon can travel to an adjacent SPAD directly, or through total internal reflection, and promptly trigger another avalanche - referred to as internal cross-talk. Cross-talk photons can also escape the SiPM and trigger an avalanche in the SPAD of a different SiPM in the detector, which is referred to as external cross-talk. The performance of

the PDE, dark noise, after-pulsing, and cross-talk have been steadily improving for detecting scintillation light in liquid xenon, and devices from Fondazione Bruno Kessler (FBK) and Hamamatsu both meet the requirements for nEXO's energy resolution [55, 58, 59].

Figure 3-8 shows a computer rendering of the nEXO photodetector. Individual SiPMs that are $\sim 1 \text{ cm}^2$ in area are gain-matched and ganged into channels of six devices in a 2-series, 3-parallel (2s3p) subarray. Each 2s3p channel is laid out on a tile with 96 SiPMs in a 12x8 array. Each SiPM tile has integrated electronics and is assembled onto a long copper stave in a 10x2 tile array. The copper stave is 127 cm long and 19 cm wide, and 24 staves are placed around the inner walls of the TPC vessel, behind the field shaping rings. There are a total of 46,080 individual SiPMs in the nEXO photodetector design. A challenge in building a detector with so many individual SiPMs is bulk testing prior to detector assembly. The design of an optical cryostat for testing SiPM tiles with VUV light is presented in Chapter 4. The optical cryostat was used to evaluate the effects of ionization damage from VUV light on SiPMs, which is presented in Chapter 5. Hardware for rapid testing of SiPMs using current-voltage measurements is described in Chapter 6.

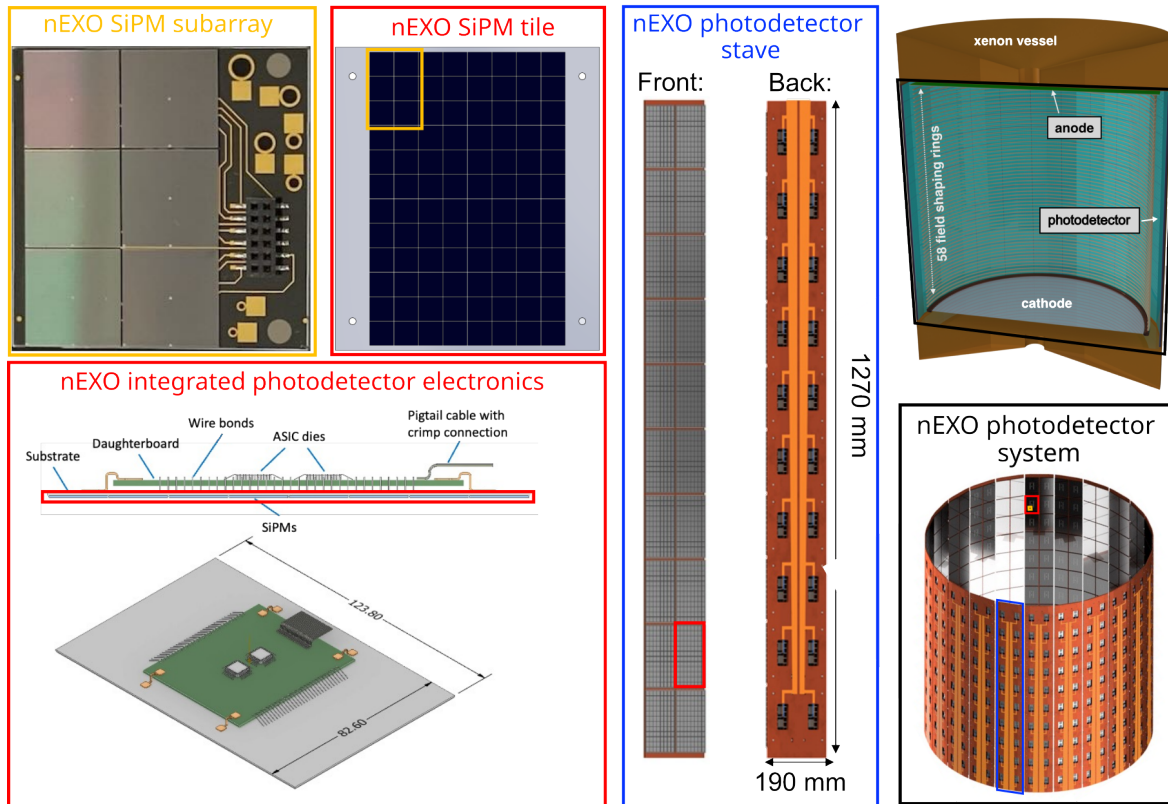


Figure 3-8: The nEXO photodetector. The nEXO TPC is shown in the top right, and a zoomed view for each component is indicated by the color of the bounding box. The nEXO photodetector is shown in black, and is assembled from 24 copper staves. Each stave holds 20 modular SiPM tiles, each with its own front-end electronics. A SiPM tile is assembled from 96 SiPMs, ganged into 16 channels, each in a 2s3p subarray. Images were reproduced from internal nEXO documents.

4 An Optical Cryostat for Testing SiPMs with Vacuum-Ultraviolet Light

4.1 Introduction

Noble liquid/gas detectors are common in searches for dark matter [60], neutrinoless double-beta decay [22], and studying other phenomena in particle-physics experiments [61–63]. The properties that make noble liquids attractive for radiation detection are their chemical inertness, ionization and scintillation yield, good energy resolution, ease of purification, and scalability. The most common noble liquid detectors use either argon or xenon, which scintillate VUV light at 127 nm [64] and 175 nm [47], respectively. Modern developments in photodetection technology have led to the adoption of SiPMs in place of avalanche photodiodes and photomultiplier tubes to detect the scintillation signals in noble liquid/gas detectors. SiPMs are solid-state photodetectors with single-photon resolution, a photodetection efficiency (PDE) of $\sim 25\%$ for xenon scintillation light, and a single photoelectron (SPE) gain of about 10^6 at low voltage [55]. SiPM operational parameters, such as PDE, SPE gain, dark count rate (DCR), and correlated noise, are dependent on the breakdown voltage, which depends on the temperature. Additionally, the DCR and correlated noise are directly dependent on temperature. Therefore, characterization of SiPMs must be conducted at specific cryogenic temperatures, 87.5 K for LAr and 165 K for LXe [65], when the intended application is for a noble liquid detector. Moreover, the temperature-dependent properties of SiPMs can be used to correct signals in noble liquid/gas detectors where temperature control is less precise: the temperature in a noble liquid detector can drift by hundreds of mK depending on how well heat and pressure are regulated [45, 66–68]. Achieving good temperature range and stability in environmental tests requires enclosing the testing stage within a shielded cavity. In systems that achieve sub-mK stability, the cavity is typically immersed in liquid cryogen [69] or nested within several other shielded cavities [70]. Single-cavity systems have achieved sub-mK stability by using a fast control program [71] or thermal dampers [72].

Although these methods provide good temperature range and stability, enclosing the testing stage in a cavity limits the working area and makes access more cumbersome. These challenges are exacerbated for optical characterization measurements where a light beam must be scanned across an area, especially when multiple light sources are used. The difficulties associated with actuating VUV light sources inside a vacuum chamber are addressed by using an unshielded stage with an external optical system and illuminating the devices through a viewport using high-precision actuators [73]. However, an unshielded thermal stage offers worse range and stability than its shielded counterparts. Additionally, using VUV light sources outside a vacuum chamber is challenging because VUV light is absorbed by humidity.

In this chapter, we present the design and performance of an optical cryostat for characterizing SiPMs using VUV light, which we refer to as the Environmental Test Stand (ETS). The design of the cryostat incorporates a large thermal mass and temperature low-pass filters to minimize temperature fluctuations. A sealed dark box and optical table are built around the top of the cryostat, which is purged of humidity using dry nitrogen. The dark box enclosure allows VUV light sources to be scanned across the entire area of the testing stage, a capability that would not be possible with internal sources. The design and features of the cryostat and optical system are described in Chapters 4.2 and 4.3, respectively. Measurements using the optical cryostat with a Hamamatsu S13775-9121 mini-tile are shown in Chapter 4.4.

4.2 Cryostat Design

The cryostat consists of a thermal chain between a liquid nitrogen (LN) containment vessel and a mounting flange at room temperature. The temperature of the sample holder is defined by selecting the relative position along the thermal chain to connect the sample holder. A photograph of the cryostat and a computer rendering are shown in Figure 4-1. LN is transferred into the cryostat containment vessel, where it vaporizes, cooling the cryostat. Heat is conducted along three parallel paths: from the bottom of the containment vessel along the LN plumbing, from the bottom of the vessel through the inner attenuating rings, and from the top of the vessel through the cold finger. The attenuating rings are an assembly of aluminum or stainless-steel spacers and aluminum rings that physically support the cold plate and the suspended containment vessel. The attenuating rings serve a dual purpose: to dampen temperature fluctuations, and to divide the temperature at the testing stage between 77 K and ambient temperature. The aluminum rings are most important in reducing the temperature fluctuations because they increase diffusivity without significantly contributing to the total thermal resistance, which is dominated by the standoffs. The inner and outer attenuating rings are joined by an aluminum plate, which serves as a temperature divider. The total and relative resistances of the attenuating rings are set so that the cryostat can operate up to room temperature with low heating power; however, this limits the range of the cryostat. A copper cold finger is brazed into an insulating flange at the top of the containment vessel and provides a conductive thermal path directly to the dividing plate, which bypasses the inner attenuating rings. This feature enables the cryostat to switch to a high-power cooling mode that activates when the liquid level reaches the cold finger. The high-power cooling mode allows the system to achieve lower temperatures than what is possible when heat is primarily conducted through the inner attenuating rings. In low-power mode, the cryostat can operate from ambient temperature to 220 K, and in high-power mode, from 220 K to 120 K. The plumbing and outer attenuating rings are coupled to a flange at ambient temperature. The radially outward surfaces of the containment vessel and attenuating rings

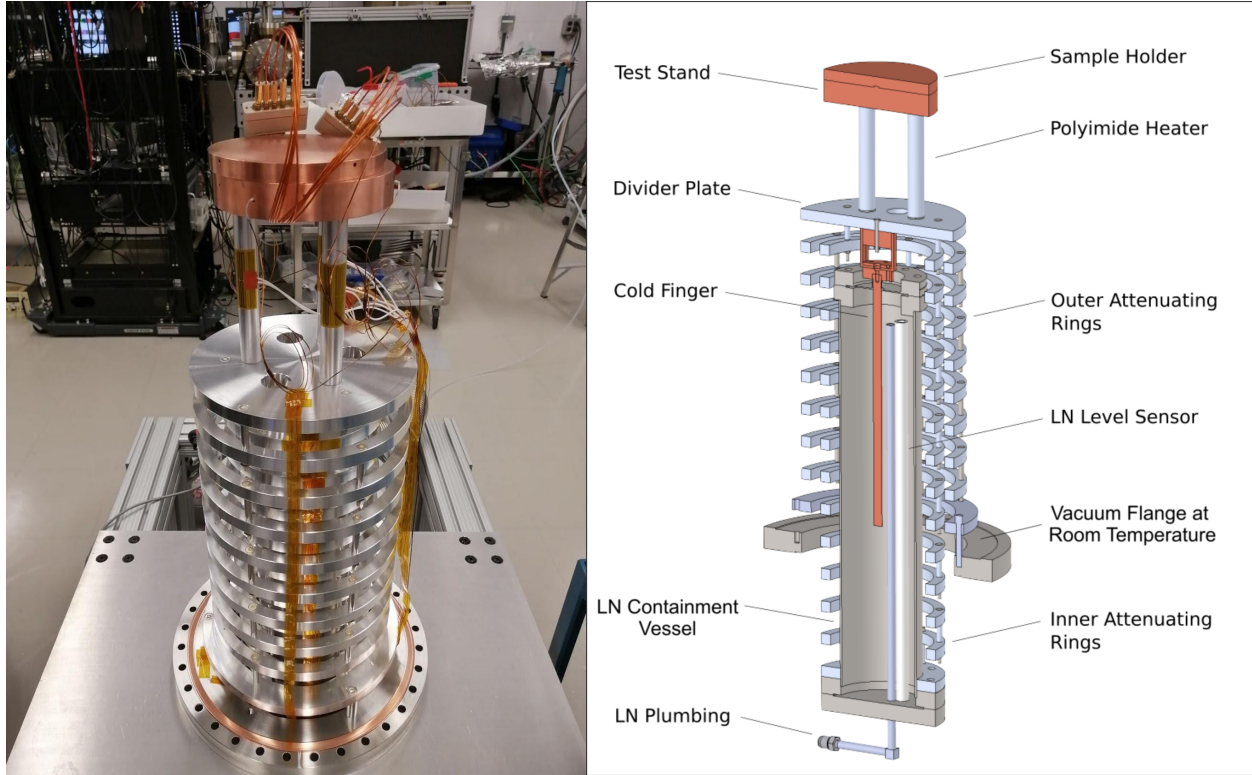


Figure 4-1: Left: Photograph of the ETS cryostat, assembled, but without MLI. Right: A computer rendering of the ETS in a sectioned view. The vaporization of LN cools the containment vessel. The containment vessel is nested within thirty-four temperature attenuating rings, with fourteen inner rings nested inside ten outer rings. An insulated cold finger allows heat to bypass the inner attenuating rings if the LN level is high enough, enabling both high-power and low-power modes of operation.

are wrapped in multi-layer insulation (MLI). The cold plate is a block of copper fixed to the dividing plate using aluminum posts. Both the aluminum posts and the copper cold plate are wrapped in MLI. The design of the cryostat is detailed in the following sections.

4.2.1 Vacuum Chamber

The cryostat is mounted within a DN250CF stainless-steel vacuum chamber [74]. All removable couplings are ConFlat (CF) style and sealed with copper gaskets, except for VCR fittings used for the in-vacuum LN plumbing, and ISO-KF fittings for the backing pump and along the foreline to the turbo-molecular pump, and an indium wire seal for a viewport window. A DN160CF 6-way cube [75] is mounted on top of the vacuum chamber, surrounding

the testing stage. The five remaining ports are used for: (1) access to the testing stage, (2) a removable photodiode sensor, (3) a pressure relief valve to prevent, a nitrogen inlet, and a combined cold-cathode and Pirani vacuum gauge [76] for measuring the vacuum inside the chamber, (4) the viewport, and (5) an additional cantilevered chamber. The cantilevered chamber is attached to a DN160CF octagonal chamber [77] with eight DN35CF ports. The DN35CF ports are equipped with eight 15-channel high-density SMP feedthroughs [78], while the DN160CF port is connected to a DN160CF to DN35CF reducer. Besides providing electrical feedthroughs, the octagonal chamber houses front-end electronics close to the devices under test. The reducer includes electrical feedthroughs for powering and controlling the front-end electronics. The bottom of the vacuum chamber is fitted with feedthroughs for LN supply/return, thermocouples, heaters, and resistance temperature detectors (RTDs), along with a turbo pump backed by a scroll pump. Prior to assembly, the parts were degreased and cleaned with acetone and then ethanol. When size permitted, parts were also ultrasonically cleaned with either solvent.

4.2.2 Cryostat

All components are assembled using silver-plated stainless steel screws and bolts [79]. Spring washers are used to prevent loosening of the nuts due to thermal contraction and expansion. Vented washers or vented screws are used between all mating surfaces to avoid the slow out-gassing of trapped air, i.e., virtual leaks.

The containment vessel is a 610 mm (24 in) long DN100CF half nipple with a DN63CF flange welded to one end of the tube. The top of the containment vessel is sealed with an insulated cold finger, which is a custom DN63CF feedthrough. The inner 3-inch diameter of the flange was milled to a thickness of 1 mm (0.04 in). A butt-lap joint was designed to provide a high strength joint that can withstand extreme temperature cycles. A 9.5 mm (0.375 in) oxygen-free copper rod was brazed into the center using Sil-Fos (Ag5%Cu89%P6%) alloy. The dimensions of the joint are machined to a tolerance of 0.025 mm (0.001 in) to

ensure a high-strength brazed joint. During brazing, the cold finger was elevated above the flange by approximately the same distance as the lap joint, so that the final joint would consist of two butt joints, and one lap joint. The vacuum-end of the cold finger was oversized so that after brazing, the vacuum-side of the cold finger and flange could be remachined for use in vacuum. The cold finger extends 457 mm (18 in) into the containment vessel and has a diameter of 9.5 mm (0.375 in). The thin walls of the milled flange provide thermal insulation between the cold finger and the containment vessel. When the LN level is at or above the rod, the power of the cryostat increases by approximately 5 times. Figure 4-2 shows the insulated cold finger. A LN level sensing rod is constructed from 24 resistors that are equally spaced inside a 480 mm (18.9 in) long Teflon tube. When measured across a voltage divider, the differentiated signal indicates when the fill level drops below a resistor. Additionally, the unsubmerged resistors are sensitive to changes in power when the LN level falls just below the cold finger, due to the reduction in boil-off nitrogen. The signal from the sensing rod is used to regulate the liquid nitrogen level in either high-power or low-power mode. LN supply and gas return feedthroughs are welded into the bottom of the DN100CF flange. These connections are VCR style and are mated to 9.5 mm (0.375 in) outer diameter stainless-steel bellows, which are welded to a feedthrough mounted on the vacuum chamber. The air-side supply line connects to an LN dewar through a solenoid valve and a cryogenic service hose. The air-side exhaust line is equipped with a thermistor to detect over-fill of the containment vessel.

The inner attenuating rings are assembled from 14 layers of aluminum rings, each offset by 25.4 mm (1 in) using aluminum standoffs. The outer attenuating rings are assembled from 10 layers of aluminum rings, each offset by 25.4 mm (1 in) using stainless steel standoffs. The rings are rotated relative to each other by 120° to exaggerate the conductive path. The rings were cut to a height of 12.7 mm (0.5 in) from 203 mm (8 in) and 152 mm (6 in) outer diameter 6061 aluminum tubes with a wall thickness of 12.7 mm (0.5 in) for outer and inner rings, respectively. Temperature is measured at the flange connected to the outer

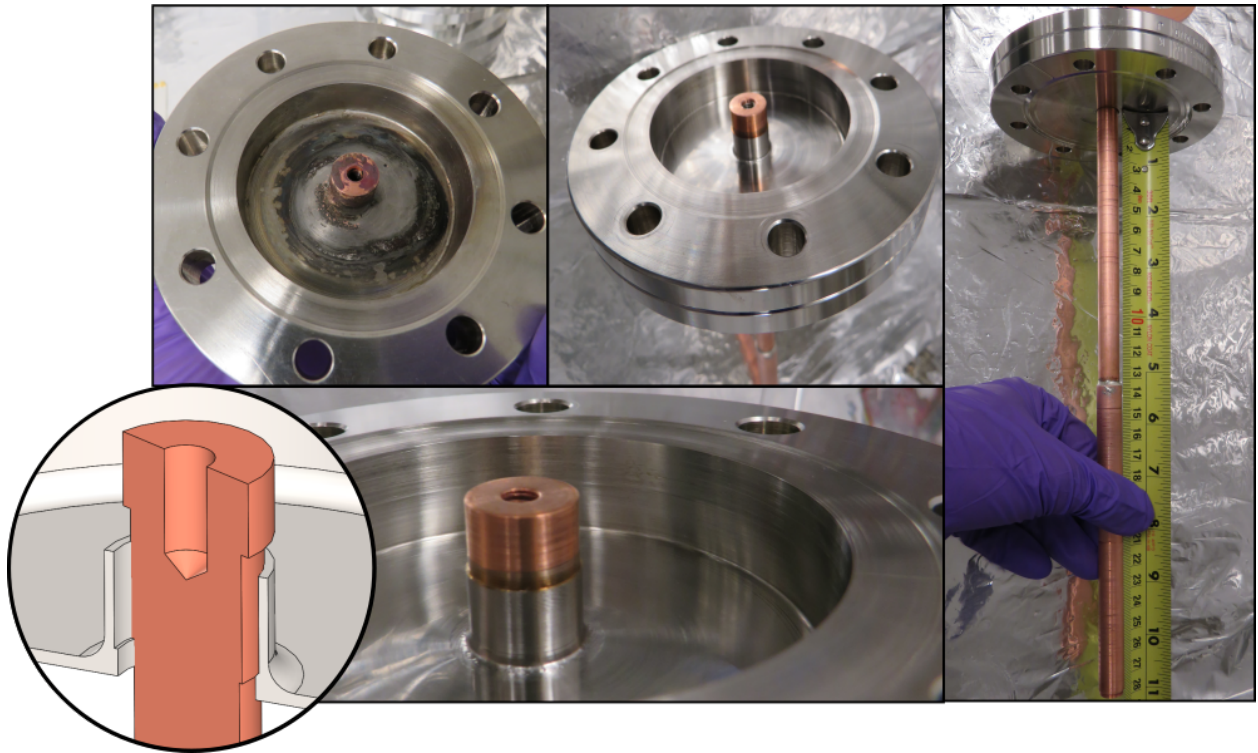


Figure 4-2: The custom cold finger flange used to control cryostat power level. The inner bore of a DN63CF blank flange was milled to a thickness of 1 mm and a 9.5 mm (0.375 in) oxygen-free copper rod was brazed into the center bore using SilFos alloy. The top-left photograph shows the cold finger and flange after brazing, the top-center photograph shows the cold finger and flange after remachining. The right photograph shows the LN side of the cold finger and flange. The cold finger was extended with a copper rod and a dowel joint, soldered using SAC305. The bottom-left photograph shows a zoomed view of the cold finger joint after remachining, and a section view of the joint. Brazing alloy filled the entire channel from the top to the bottom of the joint.

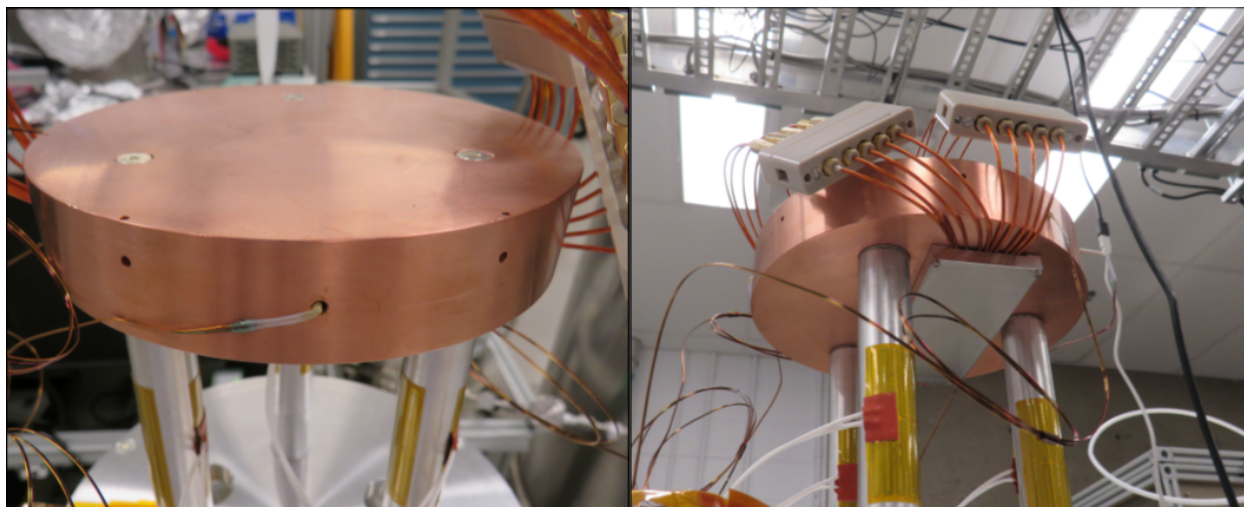


Figure 4-3: Left: The ETS cold plate. Three RTDs are embedded within the cold plate, sealed with Apiezon N vacuum grease. Right: The bottom of the cold plate and the supporting aluminum posts. Three polyimide heaters are mounted on the aluminum posts connecting the cold plate to the aluminum divider plate. Lead cables can be clamped to the bottom of the cold plate before connecting, which cools the cables and reduces heat flux through the sample.

attenuating rings, at the divider plate, and at the top and bottom of the containment vessel using T-type thermocouples.

4.2.3 Cold Plate

Three aluminum posts secure the cold plate to the divider plate. The cold plate is an oxygen-free copper cylinder with a thickness of 51 mm (2 in) and a diameter of 127 mm (5 in). Samples are mounted on a thin copper sample holder, 12.7 mm (0.5 in) thick, placed atop the cold plate. An aluminum plate is used to clamp lead wires to the bottom of the cold plate to prevent local warming of the sample through the cables. Polyimide heaters, attached to each aluminum post, control the cold plate's temperature via a proportional–integral–derivative (PID) control program. Temperature is measured using Pt100 RTDs located at the cold plate and the sample holder.

4.3 VUV Optical System

The VUV optical system is comprised of a two-axis linear rail system used to move and position light sources or other optical elements. The linear rail system is mounted on optical table that is build around a custom CaF_2 viewport. A dark box encloses the optical table, and all interfaces of the dark box and optical table were sealed with silicone and black tape to prevent humidity ingress. Custom 3D-printed feedthroughs panels are used to mount electrical and gas feedthroughs. The dark box is actively purged with dry nitrogen during measurements. Figure 4 shows a photograph of the dark box and VUV optical system. Further details of the optical system are discussed below.

4.3.1 VUV Viewport

The viewport is assembled using a CaF_2 crystal [80] that is sealed using indium wire between the crystal and a custom DN160CF flange. The crystal is 10 mm (0.4 in) thick and 178 mm (7 in) in diameter, and after assembly, the viewport has a 142 mm (5.6 in) diameter active view area. The crystal is pressed into the indium wire using an aluminum clamp, which has a soft gasket between the clamp and the crystal to protect the crystal surface. The crystal has a surface roughness of 40-20 scratch-dig and a transmittance of approximately 88 % at 175 nm. The aluminum clamp is bolted to the flange with twenty 8-32 screws, each tightened to 0.5 N-m (72 oz-in) of torque (approximately 610 N, or 137 lbf, per screw), which results in an applied pressure of about 8.27 MPa (1200 psi) on a wire seal with a diameter of 146 mm (5.75 in) and a width of 1.6 mm (0.063 in). The applied pressure is consistent with an indium wire seal described in the literature [81]. The crystal is supported by a step cut into the flange that must withstand approximately 12200 N (2740 lbf) applied through the clamp and 1600 N (360 lbf) through atmospheric pressure. Static simulations performed with SolidWorks indicate that the minimum factor of safety for the flange under the Von Mises yield criterion is about 5.5. Similar simulations show that the minimum factor of safety for the aluminum clamp is approximately 5.2. The viewport was tested with a helium leak detector, and no

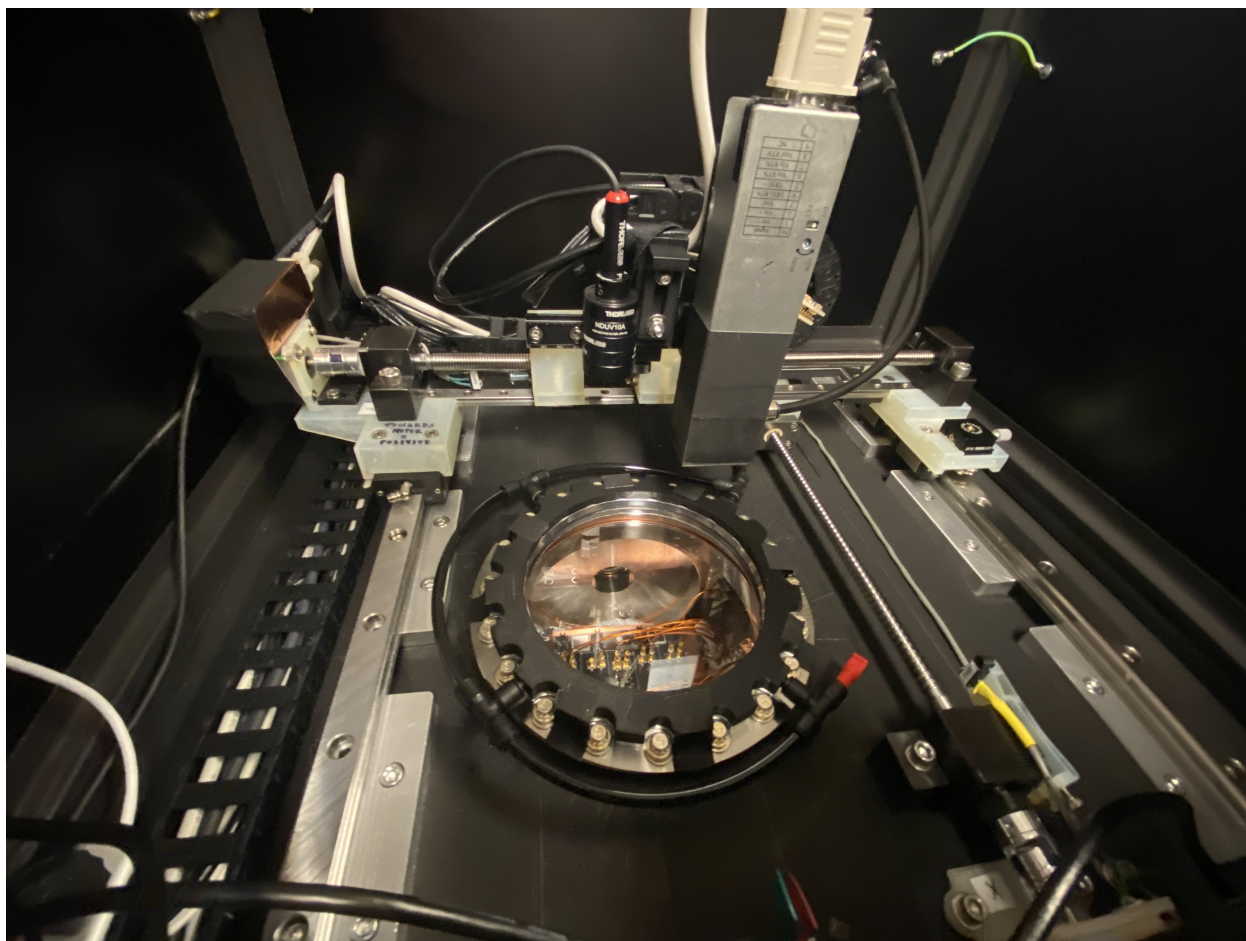


Figure 4-4: The optical rail system atop the ETS cryostat. Two orthogonal linear rail sets are used to move and position the light source in two dimensions above the testing stage. The optical system is contained within a sealed dark box that is purged with dry nitrogen to facilitate VUV light transmission. The interior is painted black to reduce light scattering. A xenon flash lamp is shown mounted on the optical railing, next to a alignment laser.

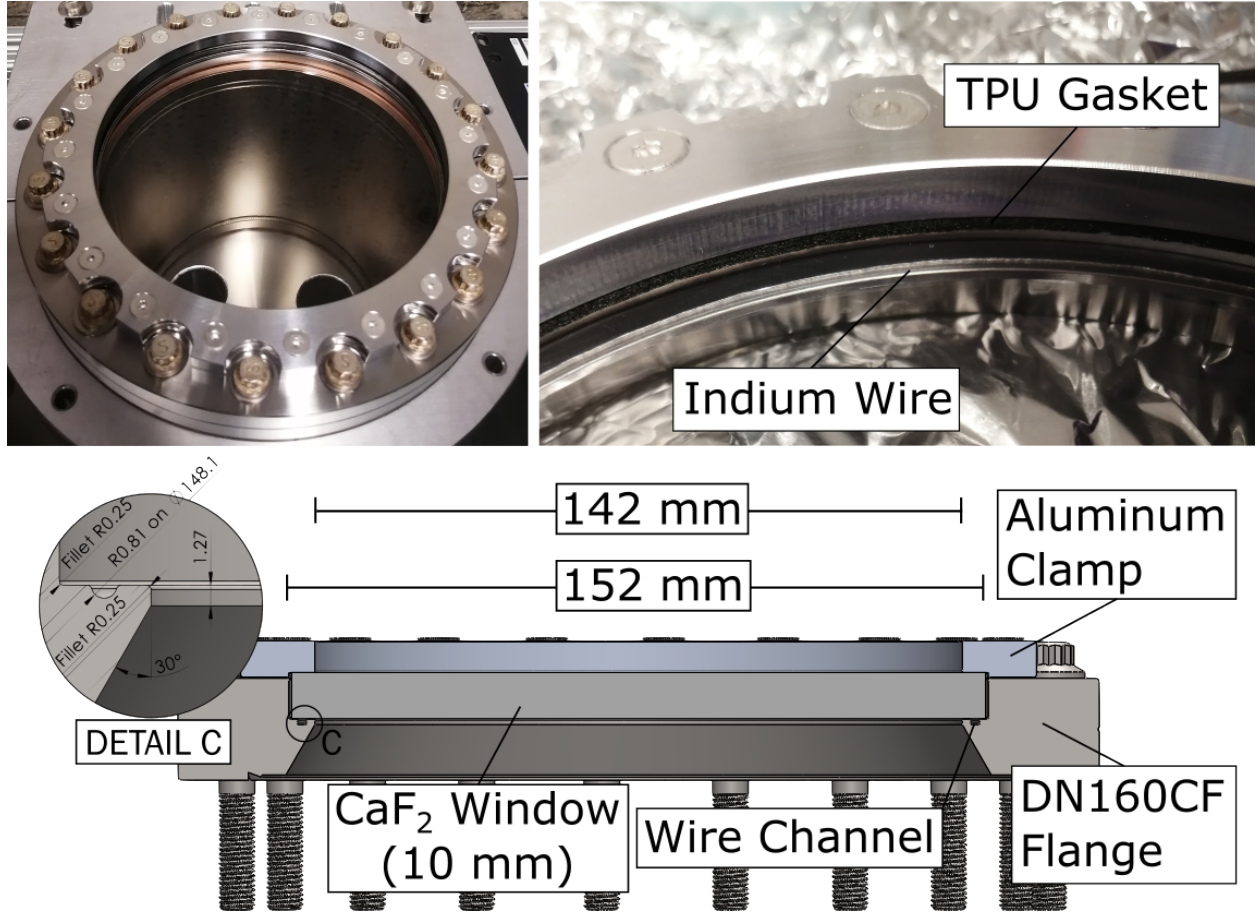


Figure 4-5: The custom CaF₂ viewport used for VUV light transmission into the cryostat. Top-left: A photograph of the viewport on a small vacuum chamber where it was tested. Top-right: A photograph of the interface on either side of the viewport window. Bottom: A sectioned view of the viewport with annotations.

leak was detected down to 10^{-12} torr-l/s. Figure 4-5 shows a photograph of the viewport, the indium seal, and a sectioned view of the viewport.

4.3.2 Linear Rail System

The motorized linear rail system enables two-dimensional movement of light sources across samples within the cryostat. This system uses two HT17-268D-WAA NEMA 17 stepper motors from Applied Motion Products [82] to drive the motion. The motors are coupled to ball screw actuators that move a load across linear guide rails. The gantry moves along the x-direction, while a carriage with a horizontal dovetail railing moves along the y-direction atop

the gantry. The gantry consists of two 3D-printed mounting blocks joined by the y-direction linear guide rail, which is also connected to the ball screw actuator that drives the gantry. The mounting blocks are attached to ball bearing carriages that slide along the x-direction linear guide rails. The carriage consists of two 3D-printed blocks that are attached through a horizontal dovetail railing, both mounted to the y-direction linear guide rail atop the gantry, and driven by a ball screw actuator. The horizontal dovetail rail supports cantilevered optical elements and lamps. Loose cabling from the motors is enclosed in a grounded compartment and connected through shielded D-sub-9 cables. Cable tracks run along both directions of motion, and additional D-sub-9 and coaxial cables for instrumentation are routed to the optical rail. The motors are controlled using a Phidget driver/controller [83] and a custom Python program.

4.3.3 Dark Box

The optical table is sealed on both sides and around the viewport with black aluminum duct tape. An enclosure is constructed using an extruded aluminum frame with aluminum panels filling the frame. The interfaces between frames and panels are sealed with silicone sealant, the joints are sealed with aluminum tape. A closed-cell rubber gasket acts as a face seal between the bottom of the enclosure frame and the optical table. The frame is bolted to the table to compress the gasket. The lid of the dark box is hinged for easy access to the optical system and is also sealed with a rubber gasket.

Electrical connectors are potted in a 3D-printed bulkhead using liquid gasket. The bulkhead is bolted to a pass-through cut from an aluminum panel and similarly sealed with liquid gasket. Boil-off nitrogen gas from the LN supply dewar is continuously fed into the dark box through a gas inlet. The gas is directed to a diffusing cap on the viewport, any light sources, and a reference humidity sensor. Helium or vacuum are typically used to facilitate good VUV transmission, however, gaseous xenon scintillation light (172 nm) is not strongly absorbed by nitrogen, which becomes opaque for wavelengths < 150 nm. A DHT22 humidity

sensor [84] is housed in a small, loosely sealed enclosure that is directly purged with boil-off nitrogen to monitor the stability of the nitrogen supply. A second humidity sensor inside the dark box measures the humidity in the open area. The gas supply is regulated by a solenoid valve controlled by a solid-state relay, which is set to maintain the humidity setpoint inside the dark box.

4.3.4 VUV Light Sources

Two VUV light sources are used inside the dark box: a xenon flash lamp and a custom xenon scintillation lamp. A schematic of the scintillation lamp and the xenon flash lamp is shown in Figure 4-6. The xenon flash lamp is a Hamamatsu L11035 [85] with a 25.4 mm (1 in) retaining ring affixed to the front. A 25.4 mm (1 in) optical tube is attached to the flash lamp and is equipped with filters and other optical elements. The lens tube is vented between each filter, and a 3D-printed enclosure is fitted around the lens tube and sealed at both ends to prevent stray light from escaping. The enclosure is purged directly with nitrogen using the boil-off supply from the inlet. The flash lamp is primarily used for studies requiring higher flux or a beam.

The xenon scintillation lamp is custom-built using a DN35CF 4-way reducer cross with two DN16CF ports. The chamber is sealed with one DN35CF CaF_2 and one MgF_2 viewport [86], a DN16CF 5 kV SHV feedthrough, and a DN16CF pinch-off tube [78]. A custom vented DN16CF double-sided flange is coupled between the chamber and the pinch-off tube, and an aluminum standoff is screwed into it and extends into the center of the chamber. An aluminum disk, electroplated with ^{252}Cf [87], is mounted on the standoff, facing the interior of the chamber. The chamber is filled with 2 bar of xenon and sealed using the pinch-off tube. Xenon scintillation light is produced from the decay of ^{252}Cf . A needle attached to the inner electrode of the SHV feedthrough can be biased to high voltage, providing additional gain for the scintillation light through electroluminescence. Light is emitted from both sides of the chamber through the viewports. One side is aimed into the cryostat, while the other

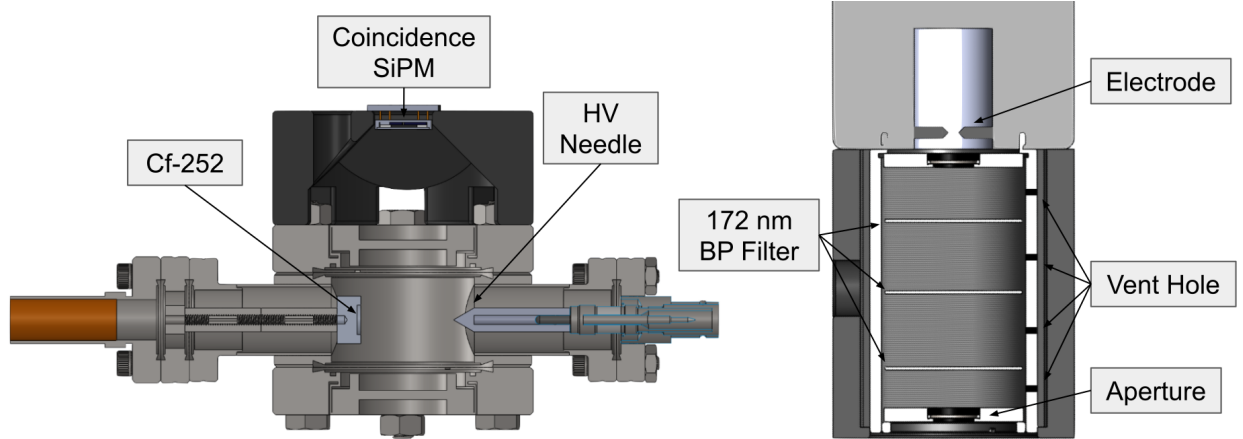


Figure 4-6: Left: The 172 nm xenon scintillation lamp. The chamber is filled with 2 bar gaseous xenon, which scintillates 172 nm light when ^{252}Cf , which is electroplated onto a disk, decays inside of the chamber. A High-voltage electrode is used to increase the amount of 172 nm light through electroluminescence. Right: The Hamamatsu L11035 xenon flash lamp. A vented lens tube is fixed to the front of the flash lamp and is outfitted with 172 nm bandpass filters and pinhole apertures, which are used to create a VUV beam.

side is equipped with a nitrogen-purged 3D-printed enclosure housing a Hamamatsu VUV4 SiPM [88]. All four channels of the SiPM quad are summed and used as a coincidence sensor to trigger the data acquisition system. The coincidence SiPM is positioned close enough to the viewport that even at room temperature, the signal from the alpha decay of ^{252}Cf exceeds the signal from dark counts.

4.4 Measurements

IV and pulse counting measurements were recorded with a Hamamatsu S13775-9121 mini-tile across a temperature range from 163 K to room temperature (RT), in increments of 10 K. A photograph of the mini tile is shown in Figure 4-7. Temperature measurements were taken using a Pt100 RTD, which was embedded in an aluminum lug attached to the front of the printed circuit board (PCB) carrying the mini tile. The RTD has been calibrated with an accuracy of ± 10 mK at 77 K, which increases to ± 22 mK at 300 K, and has a long-term reproducibility of ± 10 mK [89].

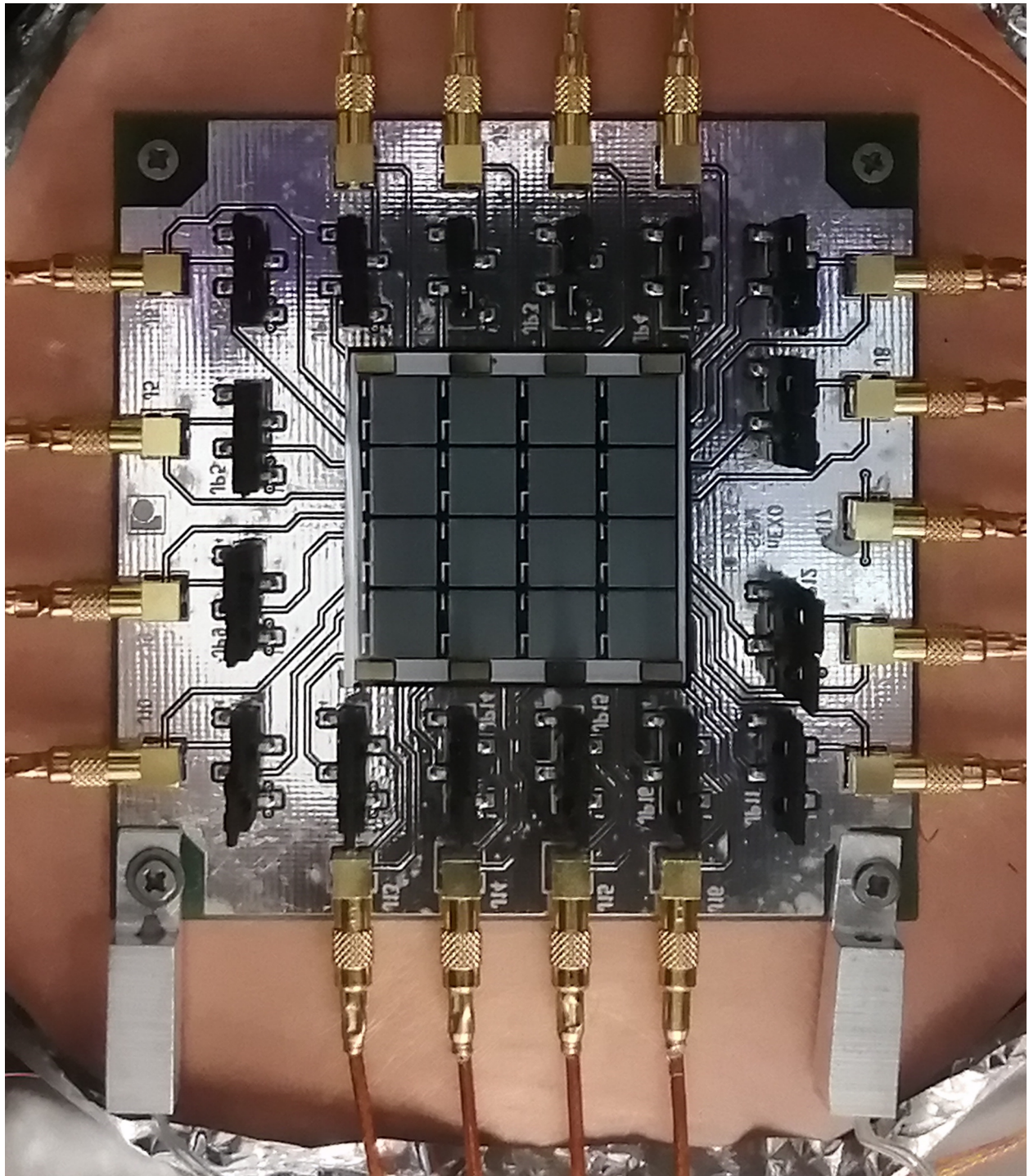


Figure 4-7: A Hamamatsu VUV4 mini tile mounted onto a custom evaluation PCB, designed for developing additional readout electronics for use with the ETS. Two RTDs are embedded in aluminum lugs, which are affixed to the front of the PCB.

4.4.1 Temperature Stability

The RTD temperature was measured using a Lakeshore model 350 Temperature Controller, which has an electronic accuracy of ± 34 mK at 77 K, which increases to ± 140 mK at 300 K [90]. Figure 4-8 shows the temperature and cumulative standard deviation over time for a typical cryogenic cycle in high-power mode at 168 K. After filling the containment vessel, a sudden increase in cooling power causes the temperature to drop by approximately 100 mK and oscillate towards the setpoint before stabilizing. The long-term standard deviation (over 6 hours) is 13.8 mK, while the short-term standard deviation (under 6 hours) improves to 1.6 mK after thirty minutes. A 2 mK temperature shift occurs two hours into the cycle when the liquid level falls below a soldered joint in the cold finger. After this transition, the standard deviation in the temperature for the remainder of the cycle is 1.2 mK, which is similar to the control stability of the Lakeshore controller. In low-power mode, the cryogenic cycle is similar to that in high-power mode, but with two exceptions: the time between fill cycles is 13 hours, and the standard deviation settles to its minimum value immediately after stabilization.

4.4.2 SiPM Measurements

The SiPM current was measured using a Keysight B2987B Electrometer [91] and a custom IV multiplexer that is described in Chapter 6. The multiplexer was housed inside an adjacent 6-way cross, attached to a DN160CF flange. A triaxial cable [92] was used to carry the sensitive current on the air-side, while a Kapton-insulated coaxial cable [93] was used on the vacuum-side. The IV response was measured with the cold-cathode gauge acting as a light source, which facilitated faster data collection at temperatures below 205 K, where the dark count rate is < 100 Hz. Figure 4-9 shows the IV response and relative derivative, which is used to determine the breakdown voltage, for 10 SiPMs from 165 K to room temperature.

The dynamic response of the SiPMs was measured using a Rohde and Schwarz RTO2024 oscilloscope [94]. The signal was amplified with custom electronics and a broadband amplifier

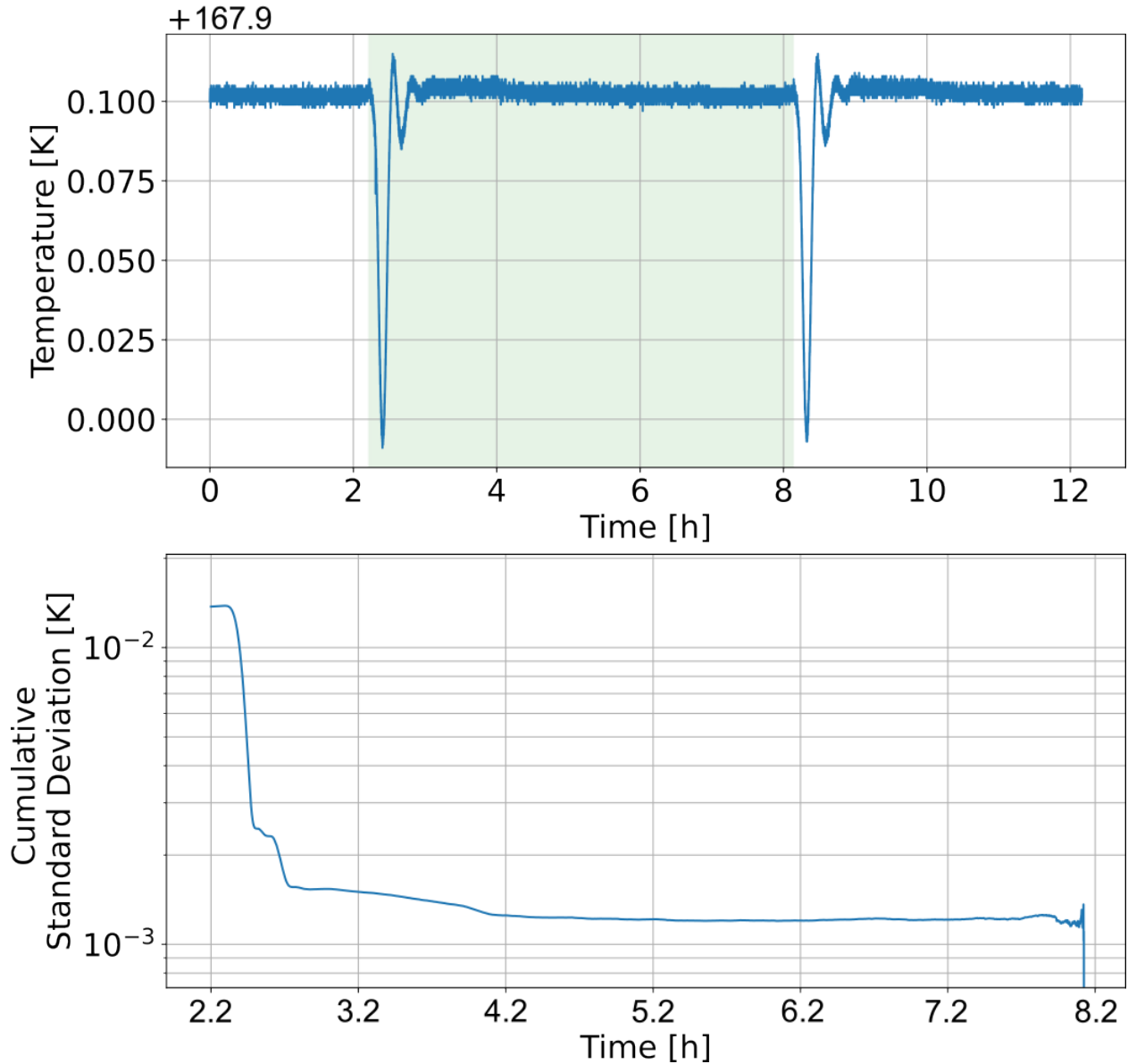


Figure 4-8: Top: Temperature of the cryostat as a function of time, with one cryogenic fill cycle highlighted in green. Bottom: Cumulative standard deviation of the temperature for the highlighted cryogenic fill cycle. The initial cumulative standard deviation of 13.8 mK reflects the long-term stability of the cryostat, including temperature oscillations after refilling the containment vessel. The standard deviation eventually decreases to 1.2 mK, indicating the electronic stability of the controller after the system has restabilized. The standard deviation drops to zero at the end of the cycle as the data array used for analysis is depleted.

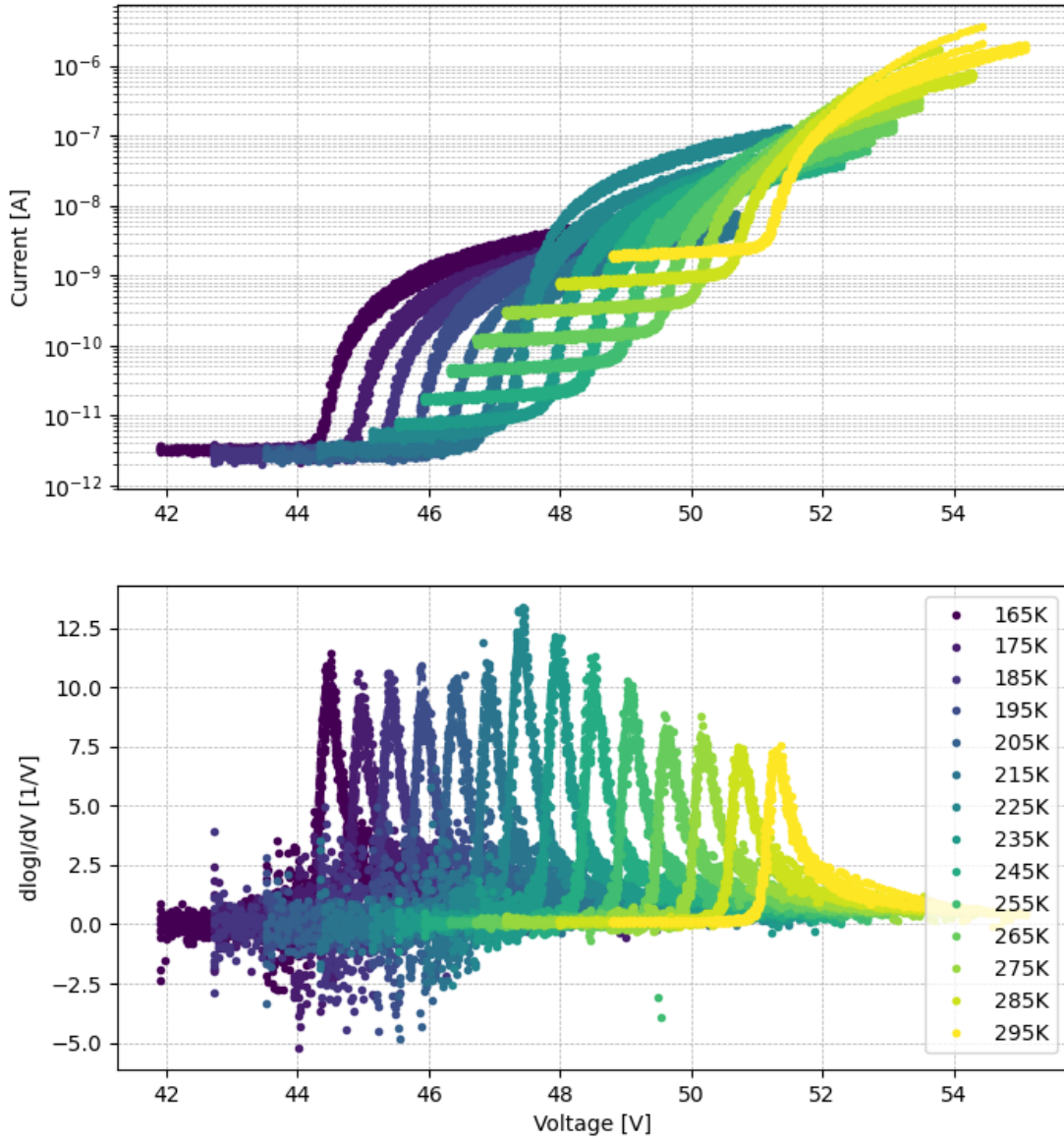


Figure 4-9: The IV response (top) and relative derivative (bottom) for ten SiPMs from the Hamamatsu mini-tile, measured from 165 K to room temperature, in 10 K increments. The relative derivative is fit using a Landau function to determine the breakdown voltage, which is defined as the maximum value of the Landau function fit.

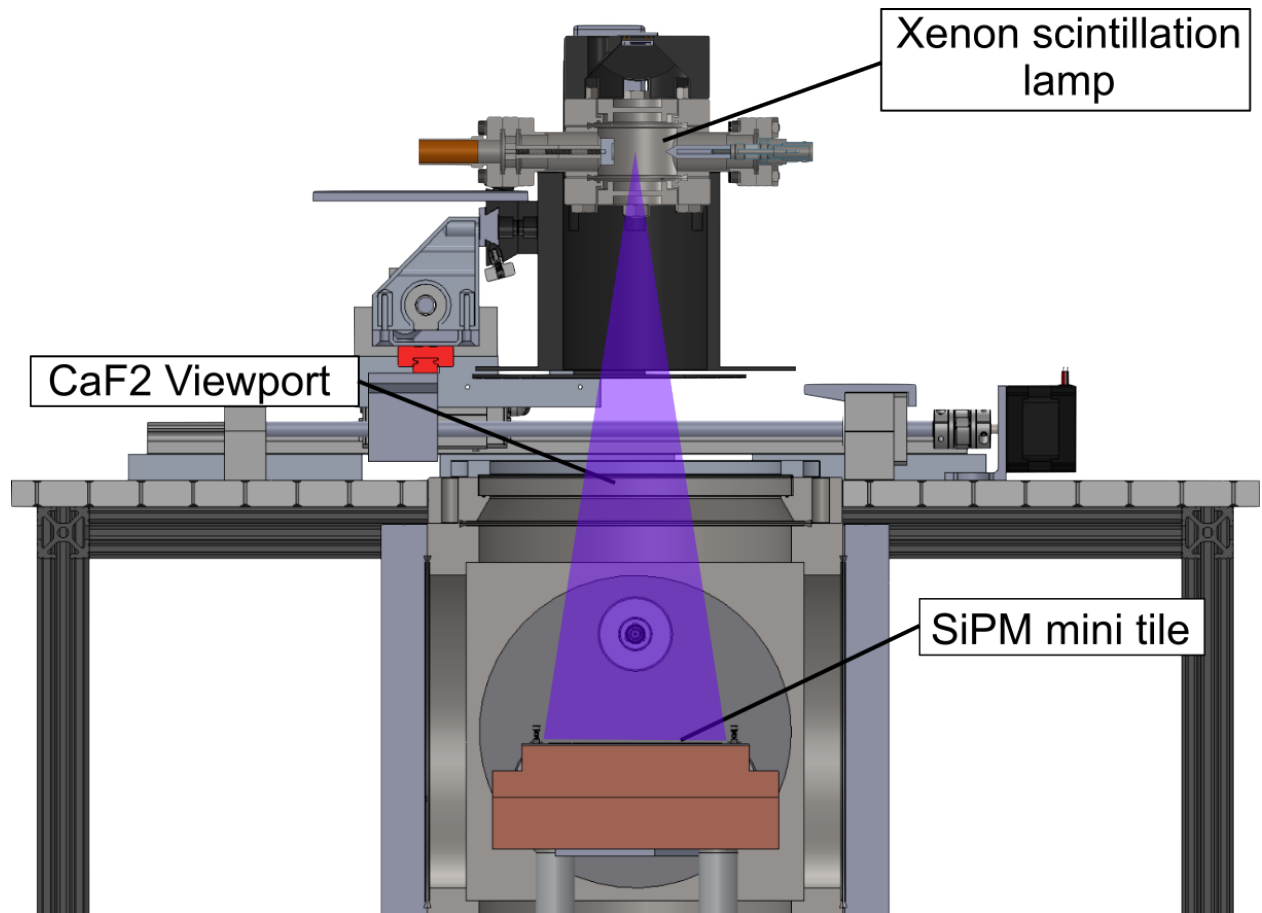


Figure 4-10: A sectioned computer rendering of the scintillation light source illuminating the SiPM mini tile inside of the ETS.

[95]. The data acquisition system (DAQ) was triggered by a rising-edge threshold from the coincidence SiPM on the scintillation light source. Figure 4-10 shows a computer rendering of the ETS cryostat and the scintillation light source positioned over the SiPM mini tile. Each waveform was integrated from $2\ \mu\text{s}$ pre-trigger to $8\ \mu\text{s}$ post-trigger, and the resulting integration value was stored in a buffer. The scintillation light source was positioned above the mini tile to ensure that all SiPMs were illuminated simultaneously. The charge spectrum for one of the SiPMs under VUV illumination is shown in Figure 4-11.

The SPE charge was determined by fitting a Gaussian to both the pedestal and the SPE peak, calculating the difference between their mean values, and then dividing by the impedance of the oscilloscope and the gain of the amplifier. This measurement was done at

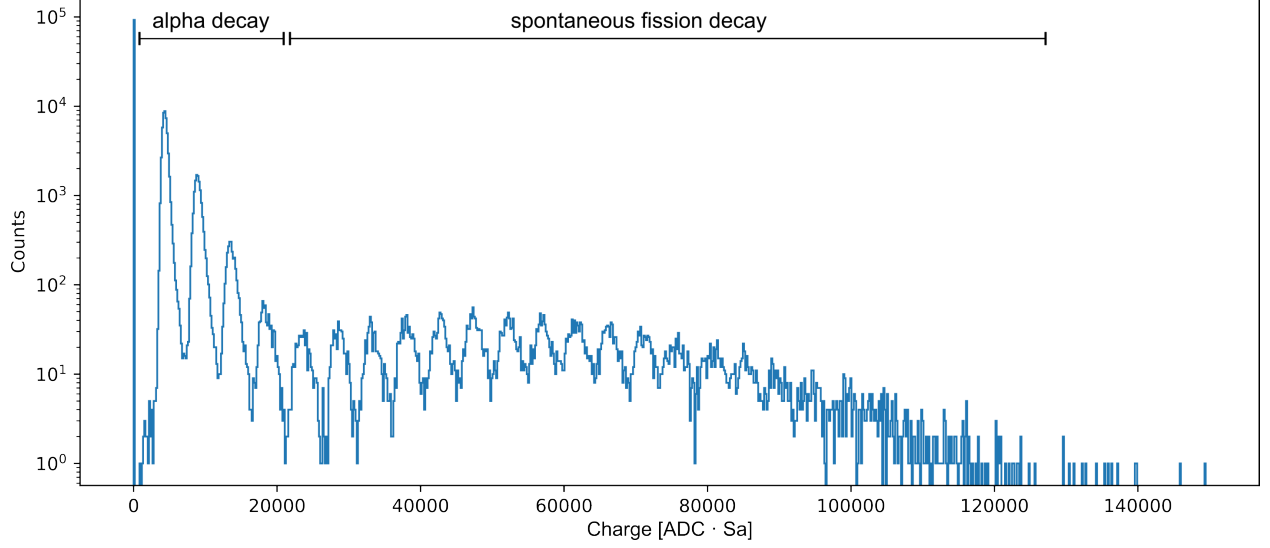


Figure 4-11: The charge spectrum of a SiPM under xenon scintillation light from the decay of ^{252}Cf . The envelope of the charge spectrum has a low-charge peak corresponding to an alpha decay, and a high-charge peak corresponding to spontaneous fission.

various voltages for each SiPM. The resulting SPE charge as a function of voltage was fit using $Q_{SPE} = C_{eff}(V - V_{BD})$, where Q_{SPE} is the SPE charge, C_{eff} is the effective SPAD capacitance, V is the bias voltage, and V_{BD} is the breakdown voltage. Figure 4-12 shows the average SPAD capacitance for each SiPM (bottom) and the entire sample (top) as a function of temperature. The data shows a small increase to the effective SPAD capacitance at temperatures lower than 193 K; however, this change is of similar magnitude as the standard deviation of the capacitance measurements for the tested SiPMs. Temperatures from 263 K to room temperature are excluded from the analysis because the resolution is compromised by dark counts clipping at the start and end of the acquisition window, which broadened the peaks in the charge spectra. Peak broadening from waveform clipping could have been mitigated by using a shorter integration window or by digitizing and fitting the waveforms.

Figure 4-13 shows the breakdown voltage measurements from both the IV and pulse counting methods over the temperature range from 163 K to room temperature. The breakdown voltage measured using the IV method is systematically 200 mV higher than the breakdown voltage measured using the pulse counting method. However, the temperature

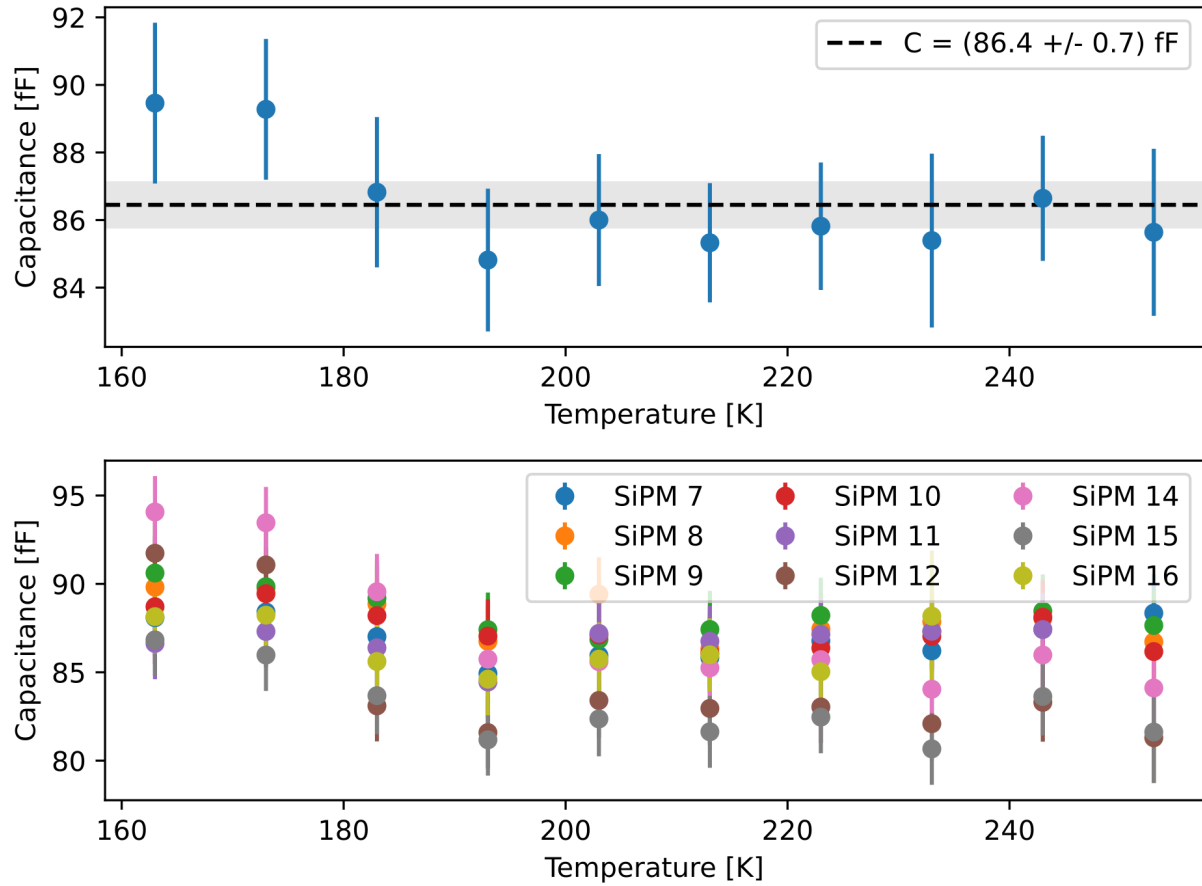


Figure 4-12: The SPAD capacitance for nine SiPMs from the Hamamatsu mini tile was measured from 163 K to 253 K in increments of 10 K. Top: The average of all nine SiPMs and the standard deviation of the sample. Bottom: The SPAD capacitance for individual SiPMs and the standard error in the mean. The average capacitance at 163 K is approximately 5 fF higher than the average capacitance at warmer temperatures.

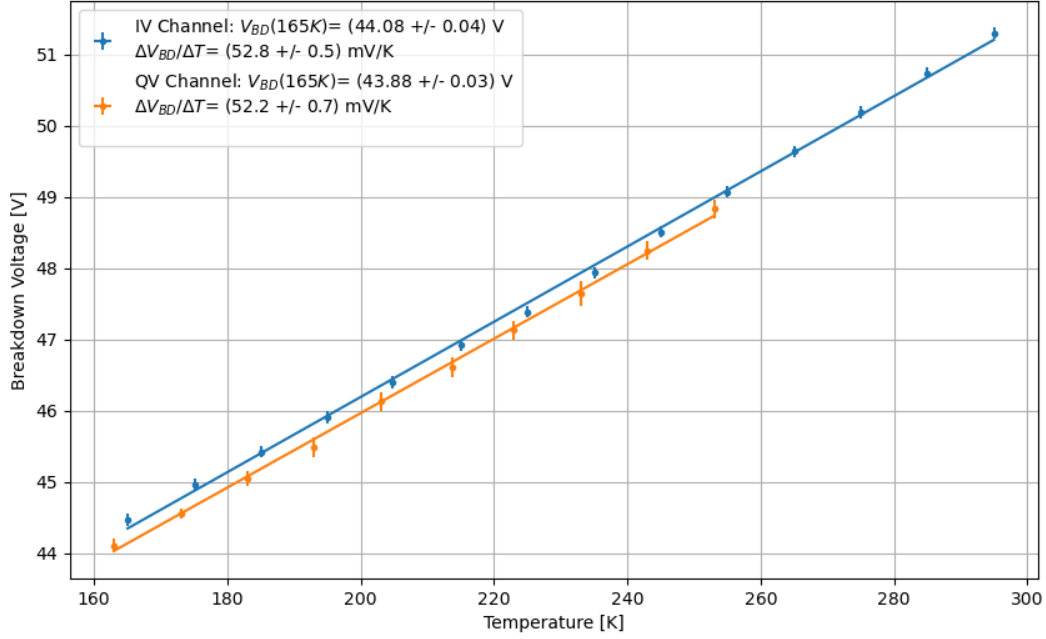


Figure 4-13: The breakdown voltage of ten SiPMs from the mini tile was measured using the IV method from 165 K to 295 K, in increments of 10 K. In comparison, nine SiPMs from the same mini tile were measured using the pulse counting method from 163 K to 253 K. The breakdown voltage obtained with the IV method was consistently 200 mV higher than that obtained with the pulse counting method.

dependence of the breakdown voltage is similar for both methods, within uncertainties. The definition of the breakdown voltage using the IV method is not physically motivated, whereas the charge-gain method is directly tied to the SPE charge-response,

$$I = \Phi \cdot PDE(V_{OV}) \cdot Q_{SPE}(V_{OV}) \cdot (1 + \Lambda(V_{OV})), \quad (10)$$

where $V_{OV} = V - B_{BD}$ is the overvoltage, Φ is the photon flux, PDE is the photon detection efficiency, and Λ is the average extra charge from correlated avalanches. When Φ has sufficient density relative the SPAD area, Λ becomes a function of Φ due to saturation.

The relative spectral irradiance was estimated using datasheets for the flash lamp [85] and filter transmission [96] for up to three series 172 nm bandpass filters. Figure 4-14 shows the estimated spectrum. The average spectral irradiance with three filters is 175.8 ± 5.5

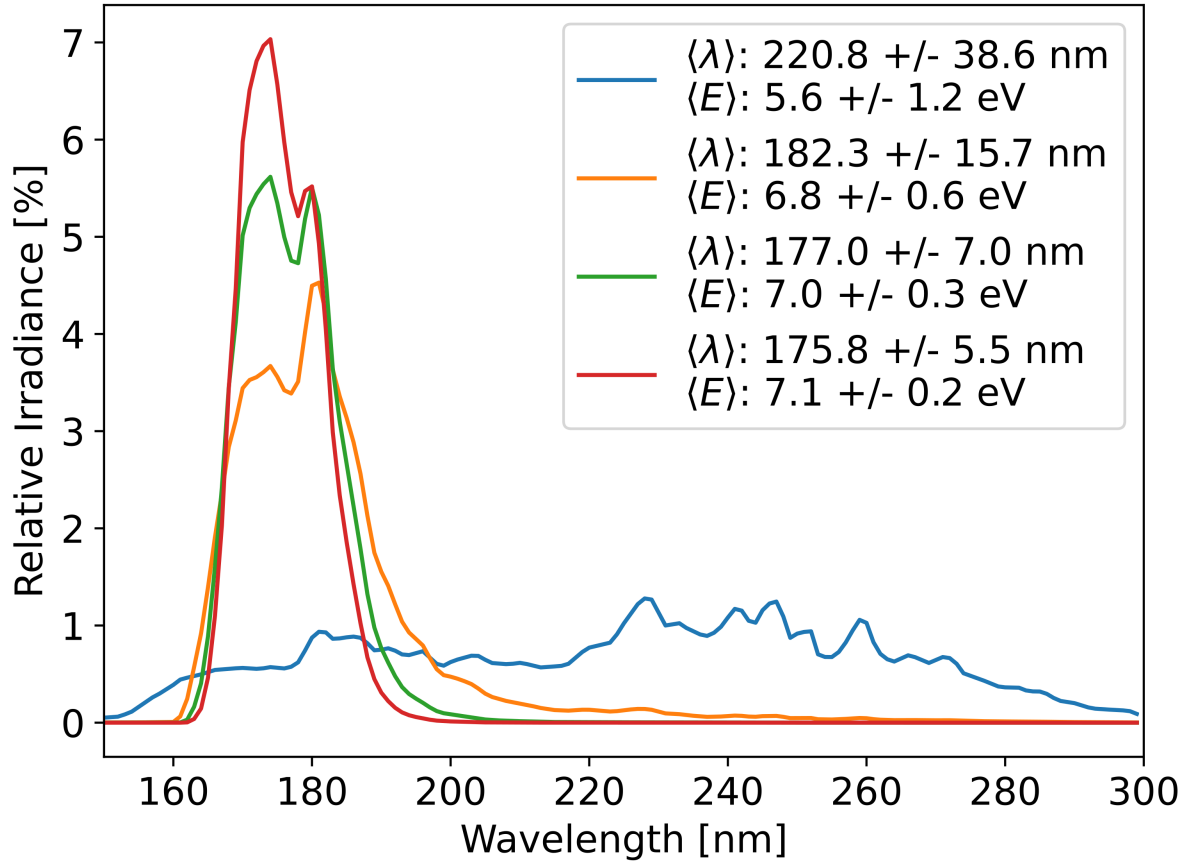


Figure 4-14: The normalised relative spectral irradiance from the xenon flash lamp, with and without 172 nm bandpass filters. The spectral irradiance is estimated using datasheets for the flash lamp and the filters. The blue, orange, green, and red curves are for no filters, one filter, two filters, and three filters, respectively.

nm. The spectral responsivity has a relative standard deviation of 10.6%, and the long-term reproducibility of the photodiode calibration is 14.9%.

A lens tube containing three 172 nm bandpass filters [96] and two 200 μm P200K pinhole apertures [97] was attached to the xenon flash lamp, which was mounted on the optical rail system. The beam was profiled by scanning across a NIST-calibrated XUV-100C photodiode [98] inside the cryostat in both the x- and y-directions. A plot of the beam intensity as a function of x- or y- position is shown in Figure 4-15.

By symmetry, the full-width-half-maximum (FWHM) of the intensity profile defines the edges of the device. The center of the device location is determined by limiting the data to

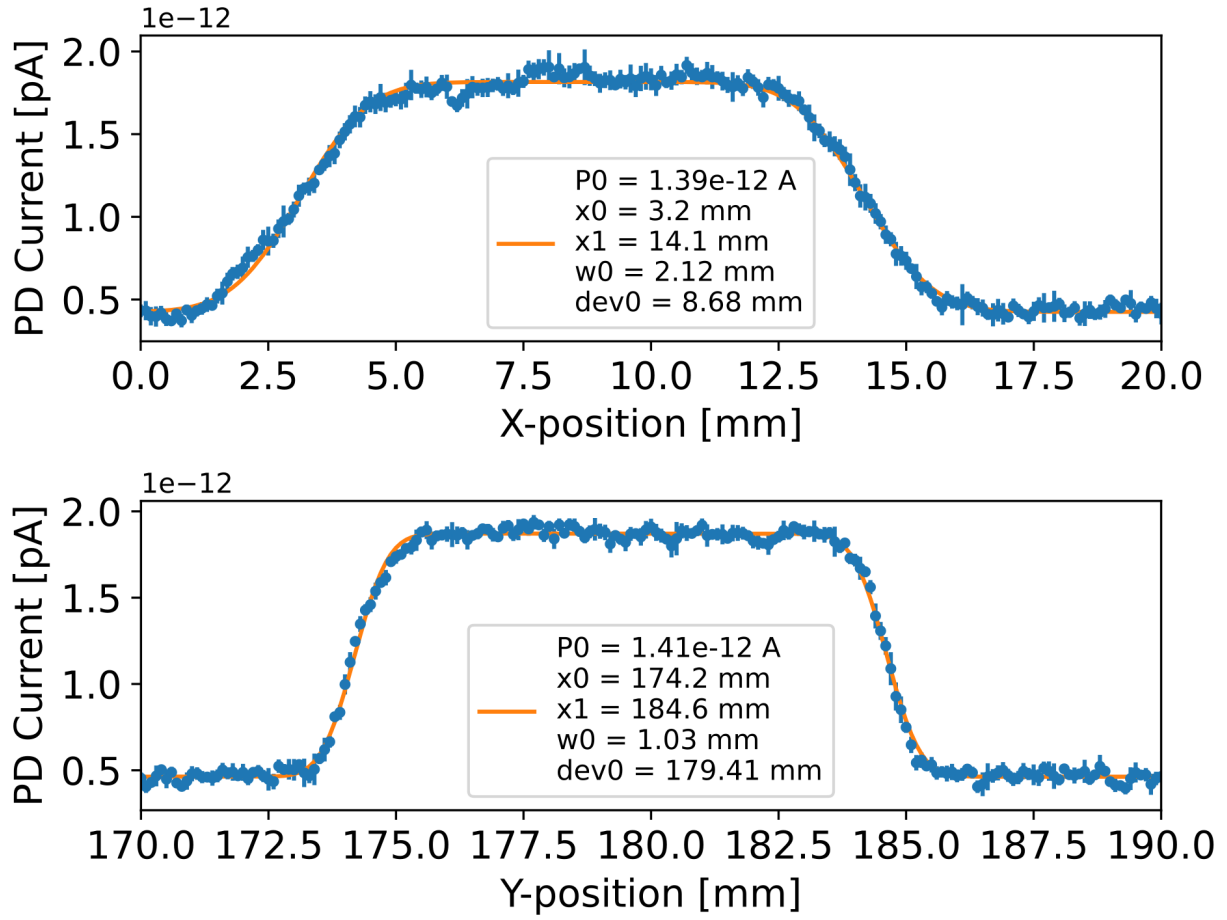


Figure 4-15: The photodiode current as a function of source position while scanning the beam linearly across the device in both the x- (top) and y-directions (bottom). An error function is fit to the data to determine the device edge and center, as well as the beam intensity and radius.

where the intensity is greater than the FWHM and taking the mean position, weighted by the intensity. The boundary and location of the device were used to define the boundary conditions for a raster scan that was used to determine the uniformity of the photodiode response. Figure 4-16 shows the light map from the raster scan superimposed onto a photograph of the photodiode. The photograph of the photodiode was scaled and positioned using the intensity-weighted centroid, calculated using data greater than the FWHM contour. The average radiant power of the elliptical VUV beam incident on the photodiode is (23.6 ± 0.1) pW with a beam radius of $w_x = 1.95$ mm and $w_y = 1.03$ mm.

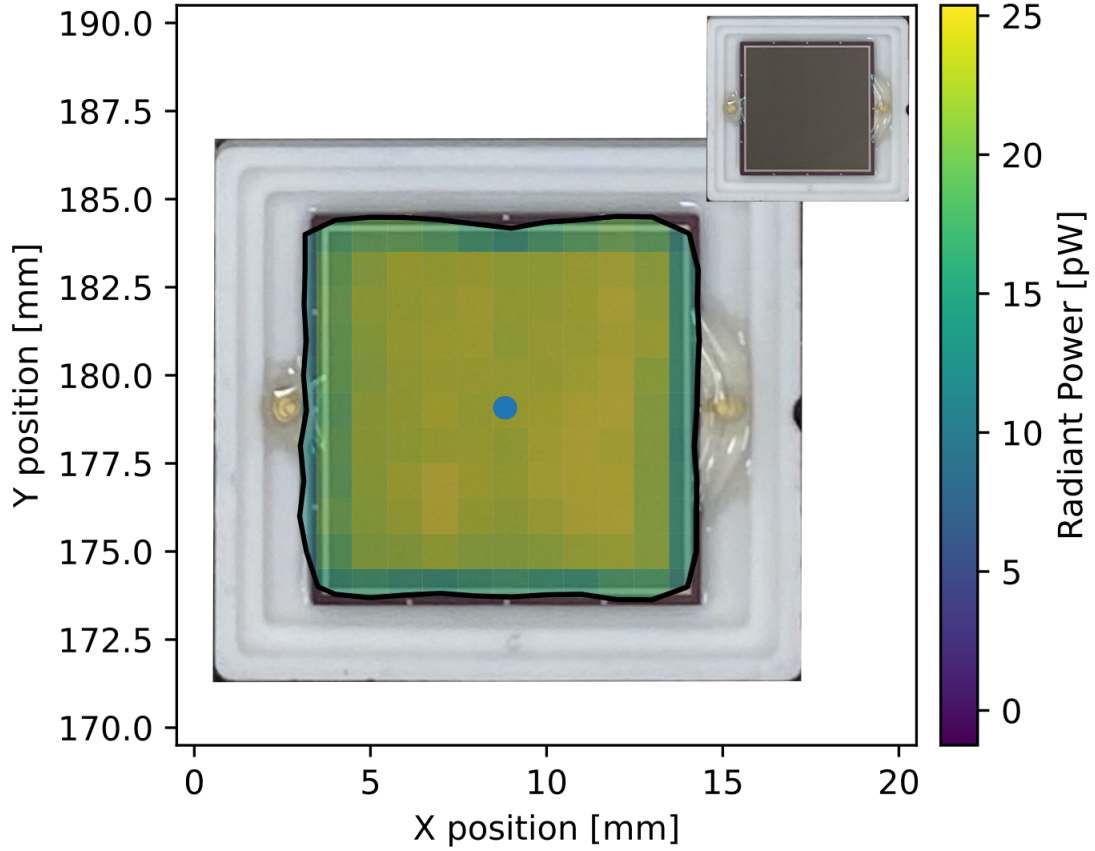


Figure 4-16: The light map from raster scanning a beam with radius of $w_x = 1.95$ mm and $w_y = 1.03$ mm across the photodiode, superimposed on a photograph of the photodiode. The light map is extracted using the FWHM contour, which is shown with a black border on the light map, and the central position of the photodiode is calculated using the intensity-weighted centroid of the remaining data. The radiant power is calculated using the tabulated spectral responsivity at 175.8 nm.

5 Ionization Damage of SiPMs from Vacuum-Ultraviolet Light

5.1 Introduction

SiPMs are commonly used to measure scintillation in high-energy, nuclear, and astrophysics experiments. In such an application, charged particles, neutrons, gamma, or X-ray radiation is common. The effects of radiation on silicon detectors has been studied extensively for hadrons and gamma rays, see e.g., [99, 100]. Damage primarily occurs through non-ionizing energy loss (NIEL), where energy is transferred to the atomic nuclei of the crystal lattice without causing ionization. NIEL leads to bulk damage in the Si lattice, known as displacement damage. Displacement damage occurs when hadrons, or the primary knock-on atom (PKA) in the case of gamma/beta radiation, displace a Si atom into an interstitial site and leave a vacancy behind. The threshold for this process is small, about 25 eV in Si, which allows the hadron or PKA to create a cluster of defects in the crystal lattice. When the energy of the impacting particle is sufficiently high, the knock-on atoms create their own cluster of defects, leading to cascades of defect clusters. Low-energy gamma rays, X-rays, and light charged particles also produce displacement damage, however, these processes have a low cross-section and are typically single site events [101]. In addition to displacement damage, low-energy gamma rays, X-rays, and light charged particles cause ionization damage through ionization energy loss (IEL). In this process, an electron-hole (e-h) pair is generated and drifts apart before recombination, with the mobilized hole often becoming trapped at the Si or SiO₂ interface. The trapped holes increase the oxide charge, which raises the flatband voltage. When an electric field is applied, this increased charge can generate a surface current [102–104]. Radiation damage of SiPMs has been studied extensively for NIEL [105–131]. Displacement damage is manifest through an increase in the dark count rate, leakage current, current noise, and at sufficiently high exposures, the current gain and breakdown voltage can also be affected. The effects of IEL in SiPMs has also been studied,

however, less extensively [121, 122, 129, 132, 133]. Ionization damage is manifest through an increased leakage current that can also leak into the bulk of the device, leading to an increased dark count rate. Additionally, it has been shown that p-on-n and n-on-p SiPMs are affected differently by ionization damage, where the former has an increase to the delayed correlated avalanches, and the latter has a decrease in the cross-talk and PDE [133]. Both displacement damage and ionization damage can be reversed by thermal annealing. SiPMs exposed to hadron radiation are typically annealed at high temperature [105, 106, 109, 111, 112, 114, 119, 121–123, 129–131, 133], however, electrical annealing [126, 128] and laser annealing [134] have also shown to reverse the effects of radiation damage. It is possible that ionization damage in SiPMs is studied less than displacement damage because the defects from ionization damage have a higher mobility than the defects from displacement damage, which prevents cumulative damage from building up through room temperature annealing. At cryogenic temperature, however, defects from ionization damage can be frozen into the lattice. The effects of ionization damage in SiPMs have not been studied for ultraviolet (UV) radiation or at cryogenic temperature. This is of particular concern for noble liquid detectors in rare-event searches that are intended to operate at cryogenic temperature for a long period of time. Noble liquids scintillate VUV light, and although exposure during rare-event searches is small, calibrating the detector can produce significantly higher fluxes. Many noble-liquid detectors are intended to run continuously for several years, and the cumulative exposure may thus become apparent and degrade the performance of the detector [9, 135–137]. The results of an experiment are presented, where Hamamatsu VUV-sensitive SiPMs were cooled to 165 K and characterized before, during, and after irradiation with VUV light, and after thermal annealing.

5.2 Experimental Setup

A Hamamatsu S13775-9121 mini-tile was tested in the ETS optical cryostat, described in Chapter 4. The mini-tile was mounted on a copper plate, which was placed on the cold plate

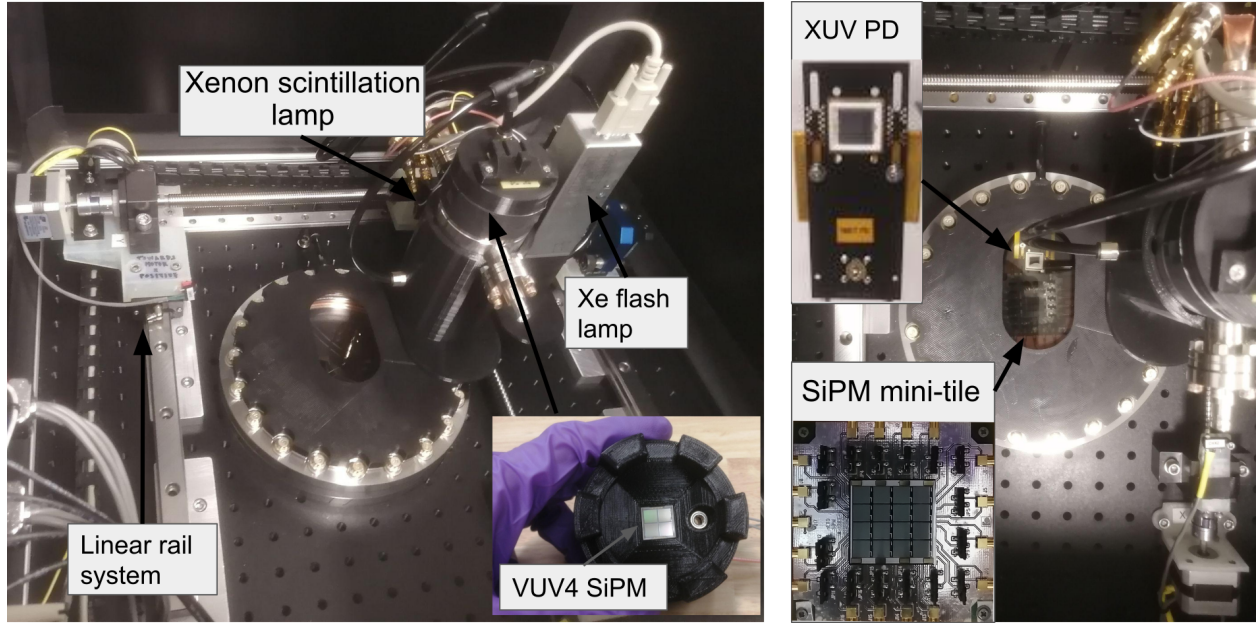


Figure 5-1: The interior of the dark box atop the ETS cryostat. The left picture shows the linear rail system and the light sources. The reference VUV4 SiPM in its enclosure is shown in the inlay. Enclosures are built around the beam path and are directly purged with dry nitrogen. The picture on the right shows a top-down perspective of the dark box, where the photodiode and SiPMs are visible. An enlarged image of the two sensors, the XUV photodiode and SiPM mini-tile, is shown in the inlay.

of the cryostat and cooled via liquid nitrogen. The temperature was measured with Pt100 RTDs housed in aluminum lugs bolted to the front of the PCB. The top of the cryostat features a custom large-area CaF_2 viewport (window diameter 142 mm) that is enclosed by a dark box and optical table. A two-axis linear stage, mounted to the optical table, was used to position light sources above the viewport, over the photosensors. The dark box and light sources were purged of humidity using dry nitrogen, and the relative humidity was monitored with a DHT22 sensor. A picture of the interior of the cryostat and dark box is shown in Figure 5-1.

Two light sources were used with the SiPMs: a custom xenon scintillation lamp and a Hamamatsu L11035 xenon flash lamp. Scintillation from the custom xenon lamp is produced by the decay of a Cf-252 source inside the lamp, which was used to illuminate all the SiPMs simultaneously with 172 nm light [138, 139] through a front-facing viewport. A Hamamatsu VUV4 SiPM was mounted on a back-facing viewport of the scintillation lamp and served as a

coincidence sensor to trigger the data acquisition system. The xenon flash lamp had a vented lens tube fixed to its front, and a nitrogen-purged enclosure was built around the lens tube to prevent stray light from escaping through the vents. A calibrated OSI Optoelectronics XUV-100C photodiode, cantilevered from a flange mounted on the side of the cryostat, was used to measure the radiant flux density of the flash lamp. The SiPMs were characterized with pulse counting measurements, both in the dark and under illumination. The photodiode was measured with a Keysight B2987B electrometer, while the SiPM dynamic response was amplified with a custom RF amplifier and recorded with a CAEN VX2740 digitizer.

5.3 Method

The cryostat was cooled to 165 K, and pulse counting measurements were recorded while the xenon scintillation lamp illuminated the mini-tile. The waveforms were analyzed by averaging a small interval in the pre-trigger region to estimate the baseline value of the waveform, which was subtracted from the waveform, and a pulse-finder algorithm was used to identify pulses within the waveform. The pulse amplitude, integral (charge), and peaking-time were tabulated and used for further analysis. When no pulse was found in a waveform, a zero was recorded for both the amplitude and charge, and the trigger time was recorded as the peaking-time. Cf-252 decays through both spontaneous fission and alpha decay, but only the scintillation from alpha decay was suitable for the analysis method, as explained in the following section. The coincidence sensor was used to discriminate alpha decays from fission decays through a threshold in the charge spectrum. This threshold was established by fitting a Landau distribution to the alpha-peak of the charge spectrum and identifying the charge value where the number of counts falls below 1. Events above this threshold were identified as fission decays and excluded from the mini-tile dataset used in the analysis. The Cf-252 charge spectrum for both the coincidence sensor and a device on the mini-tile, SiPM 8, is shown in Figure 5-2. The mini-tile data set, with fission events removed, was used to determine the single photoelectron (SPE) charge, the mean number of detections, and

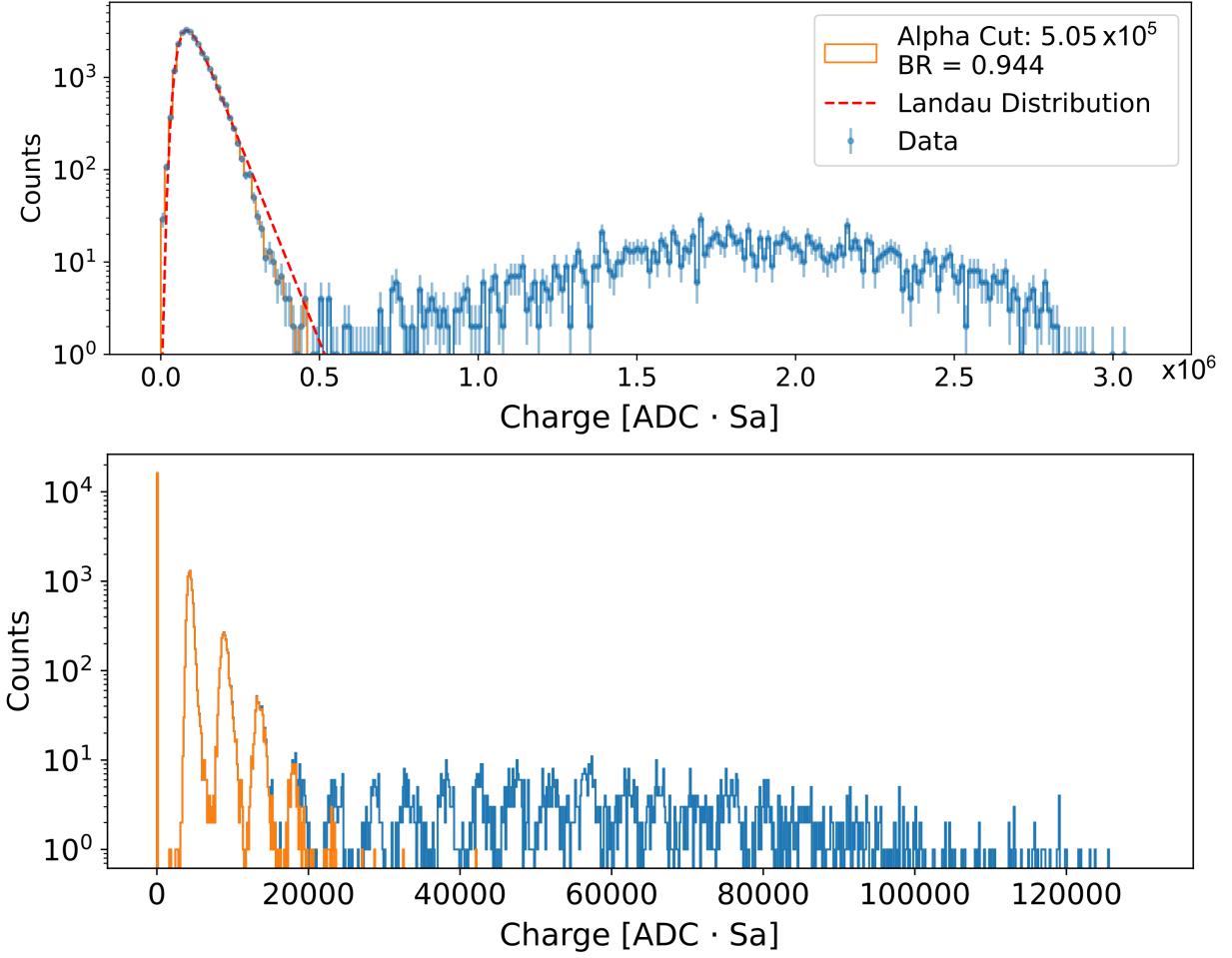


Figure 5-2: The charge spectrum for both the trigger SiPM (top), and SiPM 8 from the min-tile (bottom). Significantly more light is collected by the trigger SiPM because it is mounted to the window of the xenon scintillation lamp. A Landau function is fit to the alpha-peak of the trigger SiPM, which is used to differentiate alpha decays from fission decays using a charge threshold. The events tagged as alpha-coincidence are colored in orange for both plots.

the average extra charge. The SPE charge was determined by fitting Gaussian functions to the peaks of the SPE and two-photoelectron distributions, and taking the difference of the means. The mean number of detections is the number of primary avalanches induced by the light source, free from correlated effects. For dim light, the mean number of detections can be determined through the Poisson equation by counting the number of events in the pedestal, i.e., the number of non-detections [140]:

$$\mu = -\log(N_0/N_T), \quad (11)$$

where μ is the mean number of detections, N_0 is the number of events in the pedestal, and N_T is the total number of events. The excess charge factor for a SiPM is the ratio of the output charge to the charge from detections. The excess charge can be calculated using the relation

$$\text{ECF} = 1 + \langle \Lambda \rangle = \langle q \rangle / \mu Q_0, \quad (12)$$

where $\langle \Lambda \rangle$ is the average number of extra avalanches, Q_0 is the SPE charge, and $\langle q \rangle$ is the average output charge from the SiPM. Normally, the excess charge factor would be modeled as a geometric series in the average extra charge [141], however, the average number of extra avalanches was < 0.2 at 8 V of overvoltage, suggesting a first-order approximation to be sufficient. After characterizing the SiPMs, the xenon scintillation lamp was removed and replaced with the xenon flash lamp outfitted with a single 172 nm bandpass filter. The relative spectral irradiance was estimated using datasheets for the flash lamp [85] and filter transmission [96]. The flash lamp was rastered over the photodiode to determine the radiant power density from the flash lamp in the approximate area of the mini-tile, which was 10.3 ± 4.0 nW/mm². Figure 5-3 shows the radiant power density from rastering the flash lamp over the photodiode. The coordinate system is relative to a limit switch for both x- and y-axis. The radiant power was calculated using the spectral responsivity of the photodiode,

the relative spectral irradiance of the filtered light, the photodiode current, and the area of the photodiode. The flash lamp was moved to the center of the mini-tile and the SiPMs were irradiated. The current was recorded for both the SiPMs and the photodiode throughout the exposure, and both remained stable. After reaching a target exposure, the flash lamp was removed and replaced with the xenon scintillation lamp, which was re-positioned over the mini-tile. The characterization/irradiation measurements were repeated with 10x the exposure between irradiation cycles, until reaching a maximum exposure of 2.7 ± 1.1 mJ/mm². Following the maximum exposure, the SiPMs were characterized, and the cryostat was warmed to anneal the SiPMs. The SiPMs were annealed at 330 K for one day, then the cryostat was cooled to 165 K and the SiPMs were characterized.

The dark count rate was measured after each exposure using a method that is free from correlated effects, as described in [142]. However, solder mask was not present on the PCB carrying the mini-tile, and the fiberglass-epoxy substrate fluoresced under UV light. The fluorescence was not discovered until characterizing the annealed SiPMs. Following this discovery, the count rate was monitored, and it stabilized two days after last opening the dark box. We concluded that the stabilized count rate was the dark count rate, and proceeded to measure the dark count rate for the SiPMs on the mini-tile. It was not clear that the dark count rate after irradiation was truly the dark count rate, and not the fluorescence detection rate. We repeated the experiment to verify that the dark count rate measured after irradiation was not the fluorescence detection rate. The cryostat was cooled to 165 K, and the SiPMs were irradiated. After reaching a maximum exposure of 2.0 ± 0.8 mJ/mm², the flash lamp was turned off and the count rate was immediately measured for SiPM 5. The count rate was measured repeatedly for the same SiPM until it stabilized, and afterwards, the dark count rate was measured for the mini-tile. The cryostat was warmed to 330 K, the SiPMs were annealed, then the cryostat was cooled to 165 K. The dark count rate was again measured for all the SiPMs for a set of voltages.

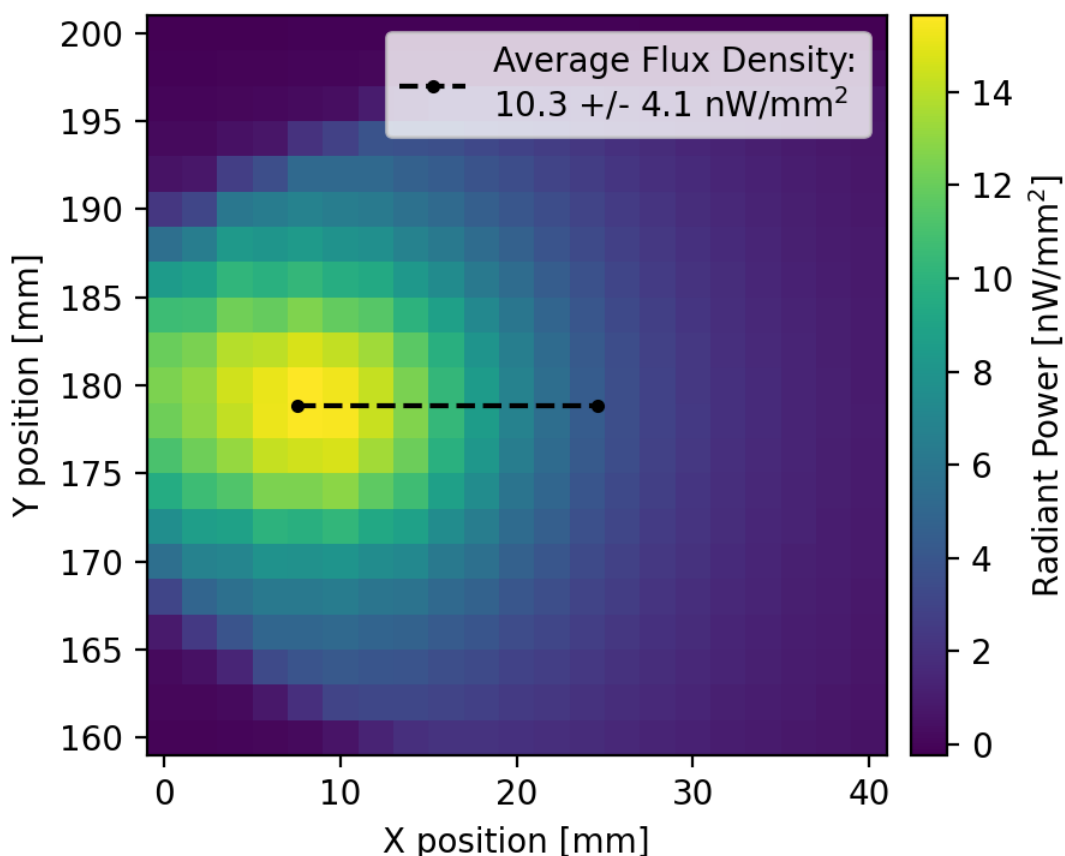


Figure 5-3: The light map of the xenon flash lamp with a single 172 nm bandpass filter, recorded by rastering the flash lamp over the photodiode. The coordinates are listed relative to an x- and y-axis limit switch. The mini-tile has a maximum radius of 17 mm, which is shown as a line segment in the plot. The flux density was integrated along the line segment starting at the center of the photodiode, and the average flux density and its standard deviation are used to approximate the flux density of the mini-tile during irradiation. The shadowing effect in the upper- and lower-left corners occurs when the flash lamp crosses the entrance to the viewport cap, which is shown in Figure 5-1.

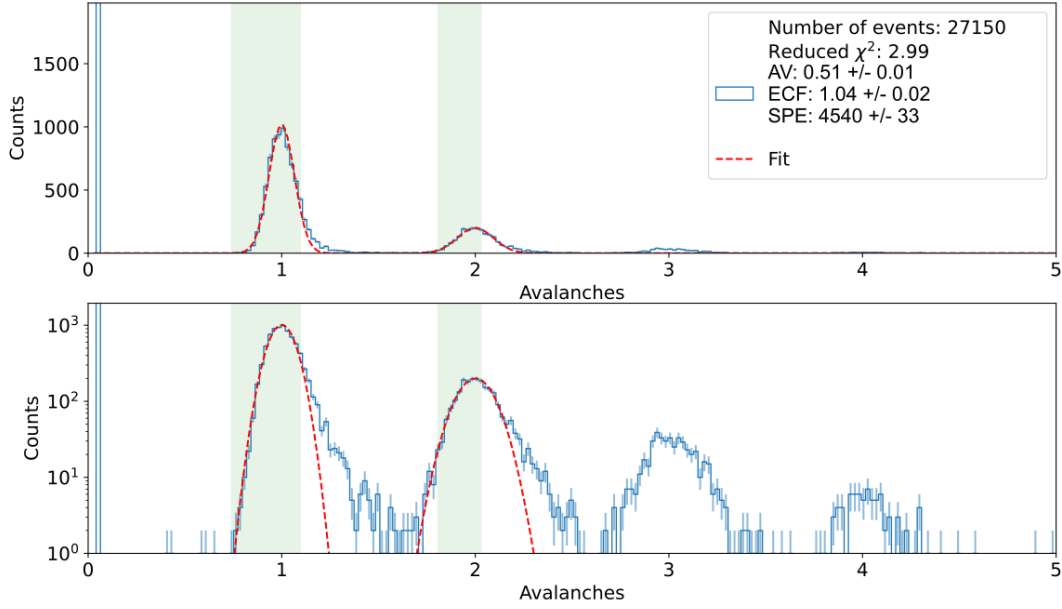


Figure 5-4: The fission-vetoed charge spectrum of SiPM 8 from the mini-tile at 48 V. The mean number of detections and the average extra charge are calculated directly from the dataset. The SPE charge is determined by fitting Gaussian functions to the SPE and two-photoelectron peaks. Only data within the green shaded region is used for the fit to prevent afterpulsing from biasing the fit location.

5.4 Results

Figure 5-4 shows the Cf-252 alpha spectrum and overlaid fits for determining the SPE charge. The measurements were repeated for a set of voltages, and analyzed for voltage-dependent behavior. A line was fit to the SPE charge measurements, which was used to determine the breakdown voltage and capacitance of the device (Figure 5-5, top). The voltage was adjusted for overvoltage, i.e., the voltage above the breakdown voltage. An exponential function was fit to the mean number of detections, and a linearly attenuated exponential was fit to the average extra charge [143]. The mean number of detections and the average extra charge are shown in Figure 5-5, in the middle and bottom panels, respectively.

For the SPE charge, mean number of detections, and average extra charge, each data point after exposure was compared against its initial value before irradiation. The relative change in the mean number of detections for all SiPMs on the mini-tile after maximum

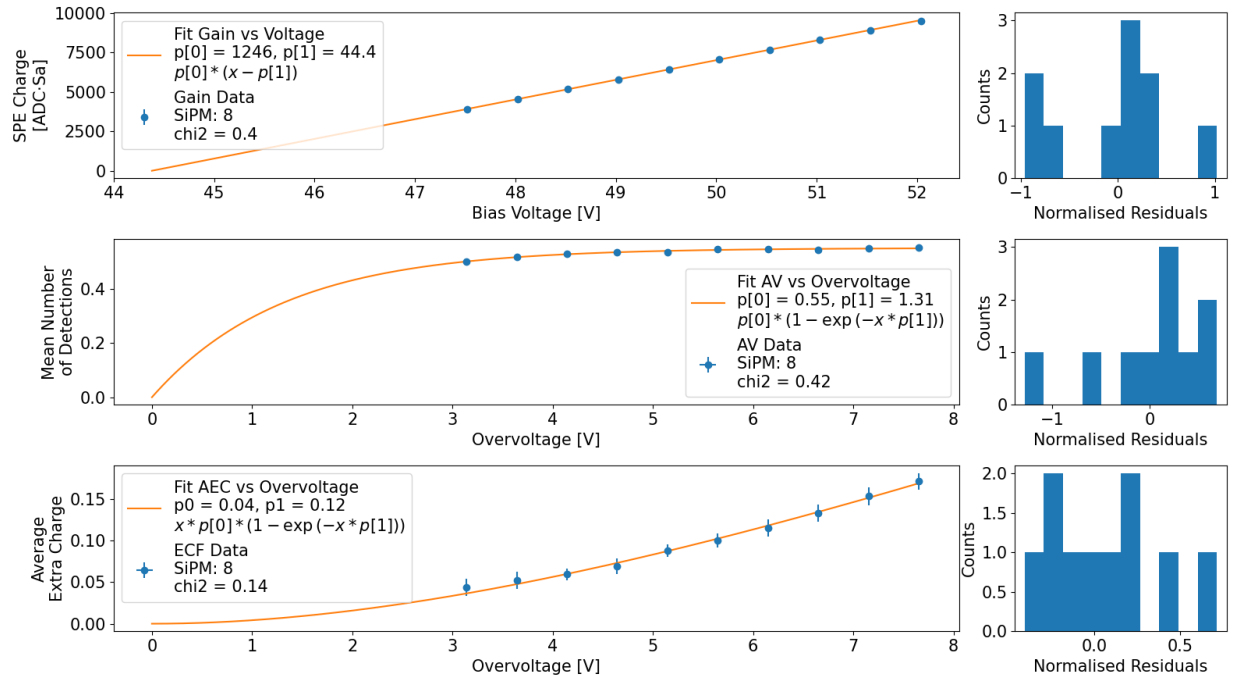


Figure 5-5: The SPE charge (top), mean number of detections (middle), and the average extra charge (bottom) as a function of bias voltage and overvoltage for SiPM 8 from the mini-tile. The x-intercept of the line fit to the SPE charge is used to determine the breakdown voltage, which determines the overvoltage ($V - V_{BD}$) for the mean number of detections and the average extra charge. Error bars are included in the plots but are too small to be observed in most cases. The binned residuals are included to help identify any systematic bias in the data.

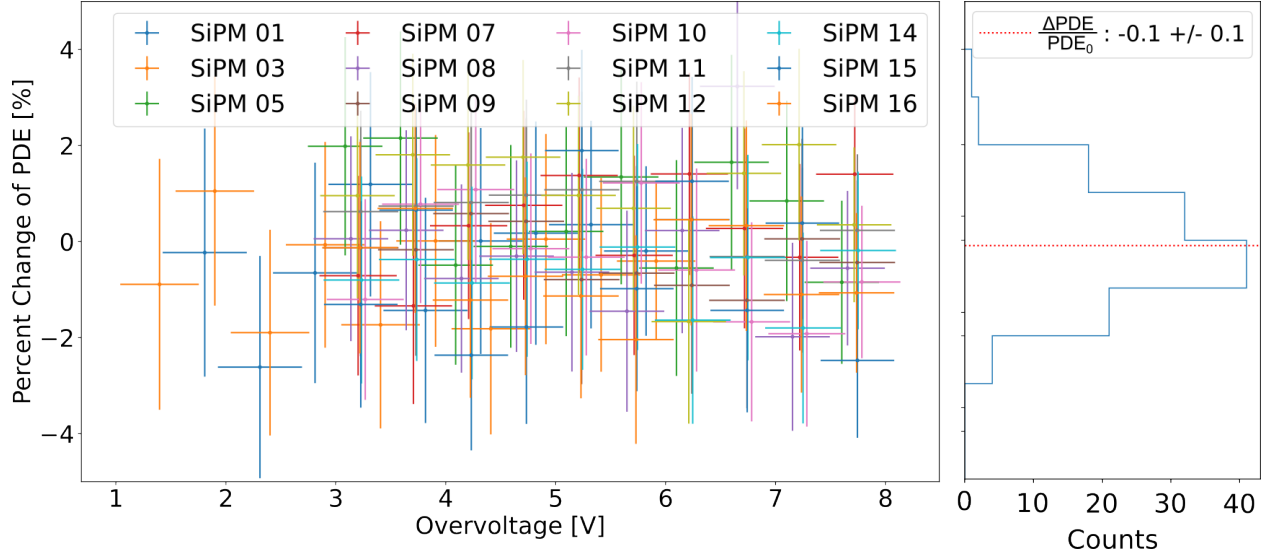


Figure 5-6: The relative change of the PDE from the baseline measurement to the measurement after an exposure of $2.7 \pm 1.1 \text{ mJ/mm}^2$ (left). The differences are calculated on a point-by-point basis, binned in a histogram, and averaged (right).

irradiation is shown in Figure 5-6. For a given measurement (SPE charge, mean number of detections, and average extra charge), the relative change values are binned into a histogram that is used to determine the mean relative change for that exposure. The PDE is the ratio of the mean number of detections to the number of incident photons. With the xenon scintillation lamp centered at the same location for each measurement, the flux was the same, hence the mean relative change for the mean number of detections is equivalently the mean relative change of the PDE at 172 nm. The mean relative change for all three parameters is shown in Figure 5-7.

A plot of the time differences between primary dark counts and the linearized pulse rate is shown in Figure 5-8. The constant region of the linearized pulse rate is averaged to determine the dark count rate. A scatter plot of the dark count rate after irradiation, and after annealing for a set of voltages is shown in Figure 5-9. The dark count rate increased by more than an order of magnitude following exposure. A plot of the dark count rate for SiPM 5 as a function of time after the repeated experiment is shown in Figure 5-10.

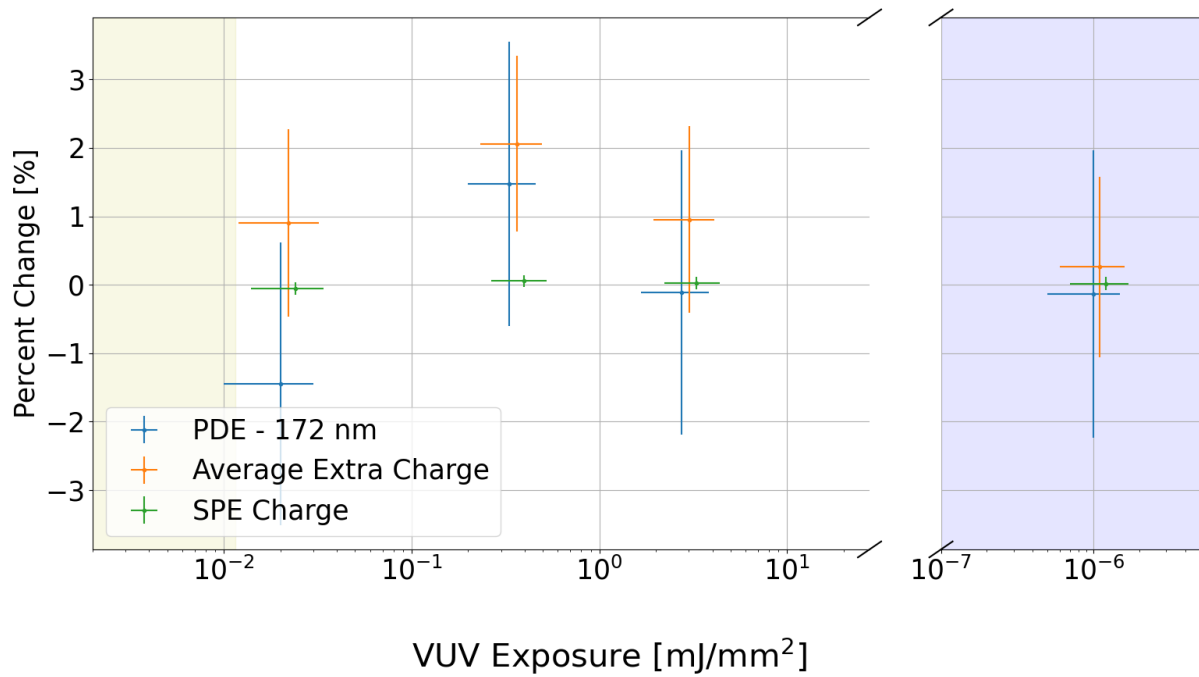


Figure 5-7: The average relative change of the PDE, average extra charge, and the SPE charge. The yellow shaded region indicates the approximate VUV exposure prior to the baseline measurements, and the blue region indicates the measurements after annealing. All three parameters are consistent with no change up to an exposure of $2.7 \pm 1.1 \text{ mJ/mm}^2$. For each group of exposures, the average extra charge and SPE charge are slightly offset from their true values, coincident with the PDE exposure, so that the position of the marker is more clearly visible.

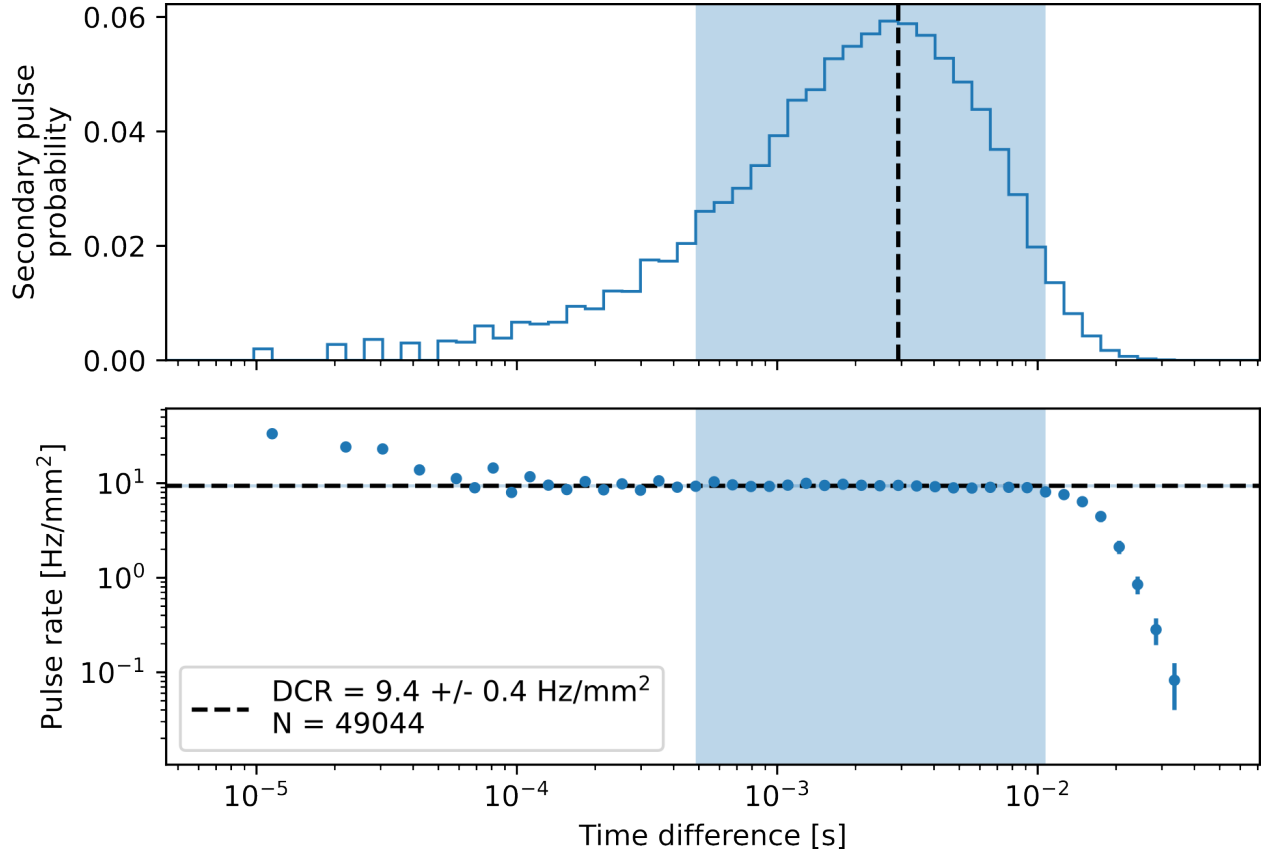


Figure 5-8: Secondary pulse distribution for SiPM 8 at 48 V, after an exposure of $2.0 \pm 0.8 \text{ mJ/mm}^2$. Top: a histogram of the secondary pulse probability. The secondary pulse distribution was determined by taking the time difference between the primary and secondary pulses. A primary pulse is a pulse with a SPE charge less than 1.5 PE that arrives later than $10 \mu\text{s}$ from the last pulse, and a secondary pulse is the next pulse following a primary pulse. Bottom: the linearized secondary pulse timing distribution. The pulse rate is determined by a method described in [142]. The average DCR is calculated using the mean value of the linearized timing distribution between $1/e$ of the maximum secondary pulse probability (shaded area).

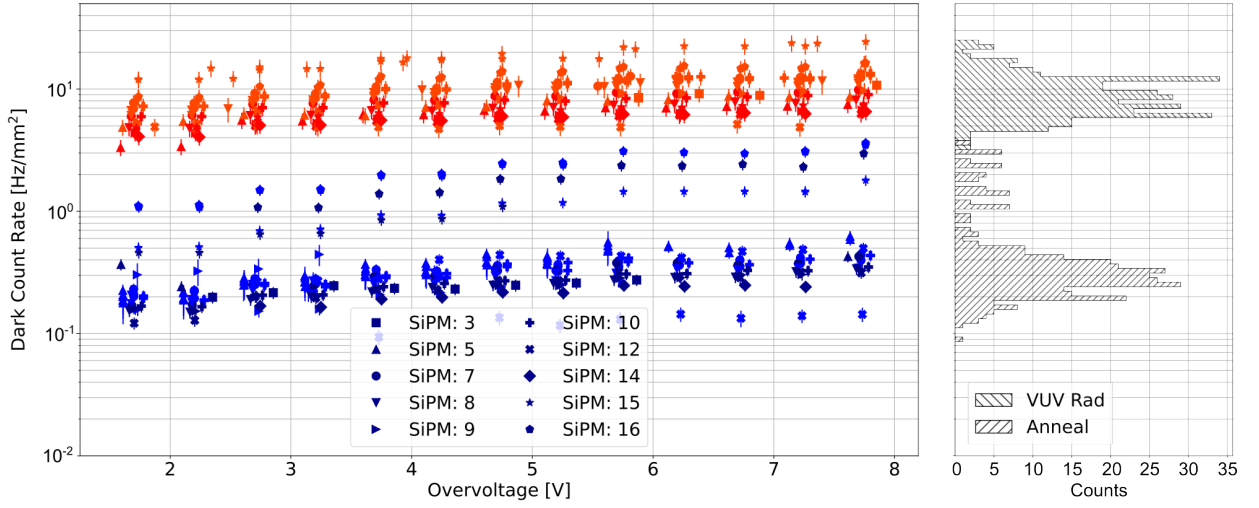


Figure 5-9: Left: The DCR as a function of overvoltage after annealing (blue) and after irradiation (red). The darker shade of each color was taken from the first irradiation/annealing procedure, and the lighter shade from the second. After irradiation the DCR increased by more than an order of magnitude. The baseline measurement of the DCR was taken in the presence of fluorescence and is not included in the figure, however, the DCR after annealing was consistent with other measurements of VUV4 SiPMs at 165 K in the dark [55, 117], which suggests a full-recovery. Right: the scatter plot values binned into a histogram, where the fill pattern indicates data after annealing and after irradiation.

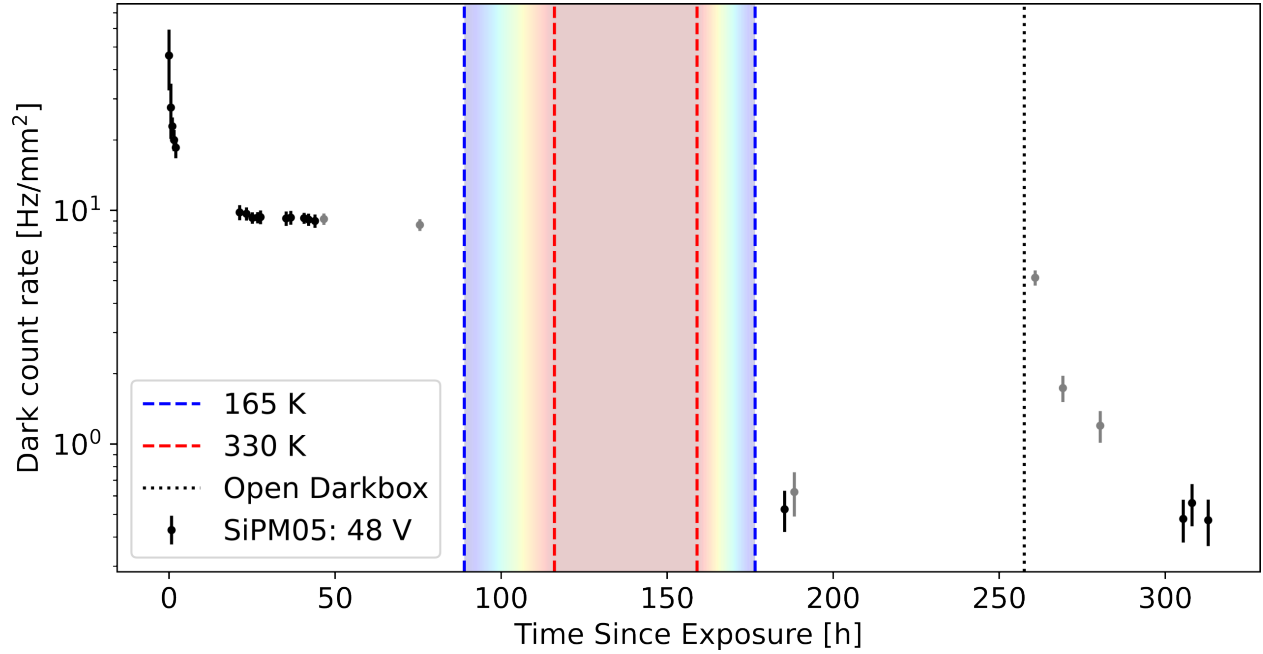


Figure 5-10: The DCR as a function of time since irradiating the SiPMs. The fluorescence decayed and the DCR settled to about 9 Hz/mm² after one day. After two days, the DCR was measured for all the SiPMs. After three days the DCR had remained stable, so the cryostat was warmed to 330 K to anneal the SiPMs. After reaching 165 K the DCR was measured and the result was 0.5 Hz/mm², then DCR measurements were repeated for all the SiPMs. After completing the DCR measurements, the dark box was opened to test the fluorescence with a lower DCR. The DCR was initially high, not as high as after irradiation, but settled back to 0.5 Hz/mm² after about one day. The gray data points were calculated using the number of events in a run divided by the time of a run, using a header file, because the waveforms were lost.

6 An IV Multiplexer for Automated Testing of Cryogenic SiPMs

6.1 Introduction

As discussed in Chapter 4, SiPMs have emerged as a popular alternative to traditional photodetection methods, such as PMTs or photodiodes. A SiPM is an array of SPADs, each operated in reverse bias mode above its breakdown voltage. SiPMs have high photo-detection efficiency, fast response, high gain, low noise, and excellent single photon resolution [144–146]. These features make SiPMs useful for counting the number of photons in a scintillation signal by dynamically measuring their response. Several next-generation particle physics experiments are implementing large arrays of SiPMs, typically of several square-meters in size, immersed in noble liquids, as the photosensors of choice [9, 147, 148]. This necessitates accurate methods to efficiently test thousands of individual SiPMs.

An current-voltage (IV) measurement is commonly performed to characterize the electrical properties of a device, such as a semiconductor, diode, transistor, or solar cell. The process involves applying a voltage across the device and measuring the resulting current. The IV response of a SiPM can be used to meet specification validity. The IV response of a SiPM can also be determined through dynamic measurements [146], with models available that predict how these measurements vary with voltage [143]. Therefore the IV response of a SiPM can be used to predict its dynamic behavior [149]. For these reasons, measuring the IV response of a SiPM may be the most practical characterization method for bulk testing SiPMs.

While there is a general understanding of how temperature affects the performance of a SiPM, cryogenic testing is often necessary to sufficiently characterize them when their end-use is in a cryogenic environment, such as in noble liquid detectors. Cryogenic testing of SiPMs is more efficient when large batches are processed in a single cooldown phase, mostly due to the time required to cycle the cryostat. Dark counts are thermally released avalanches

that are uncorrelated with any other signal. Although the dark count rate is exponentially suppressed at cryogenic temperature, in a large noble liquid detector, the ratio of detected scintillation photons to the number of channels is small [9, 147, 148]. When the probability for a coincident dark count is small, the relative increase of the scintillation signal in the presence of dark counts is $1 + \text{DCR } \Delta t / \mu e^{-\mu}$, where μ is the mean number of scintillation detections per channel, DCR is the dark count rate, and Δt is the waveform integration window [140]. When μ is small the probability for a scintillation detection is effectively the probability for a single scintillation detection, $\mu e^{-\mu}$, therefore the average number of extra avalanches per channel from dark counts is the ratio of the channel-specific dark count rate to the scintillation count rate. Therefore, the scintillation signal for a noble liquid detector in the presence of dark counts is

$$\mu' = \mu \left(1 + \frac{N_{ch} \text{DCR}}{(Q/W) \chi_{scint} \epsilon A} \right), \quad (13)$$

where μ' is the signal from both scintillation and dark counts, N_{ch} is the number of SiPM channels, Q is the Q-value of the ionizing radiation, W is the average energy required to create an electron/photon in the noble liquid, χ_{scint} is the relative scintillation yield, ϵ is the overall detection efficiency, and A is the activity of the ionizing radiation [48, 49, 150, 151]. The current generated from dark counts, the dark current, can be used to estimate the dark count rate, and is needed to subtract the dark noise contribution from the IV response under illumination. The dark current generated by a SiPM at cryogenic temperature is very small, and requires a sensitive ammeter and specialized coaxial/triaxial vacuum feedthroughs. The high cost per channel for measuring the dark current of cryogenic SiPMs motivated the development of a vacuum-compatible IV multiplexer (IV-MUX) capable of routing the signals for up to 105 SiPMs, which is the approximate population of SiPMs on a nEXO tile, through a single triaxial vacuum feedthrough to an ammeter, with minimal leakage current. In this chapter, we describe the design of the IV-MUX and present results from various tests with the device, including precision measurements of cryogenic SiPMs in the dark, where both

dynamic and IV measurements are compared, and IV measurements inside of a cryostat with a SiPM array. Together, these measurements show that the IV-MUX is a reliable and efficient tool for high throughput testing of SiPMs at cryogenic temperatures.

6.2 Design

To facilitate high-throughput IV testing of cryogenic SiPMs, our requirements for IV testing are the following: (1) bias voltage switching for up to 105 SiPMs, (2) maintaining the signal noise below 1 pA, (3) minimizing the number of vacuum feedthroughs, (4) the ability to measure current using the bias node or a dedicated current sensing node, and (5) minimal operator intervention post-initial setup. To meet these criteria, we designed an Arduino-controlled high-isolation IV-MUX, which is shown in Figure 6-1. It serves as a cost-effective way to improve the efficiency of an existing IV measurement system through multiplexing. The system can be expanded to 105 channels by interconnecting up to seven boards, controlled as a single system by one Arduino Every module [152]. Critical aspects of the design are discussed in the following sections.

6.2.1 Minimizing Leakage Current

Oils or dirt deposited on the PCB surface can open weakly conductive paths allowing small currents to leak between traces. Additionally, the relays used to switch the bias voltages and current sense lines specify non-infinite open-contact resistance. Resultant leakage currents can overwhelm the signal, particularly in the sub-pA pre-breakdown region of the IV curve. Design features intended to minimize leakage current from the current node into deactivated bias node and from power rails into the current node are discussed below.

Leakage current is intercepted using a circuit node called a guard node. The guard node is kept at a voltage within a few mV of the potential of sensitive traces. In this design, the guard node is close to ground potential. PCB traces, which are connected to the guard node and free of solder mask, form a protective ring around sensitive pads and traces. This structure,

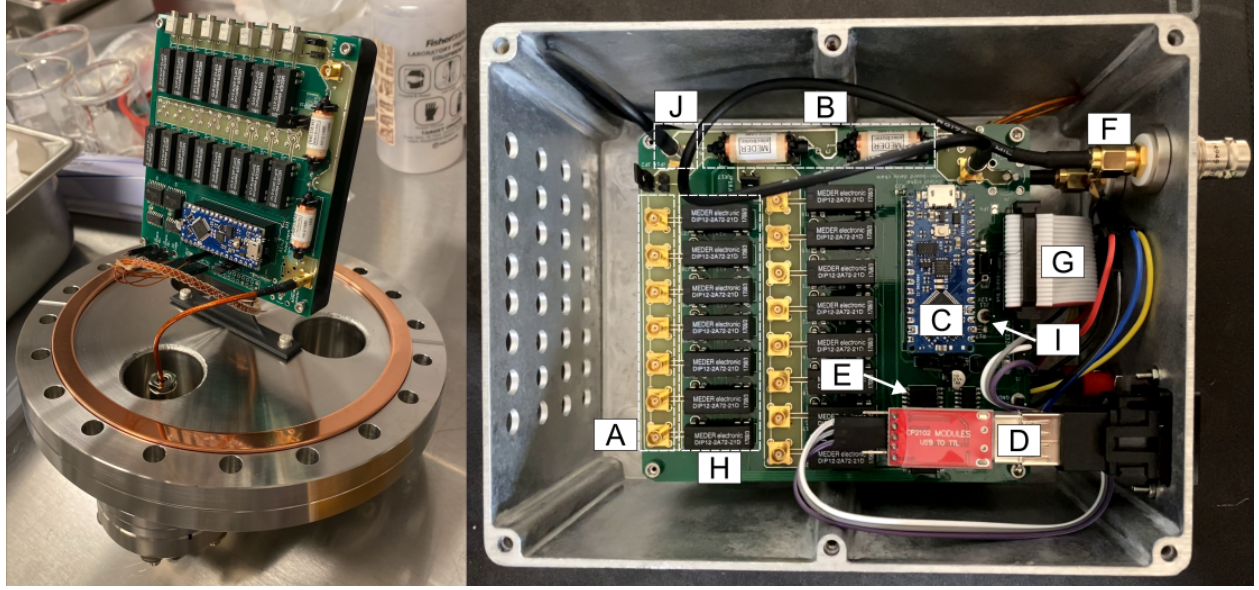


Figure 6-1: Left: IV-MUX prepared for vacuum use. The system uses one triax connection to the electrometer for current readout, and one D-Sub 9-pin feedthrough for power, bias voltage and communication with the Arduino. Right: Annotated IV-MUX in shielded enclosure for benchtop use. (A) Bias coaxial cables. (B) Sense line relays. (C) Arduino. (D) Serial communication. (E) Shift registers. (F) Triaxial readout. (G) Board interconnect. (H) Bias line relays. (I) 12V board power and bias power. (J) Sense line input for Mode B.

known as a guard ring, serves to shield the sensitive components from external influences and minimize undesirable effects such as leakage currents or electromagnetic interference [153].

Each bias channel is controlled by a Form A dual pole single throw (DPST) relay [154], where the two poles are arranged in series. To prevent current leakage into a deactivated bias channel from nearby active channels or from the 12V relay coil pins, each bias voltage connection is surrounded by a guard ring. The guard ring extends from the point where the bias voltage emerges from the bias voltage switching relay to where it connects to the MCX connector center pin. Likewise, a guard ring protects the current sensing node to minimize potential interference.

The circuit node between the two relay poles is connected to the guard node with a 100 k Ω resistor, and intercepts current which may leak through the first relay contact when in the off state. To support multiplexing between boards, the current sensing node uses two high-isolation single-pole relays [155]: one shunting the current sense trace to ground, the

other interrupting the connection between the current sense trace and the connection to the electrometer and to the corresponding outputs of any other boards in the system. To enable an additional IV-MUX board in a multi-board configuration, the shunt relay is deactivated and the series relay is activated; and inversely for deactivating an IV-MUX board. Each board on a multi-board setup can be configured with either a common or isolated current sensing node, which allows compatibility with both single and multi-channel ammeters. A simplified circuit diagram of the IV-MUX is shown in Figure 6-2. The schematics and layout of the IV-MUX are available on a public GitHub repository [156].

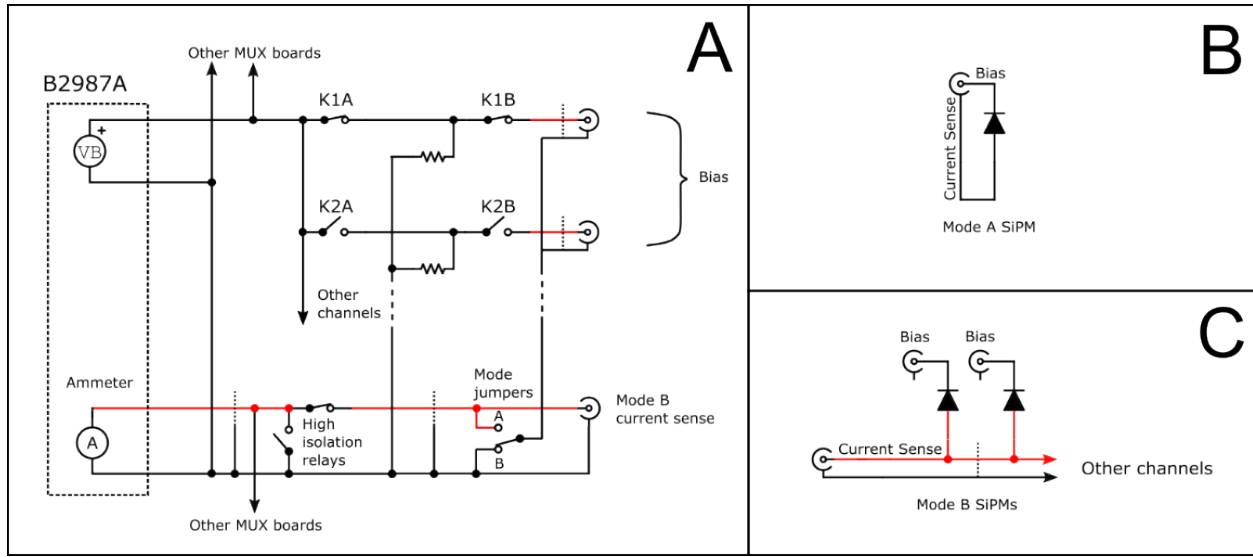


Figure 6-2: (A) A simplified circuit diagram showing the IV-MUX switches and current paths on the MUX. Red traces are guarded by the nodes indicated with the dashed lines. (B) single SiPM connected in Mode A. (C) Two SiPMs connected in Mode B.

6.2.2 Control

A system of up to seven interconnected boards is controlled by an Arduino Nano Every module, which is installed on one of the boards. The Arduino firmware communicates via a transistor-transistor logic (TTL) level serial port, and supports commands to activate or deactivate SiPM bias lines and sense outputs. The Arduino controls the relay switches (15 bias + 1 sense) via two cascaded 8-bit shift registers [157] on each board. The firmware for

the Arduino is available in the public IV-MUX repository. We developed a Python control program³ that facilitates automated channel switching and measurement using the IV-MUX and the Keysight B2987B electrometer [91]. For a typical measurement, a TTL signal is sent to the IV-MUX to set a channel, then SCPI commands are sent to the electrometer to perform a series of measurements, and then the buffer-data is saved to the computer.

6.2.3 Device Connectivity

The IV-MUX can connect to SiPMs in two different ways, which we refer to as Mode A and Mode B. Mode A works with fully isolated SiPM devices. In this mode, the center and shield of the IV-MUX bias connector are connected directly to the SiPM cathode and anode, respectively, via coaxial cable, and the coaxial shields of all the coaxial cables are connected to the current sense node. Mode A was designed to be compatible with setups where the SiPMs are individually connected to readout cables, and do not share a common anode. In this configuration, low-current performance is limited because the SiPM current is carried on the shield of the coaxial cable, and is therefore subject to electromagnetic interference. However, this effect can be mitigated by operating the IV-MUX (and the SiPM readout cables) inside of a shielded environment, such as a cryostat. Additionally, center to shield leakage current from the coaxial connectors and cables adds to the SiPM current signal, and the current sense trace is unshielded and may pick up noise current through electrostatic induction.

Mode B works with interconnected devices that share a common anode. The center of the bias connector is connected to the SiPM cathode, but the shield is at ground potential. The common anode for all SiPMs in Mode B is connected to the current sensing node through a dedicated coaxial cable. In this configuration, the IV-MUX can be operated in an unshielded environment because the sensitive current is shielded. A dedicated coaxial cable for current sensing also eliminates leakage from the bias through the cable dielectric. Mode B was

³A LabVIEW program is also available.

designed to maximize IV curve performance by minimizing electrostatically induced noise and eliminating leakage current due to imperfect cable insulation.

The IV-MUX was tested in two applications: first, both modes were tested with a SiPM array inside a cryostat. Second, the IV-MUX was tested with a benchtop setup using a SiPM in LN, and both IV and dynamic measurements are compared.

6.3 IV-MUX Performance in Vacuum

6.3.1 Hardware Setup

The IV-MUX was assembled with SAC305 solder and washable solder flux, then cleaned and sonicated in isopropanol. The IV-MUX was then mounted onto a black SLA 3D-printed bracket [158] that holds the IV-MUX to the inside of a CF flange. The CF flange has three access ports, two of which are equipped with a 9-pin Subminiature C [159] and a triaxial feedthrough [160], respectively.

The test comprised of IV measurements of a SiPM array at 165 K using both modes (A and B) of the multiplexer. The SiPM array, a 4x4 Hamamatsu S13775-9121 mini-tile, was affixed to a custom PCB specifically designed for compatibility with modes A and B of the multiplexer. Similar to the IV-MUX, all current sensing traces on the PCB were enclosed with a guard trace, and there was an additional connector for current sensing in Mode B. The PCB was then mounted onto a copper chuck and positioned atop a custom cryostat cold-plate. The temperature of the SiPM array was monitored using calibrated Lakeshore Pt100 RTDs [161] that were installed within an aluminum lug, which was securely bolted to the SiPM PCB's front, and thermally connected using Apiezon N vacuum grease [162].

The IV-MUX was mounted in the spare vacuum chamber, adjacent to the cryostat. The temperature of the IV-MUX was measured at two places. The temperature of a DPST relay was measured by gluing a temperature sensor [163] to its body, and the temperature of the ATmega4809 microcontroller was measured using the built-in sensor [164]. All cables inside the setup were Kapton-insulated and cleaned for vacuum. Inside the vacuum chamber, 50

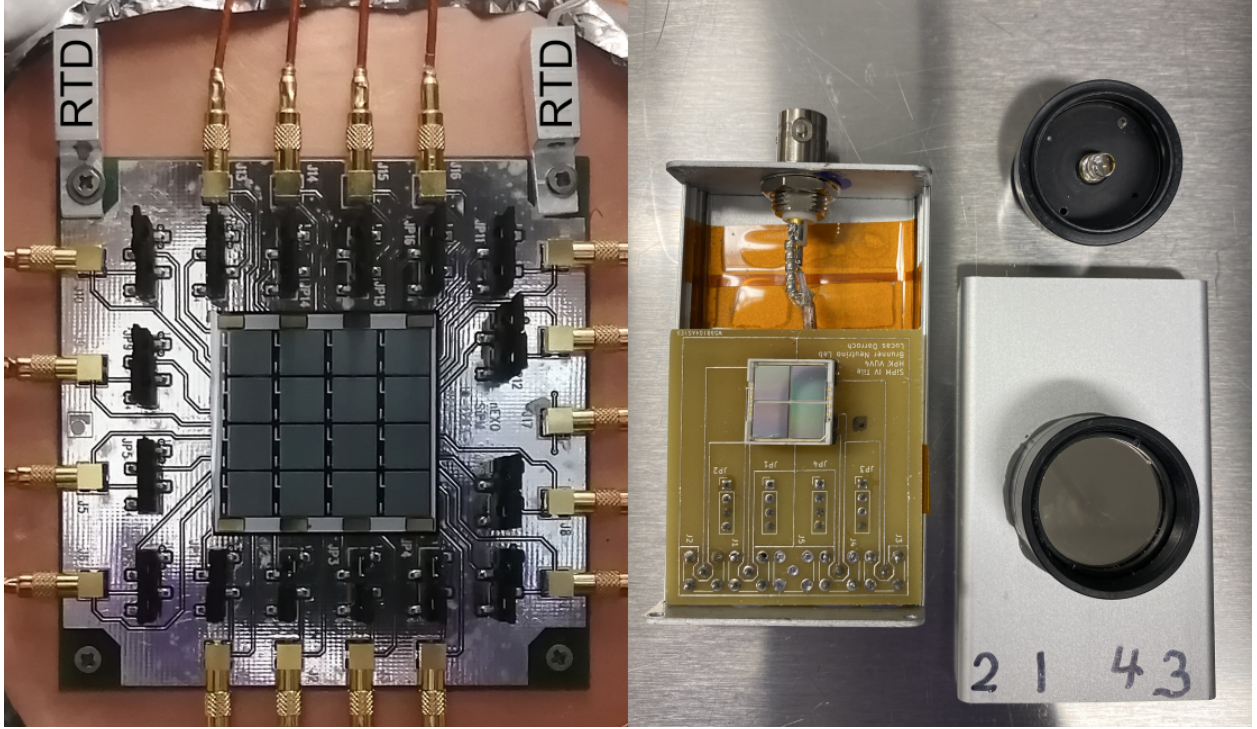


Figure 6-3: Left: A Hamamatsu SiPM mini-tile mounted atop a custom PCB configured to interface with both modes of the multiplexer. Header pins are used to switch between the two modes. The 4x4 SiPM array is used for the measurements with a cryostat presented in this section. Right: A Hamamatsu VUV4 SiPM inside an aluminum enclosure, mounted on a custom PCB with a similar design as the SiPM array. The top of the enclosure with an optical port and a demountable LED (top) are shown adjacent to the SiPM. The 2x2 SiPM is used for measurements in LN2 presented in Section 6.4.

Ω coaxial cables [165] were used for biasing the SiPMs and conducting the current. Outside the vacuum chamber, a 50 Ω triaxial cable was used to carry the current to the electrometer. A picture of the SiPM tile used for vacuum measurements is shown in Figure 6-3. The bias and current sensing connections are routed to a Keysight B2987B electrometer, the IV-MUX power to a 12 V power supply [166], and the serial control to a computer through a UART to USB converter cable [167].

6.3.2 Measurements

The cryostat was evacuated to $< 10^{-6}$ mbar, measured with a cold-cathode gauge [168], then cooled down until the RTD next to the SiPM array stabilized to 165 K. The typical

stability for each measurement was 2 mK. The DPST relay stabilized at 315 K when a single relay was active, and 350 K when all were active; the micro controller stabilized at 310 K and 330 K in both scenarios. The SiPM IV-MUX was configured first in Mode A, then in Mode B, and the IV curves were recorded for each channel. The IV curves were recorded in the dark, with the cold-cathode gauge powered off. Figure 6-4 shows the dark IV curves for 12 SiPMs in both modes. The remaining 4 SiPMs on the array were connected differently and not used in this analysis. Some IV data points in Mode A were removed due to the auto-ranging feature of the electrometer switching during the measurement, which caused a discontinuity in the IV curve due to a different zero/offset value. Data points following a range change were identified irrespective of the IV value through a time delay > 1 second between measurements (typical measurements were delayed by ~ 50 ms). A fixed range was used in subsequent measurements.

The pre-breakdown region of the IV curve is the SiPM linear-mode where each SPAD has a proportional response to the frequency of the incident light [169]. The low-gain and dark count rate of a cryogenic SiPM make the change in linear-mode current as a function of voltage effectively zero, given the resolution of the present experimental setup. Therefore, a small region in linear-mode can be averaged to determine a minimum signal resolution for each mode. The pre-breakdown region between 42 and 44 V was averaged, and each IV curve was offset by adding a constant value such that the mean value of the pre-breakdown region was 1 pA (for visual comparison). The standard deviation of all the data in the pre-breakdown region is $\sigma_A = 134$ fA for Mode A, and $\sigma_B = 92$ fA for Mode B.

6.4 IV and Dynamic Response

6.4.1 Hardware Setup

A two-board IV-MUX (30 channels) was assembled and mounted inside an aluminum enclosure, as shown in Figure 6-1. The IV-MUX was used in two configurations: in an IV configuration (Mode B), where the current from the SiPM anode was measured, and in a

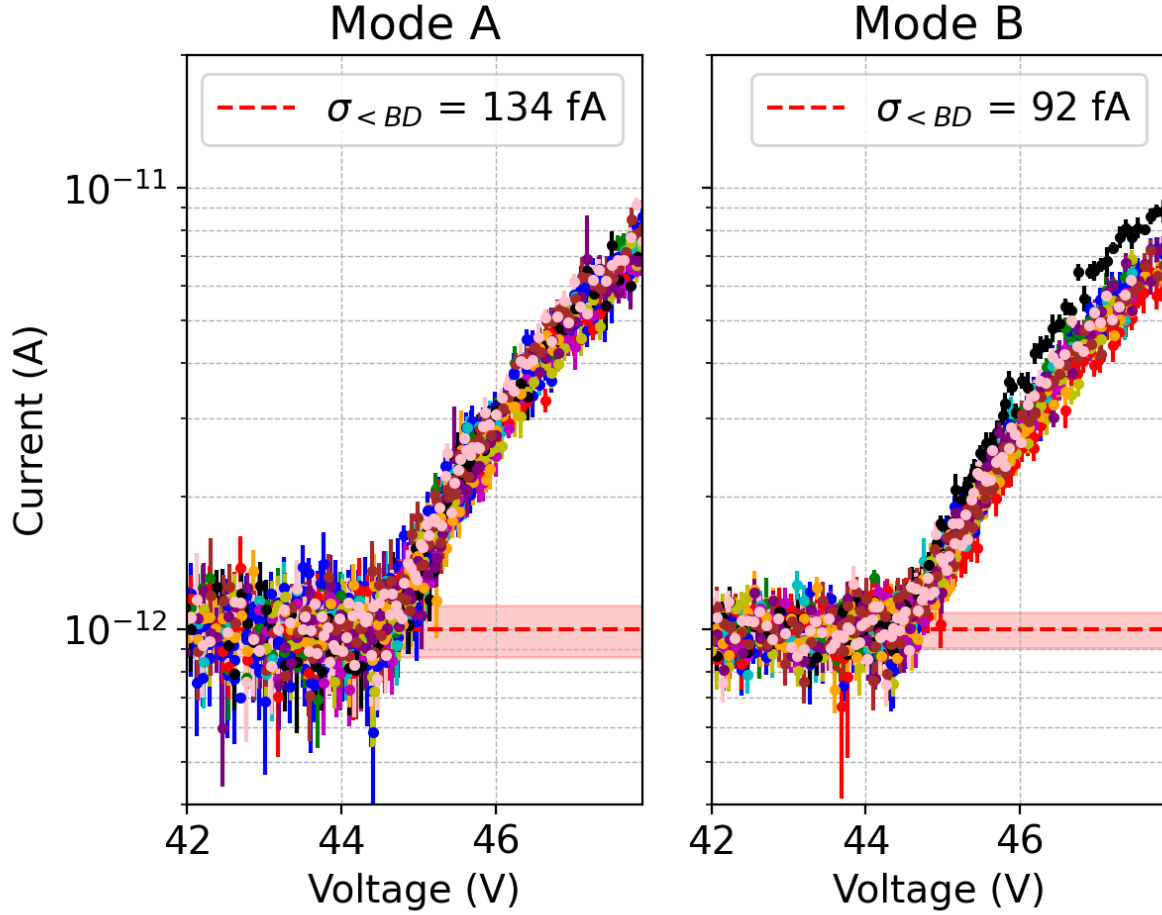


Figure 6-4: Left: Dark IV measurements of 12 SiPMs using Mode A. Right: IV measurements of the SiPM array in the dark using Mode B. The standard deviation of the pre-breakdown region was computed, which provides an estimate of the minimum signal resolution. A constant value was added to each IV curve to align the pre-breakdown region for all SiPMs, which facilitates visual comparison. The uncertainties are a combination of statistical and instrumental errors, added in quadrature.

pulse-counting configuration, where the IV-MUX was used to activate the bias voltage for an amplifier and the output was measured dynamically. To accommodate both IV and pulse-counting measurements, the bias node of the IV-MUX was connected in parallel to a SiPM and a capacitively coupled amplifier. The IV-configuration uses a Keysight B2987A electrometer to measure the current. The pulse-counting configuration uses a Cremat CSP-112 charge-sensitive preamplifier [170] and CR-200 1 μ s shaping amplifier [171] to amplify the signal, which is then recorded with a Rhode and Schwarz RTO2024 oscilloscope [94]. The test comprised IV and pulse-counting measurements of a Hamamatsu S13371-6050CQ-02 VUV4 SiPM [88] at 77 K, submerged in LN2. The SiPM was affixed to a PCB designed for compatibility with modes A and B of the multiplexer, similar to the array used in Section 6-3. The PCB was fixed within a small aluminum enclosure that had feedthroughs for four bias channels, the current sense (Mode B), and an optical port. An LED and two neutral density filters (OD4) [172] were mounted to the optical port to illuminate the SiPM with pulses of dim light. The aluminum enclosure was placed in two nested dewars, and then covered with a lid and a black blanket. A schematic of the experimental setup, and a simplified electrical diagram are shown in Figure 6-5.

6.4.2 Measurements

A simple relation is used to compare the IV measurements to the dynamic response [146]:

$$I_D = \text{DCR} \cdot \text{ECF} \cdot Q_0 + L, \quad (14)$$

where I_D is the dark current, DCR is the dark count rate, ECF is the excess charge factor, Q_0 is the SPE charge, and L is the leakage current. The dark current and leakage were measured using the electrometer, and the DCR, ECF, and SPE charge were measured using the oscilloscope. The DCR, ECF, and SPE charge were measured at nine bias voltages from 44 V to 52 V, and the dark current was measured from 38 V to 52 V in 0.1 V steps, with ten measurements at each step. The waveforms measured by the oscilloscope were digitized and

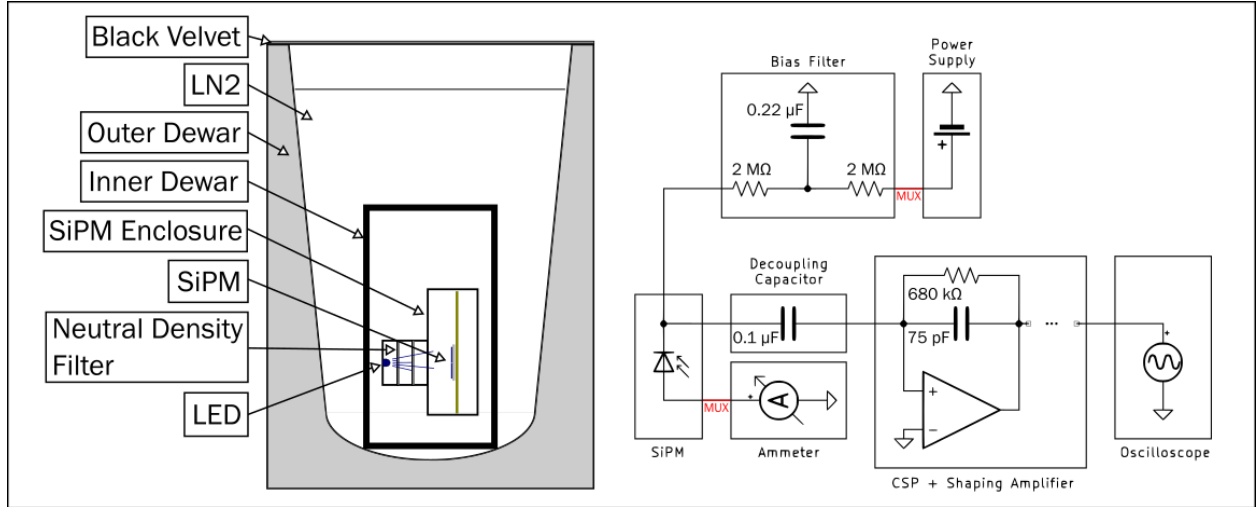


Figure 6-5: Left: a schematic of the experimental setup. The SiPM is inside of an aluminum enclosure that is outfitted an LED and neutral density filters. The enclosure is placed within two nested dewars and submerged in LN2. Right: a simplified electrical diagram of a single channel for IV and pulse counting measurements. The high-side of the SiPM is used for pulse counting measurements, and the low-side for IV measurements. The IV-MUX is used to route bias voltage to the SiPMs through the bias filter, and collect current from the SiPM.

analyzed using a custom Python script. The charge spectrum was computed by extracting the amplitude value for triggering waveforms and scaling by the gain of the amplifier, which was determined by injecting a known charge into the amplifier by applying a 214 mV square wave to a calibrated 9.5 pF capacitor. The charge spectrum was analyzed to determine the SPE charge and ECF, and the timing distribution of the peak time was analyzed to determine the dark count rate. Sporadic single-avalanche event bursts were observed with a uniformly distributed rate around kHz-MHz, which is significantly higher than the expected dark count rate, and typically comprised fewer than fifty events, but represent around 15% of all events. These burst events may be caused by a cosmic muon traversing the quartz window of the SiPM [173]. The observed burst rate is consistent with the cosmic muon flux at the experimental location in Montreal. Although the dark count rate can be determined through a Poisson fit to the timing distribution of dark events [174], the IV response captures all events. Therefore a comparison between IV and pulse-counting requires an effective dark count rate, DCR_{eff} , that includes all avalanches from the SiPM. The effective dark count

rate was determined by acquiring 10,000 waveforms that were 200 μs long, recording the peaking time for events above a 0.5 PE threshold, then taking the inverse of the mean time difference for all events. The voltage dependence was initially modeled as an exponential modulated by a sigmoid [143], however this failed to reproduce the observed trend, likely due to the burst events. An additional constant term was added to account for the mean burst rate:

$$\text{DCR}_{eff} = (Re^{kV_{OV}} + B) (1 - e^{-\alpha V_{OV}}), \quad (15)$$

where R , is the dark count rate at breakdown, k is the rate parameter, B is the mean background rate, α is the breakdown parameter, V_{OV} is the overvoltage ($V - V_{BD}$), V is the bias voltage, and V_{BD} is the breakdown voltage. A plot showing the effective dark count rate and the fit of Equation 15 to the data is shown in Figure 6-6.

The SPE charge and ECF were measured with a blue LED to acquire the measurement in a faster time, given the low dark count rate (~ 1 Hz). Both the SPE charge and the ECF were determined using the same data set of 100,000 waveforms, 200 μs long. The SPE charge was determined by fitting the SPE peak with a Gaussian function with asymmetric range constraints to prevent afterpulsing from introducing a bias to the fit. The voltage dependence of the SPE charge was modelled as a line:

$$Q_0 = C(V - V_{BD}), \quad (16)$$

where C is the effective SPAD capacitance. The breakdown voltage determined through Equation 16 is used to determine the overvoltage throughout the analysis. A plot of the SPE charge and the fit of Equation 16 is shown in Figure 6-7.

The optics were configured so that when LED pulses shorter than the SiPM's recovery time (around 100 ns) were sent at a rate of 50 kHz, the SiPM had a detection rate of nearly 100 Hz with a 0.5 p.e. threshold, at 2 volts of overvoltage. Having a large separation between

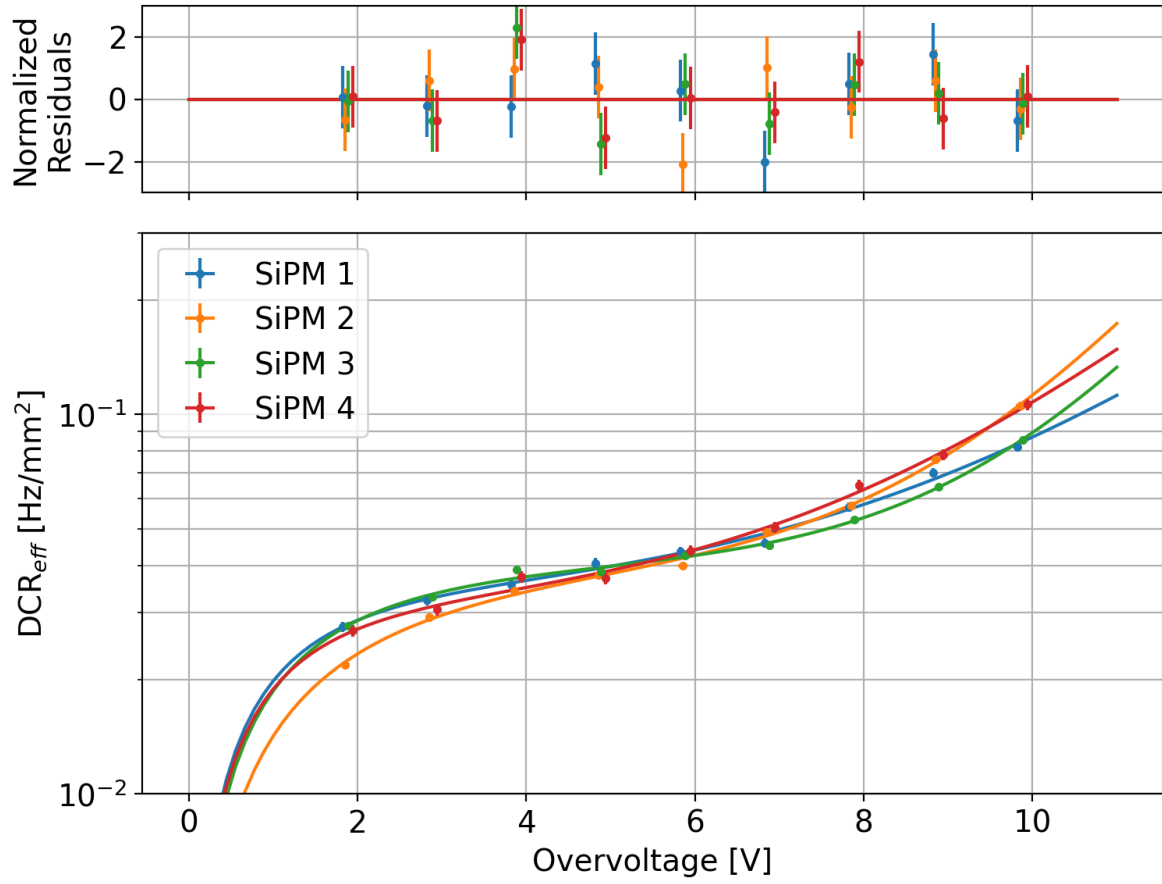


Figure 6-6: The voltage dependence of the dark count rate, measured for all quads of the Hamamatsu VUV4 SiPM.

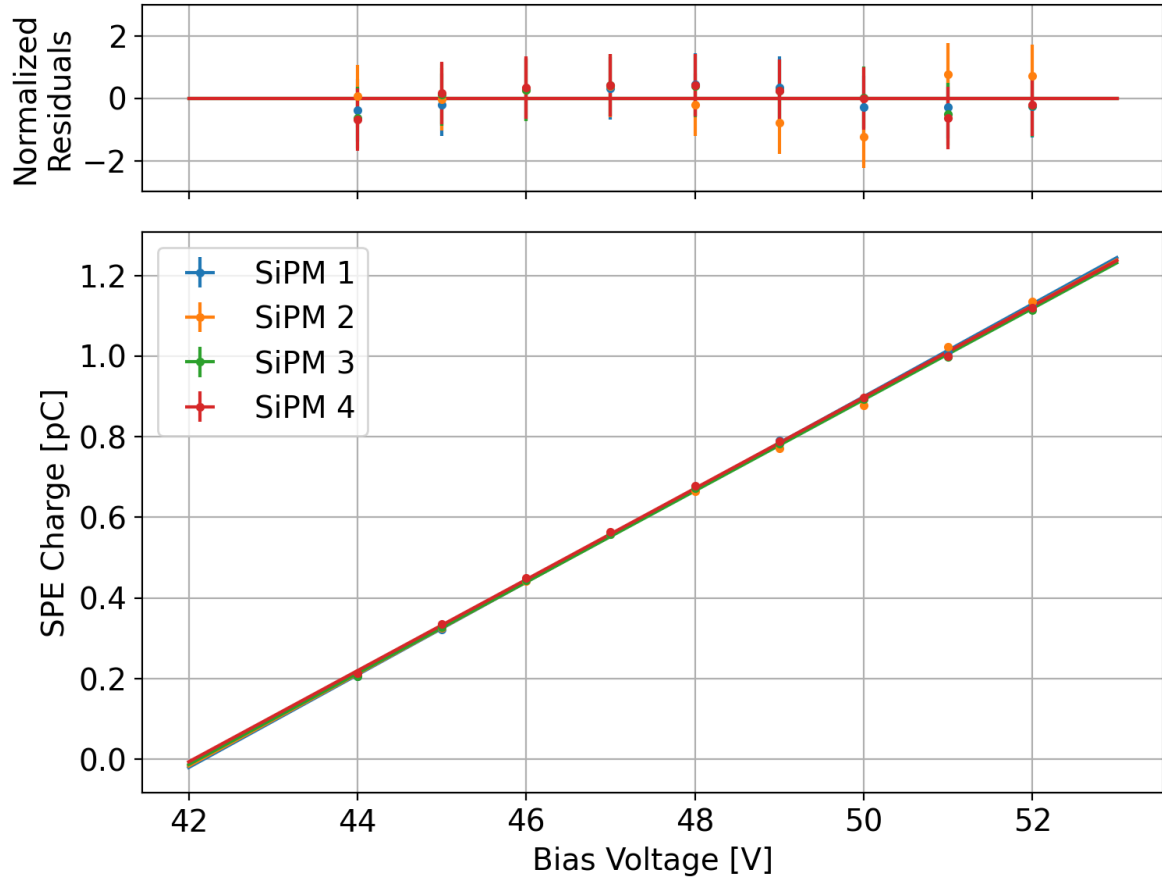


Figure 6-7: The voltage dependence of the SPE charge, measured for all quads of the Hamamatsu VUV4 SiPM. The breakdown voltage can be determined by extrapolating the linear fit to the x-intercept.

a zero detection and a SPE detection allows two methods to be used in determining the ECF. Both methods rely on the following relation for the mean number of avalanches:

$$\langle k \rangle = \mu \cdot \text{ECF}, \quad (17)$$

where μ is the mean number of detections. The first method for determining the ECF assumes Poisson statistics to determine the mean number of avalanches by counting zero-detections through the following relation [140]:

$$\mu = -\log \left(1 - \frac{R}{f} \right), \quad (18)$$

where R is the count rate and f is the flashing rate of the LED. The mean number of avalanches is determined by taking the mean of the charge distribution and multiplying it by the ratio of the detection rate to the flashing rate.

The second method for determining the ECF uses Poisson statistics in a different manner: since the mean number of avalanches from an LED flash is much less than one, the probability for two or more detections is much smaller than the probability for a single detection, which means that μ is approximately one for all recorded events [59]. In this case, the mean number of avalanches is the ECF. The ECF derived using both methods was generally in agreement to better than 0.1% accuracy, however, the first method was arbitrarily chosen for the continued analysis. To first-order, the average extra charge is the probability of a correlated avalanche multiplied by the expected charge of a correlated avalanche, however, at high overvoltage correlated avalanches can occur recursively when the probability for a delayed correlated avalanche, such as an afterpulse, is sufficiently high. It is possible to model the recursive afterpulsing using distinct processes for the different types of correlated avalanches, however, this poses a risk of overfitting the data due to insufficient degrees of freedom. A semi-empirical relation is used where the average extra charge is approximated using the product of a gain dependent term and a breakdown dependent term, and added

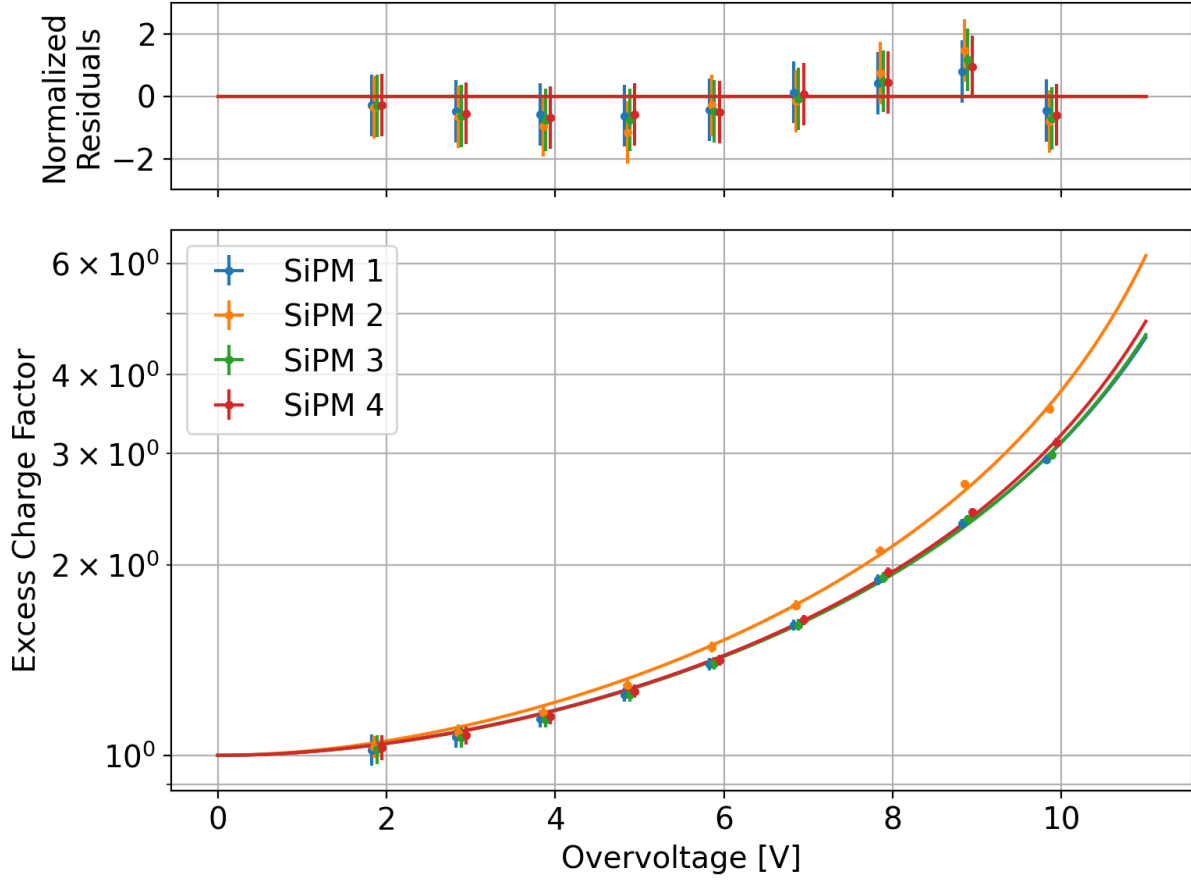


Figure 6-8: The voltage dependence of the ECF, measured for all quads of the Hamamatsu VUV4 SiPM.

geometrically [141]:

$$\text{ECF} = \frac{1}{1 - aV_{OV}(1 - e^{-bV_{OV}})}, \quad (19)$$

where a and b are fit parameters. A plot of the ECF and the fit of Equation 19 is shown in Figure 6-8.

As shown in Equation 14, the SiPM dark current can be predicted using the DCR, SPE charge, and the ECF. We calculated the SiPM dark current using the aforementioned parameters, and computed a functional form of the dark current using the voltage dependent models. Figure 6-9 shows dynamically measured dark current compared against the static dark current, as measured with the electrometer. The leakage current is calculated using

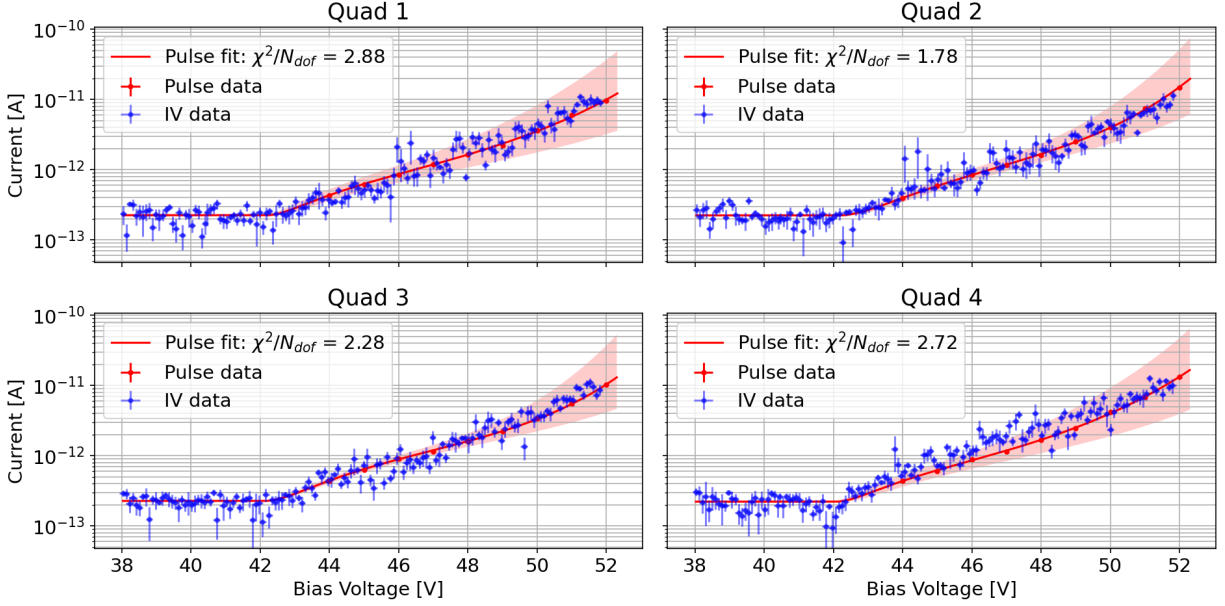


Figure 6-9: The dark current for each of the quads from the Hamamatsu VUV4 SiPM, as determined by both dynamic and static measurements. The current measured using the electrometer is shown with blue circles, the current measured using Equation 14 is shown with orange triangles, and the current measured through the voltage dependent parameter model (and Equation 14) is shown with a red line.

the pre-breakdown region, and is added to the dynamically measured dark current as a constant offset. In general, there is good agreement between the two methods, showing that the integration of the IV-MUX does not degrade the expected small signal from a SiPM at cryogenic temperature in the dark. We have also fit the functional form of the dark current to the dark IV data, and although the IV-fit trended similarly to the dynamically measured dark current, the individual predictions for the DCR, SPE charge, and ECF were inconsistent with the expectation from the dynamic measurements. This inconsistency suggests that the functional form of the dark current is overdefined.

Equation 14 demonstrates that with any two known dynamic variables, the third can be determined using a dark IV curve. To achieve this, additional dark IV measurements were taken at the same voltages as the dynamic measurements. These measurements, along with the leakage current, ECF, and SPE charge, were used to calculate the DCR. Figure 6-10 shows a comparison of the DCR obtained through pulse-counting and the DCR obtained

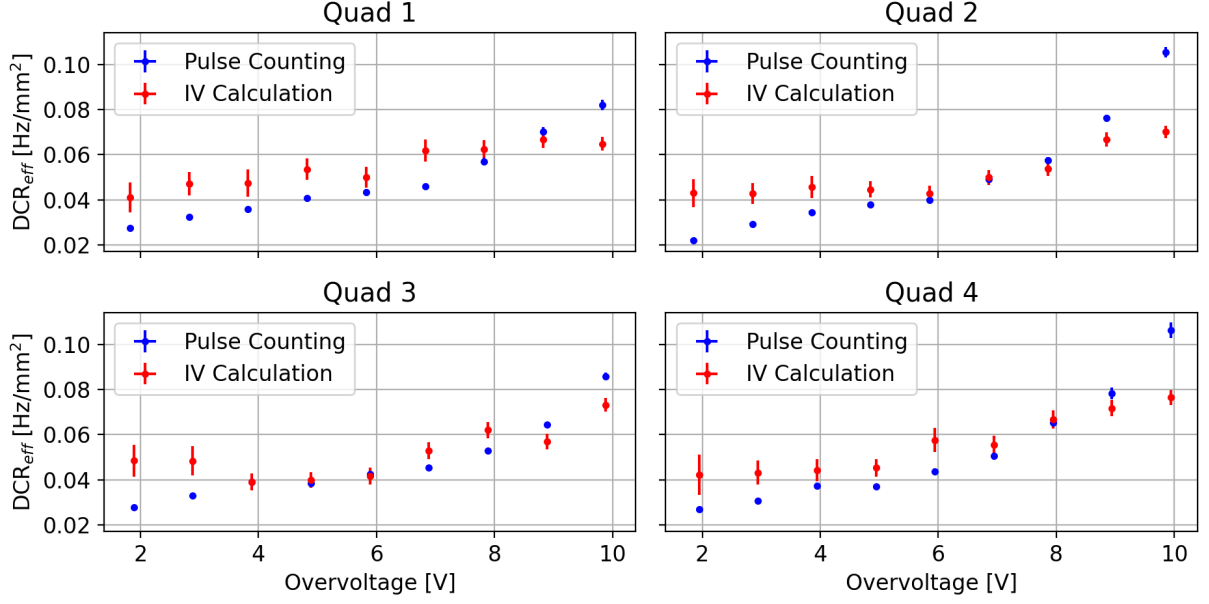


Figure 6-10: The effective DCR for each quadrant of the SiPM calculated through different methods. The pulse-counting method uses the time difference between pulses greater than 0.5 PE, as is explained in Section 6.4, whereas the IV method uses Equation 14 and a combination of pulse-counting measurements (ECF and SPE charge) and dark IV measurements to determine the effective DCR.

through a combination of pulse-counting and IV measurements. The results indicate that if the effective gain, defined as the product of the ECF and SPE charge, can be derived from an IV measurement, then the DCR can be accurately determined from a dark IV measurement.

7 Conclusions

Searches for $0\nu\beta\beta$ present an opportunity to discover new physics through the neutrino sector. nEXO, a next generation $0\nu\beta\beta$ detector, is in an advanced stage of development, which has put more focus on infrastructure for testing detector components and long-term stability studies. The McGill University nEXO group is supporting development of the nEXO photodetector through SiPM testing infrastructure.

The design and evaluation of an optical cryostat for testing SiPMs with VUV light was reported in Chapter 4. A VUV optical system was assembled around a custom 14 cm diameter CaF_2 viewport inside a nitrogen-purged dark box. The sealed dark box and CaF_2 viewport are necessary to build the VUV optical system outside the cryostat. Industrial linear motion parts were used to construct a two-axis linear rail system that positions light sources above the cryostat. A custom xenon scintillation lamp served as a 172 nm line source, and a xenon flash lamp with optical filters was used as a high-flux VUV light source. The cryostat and optical system were tested with a Hamamatsu S13775-9121 mini-tile from 163 K to room temperature, in 10 K increments using both IV and pulse counting measurements. The breakdown voltage was measured using both methods, with the breakdown voltage from the IV method being systematically 0.2 V greater than that from the pulse counting method. The average SPAD capacitance was measured for each SiPM from 163 K to 253 K, and we found the mean value to increase by 4.3 fF at 163 K compared to the mean value at warmer temperatures. The xenon flash lamp was equipped with filters and apertures to produce a VUV beam that was rastered across an OSI Optoelectronics XUV-100C photodiode. A light map was produced from the raster scan, which was used to determine an average radiant power of (23.6 ± 0.1) pW of VUV light incident on the photodiode from an elliptical beam with radii of $w_x = 1.95$ mm and $w_y = 1.03$ mm.

Hamamatsu VUV-sensitive SiPMs were tested at 165 K before, during, and after VUV exposure, and after thermal annealing. The result from this study were reported in Chapter 5. There was no significant change to the SPE charge, PDE at 172 nm, or the average extra

charge from correlated avalanches; however, the dark count rate increased by more than an order of magnitude. An increased dark count rate is expected from ionization damage in SiPMs. However, the mean energy per photon (6.8 ± 0.6 eV) that irradiated the SiPMs was lower than the energy required to make an e-h pair in SiO₂ (17 eV), and it is believed that ionization damage occurs from holes in the SiO₂ layer becoming trapped at the Si-SiO₂ interface [104]. The observed result could be explained through two different processes. First, ionization of Si (3.6 eV) close to the SiO₂ layer may cause charge carriers to interact with the Si-SiO₂ interface and become trapped. Second, electrons boosted to the conduction band in SiO₂ (8.1 eV) [175] close to the Si-SiO₂ interface may cause mobilized holes to become trapped at the interface, similar to how ionization causes holes to become trapped. These two processes could be differentiated in an experiment by irradiated SiPMs with UV light that is more energetic than the mean energy for e-h pair production in Si, but less energetic than the band gap in SiO₂. It is not likely to observe the same effects from ionization damage at room temperature due to high mobilization in the lattice, which effectively anneals these defects from the device. When determining performance expectations for noble liquid detectors, cryogenic ionization damage should be considered to prevent an unexpected performance loss during operation.

The design and performance studies of a multiplexing system specifically tailored for automated SiPM IV measurement was reported in Chapter 6. The IV-MUX can also be combined with an amplifier to facilitate both static and dynamic characterization of SiPMs. The IV-MUX is capable of routing the signals for up to 105 SiPMs through a single ammeter, or as parallelized output to a multichannel ammeter, which significantly reduces the cost and time required to measure the IV response of SiPM arrays. The IV-MUX is vacuum compatible, which further reduces the cost per channel by eliminating the need for specialized multi-channel vacuum feedthroughs. These results demonstrate that measuring the dark current with the IV-MUX is comparable to the prediction through dynamic measurements, even at cryogenic temperature (77 K) where the dark current is less than 1 pA. Integrating an

IV-MUX into a measurement system can significantly reduce the measurement time through automated multiplexing, while still maintaining the accuracy of the IV measurement. Ideally, the IV measurements would be used to predict the dynamic response of a SiPM, however, these parameters could not reliably be extracted. This is likely due to an overdefined model fit to a non-linear equation. It may be necessary to use a multi-dimensional model using additional independent variables, such as the intensity or repetition rate of a light source, to add enough constraints to the IV response to accurately predict the dynamic response of a SiPM. Although the IV-MUX was designed for SiPM testing, it can be used for similar current sensing devices where high channel count and low leakage current are required.

The hardware described in Chapters 4 and 6 have had continued development into a turn-key system for automatically testing SiPMs tiles for nEXO, with static and dynamic measurements. These future studies will continue to build on the work presented herein, helping to realise the nEXO detector.

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