DEVELOPMENT OF A COST-EFFECTIVE, PORTABLE NEUTRON IMAGER AND SPECTROMETER USING SINUSOID-BASED MULTIPLEXING OF SILICON PHOTOMULTIPLIERS AND PLASTIC SCINTILLATORS

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Abstract

Nuclear nonproliferation and nuclear security require tools to detect, characterize, and locate special nuclear material (SNM). The measurement of neutrons emitted from SNM offers a non-destructive means of doing so, and neutron imaging is a particularly attractive application of neutron measurements to better understand a neutron source for various applications. A field-deployable neutron imager could, for example, be used to locate an improvised nuclear device for emergency response, verify the presence of a nuclear warhead in a disarmament scenario, confirm nuclear material declarations for nuclear safeguards, or find a nuclear weapon in certain envisioned warfighting situations. Unfortunately, the established methods of neutron imaging are difficult to translate from a laboratory setting to the field, primarily due to large sizes and limited maneuverability.

The neutron imaging method with the greatest potential for compactness and portability is the neutron scatter camera (NSC) because it requires no modulation of the incoming signal, no moving parts, and does not use gases in the system. Beneficially, NSCs in principle also offer full four-pi angular sensitivity and inherently measure the energy of incident neutrons on an event-by-event basis. Advances in light sensor technology, for example in the development of silicon photomultipliers (SiPMs), have enabled the conception of truly compact NSCs: the single volume NSC and the quasi-single volume NSC. The close spacing of and position sensitivity within detector elements in these designs also enables much greater imaging efficiency. The quasi-single volume NSC is likely more feasible to construct in the near-term, and, within this design space, multiple imager configurations are possible with different performance in different characteristics such as detection efficiency, angular resolution, and
Performance in these characteristics typically varies inversely with that of the others, and different applications might prefer different qualities, discouraging a one-size-fits-all approach.

This dissertation develops a compact, portable quasi-single volume NSC with an emphasis on inexpensively achieving a high detection efficiency. To accomplish this objective, SiPMs and plastic scintillators are chosen to comprise the imager, and a channel multiplexing method is used to increase the number of detector elements that can be used given digitization hardware restrictions. Extensive assessment of SiPM technology is carried out, and a novel sinusoid-based multiplexing method designed for SiPMs is created and shown to be effective and to maintain good detector performance. Geant4 simulations are used to design the multiplexed neutron imager (MiNI) and understand the effects of multiplexing, leading to the selection of a 32-scintillator 16-digitizer channel configuration. A number of calibrations are carried out to enable the imaging and spectroscopy capability of the MiNI, and where appropriate, these are also used as a large-scale test of the multiplexing method.

The MiNI is tested with a $^{252}$Cf spontaneous fission source and its imaging capability is demonstrated with the source at multiple locations around the MiNI, as well as its spectroscopic capability. The MiNI developed in this dissertation is the first multiplexed NSC and the first reported quasi-single volume NSC composed of more than eight elements or plastic scintillators to fully demonstrate effective neutron imaging. Ultimately, the MiNI establishes the feasibility of multiplexing a compact NSC and demonstrates a route to achieve high imaging efficiency in a cost-effective manner.
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List of Abbreviations

AC ............... alternating current
APD ............. avalanche photodiode
CC ............... charge comparison
CTR ............. coincidence time resolution
FFT ............. fast Fourier transform
FGA ............ frequency gradient analysis
FOM ............ figure of merit
FWHM .......... full-width half-maximum
FWTM .......... full-width tenth-maximum
H2DPI .......... handheld dual-particle imager
IAEA .......... International Atomic Energy Agency
KNN ............. K-nearest neighbors
MCP-PMT .......... micro-channel plate photomultiplier tube
MiNI .......... multiplexed neutron imager
mTC ........ miniTimeCube
MLEM .......... maximum likelihood expectation maximization
NPT .......... Treaty on the Non-proliferation of Nuclear Weapons
NSC ........ neutron scatter camera
op-amp .......... operational amplifier
PET .......... positron emission tomography
PMT .......... photomultiplier tube
PSD .......... pulse shape discrimination
PSP .......... pulse shape parameter
RF ........ radio-frequency
SANDD .......... segmented antineutrino directional detector
SiPM .......... silicon photomultiplier
SNM .......... special nuclear material
SOE .......... stochastic origin ensemble
TMVA .......... toolkit for multivariate analysis
TOF .......... time-of-flight
TPC .......... time projection chamber
Acknowledgments

Finishing a PhD is an accomplishment that I am proud of, but while the degree provides a singular, tangible outcome, I think it is more representative to view it as a journey (done with clichés now). When I look at it from this perspective, it naturally breaks down into stages, each building on the last, and in every single stage it’s hard to overstate how much other people have influenced and helped me as they pushed me on to the next stage. As I prepare to start my first “real job” with NNSA - though, as a fellowship, even this might not constitute a first “real job” - I still have a lot to learn, but I at least feel ready for it, and there are a lot of people I need to thank for getting me to this point. Apologies in advance for the length of my acknowledgments, but, more than anything I have ever written, this is my space to write as I want, and I think it would be inadequate to say any less than I am about to.

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Dedication

For my Dad, Tom Wonders, my first math teacher who started me down the path to where I am today.
Chapter 1

Introduction

The study of radioactivity and nuclear science began respectively in 1896 with Roentgen’s discovery of X-rays, and in 1911 with Rutherford’s famous gold foil experiment that led to the concept of a nucleus [1, 2]. Understanding of nuclear physics fervently progressed over the next decades, and the culmination of efforts by scientists such as Fermi, Meitner, and Hahn in the 1930’s lead to the discovery of fission in 1938, setting the stage for nuclear science and its various applications to profoundly impact our society [3]. Shortly after the discovery of nuclear fission, it was applied toward its two most well-known uses: nuclear weapons and nuclear energy. The demonstration of both emphatically established that nuclear fission was to inextricably embed itself in our society, and that its misuse could have catastrophic consequences to the world it is intended to benefit. Likewise, radioactivity became essential to a number of fields, finding uses in industry and medicine, but as with nuclear fission possessing inherent dangers if applied nefariously or irresponsibly.

The goal of this thesis is the development of an imaging tool that will support the mission of preventing the use of nuclear materials by those with malevolent intentions. To thoroughly understand the importance of the proposed neutron device, the nuclear security landscape and associated tools must first be understood.
The dangers associated with nuclear fission and radioactivity, which are frequently referred to as nuclear science, necessitate the implementation of measures to ensure their safe use. Notable early international entities put into place for this purpose are the Treaty on the Non-proliferation of Nuclear Weapons (NPT) and the International Atomic Energy Agency (IAEA), put into place in 1968 and 1957, respectively [4, 5]. The NPT established the following nuclear weapons states: United States, Soviet Union, United Kingdom, France, and China. The established nuclear weapons states agreed to eventually disarm and also support the other signatories in their pursuit of peaceful nuclear science applications. In return, the non-nuclear weapons signatory states agreed not to pursue nuclear weapons. This agreement set up the safeguards regime that aims to prevent states from covertly developing nuclear weapons by verifying that nuclear fuel cycle activities are exclusively for peaceful use. The IAEA became the main body charged with verifying compliance with the NPT, while also carrying out other tasks such as promoting the peaceful use of nuclear technology. In addition to large scale treaties like the NPT, some smaller (i.e. bilateral or trilateral) agreements exist and more could be implemented in the future. These smaller agreements are important for arms control, for example, between the United States and Russia. Another relevant consideration is the possibility that nuclear material is somehow obtained by non-state actors who could subsequently construct an improvised nuclear device capable of causing mass destruction and panic. It is in this context that the related missions of nuclear nonproliferation, safeguards, security, forensics, and arms control came into existence. These terms can be confused and differences between them are subtle, so definitions of each are useful; although, it should be noted that definitions from different sources may still vary.
Nuclear safeguards describe “a system of accounting, containment, surveillance, and inspections aimed at verifying that states are in compliance with their treaty obligations concerning the supply, manufacture, and use of civil nuclear materials” [6]. Nuclear security refers to the “prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances, or their associated facilities” [7]. Nuclear forensics is “the analysis of intercepted illicit nuclear or radioactive material and any associated material to provide evidence for nuclear attribution” [8]. Nuclear forensics can also be taken more broadly to refer to any nuclear-based analysis that can aid in the attribution of the origin of nuclear material, including a post-detonation analysis. Arms control includes “measures, typically bilateral or multilateral, taken to control or reduce weapon systems or armed forces” [6]. Finally, nuclear proliferation is frequently defined as “the spread of nuclear weapons, nuclear weapons technology, or fissile materials to countries [or terrorist organizations or other armed groups] that do not already possess them,” and so non-proliferation aims to combat this [9]. Because these different objectives are so closely related, they generally share common means to support them, including both policy and technology that are interdependent on each other. The technical means of supporting these missions are the focus of this thesis, but the political infrastructure for applying them is a critical backdrop to always be kept in mind. For example, future arms control treaties will likely require a versatile tool to verify the presence of nuclear warheads while operating with severe information barriers to prevent the recording of sensitive data about the warhead under examination.

Because of the radioactive nature of special nuclear material (SNM), an essential instrumental approach for nuclear nonproliferation, safeguards, etc., is radiation detection.
SNM such as uranium-235, uranium-233, and plutonium emit radiation, including alpha particles, gamma rays, and neutrons, and thus the detection of this radiation is an effective means of detecting and characterizing SNM [10]. Radiological materials, by definition, also emit radiation. Gamma rays and neutrons are the most penetrating of the typical SNM emissions and so are the most commonly used radiation for detecting SNM nondestructively. As such, many types of gamma ray detectors and neutron detectors (semiconductor detectors, organic and inorganic scintillators, gas detectors, etc.) are widely deployed and used throughout the world to detect radioactive materials.

There are abundant naturally occurring sources of gamma rays. However, the same is not true for neutrons, so the neutron background is typically very small. This makes neutrons an excellent probe of SNM, and detecting neutrons above natural background rates is a strong indicator of the presence of SNM, making the detection of neutrons an invaluable tool for the nuclear security-related mission space. In many scenarios, however, merely detecting SNM or another radiation source is not sufficient. Locating and/or characterizing the source can also be of critical importance, and neutrons can be instrumental in inferring information about the radiation source.

Moving beyond simple detection, if the neutrons can be measured and correlated in time, a wealth of additional information is also made available, for example using neutron multiplicity counting to accurately quantify the amount of SNM present. However, many applications or scenarios require even more information about the neutron source. Specifically, for nuclear security and nonproliferation, one may need to find an unknown source or to characterize the spatial distribution of a known neutron source. In these cases, simply counting neutron events
is an insufficient mode of analysis, and neutron imaging becomes essential. Additional information that can be used to characterize and understand a neutron source is the neutron energy spectrum. Neutron energy spectra could be used to discriminate a fission source of neutrons from a non-fission source, or potentially provide information about the scattering medium composing and surrounding the source. Effective tools to conduct neutron imaging and spectroscopy are therefore essential to enable robust nuclear nonproliferation and security.

In support of the aforementioned missions, this thesis aims to develop a portable fast neutron imaging system that has spectroscopic capabilities for fast neutrons. Such a versatile tool would be useful for supporting nuclear security. Currently available neutron imaging systems are generally large, stationary, and have other drawbacks such as limited field of view or low detection efficiency per unit volume. Neutron spectroscopy is also a difficult task, and currently there are only a few solutions for portable neutron spectrometers. Consequently, deployment of neutron imaging and spectroscopy systems is not feasible and/or not worthwhile given the challenges associated with the size, cost, and complexity of the available options, but it could be with the proper technology development. A portable neutron imaging spectrometer could yield new methods and abilities for localizing or identifying nuclear material, for example conducting these measurements in environments that were not previously possible such as in confined spaces or locations in which extended set up times are not allowed. Additionally, it could streamline source characterization by combining multiple methods of analysis in a single device.

Neutron imaging could be used to locate a rogue radioactive source or SNM in emergency response situations (nuclear security). In potential interdiction scenarios, such as cargo
screening, imaging could be used to reduce background and increase sensitivity, it could localize the neutron-emitter inside a large closed container, and its spectroscopic capabilities could be used to distinguish between possible SNM and industrial (α,n) neutron sources (nuclear nonproliferation). In treaty verification, a neutron imager could be used to verify the presence of warheads (and possibly the number) while recording little sensitive gamma-ray conveyed information (arms control). It may also be used to verify the presence of nuclear material in declared locations and facilitate nuclear material monitoring (nuclear safeguards) [11]. Further, in the absence of more sophisticated neutron time-of-flight (TOF) infrastructures, it could be used for fundamental nuclear science. For example, it could measure delayed neutron spectra from various actinides, which beyond fundamental studies could potentially be applied toward identification of a fissioning isotope (nuclear forensics). The presence of a portable neutron imaging spectrometer could also prompt the conception of novel applications not mentioned above.

Radiation imaging and spectroscopy, especially of neutrons can be a powerful method tailored to the examples above, and many more. The field deployment of portable neutron imaging spectrometers could be transformative in increasing nuclear security, improving nuclear safeguards, enabling further arms control, and preventing nuclear proliferation, among other objectives. This thesis aims to advance the development of this technology and support its eventual deployment. To do so, a series of studies are undertaken to better understand the underlying technology, and a novel signal multiplexing method to greatly simplify and reduce hardware costs is created. Ultimately, a prototype is developed that emphasizes scalability and
ruggedness and demonstrates the possibility of achieving high detection efficiency in a cost-efficient manner.
Chapter 2

Neutron Imaging and Spectroscopy

2.1. Detection of Neutrons

The first step in imaging neutrons is detecting neutrons emitted from a source. Two different means of doing so exist for neutrons in different energy regimes based on either neutron capture or neutron scattering. Examining the neutron cross sections (the likelihood of reaction occurrence) of different interactions dictates how to efficiently detect neutrons. Neutron cross sections for three important nuclei, chosen for relevance to the following discussion, are shown in Figure 2.1.

It is immediately apparent that neutron interactions are far more likely at low energies, so if an interaction at such energy can produce a measurable signal it would be an advantageous approach. For some isotopes and neutron energies, the best approach is utilizing a reaction in which the neutron is captured by the nuclei and converted into charged particles. Consequently, enough energy is given to the daughter particles so they can be detected directly. $^3$He-based detectors are the most effective detectors based on this reaction and are used to detect slow or ‘thermal’ neutrons that have energy on the order of less than 1 eV. Alternative nuclei that can be used effectively for detecting thermal neutrons are $^6$Li and $^{10}$B. However, neutrons originating from actinides of interest, produced either from fission or ($\alpha$, n) reactions, primarily have energy on the order of MeV, making them ‘fast’ neutrons. Example spectra of both these
Figure 2.1. Relevant cross sections of $^1$H, $^3$He, and $^{12}$C for detecting neutrons as a function of the energy of the incident neutron, obtained from Evaluated Nuclear Data Files [12]. The second word in the parentheses of the legend describes the type of interaction considered. “Tot” indicates the total cross section including all interaction channels for a given target nucleus. For $^3$He, “P” means a capture reaction in which a proton and $^3$H are produced. “El” describes elastic scattering only.
types of neutron sources are shown in Figure 2.2. In order to detect fast neutrons in capture reactions they must be slowed significantly by scattering prior to the capture reaction in the detector.

A desire for compactness or simplicity of detection systems, or for more direct interaction with a source of interest may motivate the direct detection of fast neutrons. Capture reactions are then no longer an effective means of detecting fast neutrons and scattering reactions take precedence. When a nonrelativistic neutron scatters elastically off of a nucleus, conservation of momentum and energy yields

\[ E_r = E_n \frac{4A}{(1 + A)^2} \cos^2 \theta_r, \]  

(2.1)

where \( E_r \) is the recoiling nucleus’ kinetic energy, \( E_n \) is the incident neutron’s kinetic energy, \( A \) is the atomic mass of the recoiling nucleus, and \( \theta_r \) is the nucleus’ angle of recoil.

From Equation 2.1, the smaller the mass of the recoil nucleus, the greater energy it can possess, so the ideal nucleus is \(^1\text{H} \), simply a proton, whose recoil energy can range anywhere between zero and the full energy of the incident neutron. Consequently, organic materials that contain hydrogen make the ideal detection medium for fast neutrons, and organic scintillators are the primary detectors available. Organic scintillators create a signal by converting the energy of the scattered charged particle into excitation and ionization of molecules in the scintillator, which subsequently produce photons by recombination and de-excitation. These photons then must be converted and amplified into an electrical signal by a light sensor to obtain a measurable signal. Organic scintillators are composed of hydrogen and carbon, the cross-sections of which are shown in Figure 2.1. Interaction with carbon in these scintillators frequently takes place, but as shown by Equation 2.1, the recoiling carbon will have
Figure 2.2. From top to bottom, a typical ($\alpha$, n) differential neutron energy spectrum from an AmBe source; a typical ($\alpha$, n) differential neutron energy spectrum from an AmLi source; a typical Watt spontaneous fission differential neutron energy spectrum from $^{252}$Cf, obtained from [13].
significantly less energy than an analogous $^1$H scatter, and the signal produced will be further attenuated by quenching effects in the scintillator, making them mostly an obstruction to optimal scattering off of $^1$H [14, 15]. Both thermal and fast neutron detectors are possible to use for neutron imaging.

2.2. Gamma Ray Interactions in Scintillators

Gamma rays are not the focus of this thesis, but a brief description of their interactions in scintillators is useful for two reasons. Monoenergetic gamma ray sources are readily available (unlike monoenergetic neutron sources), which makes them useful for calibration and characterization purposes. Additionally, they can be a source of interference in neutron detection so it is important to assess such interference.

When interacting with matter, gamma rays interact mostly with atomic electrons and three major processes may take place: photoelectric absorption, Compton scattering, and pair production. Pair production has a minimum energy threshold of 1.022 MeV and is not worth discussing further since the process is not used for calibration or characterization, and gamma rays are not the radiation of interest for measurement. Photoelectric absorption scales very strongly with the atomic number of the material, so for organic scintillators, which are composed of low atomic number hydrocarbons, Compton scattering is the primary method of interaction. In Compton scattering, the energy imparted to the scattered electron is described by

$$E_e = E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)}$$  \hspace{1cm} (2.2)
where $E_e$ is the energy of the scattered electron, $E_\gamma$ is the energy of the incident gamma ray, $m_e$ is the rest mass of the electron, $c$ is the speed of light, and $\theta$ is the angle into which the electron scatters.

From Equation 2.2, the angle of scatter affects the energy transfer, and it can be seen that there is a maximum energy transfer when the gamma ray backscatters at 180°. Therefore, energy spectra produced from a monoenergetic gamma ray source produce a Compton continuum of deposited energy for interactions with a scattering angle less than 180° and a Compton edge, associated with 180° backscatter interactions, that is broadened by various factors and that can be used for calibration. Because of Compton scattering, however, organic scintillators used for detecting neutrons are also sensitive to gamma rays, requiring a method to differentiate between gamma rays and neutrons. Different radiation discrimination approaches are discussed in Chapter 4 and Chapter 7.

Inorganic scintillators are the other major category of scintillation detector and span all scintillators that are not hydrocarbon-based. While not being a part of the imager described in this dissertation, they will be used on limited occasions in this work. Inorganic scintillators are composed of higher atomic number elements and so the photoelectric effect becomes a significant process in gamma ray interactions. In photoelectric absorption, the gamma ray and its full energy are absorbed by an atomic electron, liberating it with an energy nearly identical for all photoelectric absorptions of a given incident gamma ray energy. Therefore, gamma ray spectra in inorganic scintillators are made of Compton continuums, Compton edges, and prominent photopeaks at specific energies. These photopeaks can be convenient means of assessing signal amplitude between different detector configurations because they are easier to
accurately locate and analyze than Compton edges, and they can also be used to conduct gamma ray spectroscopy, which is outside the scope of this dissertation. Further, inorganic scintillators are commonly used in timing studies.

2.3. Radiation-based Imaging

Radiation-based imaging can refer to measuring radiation emitted from a source to produce an image of the object emitting the radiation, or to using an external radiation source to produce an image of an object of interest. However, in general the goal of both approaches is to generate an image aided by the detection of radiation. The two main fields that have historically used radiation imaging are medicine and astronomy, and these fields have served as a breeding ground for the development of imaging techniques that can be applied to other areas, such as nuclear nonproliferation. Medicine uses both types of radiation imaging. Widely used examples of the latter in which an external radiation source is applied include X-ray radiography, X-ray computed tomography, and ultrasound. Examples of the former include magnetic resonance imaging and radionuclide-based imaging such as planar scintigraphy and positron emission tomography (PET) [16]. What constitutes radiation can vary with different techniques, for example using sound waves in ultrasonography, but the radiation considered henceforth will describe electromagnetic radiation - most commonly used - and neutrons. While neutron imaging is the primary focus of this thesis, gamma ray and X-ray imaging will also be discussed when beneficial to the background of important imaging methods.

Radiation imaging in astronomy relies entirely on passively detecting radiation emitted by extraterrestrial sources and is a convenient starting point for the discussion of imaging in this
thesis (i.e. not transmission-based imaging), since it shares important features of imaging schemes useful for nuclear nonproliferation. Low energy electromagnetic radiation (such as X-rays) can be imaged using mirrors and telescopes, but this technique fails at higher energies (such as for gamma rays) because coherent reflection no longer takes place, and consequently this is not typically useful for nuclear security [17]. To image high energy photons without such reflection, early imagers used collimators that scan across a field to produce an image, and this idea is still an option in nuclear security [17, 18]. Moving forward, the collimated detector technology was improved to form a coded mask, or coded aperture imaging [17]. The other prominent method of imaging small-wavelength particles in astronomy is by using multiple-interaction based scatter telescopes or cameras.

Coded aperture and scatter cameras are likely the two most prominent methods for nuclear security in the passive imager application space. Coded aperture imaging is a natural progression from pinhole imagers, which use a single pinhole to produce an (inverted and reversed) image. Excellent angular resolution can be achieved but at the expense of imaging efficiency [19]. To improve the efficiency, a multitude of pinholes can be created maintaining the angular resolution of a pinhole but with an efficiency proportional to the number of pinholes, albeit requiring deconvolution of the image from the mask. Originally the pinholes were distributed randomly but the imaging deconvolution was improved with the development of uniformly redundant arrays and then modified uniformly redundant arrays [20-22]. Coded aperture imaging can be applied both to gamma ray imaging and neutrons but requires different mask compositions and detectors for each. Thermal neutrons can be effectively imaged using a cadmium mask and position-sensitive $^3$He detectors [23]. Fast neutrons are detected using
organic scintillators, for example liquid scintillators [24, 25]. Use of organic scintillators offers the ability to create bimodal coded aperture imagers of both gamma rays and neutrons, although some bimodal imagers prefer an additional inorganic detector component to facilitate the gamma ray imaging [21, 26]. Masks for fast neutrons can include high-density polyethylene or even a mask of detectors operating in anti-coincidence with the detection plane, providing a stepping stone to the double-scatter imaging systems to be discussed shortly. A related approach is time-encoded imaging instead of spatially-encoded imaging. Instead of a mask modulating in space, a mask primarily modulating in time can yield similar results with only one or two detectors by correlating the mask’s position with the detector’s time response [27].

2.4. Scattering Kinematics-based Imaging

Double-scatter kinematic imaging is a method based on analyzing multiple interactions from the same particle in a detection system to determine the direction of the particle’s origin. It can be applied to both gamma ray (Compton) imaging and neutron imaging. Compton imaging of gamma rays usually relies on a scatter followed by a photoelectric capture, while neutron scatter imaging relies on two elastic scatters, but the same underlying principles are used in both. By looking at the locations of the two interactions (specifically the vector between them), the energy deposited in the first interaction, and the energy of the particle after the first scatter – typically deduced by full energy deposition of the gamma ray or TOF of the neutron – the scattering angle of the particle can be calculated by application of conservation of momentum and energy, yielding a cone of possible directions from which the particle came. Multiple
particles from the same source will allow a point of intersection from multiple cones produced to localize the particle source. Beneficially, such detectors can also operate as spectrometers.

Again, early development of Compton double-scatter imaging took place in the medical field as a tool for photon emission tomography [28, 29]. This should not be confused with the “Compton imaging” that refers to transmission-based imaging utilizing the Compton effect, also of interest in medicine but not to be discussed in this dissertation [30]. As with coded aperture imaging, Compton imaging also found use in astronomy and nuclear security applications [31-33]. Outside of medicine, the aforementioned neutron scatter imaging also became important, both by itself and in systems combining neutron and Compton imaging. Early implementations of neutron scatter imaging spectrometers were developed in the 1970s to study solar and albedo neutrons, and in 1986 a spectrometer was developed as a plasma diagnostic for nuclear fusion experiments [34-36]. Development of neutron imaging spectrometers continued in efforts to study solar neutrons, for example on the bimodal COMPTEL gamma ray telescope of the Gamma Ray Observatory and SONTRAC, but it quickly became clear that such devices would also find use in nuclear nonproliferation [37-40].

Interest in neutron scatter imagers for nuclear nonproliferation intensified in the 2000s. Vanier et al. demonstrated in 2005 that an effective directional neutron detector based on double-scatters could be created with two planes of four liquid organic scintillators coupled to photomultiplier tubes (PMTs) [41]. Similarly, Mascarenhas et al. created the original so-called neutron scatter camera (NSC) in 2009, using a front plane of four 2” thick liquid scintillator detectors and a back plane of seven 5” thick liquid scintillators [42]. Brennan et al. then expanded this design to a 32-element system with a separation of the two planes varying
between 13 cm to 127 cm [43]. Efforts to make this neutron scatter camera more compact and portable were carried out by Goldsmith et al. through 2016, and the resultant imager, MINER, consisted of 16 3” by 3” liquid scintillators coupled to PMTs [44, 45]. Recently, three-plane imaging systems designed to simultaneously image neutrons and gamma rays were developed independently by Madden et al. at the University of New Hampshire and by Poitrasson-Riviere et al. at the University of Michigan. The Michigan design consisted of two planes of liquid scintillators followed by a plane of sodium iodide detectors, while the New Hampshire design used planes of plastic, stilbene, and BGO scintillators [46, 47]. The New Hampshire design has evolved into a field deployable neutron imaging detector consisting of multiple planes, and most recently using three planes of plastic and inorganic scintillators coupled to silicon photomultipliers [48, 49]. Additional work on neutron scatter cameras, specifically of simulations and data analysis techniques, has been carried out by Hamel et al., Zhang et al., and Jo et al. [50-52].

Another related concept is that of the time projection chamber (TPC). TPCs are filled with a gas and array of anode wires and cathode strips that intercross throughout the volume of the chamber. Ionization from charged particles is collected at the anode wires and current is transferred to the cathode strips, oriented perpendicular to the wires, enabling a three-dimensional recording of the location of ionization. In this way, tracks of charged particles traversing the chamber can be measured, enabling an extensive measurement of particle interactions within the chamber.

While widely used for fundamental physics, TPCs can also be designed for detecting neutrons. For neutron detection, the fill gas is usually chosen to be $^2$H or $^3$He [53-55]. Similar
to NSCs, measurements of the scattered particles can enable kinematic reconstruction of possible directions of incidence for incident neutrons. Due to the additional information content provided by the measurement of the scattered particle track, broad directional information can be inferred from only a single neutron scatter per event. For a double scatter, detailed information on the original direction of the incident neutron can be gathered. A hybrid TPC-NSC has also been demonstrated [56]. While possessing impressive imaging characteristics, the use of a gas as the interaction medium reduces detection efficiency. The large volumes and weights of such devices, use of a pressurized gas, and extensive electronic readout, among other considerations make the deployment of a neutron TPC outside the laboratory a challenge. As such, despite the promising initial results, little progress toward actual deployment has been made for these systems.

As alluded to above, creating smaller and portable NSCs would be beneficial for nuclear applications, but the requirement of multiple planes and use of such large detectors fundamentally limits possible sizes, and making the NSCs discussed above portable is consequently nontrivial as evidenced by the MINER development [44, 45]. A fundamentally different design is required to make truly compact NSCs.

One such concept under development is the single volume NSC, which in addition to being more compact offers a significantly greater double scatter neutron detection efficiency per unit volume [59]. Multiple variations of this concept can be used to localize the interactions within the single volume. Significantly, the “Single Volume Neutron Scatter Camera” collaboration led by Sandia National Laboratories is devoting significant resources to this concept [57, 58].
As described by Braverman et al., a single monolithic scintillator can be surrounded on all sides by light sensors and the location of interaction reconstructed by analysis of the time of arrival of photons at different locations [59]. This “direct” method is technically daunting, requiring very fast photodetectors and sophisticated reconstruction algorithms. A similar concept described by Ziock et al. adds coded apertures around the sides of the scintillator to help localize the light origin at the expense of light collection [60]. The work of Weinfurther et al. focuses on a quasi-single volume made of optically separated columns that constrain the light source in two dimensions, while readout at both sides of the column allows determination of light in the other dimension [61, 62]. Finally, a 3-dimensional voxelization of the volume provides readout via six faces instead of two and is the basis of the NuLat neutrino detector [63].

Beyond just the NuLat detector, the single volume and quasi-single volume NSC designs are also finding application in the detection and imaging of antineutrinos. For these antineutrino detectors, the imaging capability helps reduce background, and to further suppress background they require that the neutron be captured, and this capture detected and identified. This means that they typically employ $^6\text{Li}$ or $^{10}\text{B}$ in the detector design to facilitate neutron capture and detection, although in principle neutron capture on $^1\text{H}$ could also do this, albeit much less effectively. Outside of the neutron capture component of these antineutrino detectors, they are nearly identical to and can be applied as NSCs, and their development supports the advancement of this technology as a whole. Notably, the miniTimeCube (mTC) employs a single cube of EJ-254 boron-loaded plastic scintillator surrounded by 24 Planacon micro-channel plate PMTs (MCP-PMTs), essentially the truly single volume NSC [64]. The
segmented antineutrino directional detector (SANDD) is comprised of 64 lithium-doped plastic scintillators coupled to silicon photomultipliers (SiPMs), basically the quasi-single volume NSC [65].

One final alternative being explored is the use of a single monolithic cube surrounded on all six sides by a single PMT per side [66]. This requires exceptionally fast timing and is limited to only using a subset of possible events for which the interactions are sufficiently far apart to be resolved.

In the short-term, perhaps the simplest to implement is the quasi-single volume NSC comprised of optically segmented columns, and a prototype of this type was constructed recently by Ruch et al. [67]. Ruch’s NSC used eight pillars of stilbene, each 6 mm x 6 mm x 50 mm, coupled to 6-mm x 6-mm C-series SiPMs from SensL (Cork, Ireland). Steinberger et al. have continued to further develop this design, creating the handheld dual-particle imager (H2DPI) and demonstrating its imaging capability for both neutrons and gamma rays with plutonium and exploring further modifications and improvements to the design [68, 69]. Ruch’s work demonstrated that NSCs could be made compact with SiPMs while still providing good imaging and spectroscopic capability. Additional support for the implementation of this and related designs are the experimental reports by the mTC collaboration and Weinfurther, suggesting the use of a quasi-single volume approach and SiPMs, respectively, due to improved isolation and reconstruction of events in the former case, and the observation of electrical cross-talk in MCP-PMTs in the latter [62, 64].

The multiple NSC designs under development are beneficial as different designs may apply better to different applications. This is apparent as often the performance in different desired
characteristics vary inversely depending on the design implemented. For example, increased proximity of detector elements increases efficiency but reduces angular resolution. In regard to Ruch et al.’s design, the SiPM arrays used each had 64 pixels, meaning that 56 of the 64 pixels in each array are unused. Imaging efficiency can be improved by incorporating more pillars of active scintillators, but this introduces the added problem of reading out further channels and possibly decreasing imaging resolution. Secondly, stilbene scintillators are relatively fragile and expensive and have a documented anisotropic response, adding further complexity and/or uncertainty in the localization of interactions. Novel plastic scintillators with pulse shape discrimination (PSD) capability have been developed that could enable cheaper and more rugged imagers without response anisotropies. However, these plastic scintillators are known to exhibit poorer PSD performance than stilbene, possibly introducing another challenge.

2.5. Alternative Methods of Neutron Spectroscopy

Neutron spectroscopy refers to the measurement of the energy spectrum of neutrons in an environment or emanating from a source. Unlike gamma ray spectroscopy, which can be a very precise tool and which is widely deployed for a multitude of applications, effective neutron spectroscopy is a daunting task. This is due to the different interaction mechanisms of gamma rays and neutrons with matter. As discussed in Section 2.1., neutrons do not usually deposit their full energy in a single interaction. Further, unlike gamma rays, neutrons are typically produced in processes without monoenergetic characteristic emissions. Neutron spectroscopy therefore fulfills a different role than gamma ray spectroscopy but can still be useful. Potential uses for neutron spectroscopy in a nuclear nonproliferation context are differentiation between
plutonium in metal and oxide form, differentiation between fission and (α, n) sources, and background reduction [70-72].

Excellent neutron energy resolution can be achieved using TOF measurements in which the time of transit of a neutron over an extended length can be converted into its energy [73-75]. However, these measurements require very specific setups with detailed knowledge of the environment and so are restricted to laboratory and scientific applications. For more versatile systems with organic scintillators, the primary method of obtaining neutron energy spectra uses spectrum unfolding in which the response functions of neutrons with a given energy are known and combined into a response matrix. This response matrix and sophisticated unfolding algorithms are applied to measured neutron energy spectra to yield the actual incident neutron energy spectra [72, 76, 77]. This is an extremely challenging and ill-posed problem requiring extensive knowledge of the detector’s response.

An alternative and potentially simpler method of measuring the neutron’s energy spectrum is to take advantage of the far higher neutron capture cross section at thermal energies. A detector with a capture agent such as 6Li can be incorporated in a detection medium, and the signal from this capture can be approximated as a sign that the neutron has lost all of its energy prior to that interaction. A time window prior to that signal can then be implemented and one can approximate all the energy measured within it as a measure of the incident neutron’s energy [78-80]. This approximation however is not always precise leading to limitations on the energy resolution, and the length of time windows used can limit use when exposed to high count rates.

A neutron scattering kinematic-based imager, such as a NSC inherently measures the neutron energy as an input parameter for its image reconstruction. With accurate time, deposited energy
and position resolution there is potential for a good energy resolution of incident neutrons. This dual imaging and spectroscopic ability of such NSCs thus makes them an attractive candidate to be used as a field deployable device.
Chapter 3

Project Objective and Description of the Important System Components and their Functionality

Three fundamental components are used to optimize the proposed neutron imager, and they are described in this chapter.

3.1. Summary of Objective

The goal of this research is to support the eventual deployment of an efficient, compact, inexpensive, rugged, and portable neutron imaging spectrometer for fast neutrons. If such an instrument can be developed and made widely accessible it would prove critically beneficial to the nuclear nonproliferation-related mission space as described in Chapter 1.

Of the imaging methods discussed in Chapter 2, the single or quasi-single volume neutron scatter camera (NSC) is the best candidate to accomplish this. Coded aperture imaging requires bulky masks for fast neutrons, possess no inherent spectroscopic capability, and do not have 4-pi angular sensitivity. The multi-plane NSCs are also not ideal as the plane separation imposes a minimum size of the detector, makes portability an issue, and also possess favored orientations. Thus, either a single volume or quasi-single volume NSC is necessary and enables the greatest neutron double scatter efficiency per unit volume of the possible double-scatter imagers.
The truly single volume NSC is under thorough investigation elsewhere and perhaps further from reality, so the quasi-single volume NSC is chosen here. To fully minimize the imager volume, traditional PMTs need to be abandoned; SiPMs are an attractive alternative choice, especially with the ruggedness desired, offering useful light sensor sizes in all three dimensions and with good performance in the required characteristics of timing, gain, PSD, and photon detection efficiency. Plastic scintillators are an ideal choice for the detector itself being cheaper and more rugged than organic crystals such as stilbene and p-terphenyl, and easier to work with than liquids. Finally, to achieve good efficiency without becoming prohibitively expensive the cost per channel must be kept relatively low, and this demands the use of multiplexing to read out the SiPM channels together.

To advance the mission of deploying an efficient, compact, inexpensive, rugged, and portable neutron imaging spectrometer, characterization studies of the underlying technology are carried out. Next, this dissertation develops a novel multiplexing scheme specifically tailored for SiPMs and applies it to a plastic scintillator-SiPM based detector to produce a spectroscopic neutron imager that meets the aforementioned criteria. Moving forward with field-deployable NSCs, multiplexing is likely to become an essential component of the system design. The multiplexed neutron imager (MiNI) developed in this dissertation is the first NSC employing channel multiplexing, and as discussed in Chapter 7, it is the first NSC composed of 32 optically segmented channels.
3.2. Plastic Scintillators

Organic scintillators are the primary tool used for detection of fast neutrons. Brooks first demonstrated in 1959 the ability to differentiate between neutrons and gamma rays, both of which organic scintillators are sensitive to, based on differences in the temporal light emission profiles [81]. This technique, called PSD, has been historically observed mostly in crystalline scintillators, such as anthracene or stilbene, and in liquid scintillators, but recently plastic scintillators capable of PSD have emerged as well. Advantages over crystalline and liquid scintillators include ruggedness, potential scalability and cost, and ease of use and non-toxicity. Zaitseva et al. first reported polyvinyl toluene-based plastic scintillators with PSD performance similar to the widely used liquid scintillators in 2012, with the enabling factor being an increased concentration of the primary dye, PPO, up to 30% by weight [82]. Shortly after, polystyrene was also shown to be a suitable base for PSD plastics [83]. These scintillators were commercialized by Eljen Technology (Sweetwater, TX) under the name EJ-299, but the commercialized versions were shown to have inferior PSD performance to liquid scintillators such as EJ-301 and EJ-309 [84, 85]. Further development of these plastics has taken place and Eljen has produced a new plastic scintillator, EJ-276, shown to have superior PSD properties to EJ-299, and Amcrys (Kharkov, Ukraine) has also developed its own PSD plastic scintillator [86]. Simultaneously, Zaitseva has shown that after increasing PPO concentration to 36%, her plastic samples can provide superior PSD to liquid scintillators [87]. Nonetheless, crystals such as stilbene are still known to possess superior PSD capability to plastic and liquid scintillators.
3.3. Silicon Photomultipliers

For decades, the traditional light sensor of choice for scintillators has been a PMT. However, SiPMs were created in the early 2000’s as a natural progression of avalanche photodiodes (APDs) and have undergone continued development since [88, 89]. The two main aspects of SiPMs that have traditionally been inferior to those of PMTs are the intrinsic noise level and practical detector sizes that can be produced. The primary source of noise in SiPMs is the so-called dark noise that arises from charge carriers created in the active region of the p-n junction from thermal excitation which produce signals indistinguishable from those optically generated. This in turn creates a practical limit on the feasible size of a single SiPM as larger sizes require more microcells and result in a larger dark count rate [89]. Scalability is usually achieved by tiling arrays of SiPMs together, but improvements in SiPM manufacturing processes and design have also significantly reduced noise levels in the current generation of SiPMs [90].

Improvements in the SiPM technology, as well the emergence of a wide range of applications that have found the SiPM a promising device, have caused interest in SiPMs to grow significantly since their conception nearly two decades ago. Such applications include medical physics, particle physics, optical quantum information, lidar, and homeland security, all of which take advantage of SiPMs’ ability to efficiently detect low level light down to the single photon level [91-95].

SiPMs are essentially an array of many miniature APDs connected in parallel to a common load and operating in Geiger mode [88]. Consequently, they are also known as solid-state photomultipliers, Geiger-mode APDs, or multi-pixel photon counters. Each APD is connected in series with a quenching resistor and this combination constitutes a microcell. The avalanche
photodiode consists of a p-n junction operating under a reverse bias greater than its breakdown voltage, the voltage at which Geiger multiplication begins to occur. In this configuration, photons can be absorbed by an electron in the p-n junction to produce a charge carrier that initiates a typical Geiger avalanche [96]. A more in-depth analytical model of the SiPM can be found in [97] and [98]. The difference between the applied voltage and the breakdown voltage is known as the overvoltage and affects many operational characteristics including gain, noise, and photon detection efficiency.

By operating in Geiger mode, high gains on the order of $10^6$ are possible, and, like APDs, SiPMs possess relatively high quantum efficiencies. Additionally, they display typical features of semiconductor devices including insensitivity to magnetic fields and mechanical shocks, compactness, and a relatively low operating voltage. SiPMs have also been shown to have excellent time and energy resolution [96]. These characteristics make them ideal light sensors and a candidate to replace the standard PMT in a range of applications.

3.4. Channel Multiplexing

While operating systems with many different radiation detectors can enable novel and powerful capabilities, reading out many channels (detectors) poses a serious problem. Depending on the type of information desired to be recorded (full waveform digitization for example) it can be prohibitively expensive to individually read out each channel; therefore, some channel reduction through multiplexing methods is necessary. In 1958, Anger proposed his gamma camera which used a network of resistors to process the signals from seven photomultipliers in such a way as to determine, based on his three difference circuits, the original detector that
produced the signal [99]. This is the basic idea of many charge division multiplexing schemes in which detectors are placed in a network of resistors and the charge signal produced by them divided into different paths and then eventually recorded at the end of each path. The ratio of signal amplitudes at the end of each path can uniquely identify the original detector. Such methods are applicable to any charge producing detector, including those based on SiPMs and PMTs.

One area that has recently prompted significant research in multiplexing is PET, which has especially focused on SiPMs, albeit with methods designed for light sensors in general. Examples of recent developments include further symmetric charge division schemes, capacitive readouts, and strip line readouts based on timing information [100-108]. Multiplexing radiation detectors in the frequency domain has also been investigated for PMTs by using resonator circuits that transform the PMT output pulse into a damped sinusoid, and it was shown that this method preserved information on signal origin, pulse amplitude, and timing [109, 110]. All multiplexing schemes result in some level of performance degradation and imperfect reconstruction of signal source. In this thesis, we aim to develop a novel multiplexing scheme specifically tailored to SiPMs.
Chapter 4

Assessment and Comparison of Pulse Shape Discrimination Performance of Various Silicon Photomultipliers

While SiPMs are currently the light sensor of choice for many applications, assessing their performance for this project is still necessary. Further, multiple SiPM types with different performance are available commercially, making a comparison between alternative options highly desirable. For a neutron imager employing organic scintillators, one characteristic of interest is its ability to discriminate neutrons from gamma rays using PSD. SiPMs have been shown to be capable of PSD with organic scintillators and it is of great importance to understand how efficiently this PSD can be conducted [111-114].

This chapter aims to characterize the performance of several new-generation SiPMs currently available commercially with an emphasis on characteristics relevant to nuclear safeguards and nonproliferation including neutron-gamma ray discrimination, noise, and pulse timing properties. Further, these quantities will be explored as a function of overvoltage. While SiPMs have been shown to be competitive in PSD to PMTs, and comparative studies of SiPMs have been done before, to the author’s knowledge none have been conducted at the time of this work with a focus on PSD, and certainly none with as comprehensive of a scope [97, 115-117]. As such, this chapter is meant not only to analyze the current state of the art and the effects of intrinsic SiPM characteristics, such as microcell size, on various performance parameters but also to serve as a reference for other applications in which the choice of SiPM type is relevant.
This work began in 2016 and was submitted for publication in 2017 (accepted in 2018), which serves as the time stamp for which SiPMs are available and constitute state-of-the-art for the purpose of this work.

### 4.1 SiPMs and Experimental Setup

SiPMs were acquired from five leading manufacturers for this study: AdvanSiD (Trento, Italy), First Sensor (Berlin, Germany), Hamamatsu (Shizuoka, Japan), Ketek (Munich, Germany), and SensL. Multiple types were acquired from each manufacturer, but the readout package was chosen to be the same for a given company, with the exception of SensL (two different package types were acquired). Packages selected were those with direct access to the anode and cathode via pins to provide as much control over the setup as possible, and to maximize the signal readout uniformity across manufacturers. SiPM pixel sizes range from 3 mm to 6 mm and microcell sizes range from 15 µm to 75 µm. The complete list of SiPMs is presented in Table 4.1, and the SiPM packages from each manufacturer are shown in Figure 4.1. It should be noted that multiple series of SiPM are represented from SensL and Ketek, and that Hamamatsu SiPMs typically have a breakdown voltage approximately twice that of the other SiPMs. This increased breakdown voltage is a consequence of Hamamatsu using different materials and a different internal structure than other SiPMs in an effort to decrease capacitance and improve response time, among other desired outcomes. Differences in breakdown voltage should be kept in mind when looking at how different properties scale with overvoltage as the ratio of overvoltage to breakdown voltage presents more similar results than simply the magnitude of overvoltage.

This assortment of SiPMs represents the entirety of the available current generation of SiPMs.
from each manufacturer at the time of acquisition, in size of at least 3 mm and emphasizing near-ultraviolet wavelength detection with the exception of SiPMs from SensL. From SensL, additional J-series SiPMs of 3-mm pixel size and 20-µm microcell size and 6-mm pixel size and 35-µm microcell size were not acquired to limit the assortment of SiPMs, and because they were not available in the two-pin X13 package. Most manufacturers also produce SiPMs with a light sensitivity more suitable for infrared wavelengths, but these were not chosen because of a wavelength mismatch with the emission spectra of typical organic scintillators.

As seen in Figure 4.1, the pins from each package are oriented somewhat differently, requiring a flexible setup for their testing. For this reason, a simple breadboard and wire setup was chosen and is shown in Figure 4.2. A low pass filter comprised of a 47 Ω resistor and a 100 nF capacitor was placed on the bias line as well. This filter reduces reflections and ringing that are present in some of the faster SiPMs and also creates a faster rising edge of the SiPM output pulse. A light-tight box was used for all measurements, which were performed at room temperature without any temperature regulation or monitoring. Nonetheless, the laboratory is a temperature-controlled room resulting in a relatively constant temperature throughout the measurements. A 14-bit CAEN (Viareggio, Italy) DT5730 digitizer with a sampling rate of 500 MHz and operating with a dynamic range of 2.0 V was used to capture raw waveforms to be analyzed offline using the ROOT data analysis framework [118]. It has been shown that both the sampling rate and bit resolution play a significant role in PSD performance for detection systems and that a 14-bit 500-MHz combination produces superior PSD performance to a 10-bit 1-GHz digitizer, and that a 12-bit 500-MHz combination produces superior PSD to a 10-bit 2-GHz digitizer [119-121]. It should be noted that in [119] and [120] a PMT with faster pulses
than SiPM pulses was used, so our sampling rate requirements are less stringent, and for our purposes the 14-bit 500-MHz digitizer should provide the best PSD among standard commercially available digitizers.

Table 4.1: Characteristics of SiPMs investigated in this work.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Pixel Size (mm)</th>
<th>Labeled Microcell Size (μm)</th>
<th>Series</th>
<th>Package</th>
<th>Typical Breakdown Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AdvanSiD</td>
<td>3</td>
<td>40</td>
<td>ASD-NUV</td>
<td>Socket</td>
<td>26</td>
</tr>
<tr>
<td>AdvanSiD</td>
<td>4</td>
<td>40</td>
<td>ASD-NUV</td>
<td>Socket</td>
<td>26</td>
</tr>
<tr>
<td>First Sensor</td>
<td>3</td>
<td>40</td>
<td>NUV</td>
<td>SMD</td>
<td>26</td>
</tr>
<tr>
<td>First Sensor</td>
<td>4</td>
<td>40</td>
<td>NUV</td>
<td>SMD</td>
<td>26</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>3</td>
<td>25</td>
<td>S13360</td>
<td>Cs</td>
<td>53</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>3</td>
<td>50</td>
<td>S13360</td>
<td>Cs</td>
<td>53</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>3</td>
<td>75</td>
<td>S13360</td>
<td>Cs</td>
<td>53</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>6</td>
<td>25</td>
<td>S13360</td>
<td>Cs</td>
<td>53</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>6</td>
<td>50</td>
<td>S13360</td>
<td>Cs</td>
<td>53</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>6</td>
<td>75</td>
<td>S13360</td>
<td>Cs</td>
<td>53</td>
</tr>
<tr>
<td>Ketek</td>
<td>3</td>
<td>15</td>
<td>WB</td>
<td>PM</td>
<td>27.5</td>
</tr>
<tr>
<td>Ketek</td>
<td>3</td>
<td>25</td>
<td>WB</td>
<td>PM</td>
<td>27.5</td>
</tr>
<tr>
<td>Ketek</td>
<td>6</td>
<td>25</td>
<td>EB</td>
<td>PM</td>
<td>26.5</td>
</tr>
<tr>
<td>Ketek</td>
<td>6</td>
<td>50</td>
<td>EB</td>
<td>PM</td>
<td>26.5</td>
</tr>
<tr>
<td>SensL</td>
<td>3</td>
<td>20</td>
<td>C</td>
<td>SMTPA</td>
<td>24.5</td>
</tr>
<tr>
<td>SensL</td>
<td>3</td>
<td>35</td>
<td>C</td>
<td>SMTPA</td>
<td>24.5</td>
</tr>
<tr>
<td>SensL</td>
<td>3</td>
<td>35</td>
<td>J</td>
<td>SMTPA</td>
<td>24.5</td>
</tr>
<tr>
<td>SensL</td>
<td>3</td>
<td>50</td>
<td>C</td>
<td>SMTPA</td>
<td>24.5</td>
</tr>
<tr>
<td>SensL</td>
<td>3</td>
<td>35</td>
<td>C</td>
<td>X13</td>
<td>24.5</td>
</tr>
<tr>
<td>SensL</td>
<td>6</td>
<td>35</td>
<td>C</td>
<td>X13</td>
<td>24.5</td>
</tr>
</tbody>
</table>
A single 3-mm x 3-mm x 10-mm stilbene crystal, shown in Figure 4.3, was used for all measurements. While this choice results in only partial illumination of the larger SiPMs, it was chosen as the best way to produce uniform testing and comparison between different SiPMs when considering the three different SiPM sizes and limited availability of crystals in multiple sizes that would maintain the same aspect ratio. Further, even if the same aspect ratio was maintained, differences in the actual crystal size would result in different testing conditions, not to mention the crystal to crystal non-uniformity. The crystal was wrapped with reflective Teflon tape that was not changed during the course of the measurements, and EJ-550 optical grease from Eljen Technology coupled the crystal to the SiPMs. Stilbene was chosen as the organic scintillator because of its excellent PSD properties and effective matching of its fluorescence spectrum to the spectral response of the SiPMs which peak around 380 nm and 420 nm to 450
nm, respectively. Further, its superior PSD capabilities facilitate the comparison across more SiPMs, specifically by making quantifiable PSD possible in the worst performing SiPMs.

4.2. Pulse Waveforms

To gather representative temporal information from each SiPM, the stilbene crystal was irradiated by a $^{137}\text{Cs}$ gamma ray source while coupled to the SiPM. Stilbene has a decay time on the order of nanoseconds, and because only gamma rays were measured, all scintillation
pulses will have the same time constant [67]. The SiPMs produced pulses with widths greater than a hundred nanoseconds so these are representative of the SiPM itself, and approximate the microcell response temporal profile.

Figures 4.4-4.7 show normalized averages of two-hundred pulses for each SiPM. To determine the full-width tenth-maximum (FWTM) of each SiPM, a Gaussian was fit to the distribution of FWTM values over approximately ten-thousand events and the mean of the fit was calculated. These values are shown in Table 4.2.

A wide variety of FWTM pulse widths are observed ranging from about 100 ns to 600 ns. Larger SiPMs tend to have wider pulses, which is expected because of their larger capacitances. Further, larger microcell sizes also correspond to longer pulses. Regardless of the pulse width, all SiPMs exhibit similar rise times between 16 and 40 ns, where rise time is calculated as the time difference between the last data point below 5% of the pulse height and the peak data point. This variety of pulse widths compels consideration of the effect of the sampling rate on data analysis, but the sampling time step of 2 ns should be sufficiently fine to accurately reflect even the shortest waveform produced. Further, even though the rise time may be quick enough to only contain a few samples, it plays a lesser role in PSD performance compared to the more extended, delayed structures. Characterization of the SiPM pulse widths also enables an assessment of whether or not longer pulse widths explicitly deteriorate PSD performance.
Figure 4.4. Normalized average waveforms for SensL SiPMs tested in this work.

Figure 4.5. Normalized average waveforms for Hamamatsu SiPMs tested in this work.
Figure 4.6. Normalized average waveforms for Ketek SiPMs tested in this work.

Figure 4.7. Normalized average waveforms for First Sensor and AdvanSiD SiPMs tested in this work.

4.3. Noise and Signal Amplitude

To determine the noise from each SiPM, the setup described in Section 4.2 was used, but without a scintillator coupled to each SiPM. A repetitive, forced trigger was used to record
random events, each 500 samples in length. For each event, the noise of that event was
determined as the root mean square of voltage deviations from the baseline,
\[
\text{Noise} = \sqrt{\frac{\sum_{i=0}^{N} (V_i - \text{baseline})^2}{N}},
\]
where \( N \) is 500, the number of samples in an event, and the baseline is the average of the first
50 samples in that event.

Approximately two-hundred thousand events were gathered for each measurement and the
mean of this distribution was calculated to be the noise for the particular SiPM-overvoltage
configuration. Noise values for all SiPMs as a function of overvoltage are shown in Figures 4.8
and 4.9. Error bars on the root mean square of voltage deviations from baseline in Figures 4.8
and 4.9 are not included because they are a nontrivial combination of bit resolution, electronics
noise, and dark noise uncertainties.

Because of how the noise was evaluated, the noise from the digitizer is convolved with the
noise from the SiPM and dominates at lower overvoltages, yielding the asymptotic behavior as
the overvoltage approaches 0 V. No effort was made to subtract this digitizer noise from the
total noise because the different noise contributions do not add linearly, and the actual noise
that affects SiPM performance is the resulting combination. The digitizer noise level shown in
Figures 4.8 and 4.9 is typical among digitizers of comparable dynamic range, bit resolution,
and sampling rate.

The noise increases at a faster than linear rate, and this is caused by the combination of
increases with overvoltage in both the dark count rate and the size of individual dark pulses.
Larger microcell sizes tend to have greater noise for a given overvoltage and a faster increase
Figure 4.8. Overvoltage dependency of noise for 3-mm x 3-mm SiPMs.

Figure 4.9. Overvoltage dependency of noise for 6-mm x 6-mm SiPMs.
in noise with overvoltage. The smaller microcell SiPMs have noise levels that remain at low levels at higher overvoltages, and it should be recalled that the Hamamatsu SiPMs have a significantly higher breakdown voltage.

The signal amplitude, being proportional to the product of the gain and photon detection efficiency, both of which increase with overvoltage, also increases superlinearly with overvoltage. To gain an idea of the relative size of the noise compared to typical pulses, a normalized noise was defined as the ratio of the noise defined in Equation 4.1 to the pulse height of the $^{137}$Cs Compton edge,

$$\text{Normalized Noise} = \frac{\text{Noise}}{\text{PH of } ^{137}\text{Cs Compton Edge}},$$  \hspace{1cm} (4.2)

where $PH$ is the pulse height. The calculated results are shown in Figures 4.10-4.13.

Figure 4.10. Normalized noise for SensL SiPMs.
Figure 4.11. Normalized noise for Hamamatsu SiPMs.

Figure 4.12. Normalized noise for Ketek SiPMs.
Figure 4.13. Normalized noise for AdvanSiD and First Sensor SiPMs.

This normalized noise is greater at lower overvoltages because the digitizer noise is relatively large compared to the signal amplitude, which has not increased accordingly with the overall noise. Unlike the noise, the normalized noise tends to be lower for those SiPMs with larger microcells. The larger gain and photon detection efficiency combined with the smaller microcell fill density are likely the largest contributors to this. At the optimal overvoltages, the noise is seen to be less than 1% of typical pulse heights for all SiPMs.

In addition to differences in the magnitude of noise, when the overvoltage applied approached the upper limit of our measured range two different extremes of the behavior were observed based on the SiPM size and microcell size and fill density. The first case presents itself in smaller SiPMs with larger microcells. In this case, the fewer number of microcells and larger gain leads to sporadic dark counts that are larger in magnitude than is observed in the
second behavior extreme. The second case occurs when the larger number of microcells leads to much more frequent dark counts and essentially a continually fluctuating baseline elevated above the digitizer baseline. Two examples of each behavior are shown in Figures 4.14-4.16, where the first case is represented by a 3-mm x 3-mm, 40 µm First Sensor SiPM biased with an overvoltage of 6.06 V. The second case is represented by a 6-mm x 6-mm, 35 µm C-series SensL SiPM biased with an overvoltage of 5.54 V.

In Figure 4.15, it is seen that the First Sensor SiPM in this configuration has a higher mean noise but a lower mode than the SensL SiPM, which has a higher mode but extremes that are lesser in magnitude. This can be used to quantify these two different behaviors in which a larger ratio of mean to mode implies behavior of fewer dark counts but greater in magnitude. The majority of SiPMs have a ratio between 1.14 and 1.45 with the exception of the SensL 30050, First Sensor 3040 and 4040, and AdvanSiD 3040 which have ratios of 1.73, 2.95, 2.62, and 2.57 respectively. This also leads to the different distributions of baselines in Figure 4.16. The first case usually has a baseline of approximately the digitizer baseline, while the second case has a greater spread in calculated baselines and which are consistently greater than the digitizer baseline.
Figure 4.14. Example noise observed in a) a 3-mm x 3-mm, 40 µm First Sensor SiPM with overvoltage 6.06 V and b) a 6-mm x 6-mm, 35 µm C-series SensL SiPM biased with an overvoltage 5.54 V.
Figure 4.15. Distribution of noise defined according to Equation 4.1 for a) a 3-mm x 3-mm, 40 µm First Sensor SiPM with overvoltage 6.06 V and b) a 6-mm x 6-mm, 35 µm C-series SensL SiPM biased with overvoltage 5.54 V.
Figure 4.16. Distribution of baselines, calculated as the average of the first 50 samples in an event, for a) a 3-mm x 3-mm, 40 μm First Sensor SiPM with overvoltage 6.06 V and b) a 6-mm x 6-mm, 35 μm C-series SensL SiPM biased with overvoltage 5.54 V.

4.4. Pulse Shape Discrimination

PSD can be used to discriminate neutrons from gamma rays. PSD takes advantage of the differences in pulse shapes produced by neutrons and gamma rays. This difference arises because of the type of interaction each radiation type primarily undergoes to produce
scintillation light. Gamma rays interact primarily with electrons, while the free charged particles produced by neutron interactions are usually protons. As the charged particle passes through the scintillator, two types of excited state are formed: singlet states and triplet states. De-excitation from a singlet state occurs rapidly, usually with a time constant on the order of nanoseconds. However, de-excitation from a triplet state occurs over significantly longer time scales and are generally inconsequential [67]. The one exception is the interaction between two molecules that are both in a triplet state and results in a transfer from triplet states to a singlet state and a subsequent rapid de-excitation, producing another fluorescence source delayed by the triplet recombination time [112]. Thus, the strength in a light pulse of this delayed component is strongly dependent on the density of triplet states, and so charged particles with a higher energy deposition per unit path length will exhibit a greater amount of delayed light for a given energy charged particle. This manifests in neutron pulses having a greater fraction of delayed light than gamma ray pulses [122].

Different ways to exploit this difference in pulse shape have been developed, including charge comparison, pulse gradient analysis, and frequency gradient analysis [123]. Charge comparison is most frequently used because of its simplicity of implementation and effectiveness, and it is used here. This method defines a tail integral and a total integral of the pulse and derives a pulse shape parameter (PSP) from the ratio of these two integrals. This parameter quantifies the fraction of delayed light in the pulse and differentiates between neutrons and gamma rays. Example neutron and gamma ray pulses produced from a stilbene-SiPM detector are shown in Figure 4.17.
Figure 4.17. Depiction of the charge comparison method for neutrons and gamma rays.

A typical one-dimensional histogram of the PSP is shown in Figure 4.18. The grouping at larger values of the PSP corresponds to neutrons.

Figure 4.18. Example PSP histogram (blue) with Gaussian fits (red) to each distribution.
To quantify the effectiveness of PSD between neutrons and gamma rays, a figure of merit (FOM) is typically defined as

\[
FOM = \frac{\text{Distance Between Peaks}}{\text{FWHM}_N + \text{FWHM}_G}.
\]

(4.3)

To determine the full-width half-maximum (FWHM) and distribution centroid, Gaussian shapes are fit to each peak, and values are taken from the fit.

For each SiPM, the FOM is determined in the light output window between 200-1000 keVee, where keVee, or keV electron equivalent, is the average amount of light produced and measured by an electron depositing that amount of energy in the scintillator in keV. This energy range was chosen partly to ensure that no clipped pulses were included in the FOM determination as some of the SiPMs produced pulses larger than the dynamic range of the digitizer at their highest tested overvoltages. Light output calibration was performed using the Compton edge of \(^{137}\text{Cs}\). Customized time windows for the tail and total integral were chosen for each SiPM and then kept constant as overvoltage was varied. To determine optimal time windows, a script was created to automatically run the data analysis for a variety of different time windows. The PSD performance as a function of overvoltage for all SiPMs is shown in Figures 4.19-4.22.

The SiPMs show plateaus in PSD performance around their ideal operating voltage and a decrease in the FOM as the overvoltage moves away from the plateau in either direction. Plateaus tend to occur in similar ranges around \(+3\) V except for the Hamamatsu SiPMs with 25 \(\mu\)m microcells, but again, their plateau occurs at a similar fraction of the breakdown voltage as the other SiPMs. This overvoltage range is the same as was shown for the normalized noise with the exception of points in which a FOM could not be determined due to poor separation between particle groupings preventing two distinct distributions from being fit well.
Specifically, the lowest normalized noise point for the Ketek 3315 and SensL 30020 SiPM and highest First Sensor 3040 point are omitted.

Figure 4.19. Pulse shape discrimination performance as a function of overvoltage for SensL SiPMs.

Figure 4.20. Pulse shape discrimination performance as a function of overvoltage for Hamamatsu SiPMs.
Figure 4.21. Pulse shape discrimination performance as a function of overvoltage for Ketek SiPMs.

Figure 4.22. Pulse shape discrimination performance as a function of overvoltage for AdvanSiD and First Sensor SiPMs.
The eventual decline in FOM at higher overvoltages for all SiPMs is in contrast to the normalized noise behavior in which some SiPMs did not show an increase in normalized noise. Table 4.2 displays the best FOM for each SiPM.

Table 4.2 is ordered by the FOM and it is observed that the best FOMs tend to belong to the SiPMs with the largest microcells. This relationship is shown explicitly in Figure 4.23. All manufacturers here, except SensL, label their microcell size as the distance between the center of adjacent microcells. Thus, this size includes dead space between cells instead of just the dimension of the active area. Defined in this manner, the microcell sizes for SensL’s SiPMs are shown in Table 4.2 and are adjusted in Figures 4.23 and 4.24 to match the measurement scheme of the other companies. The fact that there appears to be an increase in FOM with microcell size, albeit with a relatively large variation around the trend, is made more significant by the large number of different manufacturers, packages, and series that are represented in Figure 4.23. The impact of the pulse width on the FOM is also shown in Figure 4.24, and there does not appear to be a strict relationship. From Table 4.2 and Figures 4.19-4.22, there also does not appear to be a clear advantage between SiPMs of the same type and different pixel size. The equivalent Hamamatsu SiPMs of different pixel size have very similar FOMs, as do the AdvanSiD SiPMs. The larger First Sensor SiPM actually has a superior FOM and the larger SensL SiPM in the X13 package has a lesser FOM than the smaller one. Direct comparison between the Ketek SiPMs is not possible because the two different sizes also belong to a different series, but the Ketek 3325-WB series has the highest FOM of all 25 µm SiPMs while the Ketek 6625-EB series has the lowest.
Table 4.2: Performance Characteristics of Silicon Photomultipliers

<table>
<thead>
<tr>
<th>SiPM Type</th>
<th>Microcell Size (µm)</th>
<th>Pixel Size (mm)</th>
<th>FWTM (ns)</th>
<th>PSD Figure of Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu 3075</td>
<td>75 [3]</td>
<td></td>
<td>253</td>
<td>2.81</td>
</tr>
<tr>
<td>Hamamatsu 6075</td>
<td>75 [6]</td>
<td></td>
<td>383</td>
<td>2.75</td>
</tr>
<tr>
<td>Hamamatsu 3050</td>
<td>50 [3]</td>
<td></td>
<td>137</td>
<td>2.52</td>
</tr>
<tr>
<td>Hamamatsu 6050</td>
<td>50 [6]</td>
<td></td>
<td>298</td>
<td>2.52</td>
</tr>
<tr>
<td>SensL SMTPA 30050C</td>
<td>59 [3]</td>
<td></td>
<td>364</td>
<td>2.34</td>
</tr>
<tr>
<td>First Sensor 4040</td>
<td>40 [4]</td>
<td></td>
<td>333</td>
<td>2.18</td>
</tr>
<tr>
<td>SensL X13 30035C</td>
<td>44 [3]</td>
<td></td>
<td>280</td>
<td>2.09</td>
</tr>
<tr>
<td>SensL SMTPA 30035C</td>
<td>44 [3]</td>
<td></td>
<td>261</td>
<td>2.02</td>
</tr>
<tr>
<td>AdvanSiD 4040</td>
<td>40 [4]</td>
<td></td>
<td>363</td>
<td>1.96</td>
</tr>
<tr>
<td>AdvanSiD 3040</td>
<td>40 [3]</td>
<td></td>
<td>243</td>
<td>1.91</td>
</tr>
<tr>
<td>Hamamatsu 6025</td>
<td>25 [6]</td>
<td></td>
<td>236</td>
<td>1.87</td>
</tr>
<tr>
<td>First Sensor 3040</td>
<td>40 [3]</td>
<td></td>
<td>241</td>
<td>1.85</td>
</tr>
<tr>
<td>Hamamatsu 3025</td>
<td>25 [3]</td>
<td></td>
<td>95</td>
<td>1.82</td>
</tr>
<tr>
<td>SensL SMTPA 30020C</td>
<td>29 [3]</td>
<td></td>
<td>164</td>
<td>1.74</td>
</tr>
<tr>
<td>Ketek 6650-EB</td>
<td>50 [6]</td>
<td></td>
<td>571</td>
<td>1.71</td>
</tr>
<tr>
<td>Ketek 3315-WB</td>
<td>15 [3]</td>
<td></td>
<td>139</td>
<td>1.71</td>
</tr>
<tr>
<td>SensL 60035 X13C</td>
<td>44 [6]</td>
<td></td>
<td>633</td>
<td>1.70</td>
</tr>
</tbody>
</table>

Benchmarking of PSD performance with a fast PMT was also performed. The stilbene crystal was coupled to a Hamamatsu H10580 PMT assembly, and the FOM was calculated to be 1.92 in the 200-1000 keVee window. This PMT assembly was chosen because of its fast timing, relatively small light-sensitive area (1” in diameter), and widespread use [112, 124, 125]. The setup used for these tests is shown in Figure 4.25, and the associated PSD plot, as well as FOMs for other energy windows, is shown in Figure 4.26. The PSD plot from the Hamamatsu 6075 SiPM and its FOM in the same energy windows is shown in Figure 4.27.
Figure 4.23. Relationship between microcell size and FOM. PSD time windows are optimized individually for different SiPMs.

Figure 4.24. Relationship between pulse width and FOM. PSD time windows are optimized individually for different SiPMs.
Figure 4.25. A 3-mm x 3-mm x 10-mm stilbene crystal coupled to a Hamamatsu H10580 PMT assembly.

Figure 4.26. Pulse shape discrimination plot for the Hamamatsu H10580 PMT assembly coupled to stilbene.

Figure 4.27. Pulse shape discrimination plot for the Hamamatsu S13360-6075CS SiPM coupled to stilbene.
This PMT has an inferior FOM in the 200-1000 keVee and 200-500 keVee energy window, but a superior FOM in the small energy window of 100-200 keVee. The diminishing of the PMT’s FOM in larger energy windows at higher energies is likely partly because of its non-constant relationship between pulse shape parameter and light output for a given particle type. It is for this reason that the upper limit of the light output window for FOM evaluation was chosen instead of having no upper bound in the first place, but even the bound of 1000 keVee contained light outputs for the PMT that had different centers of the PSP for a given particle type. Nonetheless, in a similarly narrow light output window of 100 keVee, the Hamamatsu 6075 SiPM has a larger FOM at the higher energy range of 500-600 keVee. This SiPM also appears to have a lower maximum light output than this PMT, and this arises from the nonlinearity of SiPM response at high detected photon numbers compared to the number of microcells in the SiPM. This artifact is most pronounced in the Hamamatsu 6075 SiPM whose PSD plot is shown in Figure 4.27 and has the smallest microcell fill density because of its 75 µm microcell size.

4.5. Conclusions on SiPM PSD Performance

While the FOM is not an exact measure of the discriminating power of the detector such that a slightly higher FOM dictates that detector to be decisively superior in particle discrimination, the similar (and sometimes superior) FOM of some SiPMs to this PMT shows that the current generation of SiPMs can provide comparable PSD performance to traditional fast PMTs. While the PMT showed a higher FOM in a small energy window at low light output, the SiPM explicitly compared against it showed a higher FOM in the larger energy windows and same
size energy window at higher energy. While effective discrimination at low energies is of great importance for some applications, a higher FOM over larger energy windows and at higher energies is also advantageous because it allows for more easily implemented PSD analysis – especially for real time data processing – such as by allowing filtering by a single PSP rather than different PSPs for different energies.

There also appears to be a correlation between a larger microcell size and a higher FOM. SiPMs with a larger microcell size generally have higher gains produced from a single avalanche and greater photon detection efficiencies caused by higher geometrical fill factors from less dead space between microcells. The lesser number of microcells also can provide a lower dark count rate, and this is seen in the normalized noise in which the SiPMs of larger microcell sizes had lower normalized noise. These factors combine to offer an explanation for the improved PSD performance of SiPMs with large microcells. As expected, larger SiPMs and microcells lead to longer pulse widths, but when all different types of SiPMs were compared together, no relationship between pulse width and PSD performance was observed.

Differences in noise behavior between some SiPMs was also seen in the overvoltage ranges tested in this work. Specifically, when the overvoltage was high enough to produce observable discrete dark counts above the digitizer noise, some SiPMs did not produce an omnipresent noise constantly changing the baseline. Instead they would produce dark counts and then enough time would pass before the next dark count that the voltage would return to the digitizer’s baseline. As chosen by the ratio of the mean to the mode of the noise distribution, these included the 3-mm x 3-mm SiPMs with microcell size of at least 40 µm from SensL, First Sensor, and AdvanSiD, and the 4-mm x 4-mm SiPM with microcell of 40 µm from First Sensor.
This shows that smaller pixel size SiPMs with larger microcells can operate without a dark count rate high enough to constantly distort the baseline. The Hamamatsu 3050 and 3075 notably do not have elevated ratios of mean to mode but this may be because the overvoltage applied to them was not high enough in the range tested to frequently enough produce dark counts of a magnitude to skew the mean to higher values.

It is also seen that the PSD relationship with overvoltage of SiPMs does not directly follow the inverse of the normalized noise relationship with overvoltage. This suggests that a simple signal-to-noise ratio is not the only factor that influences PSD performance. For example, at higher overvoltages with greater photon detection efficiencies and noise levels, the impact of a finite dynamic range may become increasingly important as saturation of available microcells takes place.
Chapter 5

Assessment and Comparison of Time Resolution in Silicon Photomultipliers

Timing is a key performance characteristic for many radiation detection systems, especially a neutron scatter-based imaging system. Extensive research has taken place to determine and maximize timing performance with SiPM-based scintillation detectors, usually by incorporating significant front-end electronics. By doing so, coincidence time resolutions have been achieved down to approximately 100 ps with small LYSO, LSO, and LaBr crystals. With only one single photon avalanche diode, essentially a single microcell of a SiPM, the single photon time resolution after removing all external contributions to uncertainty has been reported as approximately 30 ps, which represents the absolute limits of time resolution for which all practical implementations will be greater [61, 126-132].

The majority of the reported values reflect strongly on the electronic readout scheme used with the SiPMs, and examination of the intrinsic SiPM time resolution independent of sophisticated readout is worthwhile, and especially as this characteristic varies from SiPM to SiPM. This is especially true for a compact, many-channel system in which simplicity in readout electronics is desirable. The goal of this chapter is to characterize and compare the timing performance of available SiPMs. Minimal analog signal processing is implemented in an attempt to compare the timing performance of the different SiPMs against each other. After evaluating the coincidence time resolution at room temperature, the timing at reduced
temperature is investigated, and both organic and inorganic scintillators are used. While inorganic scintillators are not intended for use in the MiNI at this stage, the inclusion of inorganic scintillators in the timing studies provides a more comprehensive understanding of timing performance for different SiPMs.

5.1. Materials and Methods

SiPMs under test come from three manufacturers: Hamamatsu, Ketek, and SensL. From Ketek and SensL two different series are characterized, and, from all three, multiple microcell sizes have been acquired. Table 5.1 shows the SiPMs to be tested, and the different packages are shown in Figure 5.1. Timing is characterized for both organic and inorganic scintillators. A pair of 4-mm x 4-mm x 40-mm LYSO scintillators and a pair of 6-mm cubic p-terphenyl crystals are used, representing typical inorganic and organic scintillators respectively. The LYSO scintillators were purchased from eBay with unknown manufacturer, and the p-terphenyl scintillators are from Proteus (Chagrin Falls, OH). The scintillators are shown in Figure 5.2 and the different sizes should be kept in mind when looking at timing results. Averaged waveforms for the two scintillator types when coupled to a fast PMT and a SiPM are shown in Figure 5.3.

All SiPMs in Table 5.1 have similar size specifications where the first digit describes the size of the SiPM (either 3 mm or 6 mm) and the last two digits provide the microcell size in µm.
### Table 5.1: Silicon Photomultipliers Tested for Timing Resolution.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Series</th>
<th>Package</th>
<th>Size</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu</td>
<td>S13360</td>
<td>CS</td>
<td></td>
<td>6075</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S13360</td>
<td>CS</td>
<td></td>
<td>6050</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S13360</td>
<td>CS</td>
<td></td>
<td>6025</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S13360</td>
<td>CS</td>
<td></td>
<td>3075</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S13360</td>
<td>CS</td>
<td></td>
<td>3050</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>S13360</td>
<td>CS</td>
<td></td>
<td>3025</td>
</tr>
<tr>
<td>Ketek</td>
<td>EB</td>
<td>PIN</td>
<td></td>
<td>6650</td>
</tr>
<tr>
<td>Ketek</td>
<td>EB</td>
<td>PIN</td>
<td></td>
<td>6625</td>
</tr>
<tr>
<td>Ketek</td>
<td>WB</td>
<td>PIN</td>
<td></td>
<td>3325</td>
</tr>
<tr>
<td>Ketek</td>
<td>WB</td>
<td>PIN</td>
<td></td>
<td>3315</td>
</tr>
<tr>
<td>SensL</td>
<td>C</td>
<td>X13</td>
<td></td>
<td>60035</td>
</tr>
<tr>
<td>SensL</td>
<td>C</td>
<td>X13</td>
<td></td>
<td>30036</td>
</tr>
<tr>
<td>SensL</td>
<td>C</td>
<td>SMTPA</td>
<td></td>
<td>30035</td>
</tr>
<tr>
<td>SensL</td>
<td>J</td>
<td>SMTPA</td>
<td></td>
<td>30035</td>
</tr>
<tr>
<td>SensL</td>
<td>C</td>
<td>SMTPA</td>
<td></td>
<td>30050</td>
</tr>
<tr>
<td>SensL</td>
<td>C</td>
<td>SMTPA</td>
<td></td>
<td>30020</td>
</tr>
</tbody>
</table>

**Figure 5.1.** Packages of silicon photomultipliers from each manufacturer.

**Figure 5.2.** Two 4-mm x 4-mm x 40-mm LYSO crystals and two 6-mm$^3$ p-terphenyl crystals wrapped in reflective tape.
Characterization was carried out on a breadboard, and each SiPM had a low pass filter (47 Ω and 100 nF) placed on its bias line. Optical grease coupled the light sensors to the scintillators, Teflon tape was wrapped around the scintillators to maximize light collection, and measurements were carried out in a dark box. Example setups for both scintillator types are shown in Figure 5.4. A $^{22}$Na source generated the annihilation photons used to produce coincident events, and for the LYSO crystals the source was elevated toward the top of the scintillators.
A CAEN DT5730 digitizer recorded the waveforms, only triggering on coincident events, and configured to operate with a 0.5 V dynamic range. Data were processed offline using the ROOT analysis framework and a constant fraction discriminator method was applied, with the discriminating fraction optimized for each measurement [118]. The 500-MHz sampling rate of the digitizer required extrapolation between points, and a six-degree polynomial (arbitrarily chosen as sufficiently fast for fitting and performing well with a smooth shape) was fit to the point below and two above the fraction. An example of this is shown in Figure 5.5. The time difference of many pulses is then histogrammed and a Gaussian fit to the distribution from which the FWHM is extracted and used as the coincidence time resolution (CTR).

Figure 5.4. Setups used for CTR measurements
Figure 5.5. Example coincident pulses from a pair of LYSO scintillators and SiPMs, with both figures depicting the same two pulses. The red fits are used to extrapolate to a time-stamp with a resolution better than the resolution of the time step. A very low fraction of the pulse height is used.

The final significant piece of data processing was the selection of events based on light output cuts. Example LYSO and p-terphenyl spectra are shown in Figure 5.6, clearly showing the Compton edge (341 keV) and photopeak (511 keV) in a and b respectively. For LYSO CTR, events that were +/- 2σ of the mean of the Gaussian fit to the photopeak were selected, and for
p-terphenyl CTR, the energy deposition was required to be between 171-341 keVee to compare detectors in a uniform energy range. Events used are shown in Figure 5.7.

![Coincident energy spectra for a) p-terphenyl and b) LYSO. The red fit in a was used to locate the Compton edge and calibrate the spectrum so that uniform energy windows could be used. The red fit in b was used to directly select events for LYSO detectors.](image)

Figure 5.6. Coincident energy spectra for a) p-terphenyl and b) LYSO. The red fit in a was used to locate the Compton edge and calibrate the spectrum so that uniform energy windows could be used. The red fit in b was used to directly select events for LYSO detectors.
5.2. Room Temperature Results

Measurements were carried out at room temperature for the SiPMs described in Table 5.1 and made as a function of applied voltage to find the best time resolution. If enough voltages are used one might expect that a valley would be observed, where there is an optimal voltage and the CTR decreases as one moves toward higher or lower voltages. For nearly all sets of tests,
initial improvement in CTR as voltage increases is observed, but, in the applied voltage ranges used, a worsening of timing performance toward higher voltages is not always seen. Reasons for the chosen applied voltages include avoiding pulse heights being larger than the dynamic range of the digitizer, and sharp increases in noise rates past a certain voltage that makes operation in such a region nonideal. Figures 5.8-5.14 show the CTR for the different SiPMs as a function of voltage.

![CTR vs Voltage Graph]

Figure 5.8. Coincidence time resolution for 6-mm Hamamatsu SiPMs.
Figure 5.9. Coincidence time resolution for Hamamatsu SiPMs with LYSO.

Figure 5.10. Coincidence time resolution for Ketek SiPMs with p-terphenyl. Only three data points are shown with the Ketek 3315 SiPM because it has a smaller usable range of overvoltages.
Figure 5.11. Coincidence time resolution for Ketek SiPMs with LYSO. Only three data points are shown with the Ketek 3315 SiPM because it has a smaller usable range of overvoltages.

Figure 5.12. Coincidence time resolution for SensL SMTPA SiPMs with p-terphenyl.
Figure 5.13. Coincidence time resolution for SensL SMTPA SiPM with LYSO.

Figure 5.14. Coincidence time resolution for SensL SiPMs of C-series 35 µm in different packages and sizes.
From Figures 5.8-5.14 it is seen that the time resolution for p-terphenyl is superior to that of LYSO for the same SiPM, and that the ideal applied voltages vary for the different scintillators. Contributing factors to the above observations are increased brightness from LYSO, faster light scintillation times in p-terphenyl, and different sizes of the scintillators. From Figure 5.8 and Figure 5.14, no clear and systematic advantage for SiPMs of a different size but same microcell size and series (i.e. the same microcell/basic unit is used) is observed. The fact that for both scintillator types, the 3-mm SiPMs had incomplete light collection means that given a scintillator whose surface is completely covered by the two different sized SiPMs, the smaller SiPM likely has an advantage. Table 5.2 displays the best CTR for each SiPM. Both scintillators are shown to be capable of time resolution of less than 500 ps.

5.3. Temperature-Controlled Time Resolution

Investigation into how time resolution in SiPMs is affected by temperature was also carried out by slightly altering the setup. An AC-046 thermoelectric cooler with a TC-24-10 temperature controller from TE Technology, INC. (Traverse City, MI) was used with an insulating structure to provide a temperature-controlled environment. Using this setup, temperature in the environment could be regulated and monitored down to -10 °C. Figure 5.15 shows the modified setup used. Understanding of how time resolution varies as a function of temperature is useful for the development of a field-deployable system in which use in a variety of temperatures and environments may take place.
Table 5.2: Coincidence time resolution for each SiPM at room temperature. P-terphenyl measurements with 3-mm Hamamatsu SiPMs were not conducted.

<table>
<thead>
<tr>
<th>Silicon Photomultiplier</th>
<th>Time Resolution – FWHM (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-Terphenyl</td>
</tr>
<tr>
<td>Hamamatsu S13360-6050</td>
<td>222</td>
</tr>
<tr>
<td>Ketek 6650 EB</td>
<td>225</td>
</tr>
<tr>
<td>Hamamatsu S13360-6075</td>
<td>231</td>
</tr>
<tr>
<td>Hamamatsu S13360-6025</td>
<td>257</td>
</tr>
<tr>
<td>SensL SMTPA 30035 J</td>
<td>290</td>
</tr>
<tr>
<td>SensL X13 30035 C</td>
<td>308</td>
</tr>
<tr>
<td>SensL X13 60035 C</td>
<td>309</td>
</tr>
<tr>
<td>Ketek 6625 EB</td>
<td>330</td>
</tr>
<tr>
<td>Ketek 3325 WB</td>
<td>343</td>
</tr>
<tr>
<td>SensL SMTPA 30035 C</td>
<td>386</td>
</tr>
<tr>
<td>SensL SMTPA 30050 C</td>
<td>401</td>
</tr>
<tr>
<td>Ketek 3315 WB</td>
<td>442</td>
</tr>
<tr>
<td>SensL SMTPA 30020 C</td>
<td>453</td>
</tr>
<tr>
<td>Hamamatsu S13360-3075</td>
<td>339</td>
</tr>
<tr>
<td>Hamamatsu S13360-3050</td>
<td>404</td>
</tr>
<tr>
<td>Hamamatsu S13360-3025</td>
<td>517</td>
</tr>
</tbody>
</table>

Figure 5.15. Temperature-controlled enclosure used to test time resolution at different temperatures.
Measurements were again made as a function of applied voltage for the 6-mm SiPMs under study using both scintillator types and at four different temperatures each. Figures 5.16-5.21 show the CTR behavior at the different temperatures.

Figure 5.16. Time resolution of Hamamatsu 6075 for a) p-terphenyl and b) LYSO. Different overvoltage ranges were used for different scintillators because of the different light outputs of each.
Figure 5.17. Time resolution of Hamamatsu 6050 for a) p-terphenyl and b) LYSO. Different overvoltage ranges were used for different scintillators because of the different light outputs of each.
Figure 5.18. Time resolution of Hamamatsu 6025 for a) p-terphenyl and b) LYSO. Different overvoltage ranges were used for different scintillators because of the different light outputs of each.
Figure 5.19. Time resolution of SensL X13 60035C for a) p-terphenyl and b) LYSO. Different overvoltage ranges were used for different scintillators because of the different light outputs of each.
Figure 5.20. Time resolution of Ketek 6650 EB for a) p-terphenyl and b) LYSO. Different overvoltage ranges were used for different scintillators because of the different light outputs of each.
Figure 5.21. Time resolution of Ketek 6625 EB for a) p-terphenyl and b) LYSO. Different overvoltage ranges were used for different scintillators because of the different light outputs of each.

The trends for each scintillator type as a function of temperature after selecting only the best voltage point for each SiPM are shown in Figure 5.22.
Figure 5.22. Time resolution of each SiPM at the best overvoltage point for each as a function of temperature for a) p-terphenyl and b) LYSO.
5.4. Timing Performance of a Fast Photomultiplier Tube

For benchmarking with a fast PMT, a pair of Hamamatsu H10580 PMTs were chosen and setup similarly, with the $^{22}$Na source between the scintillators coupled to the PMT window. Figure 5.23 shows the setup for the p-terphenyl scintillators, and Figure 5.24 shows the results for both scintillators. Figure 5.3 shows example waveforms with this PMT.

![Setup used to determine time resolution with the photomultiplier tubes.](image1)

**Figure 5.23.** Setup used to determine time resolution with the photomultiplier tubes.

![Time resolution measured with the H10580 photomultiplier tubes.](image2)

**Figure 5.24.** Time resolution measured with the H10580 photomultiplier tubes. Different overvoltage ranges were used for different scintillators because of the different light outputs of each. Specifically, overvoltages that would result in clipped pulses are avoided in the p-terphenyl case.
With these two fast PMTs, time resolution is achieved below 100 ps, and again the voltage range used with the LYSO scintillator is cut off because of the dynamic range of the digitizer, preventing the upward trend of diminishing time resolution with increasing voltage as observed with p-terphenyl. Unlike with the SiPMs, the LYSO scintillator with the PMT showed superior timing properties to the p-terphenyl.

5.5. Conclusions on SiPM Time Resolution

For SiPMs with a simple setup and no active front-end signal processing, CTR down to 222 ps with p-terphenyl and 348 ps with LYSO was achieved with the 6-mm SiPMs. It should be emphasized that this is the timing resolution from the pair of SiPMs and not each SiPM individually, and that the value reported is the FWHM of the timing distribution, not the 1σ value. From Table 5.2, it is seen that the Hamamatsu SiPMs perform very well with timing. Hamamatsu SiPMs have a different structure than other typical SiPMs as evidenced by the higher applied voltages used for the Hamamatsu SiPMs. By modifying the SiPM structure to use higher applied voltages, the capacitance of the SiPM can be reduced yielding faster pulses as one aspect supporting their effective time resolution. Further, SiPMs with larger nominal microcell sizes tend to have better CTR up to a point, but past that point improvement in CTR with larger microcells diminishes. For example, the 50 µm SiPMs from Hamamatsu and Ketek perform better than the 25 µm SiPMs, but the Hamamatsu 6075 does not show significant improvement over the Hamamatsu 6050. Similarly, with SensL, the 35 µm SiPM performs better than the 20 µm but competitively with the 50 µm SiPM. It should be noted that SensL has a different measurement scheme (active area vs microcell pitch) for labeling their SiPMs.
so the nominal 35 µm SiPM from SensL is more similar in microcell size to the 50 µm from Hamamatsu and Ketek than the nominal 50 µm from SensL, supporting that microcell size as ideal for timing applications.

Although not observed directly here due to experimental limitations, it is expected that for a scintillator whose face is completely encompassed by the SiPM, smaller SiPMs will perform better due to their lower capacitance and noise levels. The PMTs used here showed excellent timing resolution, superior to the SiPMs, but given the additional front-end circuitry used in other SiPM timing studies it is possible that the SiPM could compete with the PMT in CTR in some scenarios. Also, it is observed that with the PMT, the voltage used for the LYSO measurements was actually greater than for the p-terphenyl measurements, opposite the behavior when used with SiPMs. This can be explained by the slower time constants with the SiPMs combined with the longer scintillation times of the LYSO yielding a build-up of charge where the amplitude of the SiPM pulse continues to rise since more scintillation light is incident on the light sensor before the SiPM’s pulse is quenched. The PMT on the other hand is fast enough to more closely reset to the baseline before detecting more light. These features can be observed in Figure 5.3.

Finally, as the temperature of the SiPMs was decreased the CTR curves shifted toward lower applied voltages. This is expected because as SiPMs are cooled, their breakdown voltage shifts to lower voltages so that a lower applied voltage yields the same overvoltage, or effective voltage. Despite the shifting of these curves toward lower voltages, all SiPMs did not exhibit a shift toward better CTR with lower temperature. The two SiPMs that appeared to systematically improve toward better CTR with lower temperature were the Hamamatsu 6050 and SensL X13.
60035C, but as a group the SiPMs did not show a significant CTR improvement above the uncertainties as temperature varied.

Multiple scintillators are used in this study to gain an idea of how different time constants and light outputs affect the time resolution of different SiPMs, which can result in different SiPM preferences for different scintillators and provide information on which SiPMs are suffering more from smaller amplitudes. Further, it is useful for future systems that might hope to incorporate inorganic scintillators to accommodate gamma ray imaging as well.
Chapter 6

Development of a Novel Multiplexing Scheme for Silicon Photomultipliers

SiPMs can be made extremely compact, which can be beneficial for the design of certain detection and imaging systems. However, a negative consequence of such small detector pixels is the associated large number of channels to be processed, which makes the implementation of large SiPM-based detectors difficult and expensive. Reduction of channel number at the expense of information on the location of signal origin without performance degradation is nontrivial, but reducing channel number while maintaining information on which SiPM triggered is challenging. A novel method is proposed that takes advantage of the longer charge pulses in SiPMs compared to PMTs by mixing the SiPM pulse with a sinusoid of specific frequency that serves to tag the origin of the signal. This method uses a simple scheme and aims to minimize performance degradation and maximize position reconstruction. This chapter describes the setup of the scheme, characterizes the impact of using sinusoids of different frequency and amplitude on the performance with organic scintillators, and the construction of a four-channel prototype to demonstrate scalability of the method. Following the initial description, subsequent modifications to the scheme following comprehensive characterization are described. The characteristics to be examined include pulse amplitude response and linearity, time resolution, PSD, and the tagging efficiency, or fraction of pulses for which the
correct mixed frequency is determined. More information on alternative multiplexing methods is found in Section 3.4.

6.1. Description of the Method and Experimental Setup

6.1.1 Added Sinusoid Multiplexing

This method is based on the premise that by mixing SiPM pulses with a sinusoid of a specific frequency prior to combining multiple SiPMs into one readout channel, knowledge of which SiPM triggered can be maintained based on the sinusoid frequency. Fast Fourier transforms (FFTs) are computationally fast and allow for simple analysis of the frequency composition of the SiPM pulse. Instead of transforming the detector pulse into a damped sinusoid, our novel method aims to superimpose a sinusoid on the detector pulse, thereby maximizing the information preserved from the detector pulse, for example to allow effective PSD to be carried out, while also sufficiently tagging the pulse. The long, relatively smooth pulses produced by most SiPMs enable this concept.

To implement this methodology, two diodes and a sinusoid source are required for each SiPM in a single readout channel. One diode between the sinusoid source and the SiPM is required to separate them from each other to maintain an appropriate line impedance and the integrity of the SiPM pulse. The other diode separates the SiPM-sinusoid combination from the others to be multiplexed together, preventing omnipresent sinusoidal modulation of the baseline by only allowing signal through if the SiPM triggers and produces a voltage greater than the threshold voltage of the diode. Adding the diode in series with the SiPM output pulse lengthens
the pulse width and consequently alters its shape, but an added benefit of the diode segregation is that each SiPM’s capacitance does not contribute to the others’ that are in parallel with it, effectively isolating the performance of each SiPM from the others and enabling scalability. Further, using a diode in series with the SiPM is an effective method of preventing a huge dark count rate and elevated baseline when combining many SiPMs together. The layout is depicted in Figure 6.1, and mixed pulses are shown in Figure 6.2. It is also found that upon incorporating the sinusoid source into the circuit, the SiPM pulse width is reduced to be similar to the pulse width of the SiPM without a diode in the readout circuit and that larger sinusoids further decrease the pulse width.

Figure 6.1. Layout of the mixed sinusoid multiplexing.
Mixed gamma ray waveforms with sinusoids of varying frequency and amplitude from a Hamamatsu 6050 SiPM.

6.1.2. Frequency Tagging

To determine the frequency mixed with the SiPM pulse, a tagging window is selected on the falling slope of the pulse. To enhance the ability to determine the correct frequency, especially
for lower frequencies, a Landau function is fit to the pulse and subtracted from the pulse prior to transformation into the frequency domain. This process and the resultant frequency spectrum are shown in Figure 6.3. Gaussian and exponential functions were also considered but shown to be less effective in matching the SiPM pulse shape.

Figure 6.3. Subtraction of the SiPM component from the original mixed pulse within the tagging window and the subsequent frequency spectrum.
6.2. Characterization of the Method and Impact on Detector Performance

Experimental characterization of this technique is carried out on a breadboard with Hamamatsu 6050CS SiPMs and SensL 60035 C-series X13 SiPMs; a low pass filter was placed on the bias line of each SiPM. Function generators with maximum frequencies of 25 MHz are used to provide the sinusoid signals. A CAEN DT5730 digitizer is used to digitize all waveforms, and offline data analysis is conducted within the ROOT analysis framework [118]. To characterize the effectiveness of this technique with organic scintillators, sinusoids of different frequency and amplitude are tested. The impact of these different sinusoids on the tagging efficiency, pulse amplitude and linearity, PSD, and time resolution is examined.

6.2.1. Pulse Amplitude and Linearity

Characterization of this method must start by examining the size of pulses and introduction of any deviations from linearity as this will be necessary to compare the different characteristics to follow. To do so, a $^{22}$Na source was used and the locations of the Compton edge of its two dominant photons produced (511 keV and 1275 keV), shown in Figure 6.4, were determined as a function of sinusoid characteristics. These tests are done with the Hamamatsu 6050 SiPM.
Figure 6.4. Effect of mixing different sinusoids on the pulse size of Compton edges. The bottom figure is for 10 MHz sinusoids.
It is observed that as the amplitude of the mixed sinusoid increases the resultant charge integral corresponding to the two Compton edges decreases, implying reduction of the pulse amplitude, and that the rate of decrease is impacted by the frequency used. The slope between the two known light outputs however, remains relatively constant, alluding to the possibility of linearity between the charge integrals observed here, but the significant altering of pulse amplitude based on these different setups motivates better characterization of the linearity. To do so, two SiPMs were setup on a breadboard inside a light-tight dark box. Only one was setup as described in the multiplexing method and the other served as a reference light sensor. An LED was placed above both in a manner to illuminate them with roughly the same amount of light such that any deviation in linearity from the SiPM itself is negligible, especially at the low light levels used. Figure 6.5 shows the setup and presents the results.

Different forms for the behavior of the relationship between incident light and output signal are fit over different regions of incident light, and it is seen that for low levels of incident light there is non-linearity and the SiPM’s charge output obeys a quadratic fit well, though clearly this behavior does not extend to larger light levels. A linear function does not fit well down to these smaller pulses but for higher light levels is a good description. Characterization should take place in this linear region to ensure accurate energy calibration. 500 keVee is safely in the linear region for the configuration tested with the most attenuation, that with a 25 MHz-250 mV sinusoid. Thus, characterization of the following characteristics will take place between 500-1500 keVee to ensure fair comparison.
Figure 6.5. Depiction of the setup used for linearity testing and fits to the data for a 25 MHz-250 mV sinusoid.

6.2.3. Tagging Efficiency

The method used to determine tagging efficiency, or the fraction of events for which the frequency is correctly identified, is described in Section 6.1.2, but one modification was made for the results presented below. Instead of fitting a Landau function to each pulse, reference
Landau functions in different pulse height windows were used to quicken the data analysis.

Tables 6.1 and 6.2 show the tagging efficiency across different sinusoids for the two different SiPMs tested between 500-1500 keV.

Table 6.1: Tagging Efficiency for Sinusoids of Different Frequency and Amplitude with the Hamamatsu 6050 SiPM

<table>
<thead>
<tr>
<th>Amplitude of Sinusoid (mV)</th>
<th>2 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
<th>25 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>.926</td>
<td>.941</td>
<td>.952</td>
<td>.912</td>
<td>.665</td>
<td>.889</td>
</tr>
<tr>
<td>100</td>
<td>.899</td>
<td>.910</td>
<td>.984</td>
<td>.947</td>
<td>.867</td>
<td>.932</td>
</tr>
<tr>
<td>150</td>
<td>.632</td>
<td>.794</td>
<td>.994</td>
<td>.961</td>
<td>.963</td>
<td>.820</td>
</tr>
<tr>
<td>200</td>
<td>.502</td>
<td>.776</td>
<td>.996</td>
<td>.987</td>
<td>.984</td>
<td>.997</td>
</tr>
<tr>
<td>250</td>
<td>.389</td>
<td>.805</td>
<td>.993</td>
<td>.987</td>
<td>.986</td>
<td>.990</td>
</tr>
</tbody>
</table>

Table 6.2: Tagging Efficiency for Sinusoids of Different Frequency and Amplitude with the SensL 60035 C-series SiPM

<table>
<thead>
<tr>
<th>Amplitude of Sinusoid (mV)</th>
<th>2 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
<th>25 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>.963</td>
<td>.978</td>
<td>.978</td>
<td>.961</td>
<td>.980</td>
<td>.977</td>
</tr>
<tr>
<td>100</td>
<td>.998</td>
<td>.995</td>
<td>.994</td>
<td>.993</td>
<td>.993</td>
<td>.993</td>
</tr>
<tr>
<td>150</td>
<td>.998</td>
<td>.997</td>
<td>.998</td>
<td>.997</td>
<td>.997</td>
<td>.996</td>
</tr>
<tr>
<td>200</td>
<td>.967</td>
<td>.998</td>
<td>.999</td>
<td>.998</td>
<td>.998</td>
<td>.998</td>
</tr>
<tr>
<td>250</td>
<td>.816</td>
<td>.999</td>
<td>.999</td>
<td>.999</td>
<td>.999</td>
<td>.999</td>
</tr>
</tbody>
</table>

It should be noted that more accurate subtraction of the unwanted low frequency component that comes from the original SiPM pulse could take place if a Landau function was fit to each pulse individually, with the impact on tagging efficiency varying for each sinusoid. These results inform which sinusoids can be used to effectively determine the origin of different pulses.
6.2.4. Pulse Shape Discrimination

Two methods of PSD are presented here: the standard charge comparison method (CC) in the time domain discussed in Chapter 4, and the so-called frequency gradient analysis (FGA) that conducts the analysis in the frequency domain [123, 133]. FGA is a relatively simple method in which the pulse, or a portion of it, is transformed into the frequency domain, and then the ratio of power between two different frequencies is taken as the PSP. Combinations of frequencies can be incorporated into the ratios if desired, but for this work only two frequencies are used, one of which is typically the zero-frequency component of the FFT. The alteration of the pulse induced by our scheme would seemingly deteriorate the time-based PSD significantly but will nonetheless be characterized. Conducting the analysis in the frequency domain at frequencies away from the added frequency is expected to be superior. To calculate the quality of PSD, the FOM defined in Equation 4.3 is used. The two-dimensional PSD plot is non-Gaussian over extended energy ranges so to calculate the FOM the plot was straightened before calculating the required properties. An example of this is shown in Figure 6.6. Tables 6.3 and 6.4 show the performance of PSD in the light output range from 500-1500 keVee in both the time (CC) and frequency (FGA) domain. A hyphen indicates that there is either no separation of the particle groupings or insufficient separation to quantify. A 6-mm x 6-mm x 6-mm stilbene crystal from Proteus was used for these tests to match the active area of the SiPMs.
Figure 6.6. The two-dimensional plot of the discrimination parameter using the charge comparison method against the amplitude of pulses before and after straightening. Straightening is done by making pulse height windows and aligning each window with the center of the lowest energy window.

<table>
<thead>
<tr>
<th>Sinusoid Amplitude (mV)</th>
<th>2 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
<th>25 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.72: -</td>
<td>2.53: 2.2</td>
<td>2.72: 2.69</td>
<td>2.62: 2.81</td>
<td>2.59: 2.84</td>
<td>2.53: 2.83</td>
</tr>
<tr>
<td>100</td>
<td>1.72: -</td>
<td>2.36: 1.84</td>
<td>2.56: 2.58</td>
<td>2.55: 2.77</td>
<td>2.45: 2.85</td>
<td>2.40: 2.82</td>
</tr>
<tr>
<td>150</td>
<td>1.41: -</td>
<td>2.25: 1.45</td>
<td>2.32: 2.54</td>
<td>2.26: 2.83</td>
<td>2.23: 2.88</td>
<td>2.11: 2.88</td>
</tr>
<tr>
<td>200</td>
<td>0.99: -</td>
<td>1.80: 1.19</td>
<td>1.22: 2.46</td>
<td>1.75: 2.88</td>
<td>1.86: 2.84</td>
<td>1.82: 2.76</td>
</tr>
<tr>
<td>250</td>
<td>- : -</td>
<td>0.88: 0.82</td>
<td>0.88: 2.30</td>
<td>1.30: 2.83</td>
<td>1.73: 2.66</td>
<td>1.42: 2.48</td>
</tr>
</tbody>
</table>

For comparison, an isolated (reference) Hamamatsu 6050 SiPM yields a FOM of 2.88 for CC and 2.80 for FGA. A SiPM setup as is shown in Figure 6.1 (with diodes) but with no sinusoid mixed yields a FOM of 2.27 for CC and 2.87 for FGA. The inclusion of a diode but without a sinusoid mixed in (with diodes) lengthens the pulse width compared to the case when a sinusoid is mixed in. The longer pulse width explains the degradation of PSD without sinusoids compared to the case with sinusoids.
Table 6.4: Figure of Merit (CC:FGA) for the SensL 60035 C-series SiPM

<table>
<thead>
<tr>
<th>Sinusoid Amplitude (mV)</th>
<th>2 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
<th>25 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.18: -</td>
<td>1.02: 1.88</td>
<td>1.07: 2.02</td>
<td>1.04: 2.02</td>
<td>0.98: 2.00</td>
<td>0.90: 1.92</td>
</tr>
<tr>
<td>100</td>
<td>1.17: -</td>
<td>1.06: 1.70</td>
<td>1.06: 2.10</td>
<td>1.05: 2.16</td>
<td>0.99: 2.03</td>
<td>0.84: 1.91</td>
</tr>
<tr>
<td>150</td>
<td>1.14: -</td>
<td>1.07: 1.67</td>
<td>1.14: 2.22</td>
<td>1.04: 2.22</td>
<td>0.98: 2.10</td>
<td>0.84: 1.98</td>
</tr>
<tr>
<td>200</td>
<td>1.1: -</td>
<td>1.08: 1.45</td>
<td>1.20: 2.11</td>
<td>1.04: 2.14</td>
<td>0.97: 2.03</td>
<td>0.86: 1.93</td>
</tr>
<tr>
<td>250</td>
<td>1.12: -</td>
<td>0.96: 0.78</td>
<td>1.07: 1.78</td>
<td>0.93: 1.80</td>
<td>0.82: 1.72</td>
<td>0.74: 1.62</td>
</tr>
</tbody>
</table>

For comparison, an isolated (reference) SensL 60035 C-series SiPM yields a FOM of 2.18 for CC and 2.04 for FGA. A SiPM setup as is shown in Figure 6.1 (with diodes) but with no sinusoid added yields a FOM of 1.24 for CC and 2.46 for FGA.

For the Hamamatsu 6050, some deterioration in PSD performance is observed compared to the isolated case, with increased deterioration as the sinusoid amplitude is increased, although, for some sinusoids, PSD is competitive to the reference case. Using the frequency-based method does not offer much improvement at smaller amplitudes but as the amplitude of the sinusoid is increased it becomes a more favorable approach. For the SensL 60035 C-series case, significant deterioration is observed in the time domain when mixing sinusoids, but with little impact of the sinusoid amplitude. However, for this SiPM there is an enormous advantage gained by performing the discrimination in the frequency domain allowing effective PSD to be maintained. For both SiPMs the lower frequency sinusoids do not show effective frequency-based PSD because the added sinusoid is of a frequency similar to the frequencies chosen to compare for the FGA method, always chosen to be some of the smallest frequencies available.
6.2.5. Coincidence Time Resolution

To assess the time resolution when using this method, two SiPMs were set up as in Figure 6.1 but each was read out to its own channel. As in Chapter 5, a $^{22}$Na source was placed in between them, and a digital constant fraction discriminator was used to determine the time difference between coincident events. A Gaussian function was fit to the distribution of time differences and the FWHM was extracted from the fit. A 6-mm x 6-mm x 6-mm p-terphenyl crystal from Proteus was used for these tests, and only pulses with a light output greater than 170 keVee were analyzed. The setup and performance of different sinusoids are shown in Figure 6.7. Time resolution is observed to deteriorate as the amplitude of the sinusoid is increased, but for appropriately chosen sinusoids, the time resolution can remain close to the reference case.

6.3. Prototype Construction

A four-channel prototype with Hamamatsu 6050 SiPMs was setup on a breadboard to demonstrate the scalability of this multiplexing scheme and is shown in Figure 6.8. Table 6.5 shows the tagging efficiency and PSD performance in the time domain for this setup. Again, these are for the light output range 500-1500 keVee. Good tagging efficiencies and good PSD performance, comparable to the results established in Sections 6.2.3 and 6.2.4, are shown.
Figure 6.7. The setup shown along with the impact of different sinusoids on the coincidence time resolution. “No diodes” indicates an isolated SiPM and “0 MHz” indicates the SiPMs setup for mixing but with no sinusoid added. Top is for Hamamatsu 6050 and bottom is for SensL 60035 C.
Figure 6.8. Four-channel prototype of this multiplexing method.

Table 6.5: Performance parameters of the prototype

<table>
<thead>
<tr>
<th>Multiplexed Setting</th>
<th>Tagging Efficiency</th>
<th>PSD Figure of Merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MHz, 100 mV</td>
<td>.993</td>
<td>2.31</td>
</tr>
<tr>
<td>10 MHz, 100 mV</td>
<td>.971</td>
<td>2.31</td>
</tr>
<tr>
<td>15 MHz, 100 mV</td>
<td>.996</td>
<td>2.48</td>
</tr>
<tr>
<td>20 MHz, 150 mV</td>
<td>.984</td>
<td>1.75</td>
</tr>
</tbody>
</table>

6.4. Summary of Original Multiplexing Scheme

A relatively simple multiplexing scheme for SiPMs and organic scintillators based on adding sinusoids of specific frequencies to the SiPM pulses has been described, and its effectiveness characterized for different sinusoids. Attenuation of the signal amplitude is observed, and some minor deterioration in the PSD and timing performance observed, but for appropriately chosen sinusoids these parameters can still stay at acceptable levels. Specifically, choosing added sinusoids with smaller amplitudes (150 mV or less) and frequencies greater than 5 MHz gives good tagging efficiency of approximately 99%, sub nanosecond time resolution, and effective PSD. Interestingly, the frequency tagging efficiency does not always increase with increased
sinusoid amplitude, showing that adding such large sinusoids to the pulse results in enough pulse distortion that this method no longer works well, especially at lower frequencies. The benefits of performing the PSD in the frequency domain have also been analyzed, and shown to be especially beneficial for the SensL 60035 C-series SiPM. Further, these characteristics are shown to remain when a prototype multiplexing system of four SiPMs is created. Overall, this is a promising multiplexing method for SiPMs.

### 6.5. Improvements to Sinusoid-Based Multiplexing Scheme

The initial development and characterization of the multiplexing scheme used only one pair of Schottky diodes to carry out the implementation. In an attempt to further optimize the method, additional Schottky diodes were acquired and tested. The primary characteristic of interest in the Schottky diodes that affected performance was the forward voltage drop of each, and the main improvement targeted was the signal attenuation of the multiplexing scheme.

#### 6.5.1. Schottky Diodes Tested

The initial Schottky diode used was the 1N5711, and it was used in both diode positions for a given channel. Additional diodes with different forward voltage drops were tested and are shown in Table 6.6. Forward voltage drops are taken from the data sheets for each and not all are listed at the same forward current.
### Table 6.6: Forward Voltage Drops of Selected Diodes

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>IN5711</th>
<th>IN4151</th>
<th>IN5282</th>
<th>BAT48</th>
<th>BAT85</th>
<th>SD103</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.490</td>
<td></td>
<td>0.240</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.41</td>
<td>0.600</td>
<td>0.3</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>15</td>
<td>1</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td></td>
<td></td>
<td>1</td>
<td>0.600</td>
<td></td>
</tr>
</tbody>
</table>

#### 6.5.2. Characterization of Differing Diodes

The effects of combining different diodes in the same multiplexing scheme is of interest, so labeling the two different diode positions is necessary and shown in Figure 6.9. To assess the amplitude of SiPM pulses with different diodes, charge spectra were collected with the Hamamatsu 6050 SiPM, a LYSO scintillator, and a $^{22}\text{Na}$ source. The effects of replacing the original IN5711 diode(s) with the BAT48 diode on the signal amplitude are shown in Figure 6.10.

![Multiplexing scheme with different diode positions labeled.](image_url)

Figure 6.9. Multiplexing scheme with different diode positions labeled.
Figure 6.10. Energy spectra with different diode schemes.

For the case where both D1 and D2 are the same, little difference in signal amplitude is observed, although the pulse height can change, showing that while total charge remains similar the timing properties change slightly. Clearly the most improvement in forward signal transmission occurs when the diodes used are different from each other. Further, the diode with the lower forward voltage drop should be placed in the D2 position. This reflects that the forward voltage drop behaves similarly to an impedance in that a lower forward voltage drop
pulls more current in its branch than the other branch segmented by a diode with a higher voltage drop. This is supported by the nonlinear nature of the diodes’ I-V curves in which the Schottky diode with the lower forward voltage drop is operating at a higher point on the curve enabling it to pull more current. To attempt to push this concept further, diodes with a lower forward voltage drop than the BAT48 and with a higher forward voltage drop than the 1N5711 were searched for. Diodes tested with perceived larger forward voltage drops were the 1N5711, 1N5282, and 1N4151 and were tested in the D1 position. Diodes tested with perceived smaller forward voltage drops were the BAT48, BAT85, and SD103A and placed in the D2 position. The signal amplitudes of the different orientations with a Hamamatsu 6050 SiPM are shown in Figure 6.11.

Some improvement of forward signal transmission can be gained by swapping out the D1 1N5711 diode with either the 1N5282 or the 1N4151 diode, but, of the diodes tested, the BAT48 seems to perform best in the D2 position. Moving forward, the best combination seems to be the 1N5282 in the D1 position and BAT48 in the D2 position. This setup is characterized with the SensL 60035 C-series SiPM, a stilbene crystal, and a $^{22}$Na source in Figure 6.12.

Previously when the two diodes used were the same, the SiPM signal was split roughly in half, limiting the maximum signal size, and then increasing the amplitude of the sinusoid further decreased signal amplitude and forward transmission. By using different diodes in each position more than half the charge can be pushed forward, changing the maximum signal size achievable. Further, when different diodes are used, the amount of attenuation for larger sinusoids is diminished, staying closer to the maximum signal amplitude. Thus, using the new diode combination, excellent preservation of signal transmission in the forward direction can
Figure 6.11. Charge spectra of different diode configurations.
Figure 6.12. Energy spectra of a multiplexed SensL 60035 C-series SiPM with three different diode setups. “0 MHz” corresponds to the inclusion of a diode between SiPM and digitizer, but no applied sinusoid.

be achieved. It should be noted that the diodes do lengthen the pulse, so that even while total charge collection is similar, the pulse height is smaller. It is necessary to ensure that despite the
altering of relative current flowing in each branch, the ability to determine what sinusoid is used remains. Because less current is pushed backward toward the sinusoid source, a larger original sinusoid amplitude is necessary to add enough sinusoid content to the SiPM pulse. For the case of 10 MHz and 150 mVpp sinusoid shown in Figure 6.12, the tagging efficiency was determined and shown in Figure 6.13.

![Distribution of determined mixed frequencies. The single significant measured frequency of 10 MHz indicates that tagging efficiency is excellent.](image)

Figure 6.13. Distribution of determined mixed frequencies. The single significant measured frequency of 10 MHz indicates that tagging efficiency is excellent.

From Figure 6.13 it can be seen that excellent tagging efficiency remains in the new setup. As long as the use of large amplitude sinusoids does not create interference transmitted between channels, the new diode setup seems preferable. To actually test and confirm this, a more extensive prototype must be constructed.
6.5.3. Summary of Improvements from Diode Changes

During initial development, the primary drawback of the added-sinusoid multiplexing scheme was signal attenuation. By changing the diodes used, and especially using different diodes for a given channel the forward signal transmission can be maximized. With the optimal diodes selected, signal transmission can actually become an advantage of this method where most of the signal amplitude is preserved. Further, the ability to correctly determine the frequency of the mixed sinusoid remains excellent in the new scheme.

6.5.4. Implementation of KNN Frequency Analysis

The multiplexing scheme was originally developed using waveform fitting followed by FFTs and frequency analysis. Waveform fitting is time-consuming but yields excellent frequency identification. Replacing the fitting with reference functions quickens the analysis considerably at a small performance cost. However, a more sophisticated algorithm may be able to accomplish excellent tagging efficiency at a faster rate, while possibly accommodating less pure sinusoids.

A supervised K-nearest neighbors (KNN) regression algorithm, using the TMVA toolkit of the ROOT framework, was implemented to do the frequency tagging [134]. KNN is a type of machine learning algorithm, meaning that instead of explicitly programming it for a task, it is trained to learn how best to accomplish it, and regression means that the target variable it is predicting is continuous, as opposed to classification algorithms. Regression is chosen instead of classification for this task because it gives both an idea of the confidence in a prediction, via
the closeness of the continuous variable to one of the known options, and an idea of how closely frequencies can be spaced apart, via the width of the distribution around each known frequency.

Supervised machine learning algorithms, such as supervised KNN algorithms, “learn” by providing them with a set of input features along with a label or target variable for each input, which it uses to determine the best way to predict the target variable for new sets of features. Specifically, KNN algorithms predict the target feature by simply determining the \( k \) nearest neighbors in the \( n \)-dimensional input feature space of the training data and averaging their target value as the predicted target value, where \( k \) is a user-specified variable and \( n \) is the number of input features. KNN algorithms then are very simple algorithms but robust and excellently suited to the task of determining what frequency is mixed with a pulse based on comparing it to pulses with known frequencies mixed. Specifically, a KNN algorithm is chosen over alternative machine learning algorithms because the frequency tagging can be accomplished simply by pattern matching, which KNN algorithms are excellently suited to do quickly based on comparing an unknown pulse to the most similar ones in the input feature space and averaging their known frequency. Once the algorithm is trained it is also extremely fast in identifying the mixed frequency, such that the frequency analysis is a less significant contributor to the data processing.

To develop and test a KNN algorithm for the frequency tagging, a SiPM is set up for multiplexing and different data sets are collected separately with 2 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz, and 25 MHz sinusoids. To generate training and testing data, the different data sets with different added frequencies are then combined. 15,000 pulses with each added frequency are combined into the training and testing data set, resulting in 90,000 pulses. 80,000
pulses are used for training and 10,000 pulses that are not used in the training data are used for validation. An example of the frequency tagging accuracy and precision for a 50-mV sinusoid mixed with the SensL 60035 C-series SiPM is shown in Figure 6.14. Excellent tagging efficiency is found, sufficient to carry out the multiplexing. Further, the KNN-based frequency tagging is much faster than fitting individual pulses with Landau functions, so for extremely large data sets, the use of the KNN-based method is motivated. In Figure 6.14, the events that do not fall in one of the bins around the known frequencies have nearest neighbors of multiple frequencies and so their “measured” frequency is between the different frequencies, weighted toward a specific frequency by how many of the nearest neighbors have that frequency.

It is found that in the initial development of the KNN tagging, simply feeding the time domain information into the algorithm can perform as well as using the frequency domain so that FFTs are no longer always necessary in the frequency analysis. Therefore, an example of input features to the algorithm are a two times down-sampled version of the time domain information originally used. This set of input features is used to produce the distribution in Figure 6.14. An additional advantage of using the KNN is that because it is simply pattern matching, less-pure sinusoids can still be processed effectively, an attractive feature as the multiplexing setup moves away from sophisticated arbitrary function generators to simple sinusoid-producing circuits. It also can enable the use of alternative mixed functions, such as square or triangle waves or even more exotic mixed patterns, that could significantly relax the complexity of the sinusoid-producing circuit or using patterns that affect performance less.
6.6. Conclusions from Timing, PSD, and Multiplexing Studies

In Chapters 4 and 5, many commercially available SiPMs have been characterized in terms of their PSD and timing capabilities. SiPMs have been shown to possess excellent timing and PSD properties, and preferred SiPMs in regard to those determined. SensL and Hamamatsu are two of the leading SiPM manufacturers and the SiPMs most commonly used in their arrays are the 60035 C-series and 6050 respectively. Thus, these two will be the main choices. The Hamamatsu 6050 SiPM showed better time resolution and especially PSD properties, but the SensL 60035 C-series performed well enough in both to be suitable. In Chapter 6, a novel multiplexing scheme based on adding sinusoids to the SiPM pulses was developed and
characterized with both SiPMs. By performing PSD in the frequency domain, both SiPMs were able to maintain their PSD and timing capabilities. The SensL 60035 C-series SiPM possessed better tagging efficiency however. Further, improvement of the multiplexing scheme has been shown to be possible by altering the diodes used, and a KNN-based frequency tagging algorithm has been implemented to expedite the data processing.

Moving forward, both the SensL 60035 C-series and Hamamatsu 6050 SiPMs could serve as the basis of the prototype MiNI, but thanks to its superior tagging efficiency in our multiplexing scheme and availability in the laboratory, the SensL 60035 C-series is chosen. It should be noted however that superior PSD and timing may be possible with the Hamamatsu 6050 SiPM. PSD is an attractive trait of our imager and desired, but it is not entirely necessary and so not prioritized in SiPM selection.
Chapter 7

Simulation and Optimization of Multiplexed Neutron Scatter Camera Design

Having determined the components of the prototype MiNI and having developed an effective multiplexing scheme, the next step is to determine how to multiplex different channels together and what number of scintillators are desired.

However, the use of multiplexing to read out the events is nontrivial and can introduce biases to the recorded events. This chapter describes Geant4 simulations and uses the ROOT data analysis framework to optimize and assess the multiplexing scheme, and to compare the performance of different imager designs to determine what configuration should be pursued [118, 135].

7.1. Description of Simulations and Objectives

7.1.1. Characteristics of Interest and Setup

To evaluate the performance of, and biases introduced by, the different multiplexing schemes and configurations, four parameters are investigated: the fraction of events lost due to the multiplexing scheme, the fraction of neutron events that can be discriminated from gamma rays based on the time and distance between the interactions, the relative uncertainty in the post-scatter TOF neutron energy measurement, and the double-scatter efficiency. It is assumed that
if a single neutron scatters twice in two separate scintillators whose signal is read through the same multiplexed channel then the events will be difficult to process, and consequently will be eliminated because such events would not be recognized as a double scatter. While the multiplexing method offers the potential to correctly process two somewhat simultaneous events, it is a worthwhile first approximation to assume such events will be discarded. Consequently, the fraction of simulated events in which the neutron scatters in two different scintillators which are assigned the same readout channel serves as one of the parameters of interest.

For the prototype MiNI, 6-mm x 6-mm x 60-mm EJ-299-34 scintillators from Eljen Technology which have inherent PSD capability to discriminate neutrons from gamma rays based on differences in the temporal distribution of light production upon interaction will be used. However, such discrimination is imperfect and deteriorates for low energy deposition events, so a complementary method of identifying neutrons is offered by the imager: measuring the time between sequential scatters of a particle. Thus, the second characteristic of interest is the fraction of neutrons whose time between events for a given distance traveled is sufficient to determine it is a neutron as opposed to a gamma ray. It should be noted that for very high background or count rates, this complementary approach becomes less useful. However, the use of multiplexing to incorporate more detector elements alludes to the fact that envisioned applications do not have exceedingly high count rates. For this work, gamma ray discrimination is determined using a 1% false positive rate. This means that 1% of gamma rays are classified as neutrons, not that 1% of measured events are gamma rays. The latter fraction depends heavily on the background and radiation source of interest. The stated time uncertainty used (i.e. 0.5 ns,
0.75 ns, or 1 ns) describes the FWHM of the distribution of time differences between the pair of measurements for identical true transit times. In other words, it corresponds to 3.33 times the 1σ uncertainty of a single measurement and is provided in this manner to match a typical method for reporting measured timing uncertainties, specifically as was used in Chapters 5 and 6. Position uncertainty is not incorporated into the particle discrimination metric.

The distance and time between the two interactions is used to determine the energy of the neutron after the first scatter, and consequently the uncertainty in those measurements translates into the uncertainty in the post-scatter energy. To get an idea of the uncertainties that will be present in measurements, uncertainties in the combined position and time measurements are chosen as 15 mm (1σ) and 800 ps (FWHM), respectively. These are meant only to give an approximate, comparative estimate between different configurations. Characteristic times and positions are chosen as the mean time and position for a given configuration. Using propagation of uncertainties, the relative uncertainty in measured energy following the first neutron scatter is given by

\[
\frac{\sigma_E}{E} = \frac{4}{\nu^2} \left( \frac{1}{T^2} \sigma_X^2 + \frac{X^2}{T^4} \sigma_T^2 \right), \tag{7.1}
\]

where \( \nu \) is the neutron’s post-scatter velocity, \( T \) is the time between scatters, and \( X \) is the distance between scatters. This relative uncertainty in measured energy is used as the third performance metric. Finally, the efficiency of incident neutrons that scatter twice with an energy deposition of at least 200 keV is perhaps the most important performance measure. This energy deposition threshold is likely significantly below a realistic cutoff that would be implemented in such an imager, especially if PSD is to be relied on exclusively to identify
neutrons, but it is simply an arbitrary energy cutoff for an ideal detector and suffices for use in comparison between different simulated designs.

For the simulations used to assess the different imager configurations, particles are generated randomly from the surface of a sphere and directed toward the origin of the coordinate system, which is also the center of the array of pillars. While this preselects the direction of incidence for particles in the imager to an extent, it is necessary to acquire enough interactions to assess the performance of the imager without excessive computing power and adequately models the parameters of interest to first order. Unless otherwise specified, the energy spectrum of the incident neutrons is a $^{252}$Cf Watt spectrum.

7.1.2. Selection of the Number of Scintillators

Initially, three different scintillator configurations were considered, based on different scintillator periodicities of one, two, and three, yielding detectors with 64, 32, and 21 scintillators, respectively. These configurations are shown in Figure 7.1. To determine which configurations should be chosen, preliminary simulations were performed without multiplexing considerations. The performance metrics are shown in Figure 7.2. From these simulations the 21-scintillator configuration was judged to not be sufficiently superior over the 32-scintillator configuration in any metric to be further pursued. Thus, the remainder of the paper will focus only on the 32- and 64-scintillator configurations.
7.2. Multiplexing Optimization and Assessment

7.2.1. Multiplexing Scheme Selection

For a given number of digitizer channels and scintillators, the multiplexing scheme was determined using Geant4 simulations and the ROOT data analysis framework. Using the assumption that any event with two scatters in the same multiplexed channel will be lost, a script was developed to calculate the fraction of events lost for a given multiplexing scheme and then to swap which scintillators belong to a given multiplexed readout channel in pursuit of the configuration with the lowest fraction of events lost. As previously discussed, this was done for 32- and 64-scintillator imagers, and was also done for the cases of 16 or 8 digitizer channels. This corresponds to using one or two 8-channel digitizers, and since each scintillator must be readout on both ends, half the digitizer channels will be used to read out the tops of scintillators and the other half the bottoms. This means for the multiplexing optimization the actual number of usable channels is half the stated number of digitizer channels available. Figure 7.3 shows the chosen configuration for each combination of scintillators and digitizer channels used. The same color corresponds to the same multiplexing channel.
Figure 7.2. Performance metrics of a) time-based gamma discrimination efficiency, b) the relative uncertainty in post-scatter neutron energy, and c) the double-scatter efficiency without multiplexing of different imager compositions. Improvements for an imager with fewer scintillators in a) and b) result from longer average inter-scatter distances.
7.2.2. Investigation of Multiplexing Effects

Investigation of the effects for our multiplexing scheme are motivated by two factors: to compare the performance of different configurations in pursuit of determining what setup should be constructed, and to learn what biases might be introduced by the multiplexing scheme selected. To compare many different scenarios against each other it is useful to have one quantity represent the measurement of interest, although this comes at the expense of information that has been gathered. For example, Figure 7.4 shows how the multiplexing scheme preferentially removes events at certain distances, with the net result being that the mean distance traveled for events after multiplexing cuts shifts to shorter distances. Still, to facilitate the comparison of many simulations the mean of the distribution is chosen to represent the characteristic under study. Figure 7.5 shows how the fraction of events lost to multiplexing varies with different incident neutron energies, and Figure 7.6 displays the time-based gamma discrimination efficiency as described in Section 7.1.1. Figure 7.7 shows the two final quantities of interest as a function of energy: the double-scatter efficiency of the imager and the relative uncertainty in the post-scatter neutron energy measurement.
Figure 7.3. Depiction of which scintillators will be readout in the same channel to achieve the fewest events lost due to multiplexing for different numbers of digitizer channels available and scintillators.

Figure 7.4. Distribution of inter-scatter distances for first two scatters in the 64 scintillator 16 digitizer channel case. In the statistics boxes, events with either proton or carbon scatters are denoted “pc”, while events in which both scatters are off hydrogen are denoted “po.” The inclusion of an “m” after the previous indicators describes only those events that remain after multiplexing losses.
Figure 7.5. Fraction of events lost due to multiplexing for different neutron energies. For a given number of digitizer channels, the use of more scintillators requires a greater multiplexing ratio, which leads to more events lost.
Figure 7.6. Time-based gamma discrimination efficiency for different neutron energies assuming 0.5 ns time uncertainty (top) and 1.0 ns time uncertainty (bottom). Multiplexing slightly reduces the number of events that can be discriminated as neutrons from gamma rays.

For the simulations, two scatters off of hydrogen were required. From Figure 7.5 it is observed that more events are lost to multiplexing for higher incident neutron energies. This is expected because the multiplexing scheme attempts to minimize the events lost by shielding same-channel scintillators from each other, but at higher neutron energies with a longer mean free path the shielding becomes less effective. From Figure 7.6, it is clearly seen that lower energy neutrons are easier to discriminate from gamma rays based on the travel time between scatters. It is further observed that multiplexing reduces the fraction of neutrons that can be discriminated, and the fewer digitizer channels used the worse this effect becomes. However,
this effect is relatively small. This is attributed to the fact that scintillators multiplexed together tend to be further away from each other than scintillators of a different readout channel, which means that the multiplexing preferentially removes events with larger inter-scatter distances in which discrimination between neutrons and gamma rays would be easier. This effect can be
observed in Figure 7.4. Still, for low energy neutrons, this time-based discrimination can be quite effective making it complementary to the PSD-based discrimination which performs worse at lower neutron energies. From Figure 7.7, it is observed that the 64-scintillator configuration is significantly more efficient than the 32-scintillator configuration, up to three times. The sharp decrease in efficiency at low incident energy is caused by the requirement of two scatters with a minimum energy deposition of 200 keV each.

It should be noted that for these efficiency calculations, any scatter off of hydrogen above the energy threshold that is not lost to multiplexing is considered to be detected and processed correctly. In reality, higher energy deposition scatters will be easier to detect and process correctly. Thus, there is a competing effect not modeled here in which higher energy particles are more efficiently detected. This effect is heavily dependent on the actual detector system and its associated systematics, but it would effectively increase the detection efficiency at higher energies, flattening the curve in Figure 7.7.

From Figure 7.7, it is also seen that the relative uncertainty in energy on an event-by-event basis is rather large, but the difference in uncertainty between the 32- and 64-scintillator configuration is only on the order of 10%. The increase in the relative energy uncertainty observed at 0.5 MeV in Figure 7.7 is caused by the lower energy of the scattered particle, so that even though the absolute uncertainty in the measurement caused by longer transit times is significantly smaller, the energy of the scattered neutron decreases enough to increase the relative uncertainty in the energy measurement.
7.3. Analysis of Position Sensitivity and Preferred Directions

To investigate the imager’s response to neutrons from different directions of incidence and/or with specific geometric cross-sections of incidence, a series of source configurations were simulated as shown in Figure 7.8. Figure 7.8 shows the surfaces from which neutrons were randomly generated. Source configurations 1-6 used a surface the same size as the cross section of the imager, and particles were directed parallel to the normal from the surface of origin toward the imager. Figures 7.9-7.12 demonstrate the characteristics of interest for 16 different source descriptions.

This analysis of position sensitivity provides useful information. From Figure 7.9, it is observed that there are only slight differences in the number of events lost to multiplexing for different source descriptions, especially when only focusing on directions of incidence perpendicular to the major axis of the scintillator. This confirms that even though all directions of incidence were equally represented to choose the multiplexing method, no large difference in multiplexing performance was created for different angles or positions of incidence. However, Figures 7.9-7.12 show that the performance of the imager in other respects varies most for neutrons incident along the major axis, yielding higher gamma discrimination efficiency, lower relative energy uncertainty, and lower double-scatter efficiency. The larger fraction of empty space presented in the $x$-$y$ plane (source descriptions 1 and 2) and greater energy deposition required to change the neutron’s direction of travel enough to scatter again in another pillar may contribute to this. Finally, as expected, the double-scatter efficiency of the imager is significantly higher when the particle is incident closer to the center of the imager.
Figure 7.8. Depiction of source configurations for position sensitivity.
Figure 7.9. Events lost due to multiplexing for different source configurations. Source description refers to the source configuration as shown in Figure 7.8.

7.4. Discussion and Conclusions on Simulations

The simulations described in this chapter provide the expected performance of the imager and inform on what tradeoffs can be expected between different design options. Additionally, the study was carried out such that the results are not unique to the sinusoid addition-based multiplexing scheme to be used in our imager, but they would be pertinent to the implementation of most multiplexing schemes that might be applied. With the use of additional channels enabled by a multiplexing method, the two schemes most worth pursuing are the 32- or 64-scintillator configurations. Further, the number of digitizer channels available is a greater factor in determining the number of events lost to the multiplexing scheme than the number of channels multiplexed together per channel. This fact motivates the use of 16 digitizer channels...
as it offers significant advantages in performance and reduces the drawbacks from multiplexing enough channels together to allow for a 64-scintillator configuration.

Figure 7.10. Gamma discrimination efficiency for a) .5 ns time resolution and b) 1 ns time resolution. Source description refers to the source configuration as shown in Figure 7.8.
Figure 7.11. Uncertainty in scattered neutron TOF energy measurement. Source description refers to the source configuration as shown in Figure 7.8.

Figure 7.12. Double-scatter efficiency of imager for different source descriptions. Source description refers to the source configuration as shown in Figure 7.8.
Biases introduced by the multiplexing are characterized and observed to be small. It should be noted that only the scintillators are modeled here, so there will be additional material above and below the scintillators from the SiPMs and other electronics. Thus, the fact that the largest biases in direction come from particles originating primarily from above or below the detector further decreases the importance of biases introduced since these are not intended to be the most sensitive directions for the imager. In comparing the use of 32 or 64 scintillators, the 32-scintillator configuration has some advantages created by the gaps between the scintillators leading to greater average distances between interactions. This manifests in slightly better time-based gamma discrimination efficiency and relative energy uncertainty, which will also translate to a better angular resolution in the image construction. When dealing with large count rates, the fewer numbers of scintillators also have the potential to reduce problems associated with pile-up and dead time. The 64-scintillator configuration only has one advantage, its double scatter efficiency, but its advantage is the most considerable difference between the different scintillator number options. Therefore, without context of a specific application in mind, or for applications in which the efficiency of the imager is the most important characteristic, the 64-scintillator configuration is likely preferable. However, as a first step toward implementing a multiplexed NSC, the 32-scintillator composition will be chosen for the prototype MiNI as the simpler design and for less time-intensive calibration.
Chapter 8

Circuit Development and Imager Construction

With the composition and design of the imager determined, various circuits must be developed to implement and build the system. The sinusoid-based multiplexing scheme to be used was developed using robust and versatile arbitrary function generators. To fully demonstrate the usefulness of this multiplexing method, sinusoid generators that are simpler and cheaper than arbitrary function generators must replace the function generators in actual realizations of the multiplexing method. This requires a sinusoid-producing circuit to be developed as part of the imaging system. Second, the SiPM arrays must be supplied a bias voltage and the signals transferred to radio-frequency (RF) connectors suitable for transmission via coaxial cables to a digitizer. The interface board responsible for this should also implement the multiplexing to minimize the number of RF connectors and cables needed for the system. The development of these two circuit boards will enable the imager to actually be constructed, but physical support structures are also necessary. To hold the imager firmly together and in place, a combination of spacers and support walls are created as well.

8.1. Sinusoid-Producing Circuit Development

The sinusoid-generating circuit should ideally produce a sinusoid whose frequency and amplitude are stable and adjustable and whose output is minimally affected by the circuit into
which it is fed. Further, it should be cheap and simple, so only resistors or potentiometers, capacitors, transistors, and operational amplifiers (op-amps) are used in the design. To accomplish this, the circuit is divided into two stages. The first stage is a Colpitts oscillator that sets the frequency of oscillation, impacts the amplitude of the oscillation, and generates a sinusoid. The second stage is a non-inverting amplifier that adjusts the amplitude of the sinusoid and buffers the sinusoid between the oscillator and the rest of the circuit.

8.1.1. Colpitts Crystal Oscillator

A convenient way to set a stable frequency of oscillation is to use a piezoelectric quartz crystal whose structure defines a resonant frequency such that when it is placed in an alternating current (AC) circuit the frequency of oscillation produced by the circuit is the characteristic frequency corresponding to that crystal. Thus, by selecting a specific crystal one can set the frequency of oscillation as desired and if the circuit allows for interchangeable crystals it can be easily changed to different frequencies.

Using a quartz crystal, many varieties of crystal oscillators are possible, many of which are based around an NPN transistor. A Colpitts oscillator design is selected, with the collector of the transistor connected to ground or another voltage reference point such as a positive potential. Such an oscillator works well in the range we are interested in for our multiplexing: 1-25 MHz [136]. Even within a Colpitts design, multiple variations exist, one of which is shown in Figure 8.1. The Colpitts oscillator implemented is the same as that of Figure 8.1, except that $R_2$ is omitted. The sinusoidal voltage is taken at the node between the emitter of the transistor and $R_E$. A 2N5770 NPN transistor from Central Semiconductor (Hauppauge, NY) is used.
8.1.2. Non-inverting Amplifier

Non-inverting amplifiers are common and simple amplifiers based on op-amps, which also act as a buffer between its input and output, effectively isolating the circuit preceding it from the circuit following the amplifier. Its buffering ability is enhanced in the non-inverting configuration in which the input voltage is loaded directly onto the high-impedance positive input of the op-amp and separated from the other connections of the op-amp. A non-inverting amplifier is shown in Figure 8.2. The gain of the amplifier is determined according to

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_l}. \tag{8.1}$$

One limitation of using a non-inverting amplifier is that it limits the gain to a minimum of one.

By using an op-amp-based non-inverting amplifier the output amplitude of the sinusoid circuit is adjustable based on the ratio of the resistances of the two resistors used, and the Colpitts crystal oscillator is isolated so that the combined circuit can be fed into a subsequent circuit without adversely impacting the sinusoid characteristics, which could happen without
the amplifier stage if the next stage changed the resistive and capacitive characteristics of the oscillator circuit. Working with relatively high sinusoid frequencies requires an op-amp with a high bandwidth, and so a LM7171 op-amp from Texas Instruments (Dallas, TX) is used. As our circuit is designed, a positive and negative voltage must be supplied to the op-amp on two other pins, not shown in Figure 8.2.

![Non-inverting amplifier setup with an operational amplifier.](image)

8.1.3. Complete Sinusoid-Producing Circuit

To remove any DC offset of the sinusoid, a capacitor is placed between the two stages of the circuit. To isolate and preserve the oscillations produced by the first stage, one voltage divider is placed between the Colpitts crystal oscillator output and the capacitor, and because non-inverting amplifiers as described do not work well with a capacitive input, a second voltage divider is placed after the intermediary capacitor. Additionally, a 50 Ω resistor following the amplifier is placed between the op-amp output and the output of the circuit in an attempt to more closely match the output impedance of the arbitrary function generators used.
The Colpitts crystal oscillator requires one positive voltage supply, and the non-inverting amplifier requires a positive and negative voltage supply. To maximize versatility and flexibility in the design these three supplies would all be kept separate, but to simplify the circuit the two positive supplies are made the same. This is also necessary if multiple sinusoid generators are to be placed on one circuit board and all traces are to be kept on one layer, as will be done. This reduces the ways in which sinusoid properties can be adjusted and constrains the voltages that can be applied to the different stages. Potentiometers are used in most places to allow for changing of sinusoid properties. The circuit for a single sinusoid generator is shown in Figure 8.3. A two-layer circuit board is developed, with the bottom layer being a ground plane. Four sinusoid generators are constructed per board, and one positive and one negative supply is shared between all generators. BNC connectors are used for input voltages and output signals. Figure 8.4 shows the constructed board and its layout. This board allows for four high-quality sinusoids of adjustable properties to be fed into the multiplexing scheme using only two DC power supplies.

8.2. Silicon Photomultiplier Array Interface Board Design

While there are some limited commercial solutions for the readout of SiPM arrays, implementing our multiplexing scheme and digitizing the full analog waveforms requires custom circuit boards. The SiPM array interface board should supply the bias voltage to the SiPMs, multiplex the appropriate SiPM channels together, and transfer the multiplexed waveforms to RF connectors. Unlike the SensL recommendations and University of Michigan design, our board is setup to apply a single bias filter to the common cathode (as opposed to
Figure 8.3. Complete sinusoid-generating circuit design, with potentiometers in multiple locations to allow for adjustment of sinusoid properties.

Figure 8.4. Sinusoid-producing circuit with four generators. The quartz crystals are not in place, but their holders can be seen.
grounding the common cathode) and then the SiPM signal is read out DC via the anode. The DC readout and single bypass filter of this imager are required for our multiplexing scheme and serve as a useful demonstration for the feasibility of biasing large SiPM arrays with the same filter through the common cathode.

The lowpass filter placed on the bias line contains three 50 Ω resistors, one 100 pF capacitor, one 1 nF capacitor, one 10 nF capacitor, two 100 nF capacitors, and one 1 µF capacitor. The circuit is depicted in Figure 8.5. All connections, including eight multiplexed output channels, four sinusoid input channels, and one bias voltage input, are made with BNC connectors. A four-layer board is designed with one ground plane and one power plane in between the two planes containing the multiplexing and readout traces. Because of all the different connections that need to be made and the random location of the SiPM connectors (i.e. not ordered sequentially), it is impossible to route each trace on a single layer without intersecting, so traces use both layers to traverse the board to get to their final location. SiPM channels not used are simply not connected to the board. It should be noted that the channels to be multiplexed together and their output channels were chosen based on minimizing events lost. An alternative multiplexing determination could be made based upon minimizing the tracks to cross and proximity of the channels on the SiPM connector. The connection between the SiPM arrays and the circuit board are made with a pair of Samtec QSE-040-01-L-D-A connectors.

As described in Section 6.5, the performance of the multiplexing scheme can be altered based on the diodes used. Two different interface boards are constructed with two different pairs of diodes. The two different versions of the board are identical except for the diodes placed in the same locations. One version uses the original diode setup with two 1N5711 diodes per
channel, one in each position. The other version of the board uses a 1N5282 diode in the sinusoid-source-facing position and the BAT48 diode in the forward transmission direction. The latter scheme is tested because it allows for maximum forward transmission of the signal as shown in Section 6.5, but it also requires larger amplitude sinusoids to tag effectively, the effects of which are unclear until actually tested on the full circuit board. Figure 8.6 shows the SiPM array interface circuit board.

8.3. Interface Board Electrical Characterization

One possibility with the added sinusoid multiplexing scheme as implemented in these circuits is that sinusoidal interference is transmitted between the nearby and overlapping traces. This possibility is increased by the challenge of routing traces from locations not optimized for the multiplexing scheme. Such interference could make effective frequency identification challenging and/or ineffective and should be minimized as much as possible. Therefore, characterization of sinusoid-induced noise is carried out with both boards.

To characterize the sinusoidal noise, four different tests were done, two with the SiPM array powered off, and two with bias voltage applied to the SiPMs. First, a single sinusoid was applied to one of the board inputs and the amplitude of the applied sinusoid was varied while no voltage was applied to the SiPMs. To quantify the amount of noise induced, force triggers were randomly generated, and the recorded waveforms Fourier transformed into the frequency domain. The power at the mixed frequency and its first five harmonics are summed together to give a noise value for that event, and then the mean of many events is taken as the noise for that configuration. An example of this is shown in Figure 8.7 for a 13 MHz sinusoid with the
BAT48-1N5282 board. All measurements are taken from multiplexed output channel 1. Figure 8.8 shows that for the case of no SiPM voltage applied and a single frequency, the noise scales directly with the amplitude of the applied sinusoid.

Figure 8.5. Depiction of the circuit implemented in the SiPM array interface boards. One filter is connected to the common cathode and consequently used to bias all SiPMs.
Next, the amplitude of the applied sinusoid was set to 2.0 V and the frequency was varied, again for the case of no SiPM bias voltage applied. Figure 8.9 shows the frequency-dependent behavior of the noise. When no SiPM bias is applied, the worst frequency to use in regard to induced noise is about 13 MHz to 16 MHz and moving in either direction leads to reduced noise, although with the dual 1N5711 board, an increase in noise does appear around 20 MHz. This is inconvenient as frequencies between about 10 MHz and 20 MHz had previously been targeted as ideal.

The final two tests take place with the SiPM bias voltage applied, and this changes the behavior of the noise noticeably. Not only does this change how different frequencies induce noise, it also produces noise that is no longer a pure sinusoid but instead contains the original frequency and higher harmonics of it. Example noise and power spectra with the BAT48-1N5282 board are shown in Figures 8.10 and 8.11. To test how the SiPM bias voltage affects the noise, a 7 MHz, 200 mV sinusoid is applied to the circuit, and the applied SiPM bias varied.
Figure 8.7. From top to bottom: A force-triggered event; The power spectrum of such an event; The distribution of noise levels for this configuration.
Figure 8.8. The noise level induced in the circuit board as a function of applied sinusoid amplitude.

Figure 8.9. Impact of frequency on the induced noise in the circuit.
as shown in Figure 8.12. Simply increasing the voltage applied to the SiPM array increases the sinusoidal noise as well. Finally, another scan of frequency for noise levels is done with the SiPM bias applied and shown in Figure 8.13.

Figure 8.10. Noise generated from a 7 MHz mixed sinusoid and the associated power spectrum when SiPM bias voltage is applied.
Figure 8.11. Noise generated from a 13 MHz mixed sinusoid and the associated power spectrum when SiPM bias voltage is applied.
Figure 8.12. Impact of applied voltage to the SiPM on sinusoidal noise transmission.

Figure 8.13. Impact of frequency on sinusoidal noise transmission when the SiPM bias voltage is applied.

Clearly, the application of a bias voltage to the SiPM array affects the sinusoidal noise in previously unexpected ways. Increasing the bias voltage also increases the noise so one cannot
simply apply a very high bias voltage so that the signal overwhelms the noise because the noise will increase also, albeit at a reduced rate, such that signal to noise is slightly improved at higher overvoltages. Further, when a bias to the SiPM is applied, higher frequencies relatively induce more noise than they do when no bias voltage is applied. This drives the selection of multiplexing frequencies as low as possible. The reason for SiPM bias voltages affecting the noise as they do, especially creating noise at higher harmonics, is unclear, but the altering of voltage points throughout the circuit changes electrical characteristics making some change in behavior reasonable to expect.

The large amounts of sinusoidal noise with the 1N5282-BAT48 board prevent it from being an effective readout board, and not only does it produce more noise than the dual 1N5711 board, it requires larger sinusoids to conduct the multiplexing, further exacerbating its lack of suitability. However, it does offer the possibility to improve signal preservation if it can be implemented. Potential options for better implementation include using more layers in the circuit board, changing which layers are used for different tasks, changing which channels are multiplexed together, and rerouting the traces to minimize noise pickup.

While the diodes on the two different board versions differ, the tracks are identical so the large difference in induced noise between the different designs is somewhat unexpected and solely a product of the diodes used. One potential reason for this is that the 1N5711 diode in the sinusoid-generator-facing position has a lower voltage drop across it than in the 1N5282-BAT48 board, meaning that the node between the SiPM and this diode will have a lower voltage, likely helping alleviate noise transmission in that vicinity. Second, the forward-facing diode in the dual 1N5711 board has a higher voltage threshold before signal can pass, making
it a more effective block against noise transmission across it. These two characteristics, which make it less effective for fully transmitting signal forward, may help reduce sinusoidal noise transmission. Further, the slightly modified frequency-dependent behavior of the noise for the two boards, especially with no SiPM bias applied, implies that characteristics of the diodes themselves affect the resonances observed and that the resonances are not solely produced based on physical considerations such as the spacing of traces in the board. Example waveforms produced from gamma ray interactions are shown in Figures 8.14 and 8.15 for the different boards.

![Example pulses mixed with 5 MHz and 9 MHz sinusoids with the dual 1N5711 diode board.](image)

Figure 8.14. Example pulses mixed with 5 MHz and 9 MHz sinusoids with the dual 1N5711 diode board.

The board employing two 1N5711 diodes does not exhibit any noise with the sinusoids at amplitudes that might be used, and efficient tagging can be attained as described in Chapter 6. Thus, with the 1N5711 diodes, the multiplexing scheme segregates the channels and effectively carries out the multiplexing as intended. In the second case with different diodes, mixed sinusoid amplitudes need to be hundreds of mV for efficient multiplexing. When applying large
enough sinusoids to observe the desired superposition of the mixed frequency on the SiPM pulse, omnipresent sinusoidal modulation is observed on the baseline of the pulses. Small pulses are dominated by the omnipresent noise. Because the amount of sinusoidal modulation is proportional to the pulse size, large pulses can display enough of the desired frequency to allow for multiplexing, but the omnipresent sinusoidal noise dramatically deteriorates timing and energy resolution.

Figure 8.15. Example pulses from the 1N5282-BAT48 board.

Thus, the dual 1N5711 board will be used, and 5, 6, 7.3, and 9 MHz are selected as the multiplexing frequencies. While the use of the dual 1N5711 board has a lesser ability to pass
signal forward, this can be accounted for, to an extent, by applying a higher bias voltage to the SiPMs. Normally, elevated overvoltages create larger noise contributions from dark counts, eventually setting an overvoltage upper limit for desired operation. However, the diode, especially the 1N5711 diode, prevents dark counts from being passed because they are not sufficient to overcome the threshold voltage. This means that the dual 1N5711 board can accommodate higher applied overvoltages than the 1N5282-BAT48 board or a SiPM array set up without this multiplexing scheme, allowing for higher gains and better timing.

8.4. Imager Construction

Sections 8.1-8.3 described the construction of the necessary electronics to implement the imager, but its assembly still required deliberation. The cross-sectional face of the plastic scintillators is designed to match the size of the SiPMs to be used exactly, and on the SiPM arrays used in this imager, each adjacent SiPM is separated by 1.2 mm. Previous works have supported the pillars using rod alignment frames. Thanks to the use of fewer scintillators, the H2DPI at the University of Michigan takes advantage of a pillar layout with alternating rows of unused SiPMs, allowing for a sturdy frame to be easily used with supports at least one SiPM length across [67, 69]. The SANDD design fills a 6-mm SiPM array with 64 scintillators, but each scintillator is only 5.4 mm across and also avoids the use of any reflective wrapping, providing ample space to use plastic rod alignment frames [65].

The MiNI employs 32 scintillators in an alternating fashion which prevents the use of a frame that spans rows or columns of the SiPM array. Further the scintillators are wrapped extensively to maximize internal reflection and light collection. The reflective wrapping on
each side is about 0.3-0.4 mm thick which uses all the inter-SiPM space such that even thin supports cannot fit between the rows and columns of SiPMs.

To hold the pillars firmly in place, a combination of spacers and a wall surrounding the SiPM array is used. An outer support structure was fabricated using additively manufactured stainless steel. The outer support fits under the SiPM arrays and provides short walls that extend above the plane of the arrays to lodge spacers and scintillators against, while also providing flanges through which screws can be placed and fastened to hold firmly the opposing SiPM arrays. These structures are shown in Figure 8.16. Hollow plastic spacers were placed between the pillars. Bare spacers are 7-mm wide and wrapped with PTFE tape to fit snugly between the pillars they separate. The assembly process is shown in Figure 8.17. Once the active body of the imager is assembled, it can be connected to the necessary circuits, and is set up inside a light tight enclosure, shown in Figure 8.18.

![Figure 8.16. Additively manufactured supporting base walls used to position scintillators against.](image)

While the plastic scintillators are all machined to be approximately 60 mm in length, the length of pillars used in the imager ranges from 60.02 mm to 60.09 mm. To accommodate these
differences in length, 1.5 mm thick EJ-560 silicone rubber optical interfaces from Eljen Technology were used to optically join the scintillators to the SiPMs instead of optical grease. Additionally, these pads provided cushioning to support the weight of the circuits and other items used to prevent any long-term damage from occurring.

Upon fully assembling the imager it was found that some readout channels displayed some sinusoidal modulation of the baseline, but that the amount differed for each channel. Nonetheless, it was found that the channels read from the top board had a greater sinusoidal distortion of the baseline, suggesting its source to be from the sinusoid generators for which the elevated and exposed position of the top board makes it more susceptible. Events recorded in these channels would have greater uncertainty in their measurements due to the excess noise, and the noise also led to higher count rates at low trigger thresholds. To avoid recording low quality data and maximize data storage efficiency, three readout channels out of sixteen are not used, leading to one side of twelve different scintillators not being recorded. This leaves 20 usable scintillators for imaging, the pillars of which are labeled and shown in Figure 8.19, although all 32 scintillators contribute to the data acquisition rate and volume.
Figure 8.17. Assembly of the sensitive central part of the imager.
Figure 8.18. Incorporation of the active imager into the bias and readout circuits.
8.5. Circuit Development and Imager Assembly Conclusions

This chapter described the construction of the sinusoid-generating circuit and SiPM array interface boards that are required to build the prototype MiNI. Multiple interface boards with different diode combinations were tested to characterize the amount of sinusoidal noise that is present in the system when connected to sinusoid generators. The interface board with two 1N5711 diodes is chosen due to a lack of observed noise, but upon fully assembling the system some sinusoidal noise is still observed, primarily in the top circuit board. To avoid recording low-quality measurements only thirteen out of sixteen possible digitizer channels are recorded, leaving full readout of twenty pillars. Having detailed the physical implementation of the imager, the necessary calibrations can now be described.
Chapter 9
System Characterization and Calibration

To conduct imaging and spectroscopy with an NSC, a number of calibrations must be carried out and relationships between different quantities established. These include characterization of the time resolution and energy resolution of the detector elements, charge integral to light output calibration, light output to neutron energy deposition calibration, and determination of the relationship between the position of interaction in the vertical direction with the ratio of light detected at each side of the scintillator. Finally, because EJ-299-34 has some ability to discriminate between neutrons and gamma rays, characterization of PSD capability is important. While these measurements are all necessary for calibrating the neutron imager, some of them also serve as a useful test of the signal multiplexing method. This is the largest scale implementation of this multiplexing method to date and so the best demonstration of its performance. Therefore, the PSD and time resolution data to be presented are those that best test the multiplexing method, not necessarily being the most representative of imager characteristics. All results in this chapter use a CAEN DT5730 digitizer, configured to operate with a 0.5 V dynamic range and running CoMPASS software with DPP-PSD firmware from CAEN.

Results presented in this chapter no longer use arbitrary function generators but instead the sinusoid generators described in Section 8.1 Despite attempts to make them as similar in
sinusoid source characteristics, such as in source impedance, to the arbitrary function generators, their properties are different. Consequently, it is not possible to describe the results to follow as associated with a specific voltage corresponding to the sinusoid amplitudes as used in Chapter 6. To provide an idea of sinusoid amplitude and multiplexing effectiveness, Figure 9.1 and Table 9.1 show the determined frequencies for different events and the tagging efficiency, respectively, of the SiPMs at 29.5 V and 30.0 V applied. Measurements are made with the EJ-299-34 scintillators to be used in the imager, fully wrapped on all sides except the side coupled to the SiPM and optical grease is used to couple the scintillator to the SiPM. Tagging efficiencies presented are using the KNN frequency identification algorithm.

To arrive at the input features for the algorithm, the tagging portion of the pulse is started 20 samples after the maximum position of the pulse, and the following 300 points are down-sampled by a factor of two. The resultant 150 data points, followed by 150 zeros, are Fourier transformed into the frequency domain, and the first twenty frequencies are used as the input features. Twenty nearest neighbors are used. A data set is created with 30,000 events of each known frequency (5 MHz, 6 MHz, 7.3 MHz, and 9 MHz). This data set is then randomly shuffled and 100,000 events are used for training. This leaves 20,000 events for validation. This process was chosen because it resulted in the best frequency tagging efficiency.

Only events that are exactly one of the known frequencies are considered for data analysis, meaning that all twenty nearest neighbors are the same frequency, or that if some of the nearest neighbors are different their differences are averaged out. This gives a very high degree of confidence in the origin of pulses, and the use of twenty nearest neighbors represents the best compromise between having a high degree of confidence in the pulse origin and not discarding...
too many events as determined by the calculated tagging efficiencies. As can be seen in Table 9.1, excellent tagging efficiency is achieved. Because the KNN algorithm is based upon comparison with similar pulses, the close spacing between frequencies (~1 MHz) makes the frequency tagging less efficient than if wider spacing was used. Figure 9.1 provides a visual depiction of which pulses tend to get misclassified.

![Figure 9.1. Frequency classification for the 29.5 V data sets.](image)
9.1. Multiplexed Pulse Shape Discrimination Performance

The ability to discriminate neutron events from gamma ray events in the imager is necessary to correctly produce an image and energy spectrum. This can be done using only timing information between scatters to determine the particle type, but without perfect time resolution this method is not always sufficient. Further, it can fail for random scatters from two different particles that are interpreted as the same particle.

A complementary method for discriminating neutrons from gamma rays is desirable and PSD with EJ-299-34 offers the ability to do so, albeit with poorer performance than other PSD-capable organic scintillators. To characterize the PSD performance, considering also the desire to characterize the multiplexing method more generally, measurements are made using a 6-mm x 6-mm x 60-mm EJ-299-34 bar and a 6-mm x 6-mm x 6-mm stilbene crystal. Not only is stilbene superior in PSD performance to EJ-299-34, but the smaller size crystal with a better aspect ratio also contributes to improved PSD, mainly through improved light collection efficiency. With both scintillators, measurements were performed both using the multiplexed board and a reference SensL 60035 C-series SiPM set up on a breadboard as described in Chapter 5. Figure 9.2 shows an example setup. Energy calibration was done using a $^{22}$Na source.

Table 9.1: Frequency tagging efficiency for the multiplexing system implemented.

<table>
<thead>
<tr>
<th>Energy Window Frequency (MHz)</th>
<th>200-300 keVee</th>
<th>300-400 keVee</th>
<th>500-1500 keVee</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.5 V</td>
<td>0.907 0.982 0.991 0.937</td>
<td>0.983 0.995 0.995 0.997</td>
<td>0.972 0.948 0.959 0.967</td>
</tr>
<tr>
<td>30.0 V</td>
<td>0.954 0.994 0.993 0.903</td>
<td>0.995 0.992 0.999 0.997</td>
<td>0.970 0.938 0.959 0.953</td>
</tr>
</tbody>
</table>
Three methods of PSD are used to test the performance of the signal multiplexing method. Standard CC as described in Section 4.4 and FGA as described in Section 6.2.4 are used. Additionally, a third method is used that employs a KNN algorithm as is used in the frequency tagging analysis described in Section 6.5.4, and further information on KNN algorithms can be found in that section. This method uses a conventional PSP as the target for the regression algorithm, and it takes the input features provided to extrapolate to a more representative PSP based on comparison to similar pulses in the input feature space [137]. This implementation of the method uses the frequency ratio taken from optimization of the FGA method as the target feature and combines temporal and frequency information as the input features. The head and tail integrals, defined from the CC method, along with the power in the first four frequencies of the power spectrum of the pulse are taken as the six input features. Specifically, for training the algorithm, the PSP from the FGA method is calculated explicitly for 200,000 training events. Conceptually, the algorithm is then trained to predict that value based on the value of this feature.
for the nearest neighbors in the input feature space of the training events. For new pulses, the algorithm then uses the KNN in the input feature space to “predict” its actual PSP, which has been shown to improve the PSD performance [137]. While an extensive optimization of the input features and algorithm properties in the KNN method is not carried out for these data sets due to time constraints and the observation of improved PSD with the settings currently implemented, it serves as another alternative PSD method to demonstrate what quality of PSD can be achieved.

Plots showing the PSD performance are shown in Figures 9.3-9.6, and Table 9.3 summarizes the PSD performance for the different set ups. With the multiplexed array, only 5 MHz and 9 MHz are tested, but these two frequencies bound the range used in the prototype MiNI and so frequencies in between would be expected to have similar performance. The stilbene crystal’s far superior light collection efficiency caused saturation of the acquisition dynamic range, leading to the lower apparent upper limit of energy detected. Pulse rejection was done on the fly with the CoMPASS software. It can be seen that very little deterioration in PSD performance exists between the non-multiplexed reference case and the multiplexed system, with some cases actually being improved with the multiplexing setup. A higher bias voltage was used with the multiplexed array because of the signal attenuation from the multiplexing. However, the overvoltage used for multiplexed data may be more optimized for PSD than in the reference case, offering one explanation for improvements with multiplexing. Additionally, the use of diodes in the multiplexing can suppress noise and potentially alter pulse widths in a beneficial way.
The standard CC PSD provides very little separation with the EJ-299-34 scintillators to be used for the imager, while the FGA and KNN methods provide better separation down to lower energies. The KNN PSD is superior to the other two methods, with a FOM almost two times greater at higher energies. However, at these higher energies discrimination between the particle types is already very good and so a doubling of the FOM does not necessarily correspond to a doubling of the neutron-gamma ray discrimination capability. A more important test is the discrimination at lower energies where the KNN PSD is better but not as dramatically as at higher energies. However, 64 different SiPMs are used in the imager with four different frequencies which makes training a KNN algorithm for such a system more complex. At lower energies, the FGA method provides only slightly reduced PSD performance and is much simpler. Therefore, while the KNN-based method offers a route for some improvement in PSD performance, the FGA method will be used due to increased simplicity while maintaining acceptable performance in a first prototype. Ultimately, multiple options exist for achieving usable PSD in the imager, and multiplexing is shown to minimally impact PSD performance.
Figure 9.3. Pulse shape discrimination with stilbene and the reference SensL 60035 C-series X13 SiPM.
Figure 9.4. Pulse shape discrimination with stilbene and a 5 MHz-multiplexed SiPM.
Figure 9.5. Pulse shape discrimination with EJ-299-34 and the reference SensL 60035 C-series X13 SiPM.
Figure 9.6. Pulse shape discrimination with EJ-299-34 and a 9 MHz-multiplexed SiPM.
Table 9.2: Pulse Shape Discrimination Figure of Merit for Different Configurations. Hyphens indicate PSD too poor to quantify.

<table>
<thead>
<tr>
<th>SiPM</th>
<th>Scintillator</th>
<th>Voltage (V)</th>
<th>Frequency (MHz)</th>
<th>FOM (800-850 keVee)</th>
<th>FOM (245-255 keVee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Stilbene</td>
<td>29.0</td>
<td>-</td>
<td>1.71</td>
<td>2.63</td>
</tr>
<tr>
<td>Multiplexed</td>
<td>Stilbene</td>
<td>29.5</td>
<td>5</td>
<td>1.33</td>
<td>2.31</td>
</tr>
<tr>
<td>Multiplexed</td>
<td>Stilbene</td>
<td>29.5</td>
<td>9</td>
<td>1.03</td>
<td>2.38</td>
</tr>
<tr>
<td>Multiplexed</td>
<td>Stilbene</td>
<td>30.0</td>
<td>5</td>
<td>1.71</td>
<td>2.54</td>
</tr>
<tr>
<td>Multiplexed</td>
<td>Stilbene</td>
<td>30.0</td>
<td>9</td>
<td>1.82</td>
<td>2.6</td>
</tr>
<tr>
<td>Reference</td>
<td>EJ-299-33</td>
<td>29.0</td>
<td>-</td>
<td>0.91</td>
<td>1.00</td>
</tr>
<tr>
<td>Multiplexed</td>
<td>EJ-299-33</td>
<td>30.0</td>
<td>5</td>
<td>0.68</td>
<td>1.15</td>
</tr>
<tr>
<td>Multiplexed</td>
<td>EJ-299-33</td>
<td>30.0</td>
<td>9</td>
<td>0.67</td>
<td>1.28</td>
</tr>
</tbody>
</table>

9.2. Multiplexed Time Resolution

To characterize the multiplexing method and determine the expected time resolution of the system, coincidence timing measurements were made with three different scintillators: the 6-mm x 6-mm x 60-mm EJ-299-34 scintillator to be used in the imager, a 6-mm x 6-mm x 6-mm p-terphenyl crystal, and a 4-mm x 4-mm x 40-mm LYSO crystal. The former two scintillators are included to gain an idea of the multiplexing method’s impact in other possible detection systems. A non-multiplexed reference case was set up on a breadboard, and methods used are the same as those described in Section 5.1. For the EJ-299-34 measurements the source is elevated halfway up the scintillator as shown in Figure 9.7. Scintillators are wrapped on all sides except one with PTFE tape. Dual-sided readout as will be used in the imager is not done for timing measurements for simpler and more direct comparison of results to prior work and because the supporting structure of the imager does not easily allow for the placement of only two pillars for dual-readout.
The nominal highest voltage to use with the SensL 60035 C-series SiPM is about 29.5 V, and so this is used in all cases. In addition, 30.0 V and 30.5 V are also used with the multiplexed EJ-299-34 measurements to test if there is potential for improved timing above the specified range. For the multiplexed timing measurements, four combinations of frequencies were tested, based on SiPM positions suitably far apart for optimized count rates, physical placement of the source, and read out through different channels. The combinations presented are 5-7 MHz, 5-9 MHz, 6-7 MHz, and 6-9 MHz. Despite the four sets of measurements with four different frequencies, one cannot isolate the time resolution of each individual SiPM with the data sets shown because the associated relationships are not linearly independent. However, the measurements provide an idea of how frequencies compare to each other and the time resolution to be expected. Table 9.3 shows the time resolution for the different cases measured. Results are presented for the best fraction for each measurement, followed by the time resolution using a constant fraction of 0.2 in brackets, to give an idea of how they compare given the same fraction.
Table 9.3: Time resolution of single-ended readout of the SensL 60035 C-series SiPM and various scintillators.

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Voltage (V)</th>
<th>Unmultiplexed Reference</th>
<th>FWHM Coincidence Time Resolution (ns) [@ 20% fraction]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 MHz - 7 MHz</td>
</tr>
<tr>
<td>EJ-299-33</td>
<td>30.0</td>
<td>1.61 [1.63]</td>
<td>1.69 [1.76]</td>
</tr>
<tr>
<td>EJ-299-33</td>
<td>30.5</td>
<td>1.55 [1.60]</td>
<td>1.64 [1.72]</td>
</tr>
<tr>
<td>P-terphenyl</td>
<td>29.5</td>
<td>0.39 [0.78]</td>
<td>0.42 [0.94]</td>
</tr>
<tr>
<td>LYSO</td>
<td>29.5</td>
<td>0.87</td>
<td>1.69</td>
</tr>
</tbody>
</table>

5 MHz appears to be the worst frequency for multiplexing from a timing perspective, but little deterioration in timing compared to the reference case is observed. In fact, some measurements show an improvement in timing compared to the reference case. A suppression of noise by the multiplexing method offers one potential explanation. There also appears to be little motivation based on timing considerations to operate above the specified voltage limit of 29.5 V. The worse performance in timing resolution of the 5 MHz-multiplexed SiPMs suggests that the amplitude of this frequency is greater than the sinusoid amplitudes of the other frequencies. The 5 MHz LYSO case is substantially worse than the non-multiplexed reference, but all other cases for all scintillators are comparable or improved compared to the multiplexed case. Ultimately, this is another demonstration that for appropriately chosen sinusoid frequencies and amplitudes, effective detector performance, specifically time resolution in this case, can be maintained using the added sinusoid multiplexing method.

While these results are for one-sided readout, dual-sided readout should be expected to yield time resolution equal to or better than this [69, 138]. Multiple methods exist for combining the timing data from opposite ends of a pillar. Simply averaging the two timestamps analytically
yields the exact incident time plus a constant term, and this method is frequently used [67, 139]. However, this may not be the method that yields the best results from a statistical uncertainty perspective. For this reason, weighting the average by each pulse’s amplitude or the determined $z$-location, as described by

$$T = \frac{W_1 \ast T_1 + W_2 \ast T_2}{2},$$

is also done, where $W_1$ and $W_2$ are the pulse heights of each pulse respectively and their sum is normalized to unity, and $T_1$ and $T_2$ are the time stamps from each SiPM respectively. Both timing methods are tested in the imager and options for use, but neither is found to significantly outperform the other.

9.3. Energy Calibration and Resolution

In order to determine how much energy is deposited in a neutron interaction, it is necessary to first define a scale to convert between charge integral measured and light produced and collected in the scintillator. Such a scale is necessary to compare signals between different detector elements and assign a physical meaning associated with the interaction itself to the measured pulse. To calibrate this scale, mono-energetic sources of radiation are essential, but although the energy deposition to be measured is for neutrons, readily available mono-energetic neutron sources are essentially non-existent. Mono-energetic gamma ray sources are readily available however and can be used for calibration.

Converting the light output measured to neutron energy is non-trivial because of the different physics involved in neutron and gamma ray detection, and this is to be discussed in Section 9.4. For the purposes of light output calibration, it is sufficient to define the units in terms of the
light produced and collected from an energy deposited by electrons, or keVee (keV electron equivalent). It should be noted that when referring to gamma rays there is a one-to-one equivalency between energy (keV) and light output (keVee), although imperfect energy resolution must also be kept in mind. With neutron interactions this is not the case, and one must be careful to describe the light output in terms of keVee, the unit that is actually measured, rather than energy.

Even with mono-energetic gamma ray sources, establishing the light output associated with a certain electron energy deposition in organic scintillators requires careful consideration because no photopeak is produced as described in Section 2.2. Instead, the spectrum arising from Compton scattering must be used, and specifically the Compton edge is used to calibrate the light output scale. However, due to broadening of spectral features from systematic uncertainties and inherently finite energy resolution, the exact location of the true Compton edge energy cannot be determined by inspection, and detailed analysis must be conducted to locate it. One such analysis method involves using backscatter-gated measurements to only examine pulses associated with a full backscatter. In this case, a peak corresponding to the Compton edge energy should be isolated in the produced spectrum and provides the light output point desired. This method requires a specific and relatively more complex experimental setup.

Alternatively, one can calibrate the light output spectrum by combining simulation with experiment. To do so, a simulation of energy deposited in the scintillator volume for a given mono-energetic source is run to generate the light output spectrum without any spectral broadening factors included, leading to a sharp Compton edge in the spectrum. An advantage of using a simulation instead of an analytical Klein-Nishina expression is that it also accounts
for double scatter within the scintillation medium, and partial energy deposition prior to escaping the volume by scattered electrons. An experimentally measured light output spectrum using a source of the same energy as the simulation is then scaled both vertically (in the counts dimension) and horizontally (in the light output dimension) to closely match the simulated spectrum, which is then broadened to match the measured spectrum with an energy resolution function given by

$$
\frac{2.3548 \times \sigma_L}{L} = \sqrt{\frac{\sigma^2}{L} + \frac{\beta^2}{L} + \frac{\gamma^2}{L^2}},
$$

where $L$ is light output; $\sigma$ is the standard deviation of the Gaussian distribution; and $\alpha$, $\beta$, and $\gamma$ refer to sources of uncertainty. Uncertainty arising from position-dependent light transmission and collection is described by $\alpha$, uncertainty from the light-to-charge conversion and amplification is described by $\beta$, and $\gamma$ describes the contribution from electrical noise [140, 141].

In practice this process is implemented by iterating through different values of $\alpha$, $\beta$, and $\gamma$ to broaden the spectrum, and then the quality of the spectrum matching quantified using a chi-square calculation. The chi-square calculation is only done in the proximity of the Compton edge to focus on the most relevant spectral features and to avoid evaluating the comparison based on less important information at low energies where one would also expect a greater discrepancy between simulation and experiment. The lowest chi-square value determines the parameters of the energy resolution to be used, and once done, the comparison of the unbroadened and broadened simulations indicates where in the light output spectrum the true Compton edge is located. Taking the fraction of the maximum pulse height in the Compton
shoulder at the true Compton edge location allows one to accurately determine the light output corresponding to a given electron energy deposition for similar scintillators. This fraction is different for different scintillators based on their composition and geometry, so if these vary then the process must be repeated for the new scintillator type [140].

This process is shown for $^{137}$Cs and $^{22}$Na sources in Figures 9.8 and 9.9. The 662 keV gamma ray from $^{137}$Cs yields a 477 keVee Compton edge, and the 1275 keV gamma ray from $^{22}$Na produces a 1061 keVee Compton edge. A 511 keV photon is also produced from positron annihilation following positron emission from $^{22}$Na. This creates a 341 keVee Compton edge and is low enough in energy to not interfere with the calibration procedure using the 1275 keV gamma ray, but it is responsible for the divergence between experimental data and the broadened simulation around 500 keVee in Figure 9.9 because the simulation spectrum does not include the 511 keV photon. However, if the 341 keVee Compton edge is also to be used for calibration the Compton continuum from the 1275 keV gamma ray should be removed from the spectrum. This is done by fitting a line to the continuum and subtracting this line from the spectrum as is shown in Figure 9.10. Based on the method described here, the true Compton edge was taken to occur at 65% of the maximum pulse height of the Compton shoulder. This calibration procedure also inherently measures the energy resolution at the Compton edge energies of the detector. This is a necessary input to the image reconstruction algorithm and so is an extra benefit of the detailed calibration procedure.
Figure 9.8. The calibration procedure for a $^{137}$Cs gamma ray source, showing the broadening and rescaling of the simulated spectrum (top) and the portion of the spectrum used for the Chi-square calculation, described as “Fitted Simulation” (bottom).
Figure 9.9. The calibration procedure for the 1275 keV photon from a $^{22}$Na gamma ray source, showing the broadening and rescaling of the simulated spectrum (top) and the portion of the spectrum used for the Chi-square calculation, described as “Fitted Simulation” (bottom).
Figure 9.10. Spectrum subtraction procedure to isolate the 341 keV Compton edge. The red line shows the fit to the 1275 keV Compton continuum.

9.4. Converting Light Output to Neutron Energy Deposition

Gamma ray interactions in scintillators primarily produce free electrons, while neutron interactions liberate protons. In similar energy regimes, protons deposit more energy than electrons per unit space traversed, giving them a shorter range and leading to more spatially concentrated energy deposition. The increased spatial density of energy deposition leads to increased quenching in light production such that for a given energy deposited by a proton and electron, less light will be produced by the proton. This is the motivation for defining a light output scale and the inability to directly define a general energy scale. The amount of quenching is usually described by Birks’ law,

\[
\frac{dL}{dx} = S \left( \frac{dE}{dx} \right) \frac{dE}{dx} \left( 1 + k_B \frac{dE}{dx} \right),
\]

(9.3)
where \( dL/dx \) is the amount of light produced per unit length, \( S \) describes the scintillation efficiency, \( dE/dx \) is the stopping power or energy deposition per unit length of the particle, and \( k_B \) is a material-dependent constant that determines the amount of quenching [142].

Rather than attempting to measure the constants in Equation 9.3 directly, it is more convenient to empirically determine the direct relationship between neutron energy deposition and light output. For the purposes of generating a usable relationship, Birks’ law can be rewritten as

\[
L = \int_{0}^{E} \frac{a}{1 + b \frac{dE'}{dx}} dE',
\]

(9.4)

where \( a \) and \( b \) are parameters to fit.

Acquiring the data used to determine this relationship requires knowledge of an incident neutron’s energy, but as previously stated quasi-monoenergetic neutron sources are not widely accessible. Instead, a TOF method can be performed in which the energy of an incident neutron is inferred from the time it takes to travel a known distance. Spontaneous fission sources offer a means to do so because, for each fission, multiple particles, including neutrons, are produced essentially simultaneously. This allows for one particle to define a time of origin for a different neutron traveling toward a detector, enabling the calculation of TOF and consequently its energy. The energy of the neutron is determined by the classical kinetic energy equation,

\[
E_n = \frac{1}{2} m_n \frac{x^2}{t^2},
\]

(9.5)

where \( E_n \) is the neutron energy, \( m_n \) is the neutron mass, \( x \) is the distance traveled, and \( t \) is the time over which it traveled. This conversion of TOF to energy is also to be used in the kinematic imaging to be discussed in Chapter 10.
The TOF experiment is carried out with a $^{252}$Cf source. A 2” x 2” EJ-309-PMT assembly is used as the tagging start detector, and the stop detector for the neutron is an EJ-299-34 scintillator coupled to a SensL 60035 C-series SiPM in the SMA package. The light output calibration means that to ascertain the desired relationship between light output and neutron energy deposition, only the scintillator to be used must remain the same. Thus, a non-multiplexed SiPM in the SMA format is used to maximize PSD, helping to filter out gamma ray interactions, and because it easily sits flat, allowing for extended measurements. Coincidence triggering is implemented at the digitizer firmware level. The $^{252}$Cf source is placed 64 cm from the center of the scintillator and the TOF measurement is taken over seven days. A second background scatter correction measurement is also taken over seven days with a 12” long polyethylene cylinder placed between the $^{252}$Cf source and the stop detector. This setup is shown in Figure 9.11, and Figure 9.12 shows the TOF spectrum and associated energy spectrum without background subtraction. The sharp peak near 0 ns in Figure 9.12 corresponds to gamma rays, and the energy spectrum nicely matches an expected Watt spectrum. The peak below the Watt spectrum arises from chance coincidence and environmental scattering.

The data are sliced into 100 keV wide energy windows to produce light output spectra as a function of energy. This bin width is chosen to yield reasonable statistics in each energy bin without including neutrons of significantly different energy in the same bin. The spectra are then smoothed with a five-point moving average filter, chosen to smooth the distribution while only minimally altering the underlying features and in well-understood ways. As done by Kornilov and others, the spectra were numerically differentiated [67, 143, 144]. The higher energy end of the derivative spectrum has a peak corresponding to the total energy deposition.
Figure 9.11. Time-of-flight experiment with and without the polyethylene shadow bar.

Figure 9.12. Time-of-flight spectrum (top) and the corresponding neutron energy spectrum (bottom).
in a single scatter of a neutron of a given energy, and which, in the absence of uncertainty and imperfect resolution, would be a Dirac delta function. A Gaussian function is fit to this peak and the mean of the fit is taken as the light output corresponding to that neutron energy. Figure 9.13 shows an example smoothed spectrum and the corresponding differentiated spectrum with a Gaussian fit.

Figure 9.13. Light output spectrum (top) and differentiated light output spectrum (bottom) for 2.0 MeV neutrons. The red line indicates the fit used to extract the light output associated with full energy transfer from the neutron to the proton.
To extrapolate to neutron energies beyond those for which a TOF spectrum could be sufficiently generated, a fit to Birks’ law is carried out as in Equation 9.4. The proton stopping power to be used is taken from the NIST PSTAR database [145]. Equation 9.4 is approximated numerically by the trapezoidal rule to remove the integral. To further simplify the equation and bring it into a closed form suitable for fitting, the non-relativistic Bethe formula,

\[-\frac{dE}{dx} = \frac{4\pi e^4 z^2 N}{m_e v^2} Z \left( \ln \frac{2m_e v^2}{I} \right),\]  

(9.6)

is used, where \(e\) is the electron charge, \(z\) is the atomic number of the primary particle, \(N\) is the number density and \(Z\) is the atomic number of the medium in which the particle travels, \(m_e\) is the electron rest mass, \(v\) is the velocity of the primary particle, and \(I\) is the ionization potential of the medium [146]. This formula fails at lower energies, but in the energy regime of interest is valid. Equation 9.6 is rewritten for fitting as

\[\frac{dE}{dx} = a * \ln(E) + \frac{b}{E}.\]  

(9.7)

The stopping power and associated fit are shown in Figure 9.14, where the fit is between 100 keV and 10 MeV, energies significantly beyond those to be detected. The trapezoidal rule’s approximation does not include the data points not covered by the fit, motivating its use. The experimental data along with the approximated Birks’ fit are shown in Figure 9.15. This relationship will be used to convert light output into neutron energy deposited.
Figure 9.14. Stopping power of scintillating plastic with a fit to be used to bring Equation 9.4 into closed form, data obtained from [145].

Figure 9.15. Relationship between neutron energy deposited and light output detected. The black dots are the experimental data and the red line is the fit given by the equation on the plot.

\[ L(E) = \frac{0.8045E^2}{E + 1418 \cdot \ln(E) - 4652} \]
9.5. Determination of Vertical Position of Interaction

Measuring the location of interaction as accurately and precisely as possible is essential for effective imaging, as it influences all inputs to the reconstruction algorithm. Position information in the plane aligned with the SiPM arrays, for concreteness taken to be the x-y plane, is conveyed by which SiPMs trigger, and the uncertainty in that dimension is given by the uncertainty of a uniform distribution,

$$\sigma_{x,y} = \frac{w_{x,y}}{\sqrt{12}},$$  \hspace{1cm} (9.8)

where $w_{x,y}$ is the width of the distribution in either the x or y dimension [147]. For 6-mm x 6-mm square pixels, the uncertainty in each direction then is $6/\sqrt{12}$ mm.

To obtain position information in the third dimension, the z direction, one can compare properties of the signal produced at each end of the pillar in which the event occurred. Previous work has explored using the ratio of charge collected in each opposing SiPM and also the time of arrival of the signal at each end of the pillar [61, 67, 139]. The relatively small length of the pillars to be used in the multiplexed imager makes information based on short photon travel times difficult to use, with differences likely smaller than the time resolution of the system. Further, two different digitizers are used to read out the detected events, and while they are synchronized to the same clock, the possibility of different time offsets between the two digitizers for different runs requires calibration that makes the use of timing information for position information more challenging. Therefore, the ratio of charge collected at each end of a pillar will be used to determine the location of interaction along the length of the pillar.
Multiple factors contribute to the relative amount of charge collected at each end of a pillar. The gain and photon detection efficiency of each SiPM affects it and would vary based on different breakdown voltages of different SiPMs. Additionally, quality of coupling between the scintillator and light sensor can make a difference. These factors would ideally contribute in a constant way and cancel out when different positions of interaction are compared against each other, but it would manifest differently in different pillars. The primary driver of differences in charge collection that enables position sensitivity is the light collection at each end of the pillar for a given location of light origin. The pillars are wrapped extensively with reflective tape to attempt to maximize light preservation and collection. However, some light might still escape through the sides and reflective layer or be absorbed within the scintillator. The greater distance the light has to travel the more light that is lost and consequently smaller signal produced. Therefore, a greater signal collected at one end of the scintillator indicates the event took place closer to that end, and for a given pillar the ratio of charge collected at each end corresponds to a specific interaction location.

Many factors that affect the light collection and charge production are specific and unique to each pillar, which prevents analytical models from being effectively used. This motivates experimental characterization of the relationship between position of interaction and charge collected at each end once the imager is set up. In other words, each assembly of the imager or any significant modification(s) requires a new calibration. It should be noted that inferior light collection would lead to larger differences in charge collected at each end and therefore better position sensitivity. There is therefore a tradeoff between overall signal amplitude and position sensitivity. In this imager, maximizing light collection overall was prioritized, but there is
potential for improving imager performance by finding the ideal light collection efficiency to be implemented.

To calibrate this relationship a collimated source of radiation is used to produce data sets for analysis in which the vast majority of recorded interactions take place at the same vertical position. Lead shielding offers an effective way to collimate a source of gamma rays, so two lead bricks are placed on top of each other with a 3-mm slit between them, shown in Figure 9.16, to produce a fan beam from a 64 µCi $^{22}$Na source. The collimator and source are placed on a vertical translation stage that can shift in a smooth and controlled manner enabling the accurate placement of the beam in different steps. A 5-mm step size is used and only the middle 50 cm of the pillars are scanned across. Measurements at each end of the pillars are not conducted because of the possibility of inexact alignment and the additional interfering material from the metal support for the scintillators. While, the $z$-axis 0 coordinate may not be aligned exactly with the middle of the pillars, as long as the sources to be imaged are referenced to the same coordinate system as the collimation, the $z$-position calibration will hold. The imager is set up inside a light-tight enclosure while the collimated source is placed outside the enclosure due to space restrictions. The setup is shown in Figure 9.16.
At each 5-mm increment along the axis of the scintillators a measurement was taken for 24 hours. Halfway through each measurement the collimated source was moved to the opposite side of the light-tight enclosure to balance the count rate on each side of the imager. In total, eleven measurements were made, ranging from -25 mm to +25 mm, where the 0 coordinate was attempted to be placed at the vertical center of the pillars. For each measurement a histogram of the ratio of charge collected by the bottom SiPM to the total charge collected,

\[ R_z = \frac{\text{Charge Integral of Bottom SiPM}}{\text{Charge Integral of Bottom SiPM} + \text{Charge Integral of Top SiPM}}, \]  

(9.9)

is used as the calibration value because it is a convenient value that ranges from 0 to 1. For each measurement, a histogram of the \( R_z \) distribution is generated and a Gaussian function fit to each, with the center of the Gaussian fit being used as the value of \( R_z \) at that location. Example distributions for a single pillar are shown in Figure 9.17, and the relationship between position and charge ratio is shown for twenty pillars in Figure 9.18. In the region of positions measured,
no sufficient deviation from linearity was observed to motivate the use of any other relationships for fitting the data, so simple lines of best fit are used to extrapolate from measured charge ratios to the \( z \)-coordinate of interaction.

![Figure 9.17](image.png)

Figure 9.17. Distribution of charge integral ratios, \( R_z \), for different interaction locations in a single pillar. A) shows a three-dimensional rendering of the different distributions, and b) shows the same distributions from above with a color \( z \)-scale. The shifting of the distributions as a function of position is clearly shown in b). C) shows the normalized distribution for six different positions.
To characterize the position resolution and accuracy obtainable, the data in each measurement were converted using the calibration relations generated for each pillar to predicted $z$ positions and then compared to the known positions. The center of each reconstructed distribution conveys information about accuracy, and the width of the distribution conveys the position resolution. Gaussian distributions are fit to each distribution to extract the desired values, and an example of the reconstructed position resolution for a single pillar is shown in Figure 9.19. To gain an idea of how position resolution varies with position, Figure 9.20 shows the average position resolution across all pillars as a function of interaction location. Conversely, Table 9.4 shows the average resolution for twenty pillars when averaged across all locations.
Figure 9.19. Example relationship between known interaction location and reconstructed location for a single pillar. The blue dashed line indicates the ideal reconstruction and error bars show 1σ uncertainty.

Figure 9.20. Position resolution averaged across all pillars for different positions.
### Table 9.4: Average position resolution for different scintillators

<table>
<thead>
<tr>
<th>Pillar</th>
<th>1</th>
<th>5</th>
<th>7</th>
<th>12</th>
<th>14</th>
<th>19</th>
<th>26</th>
<th>28</th>
<th>30</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Uncertainty (mm)</td>
<td>9.75</td>
<td>10.61</td>
<td>9.14</td>
<td>9.42</td>
<td>9.35</td>
<td>10.67</td>
<td>9.52</td>
<td>8.98</td>
<td>7.19</td>
<td>8.76</td>
</tr>
<tr>
<td>Pillar</td>
<td>33</td>
<td>44</td>
<td>46</td>
<td>48</td>
<td>49</td>
<td>51</td>
<td>53</td>
<td>60</td>
<td>62</td>
<td>64</td>
</tr>
<tr>
<td>Average Uncertainty (mm)</td>
<td>9.13</td>
<td>9.41</td>
<td>9.19</td>
<td>8.44</td>
<td>9.07</td>
<td>8.54</td>
<td>8.71</td>
<td>8.76</td>
<td>8.24</td>
<td>8.00</td>
</tr>
</tbody>
</table>

It is observed that position resolution remains relatively constant for all positions, and that the different pillars tend to possess similar position resolution. This consistency across locations and pillars is extremely convenient for facilitating effective reconstruction. While position resolution in the vertical dimension is typically less than 10 mm, this is still significantly worse than the position resolution in the horizontal plane as long as effective multiplexing takes place, which is shown to be the case. Multiplexing will impact the vertical position resolution through a degradation in energy resolution, but this effect is not quantified due to an inability to measure a vertical position reference case.

### 9.6. Imager Calibration Summary

Extensive calibrations and system characterizations were performed in this chapter. The frequency tagging efficiency of the prototype MiNI is shown to be very good. The PSD performance of multiple scintillators is characterized and it is found that multiplexing minimally degrades the ability to carry out effective PSD, although PSD in EJ-299-34 is significantly worse than in stilbene, with a higher energy threshold at which discrimination can occur. Therefore, timing-based gamma rejection cuts will be required to complement PSD.
Timing resolution is also found to be minimally affected, especially for the EJ-299-34 pillars used in the MiNI, and time resolution on the order of a nanosecond is observed. Energy calibrations are carried out using a combination of simulation broadening and a TOF experiment. Finally, calibration of the position of interaction in the vertical dimension is carried out. Vertical position uncertainty is consistently shown to be approximately 10 mm. Ultimately, on the largest scale implementation of the added sinusoid multiplexing scheme, detector performance in the characteristics quantified in this chapter is shown to be minimally degraded, providing strong support for the quality of the multiplexing method. Additionally, the detector element-level performance of the MiNI is understood and the calibrations have prepared it for use. The next step is to take the measured data and use it to infer the desired information: neutron images and energy spectra.
Chapter 10

Description of the Image Reconstruction

Chapter 9 describes the necessary calibrations to acquire the information required to conduct neutron imaging and spectroscopy. Specifically, the time and location of the two scatters must be measured, as well as the energy deposited by the neutron in its first scattering interaction. In addition, for effective imaging the uncertainty in these quantities should be understood. Finally, the ability to reject gamma ray events is beneficial. While producing an energy spectrum of the incident neutrons is straightforward - excluding efficiency corrections - with these measurements, imaging requires more extensive reconstruction logic and algorithms. This chapter describes how to apply the measured information to produce neutron images, specifically with the simple backprojection method. While more sophisticated imaging algorithms exist to produce higher resolution images, these will not be implemented in this work, the goal of which is to demonstrate the feasibility of developing a multiplexed NSC. Examples of alternative imaging algorithms include maximum likelihood expectation maximization (MLEM) and stochastic origin ensemble (SOE) methods. More information on these methods and their application to neutron imagers are described elsewhere [50, 67, 69, 148-155].
10.1. Scattering Kinematics for Imaging

The fundamental premise of kinematic double-scatter imaging is that based upon a characterization of two consecutive scatters, conservation of energy and momentum can be applied to determine the angle at which the neutron scattered in its first interaction. This yields a cone of possible directions from which the neutron originated. Multiple cones can be combined together to converge on the source of the neutrons.

While conceptually straightforward, generating the uncertainty-broadened cones for pairs of scatters is non-trivial. The cone is centered around the unit vector, \( \hat{n} \), defined by the vector between the two scattering locations. Treating the mass of a proton and neutron as equal, the angle of scatter in the first interaction is

\[
\theta_s = \cos^{-1} \left( \frac{E'}{E_0} \right),
\]

where \( E_0 \) is the original energy of the neutron and \( E' \) is the energy of the neutron after the first scatter. The energy of the neutron following the first scatter is calculated using TOF as in Equation 9.5 with the relevant measured quantities in each interaction,

\[
E' = \frac{1}{2} m_n \left( \frac{|\vec{x}_2 - \vec{x}_1|}{t_2 - t_1} \right)^2,
\]

where \( m_n \) is the mass of the neutron, \( \vec{x}_1 \) and \( \vec{x}_2 \) are the coordinates of the first and second scatter respectively, and \( t_1 \) and \( t_2 \) are the times of each scatter. The original energy of the neutron prior to the first scatter is simply the sum of the energy of the scattered neutron and the energy deposited in the first scatter, \( E_{d1} \):

\[
E_o = E' + E_{d1}.
\]

A pair of scatters is depicted in Figure 10.1.
Figure 10.1. A pair of scatters used to generate a cone of possible directions from which the neutron came.

The measured quantities alone define the cone, but each value used has an associated uncertainty that makes it unlikely the neutron came exactly from one of the directions defined by \( \hat{n} \) and \( \theta_s \). For this reason, the boundaries of the cone that describe the possible directions of incidence for the neutron must be broadened based on the uncertainty in the measurements. Defining a coordinate system to project the cone onto is necessary, and so a two-dimensional system is used with the two angular coordinates of a typical spherical coordinate system. The coordinate system to be used is depicted in Figure 10.2.

\[
\theta_s = \cos^{-1} \left( \frac{E'}{\sqrt{E_0}} \right)
\]

\[
\hat{n} = \frac{x_1 - x_2}{|x_1 - x_2|}
\]

\[
E' = \frac{1}{2} m_n \left( \frac{|x_2 - x_1|}{t_2 - t_1} \right)^2
\]

\[
E_0 = E' + E_{d1}
\]
The description of the method used to project cones onto 2-dimensional angular surfaces in 3-dimensional space is described by Ruch and Steinberger [67, 69]. To determine the projection value onto each bin in the angular coordinate system, two quantities are introduced to describe two angles. First, the scattering angle, $\theta_s$, is converted into

$$\alpha = \cos^2 \theta_s. \quad (10.4)$$

Next, a similar quantity is defined between $\hat{n}$ and the vector pointing from the location of the first scatter and the coordinates of each bin on the projection coordinate system. This quantity describes the angle, $\theta_b$, between these two vectors and is defined as

$$\beta_b = \cos^2 \theta_b = \frac{(\hat{n} \cdot (\vec{x}_b - \vec{x}_1))^2}{|\vec{x}_b - \vec{x}_1|^2}. \quad (10.5)$$

When $\alpha$ and $\beta_b$ are equal, the probability of the neutron originating from that bin is maximized. This occurs when the angle specified by the vectors involved in calculating $\beta_b$ is equal to the

Figure 10.2. Coordinate system used to project cones onto.
angle specified by the vectors involved in the calculation of $\alpha$. In other words, the maximum occurs when the vector pointing to a specific bin is parallel with the surface of the cone, both vectors originating from the location of first scatter.

Bins near the maximum bins should also have finite likelihoods due to the uncertainty in reconstruction and, to accomplish this, the relevant uncertainties must be determined and incorporated into the cone projection. Uncertainties for a given quantity, $x$, are described by their variances as $\sigma^2_x$. The uncertainty in calculating $\alpha$ is

$$\sigma^2_{\alpha} = \frac{1}{E_0^2} \sigma^2_{E_0} + \frac{E^2}{E_0^4} \sigma^2_{E'}.$$  \hspace{1cm} (10.6)

The uncertainty in the incident neutron’s energy is given by,

$$\sigma^2_{E_0} = \sigma^2_{E_1} + \sigma^2_{E_{1t}},$$  \hspace{1cm} (10.7)

and the uncertainty in the scattered neutron’s energy is

$$\sigma^2_{E'} = \frac{m_n^2}{(t_2 - t_1)^4} \left( \frac{1}{4} \sigma^2_{d^2} + \frac{[x_2 - x_1]^4}{(t_2 - t_1)^2} \sigma^2_{\Delta t} \right),$$  \hspace{1cm} (10.8)

where

$$\sigma^2_{\Delta t} = \sigma^2_{t_1} + \sigma^2_{t_2}$$  \hspace{1cm} (10.9)

and

$$\sigma^2_{d^2} = 4 \left( (x_2 - x_1)^2 (\sigma^2_{x_2} + \sigma^2_{x_1}) + (y_2 - y_1)^2 (\sigma^2_{y_2} + \sigma^2_{y_1}) + (z_2 - z_1)^2 (\sigma^2_{z_2} + \sigma^2_{z_1}) \right).$$  \hspace{1cm} (10.10)

The uncertainty in $\beta_b$ is strictly a function of position and positional uncertainties. Prior to defining it, it is convenient to define some intermediate quantities. The coordinate-wise differences between the scattering locations are abbreviated as
\[ \Delta_x = x_1 - x_2, \quad (10.11) \]
\[ \Delta_y = y_1 - y_2, \quad (10.12) \]

and

\[ \Delta_z = z_1 - z_2. \quad (10.13) \]

The coordinate-wise differences between the first scatter location and each projection bin, converting from spherical coordinates to Cartesian, are

\[ \lambda_x = r \cos \phi_b \sin \theta_b - x_1, \quad (10.14) \]
\[ \lambda_y = r \sin \phi_b \sin \theta_b - y_1, \quad (10.15) \]

and

\[ \lambda_z = r \cos \theta_b - z_1. \quad (10.16) \]

where \( r \) is the radius of the sphere onto which the cone is projected. Finally, the combination of these values yields

\[ \Sigma_{\Delta^2} = \Delta_x^2 + \Delta_y^2 + \Delta_z^2, \quad (10.17) \]
\[ \Sigma_{\lambda^2} = \lambda_x^2 + \lambda_y^2 + \lambda_z^2, \quad (10.18) \]

and

\[ \Sigma_{\Delta \lambda} = \Delta_x \lambda_x + \Delta_y \lambda_y + \Delta_z \lambda_z. \quad (10.19) \]

Using these quantities, the uncertainty in \( \beta_b \) is defined by
\[
\sigma_{\bar{B}}^2 = \left( \frac{2\Sigma_\Delta \lambda}{\Sigma_\Delta^2} \right)^2 \left\{ \left[ \Sigma_\Delta \lambda \left( \frac{\lambda X - \Delta X}{\Sigma_\Delta^2} \right) + \lambda X - \Delta X \right]^2 \sigma_{\bar{x}}^2 + \left[ \Sigma_\Delta \lambda \left( \frac{\lambda Y - \Delta Y}{\Sigma_\Delta^2} \right) + \lambda Y - \Delta Y \right]^2 \sigma_{\bar{y}}^2 + \left[ \Sigma_\Delta \lambda \left( \frac{\lambda Z - \Delta Z}{\Sigma_\Delta^2} \right) + \lambda Z - \Delta Z \right]^2 \sigma_{\bar{z}}^2 \right. \\
+ \frac{\Delta Y \Sigma_\Delta \lambda}{\Sigma_\Delta^2} - \lambda Y^2 \sigma_{\bar{y}}^2 + \frac{\Delta Z \Sigma_\Delta \lambda}{\Sigma_\Delta^2} - \lambda Z^2 \sigma_{\bar{z}}^2 \left\} \right. \\
+ \left. \frac{\Delta Y \Sigma_\Delta \lambda}{\Sigma_\Delta^2} - \lambda Y^2 \sigma_{\bar{y}}^2 + \frac{\Delta Z \Sigma_\Delta \lambda}{\Sigma_\Delta^2} - \lambda Z^2 \sigma_{\bar{z}}^2 \right). 
\]

(10.20)

Having defined the necessary angles to calculate the distance between the most probable origin of the neutron and the location of each bin, as well as the uncertainties involved, a Gaussian centered around \( \alpha \) is used to determine the appropriate value of the projection for cone \( i \) in bin \( b \):

\[
C_{i,b} = e^{-\frac{1}{2} \left( \frac{(\bar{B}_b - \alpha)^2}{\sigma_{\bar{B}}^2 + \sigma^2} \right)}.
\]

(10.21)

Examples of simulated cone projections are shown in Figure 10.3. The ability to produce cones of probability of incident direction is the crucial underpinning of image reconstruction. With this established, it is possible to produce images of neutron sources.
Figure 10.3. Uncertainty-broadened cones projected onto a sphere for simulated events. The narrower cone is indicative of lower relative uncertainty, meaning that the time and distance between scatters is likely greater than that for the thicker cone.

10.2. Backprojection of Neutron Events

The simplest image reconstruction algorithm is backprojection. Conceptually, this method is simply superimposing the probability distributions of different cones on each other to produce a resultant image. Quantitatively, the image is defined by its pixel values, \( I \) for each bin \( b \),

\[
I_b = \sum_{l=0}^{n} C_{lb} ,
\]

(10.22)

for the sum from \( n \) cones. Figure 10.4. shows multiple cones combined onto the same image, although not added together, depicting the process of backprojection. For accurately projected cones, the intersection of multiple cones indicates the location of the neutron source.
It should be noted that for visually representing the image, small differences in picture generation can lead to significant visual differences. For example, the color z-scale used can sharpen or blur an image, an example of which is shown in Figure 10.5. As more cones are combined into the backprojection image, the image quality should be improved, although very few cones should be necessary to begin to observe the source of neutrons [68]. The number of cones necessary, however depends on the uncertainties involved and quality of measurements taken. Figure 10.6. shows a simulated image using different numbers of backprojected cones.
Figure 10.5. An unscaled simple backprojection image (top) and the same image with a smaller z-axis range used for the color scale (bottom).
Figure 10.6. Simple backprojection image for different numbers of $n$ superimposed cones.
Simple backprojection is a method to generate an image from a set of cones in a straightforward manner. However, it has a relatively poor resolution compared to alternative, more sophisticated image reconstruction algorithms such as the aforementioned MLEM and SOE methods. While the images in Figure 10.6. show relatively good resolution, these images were generated from a simulation for which the quantities used in reconstruction are unambiguous.

One potential route to improve image quality outside of implementing a different algorithm is to filter the image. Both high-pass and low-pass image filters could be used. Simple backprojection produces relatively broad distributions in the image so as long as the image is centered correctly, high-pass filtering the image could enhance image density around the true neutron source. An example of high-pass filtering simulated images is shown in Figures 10.7 and 10.8. With a sufficient number of cones, high-pass filtering can improve the resolution of the simple backprojection algorithm, but in the absence of sufficient counts to blur out artifacts, high-pass filtering highlights aspects of the image other than those of interest and is detrimental to the overall results. In other words, if artifacts in the image are present or the image is not perfectly centered, high-pass filtering can artificially or inaccurately modify the image and is not implemented in this work. However, with a large number of recorded events, filtered backprojection stands as one possible route to improve angular resolution without implementing a different reconstruction algorithm.

Low-pass filtering can help reduce artifacts in the image or smooth contours that suffer from fewer events or counts in the histogram, but does not increase image resolution. However, it can aesthetically improve images and aid an observer in easily drawing effective conclusions.
from the image and so is implemented in this work as complementary to the unfiltered images. The benefits of low-pass filtering are not fully demonstrated on a collection of simulated events for which all relevant information is exactly measured and image quality is already good. Therefore, the demonstration of low-pass filtered images are reserved for experimental data in Chapter 11.

This chapter described the algorithm used to produce neutron images and discussed the impact of image rendering choices. With this information, one can now produce neutron images and test the MiNI. These algorithms will be used to create neutron images in the next chapter.
Figure 10.7. Unfiltered and high-pass filtered images from simulated events for 100 cones.
Figure 10.8. Unfiltered and high-pass filtered images from simulated events for 2000 cones.
Chapter 11

Performance of the Final Neutron Imager

The envisioned imaging neutron spectrometer has two primary functions: to produce an image of a neutron source and to generate an energy spectrum of the incident neutrons. For the current implementation of a handheld NSC, cost-efficient scalability is emphasized in an overall attempt to pursue greater efficiency and move toward cost-effective deployment of a real-world system using rugged and cheap components along with multiplexing. All data sets presented use an applied bias voltage of 30.0 V. The choice of 30.0 V is primarily motivated by signal amplitude considerations as opposed to others, such as timing resolution.

In addition to gamma rejection cuts, event selection criteria are applied to improve the quality of events used for imaging. First, any backprojected cone that spans the entire range of azimuthal angles is rejected. Second, a minimum distance of 15.0 mm between scatters is required. Third, the first scatter is required to have an energy deposition between 1200 keV and 6000 keV, and the second scatter required to have an energy deposition of at least 1200 keV. These cuts reduce the apparent efficiency of the imager but improve image quality.

11.1. Imaging Performance

Achieving the best possible angular resolution is not the objective of the current imager. An imager aiming to optimize angular resolution would use fewer detector elements with greater
inter-element spacing, avoid multiplexing with the aim of yielding the best performance from
the single detector unit point of view, and apply more complex imaging algorithms. Instead, the
MiNI aims to demonstrate that multiplexing can be used to facilitate the use of more detector
elements at a lower cost per element and with fewer fully digitized channels, offering a path to
increased imaging efficiency. The evaluation criterion then is to simply show that as a neutron
source is moved around the MiNI’s field of view the generated image tracks the source location.
In addition to proof-of-concept for the application of multiplexing to NSCs, this criterion might
mimic that of an emergency response scenario in which the goal is to quickly gain an idea of
the direction in which a neutron source is located. In addition to correctly locating a source in
multiple locations, a higher neutron detection efficiency is also desirable.

To test the imager, four different data sets are taken with a 183 µCi $^{252}\text{Cf}$ source placed
approximately 50 cm from the center of the imager. This source produces approximately
805,000 neutrons per second, which to first approximation leads to approximately 900 neutrons
per second incident on the imager. For reference, one significant quantity of plutonium is
defined by the IAEA as 8 kg [156]. Weapons grade plutonium emits approximately 56,000
neutrons per second per kilogram [157]. Therefore, the neutron count rate used in these
measurements would correspond to roughly two significant quantities of weapons grade
plutonium at the same distance or one significant quantity 38 cm away from the center of the
imager.

The four different positions measured are shown in the order in which they were taken in
Figure 11.1. The first two measurements at $(0^\circ, 0^\circ)$ and $(45^\circ, -19^\circ)$ were taken for three hours.
The third measurement at $(90^\circ, -26^\circ)$ was taken five days after the first two and made for ten
Figure 11.1. Source locations for the four different measurements made.
hours. The final measurement at (-90°, 26°) was taken two days after the third measurement and data were acquired for five hours. The different measurement times were used because of lab occupancy restrictions during the 2020 Coronavirus crisis.

These four different locations span a wide range of angles in both angular dimensions, enabling an extensive testing of the system. Figures 11.2-11.5 show the images generated, both with and without low-pass image filtering, in the same order as presented in Figure 11.1. Note that the altitude axis is modified from the description in Chapter 10 such that 0° is in the x-y plane, and a positive angle corresponds to the positive z-direction at 0°. For the image taken at (0°, 0°), 162 cones are used which, if all cones are produced from neutrons, corresponds to an absolute neutron detection efficiency of 2 * 10^-8 and an intrinsic neutron detection efficiency of approximately 2*10^-5. However, in addition to these values possessing large uncertainties, some of these events are likely misclassified gamma rays, and many neutron events did not pass the event selection cuts. The neutron detection efficiency should therefore be considered with great care and is highly dependent on data acquisition and processing settings. It should also be recalled that only 20 pillars out of 32 are fully read out and being used in these images, detracting from the efficiency, although all 32 scintillators are read out on at least one side and contribute to the overall data acquisition rate.
Figure 11.2. Image generated with source at $(0^\circ, 0^\circ)$. In three hours of measurements 162 cones are used. The red circle indicates the known source location.
Figure 11.3. Image generated with source at (45°, -19°). In three hours of measurements 147 cones are used. The red circle indicates the known source location.
Figure 11.4. Image generated with source at (90°, -26°). In ten hours of measurements 159 cones are used. The red circle indicates the known source location.
Figure 11.5. Image generated with source at (-90°, 26°). In five hours of measurements 131 cones are used. The red circle indicates the known source location.

Figures 11.2-11.5 show effective tracking of the neutron source as it is placed in various locations around the imager. The first three images show excellent alignment of the image with
the known location of the source. While the last image tracks the source well, there does appear to be an offset from the center of the image distribution produced and the known location of the source in the azimuthal direction. A number of factors could influence this. First, the fourth measurement was taken with the source on a different structure and with a different scattering background than the other three measurements, the first two of which were done with the source elevated on an empty box, thereby essentially isolating it in space and reducing scattering from the source in its near vicinity. Additionally, running the SiPMs at an elevated overvoltage for extended times prior to and during the measurements could alter SiPM behavior and induce changes in system performance. Similarly, being the last measurement, the system could have had more time to change prior to it, rendering calibrations less accurate, for example in the modification of optical couplings, slight shifting of pillars, or if properties of the sinusoid generators change over time. The last image also has the fewest cones used to construct the image. The final two measurements at (-90°, 26°) and (90°, -26°) both had the most intervening material between the source and the sensitive imager volume, including both the circuit boards and cables as can be seen in Figure 8.16. Of these two, the measurement time for (-90°, 26°) was half as long as (90°, -26°), leading to the fewest cones produced for any image. More cones, or equivalently a longer measurement time, would likely improve the alignment of the image with the true source location. Finally, as with all measurements, there could be error in the knowledge of the exact location of the source relative to the imager. Further measurements would help elicit the sources of uncertainty in the reconstruction, but nonetheless these images show that the imager effectively tracks a neutron source around its field of view and could indicate from which direction the neutrons originated.
The scales and methods used to render the images can affect the interpretation of their information. The Gaussian low-pass filtering of the images shown in Figures 11.2-11.5 can reduce noise and smooth out contours, effectively adding benefits that would be derived from extended measurement times. This is also useful in guiding visual interpretation toward the true source and away from distracting or misleading image artifacts. However, it modifies the original image and can remove some information formerly there, thus meriting consideration in its application. As an example of other simple changes to the image rendering that can affect image evaluation, different color scales can enhance or reduce image contrast and lead to different subjective conclusions. Figure 11.6 shows an example of four different color scales used to convey the same information. Some color scales highlight the most concentrated region while others can better illustrate the gradients and true uncertainties involved.

Figure 11.6. Different color schemes used to depict the same neutron image.
11.2. Neutron Spectroscopy

The secondary function of the MiNI is to generate an energy spectrum of incident neutrons. Similar to the discussion in Section 11.1, energy resolution would be optimized by using more spatially separated pillars and attempting to maximize the individual detector element performance and requiring more expensive systems. Even better for neutron spectroscopy would be extended TOF laboratories. Satisfactory neutron spectroscopy in the MiNI would be able to provide an idea of the overall shape of the neutron spectrum and an upper energy limit of the neutrons. Such an ability would be able to, for example, distinguish spontaneous fission sources from some (α,n) sources.

An insufficient number of cones to produce energy spectra with reasonable statistics were used to create the images shown in Figures 11.2-11.5. Consequently, the four data sets were combined together, and the resultant neutron energy spectrum for all the events used to produce the neutron images is shown in Figure 11.7, along with the known $^{252}$Cf Watt fission spectrum. To further improve statistics, the cut removing events in which the backprojected cone spans the entire azimuthal range of angles was removed. Following the relaxation of this event selection criterion, the combined neutron energy spectrum of the four data sets is shown in Figure 11.8. Finally, the upper limit of deposited energy in the first scatter is reduced from 6000 keV to 4000 keV, and the resultant combined spectrum is shown in Figure 11.9. This final reduction in the upper limit of energy deposited in the first scatter can be interpreted either as an empirical efficiency correction and/or motivated by the upper energy limit of data collected in the TOF neutron energy deposition measurement. Excellent agreement is observed between the energy spectrum and the known Watt spectrum above 3 MeV.
Figure 11.7. Neutron energy spectrum generated from the imaged events used in all four data sets. 1-σ vertical error bars are shown.

Figure 11.8. Combined neutron energy spectrum of all four data sets following the relaxation of the maximum cone azimuthal angle span event selection criterion. 1-σ vertical error bars are shown.
Figure 11.9. Combined neutron energy spectrum of all four data sets following all event selection modifications. 1-σ vertical error bars are shown.

The spectra generated in Figures 11.7-11.9 are sufficient to discern the source of neutrons as likely coming from a fission Watt spectrum, especially with event selection criteria tailored for spectroscopy instead of imaging, with the overall shape of the spectrum represented and upper limits understood. The neutron spectroscopy objectives of the MiNI are therefore met, given the testing conditions possible at the time.

Information on the sensitivity of the MiNI to incoming neutrons can be gathered by looking at the structure of the neutron energy spectrum. As the energy of incoming neutrons decreases below 3 MeV the detection efficiency sharply decreases because the neutron must deposit enough energy to have both events surpass the trigger threshold. Above 3 MeV, the detection efficiency is diminished by the decreasing stopping power of neutrons in plastic as energy increases, but conversely in the event of an interaction the increased light output makes
detection and classification of the event more likely. It is therefore likely that above 3 MeV the imager has a relatively flat sensitivity to neutrons across different energies.
Chapter 12

Summary, Conclusions and Future Work

12.1. Summary

The overarching goal of this work is to support the development and eventual deployment of a cost-effective, portable, rugged, and efficient neutron imaging spectrometer. Portable neutron imaging spectrometers are receiving a great deal of interest, and, within that space, multiple alternative concepts are being explored. Further, all such systems have competing characteristics such as cost, complexity, imaging and energy resolution, and overall efficiency that cannot be simultaneously fully optimized. Therefore, the eventual availability of different versions that emphasize different performance characteristics is ideal so that different applications can choose the best tool for their needs.

Previous work has established that SiPMs can be a fundamental building block, along with organic scintillators, for an effective compact, portable neutron imaging spectrometer [67-69]. To advance the deployment of these devices, this dissertation performs a series of work that could be broadly applicable to many design variations as well as pushing further into the design space of inexpensive, high-efficiency designs and, especially, to demonstrate the feasibility of creating a multiplexed SiPM-based neutron imager.

Notably, to the author’s knowledge, this is the first full demonstration of commercially available PSD plastic scintillator, specifically EJ-299-34 from Eljen Technology, being used
for a SiPM-based NSC. No published and/or previous work has used commercially available or PSD-capable plastic to fully demonstrate imaging capability in an NSC. While previous work on SANDD reported PSD in a fully-instrumented array of plastic scintillators with SiPMs, the plastic scintillators used were not commercially available and the instrument was not demonstrated as an imager, with only component characterization taking place. The commercial availability of components is a key step toward scalability and deployment of an imager, and the PSD-capability enables improved performance and efficiency of imagers.

The use of plastics also offers potential improvements in cost, ruggedness, and uniformity of behavior over previously demonstrated stilbene. While other work is also exploring the use of commercially available plastics, to this point only simulations and component characterization have been reported. More importantly with the MiNI, it is the first demonstration of using channel multiplexing for full demonstration of neutron imaging using a multiplexed NSC. The multiplexing enabled the use of more scintillators for a given number of digitizer channels, and so the MiNI is also the first miniaturized NSC composed of more than eight pillars to directly demonstrate neutron imaging capability. The content of this thesis is summarized here and conclusions drawn or reiterated.

Chapters 1-3 lay out the background, motivation, and objectives of our imager. Specifically, commercially available plastic scintillators and SiPMs are chosen to compose the imager, both being cost-efficient and rugged. Through the use of cheaper detector elements, it is hoped that a greater number can be used in an imager and consequently greater detection efficiency achieved while keeping the overall cost down.
Next, a comprehensive characterization and comparison of commercially available SiPMs is carried out to assess their performance and select a suitable option for the MiNI. Chapter 4 describes the characterization of twenty different SiPMs in terms of PSD and other relevant characteristics such as noise. SiPMs are compared as uniformly as possible and minimal signal alternation or processing is done. While improved PSD may be possible with additional signal processing such as using amplifiers or circuitry to quicken pulses, this minimalistic approach is a more consistent comparison and is desirable to inform many-channel detection systems such as imagers for which simplicity is beneficial. It is found that larger microcells correspond to superior neutron-gamma ray discrimination, likely due to improved photon detection efficiency and better signal to noise ratios. The best PSD was observed in the Hamamatsu SiPMs with the largest microcells, and it was found that these SiPMs performed at least as well as the PMT they were compared against.

In Chapter 5, a similar characterization was carried out with a focus on time resolution. Again, SiPMs were set up with minimal modifying circuitry for uniform testing and to measure timing performance that could be achieved in a simple many-channel system. Characterization used multiple scintillator types and was done at multiple temperatures to attain a thorough understanding of timing properties of different SiPMs. Less dramatic trends were observed for timing than for PSD, but again Hamamatsu SiPMs as a group performed best and larger microcells tended to have the smallest time resolution.

To the author’s knowledge, the SiPM characterization and comparison studies detailed in Chapters 4 and 5 are the most comprehensive in terms of SiPM variety that have taken place for both PSD and timing. In addition to informing the choice of SiPM to be used in an NSC,
PSD and timing are both important characteristics of detector systems in a variety of different applications and so the implications of these studies extend to a broad audience and are generally applicable to SiPM use across fields.

With an idea of what SiPMs would be ideal to use, a multiplexing scheme must be applied. While various multiplexing schemes exist, none are specifically tailored for SiPMs and all have performance tradeoffs. Chapter 6 describes the development of a novel multiplexing method tailored to take advantage of SiPM characteristics, specifically long pulse lengths, by superimposing specific sinusoids on top of the SiPM pulse. This method is characterized on two different SiPMs being considered for use in the imager, the Hamamatsu 6050 SiPM and the SensL 60035 C-series SiPM. The method is demonstrated to preserve device performance, such as PSD capability and timing, while offering the ability to efficiently determine the origin of the signal, making it suitable for use in the MiNI. It is found that, for very small sinusoids, tagging efficiency is greater in the SensL 60035 C-series SiPM than in the Hamamatsu 6050 SiPM, likely facilitating an easier application of the method to use with those SiPMs. The development of this method therefore adds a multiplexing method to the literature and contributes an effective method to the set of options for multi-channel systems to choose from when implementing multiplexing. Additionally, it indirectly can serve as a sensitivity study for performance of SiPM-based detectors to waveform perturbations or modifications, especially those that are periodic in nature.

In the initial implementation, the most significant drawbacks of the method are a reduction in signal amplitude and signal nonlinearity for very small signals. Consequently, a modification to the multiplexing scheme in the form of using different diodes was made that was able to
almost entirely preserve signal amplitude compared to the non-multiplexed case but requiring larger sinusoid amplitudes to accomplish this. This modification opens up the possibility of maximizing the performance of this multiplexing method. Based on the initial development of the multiplexing method, at least a ten-to-one channel reduction should be possible.

Chapter 7 uses Geant4 simulations to assess the impact of multiplexing on the imager, determine what channels should be multiplexed together, and compare and select an imager composition. In this prototype implementation of the multiplexing, all double scatters that take place in two channels that are multiplexed together are treated as a lost event. Therefore, simulations are used to assess which channels have the highest correlation between them for inter-scattering, and a multiplexing scheme is chosen for each candidate imager configuration that minimizes the number of events lost due to a double scatter taking place in two channels multiplexed together.

The primary options considered for the imager are either 32 or 64 pillars and either 8 or 16 digitizer channels. It is found that using 16 digitizer channels instead of 8 significantly reduces the number of events lost, motivating the choice of 16 channels if possible. The 64-pillar configuration has a noticeably higher efficiency than the 32-pillar configuration, while the use of 32 pillars has better performance in every other aspect. For simplicity in a first prototype, a 32-scintillator and 16-digitizer channel design is selected. This requires a four-to-one multiplexing ratio because each scintillator is read out on both ends. Finally, the biases introduced by multiplexing are characterized. This chapter aided in the design and understanding of the MiNI, and because the assumptions that were made are shared in common
with most multiplexing methods the results can apply generally to many multiplexing methods used in a similar system.

Chapter 8 describes the construction of circuits and the imager itself. Simple sinusoid-producing circuits are developed to replace robust arbitrary function generators to further demonstrate the feasibility of the multiplexing method. Two different circuit boards are also designed for the bias, multiplexing, and read out of the SiPM arrays. The circuit board with the updated diode choice in the multiplexing scheme, designed to minimize signal loss and optimize the multiplexing approach, was found to have too much noise to use so the multiplexing method as originally developed was used. Nonetheless, some sinusoidal noise pickup remained, likely from the fabricated sinusoid-producing circuits, and three digitizer channels out of sixteen are not recorded.

Chapter 9 describes the calibrations necessary to use the imager and serves as a large-scale characterization of the multiplexing method. PSD capability with stilbene is shown to remain very good after multiplexing. PSD with the EJ-299-34 bars used in the imager is possible, but only at high energies and is significantly inferior to stilbene. Multiplexing is also found to impact time resolution very little, although again, the time resolution of the extended EJ-299-34 bars is significantly worse than that of the compact p-terphenyl crystals tested. Still, timing resolution is shown to be sufficient for the imager. A method for calibrating energy spectra from organic scintillators using broadened simulations is also detailed and used in the calibration of the imager.

A method to determine the relationship between light measured from a scattering event and the energy deposited by a neutron is described. To do so, a TOF experiment is used and
experimental data gathered in the range from about 1 MeV to 3 MeV. These data are then used to determine a relationship between neutron energy deposition and light output based on Birks’ law and this relationship is added to the literature of such relationships. This is the first relationship reported for EJ-299-34 in the dimensions used, making it a unique measurement that may be useful to other researchers. Finally, the calibration to convert the ratio of charge collected by the SiPM at each end of a pillar to vertical location of particle interaction is completed, enabling localization of each interaction. The vertical position reconstruction uncertainty is consistently found to be between 8-10 mm across the entire portion of the pillar measured and for all bars.

Following the description of the underlying physics and math used to produce images in Chapter 10, Chapter 11 describes the results obtained with the imager. Four measurements were taken with the imager for different source locations ranging from (-90°, 26°) to (90°, -26°). To demonstrate the feasibility of a multiplexed neutron imager, the imaging objective was to have the produced neutron image track the source as it moved around, and this was effectively accomplished for all positions, albeit with the final measurement showing a slight offset in reconstruction. Possible causes for this are discussed in Section 11.1. The spectroscopy performance of the imager is also demonstrated. While the combined neutron energy spectrum resembled a Watt spectrum, few events were used. Therefore, different event selection criteria were applied for the spectroscopy to acquire enough counts to generate smoother spectra, and the resultant spectra yielded good agreement with a predicted Watt spectrum.
12.2 Conclusions

In addition to the demonstration that a multiplexed neutron imager is possible, a number of additional conclusions can be drawn from the experience.

As described in Section 11.1, the rate of neutrons impinging on the imager in the measurements taken was roughly equivalent to that of 2 significant quantities of weapons grade plutonium 50 cm away from the imager. In this scenario, it took hours of data collection to produce images with high degrees of confidence in the direction of the neutron source. Many scenarios in which a neutron imager would be useful, including for example searching for a rogue source, might involve lesser quantities of SNM that are further away from the imager. For these applications, maximizing the efficiency of a neutron imager would be essential to produce a usable image in a reasonable amount of time, and the prototype MiNI would require improvements to its imaging efficiency before it would be ready for useful field deployment.

As shown in Chapter 7, increasing the number of pillars used, thereby increasing the active volume and proximity of pillars to each other, is an effective way to do so. For imagers simulated as in Chapter 7 that are composed of 8, 21, 32, or 64 scintillators, double scatter efficiencies of 0.0025, 0.0073, 0.016, and 0.058 were found. These numbers assumed far more efficient detection than is likely achievable and so should be taken comparatively only, and not as estimates of absolute neutron detection efficiency achievable. To achieve the highest possible efficiencies, the number of pillars used must be maximized. This was the goal of this work, to show that one could achieve a greater number of pillars used for a relatively lower cost by using multiplexing and cheaper components. In turn, one could eventually achieve a highly efficient neutron imager at a reasonable price.
The use of multiplexing to increase the number of detector elements used in a cost-efficient manner was demonstrated in this work, enabling greater overall detection efficiencies. However, the 32-pillar imager implemented in this work did not exhibit a high efficiency, slightly lower in fact than the eight-pillar design reported by Ruch, thereby showing the importance of other factors in overall achieving a high efficiency [67]. One factor decreasing the efficiency of the MiNI is the presence of “inactive” scintillators in the imager, or those for which data are recorded from a SiPM on only one side of the pillar. Any particle interaction in any of these inactive scintillators would produce an unusable event, although each pillar still contributes to the overall volume of data.

More importantly, despite the greater active volume in the MiNI and greater number of interactions in the scintillators, the MiNI discarded more events than the previous Ruch design. As shown in Chapter 7, multiplexing led to about 5% of double scatter events being lost, making it a small factor. More significant are the event losses due to relatively smaller pulse amplitudes and inferior neutron-gamma ray discrimination. The reduction in signal amplitude from the multiplexing scheme caused lower energy scatters to fall below the data acquisition trigger threshold and made low energy events that were recorded harder to process. This can be seen in the reconstructed neutron energy spectrum in Figures 11.7-11.9, in which very few neutron events were measured with energy below 3 MeV. Additionally, the use of 6 x 6 x 60-mm EJ-299-34 combined with multiplexed SensL 60035 C-series SiPMs led to relatively poor PSD, making it harder to recognize and select neutron events. This highlights the importance of PSD in producing efficient imagers.
Finally, in addition to events being discarded, the performance on an individual detector element basis was also diminished slightly by the components involved and multiplexing, especially for small signals. Greater uncertainty in measurements leads to more cones being required to converge to a final image location. Therefore, in addition to more cones being desired, better detector performance can more efficiently use the cones that are produced.

To achieve highly efficient, portable kinematic neutron imagers, using as large a scintillator volume as possible is necessary, and the ability to accurately process as many recorded events as possible must also be ensured. The requirement of two scatters being necessary and the quenching of light production for neutron scatters means that a highly efficient imager must be able to accurately process low energy events. This demonstrates the challenges of effective multiplexing, which, for many schemes, including the one implemented here, involve reduction of signal amplitude or at least signal to noise ratio. However, multiplexing will be a necessity if multi-channel portable neutron imagers are to be as cost-effective as possible and able to be widely and cheaply deployed. This work demonstrated that multiplexing can be implemented to achieve a greater active volume of scintillator for a many-channel NSC in a cost-effective manner. To fully achieve the potential of single-volume and quasi-single-volume NSCs, an optimized multiplexing method must be combined with the ideal detector elements to form the overall package.

12.3. Future Work

This work developed and demonstrated a multiplexed SiPM-based neutron imaging spectrometer. A variety of avenues exist for improving the current system which mainly fall
into three categories: refining the multiplexing, selecting ideal imager components, and improving imager design.

From a multiplexing perspective, signal amplitude should be preserved and noise decreased. As covered in Section 6.5, nearly complete preservation of signal amplitude can be accomplished by changing the diodes used in scheme, although this requires larger amplitude sinusoids to be added to the SiPM pulse. This version of the multiplexing scheme was attempted and described in Section 8.3, but resulted in too much sinusoidal noise transmitted through the readout board. Even the less noisy, redesigned readout board still showed sinusoidal noise, especially in the elevated board, alluding to the sinusoid-generating circuits being the source of the noise and transmitting it to the elevated and exposed board.

Both the sinusoid-generating circuits and SiPM bias-multiplexing-readout circuit boards were designed simply by a non-electrical engineer. Professional design by an expert in RF circuit design could alleviate the issues encountered with the circuits used. Potential routes for improvement include rerouting the traces used in the SiPM bias-multiplexing-readout board to minimize cross-talk, using more layers in the printed circuit board, changing track dimensions, or incorporating other means of shielding the traces from each other and outside noise. Different channels could be multiplexed together as well. For example, instead of choosing channels to multiplex together based on minimizing events lost, one could multiplex channels together based on practical considerations of their physical location on the SiPM array connector.

The sinusoid-generating circuits used could also be improved considerably. While they accomplished their objective and enabled the multiplexing to be cheaply implemented, they are likely a large source of noise in the imager. Better designed sinusoid-generating circuits would
reduce or remove completely the sinusoidal noise in the SiPM readout, and also ensure long-term stability of the multiplexing over extended time periods. Professional design of the circuits involved in the system would lead to reduced noise and increased signal amplitude, optimizing the multiplexing used and significantly improving performance of the MiNI.

From the detector component perspective, alternatives exist for both the scintillator and SiPMs. Both the SensL 60035 C-series SiPM arrays and EJ-299-34 scintillators were used in this imager because they were already available in the laboratory. As shown in Chapters 4 and 5, while the SensL 60035 C-series SiPM is an effective SiPM, improvements in PSD, timing, and signal to noise ratio can be achieved in other SiPMs, especially in the Hamamatsu 6050 and Hamamatsu 6075 SiPMs. The Hamamatsu 6050 SiPM is also available in 4 x 4-pixel arrays as the S1361-6050AE-04 SiPM array. Four of these arrays could be tiled together to achieve the same 64-element SiPM array layout. This is an attractive candidate to use as the SiPM array in an ideal miniaturized NSC and should be explored more. Additionally, from SensL, the J-series SiPMs tend to be superior in a number of characteristics, compared to the C-series SiPMs, and all other groups exploring the use of SiPMs for a SiPM-based NSC have moved to the J-series as their SiPM of choice [65, 139].

The EJ-299-34 scintillators served as proof-of-principle that plastic PSD scintillators could be used in an imager but are already outdated and a poor choice to be actually used in an optimized imager. EJ-299 has been commercially replaced by a new version, EJ-276, with considerably improved PSD performance [86, 87, 158]. The use of EJ-276 in a subsequent version of the imager would be the ideal candidate to immediately test a more optimized version of the imager using cheap, rugged, and effective scintillators. Outside of EJ-276, other plastic
scintillators are also available with faster timing properties or greater light output. Plastics with greater light output would be especially attractive for the current non-optimized multiplexing scheme. These other plastics are being explored elsewhere [139].

In addition to alternative plastics, a number of novel scintillators or those whose use has recently been made feasible are under development, and these scintillators possess exciting properties. As used in the H2DPI imager, stilbene offers excellent neutron-gamma ray discrimination, which is useful in maximizing imaging efficiency. Organic glass scintillators capable of PSD are also under development with excellent characteristics in many aspects [159-161].

Organic scintillators doped with thermal neutron capture agents such as $^6$Li or $^{10}$B are also under development. Such scintillators will be used in the antineutrino detectors of similar design, and could be attractive even without a goal of measuring antineutrinos [64, 65, 162, 163]. The ability to capture and detect thermal neutrons in the imager offers an additional ability to enhance neutron-gamma ray discrimination, and by using capture-gating as described in Section 2.5, one could employ a complementary neutron spectroscopy method in combination with the TOF method to enhance the overall energy resolution of the system.

Finally, improvements to the imager design could be carried out. Scintillator lengths were chosen based on availability, but longer scintillators could improve efficiency and should be explored. The amount of reflective wrapping for each scintillator could also be optimized to maximize position sensitivity along the bars. Less wrapping should increase position sensitivity at the cost of overall light collection, and a finalized imager would optimize this trade-off. Instead of optical pads, optical grease could also be used and would result in improved light
collection and simpler assembly. Along with this, a more robust imager support structure, enabled by lesser wrapping or smaller scintillators, would help stabilize the system and ensure consistency over longer time periods.

Employing more scintillators in the imager would also be necessary to accomplish the goal of maximizing detection efficiency. Along with this, greater multiplexing ratios would support cost-efficient implementation. For example, in moving to a 64-pillar readout, an eight-to-one channel reduction ratio would be desirable and should be possible with the multiplexing scheme developed in this work. The use of smaller unit arrays combined together could also enable more customizable array dimensions. For example, if the 4 x 4 Hamamatsu S13361-6050AE-04 array were used as a building block, nine could be tiled together to produce a 12 x 12-pixel imager with greater overall dimensions than the 8 x 8-pixel imager used in this work, yet less extreme than 16 x 16 pixels. Such an imager would result in more demanding hardware and multiplexing requirements but greater efficiency and/or imaging resolution and could be a long-term goal. Alternatively, smaller light sensor unit-cells could enable more creative imager designs that improve performance, for example slightly separating the four different 4 x 4 pixel arrays.

The improvements to the multiplexing implementation, detector components, and imager design outlined here are short-term actions to be carried out to lead to immediate improvements in imager performance and would further the demonstration of an advanced prototype MiNI. In the long-term, field deployment would require improvements to the portability and compactness of the system. This would entail miniaturization of circuit elements and creation of online data processing, likely to be carried out by FPGAs and/or ASICs. A method to
accommodate the variability of imager performance, specifically that of the SiPMs, with changing temperature would also be beneficial and could be accomplished either via a temperature compensation circuit on the SiPM front end or using an adjustable voltage source such that the applied voltage could be manually tuned based on the environmental temperature. While not the purpose of this thesis and already demonstrated elsewhere, more sophisticated reconstruction algorithms than simple or filtered backprojection would also improve image quality.
References


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