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Investigation of Higher Count Rate and Helium-3 Alternative Beam Monitors for Neutron Scattering Facilities

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To the Graduate Council:

I am submitting herewith a thesis written by Amanda Kay Barnett entitled "Investigation of Higher Count Rate and Helium-3 Alternative Beam Monitors for Neutron Scattering Facilities." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.

Jason P. Hayward, Major Professor

We have read this thesis and recommend its acceptance:

Lawrence H. Heilbronn, Laurence F. Miller

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
I would like to express my gratitude towards everyone who has helped me in my education and with the work on this thesis. In particular, I want to thank my advisors Dr. Jason Hayward and Dr. Yacouba Diawara for their support and guidance. Thanks also go to all the members of the detector group at Oak Ridge National Laboratory, including Vladislav Sedov and Loren Funk for their help with the electronic system, to Surendra Martha, Jagjit Nanda, and Shazad Akbar for their help with the Lithium Fluoride samples, and to Michael Cox for his help assembling the beam monitors.
ABSTRACT

Beam monitors are an important diagnostic tool at neutron science facilities. At high flux neutron scattering facilities, neutron beam monitors with very low intrinsic efficiency ($10^{-5}$) are presently selected to keep the counting rate within a feasible range, even when a higher efficiency would improve the counting statistics and yield a better measurement of the incident beam. This report outlines a beam monitor with a parallel-plate avalanche chamber design that is capable of measuring a high count rate without saturation. Several designs of the beam monitor using different electrode materials and different neutron conversion materials were constructed and tested. The different designs had efficiencies ranging from $9.8 \times 10^{-7}$ to $1.2 \times 10^{-3}$ for thermal neutrons. One of the designs measured $1 \times 10^6$ cps, which means it is possible to measure neutron fluxes over $10^9$ cps without saturation while maintaining a $10^{-3}$ efficiency.
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CHAPTER I
INTRODUCTION AND BACKGROUND

Neutron scattering facilities are used in a number of various fundamental and applied research areas. Neutrons have many properties including a lack of charge, large penetration depth, magnetic moment, and spin that make them ideal for use in a wide range of research applications. Additionally, neutrons are sensitive to light atoms, and cold and thermal neutrons have wavelengths and energies that match the scale of molecular structures and vibrations. The combinations of these properties have already led to and are being used to make further advancements in physics, chemistry, material science, biology, clean and alternative energy, and nanomaterials.

Neutron scattering experiments require high neutron fluxes. These high fluxes can be produced at either reactor facilities, such as the High Flux Isotope Reactor (HFIR), or accelerator facilities, such as the Spallation Neutron Source (SNS), both at Oak Ridge National Laboratory (ORNL). Operating at 85 MW, HFIR produces the highest neutron flux of any research reactor in the United States [1]. The HFIR core is a cylindrical flux trap design, where regions of highly enriched uranium fuel surround a moderating region in the center of the core. This moderating region becomes a thermalizing trap for the fast neutrons from the fuel, and is used for isotope production. Neutron scattering experiments are made possible by inserting horizontal beam tubes into the beryllium reflector surrounding the fuel, and transporting the neutrons to the experimental beam lines. Three horizontal beam tubes lead to seven thermal neutron instrument beam lines, and the fourth horizontal beam tube leads to five cold neutron instrument beam lines that utilize 4-25 Å neutrons [2].

SNS produces the most intense pulsed neutron beams in the world through the spalling of a mercury target [3]. Hydrogen ions are fed into a linear accelerator, where they are accelerated to 1 GeV. Leaving the linear accelerator, the ions pass through a foil that strips the electrons from the atoms, producing protons that are then collected in an accumulator ring. Sixty times a second, proton pulses from the accelerator ring hit the mercury target, causing neutrons to be spalled from the mercury target. Beam guides transport these neutrons to one of 16 operational beam lines [4]. The beam lines
have a wide range of instruments including diffractometers, spectrometers, and reflectometers. Special sample environments allow scientists to study liquids, powders, or crystals, operate at very high or low temperatures, operate experiments in vacuum or at high pressure, and utilize magnetic fields.

At both facilities, neutrons are transported to each of the individual beam lines through beam guides that are designed to minimize losses along the length of the guide. At the HFIR cold source, neutrons are transported 24 m away from the center of the reactor along a guide that has a curved section with an $m=3$ supermirror coating and ends in a straight section with an $m=2$ coating [5]. The $m$ value of a beam guide defines the range of the supermirror regime, and it is defined as a multiple of the momentum transfer $q$ of nickel or as the ratio of the critical angle of the supermirror to that of nickel [6]. The supermirrors are complex multilayer coatings that reflect cold neutrons along the length of the guide but prevent high energy gammas and neutrons from reaching the experiments.

Many experiments require neutrons to be of a specific energy and/or arrive in pulses, and choppers are used for both of those purposes. Choppers are designed to rotate at a specific frequency so that only neutrons of the desired energy are able to pass through openings in the chopper. One of the types of choppers that is used are the $T_0$ choppers that block the fast, high-energy neutrons coming from a pulsed source. Also used at pulsed sources are frame overlap choppers that prevent slow neutrons from one pulse from being overtaken by fast neutrons from the next pulse. Fermi choppers operate as monochromators, only allowing neutrons within a small range of energies through.

Alternatively, crystal monochromators, typically made of graphite, beryllium, germanium, or silicon, can be used to select certain wavelengths from the incident neutron beam. Monochromators work through the Bragg scattering process, reflecting only the wavelength that matches the crystalline spacing of the monochromator. A wide range of wavelengths is possible depending on the material, crystal orientation, and incidence angle.
Beam monitors are another essential component of neutron scattering facilities. Beam monitors measure the incident neutron flux, allowing scientists to calibrate detectors and other beam line instrumentation, track beam stability, and make adjustments in real time. They need to have a sufficiently low efficiency so that as little of the beam is blocked or scattered as possible, yet the count rate needs to be high enough to establish good counting statistics. Most of the beam monitor designs work on the same principles as other neutron detectors, just at lower efficiencies, and improvements in beam monitor designs have largely followed detector developments motivated by other radiation sensing applications.

Gas detectors are commonly linear position sensitive detectors (LPSD), a cylindrical detector with a high voltage anode wire running down the center of the tube [7] [8]. The incident neutron is converted into charged particles within the gas volume, and the electrons drift towards the anode wire, undergoing Townsend avalanche as they drift through the multiplication region [9]. The positive ions drift towards the cathode (located at the outer wall of the tube), and the resulting signal is produced from the drift of both the electrons and positive ions. By using a resistive anode wire, the difference in pulse size at the two ends of the wire corresponds to the distance the signal traveled in each direction, giving 1D position information.

A two-dimensional version of the LPSD capable of covering large areas is the multiwire proportional chamber (MWPC, see Figure 1). MWPC’s work on the same principle as LPSD’s, but have many parallel anode wires within the same gas volume. MWPC’s began being used in the late 1960’s as detectors for low energy x-ray or neutron imaging [10]. MWPC’s with low pressures of Helium-3 have been used as neutron beam monitors, and are the main type of beam monitor currently used at SNS and HFIR [11]. However, there is a limitation to the count rate of MWPC’s due to the buildup of positive charge from the drifting ions, which reduces the electric field and the multiplication [10].
Additionally, parallel plate avalanche counters (PPAC) have long been used in detectors requiring a high count rate and good time resolution, but without good energy resolution [13], [14]. The counter design involves two parallel plate electrodes separated by as small of a gap as possible. An electric field is applied between the two plates, so as a charged particle passes through the gap, a trail of electron-ion pairs are produced, and the electron charge cloud is subsequently multiplied through the gas multiplication process. The uniform electric field between the plates allows for good timing and energy resolution. In addition, the plates used in a PPAC are more robust and less susceptible than wire detectors to damage from electrical sparking that can occur due to the high voltages used between the anode and ground in neutron detectors.

New gaseous detectors, known as micropattern gas detectors, were introduced in the 1990’s using microfabrication techniques to make improvements in timing and position resolution, which are achieved due to the small features that allow for high electric field gradients, faster recovery time, and better charge localization. These include the microstrip gas chamber (MSGC), gas electron multiplier (GEM), and micromesh gaseous structure (micromegas). The MSCG is based on thin anode strips or alternating anode and cathode strips on a substrate [15]. The electrons are drifted towards the anode strips, which, because of their fine pitch, results in better spatial resolution. However, the fine pitch also limits the voltage that can be applied without
electrical sparking, which, in turn, limits the gain. GEM foils are used to overcome this gain limitation. A GEM foil is a thin sheet of insulating material with a conductive material on each side (see Figure 2) [16] [17]. Small holes are machined in the foil, and a voltage is applied across the conductive sides. Electrons are drifted toward the foil, and the electric field inside each hole is large enough to cause multiplication. Multiple foils can be used to increase the total amount of gain. Micromegas detectors are a variation of the PPAC. They have two parallel electrodes separated by a micro-mesh [18]. Ion pairs are formed in the region above the mesh, and electrons are attracted to the mesh by an electric field kept below what is needed for avalanche formation. The majority of the electrons pass through the mesh, where they then undergo multiplication in the region between the mesh and the anode.

Figure 2. Magnified image of GEM foil (left) [16], and electric field lines through the holes in the GEM foil (right) [17]. At right, the region where the electric field lines are highly concentrated corresponds to the multiplication region.
CHAPTER II
PARALLEL PLATE DESIGN

The beam monitor is built in a parallel plate avalanche chamber design, shown in Figure 3. The two electrode plates are held 2 mm apart by a polyetheretherketone (PEEK) spacer. The resistive plate is kept at a high voltage (3.5 – 5 kV) to establish the needed electric field, while the conductive plate is kept at ground and is used for the signal readout. The small separation distance and large potential difference between the electrodes allows for charge amplification to occur in the region between the two plates. This region is also where neutron conversion occurs.

The beam monitor is enclosed in an airtight aluminum housing. It is shaped to present a flat face to the neutron beam, and the windows through which the beam passes are machined to be as thin as feasible to minimize neutron scattering losses. Each of the plates is 5.2 cm x 11.7 cm, creating an active area of about 60 cm², while the entire beam monitor (shown in Figure 4) is 19.4 cm x 11.5 cm x 2.2 cm without the electronics box. It is 27 cm long with the electronics box attached.

Figure 3. Diagram of beam monitor design.
Neutron Reactions

As with all neutron detectors, the beam monitor depends on the conversion of the incoming neutrons into charged particles that can be detected. Neutron conversion can be achieved through any one of the neutron interactions listed in Table 1.

BF$_3$ gas was the common converter material used in neutron detectors before the 1960’s. However, once Helium-3 became available, it quickly replaced BF$_3$ due to the toxicity and corrosive nature of BF$_3$. Currently, the majority of the gaseous beam monitors use Helium-3 as the neutron conversion material. Helium-3 makes an excellent neutron conversion material due to its large thermal cross-section and low gamma sensitivity. However, due to the worldwide shortage of Helium-3, it is not practical to continue to build detectors based on this material. It is very difficult to purchase Helium-3, and if the Helium-3 can be obtained, it is extremely expensive.
Table 1. Neutron Conversion Reactions

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Nuclear Interaction</th>
<th>Cross Section at 1.8 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium-3</td>
<td>$n + ^{3}{\text{He}} \rightarrow ^{3}\text{H} + ^{1}\text{p} + 0.764 \text{ MeV}$</td>
<td>5330 barns</td>
</tr>
<tr>
<td>Lithium-6</td>
<td>$n + ^{6}\text{Li} \rightarrow ^{4}\text{He} + ^{3}\text{H} + 4.78 \text{ MeV}$</td>
<td>940 barns</td>
</tr>
<tr>
<td>Boron-10</td>
<td>$n + ^{10}\text{B} \rightarrow ^{7}\text{Li} + ^{4}\text{He} + 2.310 \text{ MeV} + 0.48 \text{ MeV γ (94%)}$</td>
<td>3840 barns</td>
</tr>
<tr>
<td></td>
<td>$n + ^{10}\text{B} \rightarrow ^{7}\text{Li} + ^{4}\text{He} + 2.792 \text{ MeV (6%)}$</td>
<td></td>
</tr>
<tr>
<td>Gadolinium-157</td>
<td>$n + ^{157}\text{Gd} \rightarrow ^{158}\text{Gd} + γ's + conversion electrons$</td>
<td>255,000 barns</td>
</tr>
<tr>
<td>Nitrogen-14</td>
<td>$n + ^{14}\text{N} \rightarrow ^{1}\text{p} + ^{14}\text{C} + 0.627 \text{ MeV}$</td>
<td>1.8 barns</td>
</tr>
</tbody>
</table>

Boron-10, Lithium-6, and Gadolinium-157 have high enough cross-sections to be used in neutron detectors, and Helium-3 alternatives are being developed using these isotopes. However, Nitrogen-14 has such a low neutron cross-section value that it is only practical for very low efficiency ($<10^{-5}$) applications.

**Gas Multiplication**

In the beam monitor, the charged particles created by the neutron interactions deposit energy in the gas volume by the creation of ion pairs. Due to the large electric field between the plates, as the electrons drift towards the anode, they gain enough energy to form secondary ion pairs. The secondary electrons are also capable of creating additional ionizations resulting in a cascade, or Townsend avalanche [9]. The electric field between the plates, expressed as

$$ E = \frac{V}{d} $$

where $V$ is the bias voltage and $d$ is the separation between the plates, is $2 \times 10^6$ V/m for a beam monitor operating at 4000 V. This electric field strength is sufficient to create
charge multiplication throughout the entire 2 mm gap. The bias voltage and fill gas are appropriately chosen so that the beam monitor operates in proportional mode, and the total charge generated $Q$ is proportional to the number of original ion pairs, $n_0$, according to

$$Q = n_0 e M$$  \hspace{1cm} (1)

where $M$ is the gas multiplication factor [9].

**Charge Migration and Collection**

The positive ions and electrons that are created drift towards the opposite electrodes. The drift velocity $v$ of each carrier type is proportional to the mobility $\mu$ and electric field strength $E$, and is inversely proportional to the gas pressure $p$ as given by [9]

$$v = \frac{\mu E}{p}$$  \hspace{1cm} (2)

In our planar geometry, the electrons are able to traverse the 2 mm gap in tens of ns; however, due to the relatively large size of the positive ions, they have a much larger mobility and take $\sim 1000x$ longer to drift towards the cathode than the electrons take to reach the anode.

In addition to the drift of the charge carriers due to the electric field, they will also undergo random thermal diffusion. This diffusion causes the electrons formed at a single point to spread out, which limits the spatial resolution that can be achieved, especially in large volumes. However, increasing the strength of the electric field increases the drift velocity, which, in turn, reduces the amount of time for electron diffusion. The resulting smaller spread of electrons improves spatial resolution.

To achieve a high counting rate, a fast signal is needed, so the beam monitor employs an electronic readout circuit which is sensitive to the induced charge from the drift of the electrons only. The pulse amplitude produced is thus given by
\[ V = \frac{n_0 e}{C} \cdot \frac{x}{d} \]  

where \( n_0 \) is the original number of ion pairs contributing to the pulse, \( n_0 e \) is the charge produced, and \( C \) is the capacitance of the chamber [9]. The \( x/d \) term, where \( d \) is the separation between the plates and \( x \) is the position between the plates where the original ion pair was formed, is due to using only the signal produced by the electron drift. The incident neutrons can deposit energy anywhere inside of the detector, so because of the dependence on the position of the signal creation, a position-dependent variation in pulse height is expected.

The induced charge is read through a custom preamplifier designed at ORNL by Vladislav Sedov. It is a fast, low-noise preamplifier that measures individual pulses in order to get good timing resolution and a high count rate. It is optimized for a 100 pF detector capacitance and has semi-Gaussian shaping with a 15 ns FWHM. The preamplifier has a gain of 1000 and a 200 Ω input impedance. The preamplifier is enclosed in an aluminum housing that is attached directly to the beam monitor, to reduce electronic pick-up noise. The electronics box has connections for high voltage input (SHV) and signal output (BNC). It also uses an HRS 4-pin connector to supply +24.5 V and -7.5 V voltages to the preamplifier.
Figure 5. Photograph of the open electronics box on the beam monitor.
CHAPTER III
BEAM MONITOR CONSTRUCTION

Electrodes

The beam monitor was built and tested with different electrode materials to compare their effectiveness. The anode must be made of a resistive material to prevent electrical discharges, and the cathode must be conductive so that the charge deposited can be quickly transferred to the readout electronics, resulting in a faster current pulse for better timing resolution.

Anode

Several different materials were tried as the anode for the beam monitor. The plates used in the different iterations are shown in Figure 6; they are made of quartz, undoped silicon, and alumina with a thin layer of cermet on the surface. The cermet has a sheet resistance of 100 MΩ/sq (0.2 MΩ-cm), silicon has a resistivity of 0.010 MΩ-cm, and quartz has a sheet resistance of 1 MΩ/sq (0.1 MΩ-cm).

Figure 6. Anodes used in the different iterations of beam monitor. From left to right: quartz, silicon, alumina.
Two different materials were used as the cathode in the different beam monitor iterations, and they are shown in Figure 7. The first plate is made of aluminum, which has a resistivity of $2.7 \times 10^{-6} \, \Omega\cdot\text{cm}$, and the second plate is made of silicon, which is doped with natural boron and has a resistivity of $0.001 \, \Omega\cdot\text{cm}$.

**Neutron Conversion Materials**

**Helium-3**

Helium-3 was used in several of the beam monitors as the neutron conversion material. Due to its large cross-section at thermal energies, Helium-3 makes an ideal conversion material for neutron detectors. It is especially advantageous, because as a gas, the charged particles that are created are not trapped in a solid converter layer.
However, due to the Helium-3 shortage discussed in Chapter 2, alternative neutron conversion materials are needed.

**Boron-10**

As an alternative to Helium-3, Boron-10 was used in two of the tested beam monitors in the form of a boron-doped silicon wafer. A commercial silicon wafer doped with $10^{20} \text{ cm}^3$ of natural boron was cut to the electrode size and used as the cathode for those beam monitors.

**Lithium-6**

Another Helium-3 alternative that was tested was Lithium-6. It was used in the form of Lithium-6 enriched Lithium Fluoride powder deposited onto carbon paper. These LiF sheets were then attached to the cathode within the amplification gap.

The LiF nanoparticles, manufactured by Eljen, are 100 nm in diameter and enriched to 95% Lithium-6. With help from members of the Materials Science Technology Division at Oak Ridge National Laboratory, the particles were mixed into poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) from Sigma-Aldrich by thorough mixing using high-energy ball milling and mixing. The slurry was coated onto two different carbon fiber papers that have similar properties, a thermal graphite sheet from Panasonic Thermal Interface Products from Mouser Electronics and Toray Carbon Paper. After coating, any excess slurry was carefully removed from the surface and the sheet was dried at 90 °C for a few hours. The choice of nanosized particles and this process represent an attempt to distribute Lithium-6 into a porous medium in such a way that the reaction products will produce energetic electrons that subsequently escape into the gas volume so that they may be multiplied.

Two of the samples made were tested at the same time (see Figure 8). Sample 1 was made with a mixture of 20% LiF in the poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) on the Toray Carbon Paper. Sample 2 was made with a 30% LiF mixture on the thermal graphite sheet. The LiF sheets were attached directly to the cathode so that the LiF sheets are in the amplification gap, with the anode and the LiF sheets separated by 2 mm.
Design Iterations

Several iterations of the beam monitor were built using different combinations of the anodes, cathodes, and conversion materials. Table 2 lists the five designs built and tested.

Table 2. Materials used in each of the beam monitor designs.

<table>
<thead>
<tr>
<th>Design</th>
<th>Anode</th>
<th>Cathode</th>
<th>Conversion Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Quartz</td>
<td>Aluminum</td>
<td>Helium-3</td>
</tr>
<tr>
<td>B</td>
<td>Alumina</td>
<td>Aluminum</td>
<td>Helium-3</td>
</tr>
<tr>
<td>C</td>
<td>Alumina</td>
<td>B-doped Silicon</td>
<td>B-doped Silicon</td>
</tr>
<tr>
<td>D</td>
<td>Silicon</td>
<td>B-doped Silicon</td>
<td>B-doped Silicon, Helium-3</td>
</tr>
<tr>
<td>E</td>
<td>Alumina</td>
<td>Aluminum</td>
<td>Lithium-6 Fluoride</td>
</tr>
</tbody>
</table>
Gas Mixture

In gas detectors, an easily ionized gas is needed for avalanche formation, and it must also have a low electron attachment coefficient. Organic gasses, such as isobutane and CF$_4$, are often used because of their large amplification factors and proportionality range. However, these gases produce secondary polymerization products, especially at high count rates [19]. The polymerization products deposit on the electrodes, leading to electrical breakdown (arching), which, in turn, results in a short lifetime of the detector.

For these beam monitors, a mixture of 95% xenon, 5% carbon dioxide was used as the fill gas. Xenon is used as the fill gas because as a noble gas, it does not react chemically or produce polymerization products. Another advantage of using noble gasses is the resulting lower electric field needed to produce avalanche multiplication than is required for complex molecules [10]. Some of the charged particle interactions in the gas can create excited rather than ionized gas molecules, resulting in photon emission from the de-excitation process, so a small percentage of carbon dioxide is needed as a quench gas to absorb any photons that are created during de-excitation. This quench gas is essential to maintain proportionality (refer to Equation 1). The first ionization potential in xenon is 12.13 eV, and its W-value is 21.5 eV/ion pair [20]. The deposited energy is then proportional to the number of initial ion pairs created.

The beam monitors filled only with Xe/CO$_2$ were filled at ORNL. After assembling a beam monitor, it remained on a vacuum pump for several days until reaching a pressure of $\leq 10^{-6}$ Torr, at which point it was filled to 800 Torr Xe/CO$_2$. The beam monitors using Helium-3 as the neutron conversion material were taken to Ordela, Inc. to be filled with 29.1 Torr of Helium-3, and 771 Torr of Xe/CO$_2$, for a total pressure of 800 Torr.

Calculation of Intrinsic Efficiency

The intrinsic efficiency of the beam monitor is dependent on the pressure of the converter gas used, the thickness of the conversion region, and the wavelength of the incident neutrons according to [21]
\[ \eta = 1 - e^{-\mu \lambda \rho x} \]  

(4)

where
\[ \mu = \text{gas absorption factor} \]
\[ \lambda = \text{specified neutron wavelength} \]
\[ \rho = \text{absolute counting pressure} \]
\[ x = \text{depth of counting volume} \]

For all of the beam monitors filled with Helium-3, the gas absorption factor is 0.0725 (atm cm Å\(^{-1}\)). The beam monitor was built with a plate separation of 0.2 cm. Thus, for thermal neutrons (1.8 Å), a gas pressure of 0.0383 atm (29.1 Torr) should result in an efficiency of \(10^{-3}\).
CHAPTER IV
EXPERIMENTAL SETUP AND PROCEDURES

The beam monitors were initially tested in the lab at SNS with a 1 mCi Americium-241 source. Americium-241 emits a 59.5 keV gamma, which can create ionization pairs leading to electron multiplication in the Xe/CO₂ gas in the region between the plates. Once tested with Americium to ensure the beam monitors were working properly and did not have a gas leak or a bad electrical connection, they could be filled with Helium-3 if necessary for that beam monitor. A moderated Californium-252 source was then used to test the beam monitors for neutron response. The Californium-252 source has a half-life of 2.64 yr, and it had a strength of 17.87 mCi in September 2011. For high flux conditions, the beam monitor was next taken to HFIR for efficiency and count rate capability tests.

The beam monitors were tested at HFIR at the Cold Guide 1 (CG-1) Beam Line. CG-1 is used for neutron instrumentation development and is split into four separate beam lines. Shown in Figure 9, the main CG-1 beam is in line with CG-1D, and is split into the other three lines within the gray shielding box in the upper left of the picture. CG-1D is able to be run in a white beam operation mode or in a pulsed mode when the chopper is operating. It has a neutron spectrum that ranges from 1.8 to 6 Å (0.025 to 0.002 eV) [5]. The white beam was used in order to find the maximum count rate capability and efficiency of the beam monitors, and the pulsed mode was used to make time-of-flight measurements. CG-1A and CG-1B are monochromatic beams of 4.22 Å and 2.35 Å, respectively. These beams are produced using pyrolytic graphite (0 0 2) monochromators. Tests were also done on these beam lines to determine the count rate capabilities and efficiencies of the beam monitors.

The beam monitor output was measured with standard NIM electronics. When testing at CG-1A or CG-1B (see Figure 10), a Phillips 771 amplifier was used to amplify the signal to a proper size so that it could be counted on an Ortec 661 ratemeter. Alternatively, the signal was viewed directly using an Agilent MSO9104A oscilloscope.
Figure 9. Photograph of the beam lines at HFIR CG-1.

Figure 10. CG-1A and CG-1B Setup
Figure 11. Photograph of beam monitor testing at CG-1D.

Figure 12. CG-1D Setup
When testing at CG-1D, the same setup involving the oscilloscope or amplifier and ratemeter was used; however, time-of-flight (TOF) measurements were also made. TOF measurements taken on CG-1D (see Figure 11, Figure 12) involved a chopper rotating at 40 Hz that also sent a timing signal to the data acquisition computer. The signal from the beam monitor was input into the discriminator of an ORTEC MCS-pci. The computer with the Multichannel Scaler card has software to analyze the TOF spectrum.

**TOF Calibration**

The time-of-flight values (recorded in μs) need to be converted to the corresponding neutron wavelength. The neutron wavelength \( \lambda \) is calculated from the de Broglie equation,

\[
\lambda = \frac{h}{mv} = \frac{3956.0339 t}{D}
\]

where the distance to the detector \( D \) is measured in meters and \( t \) is the time-of-flight in seconds. Bragg’s Law states that

\[
\lambda = 2d \sin(\theta)
\]

where \( d \) is the inter-atomic spacing and \( \theta \) is the scattering angle. At wavelengths parallel to the crystal lattice plane (\( \theta=90^\circ \)), there is a drop in the number of transmitted neutrons, resulting in the discontinuity seen for that lattice plane. The beam lines at HFIR are built with aluminum windows, so the neutron TOF spectrum contains aluminum Bragg Edges that can be used for calibration. Five of the aluminum crystal planes can be seen in the CG-1D spectrum, as shown in Figure 13. The \((2\ 0\ 0)\) and \((1\ 1\ 1)\) planes are the easiest to locate in the spectrum and were used for calibration. There is an offset in the time of arrival of the timing signal from the chopper and the actual neutron pulse. However, the distance to the chopper is known, so the time required for neutrons of a specific wavelength to reach the beam monitor can be calculated. Using this information in Equation 5, the initial time \( t_0 \) (amount of offset) was calculated from

\[
t(\lambda_{111}) - t_0 = \frac{D \lambda_{111}}{3956.0339}
\]
Figure 13. Time-of-flight spectrum posted at CG-1D. The location is marked for each of the Bragg Edges for the aluminum crystal planes that can be seen. The corresponding wavelengths are listed in the table at the right.

**Relative Efficiency Measurement**

The intrinsic efficiency of the beam monitor designs was measured using the standard method for beam monitor calibration at ORNL. The beam monitor with unknown efficiency $\varepsilon_1$ was placed behind a beam monitor with a known efficiency $\varepsilon_2$ as shown in Figure 14. A B$_4$C collimator was placed directly in front of the beam monitors to ensure that the neutrons would only pass through equally sized areas within the active regions of both monitors. The efficiency of the beam monitor was then calculated from

$$\frac{\varepsilon_1}{CR_1} = \frac{\varepsilon_2}{CR_2}$$

using a ratio of the count rates, $CR_1$ and $CR_2$. Due to scattering and absorption, the loss of neutrons through the first beam monitor is about 5%. This loss is accounted for in the quoted efficiency value for the reference beam monitor.

<table>
<thead>
<tr>
<th>Aluminum Planes (h,k,l)</th>
<th>Wavelength (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>4.6760</td>
</tr>
<tr>
<td>200</td>
<td>4.0495</td>
</tr>
<tr>
<td>211</td>
<td>3.304</td>
</tr>
<tr>
<td>220</td>
<td>2.8634</td>
</tr>
<tr>
<td>311</td>
<td>2.4419</td>
</tr>
<tr>
<td>222</td>
<td>2.3380</td>
</tr>
</tbody>
</table>
The efficiency of the beam monitors is energy dependent due to the differences in cross section values for neutron absorption. In the cold/thermal neutron range, the efficiency is proportional to the wavelength, or inversely proportional to the velocity.

Figure 14. Photograph of the experimental setup to measure efficiency. Reference beam monitor is in front (and to the right in photo) of the monitor with unknown efficiency. The B$_4$C collimator used in the relative efficiency measurements is not shown.
CHAPTER V
RESULTS AND DISCUSSION

Design A: Quartz – Aluminum – Helium-3

The first working prototype parallel plate beam monitor was built using a quartz plate as the anode and an aluminum plate as the cathode. Ordela, Inc. filled the beam monitor with 29.1 Torr Helium-3 and 771 Torr of a 95%/5% mixture of Xe/CO$_2$. As discussed in Chapter 3, it has an expected intrinsic efficiency of $10^{-3}$. The beam monitor was tested at HFIR beam line CG-1D on April 3, 2012.

Initial measurements were made on the oscilloscope in order to gain a qualitative understanding of the beam monitor response. First, the height and full-width half-maximum (FWHM) of the analog signals from the beam monitor were analyzed (see Figure 15). The threshold was set to 60 mV, and the analog pulses had an average FWHM of 30 ns and pulse height of 70 mV when a voltage of 3560 V was applied.

As one might expect, the size and duration of the pulses from a detected neutron vary somewhat from pulse to pulse, and some fraction of the pulses may lie below the discriminator setting. Decreasing the discriminator setting improves the efficiency for neutrons, but it increases the risk of detecting false events due to gamma rays or electronic noise. Increasing the bias voltage also improves the efficiency for neutrons, but it increases the recovery time between events and the risk of recording false neutron events (due to gamma ray interactions). The effect of increasing the bias voltage while maintaining the same threshold setting is shown in Figure 16, where at higher biases larger signals are seen due to increased multiplication. The pulse height variation is due to neutron conversion and charge multiplication occurring within the same region. When an ion-pair is created, the electrons drift towards the anode ~1000x faster than the positive ions, so it is mainly the signal created by the electrons that is measured. When an ion-pair is created near the cathode, the electron will travel the full distance of the gap before reaching the collecting anode, which allows for more multiplication than an electron created near the anode, resulting in a larger induced signal amplitude. However, the variation in pulse heights is not problematic for this beam monitor.
Figure 15. Shape of a typical analog signal from the beam monitor.

Figure 16. Fraction of pulses occurring at specified amplitude above the threshold. The higher bias resulted in a larger distribution of pulse heights.
Regardless of amplitude, any signal above the threshold level will be counted by the electronics, so as long as the threshold level is optimized to just above a minimized noise level, all the signals from incident neutrons may be counted.

The analog output from the beam monitor was also viewed on a wider time scale on the oscilloscope in order to assess the high counting rate capabilities of the beam monitor. The size of the aperture in front of the incident neutron beam was varied in order to vary the neutron flux, and at the maximum available flux on beamline CG-1D, the beam monitor measured count rates up to over 1,000,000 cps. With the beam shutter closed, the count rate was below one count per second. The low background rate allows for accurate measurements even under low flux situations, meaning the beam monitor has a large dynamic range.

The efficiency of the beam monitor was measured using the method described in Chapter 4. The beam monitor was compared against one of the Ordela 4511N wire proportional counter beam monitors that is currently being used at HFIR. It has a known intrinsic efficiency of 0.0045 ± 0.0002 at 1.8 Å. Using a bias of 4100 V and a threshold of 60 mV, the parallel plate beam monitor’s efficiency was measured to be 0.00040 ± 0.00005 at 1.8 Å, which is lower than the calculated value of 0.001. Part of the low efficiency is likely due to the beam monitor not being filled to the desired pressure of Helium-3. The desired fill pressure was 0.0383 atm, but 0.015 atm of Helium-3 would cause an efficiency of 0.0004 (see Equation 4). An error in filling or a leak could cause up to a 0.02 atm difference in pressure, and therefore part of the difference between the calculated and measured values.

The time-of-flight spectrum for this beam monitor was also measured, and it was compared against the Ordela beam monitor. The neutron flux was lowered to a level that the Ordela beam monitor could measure without saturating. Both monitors were placed in the neutron beam, about 5 m from the chopper, and TOF spectra were taken concurrently. The count rates were normalized due to the different efficiencies, and the results are plotted in Figure 17. Good agreement is seen between the two beam monitors. The TOF spectrum was also measured while the flux was at the previous higher level in order to verify that the beam monitor did not saturate at high flux. The
Figure 17. Comparison between the beam monitor design A and the reference Ordela beam monitor. The vertical lines indicate the positions of the aluminum Bragg Edges.

spectrum from CG-1D (seen in Figure 17) has a peak around 3 Å. If a beam monitor saturates, either no counts are recorded or there is a flattened peak at 3 Å because not all of the counts in this region are being recorded. Neither of these things occurred with the beam monitor while testing at the maximum flux of around $10^9$ neutrons per second on CG-1D.

**Design B: Alumina – Aluminum – Helium-3**

The next design of the beam monitor kept the aluminum plate as the cathode. However, the anode was changed to an alumina plate coated with cermet to test the difference in material properties, specifically the effect of a higher resistivity. The resistivity of the cermet coating is 0.2 MΩ-cm, which is twice the resistivity of the quartz plate. The beam monitor is shown in Figure 18 after assembly, just before the housing
Figure 18. Photograph showing the internal view of the beam monitor (Design B).

Figure 19. Typical pulse shape (yellow), and pulse height distribution (blue) for design B of the beam monitor.
lid was put on. It was again filled with 29.1 Torr Helium-3 and 771 Torr of a 95%/5% mixture of Xe/CO₂, for a total pressure of 800 Torr.

The beam monitor was tested at HFIR CG-1D on May 21, 2012. Running at a similar bias of 4075 V, it performed in a similar way compared with design A. A typical pulse is shown in the oscilloscope screen capture visible in Figure 19, with the pulse-height distribution shown in the blue histogram. From the screen capture, one can see that with the threshold at 100 mV, the average pulse height was over 200 mV.

The expected pulse height spectrum for a well behaved proportional detector (at a properly set operating voltage) from a neutron source (shown in Figure 20) includes a response from gammas and noise, which should have small amplitudes, and it contains a peak from neutrons, which should produce a comparably larger signal. To measure neutrons, the threshold needs to be set in the valley between the low level, extraneous counts and the neutron peak. This point was identified for the beam monitors by varying the threshold level and measuring the corresponding count rates. For the beam monitor design B, the threshold was initially set at 30 mV, then increased incrementally to 100 mV. As expected, the count rate decreased non-linearly with the increased threshold. A plateau is seen in the count rate plot in Figure 21, which corresponds to the valley in Figure 20, and indicates the optimal threshold setting region.
Figure 20. Illustration of a general, well behaved detector pulse height spectrum expected from a neutron source. Neutrons should produce a peak in the spectrum, and noise and gammas are responsible for the initial portion of the curve. The dashed line indicates the desired threshold position.

Figure 21. Count rate of beam monitor design B as a function of threshold setting.
Additionally, the TOF spectrum was measured with the beam monitor positioned 4.16 m from the chopper (see Figure 22). As with the previous design, this beam monitor matches the energy distribution from CG-1D including the aluminum Bragg peaks, indicating its capability of being used at a beamline utilizing TOF.

The beam monitor was taken back to HFIR twice to test the long-term stability of the design. On August 23, 2012, the beam monitor was tested on CG-1B, and on November 26, 2012, the beam monitor was tested on CG-1A. In August, it operated at 3700 V, and it measured $40.0 \pm 0.4$ cps/cm$^2$. In November, it operated at 4200 V, and it measured $97 \pm 1$ cps/cm$^2$, an efficiency of $1.0 \times 10^{-5} \pm 0.5 \times 10^{-5}$.

Using Equation 4, the efficiency of the beam monitor was calculated to be 0.001. Six months after filling, the beam monitor efficiency was measured to be $1.0 \times 10^{-5}$. Any long-term stability problems would be caused by a change in the gas quality or pressure inside the beam monitor. The efficiency of the Helium-3 filled beam monitors is
dependent on the Helium-3 pressure as given in Equation 4, the bias required between the plates is inversely proportional to the gas pressure as given in Equation 2, and impurities in the gas mixture reduce the gas’s ability to maintain a proportional relationship. Any or all of these things could be caused by a leak in the indium seal or by outgassing from the components. To address the possibility of a gas leak, the method of sealing the chamber was changed. The initial seal design used an indium wire with a groove in the chamber lid, which was difficult to use for creating a good seal. The modified design utilizes an o-ring with a groove in the chamber body, making it much easier to assemble the beam monitor. It does not have any problems with large leaks immediately after filling, as occasionally happened with the indium seal. However, it has not yet been tested for small leaks over long periods of time.

**Design C: Alumina – Boron Doped Silicon**

In order to develop a beam monitor that does not require Helium-3, the next beam monitor design to be tested relied on Boron-10 as the neutron converter. Alumina coated with cermet was still used as an anode, but for the cathode a commercial p-type silicon wafer doped with natural boron was used. The beam monitor was filled with 800 Torr of Xe/CO₂ in a 95%/5% mixture.

The beam monitor was tested at HFIR CG-1D on May 25, 2012. It was set up for the relative efficiency measurement as described in Chapter 4, with a 6.45 cm² aperture positioned directly in front of the beam monitors and in line with the beam monitor centers. Running at 4625 V, it measured a background rate of 0.28 ± 0.02 cps with the beam shutter closed. With the shutter opened, the beam monitor measured 2.00 ± 0.06 cps when the anode was facing the beam, and it measured 2.3 ± 0.1 cps when the cathode was facing the beam.

The same Ordela beam monitor was also used as a comparison measurement for the beam flux, and it recorded a count rate of 867 ± 1 cps and a background rate of 0.97 ± 0.05 cps. The Ordela beam monitor has a known intrinsic efficiency of 4.5 x10⁻³ at 1.8 Å, so the parallel plate beam monitor design C has an efficiency of 1.1 x10⁻⁵ ± 0.3 x10⁻⁵ at the same wavelength, which is lower than the Helium-3 filled beam monitors.
Design D: Silicon – Boron Doped Silicon – Helium-3

In design D, the beam monitor was built using the same boron doped silicon cathode as design C. However in this design, silicon was also used as the anode, but the anode was made of undoped silicon because it has a higher resistivity ($10^4 \ \text{Ω}\cdot\text{cm}$) than doped silicon ($10^3 \ \text{Ω}\cdot\text{cm}$). It was filled with 29.1 Torr Helium-3 and 771 Torr of a 95%/5% mixture of Xe/CO$_2$. This design uses two different neutron converters in order to increase the overall efficiency. The beam monitor was tested at HFIR CG-1D on October 30, 2012.

The effects of several parameter settings on the beam monitor efficiency were studied. Initially, the threshold was set to 95 mV, which was chosen as being above the noise level seen on the oscilloscope. With the threshold set, the count rate was measured as the high voltage was varied. As seen in Figure 23, the count rate reaches a plateau value around 4500 – 4600 V. At the plateau, the signals from all of the incident neutrons are amplified sufficiently such that they are above the electronic threshold, so they are all counted. At voltages above this plateau region, there are false

![Figure 23. Count rate vs. voltage of beam monitor design D.](image-url)
signals and electric break down seen between the two parallel plates, so the voltage is limited to this point. To obtain consistent measurements with the beam monitor over time, an applied voltage within the plateau region should be used.

Once the operating voltage was set at 4500 V, the count rate was measured as a function of threshold. It is clear from Figure 24 that as the threshold is increased above the noise level, the count rate drops sharply. Once above the noise level, the count rate levels off for a short range before slowly decreasing. The small plateau region in Figure 24 corresponds to the valley between the combined electronic and gamma noise and the neutron peak (refer to illustration in Figure 20). This plateau at 300 mV is the desired operating point for the beam monitor. The optimized voltage and threshold settings give the averaged pulse shape shown in Figure 25. The average FWHM is 30 ns, which is the same as the previously tested beam monitor designs because the shape is largely determined by the shaping electronics.

![Count rate vs. threshold for beam monitor with silicon plates (design D).](image-url)
Additionally, the TOF spectrum was measured with the beam monitor positioned 4.14 m from the chopper, and it is shown in Figure 26. As with the other beam monitor designs tested, the Bragg edges are visible in the spectrum, and the spectrum matches the expected output from the beam line.

On November 26, 2011, the beam monitor was taken back to HFIR and tested on CG-1A to determine the efficiency and count rate capabilities. The efficiency was measured at $3.0 \times 10^{-3}$ on that beam line, which corresponds to an efficiency of $1.2 \times 10^{-3} \pm 0.2 \times 10^{-3}$ for thermal neutrons.

The maximum count rate of this beam monitor on CG-1A was also measured using a bias of 4450 V, and was found to be 395,000 cps, which corresponds to an incident beam flux on the beam monitor of $1.3 \times 10^8$ neutrons/sec. The beam monitor had still not saturated, and was behaving as expected, so the beam monitor should be able to operate at even higher fluxes than that available on CG-1A.
Design E: Alumina – Aluminum – Lithium-6 Fluoride

This version of the beam monitor was constructed using alumina as the anode and aluminum as the cathode. Neutron conversion occurred through samples made with Lithium-6 enriched Lithium-Fluoride nanoparticles. Sample preparation was explained in Chapter 3.

Efficiency Tests

This beam monitor was tested at HFIR at CG-1B on August 23, 2012. The count rate was measured in different regions of the beam monitor in order to determine the efficiency of the individual LiF samples. In order to test only one sample at a time, a collimator with an adjustable B₄C aperture was used to define the area of the beam monitor exposed to the neutron beam. Regions in the center of each of the LiF samples were chosen, as illustrated in Figure 27. An irradiation area of 625 mm² was used for irradiation of each of the LiF sheets within the beam monitor, and an irradiation area of 525 mm² was used for the region without the LiF sheets.
Figure 27. LiF sample arrangement within the beam monitor active area.

Figure 28. Count rates from LiF samples as voltage is varied for irradiated regions shown in Figure 27.
The electric field between the plates was varied, and the count rate was measured using the ratemeter with a threshold setting of 200 mV. Measurements were taken at each voltage setting for both of the LiF samples and in the region with no sample. The results are shown in Figure 28. The count rate with Sample 1 was twice of that with Sample 2 at all voltage levels.

The count rate from an Ordela beam monitor with a known efficiency of $10^{-4}$ was also measured in order to determine the actual neutron flux and the efficiency of the LiF beam monitor. The Ordela monitor was placed 18 cm from the opening, also with a 625 mm$^2$ aperture in front of it. The beam monitor measured 41,000 cps. This gives a maximum efficiency of the beam monitor with Sample 1 of $2.2 \times 10^{-6} \pm 0.5 \times 10^{-6}$, and an efficiency of $9.8 \times 10^{-7} \pm 0.6 \times 10^{-7}$ with Sample 2.

**Sample Analysis**

After the beam monitor was tested at HFIR, the LiF samples were removed from the beam monitor and studied using a Scanning Electron Microscope (SEM). Although both types of carbon paper have fibers around 10 μm in diameter, it appears that the LiF particles did not have equal penetration into the carbon fiber matrix. It was found that the LiF particles were fully incorporated into the carbon fiber matrix of the Toray paper (Sample 1), as shown in Figure 29, but were mainly deposited on the surface of the graphite sheet (Sample 2), as shown in Figure 30.

Sample 1 had a larger counting efficiency than Sample 2, even though it was made with a smaller percentage of LiF particles. This is likely due to the combined effect of Sample 1 actually having more LiF particles within the measured area, the LiF particle distribution within the carbon papers, the distance the produced alpha and triton particles are capable of traveling in the carbon papers, and the ability of the energetic electrons to escape the matrix. In visually studying the samples (shown in Figure 8), it appears that Sample 1 has a more uniform distribution of LiF across the paper, so it could actually contain more Lithium-6 in the measured area than Sample 2. From viewing the samples with an SEM (Figure 29, Figure 30), it was seen that Sample 1 has the LiF particles incorporated throughout the carbon fiber matrix, as opposed to mainly on the surface,
Figure 29. LiF Sample 1: LiF particles (mixed at 20% concentration) were found to be incorporated into the carbon fiber matrix of the Toray Carbon Paper. The LiF particles are the small, round structures within the long, thin fibers of the carbon paper.

Figure 30. LiF Sample 2: LiF particles (mixed at 30% concentration) were found to be deposited only on the carbon fiber surface. The LiF particles are the small, round structures on the top and bottom of the carbon paper (long/ thin and large/ rectangular structures).
which could allow more of the charged particles to escape the carbon paper and contribute to the total number of counts. If the charged particles and any subsequent ionization that they cause are stopped by the carbon paper before reaching the gas and undergoing multiplication, this event will not contribute to the total number of counts, resulting in a lower efficiency for that sample. Because Sample 1 had a larger efficiency, more of the LiF particles in that sample were within the escape distance of the charged particles (and possibly the accompanying ionization clouds created by them).
CHAPTER VI
SUMMARY AND CONCLUSIONS

New neutron beam monitor designs were built and tested in neutron beam lines at HFIR using five sets of different electrode and neutron conversion materials (as listed in Table 2). With the parallel-plate design and fast preamplifier that only relies on the signal from the electron multiplication, the beam monitor is capable of measuring count rates in excess of 1,000,000 cps. Lithium-6 and Boron-10 were both used as neutron converters in some designs in order to investigate the possibility of eliminating the need for Helium-3. The efficiencies of the alternative converter materials used were measured to be very low, on the order of $10^{-5}$ – $10^{-6}$, and are listed in Table 3. However, for many beam monitor applications, a low efficiency is suitable, and further work to increase the efficiency of these converters could make them usable for the improved beam characterization afforded by higher counting statistics. The efficiency measured with each beam monitor and the voltages and fluxes used to make the efficiency measurements are listed in Table 3. The expected measureable beam flux is calculated assuming the beam monitor measures 1,000,000 cps.

From a production perspective, the parallel-plate design also has advantages over some of the current designs. Two electrodes are much easier to assemble than a proportional-wire beam monitor, decreasing the time needed to build a beam monitor. Additionally, the parallel-plate beam monitors are less expensive to produce, especially if using the silicon wafers as electrodes.

Future work will include the addition of imaging capability to the beam monitor. By adding a delay line readout (shown in Figure 31) to the current design, the spatial distribution of the flux can be measured. Knowing the beam profile is advantageous because it provides useful information about the beam shape and divergence, and the changes of these factors over time. Furthermore, the new beam monitor designs can also be used for other applications, specifically for x-ray detection and imaging. A very similar process of particle conversion and amplification can be used for x-rays, with the selection of a proper fill gas.
Table 3. Summary of Beam Monitor Properties

<table>
<thead>
<tr>
<th>Beam Monitor Design</th>
<th>Efficiency for Thermal Neutrons</th>
<th>Expected Flux that can be Measured (cps)</th>
<th>Bias Used (V)</th>
<th>Approximate Flux Used for Measurement (cps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Quartz – Aluminum – He-3</td>
<td>$(4.0 \pm 0.5) \times 10^{-4}$</td>
<td>$4.0 \times 10^{10}$</td>
<td>4100</td>
<td>$(3.0 \pm 0.8) \times 10^9$</td>
</tr>
<tr>
<td>B: Alumina – Aluminum – He-3</td>
<td>$(1.0 \pm 0.5) \times 10^{-5}$</td>
<td>$1.0 \times 10^{11}$</td>
<td>4200</td>
<td>$(1.4 \pm 0.2) \times 10^8$</td>
</tr>
<tr>
<td>C: Alumina – Boron Doped Silicon</td>
<td>$(1.1 \pm 0.3) \times 10^{-5}$</td>
<td>$1.1 \times 10^{11}$</td>
<td>4625</td>
<td>$(1.1 \pm 0.6) \times 10^5$</td>
</tr>
<tr>
<td>D: Silicon – Boron Doped Silicon – He-3</td>
<td>$(1.2 \pm 0.2) \times 10^{-3}$</td>
<td>$1.2 \times 10^{9}$</td>
<td>4500</td>
<td>$(1.4 \pm 0.2) \times 10^8$</td>
</tr>
<tr>
<td>E: Alumina – Aluminum – LiF Sample 1</td>
<td>$(2.2 \pm 0.5) \times 10^{-6}$</td>
<td>$2.2 \times 10^{12}$</td>
<td>3000</td>
<td>$(4.1 \pm 0.4) \times 10^8$</td>
</tr>
<tr>
<td>E: Alumina – Aluminum – LiF Sample 2</td>
<td>$(9.8 \pm 0.6) \times 10^{-7}$</td>
<td>$9.8 \times 10^{13}$</td>
<td>3000</td>
<td>$(4.1 \pm 0.4) \times 10^8$</td>
</tr>
</tbody>
</table>
Figure 31. Photograph of delay line readout that will be added to the beam monitor to achieve position sensitivity.
LIST OF REFERENCES


VITA

Amanda K. Barnett was born in Indianapolis, Indiana on February 9, 1989. After graduating from Plainfield High School in 2007, she attended Rose-Hulman Institute of Technology, where she received a Bachelor of Science degree in Physics with minors in Mathematics and German in 2011. Amanda then attended The University of Tennessee Knoxville, and received a Master of Science degree in Nuclear Engineering in 2013.