

UNIVERSITY OF MANCHESTER

Development of the STEFF detector for the neutron Time Of Flight facility (n_TOF), CERN.

by

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UNIVERSITY OF MANCHESTER

Abstract

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Doctor of Philosophy

by Stuart Graham Warren

Significant work has been performed on the development of STEFF (SpecTrometer for Exotic Fission Fragments), a 2E2V (2-Energy 2-Velocity) spectrometer built by the University of Manchester Fission Group. The majority of this work was in the development of the time-of-flight systems, in particular the stop detector; with the main goals of improving the timing resolution and the detection efficiency of the fission fragments. Further development of the STEFF spectrometer was done to enable 2E2V measurements of the $^{235}\text{U}(\text{n},\text{f})$ reaction with coincident γ measurements using a white neutron spectra of energies ranging from 10 *meV* to 200 *MeV* provided by the n_TOF (neutron Time Of Flight) facility, CERN.

The STEFF spectrometer was successfully operated twice on the Experimental Area-2 high flux pulsed neutron beam line resulting in 2E2V measurements for fission events with neutron energies ranging from 20 *meV* to 10 *MeV*. The first experiment received 1.36×10^{18} POT (Protons On Target) with stable conditions and the second received 1.53×10^{18} POT with stable conditions.

The development of the stop detector resulted in a replacement MWPC (Multi-Wire Proportional Counter) detector for the second of the two experiments. This allowed direct comparison for the timing coincidence resolution, σ_c , between the start and stop detectors and gave $\sigma_c = 0.81 \pm 0.08$ ns for the prior PPAC (Parallel Plate Avalanche Counter) detector and $\sigma_c = 0.40 \pm 0.04$ ns for the MWPC. The MWPC gave improved the detection efficiency per fission fragment of $\varepsilon = 0.67$ compared to $\varepsilon = 0.43$ for the PPAC.

The methods and research described in this work also provided alternate stop detector designs with greater performance. This work produced two large data sets from the two successful deployments of the STEFF spectrometer on the n_TOF beam line that will be the future work of many nuclear structure scientists to come.

Declaration of Authorship

I, Stuart Warren, declare that this thesis titled, ‘Development of the STEFF detector for the neutron Time Of Flight facility (n-TOF), CERN.’ and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
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“Anything is possible with the right motivation and a big enough hammer.”

A.N.Other

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I must thank the exceptional n_TOF local team and CERN technical staff for putting up with me for 18 months in their control room and for the incredible willingness to help out no matter what the time of day where no task was too big. In particular I have to thank Christina Weiss, for her philosophy toward experimental physics and science in general; Federica Mingrone, for reminding me of the ‘lighter side’ to being stuck in an underground bunker at 11pm on a Friday; Michael Bacak and Petar Zurgec for their patience in explaining how to use the CERN supercomputer systems and for some incredibly deep philosophical conversations; and lastly Marta Sabate Gilarte for being generally awesome and making my stay at CERN more sociable, however this does not excuse her for her genocidal behaviour during the game of duck-shoot.

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Chapter 1

Introduction

There is a world-wide demand for cleaner energies to replace the world's dependency on fossil fuels. Many countries have chosen to revitalise and replace their aging reactor fleet. As of 2016, there are about 440 nuclear reactors operating in the world and 65 more under construction providing 11% of the world electrical power demand; consumption is forecasted to increase by 40% by 2040 [1]. This Chapter outlines the fission process followed by the need for better nuclear data through these types of measurements.

1.1 Fission

Nuclear fission is a process by which a heavy unstable nucleus breaks up, most of the time into two smaller nuclei (fission fragments), each with a binding energy per nucleon which is greater than that of the unstable parent nucleus. It occurs when the strong nuclear force between the nucleons is overcome by the electrostatic Coulomb force, driving the two daughter fragments apart. Figure 1.1 shows a diagram of the two fission fragments inside the nuclear potential of the parent nucleus; in order for the fission process to occur they must overcome or escape

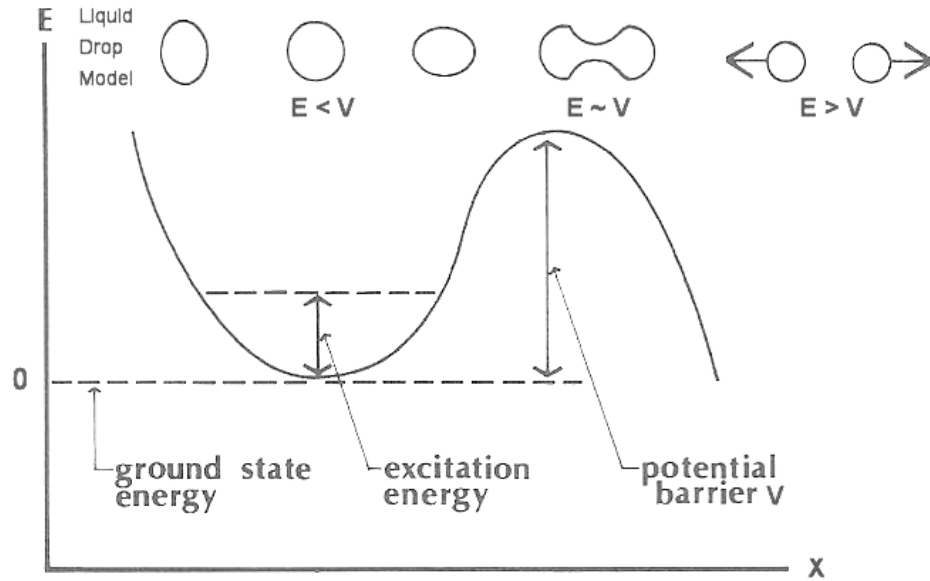
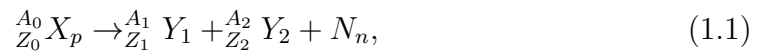


FIGURE 1.1: A diagram of the potential barrier, V , for fission with respect to the potential energy, E . The shapes above the plot represent the nucleus deformation as the potential increases and fissions occurs.

the potential barrier. This can occur by either the parent nucleus being excited above the barrier (as is the case for photofission or neutron induced fission) or by quantum tunneling from the ground state (in the case for spontaneous fission).

The masses of the fission fragments are important quantities that characterize the fission event and are given as A_1 and A_2 in the reaction



where the mass number is $A_0 = A_1 + A_2 + N_n$, the atomic number (charge) is $Z_0 = Z_1 + Z_2$ and N_n is the number of free neutrons created. In binary fission the parent nucleus ${}_{Z_0}^{A_0}X_p$ fissions into two fragments ${}_{Z_1}^{A_1}Y_1$ and ${}_{Z_2}^{A_2}Y_2$. On rare occasions the phenomenon of ternary fission can occur where there are two fission fragments and a third lighter fragment produced (typically ${}^4_2\text{He}$). It is dependent on the incident neutron energy, for an incident thermal neutron with U^{235} gives a probability of ternary to binary fission of 1 : 500 [2].

The Coulomb barrier height for a particular mass split is given roughly by

$$V = \frac{1}{4\pi\epsilon_0} \frac{Z_1 Z_2 e^2}{(R_1 + R_2)}, \quad (1.2)$$

where $R_1 = r_0 A_1^{1/3}$ denotes the radius of the heavy fragment and $R_2 = r_0 A_2^{1/3}$ denotes the radius of the light fission fragment, e is the charge of an electron and $r_0 = 1.2$ fm. If we consider the case of ^{235}U fission where the two fragments are typically ^{95}Kr and ^{140}Ba , then $V \simeq 248$ MeV. This is an order of magnitude estimate due to the spherical fragment approximation being very crude and the neglect of shell effects at large deformations and the experimental values of are found to be different [3].

1.1.1 The semi-empirical mass formula

The semi-empirical mass formula can be used to approximate the mass of an atomic nucleus from its number of protons and neutrons and is based partly on theory and partly on empirical measurements [4]. The theory is based on the liquid drop model where the nucleons behave as an incompressible nuclear fluid such that the binding energy of a particular nucleus, B , is defined by

$$B = a_v A - a_s A^{2/3} + a_c Z(Z-1)A^{-1/3} + a_a \frac{(A-2Z)^2}{A} + \delta(A, Z), \quad (1.3)$$

where $a_v A$ is the term depending on upon the volume of the nucleus, $a_s A^{2/3} = E_s$ is an energy term dependent on the surface area of the nucleus, $a_c Z(Z-1)A^{-1/3} = E_c$ is dependent on the Coulomb force created by the nuclear charge, $a_a \frac{(A-2Z)^2}{A}$ is the symmetry and $\delta(A, Z)$ is the pairing term. $\delta(A, Z)$ depends on the N (neutron number) and Z (proton number),

$$\delta(A, Z) = \begin{cases} +\left(\frac{12}{A^{1/2}}\right) & \text{Z and N even} \\ 0 & \text{odd \& even} \\ -\left(\frac{12}{A^{1/2}}\right) & \text{Z and N odd} \end{cases} \quad (1.4)$$

A plot of this function overlayed with measured data can be found in Figure 1.2 and more information and the values for constants can be found in the literature [5].

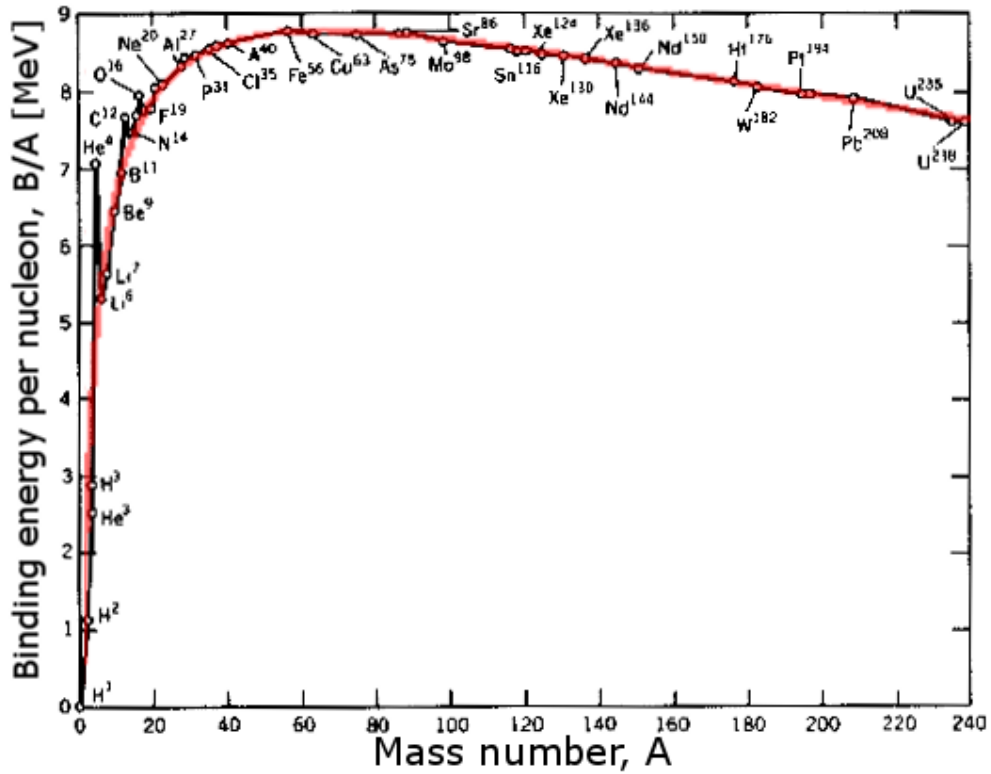


FIGURE 1.2: A plot of the binding energy per nucleon as a function of mass. The measured binding values (black) plotted against the semi-empirical mass formula values (red) [6].

As a nucleus undergoes fission, it stretches from the spherical shape into an ellipsoidal shape, ε is the eccentricity of the ellipse given as

$$\varepsilon = \sqrt{\frac{a^2 - b^2}{a^2}}, \quad (1.5)$$

where a is the length of the major axis and b is the length of the minor axis. As the parent nucleus becomes deformed, the volume will remain constant as it is relatively incompressible, and changes in the pairing term are small enough to be neglected. The Coulomb term and the surface terms do not remain constant, the change in the energy associated with the deformation, ΔE , can be expressed as

$$\Delta E = E_s(\varepsilon) - E_s(\varepsilon = 0) + E_c(\varepsilon) - E_c(\varepsilon = 0) = \Delta E_c + \Delta E_s. \quad (1.6)$$

It can be shown, by using a multipole expansion to define the nuclear shape and considering only the quadrupole expansions gives the change in the surface, the change in the Coulomb terms may be written as $\Delta E_s = (2/5a_{20}^2)E_s(\varepsilon = 0)$ and $\Delta E_c = (-1/5a_{20}^2)E_c(\varepsilon = 0)$, respectively [7]. Here a_{20} represents the quadrupole coefficient in the multipole expansion. If $\Delta E > 0$ then the nucleus is unstable and it fissions in the timescale of the strong interaction ($\sim 10^{-22}$ second). The fissility, x (as defined in the literature [8]), is given by

$$x = \frac{E_s(\varepsilon = 0)}{2E_c(\varepsilon = 0)}, \quad (1.7)$$

where $x \geq 1$ ($Z^2/A \geq 50$) indicates fission. In nature the fissility is generally found to be $x < 1$ but fission may occur through quantum tunneling processes.

1.2 Reactor heating

New types of nuclear reactors are continuously being designed, with the intention to begin demonstrations of the generation IV reactors in 2030 with improved safety features and robust protection against nuclear proliferation [9]. The generation IV reactors utilize new materials and methods for which research is still underway and the final designs some way off. The majority of the design research is performed

through the use of simulations, where it is possible to predict ‘hot spots’ from localized heating within the core of the reactor. The input parameters for the reactor programs rely heavily on data published in nuclear databases such as JEFF [10], ENDF [11] and JENDL [12]. Engineers designing the future reactors utilize these databases and rely on their accuracy; any discrepancies usually result in over-engineering or restricted operation of the reactor for safety.

Nuclear reactors exploit the energy released from fission to produce heat. The power output from the reactor is determined by the rate of heat removal from the reactor core through a coolant loop. Many forms of reactor designs exist with many forms of coolant ranging from exotic molten salts to pressurized water. The PWR (Pressurized Water Reactor) is the most common form used for commercial applications, where water under 150 Bar pressure is pumped through the core of the reactor and heated to 300 °C. It is important to understand the heat distributions within the core because the water must remain in liquid form as steam reactions with the fuel components can lead to accidents [13].

Early reactor designs assumed that the heat released from the fission process was contained within the fuel. This led to the over-estimation of the safety margins and restricted power output. More accurate information is now available to better understand the localized heating per megawatt and the distribution of the heat in a reactor can now be better predicted.

The range over which the heat is dissipated inside the reactor is key to predicting material modification and subsequent reactor fuel failure mechanisms. It is dependent on the amount of energy released in fission, the surrounding material absorption properties (thermal, radiological, etc.) and the geometry of the reactor core. The energy released during fission is in many forms, with a breakdown given in Table 1.1.

Emitted particles	Energy [MeV]	Range
Fission products	168	< mm
Prompt γ 's	7	10 – 100 cm
Prompt neutrons	5	10 – 100 cm
Capture γ 's	7	10 – 100 cm
Decay of fission products:		
β particles	8	$\sim$ mm
Neutrinos	12	∞

TABLE 1.1: Estimated energy distribution for the fission of ^{235}U with a thermal neutron and the associated range of heat distribution [14].

From the values in Table 1.1 it is possible to estimate 180 MeV is deposited within the nuclear fuel, 8 MeV is deposited in the reactor structure, 2 MeV in the moderator, 12 MeV escapes the reactor in the form of neutrinos and the remaining energy is a lost due to the accumulation of many other mechanisms [14].

The total prompt γ -ray emission in fission accounts for about 40% of the total energy release by γ -ray emission that makes up for about 10% of the total energy released within the reactor core. The heating in the nuclear reactor that is attributed to the total γ -ray emission from fission is underestimated by up to 28% using the evaluated data for the main reaction channels $^{235}\text{U}(\text{n},\text{f})$ and $^{239}\text{Pu}(\text{n},\text{f})$ [15]. The majority of measurements made for prompt γ -ray emission in fission employed a single or a few γ -ray detectors [16]. This discrepancy is significantly greater than the 7.5% upper boundary of uncertainty deemed necessary to adequately model the heat deposited within the fuel in the reactor core [17]. A prior measurement with the STEFF (SpecTrometer for Exotic Fission Fragments) spectrometer gave values for γ -multiplicity for thermal neutrons with a 12 NaI (Ti) scintillator array [18].

The Nuclear Energy Agency (NEA, an intergovernmental agency that facilitates cooperation among countries with advanced nuclear technology) have issued a high priority request that the discrepancies on γ -ray heating in a reactor are required to be within 7.5% variation for neutron induced fission energies over the range 0 – 10 MeV [17].

One of the aims of the STEFF spectrometer is to contribute towards reducing the discrepancy surrounding prompt γ -ray heating for neutron energies above and including thermal energies (that are found in many of the proposed Generation IV reactor designs) to allow for better modeling of future reactors, while also satisfying the strong desire for data to aid nuclear structure models.

The aims of this work were:

- Modify and develop the STEFF spectrometer to enable measurements with the n_TOF beam.
- Improve the fission fragment time-of-flight detection systems to obtain better fragment mass determination and efficiency.
- Produce a data-set of neutron induced fission of ^{235}U with STEFF from a high flux pulsed neutron beam with neutron incident kinetic energies ranging from 10 meV to 200 MeV at the n_TOF facility [19].

1.3 Thesis structure

Chapter 2 gives a description of the STEFF apparatus and outlines the areas where improvements are needed. This is followed by a Chapter on the theoretical considerations for the construction of improved fragment-mass detection systems using simulation. Chapter 4 shows the experimental determination of the timing properties with continued improvements to the detector format. Chapter 5 outlines the development of the secondary emission foil systems to aid in fission fragment detection. Chapter 6 gives a description of the experimental facility n_TOF and neutron production. Followed by Chapters 7 and 8 on the experiment with preliminary results of the new data-sets created from the STEFF apparatus and the final Chapter is concluding remarks.

Chapter 2

Experimental set-up

In October 2015 the STEFF (SpecTrometer for Exotic Fission Fragments) detector array was installed in Experimental Area 2 of the n_TOF (neutron Time Of Flight) facility at CERN for an experimental run and again in June 2016 with an alternate neutron beam collimator. The facility and the beam configurations are described in detail later with additional information on how the POT (Protons On Target) correlates to the neutronics of the beam in Chapter 6. For the in-beam data collection samples of ^{235}U were used for neutron induced fission and a sample of ^{252}Cf was used for detector calibration during out of beam activities, details regarding these samples can be found in Section 2.3.

An overview of the experimental set-up of the STEFF spectrometer is given here followed by a description of the individual detector systems that constitute the detector array.

2.1 STEFF

STEFF is a 2E2V (2-Energy 2-Velocity) spectrometer designed and constructed by the Fission Group collaboration at the University of Manchester and previously

used at the Institute Laue-Langevin (ILL), Grenoble, France. STEFF uses a time-of-flight array on each primary arm each coupled with an independent Bragg gas ionisation chamber to independently identify both fission fragments. In addition to the two primary arms there are two smaller single-anode Bragg gas chambers (FiFi) each with their own time-of-flight detectors and an array of γ -ray detectors, see Figure 2.1 for a false colour image of STEFF. The combination of detection systems allows the independent measurement of both fission fragments through the measurement of the atomic mass, A , and the atomic number, Z , for a given fission event.

The non-relativistic mass, m , of each fission fragment is given by

$$m = \frac{2E}{v_f^2}, \quad (2.1)$$

where E is the kinetic energy and v_f is the fragment velocity.

The fragment velocity is non relativistically determined via

$$v_f = \frac{d}{T}, \quad (2.2)$$

where d is the fixed distance between the start and stop detectors and T is the time-of-flight. The kinetic energy of the fragment is proportional to the collection of charge in the Bragg detectors. The ionisation rate dE/dX is proportional to the square of the fragment charge, Z^2 , as it slows to a stop inside the gas.

Detailed observation of the fragment velocity and the kinetic energy disposition leads to the reconstruction of the fragment mass through Equation 2.1. The fragment mass resolution is determined by the error in these measurements and is given by,

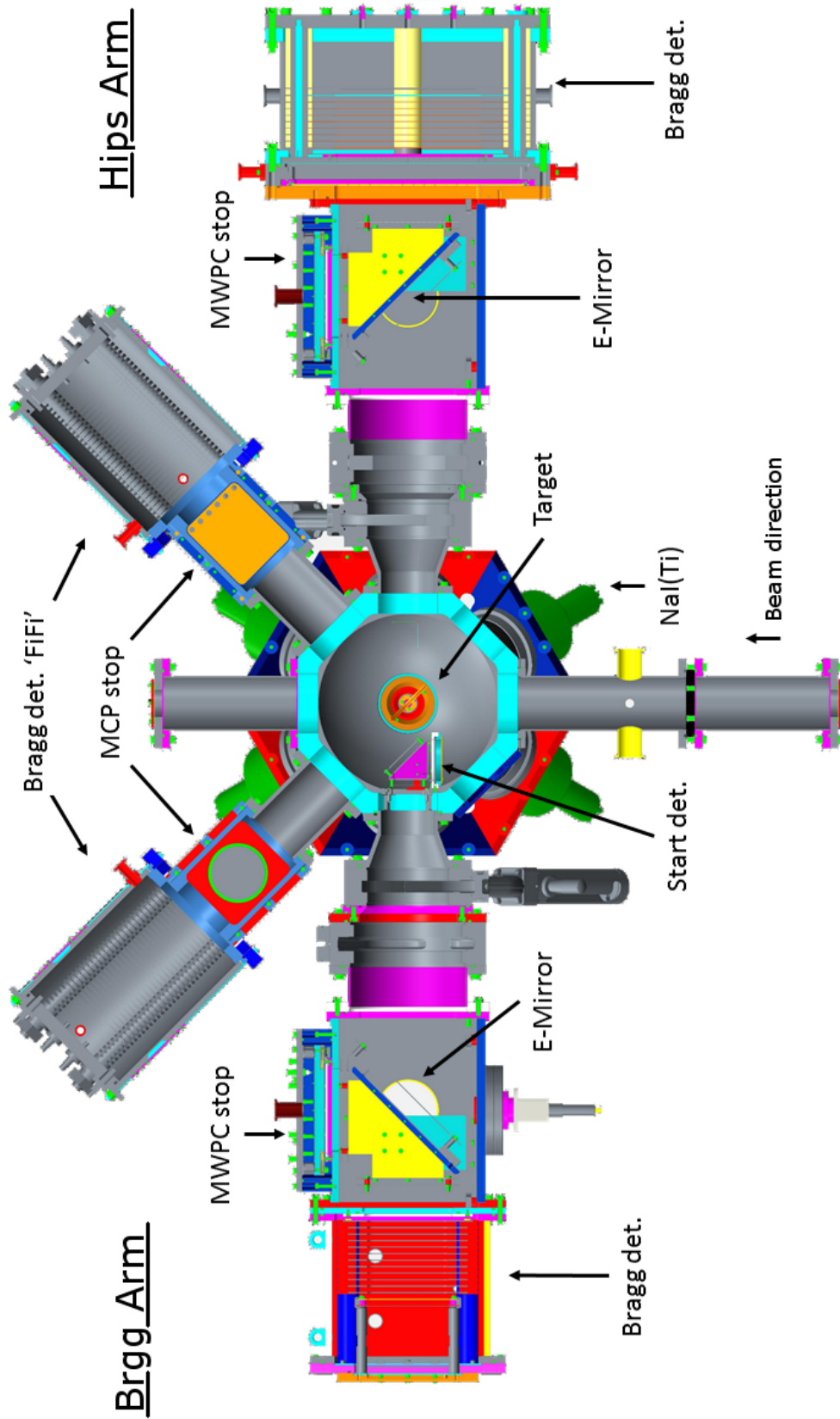


FIGURE 2.1: STEFF apparatus false colour schematic shows the target and major detection systems used. For the premier experiment the MWPC's were replaced with PPAC detectors. The neutron beam enters vertically up through the lower beam pipe where it incidents with the target, fission occurs and the fragments are ejected from the target where they will traverse into the arms of the apparatus. Binary fragment detection is only possible on with the 'Brgg' and 'Hips' arms, the FiFi arms are only capable of single fragment detection.

$$\frac{\Delta m}{m} = \sqrt{\left(\frac{\Delta E}{E}\right)^2 + 4\left(\frac{\Delta T}{T}\right)^2}, \quad (2.3)$$

where T is the fragment time-of-flight; Δm is the uncertainty in mass which gives the atomic mass resolution, ΔA ; ΔE is the kinetic energy uncertainty (energy resolution of Bragg detectors); and ΔT is the timing uncertainty (timing resolution) of the time-of-flight start stop detectors.

Independent measurements of each fragment resolves the problem of neutron evaporation but requires a mass resolution in the order of $\Delta A = 1$. This is a significant advantage of STEFF over single arm EV detectors in which the mass of the second (unmeasured) fragment is determined via the ratio of fragment properties (i.e. mass, charge, kinetic energy, etc.).

It can be seen from Figure 2.1 the target is surrounded by the central vacuum chamber which has space to allow additional external detectors to be positioned in situ; currently an array of 12 NaI(Tl) scintillation γ -ray detectors is used for γ -ray detection.

The previous STEFF run at the ILL, on a thermal neutron beamline from the high flux nuclear reactor, highlighted problems that needed to be addressed before being installed in the pulse neutron time-of-flight facility at CERN. The two key areas of focus were the timing resolution of the stop detectors and the high rate performance of the NaI(Tl) array. There were also modifications made to the apparatus between the two experimental runs during the 2015/2016 winter shutdown at CERN.

2.2 Calibration source

During the calibration runs and set-up of the detector systems a spontaneous fission source of ^{252}Cf was placed into the central chamber using the target exchange mechanism. ^{252}Cf is a spontaneous fission isotope, not naturally occurring and can only be produced through nuclear syntheses, with decay branching ratios of 0.031 for fission and 0.969 for α . The typical mass distribution can be seen in Figure 2.2 and the fission fragments with typical total kinetic energy, K_E , of 186 ± 1.2 MeV [20] are ideal for calibrating the Bragg detectors. With each spontaneous fission there are the corresponding prompt γ -rays produced, typically of total energy 8.94 ± 0.24 MeV with multiplicity of 6.26 ± 0.19 [21].

The fission source was prepared by pipetting a solution of ^{252}Cf dissolved in HCl one drop at a time onto a thin gold foil and allowing the water content to evaporate, this process was repeated until the desired source material activity; for the calibration a 44 ± 1 KBq source was prepared.

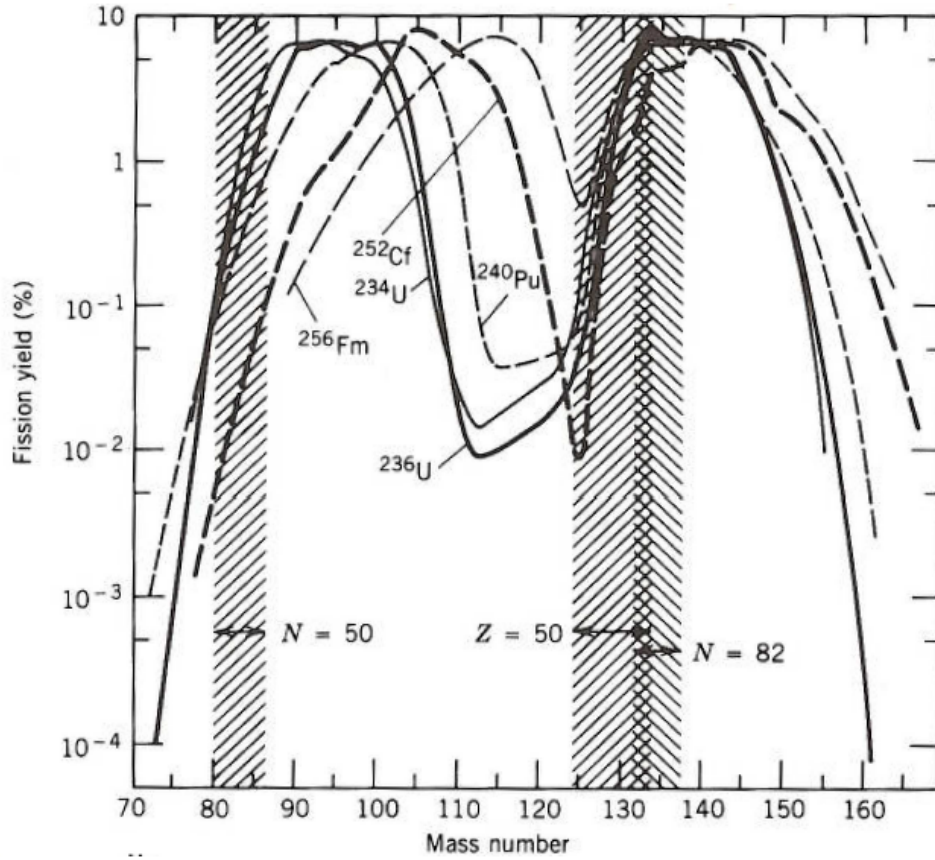


FIGURE 2.2: ^{252}Cf spontaneous fission mass distributions compared to other fission isotopes. The light mass group shifts as the mass increases, while the heavy group nearly remains stationary. The shaded areas show the closed shells of the 50 protons (Z), 50 neutrons (N) and 82 neutrons (N) orbitals [22].

2.3 Fission targets

To attain the fission fragment properties through total kinetic energy and charge measurements, it is important to reduce the amount of material the fragment has to traverse in order to reach the Bragg detectors. Therefore it is not only important to have good vacuum (10^{-6} mBar gives a mean free path of > 10 m) but also minimal amounts of backing material ($< \mu\text{m}$) the fission fragment has to traverse in order to escape the rear of the target and into the relevant detector.

2.3.1 Small diameter target

There were two targets used during the two runs of STEFF; a small diameter target for the narrow collimator, and a large diameter target for the large collimator. The first target is a small 33 mm diameter circular patch of 99.9% enriched ^{235}U metal with thickness of $300\text{ }\mu\text{g cm}^{-2}$ on a $1.5\text{ }\mu\text{m}$ mylar backing; an image of the small target is shown in Figure 2.3. The mylar has a $100\text{ }\text{\AA}$ aluminised coating. This fission target was kindly provided on loan by Professor F.Gunsing, CERN.

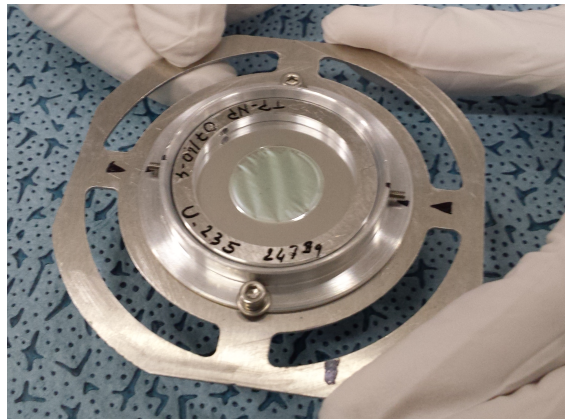


FIGURE 2.3: The small diameter ^{235}U target used for the first experimental run.

2.3.2 Large diameter target

The large 81 mm diameter target shown in Figure 2.5 is a thin film of 93% enriched $^{235}\text{UO}_2$ with a mass of $100\text{ }\mu\text{g cm}^{-2}$ of U, it is chemically deposited on a thin $0.7\text{ }\mu\text{m}$ thick Al foil via an electrolysis process. The electrolysis uses a mixture of a small volume of uranium at the +6 oxidation state in nitric acid in an organic solvent (isobutanol). The solution is then placed in an electrolysis cell and a potential (of hundreds of volts) is applied between two electrodes. At the cathode (Al foil), water and proton reduction occurs leading to an increase of hydroxide ions in the vicinity of the electrode surface. Uranium ions react with hydroxide causing $\text{UO}_2(\text{OH})_2$ to form and precipitate out of solution and onto the foil. The

foil with deposited layer of uranium hydroxide is then dried in preparation for annealing [23].

The sample is then annealed through a process of heating and cooling to 600 °C and back to room temperature through controlled heating and cooling rates. This process increases the stability of the sample adhesion to the substrate by removing the hydroxide leaving UO_2 while also removing any residual organic compounds (isobutanol) and any other volatile impurities. Figure 2.4 shows samarium target pre and post annealing on a thick ($> \mu\text{m}$) nickel substrate used during the prototyping of the sample production, using an identical chemical process. Samarium was used as an analogous to uranium in this process as it does not have the same radiological difficulties associated with production and identification of deposition quality. It has been observed that as the furnace temperature is increased the spherical formations recede and there is an increase in the fissure size, indicating a material loss process is undergone (the removal of hydroxide $\text{UO}_2(\text{OH})_2 \rightarrow \text{UO}_2$).

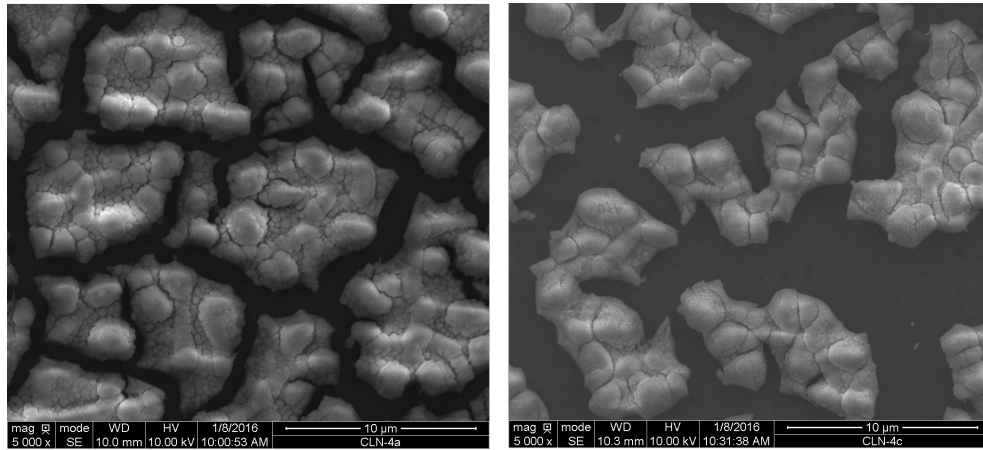


FIGURE 2.4: Scanning Electron Microscope (SEM) image of a samarium target with thickness of $100 \mu\text{g cm}^{-2}$. (Left) Target before any annealing process, (right) annealed at 600 °C. The manufacture and post-deposition annealing methods are identical to the production of the large area U^{235} target [23].

α spectroscopy of the ^{235}U preliminary production targets made with this technique from the same ‘mother’ material as the large area target have shown a presence of other uranium isotopes; mainly ^{234}U , ^{236}U and ^{238}U , with 0.0075 0.0027 and 0.063 isotropic ratio to ^{235}U respectively giving 7% impurity [24].



FIGURE 2.5: The large diameter ^{235}U target used for the second deployment of STEFF with the larger collimator. The uranium is in the form of UO_2 , hence the yellow colour.

There are some non-uniformities to the target surface caused by the deposition over such large area, it is clear to see areas of ‘light’ and ‘heavy’ deposition as well as a wrinkled surface from the annealing process. Therefore, inconsistencies with the surface structure will produce inconsistent energy losses from fission fragments exiting the target, this is unavoidable with the production of such unique target.

2.4 Start detector

The start detector is positioned 15.1 ± 0.2 cm from the center of the target in the Bragg arm, where it triggers the starting time, t_s , for the fission fragment time-of-flight measurement, see Figure 2.1 for position and Figure 2.6 for an image of the start detector. The detector is composed of three main components, a SEE

(Secondary Electron Emission) foil, an electrostatic mirror and a MCP (Micro-Channel Plate). As a fission fragment exits the sample with a trajectory to pass through the start detector it will collide with the SEE foil passing through with negligible energy loss (compared to its kinetic energy) and produces backscattered electrons. The backscattered electrons are guided from the foil to the MCP via the electrostatic mirror where they are multiplied in the MCP to produce a measurable signal. The following subsections describe each component in detail.

2.4.1 Secondary Electron Emission (SEE) foil

The SEE (Secondary Electron Emission) foil pictured in Figure 2.6 is a formvar film produced by exploiting the reaction of polyvinyl alcohol and formaldehyde to form a sub micron (typically $0.5 \mu\text{m}$) self supporting thin film substrate floating on the surface of an aqueous solution. From the solution it is possible to extract the film by drawing it onto the SEE foil support and allowing any residual water to evaporate before the coating process. Coating of the foils is performed using the thermal evaporation techniques of the desired materials under typical vacuum pressure of 10^{-6} mBar, this is a widely used process for thin film production in both laboratory and commercial applications [25].

The foils used on all of the SEE detectors consist of the formvar substrate with two layers of material, a base layer of aluminum of thickness $10 \pm 1 \mu\text{g cm}^{-2}$ and a final layer of lithium fluoride, LiF, of $10 \pm 3 \mu\text{g cm}^{-2}$. Figure 2.7 shows an image of the final SEE foil on support structure with grid transmission efficiency of $\varepsilon_{tran} = 0.9$ per fragment.

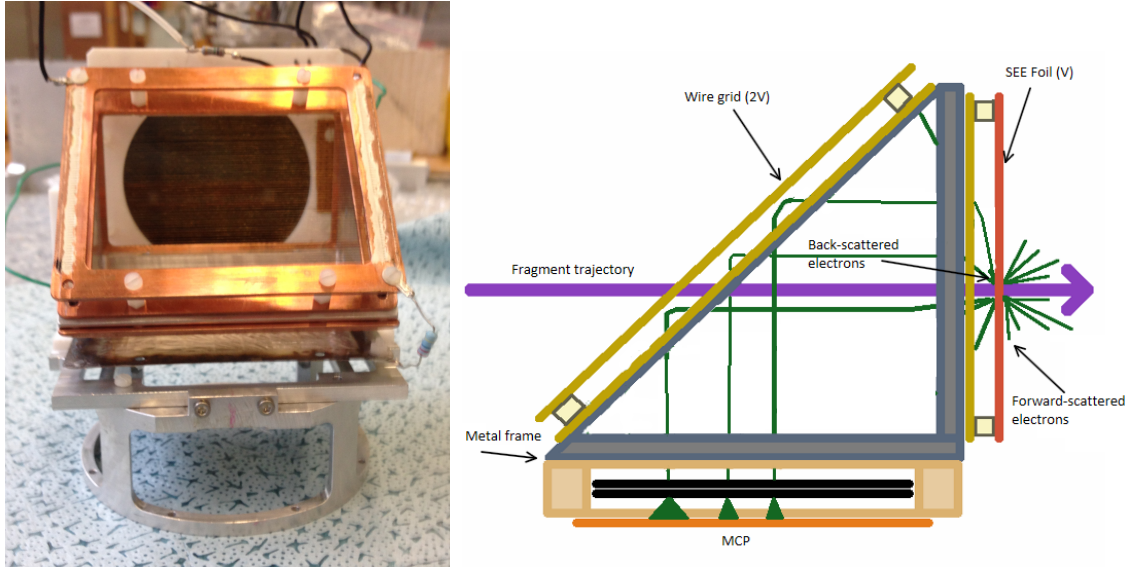


FIGURE 2.6: (Left) The start detector removed from STEFF with the view looking into the MCP (view from above when installed). (Right) A simple diagram of operation showing the path of the electrons (green) scattered from the SEE foil (orange) into the MCP (black) with post electron multiplication collection on anode plate below MCP (viewed from side).



FIGURE 2.7: An image of a formvar foil post coating and installation. The gridded support structure (as seen here) is detrimental to transmission efficiency but required to support the large area thin foils when under the influence of the electrostatic potential. It is possible to see the deformation effect on the foil in each square of the grid (bottom right area of grid) after initial use.

2.4.2 Electrostatic mirror

The electrostatic mirror is coupled to the start detector and the SEE foil, it provides an electrostatic potential to both guide and accelerate the backscattered emission electrons from the foil to the MCP, a diagram of this is shown in Figure

2.6. The field is produced by applying a potential of $V = -1750$ V to the SEE foil and grounding the central metal frame wire grid composed of 20 ± 1 μm wires evenly spaced with a 2 ± 0.1 mm pitch with a gap of 1.0 ± 0.02 cm from the foil surface. The backscattered electrons from the foil are ejected from the foil surface and accelerated in the opposite direction of the fission fragment. As the electrons traverse the interior of the mirror there is no gradient in the electrostatic field to act on the electrons until they pass through the first of the outer diagonal grids where there is a potential of $2V = -3500$ V applied across the 1 cm gap, this deflects the electrons through 90° to the MCP. The transit time of the electrons from the foil has been estimated to be 9 ns [6].

2.4.3 MCP (Micro-Channel Plate)

The MCP is used to multiply the small number of ejected electrons from the SEE foil into measurable signals, it does this by exploiting electron collisions with a highly emissive surface. The MCP is a thin sheet of doped glass (typically 0.2 to 1 mm thick with Pb dopant) with compact tubular channels (typical MCP channel diameter range from 6 to 25 μm) through the sheet with a shallow angle to the normal to encourage primary particle collisions with the side walls of the channels. Between the two glass surfaces a large electrical potential is applied (several kV cm^{-1}) to accelerate liberated electrons from the primary particle through the channel, the shallow angle then aids in secondary collisions producing yet more electrons. This process of electron multiplication repeats until the electrons are free from the channel. The gain, M , is governed by l/d , the relation between the channel length, l , and the channel diameter, D , and typically $M \approx 10^3 - 10^4$ for a single MCP layer [26, 27].

For the STEFF start detector we exploit the ability to couple multiple MCP's together to form a chevron configuration as shown in Figure 2.8, where the channels

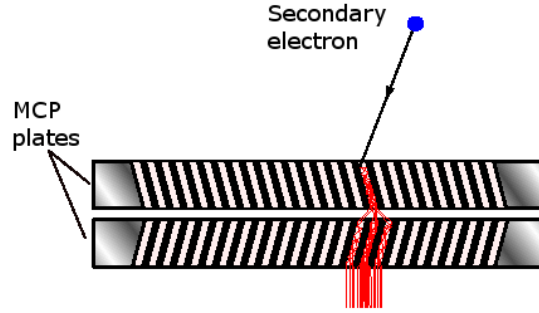


FIGURE 2.8: MCP chevron configuration where two MCP plates are stacked on top of each other to prevent any direct line through for electrons without collisions. The configuration also reduces the effects of ion feedback.

are angled opposed to each other and effectively doubling the channel length, increasing the gain to $M \approx 10^6 - 10^7$ [28]. This chevron configuration also provides protection from ions, they can drift into the channels and cause collision induced electrons ejections. It is of vital importance to keep the vacuum below 10^{-6} mBar pressure to reduce this effect to a safe operational level [28].

2.5 Gaseous detectors

There are several gaseous detectors utilised on STEFF. The time-of-flight detectors operate at low pressure (< 10 mBar) and are purely for timing purposes, the energy deposition in these detectors is only used as a trigger. The Bragg chambers operate at a much higher pressure (~ 100 mBar) required for the precise measurements of the fission fragment properties; charge, Z , and kinetic energy, E , as they are stopped inside the detector. Gases are used as an active medium over other detection media here simply because the medium is refreshed through gas flow making the detector radiation hard with no loss of signal with exposure to ionizing radiation over time.

For the case of the Bragg chamber it is necessary to consider the processes occurring when a fission fragment with typical total kinetic energy of $E_k \approx 100$

Gas	ρ [mg cm ⁻³]	E_x [eV]	E_I [eV]	W_i [eV]	$(dE/dx)_{min}$ [keV cm ⁻¹]
Ne	0.839	16.7	21.6	30	1.45
Ar	1.660	11.6	15.7	25	2.53
Xe	5.495	8.4	12.1	22	6.87
C ₂ H ₄	1.260	8.2	11.5	26	2.92
iC ₄ H ₁₀	2.490	6.5	10.6	26	5.67
CO ₂	1.840	7.0	13.8	34	3.35
CF ₄	3.780	10.0	16.0	54	6.38

TABLE 2.1: Physical constraints for various gases at NTP and approximate values of energy loss $((dE/dx)_{min})$ and ion pair production (unit charge minimum ionising particles). Where E_x is the excitation energy, E_I is the ionisation energy and W_i is the typical energy to produce an electron ion pair for a given gas. [29, 30].

MeV [20] enters the detector. When the incoming fission fragment interacts with the gaseous medium, energy is transferred from the incoming fragment into the medium. If the energy transferred in a single interaction is greater than the ionisation threshold, E_i , for the medium an electron-ion pair is formed (the average energy for an electron-ion pair is given by W_i). There will be a small fraction of the energy lost to non-ionizing events, this is discussed later in Section 3.2.1. The charges of most interest are the electrons, they are the main component of the fast signal produced, however the ions still have a great deal of influence in both the ionization process and the slow component of the signal. The number of electron-ion pairs depends on the energy deposition, the density and the ionisation threshold, see Table 2.1 for typical values for common gasses used in detectors.

If an electric field is applied to the gas via anode and cathode electrode planes, the electron-ion pairs will migrate to their respective electrodes, the charge motion induces a current, i , on the electrodes; this is discussed later in Section 3.2.5 in detail. During electron and ion drift a process of recombination can occur resulting in no net charge, this is undesirable in this gas detector but is crucial in other forms of gaseous detectors operating in the semi-proportional gain region [30]. The region where the signal from the detector is no longer proportional to the energy deposited within from the ionizing radiation, the fidelity of energy deposition becomes poor.

The applied electric field determines the detector behaviour as well as the choice of gaseous medium, Figure 2.9 shows the typical regions for gaseous detector operation.

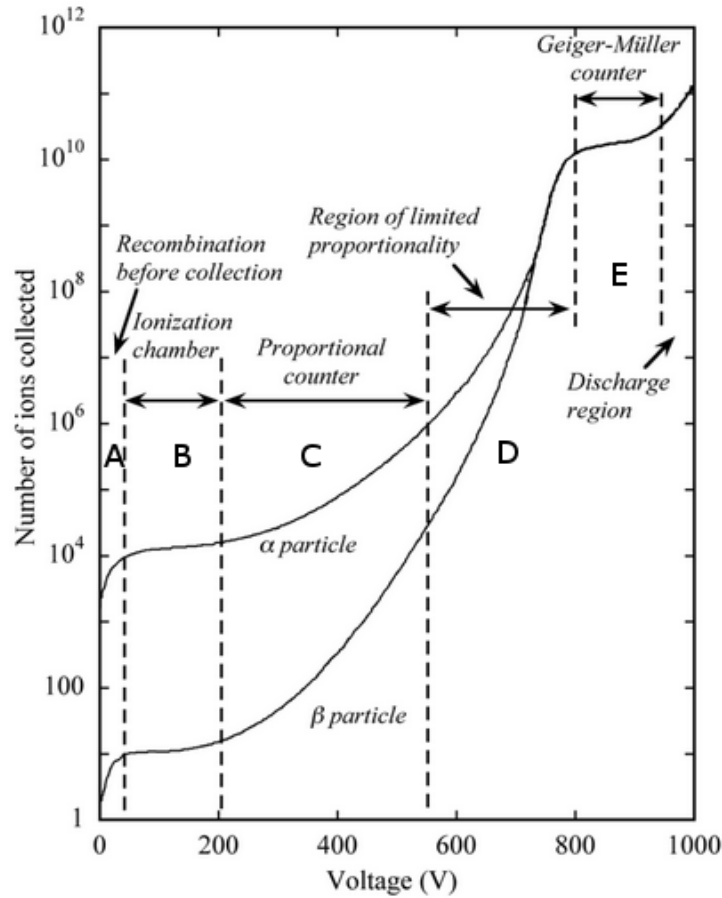


FIGURE 2.9: Various detector operational regions for a simple cylindrical single wire gas detector with applied voltage showing the dependence of applied potential [31]. The voltage indicated is simply for illustrative purposes, the regions shown are highly dependent on many other factors than just applied potential, see text for details.

There are five possible modes of operation used in gaseous detectors and they are:

- Region A - In this region charges start to be collected, however the ion recombination process is still dominant; at higher fields this process begins to diminish.
- Region B - This region is known as the ion chamber region. In this region the electric field is sufficiently high to reduce recombination to a negligible level,

as such nearly all of the ion pairs created in the detector are collected at the electrodes. This is the region that is used in ion chambers in which it is important to preserve the shape of the ion track in the medium (Bragg-curve spectroscopy).

- Region C - This is the proportional gain region. The electric field close to the surface of the anode wire is sufficient enough to initiate the charge multiplication process; gains in excess of $10^5 - 10^6$ can be obtained. This multiplicative effect on the signal is proportional to the original number of ions produced by the primary source of ionisation.
- Region D - This region is known as the limited proportional region. Here the size of the signal from the gas filled chamber is proportional to the initial ionisation. However, the proportionality no longer holds with applied voltage as the multiplication affected is now effected by other processes; the electric field around the wire begins to distort as charge build up occurs from high gain reducing locally the multiplication/gain.
- Region E - Here the field is substantial enough for the secondary processes to dominate, resulting in the breakdown. Under low pressure poorly quenched gas conditions we see photon-mediated propagation of multiplication over the full length of the anode, the Geiger-Müller operation. Beyond this electric field region we see the glow discharge effect and a continuous plasma formation.

For the Bragg chambers the ion chamber region is utilized to keep the information regarding ionisation per unit length and total ionization preserved. The modeling of this region is simplistic and does not require accommodation of secondary effects, unlike the time-of-flight detectors which operate in the region of limited proportional gain to maximise any signal production. In this proportional region we have to consider the secondary process effects on signal production and detector

stability. Although not discussed in this Chapter there is an in depth discussion of these effects on detector performance in Chapter 3.

2.5.1 Stop detector

The stop detector in the premiere experimental run was the original PPAC used at the ILL, due to unforeseen manufacturing delays, the newly designed multiple layer MWPC could not be installed. It operates with a similar principle to the start detector by recording the passage of the fission fragment via indirect measurement of electrons ejected from a SEE foil coupled to a large electrostatic mirror.

The stop detector is not a true Parallel Plate Avalanche Counter (PPAC). It has one electrode plate replaced with a plane of 2 mm pitch 20 μm gold plated tungsten wires, however for simplicity it will be referred to as a PPAC. It operates at a pressure of 10 mBar with the gas iC_4H_{10} and a potential of $V_{PPAC} = -660$ V, the ratio of applied field to pressure is important in determining the operation of the detector and is referred to as the reduced field E/p . It is arguable that running the PPAC at higher pressures will improve the performance by increasing the energy deposition within the detector, however it will reduce other performance aspects and require increased electrostatic fields to recuperate. The detector behaves similarly to a PPAC where charge multiplication occurs within the field region produced by the applied voltage over the 3.2 mm gap, it too has a homogenous field within the bulk of the gaseous region. It can be seen in Figure 2.10 the field is not homogeneous through the whole ‘active’ region, around the cathode wire it is clear to see the increased field potential. The field within the bulk of the gas detector has been calculated through simulations (described in Section 3.3.4) to be $E \approx 100$ V/cm, leading to the conclusion that very little multiplication occurs through the bulk of the detector but around the wire.

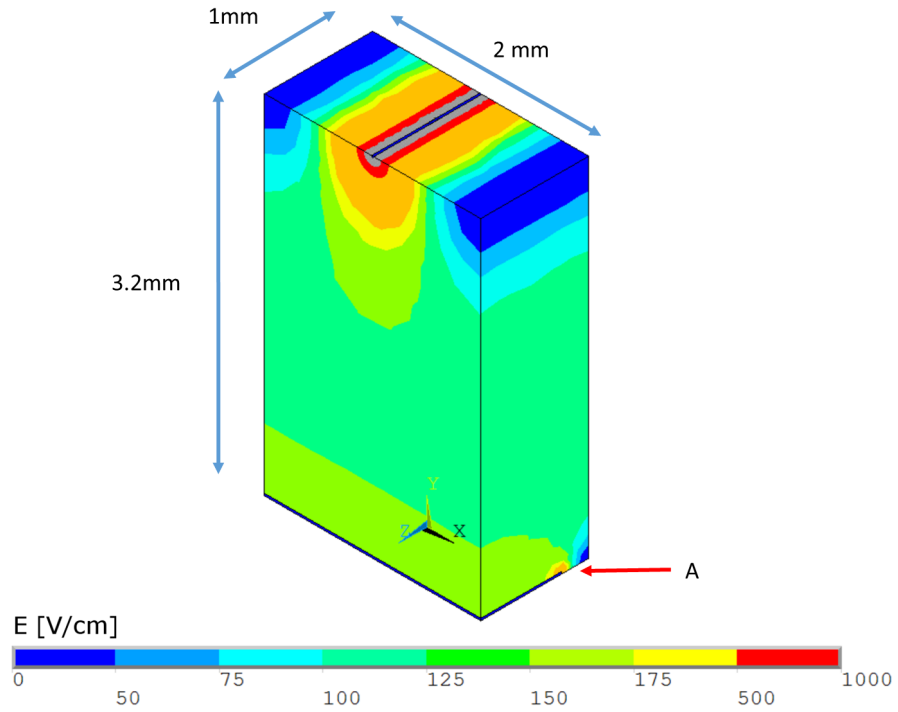


FIGURE 2.10: Electrostatic field nodal magnitude map (V cm^{-1}) as calculated with the ANSYS toolkit showing a ‘cell’ (see Section 3.3.3 for a description) of the PPAC. The image shows the anode plane charged to -660 V and at the top a central cathode wire grounded. The small aberration in the field, indicated with A, is a manifestation from the gap between the anode plates.

The electron and ion drift induces a current on the electrodes. The detector is capacitively coupled via a 1 nF high voltage ceramic capacitor (for signal output) with the voltage applied through a $10 \text{ M}\Omega$ HV resistor as shown in Figure 2.11.

The induced signal is amplified as close to the detector as possible to improve signal integrity with the amplifiers developed in partnership with the STFC Daresbury Laboratory, amplifiers are described in Appendix A.4.

2.5.2 PPAC electrostatic mirror

The electrostatic mirror used on the large fission fragment arms are similar but not identical to the electrostatic mirrors discussed on the start detector shown in Figure 2.12. The key differences are the field applied to the ejected electrons from the SEE foil, the size and an additional acceleration region. The electrons in the

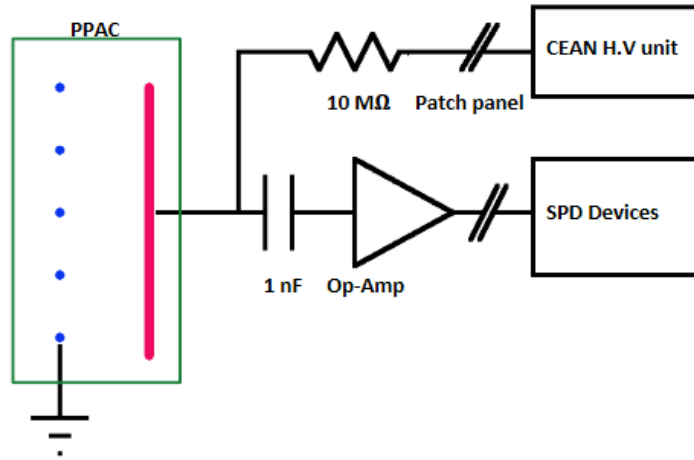


FIGURE 2.11: Simplistic layout of the wiring for the connection of the PPAC detector in the n.TOF facility. The SPD Device is the analough to digital digitizers connected to a capacitively decoupled amplifier to the anode to record the events.

start detector are accelerated once unlike the stop detector electrostatic mirrors which have two regions of acceleration with a greater potential applied, $V = -18$ kV. The second region of acceleration provides an overall acceleration potential of $2V/3$ resulting in 12 keV electron kinetic energy. This additional acceleration is required for the electrons to pass through the $0.9\text{ }\mu\text{m}$ Al-Mylar window, see Figure 3.11.

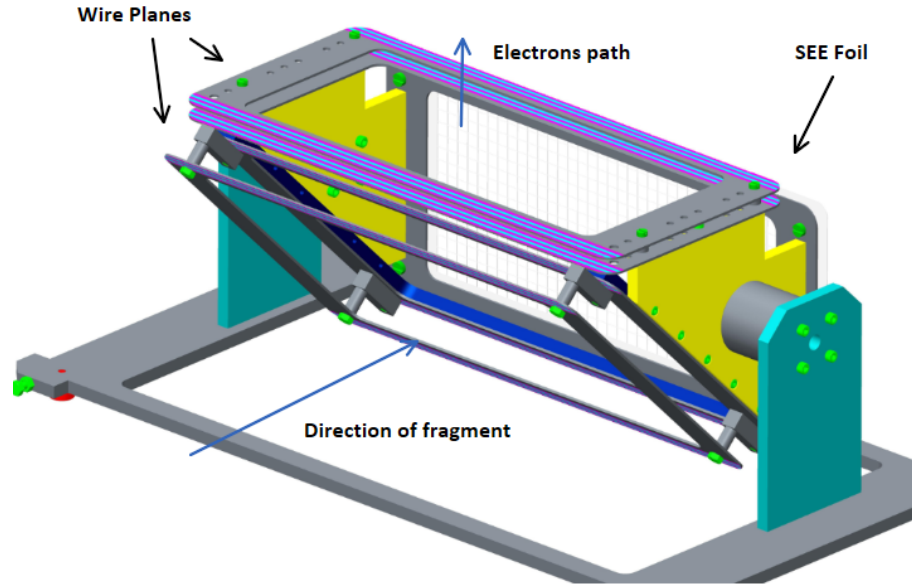


FIGURE 2.12: The false colour image of the electrostatic mirror used for the large area time-of-flight detectors.

2.6 Bragg detector

We have seen in Figure 2.9 there is a region where electron-ion recombination is negligible and any charge generated through the primary ionisation event is conserved (the ionisation chamber region). The Bragg detectors operate in this region to produce a signal that is proportional to the total energy deposited within the gas by a fission fragment. As the fission fragment enters the gaseous region it loses energy through interactions with the gas until it is stopped within the detector. The energy loss is characterized through the parameter stopping power, S , given by:

$$S = -\frac{dE}{dx} = \left(\frac{Ze^2}{4\pi\epsilon_0} \right)^2 \frac{4\pi Z\rho N_A}{Amv^2} \left(\ln \left(\frac{2mv^2}{I} \right) - \ln(1 - \beta^2) - \beta^2 \right), \quad (2.4)$$

where E is the particle energy, x is the distance traversed through the medium, ρ is the density, e is the charge of an electron, N_A is Avogadro's number, m is the electron rest mass, v is the velocity of the charged particle, I is the ionisation energy of the medium and $\beta = v/c$ where c is the speed of light. This is the

Bethe-Bloche equation and according to this formalization the energy loss of an ion depends upon its velocity and its charge. It can be represented for charged particles composed of many charges, a fission fragment, as

$$\frac{dE}{dx} \propto -Z^2 f(v), \quad (2.5)$$

where $f(v)$ represents the function v . However in low energy fission the fragments have insufficient kinetic energy to prevent electrons recombining with the naked nuclei; therefore we can no longer assume Z to be constant throughout the fragment passage. Instead, we make the following adaptation

$$Z' = Z^{1/3} \frac{v}{v_0}, \quad (2.6)$$

where Z' is the now effective charge of the fragments and v_0 is the Bohr velocity as described in literature [32] and also implemented in the past for STEFF [6]. Combining the Equation 2.5 with 2.6 results in an equation for the specific energy loss for fission fragments in the form:

$$\frac{dE}{dx} \propto -Z^{2/3} f'(v), \quad (2.7)$$

where $f'(v)$ is a new function of velocity. The main issue with performing Bragg-curve spectroscopy of the low energy fission fragments is that the kinetic energy is below that of their respective Bragg peaks for the Bethe-Bloche formalization to be effective. The use of the fission fragments range in the detector to determine the charge of the fragment has been described in literature [6, 33].

2.6.1 STEFF Bragg ionisation chambers, Bragg & Hips

Bragg and Hips are the names given to the two main fission fragment arms of STEFF. The two arms cover a solid angle of 30 mSr and are positioned such that the total kinetic energy from both fission fragments during a single fission event can be measured simultaneously. The two detectors are slightly different in size but due to the geometry of the vacuum and electrostatic chambers proceeding the angle of fragment acceptance is identical. With the solid angles the same for each detector the primary difference between the two detectors is the depth, the Bragg detector (Bragg detector on the Bragg arm) is deeper than the opposite Hips detector (Bragg detector on the Hips arm), as shown in Figure 2.1; and is accounted for with gas density. The detectors operate in the ionisation chamber region with isobutane pressures of 70 and 100 mBar with an externally applied potential of +1.0 kV and +1.2 kV for Bragg and Hips respectively over the drift regions. This gives a drift velocity of the electrons of $v_e = 2.31 \pm 0.01 \text{ cm}/\mu\text{s}$ with a field of $|E| = 66.7 \pm 0.4 \text{ V/cm}$ for the Hips Bragg and $v_e = 2.90 \pm 0.01 \text{ cm}/\mu\text{s}$ with a field of $|E| = 60.0 \pm 0.3 \text{ V/cm}$ for the Bragg Bragg, calculated with Magboltz as described in Section 3.3.2.

A potential over the drift region is applied to a series of copper field shaping rings axially spaced with PTFE 1 cm spacers with a 10 M Ω resistor between each shaping ring making a voltage divider. The shaping rings are used to form a homogenous field between the front (entrance window) to the rear Frisch grid in order to preserve the shape features of the signal. The Frisch grid is a plane of parallel 20 μm wires with pitch 2 mm to isolate the field from the charges drifting in the detector, it is situated 1 cm from the a surface of the anodes. The Frisch grid is at a depth of 20 cm and 15 cm from the cathode for Bragg and Hips respectively, only as the charges produced in drift region traverse through the grid are signals

produced. A diagram of the exploded construction of the Bragg Bragg detector is shown in Figure 2.13.

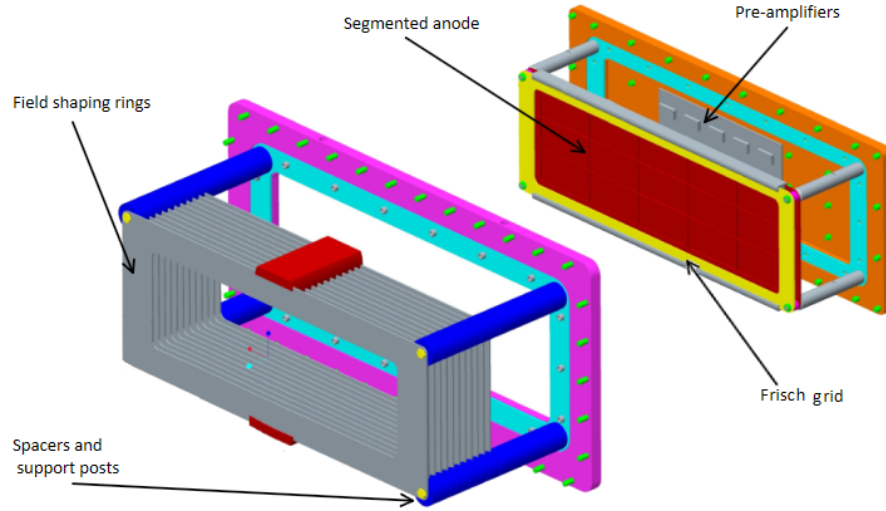


FIGURE 2.13: The Bragg chamber false colour image of the field shaping rings, the support structure with the segmented anode and amplifier locations. The Frisch grid can be seen as the yellow ring in front of the segmented anode.

The Frisch grid is connected to a filtered high voltage supply, for the second STEFF installation it was capacitively decoupled of 6.8 nF to record the signal of electron drift within the chamber as it traverses the gas to the Frisch grid. It also screens the anode planes from the drifting charge until it passes through the grid. The signal is then collected on the segmented anode PCB (Printed Circuit Board) plane charged to a potential of 1 kV. The charge is collected on the anodes where the signal is proportional to the energy deposited by the fission fragment, E . There is a small depreciation of the energy resolution by the foil used to separate the gas regions and that of the secondary emission foils (see Section 2.8 and Section 5 for more information on the windows and foils used). The energy losses have been estimated to be 7.02 ± 0.03 MeV for a heavy fission fragment with typical energy through the gas window, calculated with SRIM. SRIM (Stopping and Range of Ions in Matter) is a Monte-Carlo simulation program for calculating ion transport in matter [34].

The charge drift and collection in the region between the anodes and the Frisch grid induces a current in the respective segment of the anode plane. Each plane is 98×48 mm with a 2 mm gap separating each, they are grouped in an array of 5×3 on the PCB. Each anode is capacitively coupled by a 6.8 nF capacitor to a EV series preamplifier housed at the rear of the detector. The EV preamplifier output is then fed into a high impedance AD811 buffer amplifier to prevent current limiting losses, with a gain of 2 and the output impedance is matched the 50Ω input of the data acquisition system.

2.6.2 STEFF Bragg secondary arm detectors, FiFi's

The Bragg chambers named FiFi Brag and FiFi Hips are very similar to the Brgg and Hips Bragg detectors in their design, however they are smaller and cylindrical. They have cylindrical field shaping rings with internal diameter of 140 mm, separated with 1 cm PTFE spacers and supports. The FiFi detectors have a Frisch grid with a series resistor voltage divider, with applied potential the same as the Brag detector with a single charge collection anode, this has a distinct advantage in data processing. However due to the position and orientation to the target they cannot be used in the $2E2V$ configuration only acting as single E spectroscopes. The FiFi detectors are independently supplied with the same voltages and gas pressure as the Brgg detector.

The entrance to each of the FiFi detector contains an electrostatic mirror coupled to a SEE foil with a MCP detector to measure the time at which the fragment passes into the gas region.

2.7 NaI(Tl) scintillator array

The central reaction chamber on STEFF has an array of NaI(Tl) scintillators surrounding the reaction chamber facing inwards toward the target. There are two hemispheres of six scintillators, as seen in green on Figure 2.1, angled at $\pm 45^\circ$ to the central target arm axis to capture the fission γ -rays released during the scission of the nuclei. Previous runs at the ILL provided a 6.8% photo-peak efficiency [18]; the efficiency for producing full energy peak pulses only, rather than a pulse efficiency curve of any size for the gamma ray. There is a significant amount of work required in the calibration and analysis of these detectors in the highly demanding environment of n_TOF EAR-2. They are a vital part of the γ -ray multiplicity measurements made at n_TOF and are the domain of other STEFF group members, hence the NaI(Tl) scintillator array is not mentioned in detail in this work nor are the results other than functionality. During the second run a NaI(Tl) scintillator was replaced with a LaBr scintillator, which is a significantly faster responding detector well suited for the high background flux found following the proton pulse.

2.8 Vacuum system

The vacuum systems on STEFF are vital for preserving the fission fragment's kinetic energy and momentum vector during flight. This is achieved by keeping the vacuum chambers of STEFF at or below 2×10^{-6} mBar during operation. The vacuum pressures require significant time to attain because of the large surface area of the detectors and the chamber outgasses significantly during the first few days of pumping. Here Outgassing refers to the escape of molecules or atoms from the surface or the bulk of a material, typical stainless steel structures, like the chamber

walls, outgas at 2×10^{-10} Torr $\text{l s}^{-1} \text{ cm}^{-2}$ without baking (heating) the system for the first 24 hours [35].

Managing the system was not a simple operation as there are six $0.9 \mu\text{m}$ large-area windows between the vacuum and gas areas supported on one side by a 10 mm thick stainless steel grid. The summed area of all the gas windows is 3980 cm^2 , which increases the complexities of bringing the experiment to and from vacuum during maintenance and target installation, as it was essential to always keep a positive pressure differential between the gas and vacuum regions to prevent the thin Al-Mylar foils from coming free from the supports.

The central chamber and fission flight arms are kept under high vacuum ($< 2 \times 10^{-6}$ mBar) through the use of six turbo-molecular pumps and their respective rotary pumps, each having its own AF1K25002 inline KEF filter to prevent any possible spread of contamination. Each major section of STEFF is monitored via various gauges distributed as shown in Figure 2.15. Rather than list each individual gauge(s) it is much simpler to group them into high vacuum (penning) and low vacuum (capacitive gauges).

The key differences are the ranges; the penning gauges (also known as a cold cathode gauge) use an ionising filament in a magnetic field to measure the pressure. This limits the maximum operational pressure range from 10^{-8} mBar to 10^{-2} mBar, operating at pressures above this causes damage to the cathode. The capacitance gauge utilizes a conductive diaphragm coupled to a conductive plane adjacent, the diaphragm is deformed with pressure differential resulting in change in the capacitance; these gauges are sensitive from 10^{-4} mBar to 2000 mBar.

The whole vacuum system, gauges and temperature, were monitored via a ‘home built’ system shown in Figure 2.14. Made using an Arduino Mega2056, recycled NIM (Nuclear Instrumentation Module) electronics, some 3D printed parts and some custom built analogue circuitry. The monitor utilised LabView to provide a

useful display for novice or non-STEFF team personnel to safely monitor STEFF during beam operation as the EAR-2 bunker (being a class A lab and hence no restrictions to nuclear materials used within) is off limits to personnel with air tight doors and a 5000 *kg* sliding door/shield.

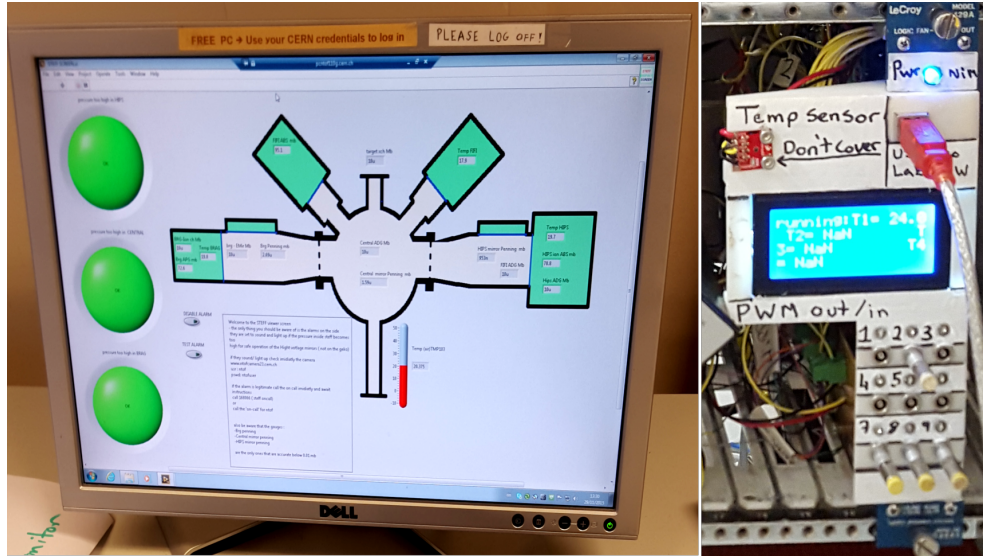


FIGURE 2.14: (Left) Shows the general user interface for the monitoring of STEFF in the control room of n_TOF. (Right) Shows the front end home built device.

2.9 Gas supply systems

The gas systems on STEFF supply the three separated isobutane systems for operation with each detector; Hips, Bragg and the PPAC (MWPC). The volume of gas in the system was $8 \times 10^{-3} \text{ m}^3$ for the PPAC (and MWPC) volumes and 0.17 m^3 for the remaining Hips, Bragg and FiFi chambers. At STP this corresponded to $\approx 0.014 \text{ m}^3$ or 0.6 Mole of isobutane in the system.

For the successful operation of both types of gaseous detector the gas was continuously refreshed. For the case of the Bragg detectors prior experiments recorded signal degradation as much as 1% per hour when left with static gas [33]. To

maintain a continued flow through the gas systems a pump out pressure (on the baritron pump out gauge) of 1 – 5 mBar for each chamber was used.

There were three baritron (MKS manometer) controller units connected each to their own respective detector(s) that operate at different pressures. The baritron has a PID (Proportional Integral Differential) controller regulating a feed in valve to supply gas to the experiment and a pump out valve to a roughing pump fixed at a constant flow rate. The system equalizes at the pressure set on the unit while still maintaining a constant flow. The PPAC's (or the MWPC's) were connected in a loop from one baritron controller in order to allow flow through one and then into the other; the same method was adopted to pressure the two FiFi detectors and the Hips Bragg detector on another controller, the final baritron was connected to the Bragg Bragg detector, see Figure [2.15](#).

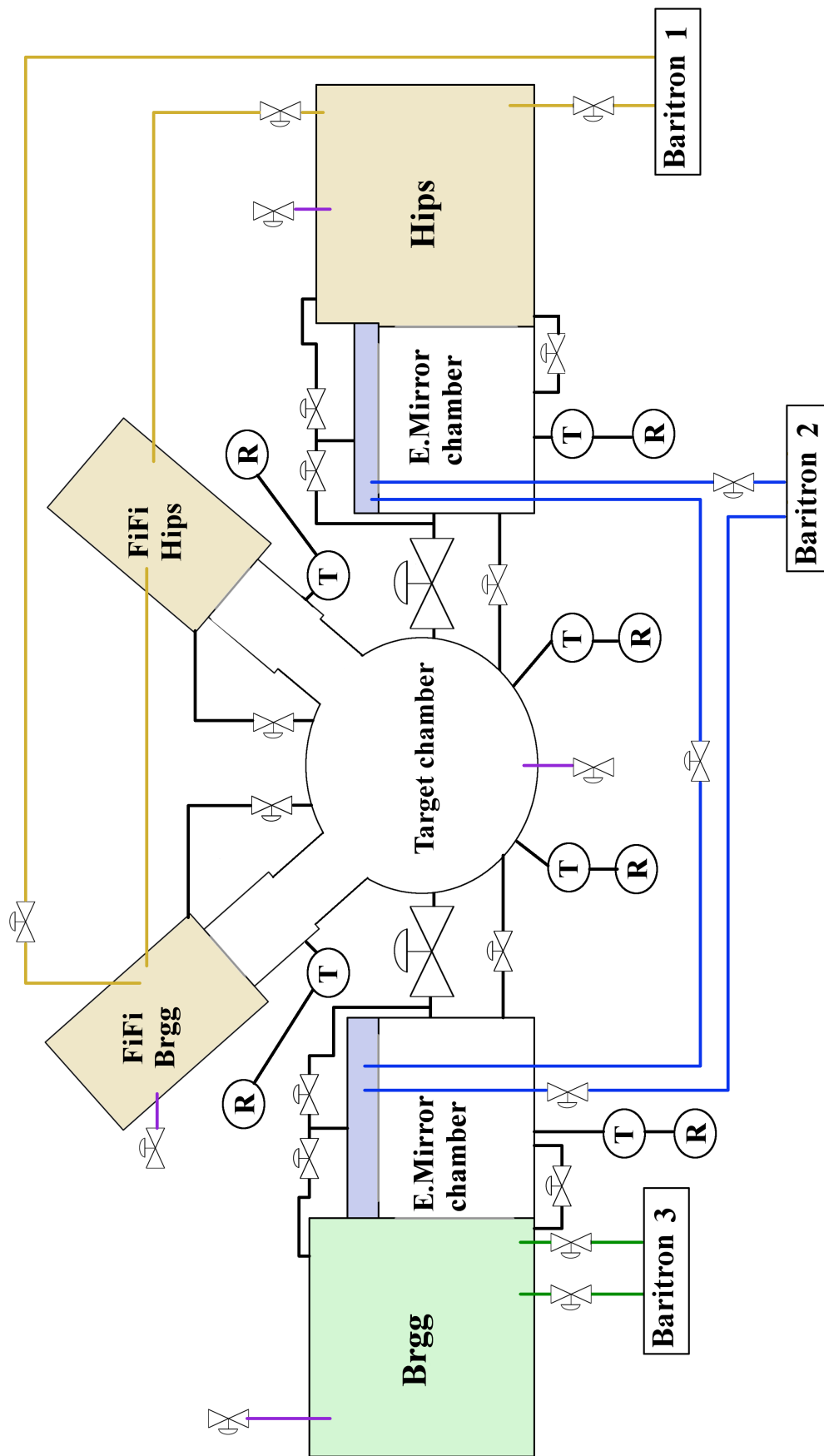


FIGURE 2.15: Diagrammatic representation of the STEFF gas and vacuum systems where the labels represent the following: R- rotary pump, T- turbo-molecular pump, each coloured line represents a gas carrying pipe on its own baritron; however the purple lines represent bleeding pipes for returning safely to atmosphere. The vacuum gauges have not been added to the diagram for simplicity as there is a penning gauge for each high vacuum region (clear), absolute capacitance gauges for each gas region (coloured) and Edwards pirani gauges attached to each section.

2.10 Low and high voltage supply

The low and high voltage electronics were supplied via a CEAN SY4527 universal power supply system crate, this has multiple slots for controlling both high and low voltage floating potentials. It is extremely important to note the floating potential aspect of the A series supply cards in this system, it uses a PID controller to regulate the supply voltage. This led to a ripple in the supply of ± 10 mV on each channel, this was a problem for the detectors with amplifiers of bandwidth sensitive to PID clock cycle (the time over which the PID computes and corrects potential). This resulted in significant noise issues during the October 2015 campaign and was entirely unforeseen, additional complications arose from the significant length of cable (+25 m) between the Data Acquisition systems (DAQ) and detector. However these problems were resolved for the second campaign by altering the PID clock, improved grounding and implementing low pass filters, as described in [Appendix A.3](#), on all the sensitive detectors high voltage supplies. Similar problems occurred with the low voltage power supply systems, which were also rectified during the CERN winter shutdown in addition to replacing the complex wiring with a break out box of several low voltage supply types.

Chapter 3

Detector development

We have seen the importance of the timing resolution, ΔT , in mass determination with a large influence on the mass resolution, ΔA , from Equation 2.3, prior experiments with STEFF gave $\Delta A \approx 4$ AMU [18]. The timing resolution is the uncertainty for time-of-flight for fission fragments and the majority of this uncertainty comes from the timing resolution of the stop detector.

This Chapter focused on the processes occurring within the stop detector with complementary simulations to give a better understanding of the stop detector and aid in the development of the replacement detector.

3.1 Previous improvements and stop detectors

The stop detector(s) installed on STEFF was a PPAC as shown in Figure 3.1, it had a Printed Circuit Board (PCB) as a segmented anode and an array of 20 μm tungsten gold plated wires with 2 mm pitch as the cathodes; the PCB is segmented to reduce the capacitance of the signal sensing plane. The wire plane and anode PCB were spaced away from each other with an additional PCB layer to give a

3.2 mm gap. The detector medium was isobutane at a pressure of 10 mBar and was continually refreshed through flow regulation.

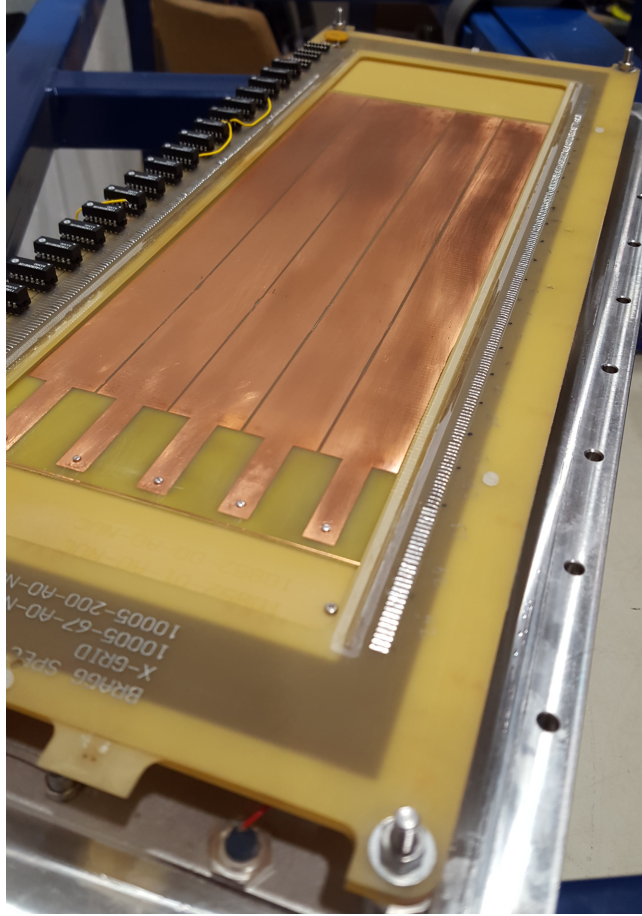


FIGURE 3.1: The original PPAC detector with anode planes on PCB and 20 μm diameter grounding wires with a 2 mm pitch spanning the shortest length of the detector. The area is 17×50 cm with a gap distance between wire plane and anode of 3.2 mm.

There have been previous attempts at improving the efficiency and timing resolution of the stop detector by A. Pollitt and E. Murray [6, 18]. However, they were limited by time constraints to make any further significant modifications but their research is none-the-less constructive for this work.

For the development process it was imperative to outline the major areas of improvement, they were:

- Efficiency, ε - The previous ILL run gave $\varepsilon \approx 0.5$ efficiency per stop detector per fission fragment [36]. Later measurements gave efficiency of $\varepsilon_B = 0.43$

and $\varepsilon_H = 0.21$ for Bragg and Hips arms respectively from the EAR-2 installation given in Section 8.3.2.

- Timing resolution, the signal timing resolution, σ_t (defined in Section 4.1), given by the prior development as $\sigma_t = 0.53$ ns [6]. Later measurements gave $\sigma_{t,PPAC} = 0.239 \pm 0.001$ ns and the timing coincidence timing resolution as $\sigma_{c,PPAC} = 0.819 \pm 0.082$ ns for the EAR-2 installation given in Section 8.3.2.

There was an attempt to produce a segmented version of a PPAC using fine stainless steel mesh and copper plates mesh by E.Murray shown in Figure 3.2, unfortunately due to mechanical instability and manufacturing tolerances the detector failed to operate as expected and consequently was not used [18].

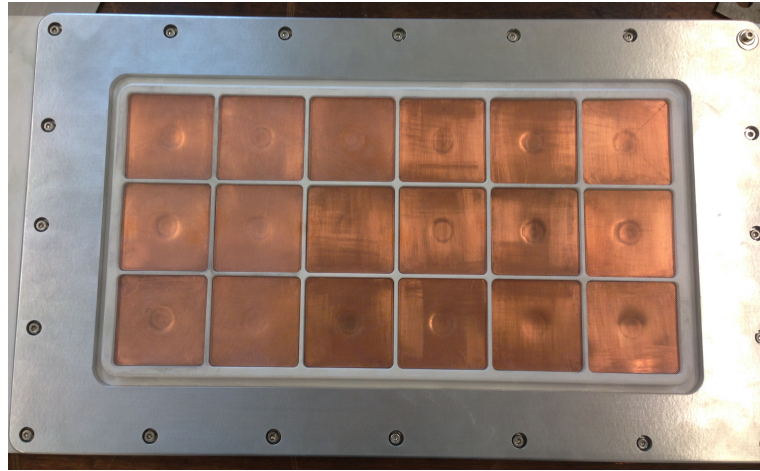


FIGURE 3.2: A prototype PPAC produced by E.Murray, a fine mesh covered the front face of the detector to act as cathode and the copper squares are the anodes.

These examples of past work (Figure 3.1 and Figure 3.2) and examples of other stop detectors, the FALSTAFF MWPC detectors [37] and the BigRIPS PPAC detector [38], served as a suitable starting point for the development. To further the progress made over the previous detectors one must first understand the process of how they function.

3.2 Theory of gas detector

The fundamentals of how charged particle interactions result in a detector signal must be well understood in order to exploit the processes; it is the process of energy conversion from the charged particle that makes it possible to be detected. The following section continues on the previously mentioned theory of gas detectors discussed in Section 2.5, expanding from the simple ion chamber into the more complex reactions that occur in the region of proportional gain and above shown in Figure 2.9.

3.2.1 Charged particle interactions with matter

Many macroscopic mechanisms can be exploited for the conversion of the energy spent in the medium into a detectable signal; such as scintillation and fluorescence, semiconductor electron hole pair breaking and chemical transformations to name a few. For charged particles the largest fraction of energy dissipated in matter is due to electromagnetic interactions between the Coulomb fields of the projectile and the electrons of the molecules in the medium, with exception to the particles coming to the end of their range where elastic interactions of the host nuclide become relevant. Except for these the energy losses are due to multiple inelastic processes of excitation and ionisation, the probability of which is a function of the energy transfers involved.

For sub eV energy electrons in matter the electrons predominately lose energy through elastic means. In the region of eV to tens of eV, the energy loss is through molecular and atomic excitations and is rather complex due to the number of possible modes of excitation each with their own energy dependent cross-sections, these are known as ‘distant’ collisions since they involve a large impact parameter. Figure 3.3 shows the complexities of atomic to molecular excitation with

a significant cross-section in the lower energies for isobutane to that of xenon. Molecules can also undergo radiationless rearrangements of bonds, disassociate or get excited or even ionized, with the emission of photons or the appearance of a free electron-ion pair [30, 39, 40].

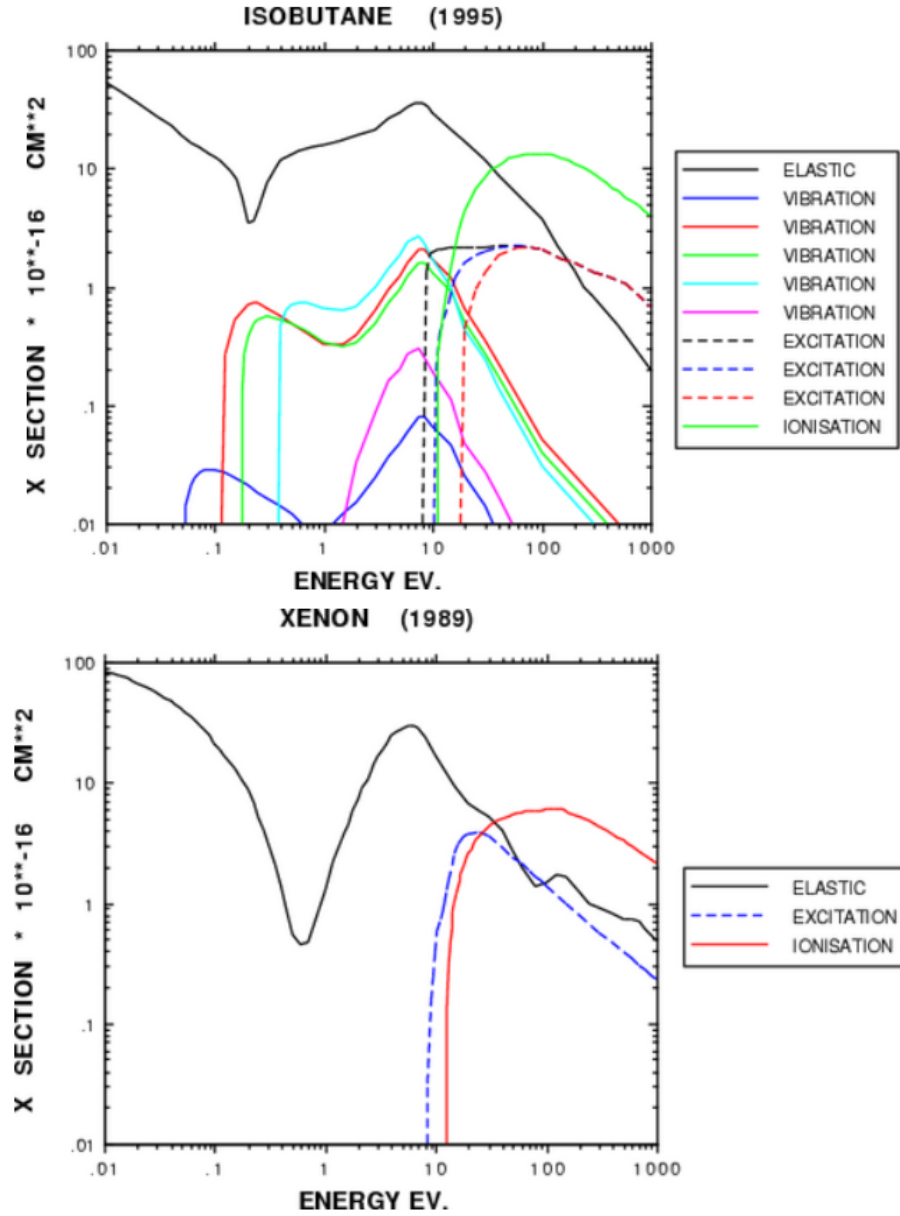


FIGURE 3.3: Cross-sections of isotropic xenon (bottom) and isobutane (top) computed with the HEED software as part of the Garfield++ toolkit (see Section 3.3.2). It is apparent when comparing the two gasses that the molecular isobutane has considerably more modes of excitation in the lower regions of electron energy interaction than that of the monatomic xenon.

For increasing energies of interaction the probability begins to trail off exponentially with energy without any particular structure where the ionisation dominates up until the maximum allowed transfers, which is dependent on the mass of the projectile and the energy. These are referred to as ‘close’ collisions with increasingly small impact parameters, they refer to the creation of excited species or electron-ion pair production.

Despite the low probability of large energy transfer yield (a delta electron) it plays a large role in the gaseous detector by creating further interaction at distant locations resulting in additional energy losses.

3.2.2 Energy deposition in gas

The majority of interactions from the primary electron within the media will be ionisations due to close collisions. The detector medium is a narrow volume of gas and the number of interactions resulting in electron-ion pairs is an important quantity in detector performance. No simple expression exists for the number of primary ionising encounters, one has to rely on experimentally determined values or dedicated simulations.

The average number of electron ionising collisions per unit length of medium and the resulting energy loss per unit length can be estimated from Table 2.1 by scaling the pressure to the desired gas value. This gives the number of secondary electrons as $n_0 = 2.2 \text{ cm}^{-1}$ with energy deposition in the detector of 56.7 eV/cm for the 10 mBar operating pressure with isobutane. However the table values refer to the minimum ionising particle, where the electron energy is typically MeV. For 10 keV electrons the cross-section is highly energy dependent making the above estimation unreliable. Monte-Carlo simulations with energy dependent cross-sections provided a better solution to the energy deposition, the results of which are in Section 3.3.6.

3.2.3 Reactions

If we consider a body of gas in the ‘real world’ environment it will contain free ions and free electrons through cosmic radiation ionisation, if we apply an electric potential over the body of gas the ions and electrons will be acted upon by Coulomb interaction. As the ions and electrons traverse the medium they will collide with neutral atoms/molecules, M ; the collisions can be classified into three categories:

- **Elastic** $e^- + M \rightarrow e^- + M$,
- **Excitation** $e^- + M \rightarrow e^- M^*$ if $E_{kin} \geq E_{M^*}$,
- **Ionisation** $e^- + M \rightarrow 2e^- + M^+$ if $E_{kin} \geq E_{ion}$.

For ionisation the kinetic energy, E_{kin} , of the incoming electron must be greater than the ionisation potential, E_{ion} , typically 10–100 eV [41–43]. Due to the energy of the incident electron going into excitation, M^* , or ionisation, these reactions are considered inelastic. For the purpose of maximising signals through charge production it is important to reduce the possibility of excitation reactions to a minimum. This reaction will reduce the possibility of ionisation by retarding the electron energy gain in a potential. The elastic reactions can be neglected in charge production [30].

3.2.4 Gas transport and multiplication

With sufficiently high electric fields in the gas we encounter avalanche multiplication and for the simple case of a homogenous field (such as a parallel plate configuration) this can be classically modeled. The primary charge produced by the primary particle interactions will exponentially increase where the total number of charges created depends on the electric field strength, E , and the number

of primary ionisations, n_0 . If we assume the simple case of a localised charge of n_0 electrons produced simultaneously near the planar cathode, the electrons will start to drift (under the electrostatic potential) away from the cathode towards the anode. As the electrons drift they will be accelerated under the influence of the electrostatic potential, the electrons will then undergo collisions with neutral gas molecules. If their kinetic energy is sufficient, inelastic collisions will result in ionisation of the neutral gas molecule. If we consider an electron traversing the gas, it will undergo multiple collisions resulting in multiple electrons produced over the path length of the original. Each of the electrons produced from inelastic collision will also undergo the same process; this process of electron multiplication is often given the name electron avalanche.

The mean free path of multiplication is given by α^{-1} , where α is the first Townsend coefficient given in cm^{-1} , it is a constant for fixed values of the field [44]. Values of the Townsend coefficient have been calculated through the use of the MAGBOLTZ program and are displayed in Figure 3.4 to provide insight into the charge production within the gas. The number of electrons produced by the multiplication process is written as:

$$dn_0 = n\alpha ds, \quad (3.1)$$

integrated over the homogeneous field it simply becomes dependent on the path length s ,

$$n = n_0 e^{\alpha s}, \quad (3.2)$$

and the ratio between initial charge n_0 and the total charge n is the gain of the detector, $M = n/n_0$.

The first Townsend coefficient is related to the energy of the electron from the applied field, E , and the number of collisions from the (density) pressure, p , of the

medium. It is expressed as:

$$\alpha(p, E) = pf(E/p), \quad (3.3)$$

where $f(E/p)$ is a gas dependent function, the most common mathematical form of Townsend coefficient, α , for the homogenous field is given by:

$$\alpha(p, E) = Ape^{-\frac{Bp}{E}}, \quad (3.4)$$

where A and B are gas constants empirically determined, see Table 3.1.

Source	Range, S [Vm ⁻¹ kPa ⁻¹] $\times 10^3$	A [Vm ⁻¹ kPa ⁻¹] $\times 10^3$	B [m ⁻¹ kPa ⁻¹] $\times 10^3$
Sharma,Sauli [45]	<32	134.0	273.6
Leblanc [46]	<282	17.1	272.0
Heylen [47]	<509	20.52	306.3
Shakkeeb [48]	620-2200	23.28	262.2

TABLE 3.1: A and B values for isobutane at various ranges of S from a variety of sources.

3.2.5 Charge inductance on the conductors

A positive charge between two conducting surfaces will produce no induced current in either conductor until motion occurs, as it moves (due to electrical potential) there will be a negative charge distribution induced on the conducting surface dependent on the relative direction of charge velocity. The charge distribution and hence induced signal shape and amplitude will depend on the geometry. Electrons and ions created within the gaseous detector by ionisation drift toward the anode and cathode respectively. For the case of the ion chamber (no multiplication, and neglecting electron ion recombination) the collection of all the charges at their respective electrodes results in a signal dependent on the geometry, the field strength and the mobility of the respective charges.

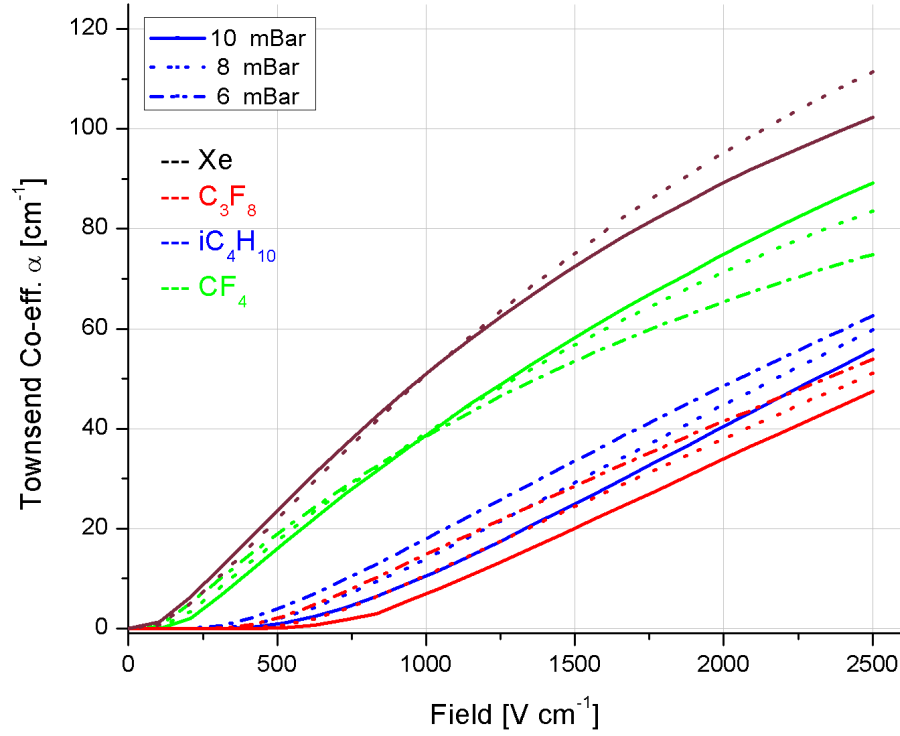


FIGURE 3.4: Calculated values of the Townsend coefficient, α , for a selection of gases with applied field to be tested within the prototype detectors at varied pressures.

The motion of charges toward an electrode increases the surface charge, the cathode toward more negative values and the anode toward more positive values. The signals detected on a load are opposite in polarity.

Methods for computing the charge induction on conductors by moving charges were developed by W.Shockley [49] and S.Ramo [50] based on the concept that current induced on the electrode is due to the instantaneous change of electrostatic flux lines which end at the electrodes, not the amount of charge received by the electrode. The instantaneous induced current, i , on a given electrode due to the motion of charges is given by,

$$i = E_v q v, \quad (3.5)$$

where q is the charge, v is the instantaneous velocity and E_v is the component

of the electric field without charge presence. Calculations become increasingly complex as the number of charges increase and the electrode geometry is not simple, fortunately extensive work has been carried out in the way of computing such induced signals and is included in the Garfield++ toolkit [51, 52]. There are extensive descriptions of analytical solutions for induced currents in a PPAC using Shockley-Ramo theory and charge multiplication available [30].

3.2.6 Breakdown, discharges and the Raether limit

MWPC and PPAC detectors run at high fields close to where they will breakdown or spontaneously spark, this can lead to irreversible damage to the detectors if not properly dealt with. Paschen curves relate the breakdown voltage, V_B , of a gas filled chamber with a uniform field between two metal electrodes with the gap distance, d , and the pressure, p . Breakdown occurs when an avalanche triggered by a single electron produces on average at least one fully fledged secondary avalanche. Secondary avalanches can be created in a variety of ways, perhaps the simplest of which is electron emission from the cathode hit by avalanche ions. The probability for secondary emission electron avalanche is given by the second Townsend coefficient, γ . The breakdown condition can be expressed via

$$\gamma(G - 1) > 1, \quad (3.6)$$

where G is the gain. We saw earlier the gain, G , is

$$G = M = \frac{n}{n_0}, \quad (3.7)$$

therefore if we consider the case of a single electron we substitute Equation 3.2 setting $n_0 = 1$ into Equation 3.7,

$$\gamma(e^{\alpha s} - 1) > 1. \quad (3.8)$$

It is then possible to estimate the Paschen curves for the pressures we expect to operate at and that of other gases for possible alternate gas mixtures. The Townsend coefficient formula provides values for α/p first ionisation coefficients for gas with measured values for breakdown given by rearrangement of Equation 3.4 to give

$$\frac{\alpha}{p} = Ae^{-Bp/E}, \quad (3.9)$$

where the values for A and B are from Table 3.1.

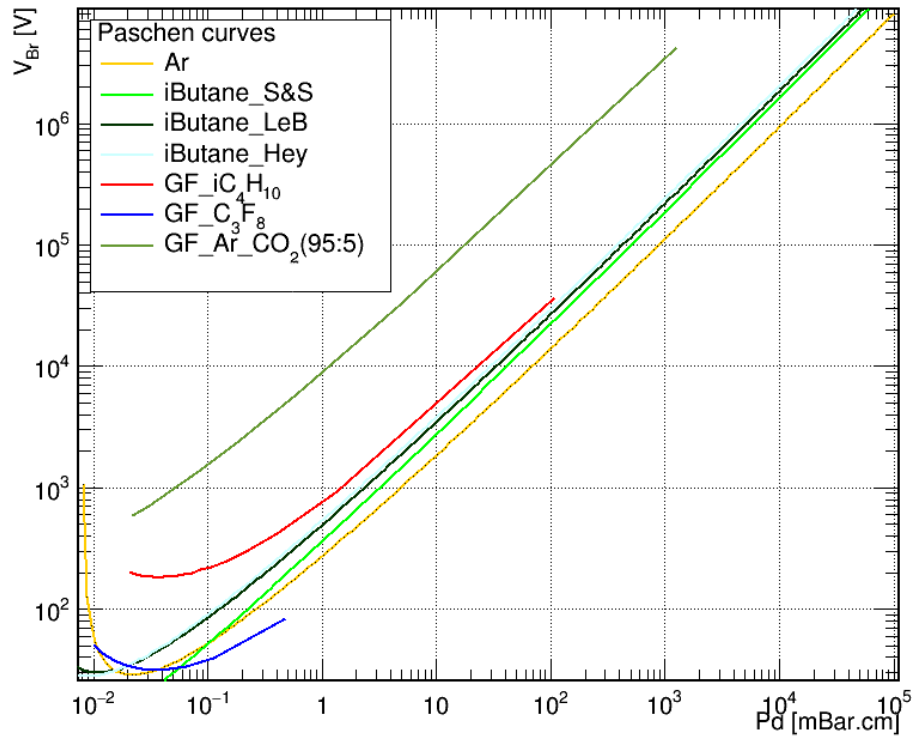


FIGURE 3.5: Paschen curves for various gases chosen for possible testing in the development of the stop detector. The measured data from Table 3.1 and the computed values from MAGBOLTZ represented by ‘GF’. From the graph it is clear the Ar and Ar:CO₂ mixtures will breakdown at considerable lower voltages than the the current isobutane, this makes them unfavourable.

In parallel calculations of α were performed with MAGBOLTZ to get a comparative for the measured to simulated breakdown pressure gap, pd . The values for the simulated pd are incorrect by several hundreds of volts, this can be explained by the lack of ion secondary effects information, which is dependent on the surface of the conductors. We consider the same gas calculations with MAGBOLTZ and alter the secondary processes coefficient γ , Figure 3.6 shows the breakdown in the low pd regions strong dependence on the value of γ .

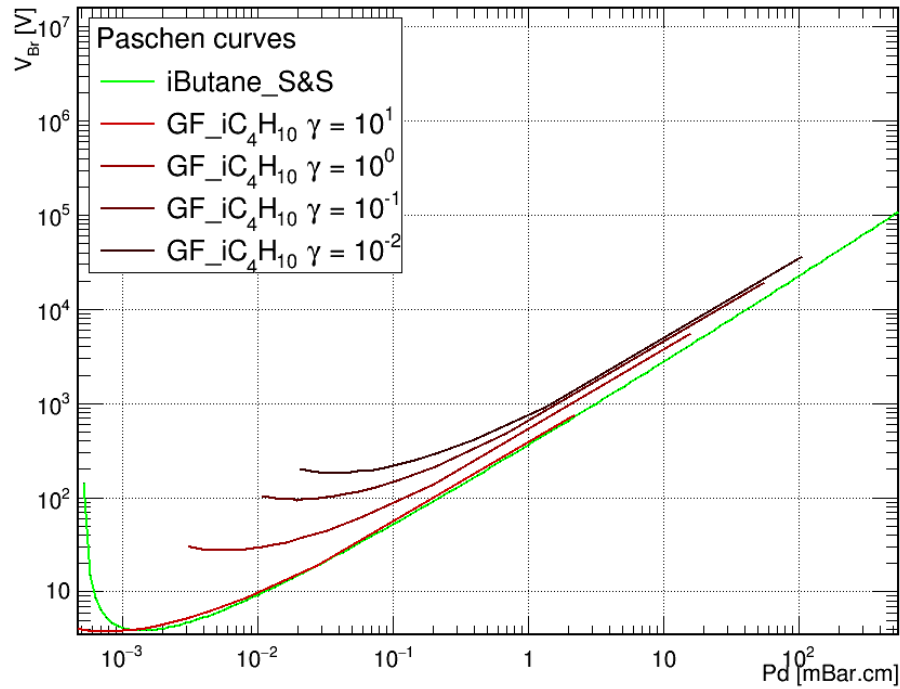


FIGURE 3.6: The breakdown voltages of measured isobutane vs the calculated values with varying γ . As the secondary emission process γ is increased it reduces the breakdown voltages to the at of the literature values, highlighting the importance of the secondary process in breakdown calculations.

This information therefore can only be utilised as a guide to geometry in the construction of any prototypes as the secondary effects clearly alter the expected breakdown voltages in the gas mixtures proposed.

From the Paschen curves one could extrapolate the conditions where a very large field can be applied at high values of pd to produce an extraordinary multiplication factor, M ; unfortunately this is not the case. There is a limit to the gain possible, this limit is where a large avalanche turns into a streamer discharge. The primary

avalanche photons cause spreading and secondary avalanches over a larger region of the detector, the space charge distortions produced by the large avalanche distort the field strongly increasing the field in front and behind the multiplying charge. This enhances the formation of secondary avalanches and further aids the transition from avalanche to streamer to spark. An excellent description of this process can be found in the literature [30].

A phenomenological limit to the proportional avalanche multiplication before the transition is given by the empirical condition and is known as ‘Raether’s limit’,

$$\alpha S < 20, \quad (3.10)$$

where α is the Townsend coefficient in cm^{-1} and S is the gap length cm; or an avalanche size of $\sim 10^8$ electron-ion pairs. However the statistical distribution of energy of electrons and the gain generally does not allow operation of gas counters at average gains above 10^6 [30, 38, 43, 53].

3.2.7 Electron drift velocity

The electron drift velocity has been studied greatly in the past for the development of high precision drift chambers, typically the drift velocity is given in units of $\text{cm } \mu\text{s}^{-1}$. The electron drift velocity has dependence on the pressure, the gaseous medium composition and the applied field. For the case of fast timing applications the drift velocity is considered to be the main source of timing discrepancies, in a MWPC detector the electron must drift to the region of multiplication. PPAC detectors have a homogeneous field providing instantaneous multiplication removing the major source of timing discrepancy. The electron drift velocity determines the signal production, Equation 3.5 has shown the induced signal is proportional to the velocity of the charges.

An electron produced by ionisation in a gas will quickly reach thermal equilibrium with the surrounding medium without the presence of electric field where it will undergo reattachment or be neutralized by an ion (typically it takes 200 ns for this to occur with thermalized electrons) [30].

When an electric field, E , is present the electron swarm moves in the direction opposite to the field vector; a simple theory of mobility was formulated by Townsend to give the electron drift, v_e , as:

$$v_e = \frac{W^-}{E}. \quad (3.11)$$

where W^{-1} is the mobility of the electron in the gas dependent on the pressure and temperature. However, the relation of electron drift with mobility does not hold true for high electrical field. This can be clearly seen in experimental results shown in Figure 3.7.

In the MWPC and PPAC detectors we encounter high electric fields where the semi empirical calculations will not suffice and the literature available for pure isobutane is limited [54]. Fortunately, the gas transport program MAGBOLTZ is capable of calculating such values with high precision [55], simulations for the transport properties of the gases most applicable for the stop detector were performed, see Figure 3.8.

The simulations provide the electron drift information and information on the electrons drifting perpendicular to the electric field, where multiple electron-gas collisions will aid in the diffusion and spreading of the original localised electron swarm. The extent of the diffusion depends on the gas, but also very strongly on the field. The diffusion, σ_x , of the electron swarm can be shown with its

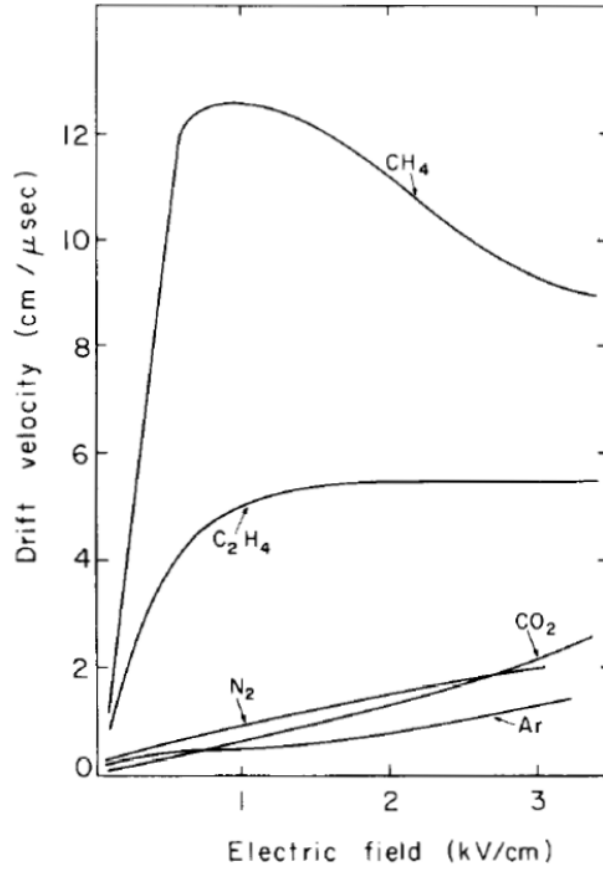


FIGURE 3.7: Experimentally determined electron drift velocities over a wide range of electric field [30].

dependance on the reduced electric field E/p as,

$$\sigma_x = \sqrt{\frac{2k_b T}{e}} \sqrt{\frac{p}{E}} \sqrt{\frac{x}{p}}, \quad (3.12)$$

where k_b is the Boltzman constant, T is the absolute temperature and x is the path length over which the charge drifts [30].

3.2.8 Space charge effects

The process of charge multiplication around the anode wire during the avalanche process gives rise to a spacial charge distribution, a positive ion ‘sheath’ will form reducing the electrical field locally. The field will only be restored when the ions

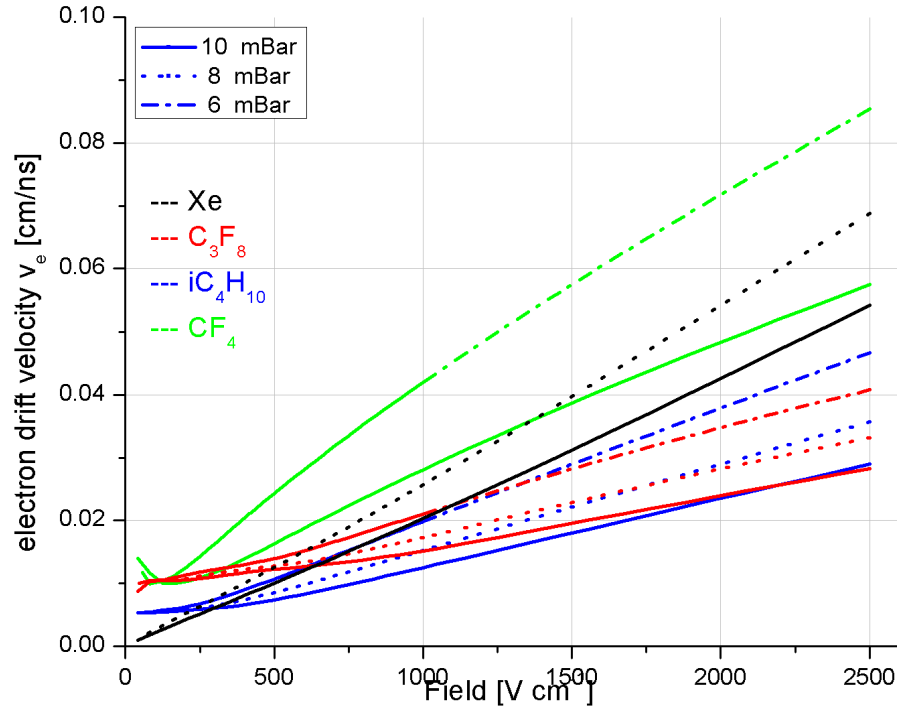


FIGURE 3.8: Computed electron drift velocities for candidate gases for the stop detectors over a wide range of electric field potentials. The increased electron drift velocities will aid in charge collection times and from the graph it is clear there is a large pressure and composition dependence.

have sufficiently dispersed, this can be up to several hundred microseconds later for conventional atmospheric pressure multiplication gas detectors; hence affecting the multiplication factor and preventing any further detection locally [30]. When a typical detector is operated in the limited proportional region (such as the stop detectors) the extension of the avalanche along the wire is typically 0.1 to 0.5 mm and the modified field is only confined to a small region.

For high incidence fluxes the detector gain is reduced, Figure 3.9 shows this effect on a typical MWPC detector, this can be problematic when considering the stop detectors coupling to an spontaneously emitting electron mirror with considerable electron flux.

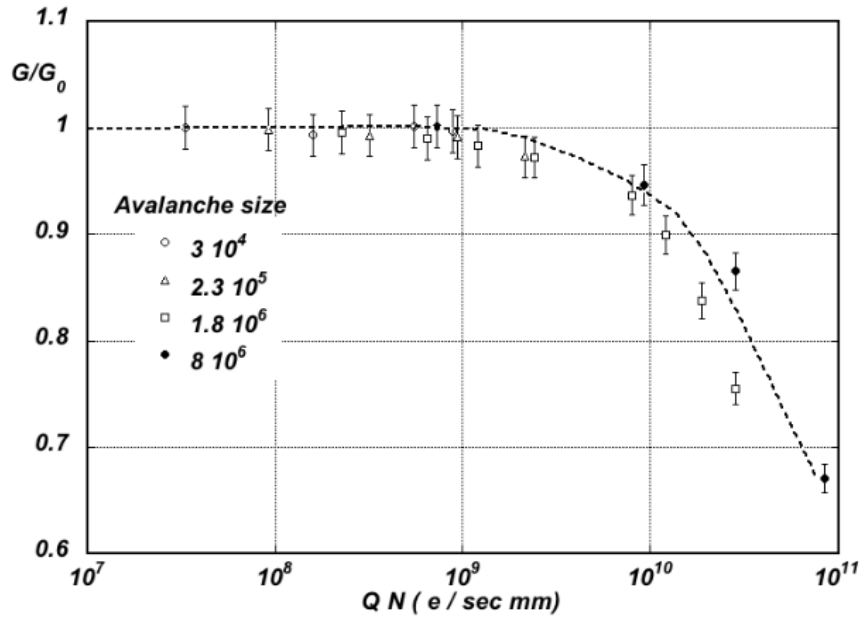


FIGURE 3.9: The gain of a typical MWPC detector plotted versus increasing flux rate [56]. The charge produced within the detector will temporarily impede charge multiplication, as the flux/rate is increased this effect becomes severely detrimental to detector performance.

This is an inherent issue with all wire based gaseous detectors and there is very little that can be done to prevent the gain losses.

3.2.9 Ion drift velocity

The process of electron multiplication around an anode wire in a proportional counter or drift chamber gives rise to the production of ions. These ions play a small role in producing the electrical pulse collected on the sensing wire, the ion average velocity is relatively slow, however, they are important for the cathode-ion electron emission process, γ processes. Ion drift is given the notation W^+ and is linearly proportional to the electric field, E . This is applicable for even very high values of electrical field (5 kV cm^{-1}), it is therefore possible to define a unit, μ_i , known as ion mobility as

$$\mu_i = \frac{W^+}{E}. \quad (3.13)$$

The value of mobility is specific to each ion moving in a given gas, values of which are given in Table 3.2, and it depends on the pressure, P , and temperature, T , through the expression:

$$\mu(P, T) = \frac{P_0}{P} \frac{T}{T_0} \mu(P_0, T_0). \quad (3.14)$$

A constant for mobility is the consequence of the average energy of the ions is almost unmodified by the applied field; this as we have seen is certainly not the case for electrons.

Gas	Ion	μ [cm ² V ⁻¹ s ⁻¹]
Ar	Self	1.7 [57]
CH ₄	Self	2.22 [58]
C ₂ H ₆	Self	1.23 [58]
C ₃ H ₈	Self	0.793 [58]
iC ₄ H ₁₀	Self	0.612 [58]
iC ₄ H ₁₀	(OCH ₃) ₂ CH ₂	0.55 [59]
CF ₄	Self	0.7 [58]

TABLE 3.2: Mobility of ions from various sources.

It is common practice to use isobutane as the quench gas, the ATLAS detectors trigger chamber is CF₄-isobutane (80:20) [29]. However it was found that using isobutane leads to hydrocarbon ions and cations drifting towards the electrodes polymerizing and forming a thin insulating layer. This layer has been speculated to be the cause of discharges, known as the ‘Malter effect’ which considerably reduces the lifespan of the detectors [60].

3.3 Simulation of PPAC

The prior section has shown how the primary particle interactions form detectable signals through the multiplication process. It is possible for the most simple cases to use the semi-empirical solutions for the parallel plate configuration (PPAC).

However the electric fields within the detectors used on STEFF do not permit such simple calculations and require a more sophisticated approach.

There still remained the need for better understanding of energy deposition within the detector and the energy of the primary electrons remained an unknown following their transmission through the gas window. The following section investigates the dominant effects on the PPAC detector through finite element analyses and Monte-Carlo simulation techniques.

3.3.1 Geant4 gas window simulation

The efficiency of the detectors given in Section 2.5.1 was low. This was originally speculated to be due to the electron transition from the SEE foil to the active gas region through the $0.9\ \mu\text{m}$ Al-Mylar window. There was also some concern that the ‘dead zone’ (a region of gas between the entrance window and detector where no detection was possible, shown in Figure 3.10) was retarding and attenuating electrons before the PPAC. Both concerns were alleviated through the use of the Geant4 simulation toolkit, a powerful physics simulation toolkit for the passage of particle through matter [61]. This gave the probability of an electron exiting the mirror with kinetic energy of 12 keV and traversing the gas window as $\varepsilon = 0.83$ with an energy loss of $2290 \pm 20\ \text{eV}$, Figure 3.11 shows a visual interpretation of the simulation.

A further investigation was attempted to characterise the energy deposition within the gas of the detector. This would provide a needed insight into the number of primary ionisations, n_0 . However the Geant4 toolkit is incapable of tracking particles of energies less than $250\ \text{eV}$, this is the limit of the low energy *Livermore* physics list used for the simulations and could not provide n_0 [62].

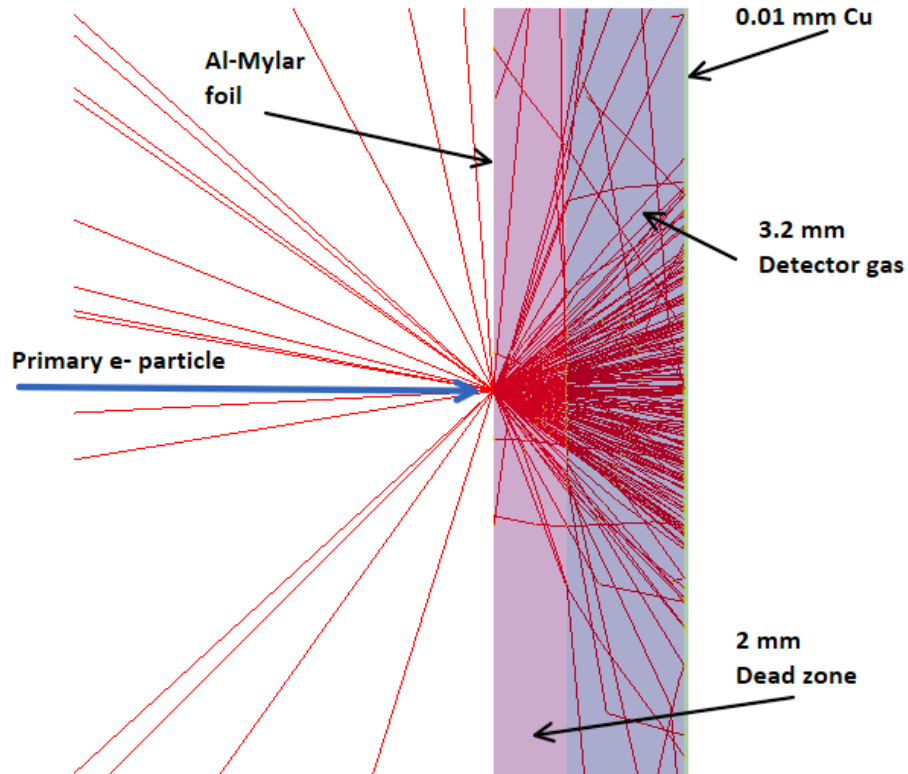


FIGURE 3.10: A visual interpretation of the Geant4 particle tracking of 100 primary 18 keV electrons through the foil into the detector. The red lines represent electrons and the gaseous medium was 10 mBar of isobutane. The ‘dead zone’ is the region between the detector and the Mylar window where it was not possible to implement any electron detection means, any ionising events would go undetected in this region.

3.3.2 Garfield++ and MAGBOLTZ

To track electrons within the gas and provide the details on the primary interactions within the detector Garfield++ (a CERN software package freely available [63]) was used. Garfield++ is a toolkit for detailed simulations of particle detectors with gas or semi-conductors as the sensitive media [64, 65]. Garfield++ has several add-on programs to calculate gaseous properties, such as electron transport inside the gaseous medium, where detailed information about the gas behaviour are calculated with use of the MAGBOLTZ (V10.14) software [55]. MAGBOLTZ solves the Boltzmann transport equations via numerical integration for gas mixtures under the influence of electric and magnetic fields for arbitrary compositions and pressures [66].

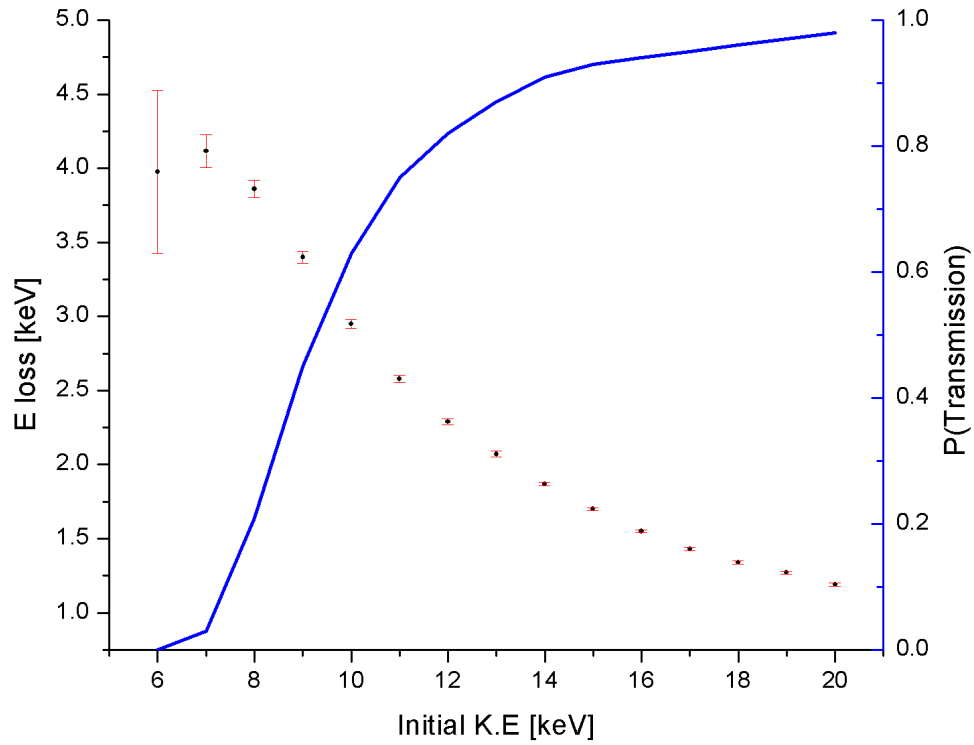


FIGURE 3.11: The statistical distribution of the probability of the electron passing the Al-Mylar window, $P(Transmission)$, represented by the solid line. The energy losses in the foil as a function of the initial electron kinetic energy, E , represented by the data points. The values were calculated with the Geant4 toolkit simulating 10^6 electrons impacting normal to the foil.

Garfield++ is capable of using externally produced 3D electrostatic and magnetic field maps or producing its own 2D field maps for simple geometries such as a drift tube. However for consistency with complex future designs the PPAC field maps were modeled using the Ansys mechanical APDL (V16.0) design suite, this produced a FEA (Finite Element Analysis) field map.

3.3.3 The finite element method

The finite element method is a technique for solving partial differential equations that are widely used in engineering to perform stress-strain analysis of mechanical

structures, to compute heat flow, magnetic flux, etc [67]. Here we applied the technique to compute an approximation for the electrostatic potential and electrostatic field, to construct a FEA map for the use with Garfield++. The calculations of the fields using the Ansys finite element methods with option SOLID123 broadly consisted of:

- Breaking the domain in which the field is to be computed into a number of smaller elements.
- A potential value is computed for each of the nodes (a node being the vertices of the element) of each tetrahedral volume (element) to satisfy the Poisson equation. The result being that one node can be connected to many neighbouring elements and that node will share the same value with boundary conditions applied.
- The potential at any point inside an element is interpolated using shape functions (see the Ansys Manual [68] for more information on shape functions).
- The potential obtained generally does not satisfy the Poisson equations, however the Ansys solver resolves this problem by subdividing those elements with large discrepancies. This is repeated until the discrepancy is negligible.

The modeled ‘cell’ corresponds to the geometry meshed and is made to be as small as possible while still maintaining the physical properties required for the simulation and here was symmetrically replicated in the two planer dimensions infinitely. Figure 3.12 shows the small $2 \times 2 \times 3.2$ mm (x, z and y respectively) segment of the much larger detector volume of the PPAC detector.

This is a simple overview of how the finite element mesh is generated, after which the mesh (a node list with potentials) is loaded into Garfield++ where the field

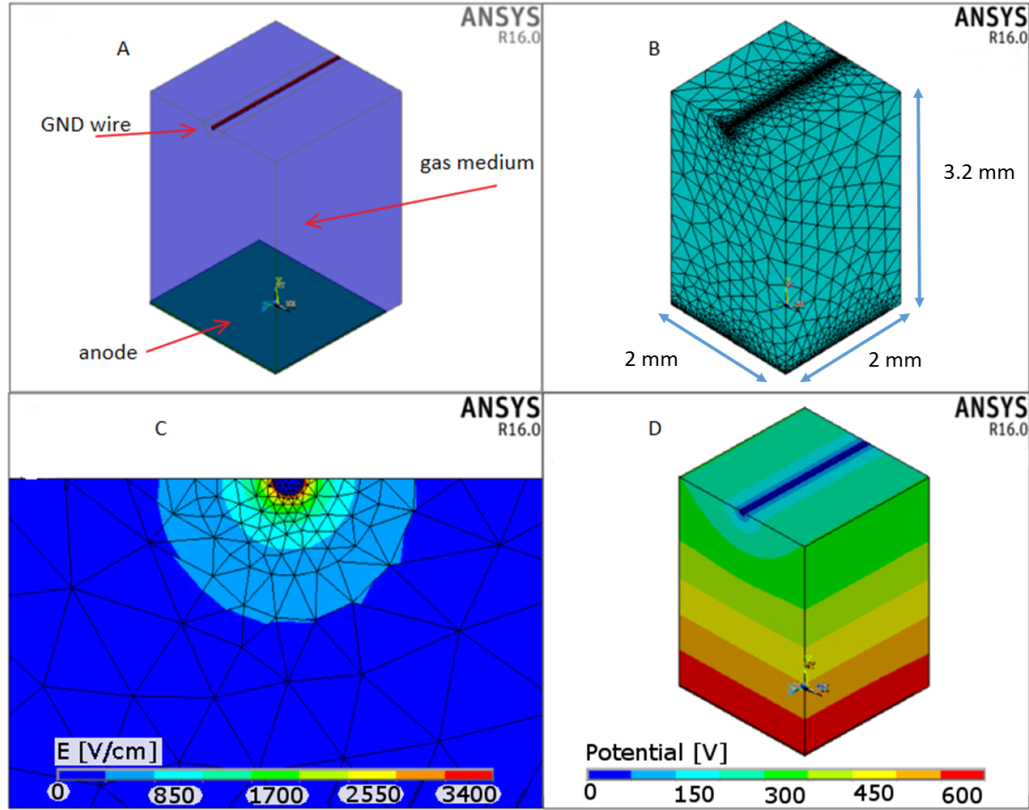


FIGURE 3.12: (A) The ‘cell’ structure showing the chosen components to include in the FEA. (B) The meshed structures before the processing of element potentials, the raw mesh. (C) A close-up of the E-field potential as calculated from Ansys, demonstrating the complexities of the mesh close to the conductor surface. (D) The voltage potentials of the whole ‘cell’ of the PPAC.

map is given gas properties. Figure 3.12 shows the resultant mesh complete with field potentials for the PPAC show regions of high electric field potentials around the wire without significant propagation into the remaining detector volume.

3.3.4 Calculations of PPAC

It was possible to simulate the stop detector in Garfield++ as each electron is individually tracked as it drifts, the tracking of every electron allows precise calculations for induced signals and production of new charges. However, tracking of every electron in the microscopic avalanches over the gains expected in the detector produced a quantity of charge not practically manageable. In addition we have

the scattering caused by the foil distributing charge over multiple regions of the detector further increasing the charge quantity. Given the time and computation power one could manage the number of charges, but the result would be non-physical. Garfield++ does not have the capability to include field perturbations caused by the charge, close to the anode surface this becomes most important as charge multiplication is at its greatest.

For these reasons full simulations of the PPAC detector were avoided, instead calculated gas values plotted against the field to produce a graph of the electron multiplication and drift along a one-dimensional geometry were used as a guide.

Figure 3.13 shows where the Townsend coefficient of charge multiplication, α , is non zero, hence charges are produced close to the wires (the PPAC has a negative polarity applied to the PCB electrode making the grounding wire behave as an anode). The simulation suggests the charge produced by the primary particle must drift some distance before the multiplication process begins and subsequent detection occurs.

3.3.5 Simulated electron drift times

Although the full avalanche was not simulated in Garfield++ it was possible to use the field maps and the gas parameters to simulate the drift times for a single electron to traverse from various locations within the detector to the wire surface. This method provided information on the delay between primary ionisation and signal over a 2D ‘slice’ of the detector. However, along the electron drift path there will be instances of ionisation removed for the simulation that would have produce a signal sooner than the initial electron. The resultant drift map shown in Figure 3.14 for electrons created in various locations within the PPAC detector at 10 mBar pressure operating at nominal voltage gave indication for signal delay.

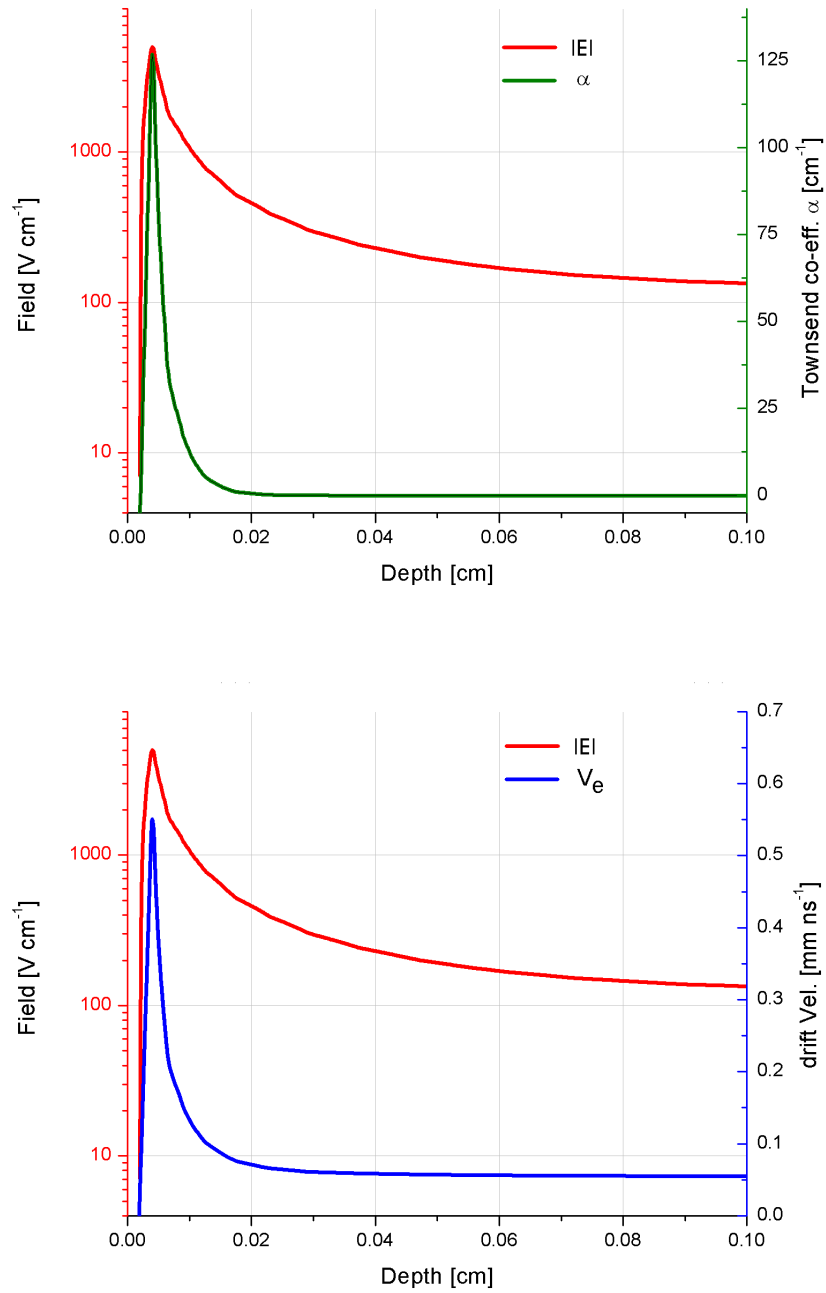


FIGURE 3.13: (Top) Calculated Townsend coefficient, α , and magnitude of electric field, $|E|$, within the detector. (Bottom) Calculated electron drift velocity, v_e , and magnitude of electric field, $|E|$, within the detector. the calculations are for the PPAC detector where the depth is the distance from the ground wire centre through the active medium.

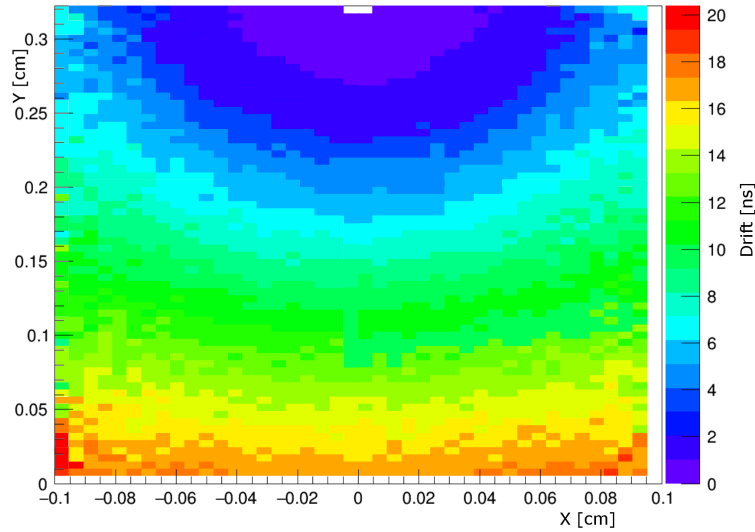


FIGURE 3.14: A 2D map of electron drift times simulated with Garfield++ toolkit for the PPAC stop detector installed on STEFF under operational conditions, where the y-axis is the depth into the detector with the wire located at the centre of the x-axis.

3.3.6 Simulated energy deposition

The calculation of the number of electrons and consequent energy deposition cannot be resolved without the use of Monte-Carlo simulations, as seen previously. The Garfield++ toolkit was capable of calculating the interaction with the primary electrons within the gas mixture using HEED, a modified version of the PAI model specifically for the gas detector environment [69].

The primary electron energy before traversing the Al-Mylar gas window is 12 keV and post window energies have been simulated in Section 3.3.1 to be ~ 10 keV with a considerable distribution extending below this. The simulations did not take this energy or angular distribution into account, the mean transferred energy was used for simplicity and the momentum vector of the electron was perpendicular to the detector face, 10^5 events were simulated per elected pressure.

From Figure 3.15 and Figure 3.16 a Landau fit was applied to acquire the MPV (Most Probable Value) for the number of electrons produced and energy deposition

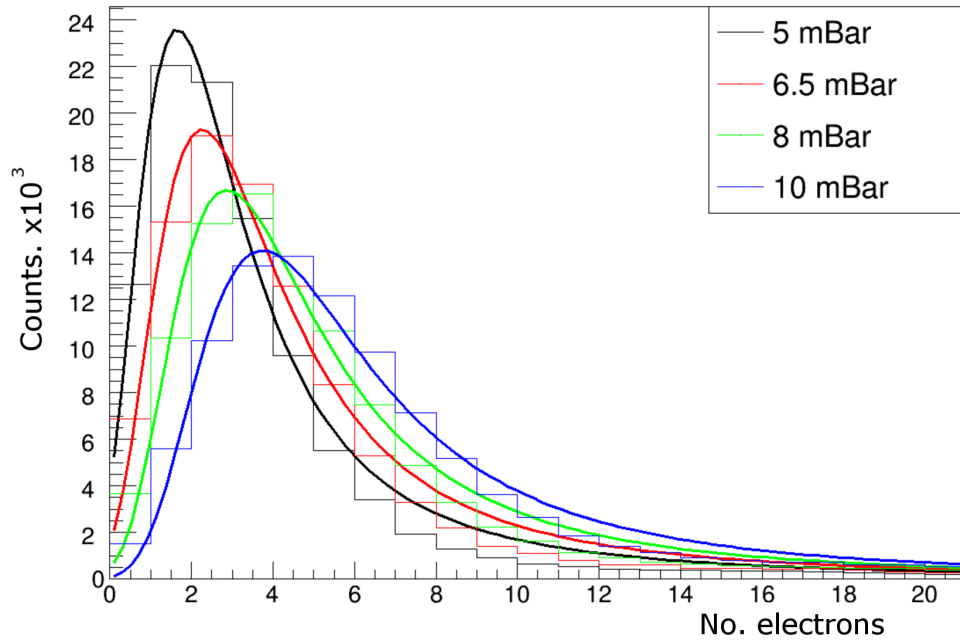


FIGURE 3.15: Mean number of ionisation electrons, n_e , produced inside the 3.2 mm detector active gas region with pressure simulated for 10^5 incident electrons.

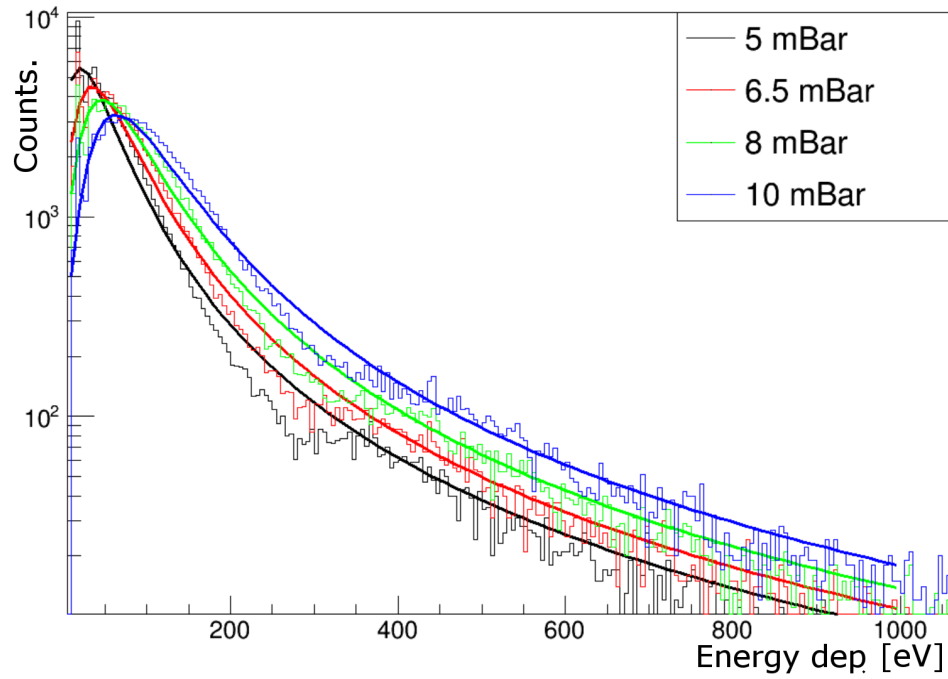


FIGURE 3.16: Mean energy deposition inside the 3.2 mm detector active gas region with pressure simulated for 10^5 incident electrons. The large tail indicates the production of delta electrons depositing additional energy through the detector region.

Pressure [mBar]	n_e electron	Energy Dep. [eV] electron	n_e $\alpha(5.49 \text{ MeV})$	Energy Dep. [eV] $\alpha(5.49 \text{ MeV})$
5.0	1.84 ± 0.01	24.1 ± 0.3	93 ± 15	2400 ± 573
6.5	2.48 ± 0.01	39.3 ± 0.2	115 ± 11	2963 ± 548
8.0	3.14 ± 0.01	51.4 ± 0.2	118 ± 6	3030 ± 170
10.0	4.05 ± 0.01	69.5 ± 0.2	145 ± 1	3720 ± 11

TABLE 3.3: Simulated values for the energy deposition and number of electrons, n_e , for the 3.2 mm PPAC with the Garfield++ toolkit for electron primary particle and SRIM for the 5.49 MeV α . See text for additional details.

within the 3.2 mm PPAC for varied pressures, see Table 3.3.

Chapter 4

Detector prototyping

The previous Chapter gave an insight into the processes occurring inside the PPAC detector. The Garfield++ simulations and semi-empirical approach highlight areas where improvements could be made, but it had its limitations. There still remained questions regarding the detectors stability (electrostatically and mechanically), maximum operational field under an irradiated environment, timing resolution and efficiency. The following Chapter shows some of the experimental prototypes and testing undergone at the University of Manchester to determine the stop detector replacement design.

4.1 Timing resolution

The timing resolution, ΔT , of a detector is the measure of its accuracy to determine the time of the detected events occurrence. Two intrinsic effects lead to a degradation of the detector time resolution: the time fluctuations due to the noise of the output signal and the variation of the geometrical distribution of the deposited energy inside the sensitive volume.

The first contributing effect to the timing resolution, depends mainly on the preamplifier noise, N , whose contribution to the time resolution is given by the signal properties given by:

$$\sigma_t = \frac{\sigma_V}{\left(\frac{dV}{dt}\right)} \cong \frac{t_{RT}}{\frac{S}{N}} = \frac{N}{S} t_{RT}, \quad (4.1)$$

where σ_V is the RMS voltage noise of the amplifier, $\frac{dV}{dt}$ the pulse slope, t_{RT} the rise-time (the time the signal takes to reach from 10% to 90% of full amplitude) and $\frac{N}{S}$ is the noise to signal ratio [70].

The second effect is the charge collection. Variations in the time-dependence of the signal can occur where individual clusters of electrons induce current on the conductors at different spacial positions and at different times depending on the energy deposition within the detector. The drift of the charge inside the sensitive volume to a region where multiplication and sensing occurs is speculated to be the primary contributing source.

The first of the two can be simply measured using a single detectors output, this is referred to in this work as the signal timing resolution, σ_t . The second effect can only be determined via the coincidence technique with another fast detector and referred to as coincidence timing resolution, σ_c . Given the coincidence between two identical detectors the measurement of both the preamplifier noise and the spacial energy deposition inside the detector can be quantified to give the detectors timing resolution, ΔT .

4.2 Wire mesh PPAC

Taking into consideration other PPAC examples [38, 71] and the prior stop detector designs, Figure 3.1 and Figure 3.2, it was clear to see there were some interesting differences between the two; in particular the choice for the grounding plane. One has 20 μm gold plated tungsten wires (see manufactures specifics regarding errors

with the wires used throughout this work [72]) spaced with 2 ± 0.1 mm pitch, the original stop detector as shown in Figure 3.1. The other has a fine wire mesh made from 24.5 ± 0.8 μm diameter stainless steel wires woven in a grid with 462 ± 4 μm between each wire, giving transition of $P_m(T) = 0.90 \pm 0.01$, which is less than that of the wire plane, $P_w(T) = 0.98 \pm 0.01$.

Electrostatic field mapping indicated that the mesh grounding plane will produce a stronger field within the bulk of the detector, Figure 2.10 and Figure 4.1 show the differences in the field maps, with better timing properties due to increased electron drift. A simulation with $V_{app} = -660$ V gave the magnitude of electric field in the bulk as $|E| = 211$ V/cm and the electron drift velocity as $v_e = 0.057$ cm/ns. A prototype was constructed to test the mechanical and physical properties to see if improvements could be made over the limited success of prior attempts [18].

Figure 4.3 shows the prototype detector which consisted of a single mesh grounding plane and planar copper anodes on a sheet of 1.6 mm PCB. The PCB had four 4.5×6.0 cm anodes spaced 1 cm apart with a 1 mm hole drilled centrally to solder a contact through to the rear of the detector. The solder protruding from the anode surface was sanded down and polished to match the surface consistency of the copper.

The wire mesh was clamped between two rectangular 1 cm frames under a slight tension applied by hand using the frame as indicated in Figure 4.2. Between the mesh and the anodes a 3 mm 3D printed ABS (Acrylonitrile Butadiene Styrene) spacer was fixed in place with several dowels protruding through the PCB. This maintained the gap distance throughout the detector and served as a means to tensioning the mesh further. Precautions were taken to remove any surface deformations in the mesh that could produce local regions of high electrostatic fields within the active detection volume. The source of ionising radiation is a collimated

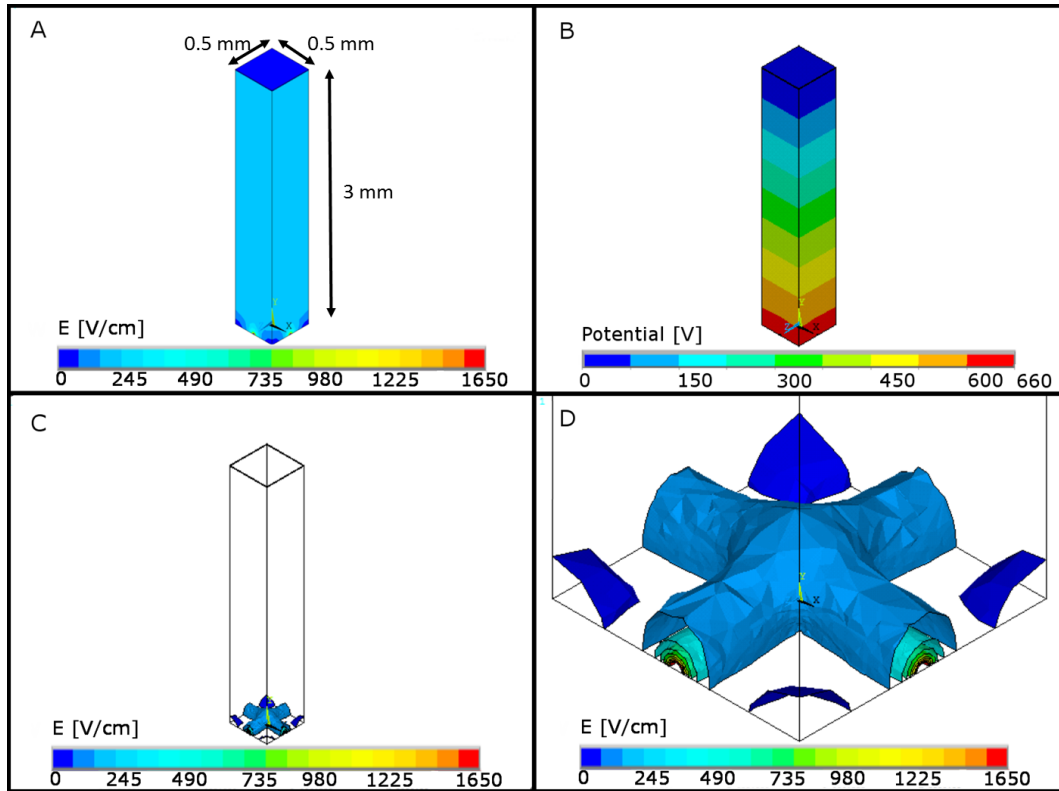


FIGURE 4.1: The field map of the 3.0 mm PPAC with fine mesh plane as the ground plane. (A) A full view of the E-field magnitude. (B) The magnitude of applied electrical potential. (C) A contoured view of the E-field magnitude where the values are greater than 271 V/cm. (D) A close-up view of the contours around the mesh showing the regions where multiplication occurs.

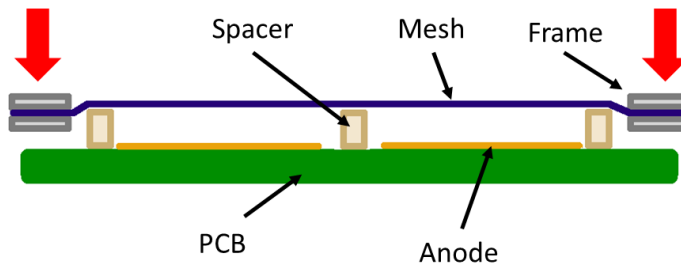


FIGURE 4.2: The construction off the mesh PPAC with mesh clapping frame and tensioning method (red arrows). As the frame is clamped to the PCB with screws the tension in the mesh is increased uniformly over the front of the detector.

^{241}Am α source of 288 kBq activity and is situated 5 cm from the detector held by mechanical fixing normal to the detector aperture.

To remove the possibility of gas contamination the vacuum chamber and detector

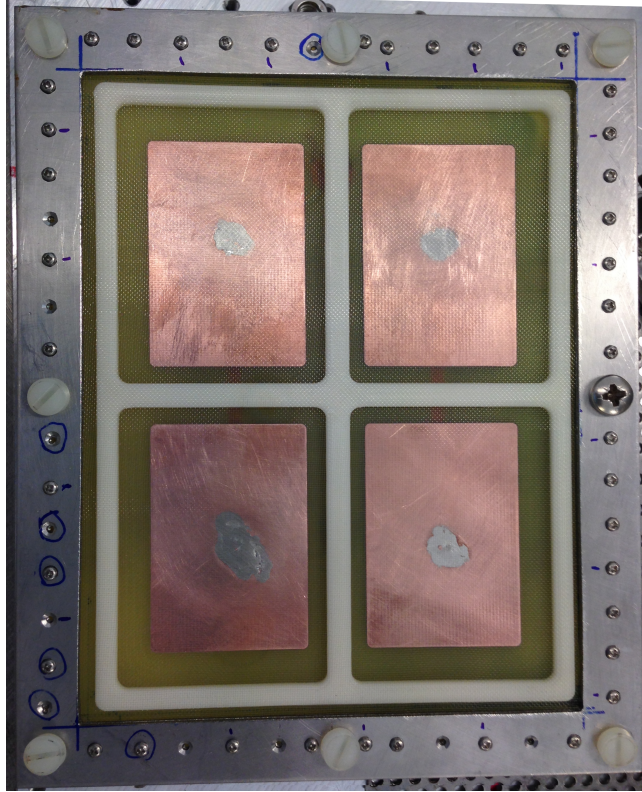


FIGURE 4.3: The mesh PPAC detector prototype constructed with 3 mm gap and wire mesh grounding plane. The copper anodes can clearly be seen through the fine mesh along with the white ABS 3D printed spacer.

are placed under high vacuum ($< 2 \times 10^{-6}$ mBar) for several hours to degas the materials (particularly from the 3D printed spacer) before filling with the desired detector medium. The gas supply and regulation systems shown in Figure 4.4 are identical to the systems used for STEFF, see Chapter 2 for more information.

The detector, when newly installed, was put through a process of electrostatic conditioning, where a voltage is applied to the electrodes and increased to operational voltages. The sparking inside the detector is caused by debris or surface imperfections on the electrodes forming a local region of high field [73]. Over a period of a few hours the sparking rate reduces and normal operation can begin. Once this process has been completed it generally does not need to be repeated, unless contaminated with debris.

The detector was supplied with a DC potential from a Cooknell HV3 PSU (see

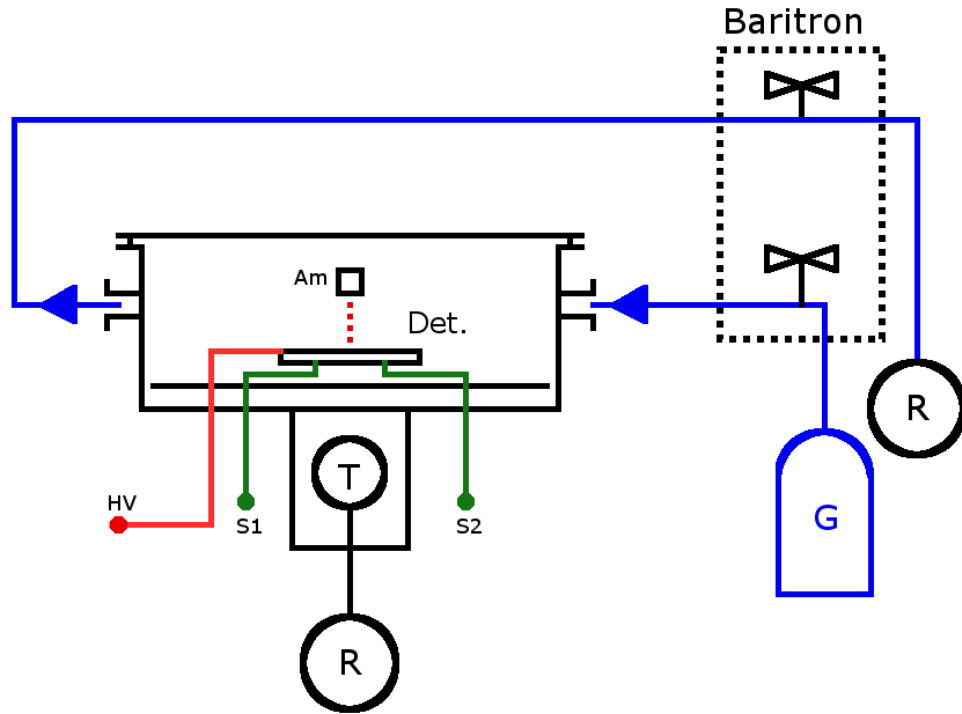


FIGURE 4.4: The experimental set-up with the vacuum and gas supply systems (Baritron). R represents roughing pump, T represents turbo molecular pump, G is the gas bottle, the blue lines represent the detector gas lines, the red is the detector power and green is the signal lines to the preamplifiers. The detector is irradiated with an ^{241}Am 288 kBq collimated source as the source for ionisation in the detector.

Appendix A.1 for detector electrical connections), signals were recorded with a Tektronix TDS3054c oscilloscope with 2.5 GS/s sample rate controlled by a *LabView2014* script over LAN to record the desired data (written as part of this work). The sample size was 2.5×10^3 triggers per test measured directly from the preamplifier (see Appendix A.4 for amplifier information) and was chosen for time restriction reasons. The gas pressure for the experiment ranged from 3 – 10 mBar similar to the previous prototyping development work [18].

The recorded data were processed on line using *LabView2014* to provide information such as signal amplitude and rise-time. It was possible to record multiple channels at once to check for induced signals in adjacent anodes.

4.2.1 Results for mesh PPAC

The results of the mesh PPAC detector are not given in the typical reduced field units of E/p but instead in units of V/p , where V is the applied potential in Volts and p is the pressure in mBar, because E is not constant over the detector volume. The rise-times_(10–90%) for the PPAC improved significantly with the increase of V/p as seen in Figure 4.5. The reduction of the pressure aided the electron drift velocity, resulting in faster signal production and increased induced current in the conductor as discribed in Section 3.2.5. However, the effect of reduced pressure and reduced electron-ion collision frequency does not increase the amplitude of the signal indefinitely; below 6 mBar it can bee seen in Figure 4.6 the signal amplitude diminishes. Below 6 mBar the detector breaks-down before we can take advantage of the increased Townsend first order coefficient, α , which indicates greater multiplication for reduced pressure with equivalent field as can be seen in Figure 3.4.

The most significant result from the investigation is the maximum field at which breakdown would occur, from Section 3.2.6 the theory suggests that breakdown for the 3 mm planar gap at 10 mBar should occur at $V_{breakdown} \approx 800$ V, significantly greater than what we have seen in this detector of $V_{max} = 640$ V. The reduction of pressure did not result in breakdown at the same reduced potential (V/p), this provided an opportunity to take advantage of the high fields.

The polarity of the supplied voltage was swapped to see how the wire wave contributed to the signal production, the detector failed to produce detectable signals with breakdown occurring at applied potentials ~ 20 V less than the opposite polarity magnitude. This confirmed the simulations within the detector, the lack of signal production proves the multiplication process is occurring around the wire surface and not the bulk of the detector.

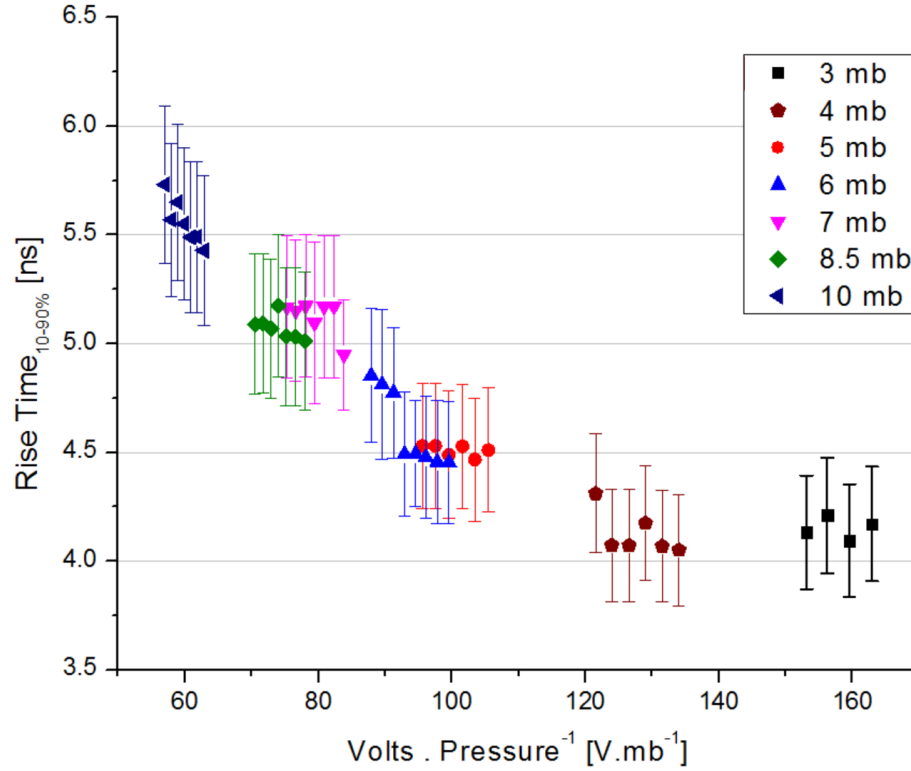


FIGURE 4.5: Rise-times of the induced signal from the mesh PPAC detector at varied pressures and applied potentials post pre-amplification. The error bars represents the sigma variation of the amplitude distribution of 2500 triggered events.

The breakdown of the detector occurred prematurely with respect to predictions, surface imperfections of the wire mesh, possible uneven plane or damaged wire threads in the weave were suspected. After the experiment imaging of the mesh structure probed the surface quality, Figure 4.7 shows the result of the imaging and the mesh was intact.

The Paschen theory of breakdown described in Section 3.2.6 states the ion-cathode induced electron emission is one of the primary factors in the breakdown process and is dependant on the surface of the conductor, hence an investigation was initiated into coating the surfaces of the wire and the anode to see if greater maximum potential could be applied. The anode mesh was suspected to have microscopic imperfections on the surface which would lead to local regions of high

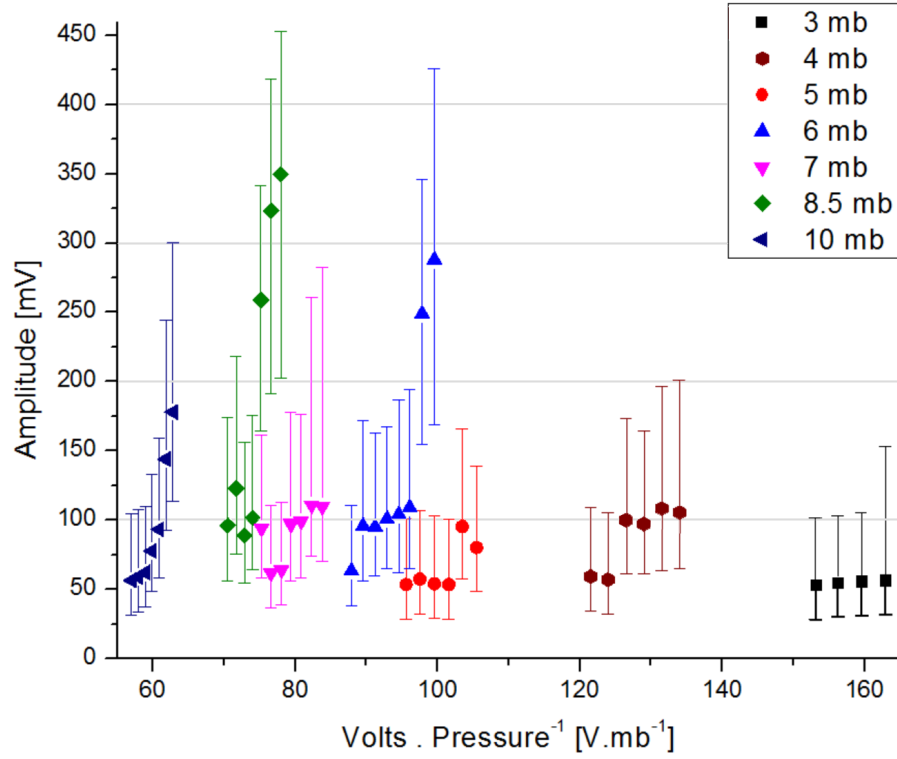


FIGURE 4.6: Peak amplitudes of the mesh PPAC detector at varied pressures and applied potentials post pre-amplification. The error bars represents the sigma variation of the amplitude distribution of 2500 triggered events.

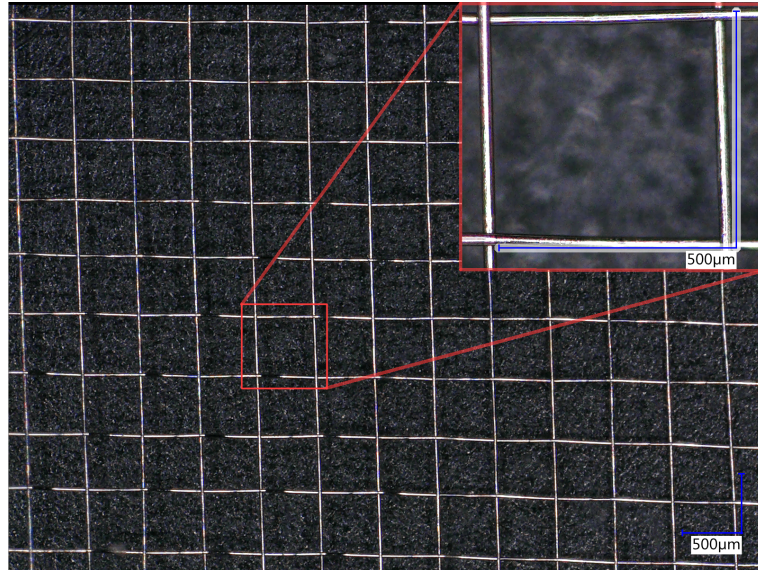


FIGURE 4.7: The fine stainless steel mesh used in the detectors. The scale indicates the dimensions of the wire and spacing where the wires are of diameter $24.5 \pm 0.1 \mu\text{m}$ and spaced evenly in square of diameter $462 \pm 4 \mu\text{m}$, the vertical displacement of the wire weave is that of the wire thickness when under tension.

field and breakdown; by coating the surface the effect of the imperfection would be diminished. The detector was spilt into four sections (an anode per section) and the surfaces for the respective regions coated. One region with Al of $10 \pm 1 \mu\text{g cm}^{-2}$ and another with $30 \pm 1 \mu\text{g cm}^{-2}$, the other two sections were the control. Later a complete replacement of the steel mesh with Al-Mylar (described in detail in Chapter 5) was installed to investigate the effect on breakdown for homogeneous planar surfaces.

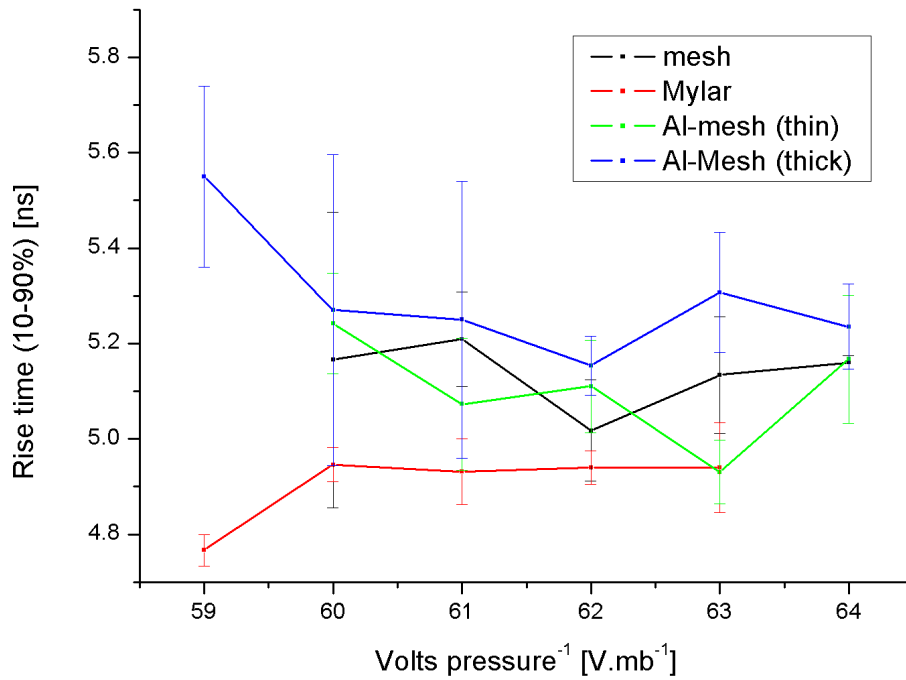


FIGURE 4.8: The rise-times of the signals from 10 – 90 % with varied applied potential showing no major gains to be made with coating the mesh.

For the testing of the coatings it was chosen (due to acquisition time) to use a fixed pressure of 10 mBar and investigate the maximum field before breakdown. In Figure 4.8 the rise-time for the planar Al-Mylar sheet is reduced over the entire range of voltage compared to any of the mesh coatings. The field close to the surface of the conductor will remain homogeneous allowing the charge to spread over the surface without significant space charge effects locally forming; unlike the fine wires of the mesh where close to the conductor surface the field is no

longer homogeneous. The amplitude of the signals for the two Al coated conductors remained within error of the prior test over the range of applied potentials. The effect of coatings was negligible to the amplitude and failed to improve the maximum operating applied potential before breakdown. The planar Al-Mylar foil produced a homogenous field where multiplication occurred throughout the detector, but it failed to produce comparable amplitudes, the signal amplitude was ≈ 0.6 that of the mesh and electrostatic breakdown occurred earlier with reduced detector stability; diminishing any gains made in the overall performance with faster rise-times.

4.3 Multi-planar mesh PPAC

The success of the previous prototype proved the use of wire mesh as a conducting surface for electrode planes, the next prototype, as shown in Figure 4.9 and Figure 4.10, developed this further into five mesh layers stacked. Each layer was stacked 3 mm apart from the next producing four active regions of 3 mm gap with an anode and ground plane, making the detector depth 12 mm. The geometry of the detector was a 6 cm square frame with 1 cm frame width giving an aperture of 4×4 cm and depth of 1.7 mm, with the wire mesh glued directly to the surface of the frame.

This detector tested the possibility of independent measurements of the same ionising event, to repeat the α measurements of the previous detector and enable measurement of the coincident timing resolution, σ_c , between the detector layers.

There were additional improvements made to the experimental set-up compared to the prior, the data acquisition system was replaced with a Picoscope 6404D oscilloscope. This made it possible to record 10^4 events with an 8-bit full scale resolution recording of every data point for every trace. The new data format

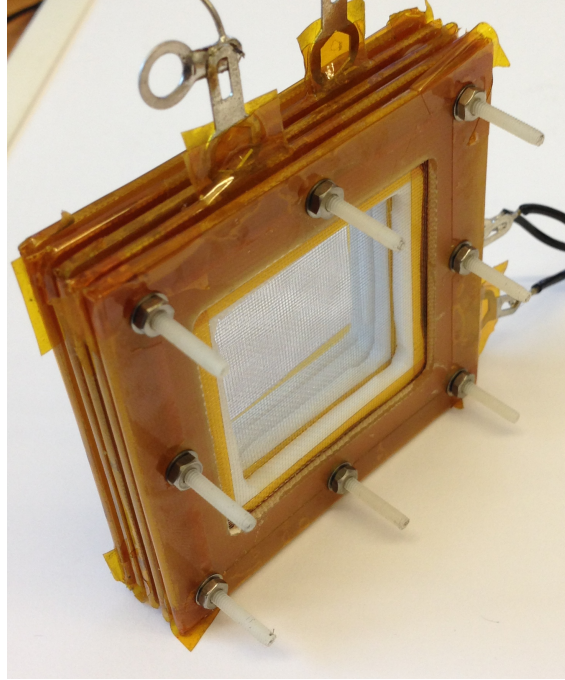


FIGURE 4.9: The rear detector face of the 3 mm mesh PPAC with 4 active regions with 2 sensing anodes. Five PCB's stacked and held in place with M2 nylon bolts.

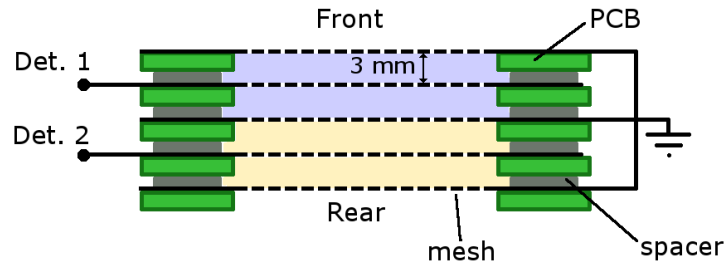


FIGURE 4.10: The multi-layered mesh PPAC where the yellow and blue represent the two independent detectors, each region has two active volumes of gas above and below the central sensor planes.

allowed for more advanced data processing routines (as described in Appendix A.5) to check coincidence event timing measurements between layers. For the testing of the multilayered PPAC three pressures were chosen 10, 7.5 and 5.0 mBar for the efficiency and coincidence timing measurements, using the same experimental apparatus as the prior experiment.

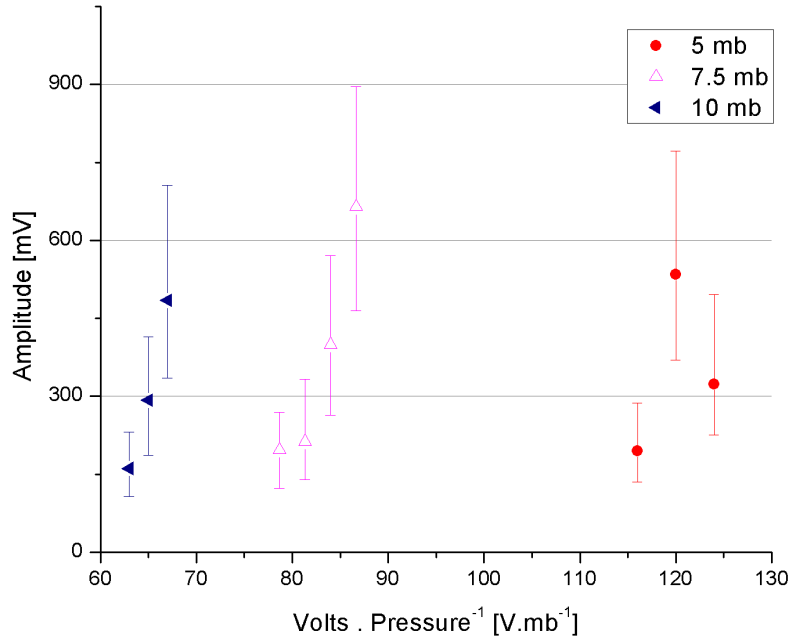


FIGURE 4.11: The amplitude distribution and mean as a function of increasing applied potential and reduced pressure, V/p . The error bars represent sigma, σ_{low} and σ_{high} , of the asymmetric gaussian fit of 10^4 events to show the spread of amplitudes from the detector.

4.3.1 Results of Multi-planar mesh PPAC

The distribution of amplitudes with respect to V/P was similar to the previous experiment with the exception of increased applied potential before breakdown during the experiment. The smaller detector area was speculated to be the cause of this, there will be less mechanical deformation of the mesh under applied field and the probability of having a ‘kink’ or other form of imperfection within the plane will be reduced.

The timing resolution properties of the detector were measured for the signal timing resolution, σ_t , and timing coincidence resolution, σ_c . As V/p is increased the timing resolution improves as expected for both timing measurements, either as a result of increased signal amplitude or improved electron drift velocity through the bulk region.

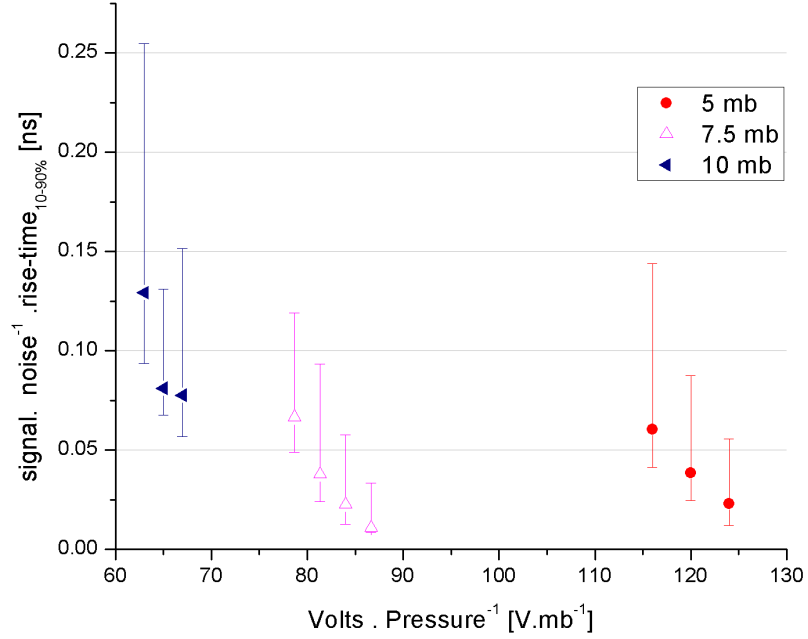


FIGURE 4.12: The signal timing resolution, σ_c , against increasing applied potential and reduced pressure, V/p . The error bars represent sigma, σ_{low} and σ_{high} , of the asymmetric gaussian fit to show the spread for the theoretical timing resulting calculated for each pulse over 10^4 triggered events.

Comparison of the two timing determinations for the timing resolution, Figure 4.13 with Figure 4.12, shows significant discrepancy between σ_c and σ_t . This indicated the charge multiplication from initial ionisation is not instantaneous. This suggests there was significant drift time to a region of multiplication where signal production occurs. From the signal timing resolution, Figure 4.12, the expected timing coincidence resolution, σ_c , for the 7.5 mBar and the 5 mBar should be similar; however, Figure 4.13 shows there is a significant improvement in the measured σ_c . This further suggests there is a significant influence from electron drift velocity as the charge is multiplied some distance from the instance of primary ionisation, leading to a delay in the creation of a detectable signal.

The measured timing coincidence resolution of $\sigma_c = 0.85 \pm 0.03$ ns at 5 mBar is a significant improvement on the current detector and of previous detector studies. Appendix A.5 shows the oscilloscope contributes of $\sigma_c = 0.46 \pm 0.04$ ns to the

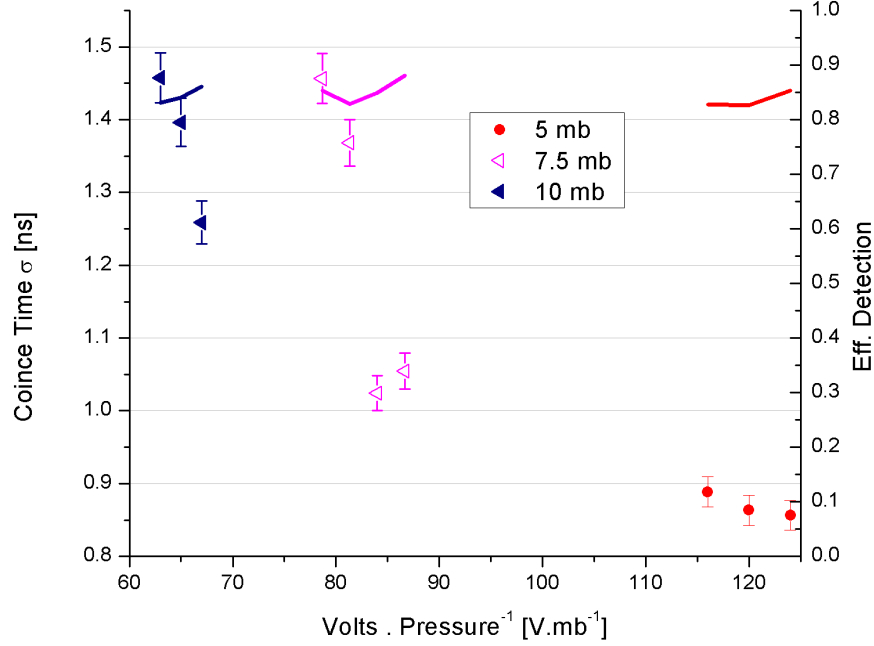


FIGURE 4.13: (Left axis, data points) The σ_c of the timing coincidence peak with increasing applied potential and reduced pressure, V/p . (Right axis, solid line) The efficiency of detection calculated from the number of coincident triggers in the front and rear of the detector with α source.

timing measurements; if the oscilloscopes timing contribution is taken into consideration, the measured value becomes $\sigma_c = 0.71 \pm 0.09$ ns per detector at 5.0 mBar.

For operating the mesh PPAC at 10 mBar the coincidence timing resolution is $\sigma_c = 1.25 \pm 0.03$ ns and with the oscilloscope contribution removed $\sigma_c = 1.16 \pm 0.09$ ns; the electron drift clearly hindered the timing capabilities through low mobility in the low field regions of the detector. The remaining values and detector timing resolution, ΔT , are given in Table 4.1.

There were several attempts to reduce the σ_c further by reducing the gap distances to 1.7 mm, unfortunately it was not possible to reach sufficient voltage for the multiplication effect to produce detectable signals before breakdown. A test was made using various other gases with greater electron mobilities such as the Ar:CH₄

(P10) mixture and mono-atomic gases (Ar and Xe) with no signal production before breakdown for both 3 mm and 1.7 mm. There was also a test with the CF_4 where the electron mobility is similar, this also failed to produce signals before breakdown.

Reducing the pressure led to significant improvements in the timing resolution and signal production for the α source. We saw in the simulations, in Section 3.3.6, the energy deposition within the detector is significant for α 's and experimentally we saw a reduction in detection efficiency with reducing pressures. The detection efficiency with the low energy $E_k \approx 10$ keV electrons for this detector remains unknown. The next prototype and experimental set-up was aimed at addressing these issues. The problems discovered during the construction of this and the prior prototypes have made the mesh undesirable for any large area detector requiring split anodes. Applying tension to the mesh was a tricky and time consuming process, although possible for a large area of grounding (does not require segmentation) a solution to have small areas of mesh anodes stacked within the detector was not found.

Valuable information was gained from the two mesh prototypes which was applied to the design and production of the next prototype:

- The mesh-anode plate detector combination works as a moderate sized PPAC and is more stable than the planar Al-Mylar PPAC.
- Coating the electrodes with small quantities of Al does not improve breakdown potential.
- The mesh PPAC performance is improved by reducing the pressure.
- The mesh-PCB detector only operates in one polarity, the wire mesh has a large role in signal production as the field maps indicate.

- Drifting of the electrons before multiplication is significant within the detector medium.
- The mechanical stability and manufacturing issues for the mesh made it unsuitable of a large area anode plane.

4.4 Multi-planar multi-wire detector - $20\ \mu\text{m}$ wire

From the results of the prior mesh PPAC the next prototype investigated an alternate for the anode plane. This led to the production of a detector with an anode constructed from a plane of $20\ \mu\text{m}$ gold plated tungsten wires spaced (pitch) 1 ± 0.1 mm apart and are glued and soldered onto a PCB board (common practice for MWPC detectors [30]). The planes were constructed using the methods described in Appendix A.6 with a friction plate on the wire spool. The grounding planes were made from the fine mesh adhered to 1 mm stainless steel frames using identical methods to prior detectors.

Simulations and literature [30, 74, 75] have shown condensing the pitch of the wires increases the field within the bulk media of the gas, $|E| = 150$ and $|E| = 120$ V/cm for two identical MWPC detectors with $20\ \mu\text{m}$ wires with 1 ± 0.1 and 2 ± 0.1 mm pitch respectively; and reduces the maximum drift distance and time for electrons as can be seen in Figure 4.14.

The constructed wire plane was paired up with mesh grounding frames and 3D printed spacers to fix the gap distance at 3 mm and to provide insulation for the anode wires from the grounding frames as shown in Figure 4.15. The detector had an area of 6.0×6.4 cm with depth of 2×3 mm, the wires were grouped together to form a single anode, this formed one of detector layers in the detector stack.

With this configuration it was possible to take greater advantage of the field increase as the electrons drift to the wire where the field has $E(r) \propto 1/r$ relation.

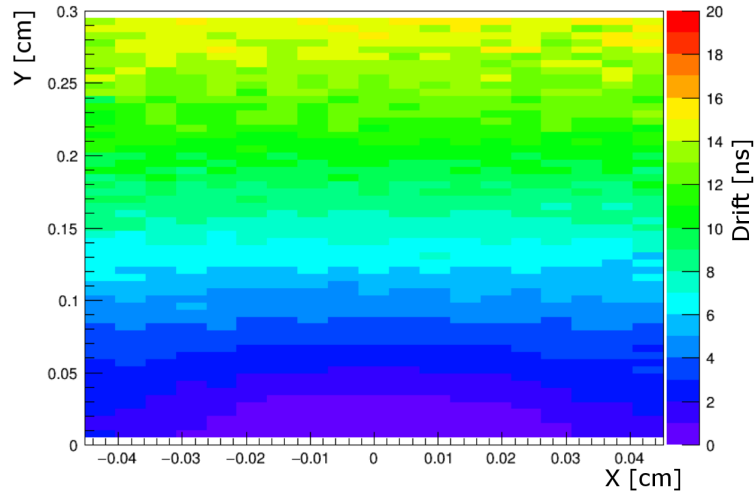


FIGURE 4.14: Garfield++ simulated electron drift to anode wire times from locations within the 3 mm MWPC detector with 20 μm wires with 1 mm pitch for gas pressure of 10 mBar isobutane. The Y-axis represents the depth into the detector and the X-axis runs along the plane of detection (anode).

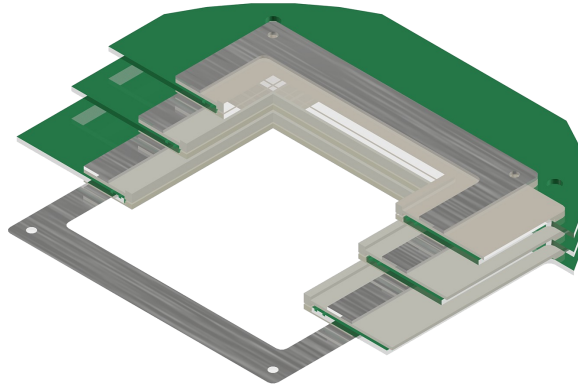


FIGURE 4.15: A false colour image of a stack of three MWPC detectors with alternating mesh grounding and 20 μm wires. (Green) The 1.6 mm PCB on which the wires are soldered and electrical connections made, (off-white) the 3D printed varied sized spacers to maintain the 3 mm gap and (silver) is the 1 mm thick stainless steel frame the grounding mesh is glued to.

There are examples of analytical solutions with wires in parallel with planar cathodes [30, 76], however the calculations become increasingly complex for binary wire planes. Fortunately, it is possible to use the simulation methods mentioned previously in Chapter 3 to compute this, Figure 4.16 shows the Townsend parameter and inferred charge production around the wire.

The experimental chamber was modified to accommodate ionising radiation from

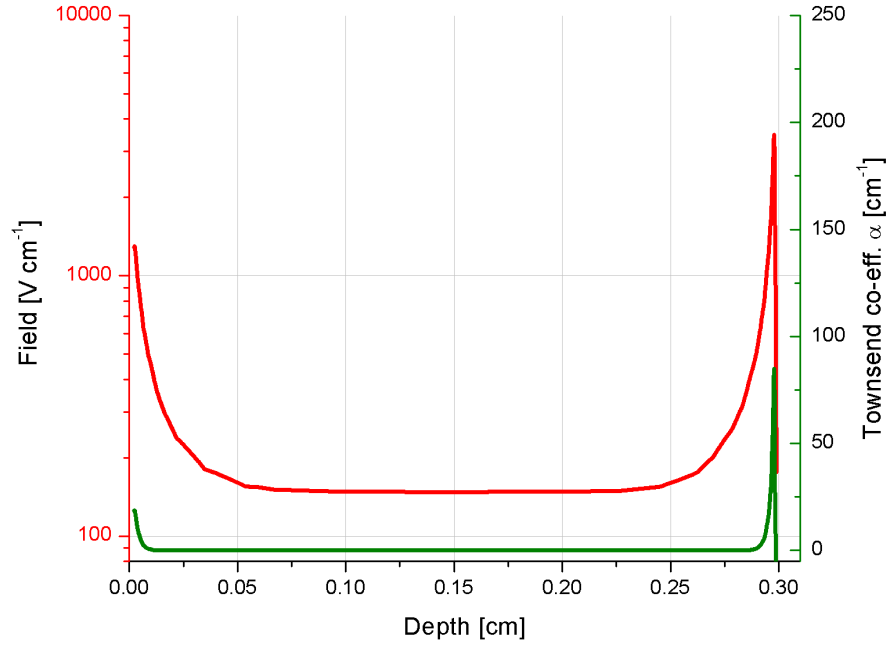


FIGURE 4.16: A plot of the electrostatic field (left axis, red) with Townsend coefficient, α , (right axis, green) plotted along the detector depth indicating the regions of most multiplication.

an α source (^{241}Am) and the production of secondary emission electrons from nuclide impact on a Al-Mylar SEE foil. The experimental chamber contained two electrostatic mirrors paired to share the same SEE foil, this produced electrons with trajectories perpendicular to the initial nuclide trajectories and is shown within the chamber in Figure 4.17.

The electrostatic mirror coupled to the MCP has one of the two acceleration regions removed, this results in an electron kinetic energy of $E_k = V/3$, where V is the applied potential. Reduction of the acceleration potential increased the efficiency of the MCP for forward scattered electrons. The opposite electrostatic mirror accelerated the backscattered electrons to kinetic energies of $K_E = 2V/3$ of the applied potential, V , producing guided electrons with kinetic energies of $E_k = 12$ keV. This replicated the energy of the electrons for the stop detectors on STEFF, unfortunately it did not replicate the number of electrons produced

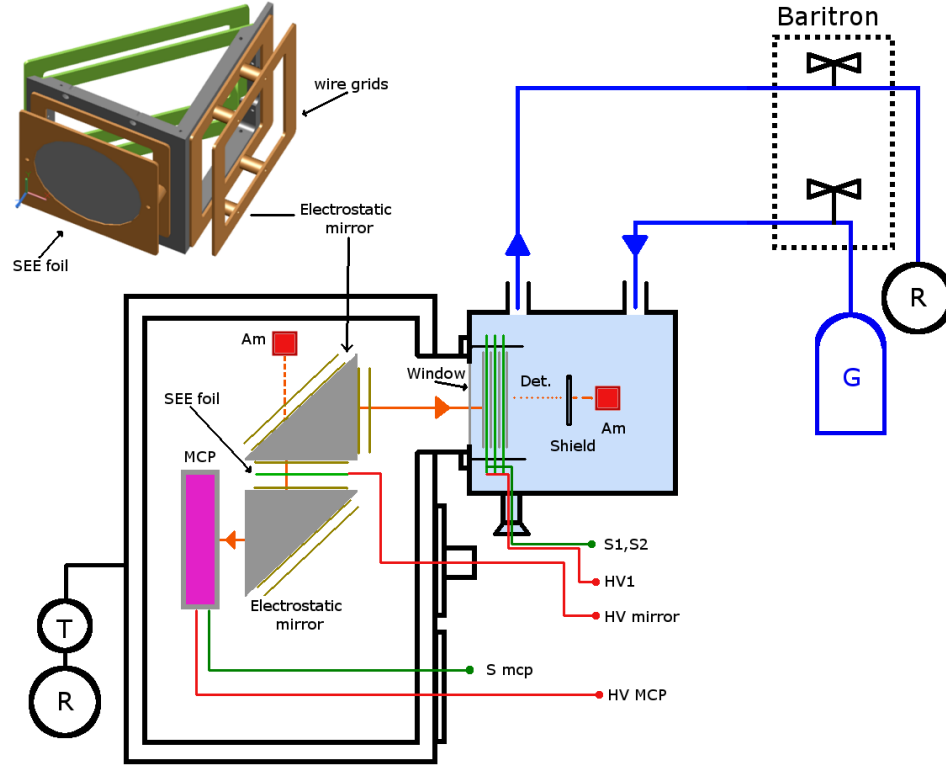


FIGURE 4.17: Experimental set-up with the vacuum and gas systems, R represents roughing pump; T represents turbo molecular pump; G is the gas bottle; the blue lines represent the detector gas lines; red are high voltage lines and green are the signal lines to the preamplifiers. The detector is located in the light blue zone where a gaseous atmosphere with a Al-Mylar window separating the vacuum region. The detector is irradiated with 12 keV secondary emission electrons (highlighted in a solid orange line) from the foil (green).

for fission fragment ejection; the number of electrons ejected for a 5.49 MeV α is $\approx 4\%$ compared to a fission fragment with a carbon foil [77].

The second collimated α source provided a means of direct comparison between e and α detector responses without modifying the experiment; by grounding the mirror and removing the shield from the second ^{241}Am source.

The first set of measurements made with the MWPC 20 μm wires with 3 mm gap were a replica of the mesh measurements, this ensured proper detector functionality before attempting to use the secondary electron set-up.

4.4.1 Results Multi-planar multi-wire detector - α source

The amplitude distribution shown in Figure 4.18 for the MWPC showed greater values for amplitude than that of the mesh PPAC, indicating the non linear radial field is significantly contributing a greater multiplication effect due to wire pitch and slightly narrower diameter.

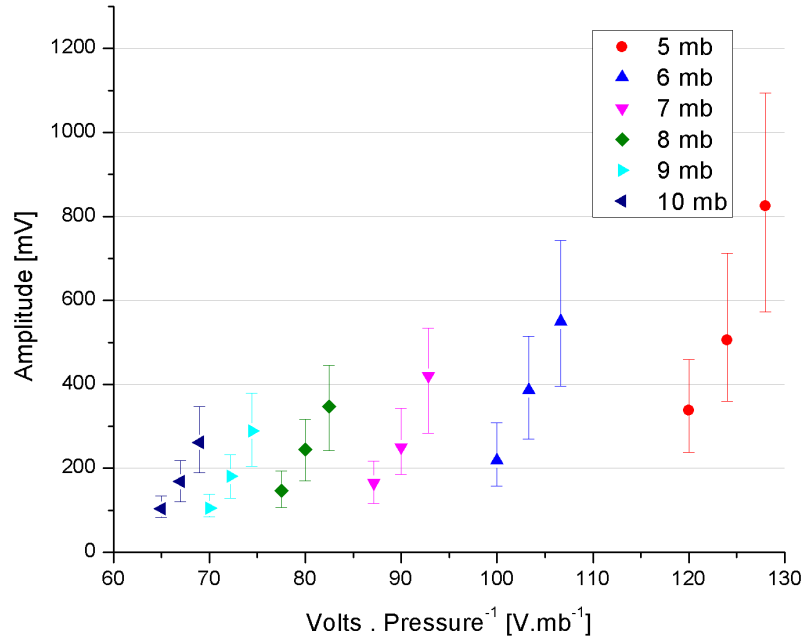


FIGURE 4.18: Amplitude distribution for varied pressure and applied potential on the MWPC detector with 3 mm gap and 20 μm diameter wires spaced with 1 mm pitch irradiated with α 's from ^{241}Am source. The error bars represent σ_h and σ_l of the fitted asymmetric gaussian on the distribution of 10^4 triggered events on the oscilloscope.

The signal rise-time was detrimentally effected with increased charge collection time by ≈ 1 ns in comparison to the mesh PPAC but showed an identical trend with pressure reduction and increased values of V/p . The significant increase in charges produced and at further distance from the anode surface of the anode is speculated to reduce the field locally and temporarily, retarding the charge collection process resulting in slower rise-times.

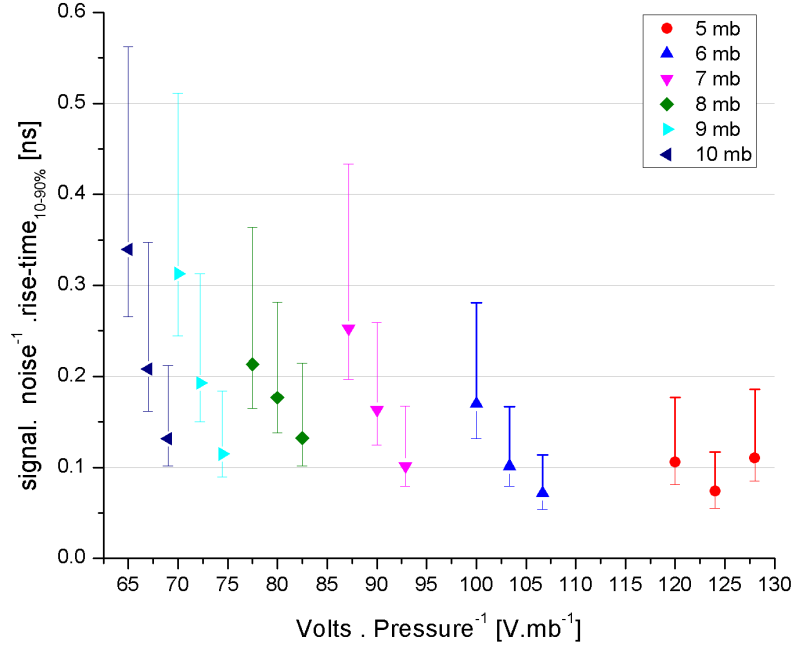


FIGURE 4.19: The signal timing resolution distribution for varied pressure and applied potential on the MWPC detector with 3 mm gap and 20 μm diameter wires spaced with 1 mm pitch irradiated with α 's from ^{241}Am source. The error bars represent σ_h and σ_l of the fitted asymmetric gaussian on the distribution of 10^4 triggered events on the oscilloscope.

The signal timing resolution, σ_t , shown in Figure 4.19 was effected from the changes in the amplitude and rise-times as expected. However, the main contribution to the PPAC and MWPC was the significant increase in the RMS noise. The noise $\langle N_{PPAC} \rangle = 6.1 \pm 0.7$ mV and $\langle N_{MWPC} \rangle = 22 \pm 3$ mV was mainly due to the lack of resolution on the 8-bit ADC's for digitization. The ADC full scale had to be increased to accommodate the increased amplitude of the signals and additionally the changing of experimental conditions introduced some noise, the introduction the additional chamber and window.

The timing coincidence resolution, σ_c , Figure 4.20 reflects what has been seen in the prior mesh PPAC detector, the variance in the timing coincidence measurement reduces with declining pressure giving better timing properties. The values for σ_c are significantly better for the MWPC detector when compared to the mesh PPAC,

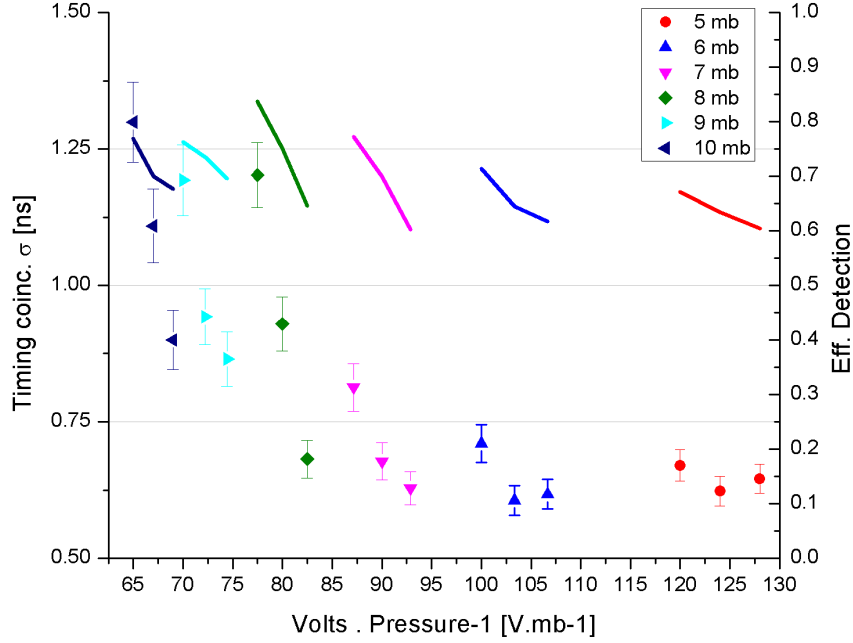


FIGURE 4.20: (Data points) The σ_c of the timing coincidence between the two layers of the detector plotted and (solid line) the efficiency of detection in both detectors using an ^{241}Am α source from 10^4 triggered events on the oscilloscope.

a comparison at 7 mBar gives $\sigma_c = 0.63 \pm 0.03$ ns for MWPC and $\sigma_c = 1.02 \pm 0.03$ ns at 7.5 mBar for PPAC without corrections; for the values post corrections see Table 4.1.

This effect is strongly related to the maximum field within for each test. The maximum reduced potential for the mesh PPAC was $V/p = 620/5.0 = 124$ V/mBar and MWPC $V/p = 640/5.0 = 128$ V/mBar. Simulations show in the bulk of the detector the field in the mesh PPAC was $|E| = 204$ V/cm and the MWPC of $|E| = 147$ V/cm, the drift inside the mesh PPAC is greater than the MWPC. This suggested the mesh PPAC should perform better than the MWPC with greater electron drift velocities. However the improved values indicated the signal induction occurred earlier, the simulated field showed multiplication occurs ($\alpha > 1$) at $25 \mu\text{m}$ and at $88 \mu\text{m}$ from the conductor surface for mesh PPAC and MWPC respectively with the applied fields in the experiments. The multiplication point was

arbitrarily chosen to be when the Townsend coefficient $\alpha \geq 1$ but multiplication extends back into the detector until the field is below 300 V/cm where $\alpha \approx 0.001 \text{ cm}^{-1}$.

The efficiency of the detector shown in Figure 4.20 became problematic to measure, the signals produced in one detector were very often the result of significant induction in the adjacent region. The signals are significantly larger than in prior detectors. The methods of rejection used in the data processing described in Appendix A.5 struggle to distinguish the induced event from accepted, since we have the possibility of induction from electrons drifting away and toward the sensitive anode resulting in induced signals of both polarities.

There was an additional small investigation into using alternates to isobutane. C_3F_8 and P10 (a mixture of Ar and methane 90 : 10) were chosen for their common availability and non volatile qualities. The P10 failed to produce detectable signals with the α source for the desired pressures of 5 – 10 mBar. The CF_4 produced signals with the α source, typically just above the 50 mV trigger. They are small compared to the isobutane and failed to perform for the electron source instantly ruling it out as an option. As with the mesh PPAC testing there was a test to reduce the gap from 3.0 to 1.7 mm and operate the detector but the potentials to operate were unattainable with no success in measuring signals.

Results from this prototype under α testing showed a significant improvement in the timing coincidence resolution, σ_c , and proved that the detector is operating well for the second stage of testing with the electrostatic mirror and secondary electrons (see Table 4.1 for the timing resolution results).

4.4.2 Results Multi-planar multi-wire - Secondary electron source

The electrostatic mirror for STEFF operates at 18 kV and the laboratory prototype was constructed to replicate this. There were some noise issues from the HV power supply used for the mirror inducing noise within the detector; this was minimised by using a coincidence trigger on the MCP. The MCP was used as the AUX trigger on the oscilloscope in combination with a AND trigger with the MWPC ¹.

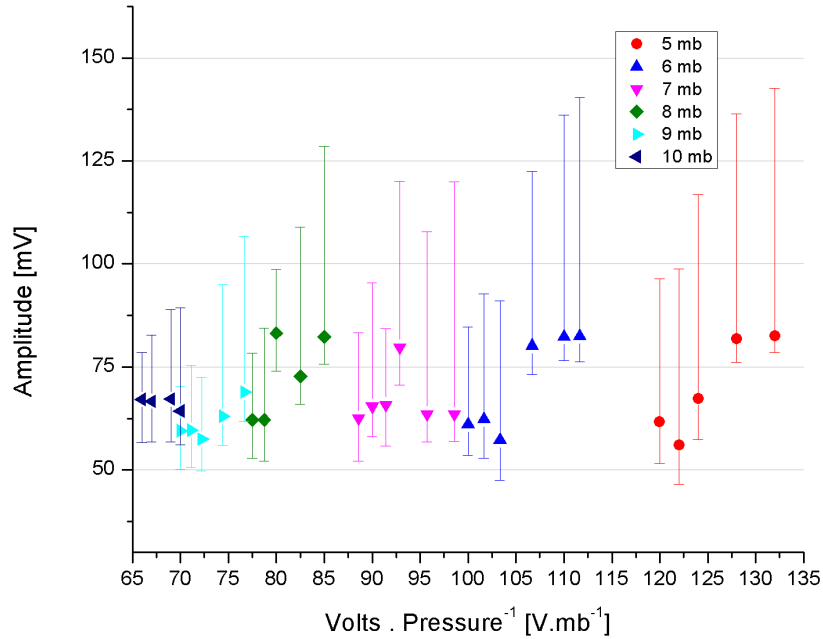


FIGURE 4.21: Amplitude distribution for varied pressure and applied potential on the MWPC detector with 3 mm gap and 20 μm diameter wires spaced with 1 mm pitch irradiated with 12 keV electrons. The error bars represent σ of the fitted asymmetric gaussian on the distribution of 10^4 triggered events on the oscilloscope.

The MWPC detector was tested with the same ranges of pressure and applied voltage as before, the results showed a significant difference in performance. The

¹ The primary reason for choosing to not record the MCP signal on one of the two free oscilloscopes channels was the sample rate, using one channel can record at 5.0 GS/s, two channels 2.5 GS/s and three or four channels 1.25 GS/s.

signal amplitudes for the secondary emission electrons were considerably smaller as expected from the reduced number of initial ionisation events within the detector, n_0 .

Similarly to the α testing, the signal amplitude increased with decreasing pressure and increasing field; the rise-times were also improved by this action. The rise-times of the signals were reduced by ≈ 1 ns with the same detector and V/p when compared to the α measurements. This gave indication toward space charge effects. A large quantity of charge around the wire will shield the remaining charges from the anode field; a reduction in charge will reduce this effect and aid charge collection time.

As mentioned previously the RMS noise, N , significantly effected the signal timing resolution, a large contribution to this noise was speculated to be the ADC jitter on the oscilloscope. Due to the reduced signal amplitude the full scale range was also reduced, this resulted in a RMS noise of $\langle N \rangle = 7.3 \pm 0.4$ mV which confirmed the prior hypothesis. The signal timing resolution in Figure 4.22 showed significant improvements in the signal characteristics for each pressure as the potential was increased. The reduced noise and improved signal rise-time gave the signal timing resolution comparable to the α measurements.

The timing coincidence resolution, σ_c , reflected the difficulties associated with electron measurements, as seen from the simulations in Section 3.3.1 the electron will scatter over a wide range of angles post foil transition and produce few secondary electrons as it traverses the detector. The timing coincidence resolution was measured as $\sigma_c = 1.55 \pm 0.15$ ns at 9 mBar, if we include the effects of the dual coincidence and oscilloscope we have $\sigma_c = 0.99 \pm 0.13$ ns, see Table 4.1 for the remaining values.

Unlike the prior α testing, the timing coincidence did not significantly improve with the reduction of pressure, this suggested electron drift within the detector was not

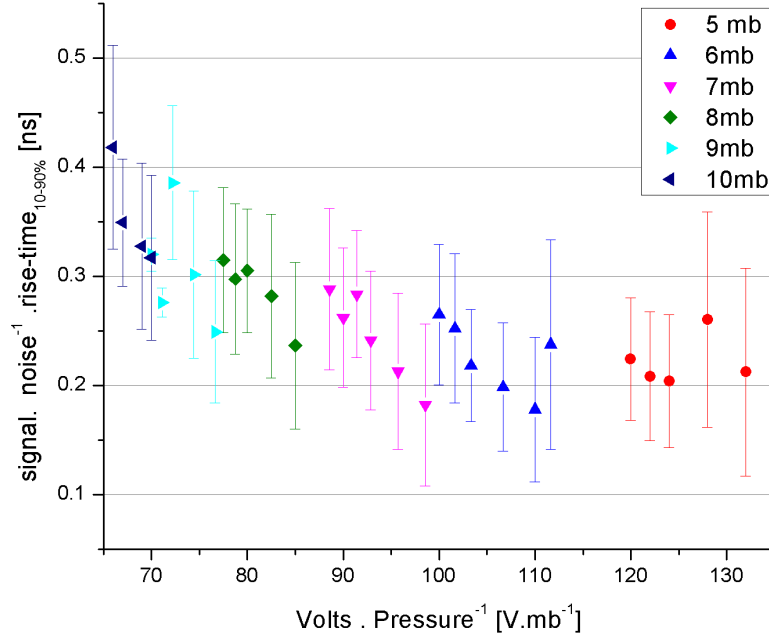


FIGURE 4.22: The signal timing resolution distribution for varied pressure and applied potential on the MWPC detector with 3 mm gap and $20\mu\text{m}$ diameter wires spaced with 1 mm pitch irradiated with 12 keV electrons from mirror set-up (Figure 4.17). The error bars represent σ of the fitted asymmetric gaussian on the distribution of 10^4 triggered events on the oscilloscope.

the primary source for the inferior performance but the number and location of charges produced.

The efficiency of the detector was measured using the coincidence between the two detectors and only when the single rear detector was triggered. Figure 4.23 shows the efficiency of the detector layer with applied potential and pressure. The efficiency improved with greater pressure and with increasing field, the graph indicates a significant region of inefficiency at 7 mBar with average values below $\varepsilon < 0.1$. This prototype has shown important features that were applied to the design and production considerations for the next prototype.

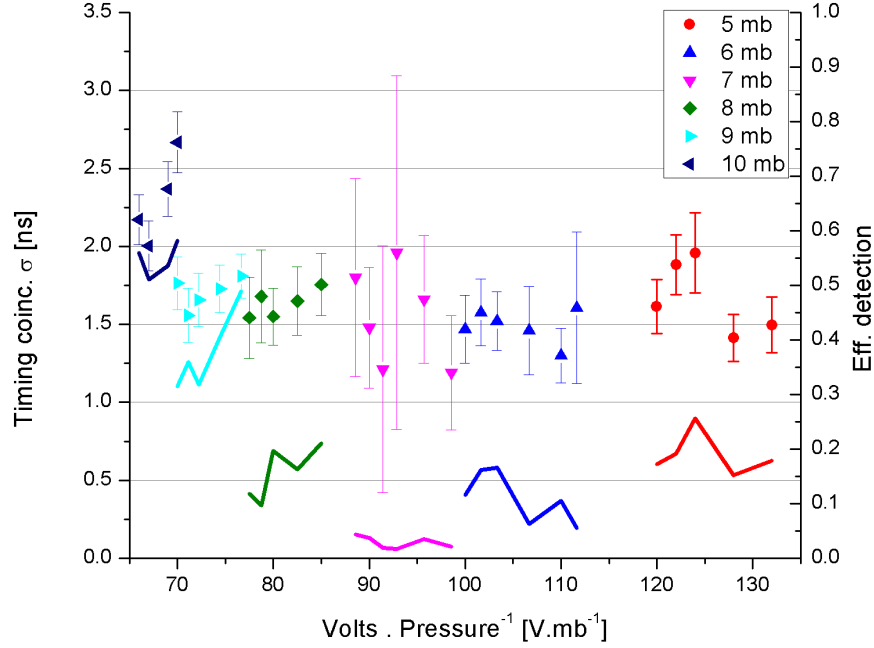


FIGURE 4.23: (Data points) The coincidence timing, σ_c , between the two layers of the 3 mm gap and 20μ m diameter wires spaced with 1 mm pitch detector. Plotted and (solid line) the efficiency of detection in both detectors using the 12μ m electrons from mirror set-up. Data produced from 10^4 triggered events on the oscilloscope. The error bars represent the σ of the gaussian fit.

4.5 Multi-planar multi-wire detector - 10μ m wire

The design of the final detector prototype was aimed at reducing the gap between anode and cathode planes as the prior detectors have shown the drifting of the electrons is a significant source for timing coincidence discrepancy. We have also seen that reducing the gap has resulted in breakdown before measurable signals are produced as the bulk field becomes too great for stable operation. Scaling down the detector geometry reduces the drift distance for any electrons before multiplication and reduces the wire diameter to 10μ m. Simulations of a 10μ m wire 1.7 mm gave the field to be $|E| = 200$ V/cm for an operating voltage of 700 V for the 10 mBar. The high-field magnitude gives rise to a fast electron drift velocity of $V_e = 0.057$ cm/ns for 10 mBar in the bulk of the detector. Figure 4.24 shows the results from a Garfield++ simulation for the electron drift within the

scaled detector, where the drift times have been reduced significantly throughout the detector volume.

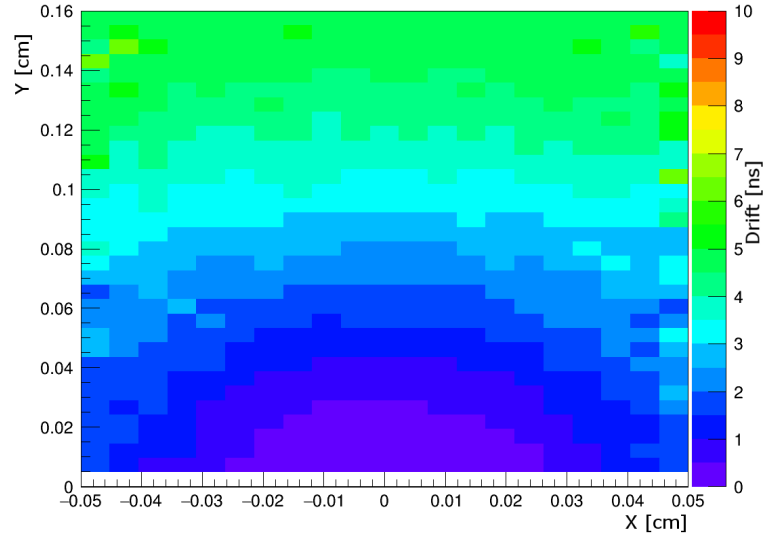


FIGURE 4.24: Garfield++ simulated electron drift to anode wire times from locations within the 1.6 mm MWPC detector with $10\ \mu\text{m}$ wires with 1 mm pitch for gas pressure of 10 mBar isobutane.

The construction consisted of an anode plane made from 10 μm gold plated tungsten wires with 1 mm pitch with two wire grounding planes with 50 μm gold plated tungsten wires with 1 mm pitch adhered to PCB of the same design as the anodes. The construction of the 10 μm wire planes was difficult with the winding rig (described in Appendix A.6) with friction plate and only one anode plane could be constructed due to material limitations. The desired gap of the detector was 1.6 mm, after careful construction the final depth was 1.7 mm. Two layers of Kapton tape were required to insulate some through hole solder points on the PCB resulting in the additional 0.1 mm of material. The single detector was coupled to the prior 20 μm dual MWPC assembly to perform coincided measurements.

The difficulties associated with stretching the grounding mesh and the surface deformations from the weave lead to replacing the grounding plane with a wire plane constructed from 50 μm gold plated tungsten wires with 1.0 mm pitch to

As can be seen from Figure 4.27, the results from the 10 μm diameter wires with 1.7 mm gap resembles the results of the 20 μm wire plane with 3 mm gap for signal timing resolution.

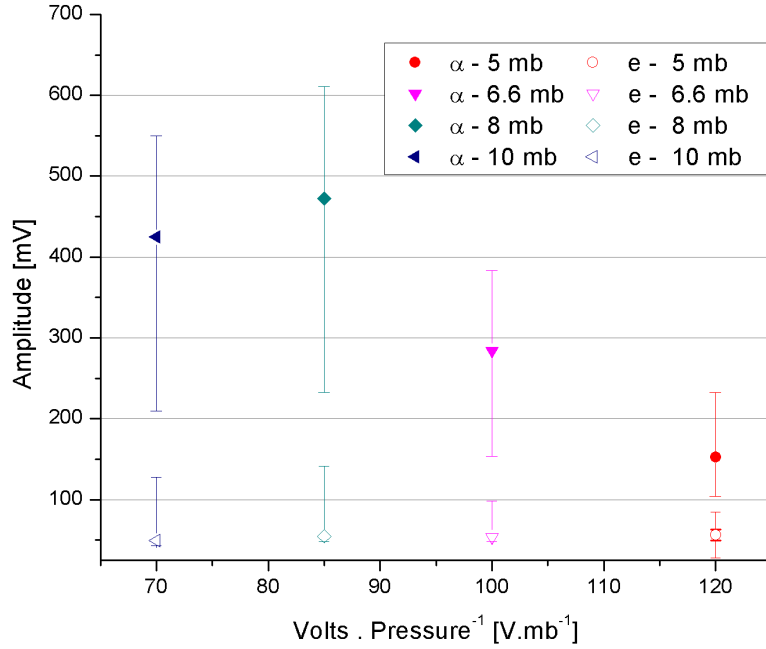


FIGURE 4.26: The amplitude distribution for varied pressure and applied potential on the MWPC detector with 3 mm gap and 20 μm diameter wires spaced with 1 mm pitch irradiated with 12 keV electrons from mirror set-up and with α 's from ^{241}Am source separately (Figure 4.17). The error bars represent σ of the fitted asymmetric gaussian on the distribution of 10^4 triggered events on the oscilloscope.

From Figure 4.26 we can see the amplitudes for 10 μm wires for both α and secondary electrons, where the α signal amplitudes are comparable to the 20 μm wire plane for the 10 mBar but trail off for lower pressures. The narrower diameter wire resulted in increased field potential close to the surface, aiding multiplication and increasing the path length over which multiplication can occur. $\alpha > 1$ occurs 135 μm from the anode surface with 10 mBar isobutane compared to 88 μm for the same pressures and potential with the 3 mm MWPC. The signal amplitudes for electrons was problematic as the peak values for the amplitudes are at the trigger threshold for the oscilloscope; the signals recorded were the trailing edge

of the amplitude distribution. The electron values for this detector cannot be quantitatively compared to the performance of the prior detector for this reason.

There was a concern the rise-times may be detrimentally effected by the saturation of charge as we have significantly increased the field strength on the wire surface. However, we saw no significant change in the rise-times with increasing V/p indicating the wire was not saturating with charge and values similar to the prior detector. The electron results were disregard but the α results are comparable to the prior MWPC detector.

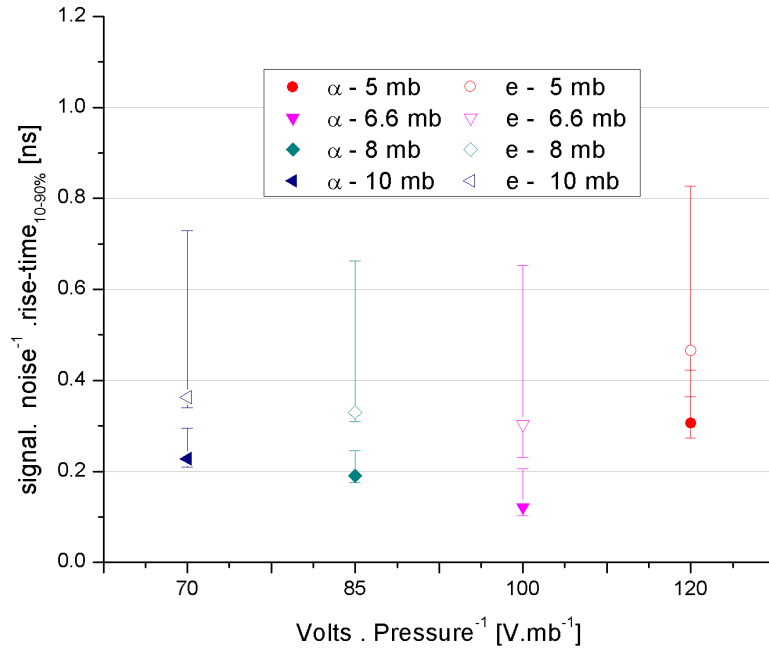


FIGURE 4.27: The signal timing resolution, σ_t distribution for varied pressure and applied potential on the MWPC detector with 1.7 mm gap and 10 μm diameter wires spaced with 1 mm pitch irradiated with 12 keV electrons from mirror set-up and with α 's from ^{241}Am source separately (Figure 4.17). The error bars represent σ of the fitted asymmetric gaussian on the distribution of 10^4 triggered events on the oscilloscope.

The timing coincidence resolution, σ_c , for the 10 μm diameter wires with 1.7 mm gap irradiated by the α source is similar to the 20 μm wire plane with 3 mm gap detector. Only when we run at the higher pressures does the difference between the

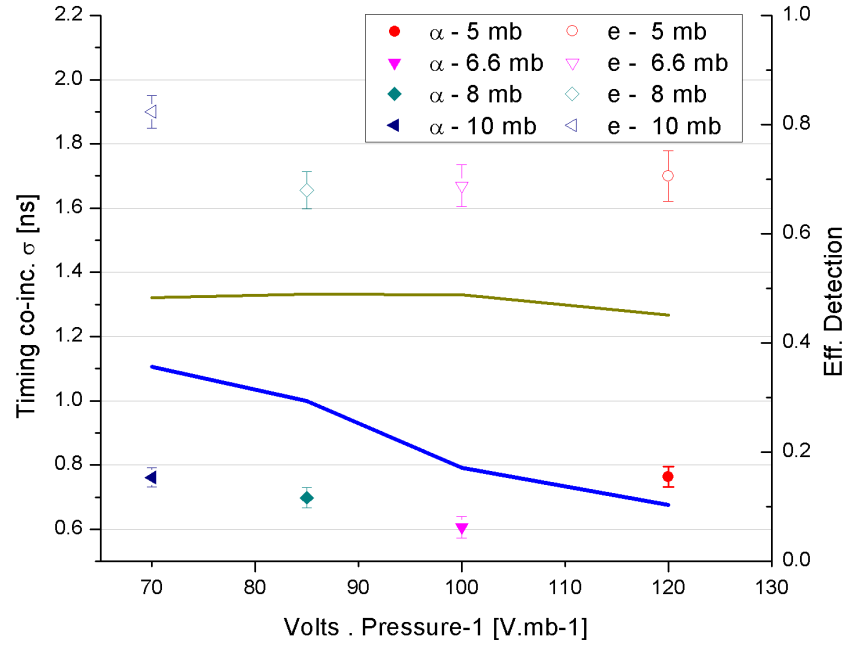


FIGURE 4.28: (Data points) The σ_c of the timing coincidence between the two layers with 1.7 mm gap with 10 μm diameter wires and 3 mm gap with 20 μm plotted (blue solid line). The efficiency of detection in both detectors using the 12 keV electrons from mirror set-up and (gold) with α 's from ^{241}Am source separately. Data produced from 10^4 triggered events on the oscilloscope.

two become noticeable, it is important to note that this is the coincidence between two dissimilar detectors each with their own timing properties. The value of timing coincidence, σ_c , can be estimated from measurements with 20 μm coincidence to give the results shown in Table 4.1 with the influence of the oscilloscope removed for α measurements.

Figure 4.28 shows the efficiency of the detector indicating the reduction of the pressure results in poorer detection efficiency as seen in the prior detectors. The number of primary electrons will be approximately halved with the reduction in detector volume, for the secondary electron measurements this is clearly evident and was a significant issue with reducing the detector volume.

4.6 Consolidated results

The timing coincidence results, σ_c , from all the detector prototypes are given in Table 4.1, with the reconstructed timing resolution, ΔT , values and the efficiency of detection per detector layer, ε . The reconstructed coincidence timing, σ_{cor} , is the timing coincidence results, σ_c , with the oscilloscope timing influence removed (described in Appendix A.5). This value is the combined timing coincidence for the two detectors with identical timing properties, hence $\sigma_{cor}/\sqrt{2}$ gives the ΔT , the timing resolution of the individual detector layer. The values for ΔT for the 10 μm MWPC were calculated using the measured timing resolution of the 20 μm and subtracted in quadrature from the σ_{cor} values.

Pressure p [mBar]	Mesh PPAC			MWPC 20 μm			MWPC 10 μm		
	σ_c [ns]	ΔT [ns]	ε	σ_c [ns]	ΔT [ns]	ε	σ_c [ns]	ΔT [ns]	ε
10	1.26 ± 0.03	0.83 ± 0.02	0.85	0.90 ± 0.05	0.64 ± 0.04	0.76	0.76 ± 0.03	0.42 ± 0.07	0.45
9	/	/	/	0.68 ± 0.03	0.48 ± 0.02	0.73	/	/	/
8	$1.02 \pm 0.02^*$	$0.65 \pm 0.01^*$	0.84*	0.68 ± 0.03	0.48 ± 0.02	0.75	0.70 ± 0.03	0.51 ± 0.06	0.49
7	/	/	/	0.63 ± 0.03	0.44 ± 0.02	0.69	$0.61 \pm 0.3^\dagger$	$0.43 \pm 0.06^\dagger$	$0.49^\dagger$
6	/	/	/	0.61 ± 0.03	0.43 ± 0.02	0.64	/	/	/
5	0.86 ± 0.02	0.51 ± 0.01	0.84	0.62 ± 0.03	0.44 ± 0.02	0.63	0.76 ± 0.03	0.62 ± 0.05	0.48

TABLE 4.1: The ^{241}Am α source detector results for timing coincidence, σ_c , values with efficiency of detection, ε , for the detectors discussed in this work with the calculated individual detector, ΔT , timing resolution. The symbol * denotes the pressure was 7.5 mBar and † denotes 6.6 mBar.

4.7 Detector aging and postmortem

The high fields and ionised isobutane environment leads to the production of hydrocarbon radicals, these can lead to detector aging known as the ‘Malter effect’, as described in Section 3.2.9. Literature states this process occurs over years of operation in drift chambers, however the detectors used here ran with fields orders of magnitudes greater than the a drift chamber with high particle flux. One of the 20 μm wire planes has been used in many of the experiments and this detector plane was deliberately run at a potential where frequent discharges and detector breakdown occurred for a period of two hours, to further age the detector.

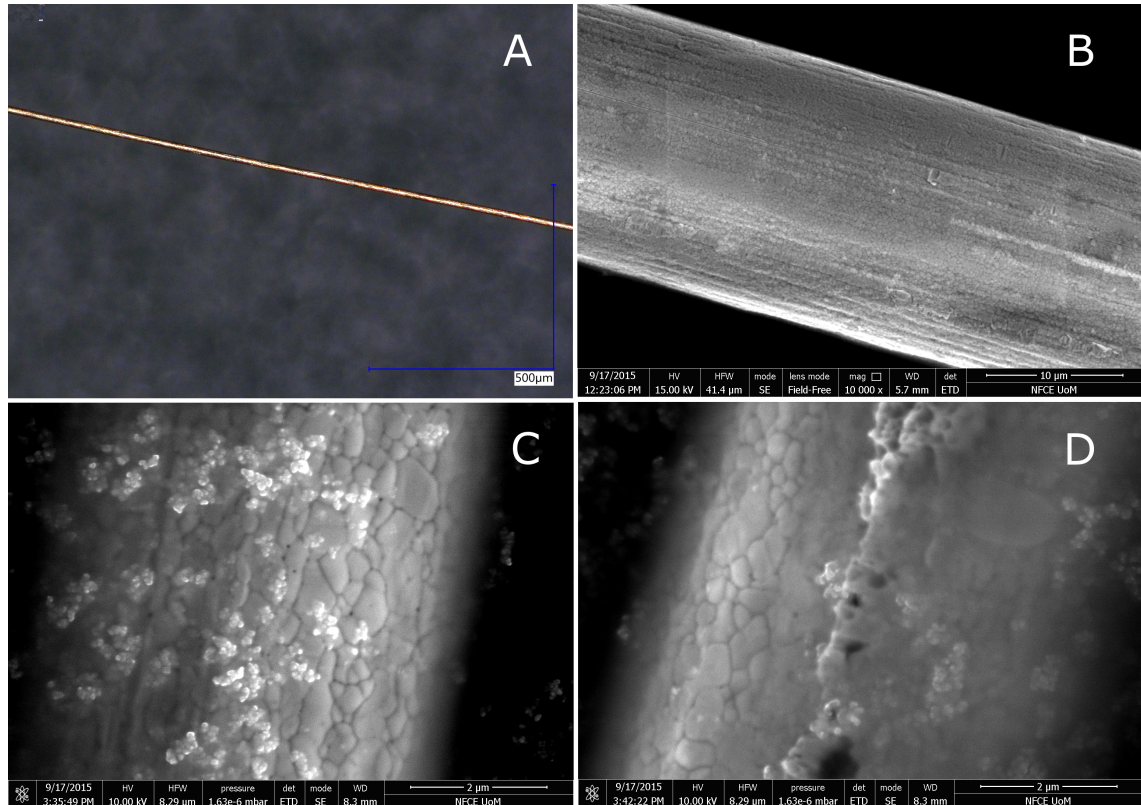


FIGURE 4.29: (A) An optical image of a 20 μm gold plated tungsten wire after use in the MWPC detector. (B) A SEM image of a 20 μm gold plated tungsten wire before use in the MWPC detector. (C) A SEM image of a 20 μm gold plated tungsten wire after use in the a MWPC detector. (D) SEM image of the 20 μm gold plated tungsten wire from a MWPC deliberately allowed to breakdown for a period of 2 hours. Images courtesy of M.Roy and J.Buckley, University of Manchester.

The detector was then striped down and a sample wire was removed and imaged under an optical microscope, there are no noticeable features resembling damage as shown in Figure 4.29 (A). The same wire was then imaged using a SEM (Scanning Electron Microscope) along with a control sample of wire from the bobbin. Figure 4.29 (B) shows the control wire with features of wire scoring in better detail and indentations formed on the soft gold surface from manipulation and manufacturing. Figure 4.29 (C) shows MWPC wire with spherical formations along it and Figure 4.29 (D) shows the formation of a jagged structure and what looks to be the de-adhesion of the gold plating from the wire.

The postmortem of the MWPC detectors revealed several locations of discharge made visible by a circular ring of discolouration on the grounding mesh. Within these regions the anode wire grids showed uneven tension in adjacent wires, blowing a jet of compressed air across groups of wires resulted visible difference. The most stable detectors during operation at the higher applied potential had more homogeneous tensions with very little deformation with an air jet. The importance of proper wire tensioning is evident from the prototype detectors and in literature for large area detectors [30]. It is possible conclude the friction plate method of production described in Appendix A.6 is not suitable for grid production with the tolerances required and shown in Table 4.2.

Wire diameter [μm]	Tension [N]	Pitch [mm]	L [cm]
5	0.04	/	/
10	0.65	1	25
20	0.65	2	85
30	1.45	/	/

TABLE 4.2: Maximum wire tension and stable support length, L , for tungsten wires with pitch operated at high field deformation [30].

New methods for wire winding were investigated with a prototype winding ring constructed to remove the tensioning issues is described in Appendix A.6, however it was not put into production for the construction of the large stop detector grids.

4.7.1 Conclusion

The detectors described in this section were all tested using the same methods to give a fair comparison in performance in the measured values of amplitude; rise-time; signal timing resolution, σ_t ; timing coincidence resolution, σ_c ; and detector efficiency, ε . The primary objectives set out for the development of the stop detector were; the improvement of the timing resolution, ΔT , for the fission fragment time-of-flight; increase the detection efficiency, ε , from the previously measured values at the ILL.

The development process has shown there are several possible designs as well as excluding others, the mesh PPAC provided significant improvements over all the requirements but was limited by mechanical construction problems. Investigations then showed a 20 μm gold plated tungsten wire plane can be used as an alternate to the mesh with significant improvement in the timing resolution, ΔT , with a slight reduction in the detector efficiency. However, the detector is capable of being stacked with duplicities, this makes any losses of efficiency recoverable with the additional detector layers. All of these 3 mm gap detectors designs performing better at low pressures, making them inefficient and indicating the influence electron drift has on ΔT .

Investigations into reducing the gap from 3 to 1.7 mm were only possible for the 10 μm , there were many unsuccessful attempts at this with the larger wire diameter planes. By reducing the gap we have shortened the drift distance of any charges produced before detection, the 10 μm wire MWPC reflects this with good ΔT performance at higher operational pressures for the α measurements.

The secondary electron testing provided a limited means to measure the performance of the detectors in the STEFF stop detector environment, the number of electrons ejected from the foil for an α is fractional to the number expected from fission fragments. For fission fragments the expected energy deposited and the

primary ionisations in the detector from the SEE foil would increase by a factor of 25; this makes the α measurements more relevant for the expected signals. Further testing with use of a fission source would have been preferable, however the time for prototyping was restricted.

The development process resulted in two designs where it was possible to stack the detectors allowing for transmission between multiple detection layers and allowing multiple measurements of the event. With the investigation concluded the choice of stop detector to be constructed to replace the STEFF stop detectors was a stack of two 10 μm wire planes with 1.7 mm gap and 1 mm pitch detectors.

The production of the wire planes was a difficult process, planes of these dimensions have not been constructed in the Schuster laboratories before, hence a backup detector of two layers 20 μm with 3.0 mm gap and 1 mm pitch was also commissioned.

From the results in Figure 4.23 a choice can be made to favour either efficiency or performance, with a limit of 10 to 8 mBar as the best regions of operation for both MWPC detectors.

Chapter 5

SEE foil development

The SEE (Secondary Electron Emission) foils are responsible for ejecting detectable electrons as fission fragments traverse, these are the source for the electrons triggering the start and stop detectors in Section 2.4. The foils are held at potentials of $V = -18$ kV and $V = -4$ kV, for stop and start detectors respectively, and positioned such that any SEE electrons are instantaneously accelerated to their respective detectors.

The fission fragment timing resolution is determined from two detectors, the start and the stop detectors. The start detector utilizes an MCP, where the rise-time and gain, M , are fixed to the applied potential. The stop detector shown in Chapter 4 has been optimised and is at the limits for what can be feasibly done. Ultimately both of these detectors have a response proportional the initial charges, n_0 , therefore increased electron emission from the foils will improve detector response.

The following Chapter discusses the development of the SEE foils with methods to get a quantifiable measure of performance and ultimately replacing the indium coated foils used in the prior STEFF deployment [6].

5.1 Prior work on SEE foils

Information on SEE for elemental and chemical compounds is common for electron collisions with low energies < 1 keV, with detailed information for elemental Z values from 1 – 40 as they play a significant role in scanning electron microscopy (SEM) [78–80] and photo-multiplications applications as well as the material development of MCP detectors [81].

The information available for fission fragment (with kinetic energies of 100 MeV) and 5 MeV α collisions resulting in ejecting backscattered secondary electrons is rare. There is some information available for small area SEE carbon foils giving the number of ejected electrons to be ~ 50 for heavy fragment collisions with fission energies [77]. There is also some elemental beam incident information with H^+ , He^{2+} and Li^{3+} beam on carbon foils for energies < 2 MeV from a tandem beam [82, 83]. For large area SEE foils (> 1000 cm²) carbon is not a suitable option, therefore an investigation was initiated into self supporting SEE foils that would be an improvement over the original SEE foils used for the STEFF time-of-flight detection.

5.2 Experimental set-up

In order to determine if the SEE foil was an improvement two parameters were chosen:

1. Number of backscattered electrons ejected from the surface of the foil per event. This is not strictly possible without a method of single electron counting, instead a fixed gain detector and the signal amplitude were used as a measure of number of electrons ejected.

2. Efficiency of detection. Through coincidence measurements it is possible to determine the relative efficiency of each foil.

For the SEE foil testing commercially available Al-Mylar was used, with $0.9 \mu\text{m}$ Mylar thickness and coated with a $0.2 \mu\text{g cm}^{-2}$ aluminium film on both sides to provide a stable, consistent and self supporting medium for the testing of foil coatings in this work. The merits of Al-Mylar have been proven in the past with VAMOS (an ion time-of-flight detector [84]) as well as other detector systems [85].

The foil coatings selected have been used in the past with photomultipliers and previous experiments [84, 86] and were CsI, LiF and In deposited on to the Al-Mylar surface with thickness of $10 \pm 1 \mu\text{g cm}^{-2}$ and the Al-Mylar as control. Each foil was prepared 24 hours in advance of the experiment by the process of thermal evaporation under a vacuum of $< 5 \times 10^{-6}$ mBar, with a large foil supported by a frame to be then divided and transferred onto the respective start or stop foil supports.

The source of ionising radiation was a ^{241}Am 288 kBq α source collimated to project α particles along a flight path of 30.4 cm through both electron foils. The initial start detector shown in Figure 5.1 is a double annular MCP, with a SEE foil charged to $V_{\text{strt-foil}} = -2$ kV angled at 6° to guide backscattered SEE electrons into the MCP as α 's pass through the foil. The angle of 6° has been shown in prior studies with the detector to be the optimum for electron detection [87]. The energy losses in the foil from the α particle transmission will effect the velocities and the time-of-flight between the two detectors. The consistency between the foils from the commercial Al-Mylar keeps the energy losses, ΔE_α , consistent. SRIM calculations gave the energy losses to be $\Delta E_\alpha = 0.102 \pm 0.006$ MeV for a 5.49 MeV α particle traversing the Al-Mylar foil.

The second MCP (Hamamatsu *f1942-04*) was angled parallel to the path of the α particles, electrons are emitted by a SEE foil supported in the flight path of

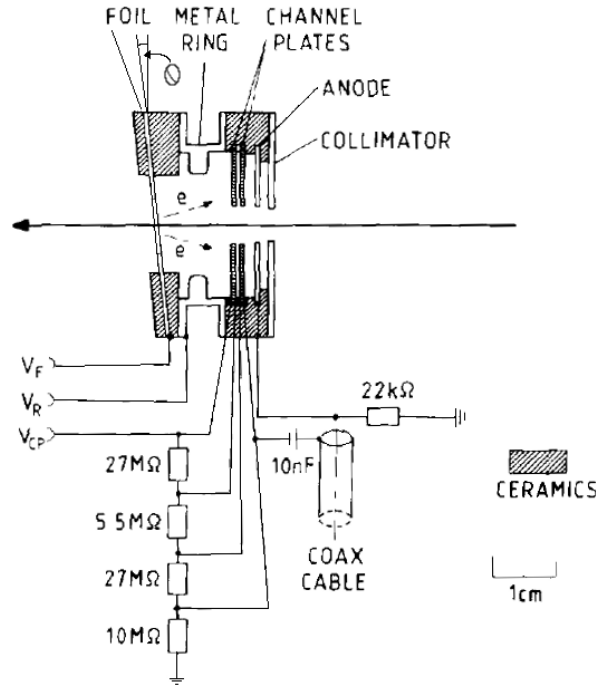


FIGURE 5.1: Start detector schematic layout with dual annular chevron MCP's with 6 mm aperture. The backscattered electrons from the SEE foil, angled at $\theta = 6^\circ$, are guided onto the MCP via the electrostatic field between the applied potentials on V_F , V_R , V_{CP} and MCP.

the α particles. The foil is charged to $V_{stop-foil} = V_{app}/2 = -2.0$ kV such that the backscattered electrons are guided by the electrostatic mirror into the MCP. The experiment was contained within a moderate sized vacuum chamber with two Edwards turbo molecular pumps maintaining an operational pressure of $< 2 \times 10^{-6}$ mBar. The high voltage was supplied with four Cooknell HV3 power supply units. The preamplifiers used were Ortec VT120 1 GHz bandwidth with a gain of 200 for the start and the customised Texas Instruments series high gain high bandwidth amplifier for the stop (described in Appendix A.4).

The signals were fully digitized with a PicoScope 6404D for every event triggered in the start MCP and also in the stop MCP. This gave improved methods of noise rejection and false coincident events rejection, a significant advantage over analogue techniques. Post processing of the data gave the signal timing resolution, σ_t (given by Equation 4.1), per event and the timing coincidence resolution, σ_c , of the two coincident detector events per α coincidence detection.

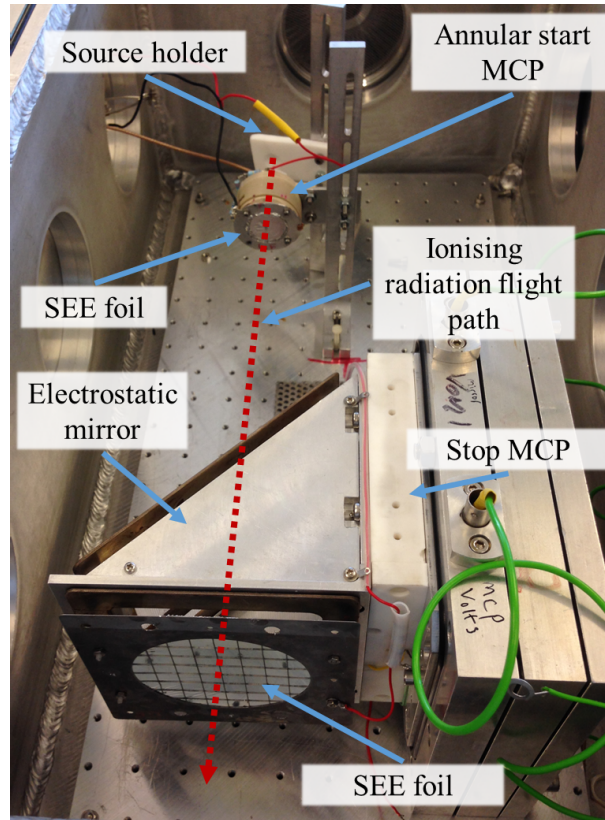


FIGURE 5.2: Experimental configuration of the two coincidence detectors with electrostatic mirror. The α particles ejected from the source that follow the red dashed line will pass through the start detector SEE foil and then through the stop detector SEE foil.

Due to the dark current on the MCP's the trigger threshold was set above noise at 60 mV and remained at this value throughout the course of the experiment. The PicoScope 6404D was set to record both channels with a 2.5 GS/s record rate with 8-bit scale, using one detector as a trigger to record 5×10^5 events (trigger start detector) and then repeated with the opposite detector as trigger (trigger stop detector).

5.3 Data processing

The flow diagram of the data processing is shown in Figure 5.3, the data was first prepared by applying a low pass SavitzkyGolay filter (a n-polynomial convolution digital filter specifically designed to increase signal to noise ratio) with cut-off -3

3db at 1.0 GHz to remove any high frequency noise and digitizer jitter without effecting any rising edge properties [88]. Followed by a base line linear fit to the pre-trigger samples and then subtracted to remove any amplifier offset. Then the induction reduction procedure was then applied, where a common shape is determined from a select group of non-coincidence events where there is an induced signal in the electronics. This was then fit to the data excluding the area of the peak (if any), when and if the reduced chi squared, χ_{red}^2 , values are below acceptance the fit was subtracted from the filtered data to produce the reduced induction signal, see Appendix A.11 for examples of this routine.

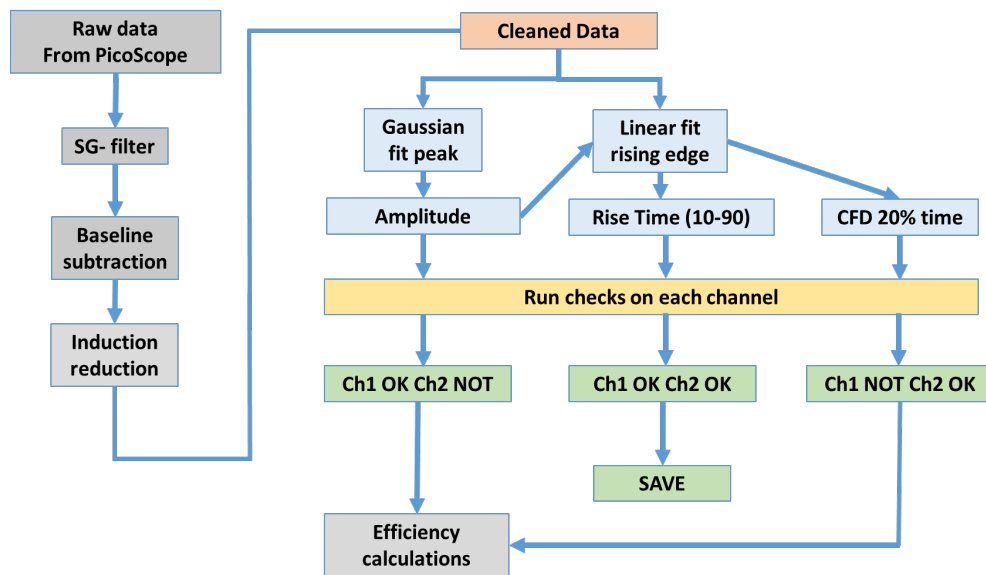


FIGURE 5.3: The digital processing program flow showing process from raw data to useful data.

After data pre-processing the signals were then analysed; a gaussian fit over top 20% of the rough peak amplitude, to get the amplitude value; from the amplitude and peak location it is possible to produce a linear fit along the rising edge of the signal, a fit was more preferable than a threshold dependent on amplitude due to effects of digitization (typically we had 8 – 12 digitizer bins along the rising edge) to get $\text{rise-time}_{10-90\%}$; and from the linear fit a CFD (Constant Fractional Discriminator) 20% trigger time measurement was applied. This information is then stored for later graphical processing and quantification of the foil's performance.

5.4 Results

There were two main objectives in this investigation, increase the number of SEE electrons, n_0 , and to improve the relative efficiency of detection via coincidence of the two detectors. The former can only be inferred via the amplitude.

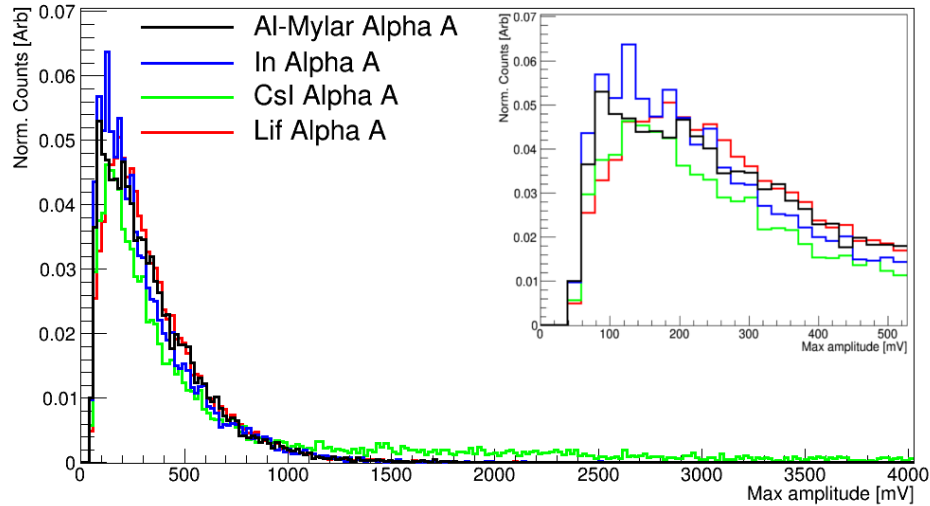


FIGURE 5.4: The amplitude distribution of the stop detector signals. Clearly some foils performed better than others as some peak distributions have greater maximum amplitude with a greater number of high amplitude events, such as the CsI (green).

The amplitude distribution of accepted events shown in Figure 5.4 gives an indication to the number of electrons ejected from the foils with nuclide impact. The peak is lacking in fidelity due to the distribution of electron emission from impact but was still possible to utilise the distribution as an indicator of secondary electron emissivity by utilizing a Landau fit. The results for each foil tested are given in Table 5.1.

The majority of energy deposited within the surface layer of the SEE foil will be through inelastic collisions, the electrons ejected from the reaction will scatter within the structure until ejected. The LiF reflected this with the largest simulated energy deposition and a peak separating from the trigger with and a large distribution of amplitudes. The CsI and In had similar energy deposition, the In

SEE Foil	Electrochemical Potential [eV]	SRIM ΔE [keV]	MPV Amp [mV]
CsI	7.2 ± 0.2 [89]	2.48 ± 0.01	171 ± 11
LiF	11.3 [90]	5.48 ± 0.02	201 ± 8
In	5.78 [91]	2.52 ± 0.01	154 ± 10
Al-Mylar	5.98 [92]	1.56 ± 0.01	N/A

TABLE 5.1: Amplitude for the various foils tested with surface ionisation energies and the simulated energy deposition within the foil coating layer of the SEE foil. There is a clear correlation for ΔE with the MVP signal amplitude

has a lower electrochemical potential leading one to conclude the work-function for electron emission be smaller, hence greater signal amplitude. However the surface of the In oxidises, this is speculated to produce an oxide ‘skin’ with electrochemical potential of 13.3 ± 0.2 eV [93], hindering the electron emission. The Al-Mylar showed no peak in the amplitudes and is below the trigger values selected. With low energy deposition within the Al and speculated surface oxidation issues leading to a skin with electrochemical potential of 10.5 ± 1.0 [94], it performed the worst of the chosen group.

The timing resolution was analysed using two methods, the signal timing resolution, σ_t , and the timing coincidence resolution, σ_c . Both of these values give a measure of the number of electrons emitted, as we have seen from Section 4.1 the signal timing resolution is proportional to the amplitude. The timing coincidence resolution, σ_c , is a measure of the energy deposited in the detector and the distribution within. The design of the stop detector mirror captures and accelerates almost all liberated electrons from the foils guiding them into the MCP, the more electrons entering the fixed gain MCP the better the timing signal timing resolution, σ_t .

The distribution of signal timing resolution for the varied foils given in Figure 5.6 shows the CsI and LiF had better timing properties, with Landau fits (not shown) giving the most probable value of $\sigma_t = 66 \pm 6$ ps, followed by LiF at $\sigma_t = 164 \pm 8$ ps. The peak performance of the In and Al-Mylar was not as poor as the amplitude distribution indicated, $\sigma_t = 204 \pm 24$ ps and $\sigma_t = 188 \pm 15$ ps respectively.

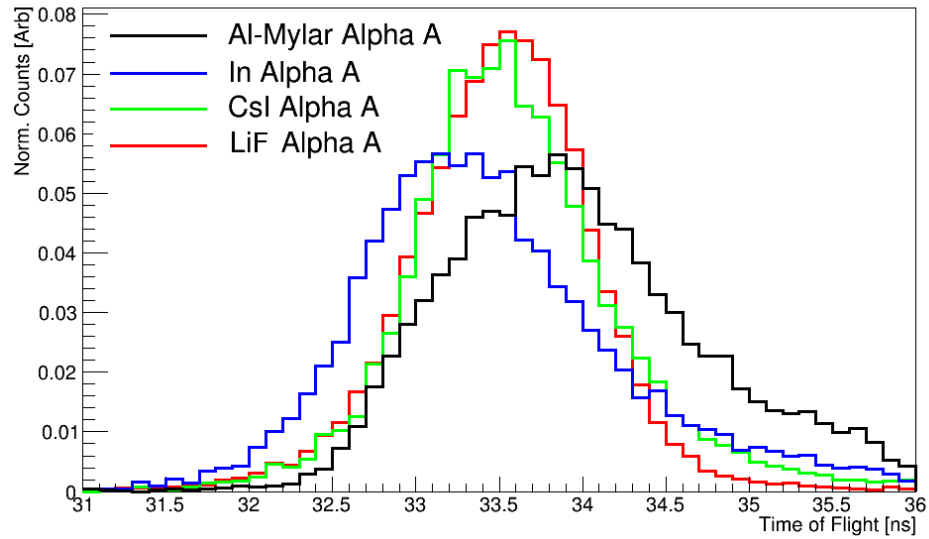


FIGURE 5.5: The time-of-flight for start and stop coincidence for various SEE foils. The narrower the peak the better timing performance achieved through change of the SEE foil, the LiF and the CsI showed better performance compared to the other SEE foils.

The timing coincidence resolution, σ_c , between the start and stop detectors, Figure 5.5, shows a slight variation in the time-of-flights with a significant variation on σ_c . From Figure 5.5 the timing coincidence resolution was determined via a gaussian fit of each timing peak for each of the foils. The gaussian fits give the σ_c for LiF and CsI as $\sigma_c = 494 \pm 35$ ps and $\sigma_c = 518 \pm 64$ ps respectively and the In and Al-Mylar as $\sigma_c = 660 \pm 87$ ps and $\sigma_c = 741 \pm 63$ ps respectively. These show similarities to the signal timing resolution results with the CsI and LiF showing better values in Figure 5.6.

The efficiency of the foils was calculated by comparing the coincidence and non-coincidence events in the start and stop detectors, then normalising to the In values, keeping all variables fixed but the foils.

The efficiency of the foils given in Table 5.2 shows all the alternate foils perform better than the In. CsI and LiF show a 12% and 6% improvement over the In previously used SEE foils, with the exception of the Al-Mylar foil.

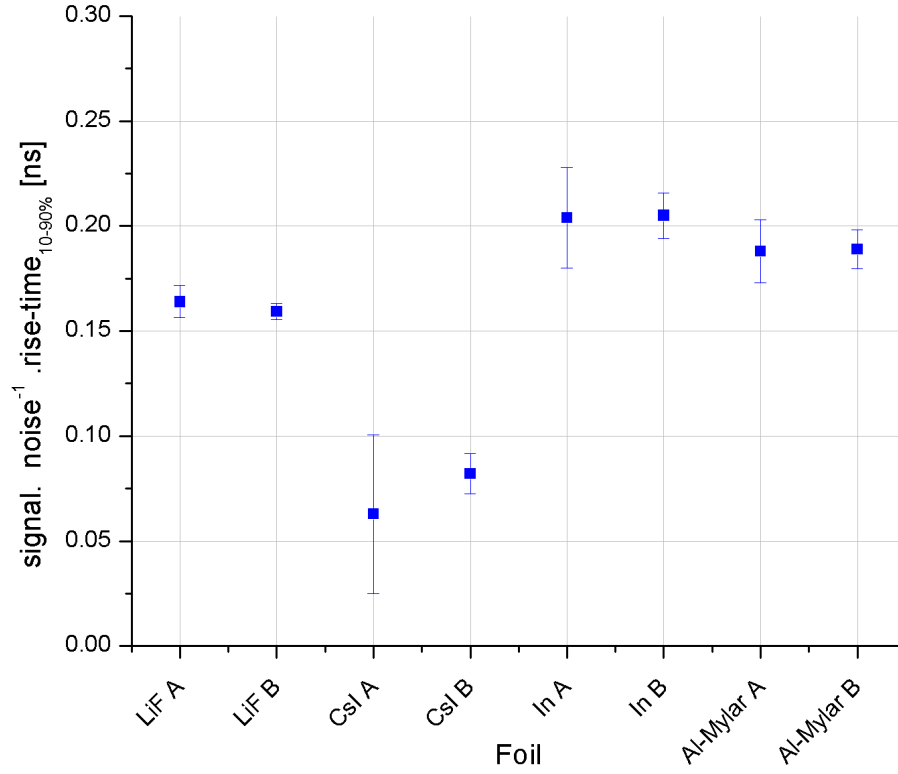


FIGURE 5.6: The signal timing resolution, σ_t , MPV values for Landau fits for each foil. The values for A and B representing the two triggering positions.

Foil	Rel. Inc.
CsI	1.06
LiF	1.12
In	1.0
Al-Mylar	0.98

TABLE 5.2: The relative detection efficiency of the two detectors with varied foils compared to the current In SEE foils in use. Normalized to the currently used In foils in STEFF showing two candidates for improved efficiency, LiF and LiF.

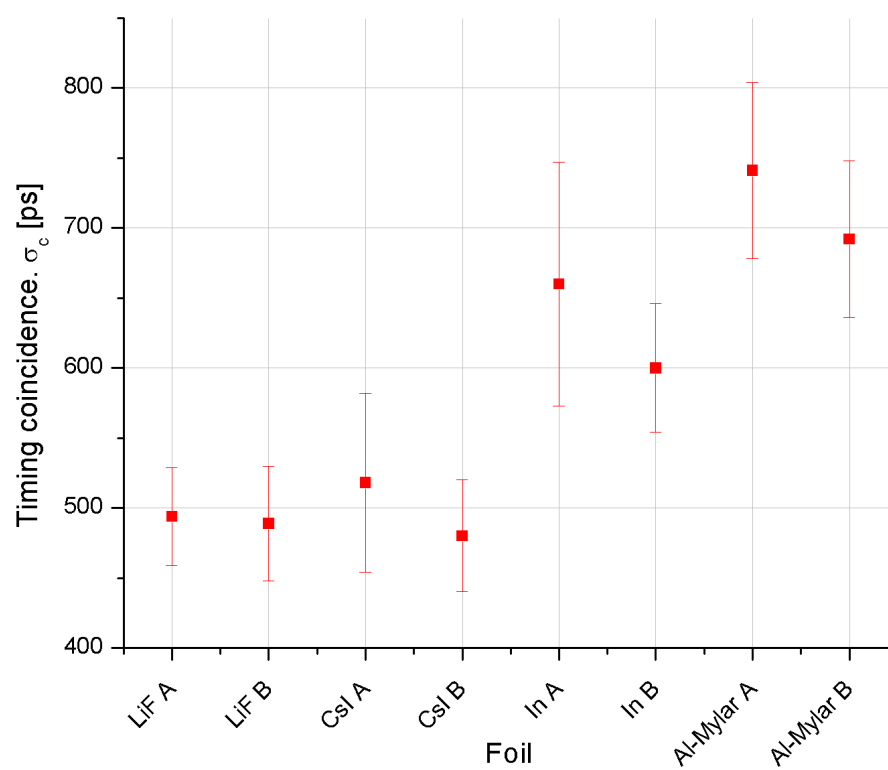


FIGURE 5.7: The σ_c values for the timing coincidence peaks where the values for A and B representing the two triggering positions for the selection of SEE foils tested.

5.5 Conclusions

The objective of this investigation was to determine if and what improvements could be made to the SEE foils in use on the STEFF experiment. From the perspective of timing resolution, ΔT , of the stop detectors, the signal timing resolution, σ_t , gave an indication to improvements relative to each foil but cannot give the timing resolution of the detector array. The time-of-flight distribution gave the timing coincidence resolution, σ_c , of the combined detector array. Since we did not have a measure of either detectors individual timing resolution other than σ_t , it is not possible to determine the timing resolution without using identical detectors. We can determine the relative improvement made to the detection and the efficiency from the SEE foils tested.

The results of this investigation were LiF and CsI give better timing performance over the current In foils. The CsI showed good performance, however it is hydroscopic [95] and deteriorates when exposure to atmosphere. During the SEE foil experiment it was possible to see the normally colourless CsI compound had an intense blue and over the course of a few days exposed to atmosphere it changed to an off white milky colour. The discolouration was due to the dissolution of the crystal lattice with water molecules; an electronegative compound that reduces emission and the plausible cause for the reduced amplitude and efficiency. The hydroscopic nature of this material made it unsuitable for the STEFF spectrometer as it would be frequently exposed to atmosphere during maintenance.

The efficiency measurements were only comparable to the baseline foil of In, any further investigations should include a third detector system for measurement of coincidence between the two MCP detectors.

Future investigations should look into layer thickness and substrate composition,

with additional compounds such as copper iodide, magnesium fluoride and potassium bromide. With the use of a fission fragment source it would be possible to gain very useful information on the relative electron ejection for light and heavy fission fragments.

From the results and considerations during the investigation the optimum choice for SEE foil coating was LiF with a $10 \pm 1 \mu\text{g cm}^{-2}$ layer on the much thinner formvar substrate foil for the STEFF replacement SEE foils.

Chapter 6

The neutron Time Of Flight (n_TOF) facility

The neutron Time Of Flight facility (n_TOF) is a pulsed neutron source situated at CERN, Geneva, and is a response to satisfy the needs for new and accurate nuclear data. n_TOF began operation in 2001 and since then it has been used for a multitude of important neutron cross-section measurements with unprecedented energy resolution for both fission and neutron capture measurements. The notable advantages over other neutron beams, such as ORELA and GELINA, is the high instantaneous flux, the high resolution and the wide energy spectrum of the neutron beam; ranging from meV energy up to GeV. n_TOF also has high performance detection systems available with ‘cutting-edge’ data management systems. Recent experiments have greatly aided the understanding and solution to many long standing problems, such as the light particle solution to the cosmic lithium problem [96], nuclear waste management, the ${}^7\text{Be}(n,\alpha)$ reactions cross-section, as well as many other important measurements made at n_TOF [19].

The n_TOF facility has two areas for experiments to be carried out, EAR-1 (Experimental ARea 1) and EAR-2 (Experimental ARea 2), each area has its own

beamline from the neutron source, 185 and 20 m for EAR-1 and EAR-2 respectively as shown in Figure 6.1. The two experimental areas are Class A laboratories allowing the use of unsealed radioactive sources with very high activity. The following Chapter will discuss the n_TOF facility in detail, with particular attention on the aspects used during STEFF ^{235}U campaign.

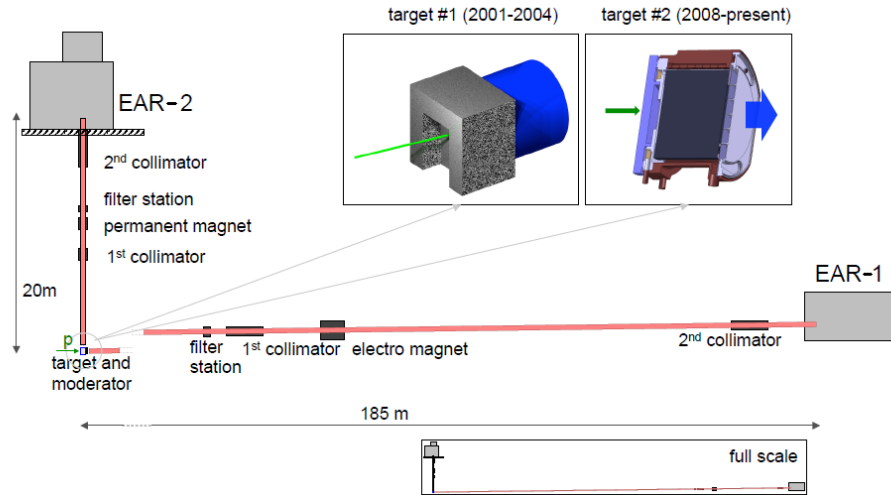


FIGURE 6.1: Layout of the n_TOF facility with its two beam lines ending in the experimental areas EAR-1 and EAR-2. The neutron source is a Pb spallation target surrounded by cooling water. The incident proton beam with a nominal energy of 20 GeV/c makes an angle of 10° in the horizontal plane. In the direction of EAR-1 a separate neutron moderator is located. The two types of targets that have been used up to now are shown in the inset. The horizontal beamline has in reality a small angle of approximately 0.68° upwards [19].

6.1 Neutron beam production

The neutrons are produced from the spallation reaction of high energy protons (20 GeV/c) impacting a Pb target, the neutrons produced are moderated in the fast region as they propagate out of the target and then drift through the beam pipes to the respective areas. The neutron energy is determined via time-of-flight techniques from the detectors in the area and exploiting the electromagnetic processes that occur during the spallation process.

The protons used for the spallation reaction are accelerated via three stages; they begin in the Linac2 (Linear accelerator 2) where they are accelerated to 50 MeV, then the beam is injected into the PS (Proton Synchrotron) booster where the beam energy is increased to 1.4 GeV/c, this is also the point at which it is possible to add up to four bunches in close succession for injection into the PS (Proton Synchrotron) as a single ‘pulse’. The PS is the final stage of acceleration before extraction to n_TOF where the protons are accelerated to 20 GeV/c. This is also one of the many branching points for other experiments. For example the parasitic pulses that n_TOF receive are from sharing a ‘pulse’ with the East area experimental hall, who have different beam requirements and resulting in a larger RMS than the primary ‘pulse’.

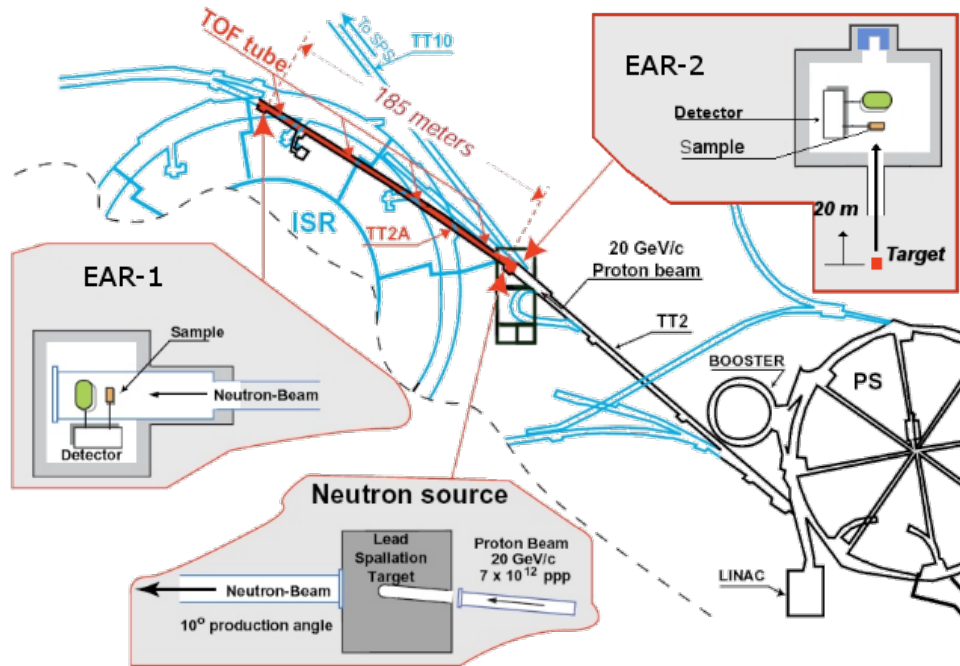


FIGURE 6.2: Layout of the CERN accelerator complex with the n_TOF facility EAR-1 and EAR-2 shown, see text for further information.

The demand for protons by all the experiments that use the PS are distributed in the form of the ‘super-cycle’, where pulse frequency is determined with a minimum of 1.2 s per pulse (the 0.8 Hz PS duty cycle). The ‘super-cycle’ generally contains several pulses destined for the n_TOF spallation target, this varies depending on

the demand from other experiments and the spallation target power dissipation limitations; the result of which is a nominal duty cycle of $0.2 - 0.4$ Hz. The $20\text{ GeV}/c$ primary proton bunches have 7×10^{12} charges per primary pulse and 2.5×10^{12} charges parasitic pulses with a bunch width of r.m.s of 7 ns for primary and $\sim 15\text{ ns}$ for parasitic. The intensity of each proton bunch is probed with a BCT (Beam Current Transformer) which is an electromagnetic loop sensing the beam current. The BCT delivers a fast signal which gives a time reference of the bunch and whose amplitude is proportional to the number of protons.

The n_TOF spallation target consists of a Pb cylinder 400 mm in length and 600 mm in diameter surrounded by a layer of demineralized water acting as coolant and in the forward direction an additional moderator layer filled with borated water in saturation. The target is surrounded by an Al container and supported by an Al alloy structure. The support structure has a polygonal opening on the top to allow the lowering of a vacuum chamber for the vertical beamline down to the level of the target, see Figures 6.3 and 6.5.

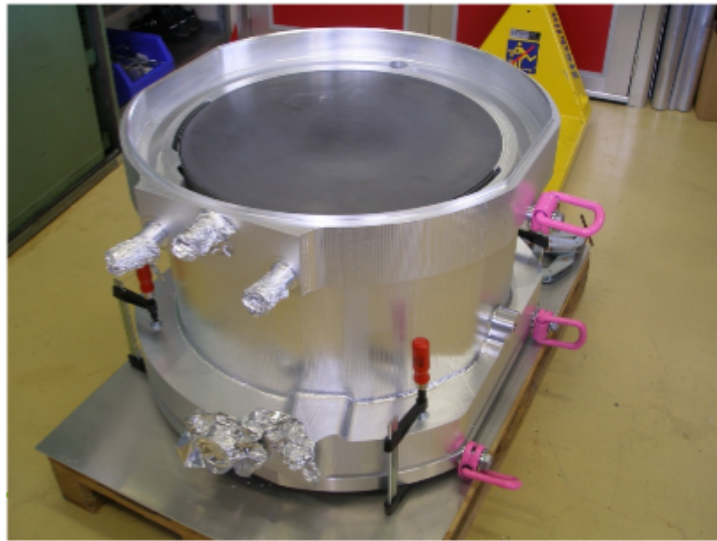


FIGURE 6.3: A photograph of the Pb spallation target (side facing up) before installation during the 2012 long term shutdown. Courtesy of C.Weiss.

The term spallation generally refers to all processes which occur on varied time

scales when high energy relativistic light particles collide with heavy nuclei targets resulting in ejected ‘spall’ particles. The processes that occur can be broadly surmised by first an intra-nuclear cascade (nucleon-nucleon collisions) where some fraction of the energy is lost. This ‘fast stage’ of nucleon-nucleon scattering interaction leads to the ejection of some of the nucleons and to the excitation of the residual nucleus which will cool afterwards (in the second stage). The de-excitation of the residual nucleus can proceed in two main ways: evaporation and fission. The evaporation is the dedicated de-excitation channel and the excited nucleus emits neutrons, nucleons or light nuclei such as D, T, α , Li, Be. The second important de-excitation mode is fission, generally the fate of the nucleus is its fragmentation. The nucleus emits particles until its excitation energy falls below the binding energy of the last nucleon, at this state about 8 MeV is remaining and will be emitted by γ -ray radiation. The de-excitation process does not end with the ending of the γ -ray emission. In fact the nucleus resulting after γ -ray decay is often radioactive which will decay until the corresponding stable nucleus is reached. Figure 6.4 shows the various reactions that can occur [97].

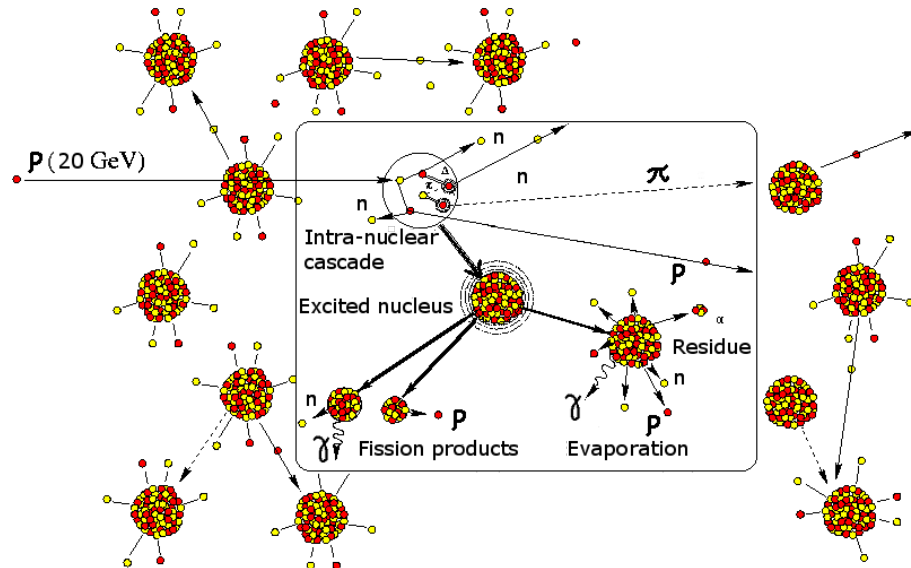


FIGURE 6.4: Schematic of the spallation processes and reactions, there are many processes that result in the production of neutrons as well as many other particles, charged and neutral. See text for further description [98].

All the processes described result in the emission of a considerable number and variety of secondary particles ($\mu^\pm$, p, n, $\pi^{\pm,0}$, γ , etc.) among which neutrons represent a large fraction, typically 300 per incident proton [19, 99]. The number and energy of which depend on the material of the target and the projectile energy [98]. This is a key area of interest at n_TOF as the current target is to be replaced during the next long term shutdown due to corrosion issues and excessive contamination of the coolant circuit.

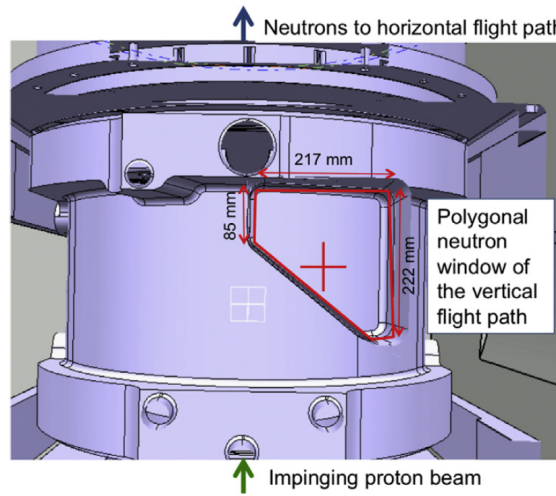


FIGURE 6.5: A false colour CAD image of the Pb Target, birds eye view. The proton beam is impacting from the low edge of the image, the polygonal window for the EAR-2 flight path is highlighted red and the cross highlights the center of the EAR-2 vacuum beam pipe. Courtesy of C.Weiss.

Post spallation the neutrons (and other particles, charged and uncharged) isotropically radiate out of the target (particles will preserve some of the proton momentum higher energy particles will radiate forward, hence higher neutron energies found in EAR-1. They traverse their respective beam lines where both beam lines are fitted with primary collimators and sweeping magnets to remove the undesirable charged particles. Post sweeping magnet the beam reaches a secondary collimator, this final collimation stage determines the beam geometry for their respective areas, see Figure 6.1 and Figure 6.6 for the layout.

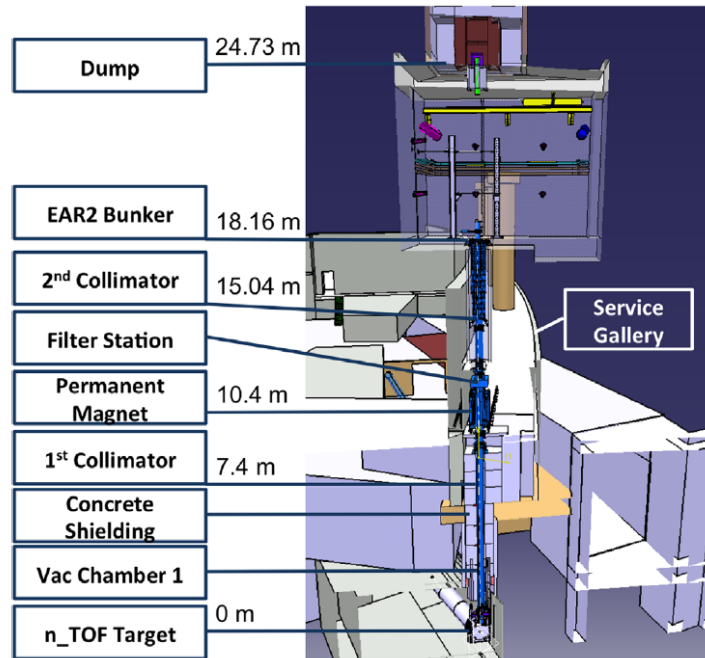


FIGURE 6.6: The layout of EAR-2 showing the positions of the beam components (beam lines, sweeping magnets, collimators and dump) and their positions in the beam line [100].

The neutron fluence (neutrons flux per unit time) in each area has been determined with use of simulations and experimentally verified via several flux monitoring experiments, some of which have been ongoing as a passive permanent beam measurement installation in both EAR-1 and EAR-2. An example of which is the SIMON (SIlicon MONitor) beam monitoring system which uses the well known ${}^6\text{Li}(n,t)\alpha$ reaction to gauge the fluence of the beam [99]. This combination of detector systems and simulations provides a neutron spectra of the beam per nominal proton pulse, 7×10^{12} , see Figure 6.7.

Neutron energy is determined via time-of-flight, where the neutron is created at a time, t_0 , and traverses the beam pipe to the experimental area at a distance, L , where they are detected time $t_0 + t$. The measured time-of-flight, t , of the neutron with rest mass, m_0 , together with the known flight distance, L , determines the neutron kinetic energy, E_n , using the energy-momentum relation with the neutron velocity $v = L/t$ and momentum $p = m_0 v$ as

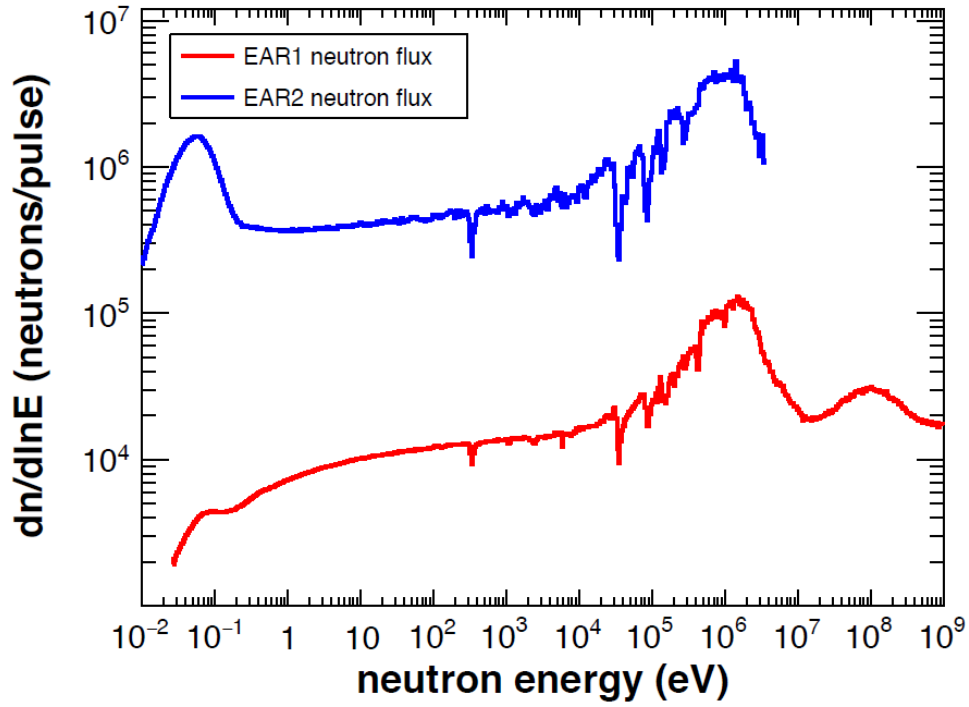


FIGURE 6.7: Neutrons per pulse as a function of isoethargic energy ($dn/d\ln E$) per 7×10^{12} protons on target, as seen at the sample positions at normal distances of 185 m, EAR-1, and 20 m, EAR-2. The resulting neutron spectra or evaluated flux is the result of simulations and beam measurements. The strong reduction in thermal peak in EAR-1 is due to the borated water moderator of the face of the lead target.

$$E_n = E_{tot} - m_0 c^2 = m_0 c^2 (\gamma - 1), \quad (6.1)$$

where

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}, \quad \beta = \frac{V_n}{C} = \frac{L}{ct_{tof}}, \quad (6.2)$$

where c is the speed of light, V_n is neutron velocity, m_0 is the neutron rest mass, L is the flight path length and t_{tof} is the neutron time-of-flight. In the non-relativistic case the calculation becomes much simpler,

$$E_n = \frac{1}{2} m_0 \left(\frac{L}{t_{tof}} \right)^2. \quad (6.3)$$

The reality of this is the neutron energy, E_n , will be detected with a distribution of energies determined by; the measured time-of-flight, from the detector resolution; the flight path, L , due to moderation within the target; and the proton r.m.s pulse width. The distribution in neutron energies due to target moderation is referred to as the resolution function and is determined via simulations and validated with experimental measurements [100].

6.2 EAR-2

The STEFF ^{235}U campaigns for both large and small target diameters were conducted in the EAR-2 facility with two different collimator configurations, narrow and wide, providing a narrow diameter beam and large diameter beam respectively. EAR-2 was chosen to stage the experiment as it has a higher instantaneous neutron flux over EAR-1, this radically reduces the target mass or the beam time required for the measurement.

6.2.1 Narrow collimator

The narrow collimator shown in Figure 6.8 provides a narrow beam profile with 21.8 ± 0.2 mm diameter aperture well suited for sensitive experiments requiring a low background. This set-up has significant amounts of shielding around the beamline and the collimator, intricate details of which are readily available [100].

The beam spot produced from the capture collimator is dependent on the distance from the aperture, simulations in FLUKA provide the beam cross-section profiles and are noticeably different, see Figure 6.9. The FLUKA software package is a general purpose toolkit for calculating transport and interactions with matter and has been used extensively to model aspects of the n_TOF facility with the goal of beam optimisation [101–103].

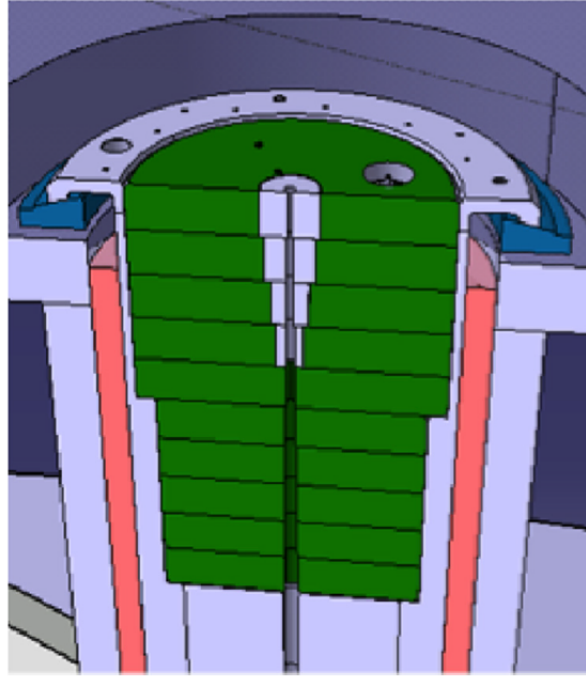


FIGURE 6.8: The narrow collimator housed inside the large vacuum vessel which is supported 120 mm below the EAR-2 floor. The B-PE (Borated Poly-Ethylene) is shown in green with the B_4C core in the last 400 mm in light blue. The stainless steel spheres installed in the vacuum vessel, for shielding, are highlighted in red.

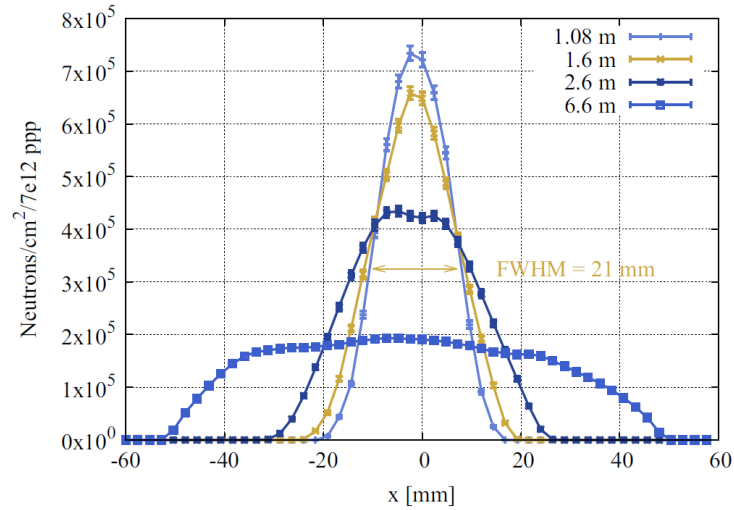


FIGURE 6.9: Neutron beam profile projections at different heights from the experimental area floor for thermal neutrons with the capture collimator. The beam profile for STEFF sample height is given as 21 mm and the beam dump entrance window is at 6.6 m from the floor [100].

6.2.2 Wide collimator

Extensive simulations in co-operation with the CERN design team led to a new design of collimator, the wide collimator, for a larger beam spot with increased neutron luminosity. Simulations were completed in co-operation with M.Sabate (CERN) to provide a beam profile at STEFF target height and is shown in Figure 6.10. The wide collimator has similar design to the narrow collimator with a larger and different aperture, it was newly constructed for a set of experiments of which STEFF was the first and installed two days prior the STEFF second installation.

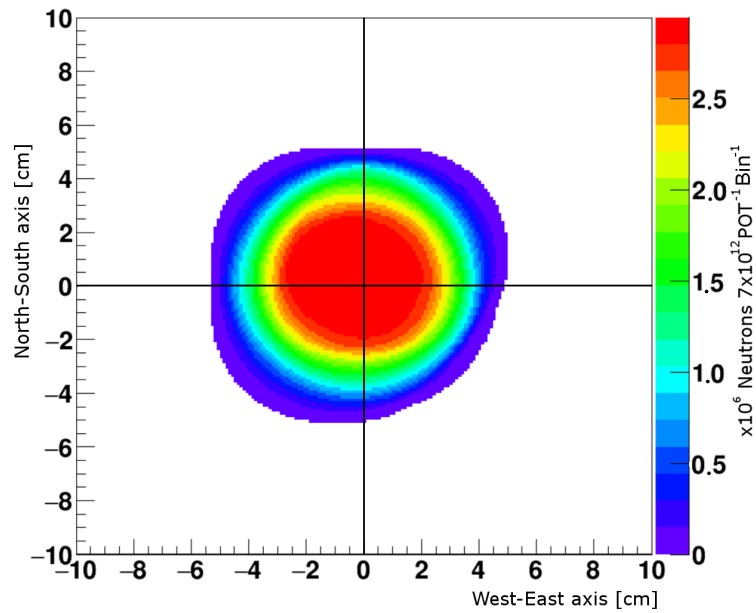


FIGURE 6.10: Neutron beam profile image at 2.0 m from the bunker floor for the large collimator for an energy window of 1 – 10 eV.

The large collimator installation also requires a modification to the beam dump reducing its effectiveness, with increased neutron flux and therefore background in the area is increased.

6.3 γ -flash

From the spallation reaction a significant amount of charged and neutral particles are produced other than the desired neutrons, this is problematic for measurements as it can blind the detector for significant periods of time if not properly dealt with. To combat this a large sweeping magnet is situated 10.4 m above the target with $\text{Sm}_2\text{Co}_{17}$ permanent magnets with a large iron yolk to smooth possible field perturbations along the 1.13 m dipole length.

The magnet design was based on a simulated charged particle spectra resulting from the spallation reaction and is capable of removing the charged particles in the beamline up to protons with 1.205 GeV/c momentum.

Unfortunately there is no possibility to remove unwanted neutral products from the beam, fortunately the short lived exotic neutral particles decay before the magnet however the γ -rays will remain. The inability to remove the γ -ray component and other contributions from the beam, results in burst of energy in the detectors in the experimental areas; this effect is referred to as γ -flash. This combined with high energy neutron scattering within the walls of the area represents the majority of the background associated with experiments sensitive to these effects in this environment. The magnitude of the γ -flash is dominated by the choice of collimator used in the beamline (changing the beam collimator to the larger aperture also results the removing of a ring of B-PE shielding for neutron backscatter prevention in the beam dump) and the position of the detector relative to the beam [101].

The majority of detectors are effected by the γ -flash, some blinded for a period of 50 – 100 μs and others unaffected, examples of γ -flash with the STEFF detectors are shown in the Appendix A.8.

6.4 Data acquisition systems

The n_TOF facility includes a maintained digital acquisition system with capabilities of recording 120 channels at varied rates from 0.125 – 1.800 GS/S for recording windows of up to 350 million samples per channel depending on the specific model of card used [104]. There are available three type of digitizers, Aqciris DC282 10-bit cards, SP-device ADQ412 12-bit and the SP-device ADQ14 14-bit cards. Each of the cards takes advantage of the FPGA (Field-Programmable Gate Array) chip, with four channels per card and four cards are coupled together into a DAQ machine crate.

A DAQ machine crate is its own independent computer with Supermicro 4027GR-TRT chassis, dual Xeon CPUs (E2650-V2) (giving it 16 physical cores), 392 GByte of RAM and 28 TB of HDD space raided for maximum performance while maintaining a backup clone partition with read/write speeds of 5 GByte/s.

The cards are triggered to record by an external triggering system linked to the beam pick-up or the timed calibration clock pulse. Once the time window has been captured the data is then transferred from the card to RAM via the PCI-e port. From the memory an optional routine called *0-suppression* can be utilised to only record the values that exceed a given threshold over a given time window. The data is then written to the DAQ HDD for temporary storage. Each of these independent systems is referred to a DAQ of which four were utilised for the STEFF experiment, a map of the system is outlined in Figure 6.11.

The DAQ HDD's hold the recorded data temporarily before transferring too two non-local hard disk pooled servers, after which the DAQ data is deleted. The pooled hard disk server then transfers the data to long term storage on the CASTOR (Cern Advanced STORage) tape store. The data on the hard disk pooled server is deleted after a confirmed clone to tape to allow for continued recording

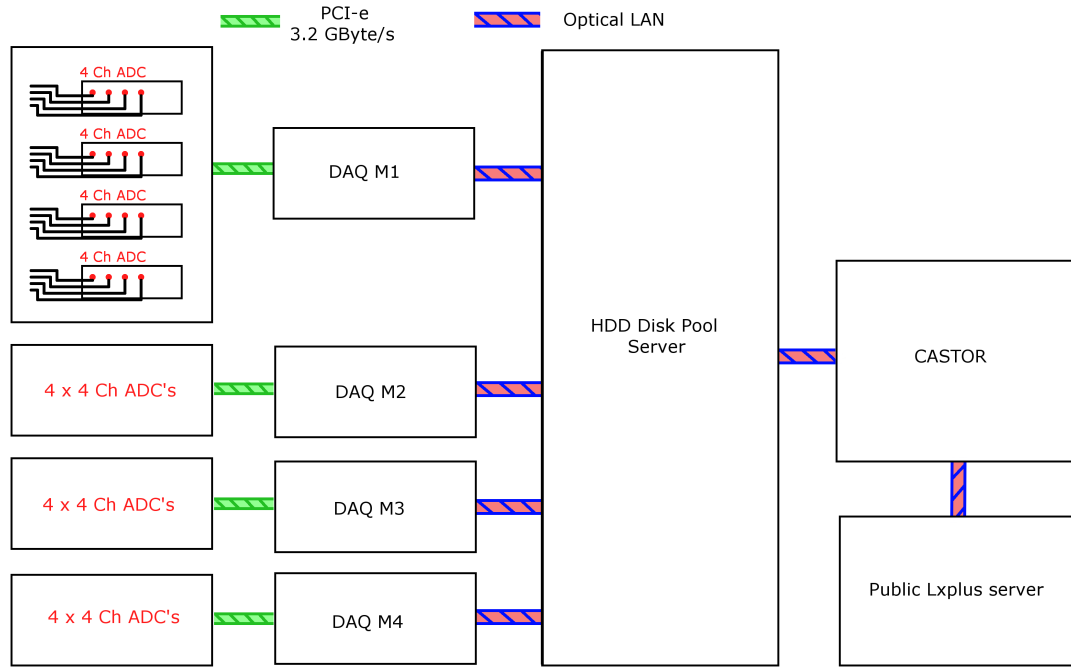


FIGURE 6.11: A diagrammatic layout of the data acquisition systems used in the STEFF experiment in EAR-2. The DAQs represent independent data taking machines connected to a HDD disk pool server located some distance away in the data storage centre of CERN.

of data. The DAQ HDD's also form a buffer in case the connection to hard disk pooled servers is overloaded (due to other experiments) or goes down.

To access the recorded data there are two methods: a program located within the n_TOF control room DAQ control room computers called *FileViewer* - a java script GUI (General User Interface) to view individual channels of raw data as it is recorded on the HDD disk pool; and the *SignalAnalyzer* code written to aid the production of the *UserInput* file for processing of the data. The *FileViewer* can only view data that is temporarily on the hard disk pool (its duration of availability is typically a few days), the second *SignalAnalyzer* method can only view data that has been 'staged' from CASTOR to the public LXPLUS server. 'Staging' the data is the process of copying the data from the tape drives of CASTOR on to a public LXPLUS disk where it becomes read only accessible, if the data is not 'staged'

it is inaccessible. The process of ‘staging’ a file can take from 4 – 12 hours per file depending on the number of files requested and server demands. Alternately to view online signals from detectors the other option is an oscilloscope in the electronics area of the EAR-2 bunker and connect directly to the detector output.

6.5 Summary of n_TOF

The outstanding features of the n_TOF AREA 2 neutron beam facility are the very high instantaneous neutron flux, excellent TOF resolution, low intrinsic background, the coverage of a wide range of neutron energies and dedicated DAQ and data management systems. These features make it possible to perform the proposed fission studies of ^{235}U without the need for a large amount of fission material or an extensive beam time exposure.

Chapter 7

STEFF premier at n_TOF

The premier run of STEFF at n_TOF was scheduled for installation on the 13th of October 2015 in EAR-2 for a duration of 21 days of beam which equated to 2.2×10^{18} POT delivered from the PS; a total of 1.36×10^{18} POT were delivered while the detector and acquisition systems were stable. The experiment used the narrow collimator installed on the n_TOF beamline and the small diameter ^{235}U target with an additional B-PE insert in the beam dump to reduce the background of scattered neutrons, which were a concern because they interact with the NaI(Tl) γ -ray detectors.

This Chapter discusses the details of the run, data processing and preliminary results from the first installation of STEFF at the high flux vertical neutron beamline in EAR-2.

7.1 Preparations

The experiment required several months of construction and testing of all the components prior to the installation in the experimental area. The STEFF experiment would first require replacement of several parts and installation of new components

including the complete dismantling of every vacuum seal, installing new support frames, replacing SEE foils, additional FiFi arm installation and new methods of filling and evacuation of gaseous and vacuum regions as seen in Chapter 2. All these works were completed on time in the staging area (warehouse B-272 R-005, CERN). The system was kept under vacuum for the duration of the month leading up to the experiment to allow for the chambers to degas; typically outgassing takes a week to achieve good ($< 2 \times 10^{-6}$ mBar) vacuum and a month to get the limit of vacuum in STEFF ($< 5 \times 10^{-7}$ mBar). Testing of the detectors with a fission source was restricted due to radiological limits placed on the area and a ^{241}Am α was used to test the detectors.

7.1.1 Alignment with beam

Great care was taken to ensure the beam profile impinged on the target positioned centrally to optimise the fission rate and reduce scattering. The target was angled at $\phi_{beam} 21 \pm 2^\circ$ to the horizontal axis with the uranium surface facing the Brgg arm. Poor beam alignment results in neutron interactions with the surrounding STEFF structure and producing background reactions that can result in photons that have detrimental effects on γ -ray measurements.

The STEFF experiment was adjusted in the vertical Z-axis by four large jacking screws to minimise the air gap between the two vacuum windows on the lower section of the STEFF chamber. To align the horizontal X-Y axis to the beam gafchromic film was utilised; several films were placed on the STEFF beam in and out windows and the beamline entrance and beam dump window.

The gafchromic foils darken with exposure to the neutron beam as shown in Figure 7.1. From the darkened foil an alignment measurement was made; to improve the beam image a post-processing operation took place. A process of scanning the foil and using digital photo editing software *Gimp2.0* [105] it was possible

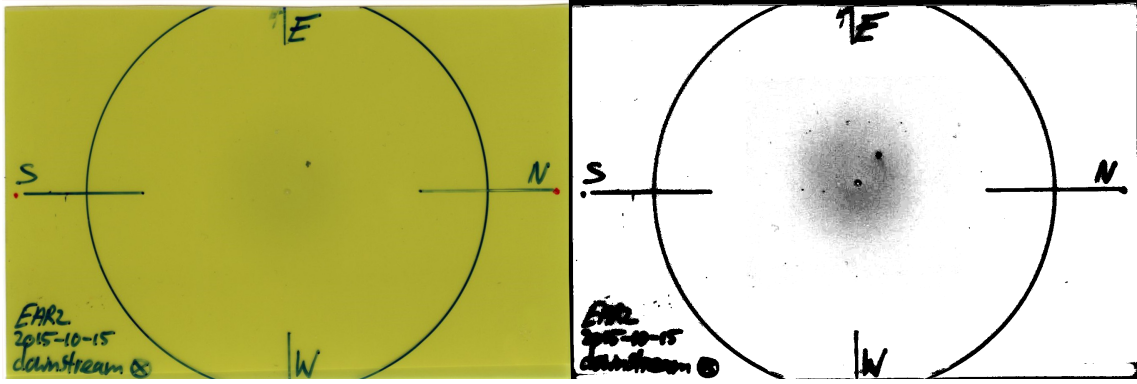


FIGURE 7.1: (Left) The gauchromic foil after 12 hours of beam exposure with the alignment cross-hairs drawn on aligned to the bunker walls. (Right) Post-processing the beam exposure on the foil becomes more apparent.

to de-saturate and enhance the darkened regions. Then with the *ImageJ* [106] program a straight line trace across the cross-hairs produced a histogram plot of the pixel value with respect to position providing the beam location accurately. This process resulted in a ± 2 mm beam alignment to the target, the majority of the error was associated with the physical moving of the experiment to alignment (the weight of the experiment would sink the castors into the concrete floor making fine adjustment impossible).

7.1.2 Calibration

Following installation in the EAR-2 facility (a class-A laboratory) it was possible to use the ^{252}Cf binary fission fragment source described in Section 2.2 to test the Bragg and Hips detectors; the previous α testing did not deposit enough energy to produce large enough signals. This was used as a test of functionality for the detectors. After the experimental beam run there was the CERN winter shutdown allowing a long duration calibration run of two weeks in experimental conditions and with the n_TOF DAQ.

The ^{252}Cf sample was placed in the target position by removing the sealed target changing mechanism and taking the unit to the ISOLDE class A α laboratories,

where under a fume cupboard it is possible to handle the unsealed sources. After sample installation the target-changing arm is sealed and re-attached to the gate valve of STEFF. After pumping the small volume of the sample changing arm it was possible to equalize the central chamber by opening the gate valves, then slide the sample into the beam position.

The n_TOF DAQ did not have the capability to self trigger on multiple on channels at this time nor did the DAQ have the ability to accept an external trigger other than the beam/calibration trigger. This made data taking for the duration of ^{252}Cf calibration measurement difficult as we could only set an un-triggered periodic record window of 30 ms every 2.4 s and rely on accidental coincidences between the trigger and the fission event. This gave a predicted rate of 1.3 fissions per record window per large Bragg chamber.

7.1.3 Channel configuration

The data acquisition systems digitizes the analogue signals from 63 channels over 4 DAQ machines, with channel configuration shown in Table 7.1 and a recording window of 30 ms.

Detector	Det. Name [ID]	Channels	0-sup.	Sample rate [GS/s]
Brgg arm Bragg	Brgg [1-15]	15	NO	0.125
Hips arm Bragg	Hips [16-30]	15	NO	0.125
FiFi anode + frish $\times 2$	FiFi [1-4]	4	NO	0.125
FiFi start MCPs	FiSH(B) [1-2]	2	YES	1.800
NaI(Ti) scint.	NaID [0-11]	12	YES	0.450
Start det. MCP	STRT [1]	1	YES	1.800
Beam Pick-up	PKUP [1]	1	YES	0.900
PPAC Hips arm det.	MWPC [1-5]	5	YES/NO	1.800
PPAC Brgg arm det.	MWPC [10-15]	5	YES/NO	1.800
Extraction line pickup	PKUP[1]	1	YES	0.900

TABLE 7.1: The 63 channel configuration for the n_TOF DAQ for the first installation of STEFF in EAR-2, showing the significant volume of data taken over a triggered pulse and the data rates per detector type.

It was not possible to run with 0-suppression (a threshold trigger to reduce data) on some channels as the Bragg detectors had small components of signals spread over multiple anodes and some channels had a persistent 50 Hz. This persistent noise was a known problem during many of the first phase of EAR2 experiments but was resolved in time for the second STEFF experiment.

7.2 Data analysis

The success of the first implementation of STEFF in EAR-2 resulted in a substantial 550 TByte of data stored on CERN data systems. Highly optimized routines were implemented to perform their own unique tasks on the CERN LXPLUS servers to reduce the volume of data to more manageable quantity. This section describes the methods and routines used to manage and process the data as shown in Figure 7.2. All of the codes represented in this section were written as part of this work, with the exception of the *raw2root* and *acrontab* which were extensively modified existing codes written by P.Zugec as part of the n_TOF data framework [107].

7.2.1 *acrontab*

acrontab is a service on the LXPLUS servers that allows for a bash script to be executed at a set time interval, for the data processing we chose to operate with a 10 minute interval. The service would execute a bash script (*Cronjob.sh*) to check if the data were staged, if not it would request again the data to be staged to the public server (LXPLUS). In the case that the data were staged it would execute the desired processing scripts (*raw2root* and *STEFF_CUT*) as a queued job for the ‘batch-jobs’ service; where the 40000 CPUs of the CERN supercomputers are shared between the groups of CERN to form nodes. The Processing ran with the

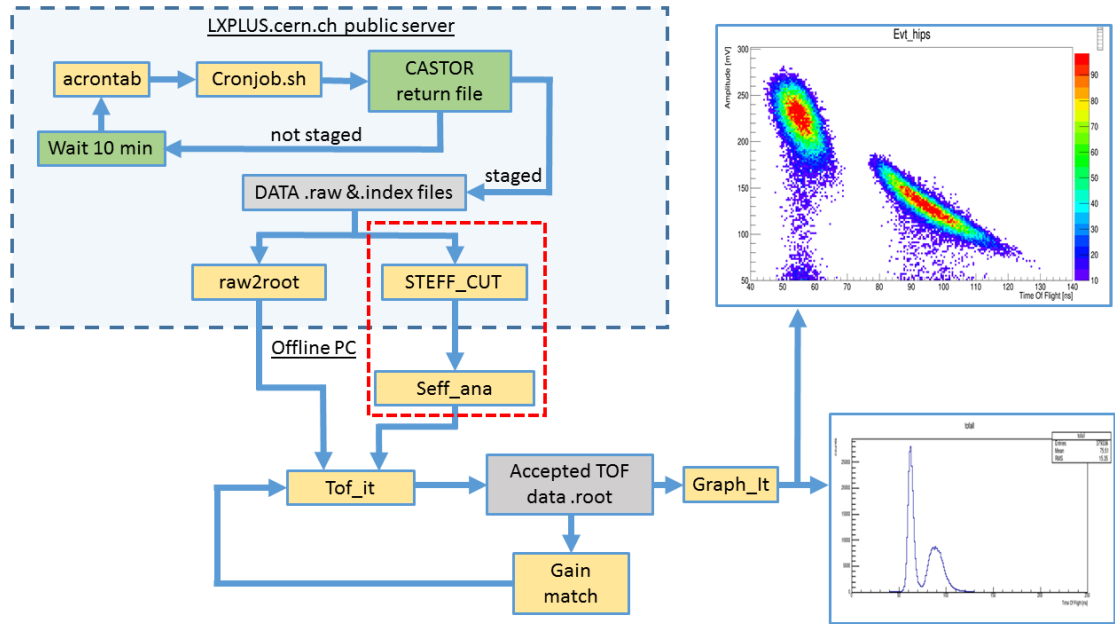


FIGURE 7.2: The flow diagram of the codes used in the processing of the data. Yellow represents the executable or .sh codes, green a logic or return value. The blue dashed square represents the codes that were run on the LXPLUS servers accessing the .raw data files from CASTOR, the red dashed line shows the codes used only for the first run of STEFF in EAR-2.

maximum of 400 jobs, each of the jobs was placed in the ‘8nh’ (eight hour) queue as the CPU time per job is in the order of 45 seconds per event. This was a conservative queue time but as the bottle neck in processing is not the computer performance in terms CPU time but the data read/write from disks. The jobs are frequently ‘parked’ (paused) to allow higher priority jobs run thus dumping the RAM to disk. If the job overruns its allotted queue time it would be terminated; this was not uncommon even with the conservative time as some jobs would take days in real time but only minutes in CPU time.

7.2.2 *raw2root*

For a large number of channels it is possible to use the n_TOF *raw2root* pulse shape analysis framework. This particular code has the added benefit of being maintained by the n_TOF group with clear and user friendly viewing software

for creating *User_Input* files [19, 107]. The routines are applicable to a wide variety of detectors suited to the specific requirements of particular detectors by adjusting the set of external input parameters, *User_Input* file. A special emphasis is put on their computational efficiency, since the most basic implementations of these conceptually simple methods are often computationally inefficient, a full description of this code is readily available [108]. This code does perform some of the more complex processing requirements for the Bragg detectors but was used for the other detectors, a separate code was written for the processing of the Bragg signals.

7.2.3 *STEFF_CUT*

STEFF_CUT is a program to process the Bragg detector signals and is outlined in Figure 7.3, it selects the data only from the regions of interest as shown in Figure 7.4. The data is saved for later use and is executed by *Cronjob.sh* on the LXPLUS servers to access the *.raw* files on the CERN data servers. This code has been highly optimised to minimise RAM usage, produce the minimum possible output file size (the maximum online disk space available is 100 GBytes) and be as computational efficient as possible and with addition features to allow multiple instances to process data over multiple nodes of the LXPLUS ‘batch jobs’ systems.

STEFF_CUT performs the above operations by first using the *ntoflib.lib* classes to open the *.raw* data file with the *.index* file on the ‘staging’ server to get the ACQC, MODH and ENVH static class pointers. From these, the relevant channel information (Nbits, number of bits for ADC scale; DC offset for the baseline correction, etc.) was stored along with the ADC values in memory, during the process of storing channel ADC values a pulse recognition routine (with channel defined parameters from the *input_options.txt* file) checks for pulses and stores pulse times.

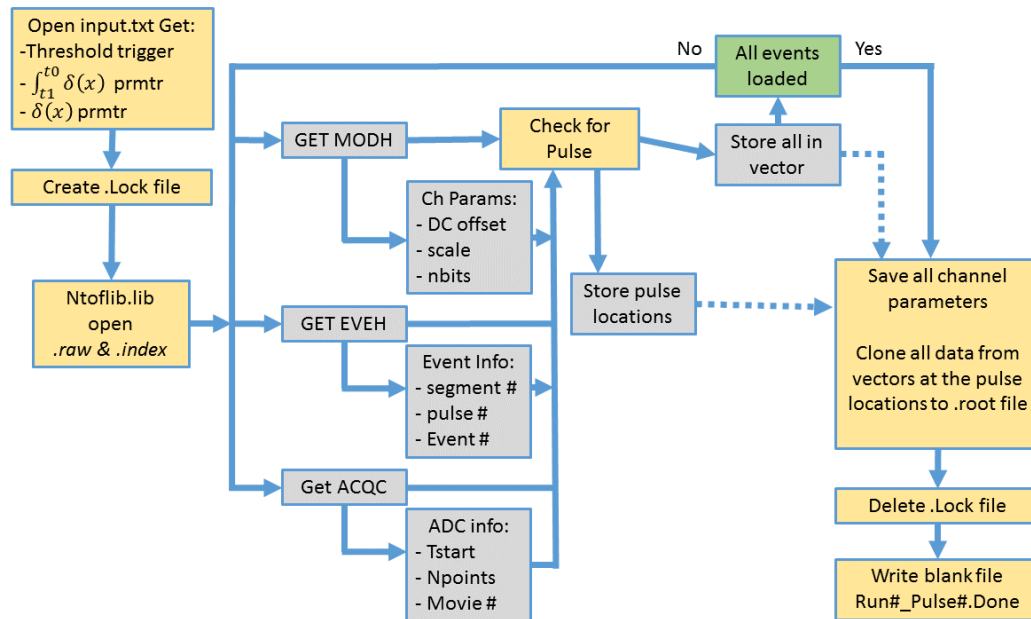


FIGURE 7.3: Flow diagram of the *STEFF_CUT* code as it performs the process of cloning the pulse from the considerably larger *.raw* data files to the output *.root* file.

Pulse recognition is performed using a modified differentiation function, the same routines as found in the *raw2root* code [107]. As the channels are loaded into memory the pulses recognition routine triggers regions of interest, these are given a $T_{S,i}$, time start and $T_{L,i}$, time duration. After loading into memory the acceptance window, $T_{S,i} + T_{L,i}$, is applied to all the channels associated to the detector (i.e. channels 1–15 for the Bragg arm Bragg anodes), the data in the acceptance window is then written to a *.root* file with a baseline correction applied along with the event and channel information; this is repeated over the all Bragg detectors from the event.

The creation of the *.lock* file prevents multiple instances of the same code running with the same *.raw* file, the completion of the code removes this file and writes a blank file with *run#_Pulse#.done* to denote successful completion of the processing. The resulting *STEFF_CUT* output data per event is typically of size $0.5 - 1.0$ *MByte*, a reduction from the *.raw* file size of $600 - 1000$ *MByte*.

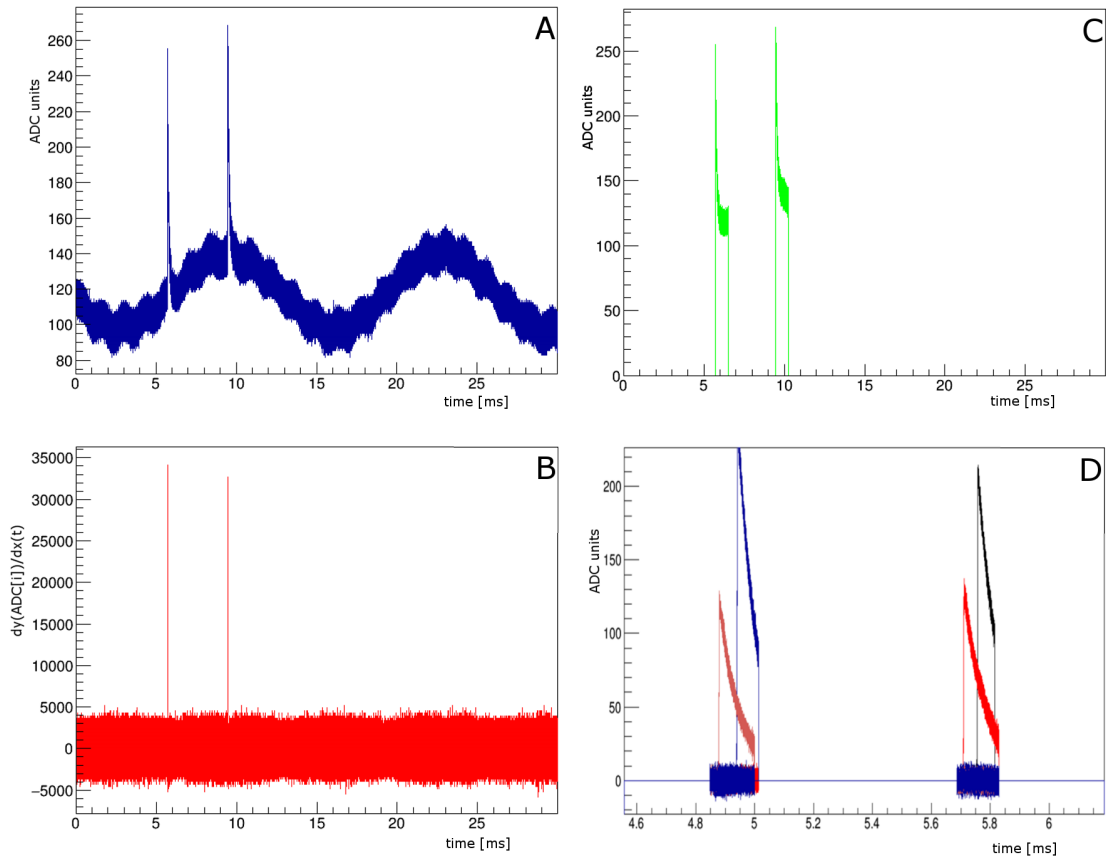


FIGURE 7.4: A series of graphical outputs from the *STEFF_CUT* code as it took the raw signal (A) and applied the derivative routine (B). (C) The cut data were stored in memory and then saved post baseline correction, storing only the regions of interest (D).

7.2.4 *Steff_ana*

Steff_ana is the off-line program to process the collated output files of the *STEFF_CUT* code and depending on the input options; sums adjacent anodes to produce a summed signal or independently analyse each anode of the detector, Figure 7.5 shows the flow of the program. Before summing or processing of pulses several modifications are made:

- Filtering - A 6th order Butterworth low-pass filter is applied and a second baseline correction is applied to remove the high frequency component of the noise or residual off set. See (B) Appendix A.7 Figure A.9 for typical processed signal

- Ballistic deficit correction - The amplifiers leak a small amount of charge, ΔQ , as they integrate the signal, this is unavoidable. It is possible to correct for this by adding a small fraction, C_b , of the ACD value, S , back to the previous time bin and repeating over all the bins it is possible reconstruct the signal as it were with no charge loss, Q . Implementation of this correction is relatively simple $S_i = S_i + S_{i+1}C_b$, determination of C_b depends on the fall time of the preamplifiers and was determined through tests of the electronics, a processed signal is shown in (C) Appendix A.7 Figure A.9.
- Gain matching - The amplifiers have different gains and subtle differences in the charge collection for each anode and amplifier, if not dealt with properly detrimentally effects the energy resolution of the detector. The gain is corrected by applying $S_i = S_i C_{gain} - A$ over the ADC values, where A is the bias offset of the amplifier determined via linear fit over the pre-triggered ADC points.

The signal in the detector can be spread over multiple anodes as the electrons created by the ionising collisions thermally diffuse over the detector volume perpendicular to the electrostatic field, Section 3.2.7 describes this process. Electron transverse diffusion, δ_t , for the Brgg was computed (via MAGBOLTZ) as $\delta_t = 0.046 \pm 0.006 \text{ cm}^{1/2}$ and for a typical fission fragment would diffuse ~ 0.3 cm from the central axis of the fragment flight path. There will also be instances where the fragment flight path is not perpendicular to the anodes, it is possible for fragments to enter with a 10° angle to the central axis. To prevent losses in the collected charge the anode with the greatest amplitude is summed with all adjacent anodes. This has been successfully applied to the central anode of the Hips and Brgg detectors. Determinations of the gain matching parameters per anode C_{gain} was calculated by disabling the summing function and producing an amplitude distribution for a selected time-of-flight value per anode. A gaussian

peak was fitted to each distribution and the centroids measured, normalising these values to the central anode centroid value served as the gain matching.

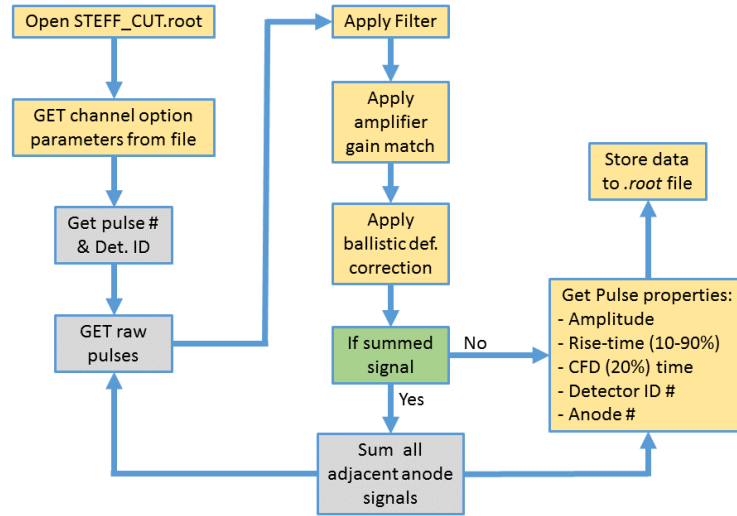


FIGURE 7.5: Flow diagram of the *Steff_ana* program for pulse processing and data manipulation.

The resulting waveform (summed signal or not) was processed and the pulse parameters, rise-time (10–90%), amplitude (determined by a linear fit over the peak) and CFD time (Constant Fractional Discriminator, set to 20% of amplitude) were saved (along with other parameters such as anode number and detector ID) to a *.root* file for further processing.

7.2.5 *Tof_it*

Tof_it was the final program in the chain of processing, it collates the output from the *raw2root* with the output of *Steff_ana* so all the detectors from the STEFF experiment are available for the analysis, Figure 7.6 shows a flow diagram of the code. The time-of-flight coincidence correlation of the start detector (STRT), the stop detector (MWPC) and the Bragg detectors (Hips or Bragg) are used to determine the first sorting of the data, to remove incomplete events. After the sorting, a ‘remove duplicate events’ routine is applied to remove coincident events

caused by multiple signals in the stop detectors (pileup) and rejecting induced signals.

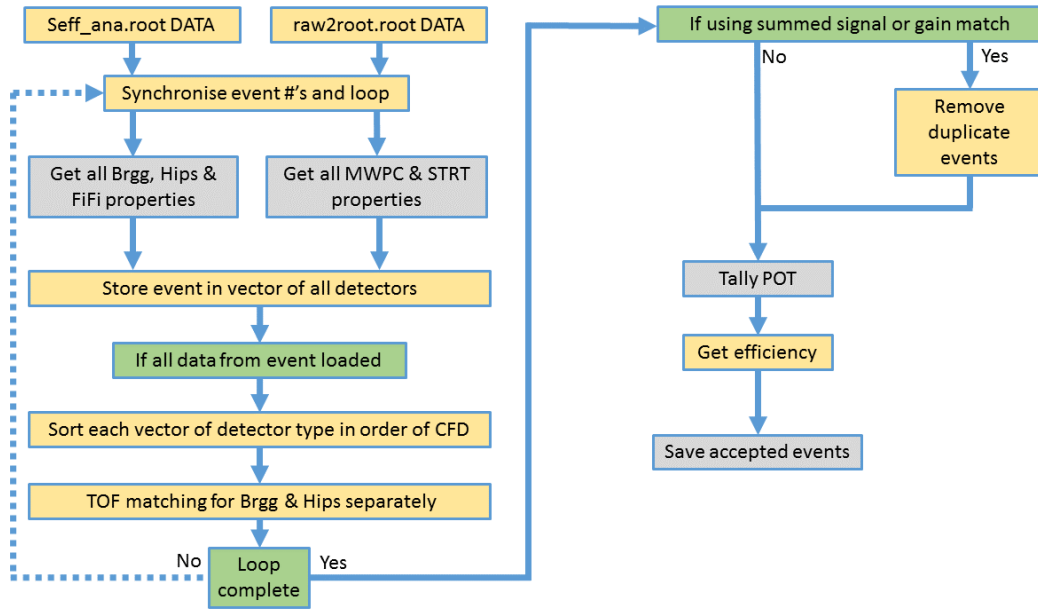


FIGURE 7.6: Flow diagram of *Tof_it* program for the fragment triple coincidence acceptance for the STEFF arm with the start (STRT), stop (MWPC) and Bragg (Hips or Bragg) detectors.

Post sorting, the data contain only fission events for each Bragg detector arm individually; a routine to determine the binary fission was implemented post sorting for the 2E2V data. All the events binary fission were saved to file to allow skipping the lengthy sorting process and enable quick development for the final analysis routines to produce the relevant data. Programs to present the data, *Graph_it*, can be implemented to create the graphs and apply additional calculations, such as fragment velocities.

7.3 Results and discussion

The STEFF spectrometer operated with the neutron beam successfully with the small diameter target to produce a large volume of data, here the volume of data

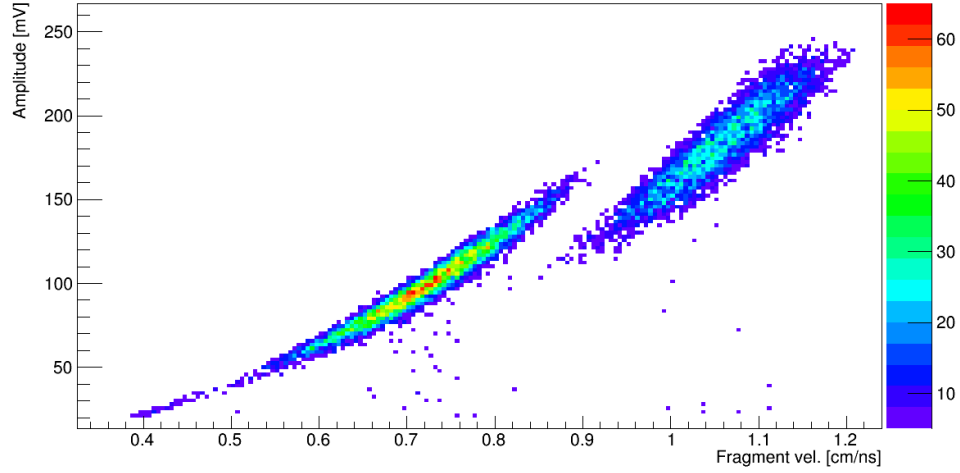


FIGURE 7.7: Velocity vs amplitude 2D plot of 34091 fission fragments in the Brgg arm detectors with the small diameter ^{235}U target with the narrow collimator post correction.

which were analyzed to give the results discussed in this section. However, the γ -multiplicity measurement with the NaI (Tl) will not be discussed as it was the work of other STEFF group members, this work was focused on the fission fragments and fission coincidence tagging.

There are small and unknown delays in the electronics and the detector timing; to correct this a constant, ΔT , was applied to the time-of-flight for the fission fragments for start, T_{Str} , and stop, T_{Stp} , detector coincidence, $T_{Str-Stp} = T_{Stp} - T_{Str}$, in both arms. The calculation of the constant, ΔT_{tof} , was achieved by fitting a double gaussian distribution to the fragment velocities. The centroid of the light fragment peak $V_B(L) = 0.927 \pm 0.002$ cm/ns and $V_B(H) = 0.868 \pm 0.004$ cm/ns for the Brgg and Hips arms respectively, and comparing to the literature values shown in Appendix A.10 Table A.1.

SRIM calculations have provided the simulated energy losses for a typical light, ^{95}Kr , and heavy, ^{140}Ba , fission fragments for thermal fission with typical fragment energies of $E_L = 100$ MeV and $E_H = 68$ MeV from the literature [109], with losses of $\Delta E_L = 18.45 \pm 0.05$ MeV and $\Delta E_H = 17.00 \pm 0.07$ MeV through the target backing for light and heavy fragments respectively. The energy losses for

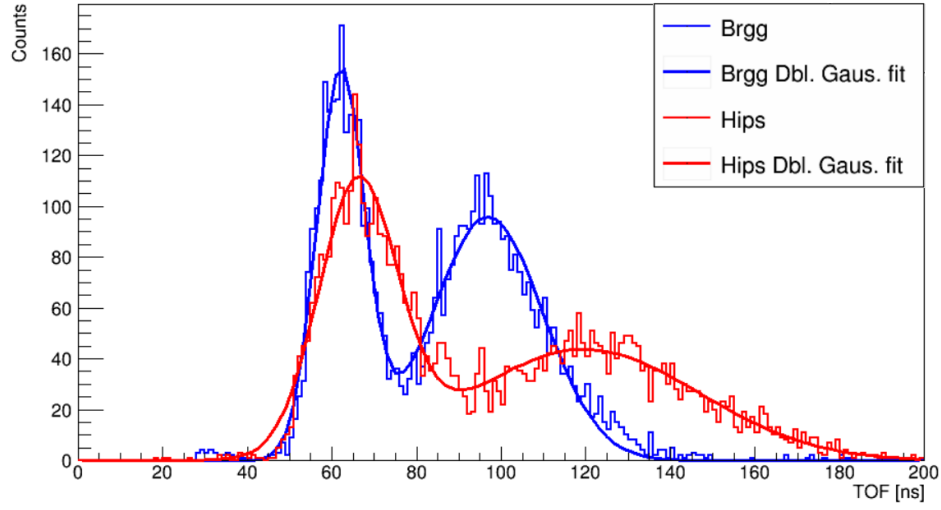


FIGURE 7.8: The time-of-flight spectra for the Brgg arm triple coincidence detectors for the small diameter ^{235}U target with the narrow collimator post correction.

the fission fragment through the uranium, if fission occurs within the target center, was simulated to be $\Delta E_L = 5.69 \pm 0.02$ MeV and $\Delta E_H = 5.02 \pm 0.01$ MeV.

By using the energy losses simulated by SRIM to correct for the fragment velocity after exiting the target, the time correction was calculated by $V_f = L/T_{tof}$, where L is the flight path and the fragment time-of-flight became $T_{tof} = T_{Str-Stp} + \Delta T$.

Post correction the time-of-flight double gaussian fits gave the light fission fragments time-of-flight as $T_{tof}(L) = 62.42 \pm 0.15$ ns and $T_{tof}(L) = 66.14 \pm 0.41$ ns for the Brgg and Hips arms respectively. The width of light fission fragment time-of-flight peaks was given by σ_{tof} as $\sigma_{tof}(L) = 4.99 \pm 0.02$ ns and $\sigma_{tof}(L) = 9.25 \pm 0.04$ ns for the Brgg and the Hips arm detector arrays respectively for the light fission fragments. The heavy fission fragments lost a considerably larger fraction of their total kinetic energy escaping the target, this is reflected in the time-of-flight distribution where $T_{tof}(H) = 97.21 \pm 0.29$ ns and $T_{tof}(H) = 119.72 \pm 0.18$ ns for the Brgg and Hips arms respectively; with peak widths of $\sigma_{tof}(H) = 13.83 \pm 0.29$ ns and $\sigma_{tof}(H) = 43.77 \pm 0.17$ ns for the Brgg and the Hips arm detector arrays respectively.

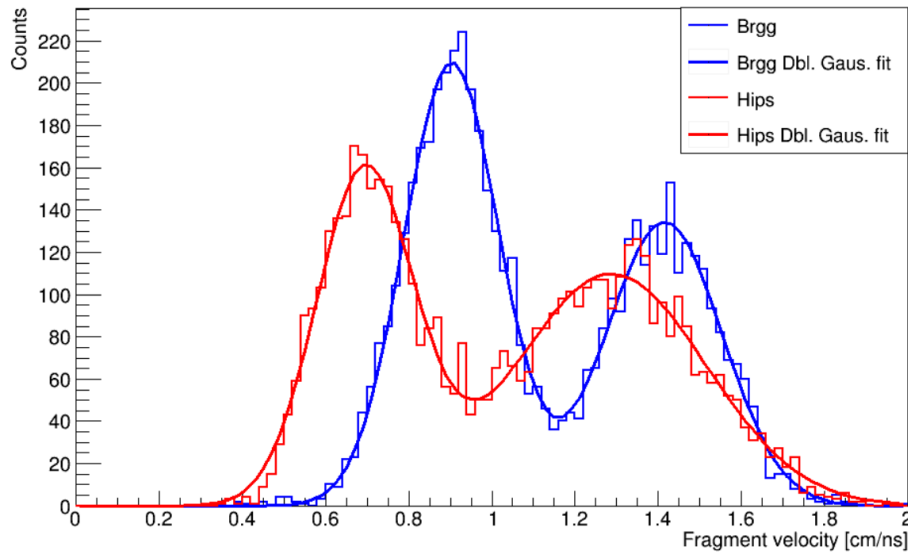


FIGURE 7.9: Fragment velocities for 5430 detected binary coincidences with both detectors, for the Brgg (red) and Hips (blue) arm detectors with the small diameter ^{235}U target with the narrow collimator post correction.

The correction for the heavy and light fragments was relatively simple for the Brgg arm detectors. The fragment energy losses in the target influence their velocity by $< 1\%$, contrary to this the Hips arm detectors had substantial energy losses influencing the velocity by $\sim 9\%$; as the fragment had to escape the uranium and traverse the Mylar backing. The fragment energy losses traversing the backing are clearly evident on the fragments velocities in the Hips detector and can be seen in Figure 7.9. The velocities were smeared with the heavy fragment peak centroid located at dissimilar locations for the Brgg and Hips arms. With time-of-flight corrections applied it became possible to measure the timing properties of the detectors with fission fragments, the distribution of fragment velocities gave a good indication for timing properties.

The reconstructed fragment velocities for the Brgg arm were $V_{Brgg}(H) = 0.931 \pm 0.001 \text{ cm/ns}$ and $V_{Brgg}(L) = 1.411 \pm 0.001 \text{ cm/ns}$ for light and heavy fragments. For the Hips arm the reconstructed fragment velocities were $V_{Hips}(H) = 0.694 \pm 0.001 \text{ cm/ns}$ and $V_{Hips}(L) = 1.287 \pm 0.007 \text{ cm/ns}$. This gave the reconstructed

light fragment velocity peak width, σ_v as $\sigma_{v(L)} = 0.1401 \pm 0.0004$ cm/ns for the Bragg arm and $\sigma_{v(L)} = 0.161 \pm 0.001$ cm/ns for Hips arm.

By integrating each of the peaks in the dual gaussian fit we acquired the ratio of the number of light to heavy fragments (L/H), for the Bragg arm $L/H = 0.76 \pm 0.03$ and for the Hips $L/H = 1.40 \pm 0.06$. The light to heavy fission fragment mismatch highlighted the detrimental effect of the thick Mylar backing, the lower energy heavier fission fragments were straggling in the target with significant energy losses leading to modified trajectories preventing detection in the Hips arm detector array.

The efficiency of the PPAC detectors was one of the main concerns with the detector array; for binary fission detection it was imperative to have good efficiency to maximise the statistics for the measurement. The efficiency of the individual PPAC detectors in laboratory experiments with a similar detector volume gave $\varepsilon \approx 0.3$, the measured efficiency through coincident of the start detector with the Bragg (or Hips) detector with AND logic for the PPAC signal gave the efficiencies as $\varepsilon_B = 0.43$ and $\varepsilon_H = 0.21$ for the Bragg and Hips PPAC detectors respectively. The greater efficiency for the Bragg PPAC indicated the fission fragment electron ejection from the SEE foil was considerably greater than the laboratory testing. The identical Hips PPAC shows lower efficiency, as it must coincide with the other binary fragment start trigger. The efficiency of binary fission detection was determined using AND logic with the Bragg and Hips arm detector arrays (a trigger in the start, Bragg PPAC, Bragg Bragg, Hips PPAC and Hips Bragg detectors) and was $\varepsilon_{Bin} = 0.16$.

The number of pulses (proton bunches on the target) processed in this data was 49442. This was a combination of primary $N_{pri} \approx 7.9 \times 10^{12}$ POT and parasitic $N_{par} \approx 3 \times 10^{12}$ POT pulses. It is n_TOF practice to present this in the format of nominal pulses by dividing the summed POT by the nominal bunch size of

$N_{nom} = 7 \times 10^{12}$ POT giving the number of nominal pulse processed as 36168; this gave the detection of a binary fission per nominal pulse as $N_{Bin} = 0.22$ for the data processed.

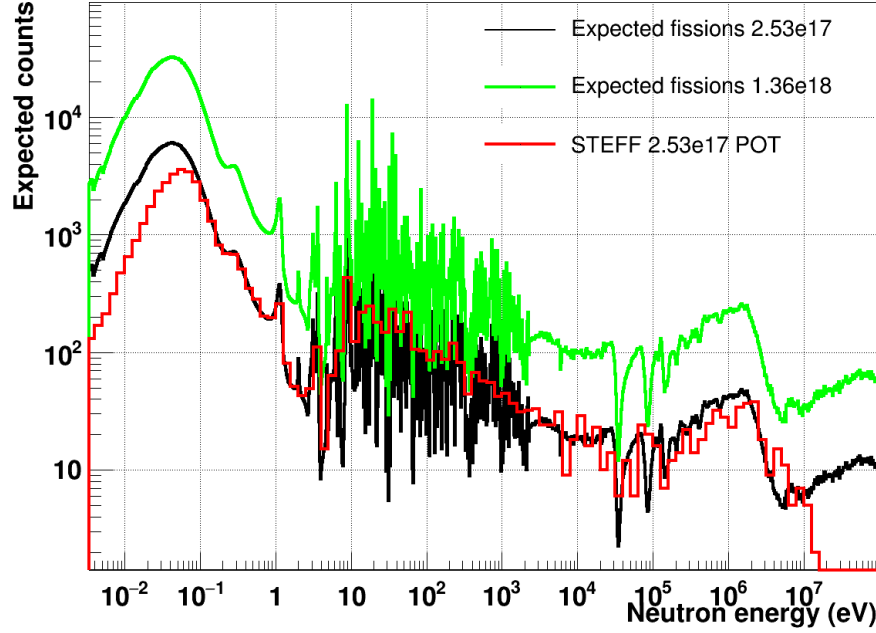


FIGURE 7.10: The fission events vs neutron energy computed for a number of processed events (black), the predicted number of fissions detected for the entire data set (green) and the fission events detected vs the neutron energy measured with STEFF in EAR-2 with small diameter target and narrow collimator flux.

The fission rates of the target were computed for the given energy n_TOF flux energy range via:

$$N_f(E) = \varepsilon \Phi_n (1 - e^{-n\sigma_f}), \quad (7.1)$$

where ε is the efficiency of detection including the solid angle of the detectors and geometric correction for target angle, $\Phi_n(E)$ simulated neutron flux for the EAR-2 narrow collimator for 36168 nominal pulses, σ_f the ^{235}U cross-section [110] and n is the target material in the beam (atoms cm^{-2}). The computed values are compared to the measured rates in the Bragg arm of STEFF for single fission fragment measurements to provide confirmation of proper operation of the detectors system

in Figure 7.10. The fission detection rate is limited to $E_n < 10 \text{ MeV}$ due to the γ -flash influence on the start detector, which blinds it for $\sim 500 \text{ ns}$ for a primary pulse. However, the saturation of the γ detectors occurs at significantly lower energies hence the fragment velocity and energy measurement is not the limiting factor.

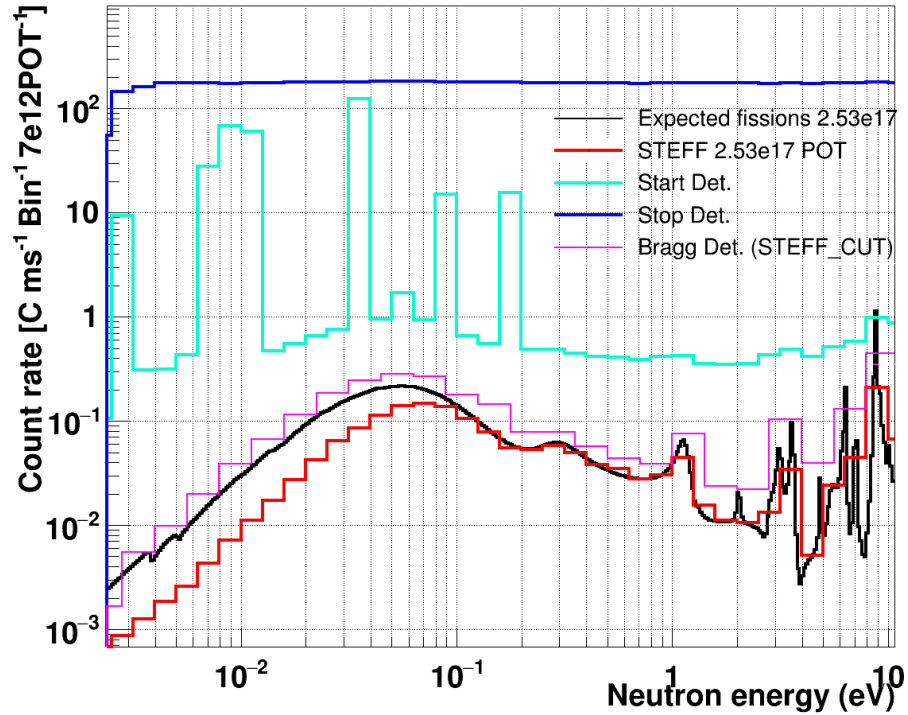


FIGURE 7.11: Count rates with neutron energy for the fragment detection systems on STEFF for the thermal to slow neutron region. There is a significant count rate in the thermal region and detection issues for the start detector within this region. The *STEFF_CUT* processing of the Bragg events follows the expected rate well, this indicates proper operation.

Within the thermal neutron region the count rate deviates from the expected values, as seen in Figure 7.11. The reduced count rate for full fission fragment reconstruction, labeled ‘STEFF’ in Figure 7.11, in the thermal region is of undetermined origin for time-of-flight detectors. The start detector showed an unexpected count rate response, observations of the detector signals during installation showed slight signal ringing over a duration of $0.5 \mu\text{s}$. Such effects of signal ringing and noise fluctuations should average out over the many pulses, however these

features remain at fixed energies. In addition the stop detector shows a distribution of continuous background triggering, this was a result of PPAC detector spontaneous triggering and emission from the SEE foil.

7.4 Problems and solutions

As with any experiment there were many obstacles to overcome during the first installation and run of STEFF spectrometer at the new EAR-2 facility that were not expected nor anticipated, most problems were resolved either before or during the beam time. The most severe problems are briefly discussed here:

- Acqiris ADC cards - A corruption of the Acqiris DC282 10-bit ADC memory during readout rendered them unusable. 12 Bragg detector channels were swapped (six brgg and six Hips channels) to the NaI (Tl) detectors, this was unfortunate but a necessary action.
- Isobutane condensation - The isobutane cylinder was housed externally to the experimental hall and electronics rack room, this lead to the condensation of the isobutane in the gas lines as temperatures fell, the actions to vent and re-establish operations took 3 days.
- Data volume and DAQ - The volume of data (600 – 1000 MByte/pulse) caused persistent crashing the DAQ systems requiring a DAQ reset.
- Contamination - The use of the unsealed radioactive ^{235}U target and ^{252}Cf source in the central chamber of STEFF resulted in contamination of the vacuum regions. Unfortunately there was no facility available to work with STEFF experiment with the contamination, it had to be dismantled into contaminated and non-contaminated sections, only the two Bragg and Hips arms were contamination free.

- Data processing - During the 2015/2016 winter shutdown several major changes were made to EAR-2 and the DAQ systems, a large change to the data structure and the *ntoflib.lib* library for accessing the *.raw.finished* and *index* files prevented further data processing.

7.5 Conclusion

The results from the premier run of STEFF at n_TOF have shown that the detector systems operated under the difficult conditions found in EAR-2. Time-of-flight and fragment velocities measurement for neutron induced fission have been performed over a large span of neutron energies.

The efficiency of binary detection was disappointing, in particular the Hips arm PPAC detector response to fission fragments, $\varepsilon_H = 0.21$, and was prone to spontaneous discharge. The binary fragment detection efficiency was detrimentally effected by the low PPAC efficiency giving the system efficiency as $\varepsilon_{Bin} = 0.22$ per nominal pulse, however it was capable of reconstructing the fission event (w.r.t. fragments) to neutron energies much higher than what was expected. The target was implicated as the primary source for the poor timing characteristics for the fission velocity measurements and particularly for the reduced heavy fragment data in the Hips arm, this was shown in the fragment velocity distribution in Figure 7.9 and in the fragment time-of-flights in Figure 7.8. The effect of fragment straggling on the Bragg arm detectors was minimal but gave considerably larger values for σ_v than literature values [3]. Unprocessed data from the calibration source, ^{252}Cf , will better determine the variables and provide a better source data reconstruction reducing the current uncertainties. However, even with the partially processed data it was clear a replacement for PPAC detectors was required to improve the efficiency, fission fragment velocity measurements and remove the spontaneous triggering.

The loss of the Aqciris cards and the seven days of corrupted data resulted in large loss of statistics, there was still fission fragment data for the entire Bragg detectors which should be processed to aid in the fragment mass reconstruction. The lack of statistics was unavoidable, data processing was prematurely halted due to a change in the *ntoflib.lib* and accessing of data on CERN data servers. Without the interruption it would have taken 124 days to process the raw ^{235}U data and 262 days in total including the ^{252}Cf data with the 400 computer nodes. This was not the problem of the CPU performance or bloated code, the problem was the data transfer and accessing from CASTOR tape to LXPLUS public hard disks. However it is clear from the detector counts comparison that significant work still needs to be done to manage the time-of-flight detector signal processing as the n_TOF *raw2root* pulse processing does not reconstruct the thermal neutron events completely.

There were concerns that the STEFF experiment could not operate under the harsh conditions of the EAR-2 and this was certainly not the case, the experiment ran and produced a very large data set, successfully taking 2E2V measurements with γ -ray coincidences for the individual fission events and will be a vital source for nuclear data in for STEFF group.

Chapter 8

Second run at n_TOF

The second run of STEFF at n_TOF was scheduled for installation on the 8th of June 2016 in EAR-2 for a duration of 30 days of beam, which equated to 2.41×10^{18} POT of which 1.53×10^{18} POT was under stable measurement conditions. This installation of STEFF featured many improvements made to the electronics during the winter shutdown. Namely: the new MWPC stop detector; the new wide collimator installed on the EAR-2 beamline for the first time; and the large diameter ^{235}U target.

This chapter discusses the experimental aspects of the run, data processing and preliminary results from the installation of STEFF at the high flux vertical neutron beamline in EAR-2 with large area target and wide collimator.

8.1 Preparation and installation

The winter shutdown allowed for modifications to STEFF and to rectify problems discovered during the prior run, including the reduction in sources of electronic noise from STEFF and EAR-2. Due to the contamination mentioned previously, the components of STEFF that were available to work on was very limited and

any modifications were carried out in a ‘supervised area’ (B867-R-S57). The major modifications made were; a complete replacement of the Hips Bragg detector back plate with the total reconstruction of the Hips Bragg detector (the signal and high voltage feed through were a persistent source of intermittent noise); the preparation for the installation of the new MWPC detector; and the re-routing of many of the power and signal cables with the introduction of passive filters where required.

8.1.1 Construction

Due to the contamination issues, STEFF was in several pieces as it was brought back into the EAR-2 facility. The two main arms (Brgg and Hips), the central chamber and the two FiFi detectors all required re-assembly. This was a delicate task as each section had sensitive detectors and fragile sealing surfaces, made more tricky with the difficulties associated with handling contaminated materials. The reconstruction was successful and the process of pumping down could begin, as discussed previously in Section 2.8. The outgassing of components left to atmosphere for several months took several days. This presented a problem when searching for potential leaks on newly constructed components (the Hips Bragg back plate and the pair of new MWPCs) but was successfully completed on time.

8.1.2 New MWPC

The construction of the newly designed multilayered MWPC with 10 μm wires (developed as part of this work) was performed by the University of Manchester technical staff and is shown Figure 8.1. During production several grids were shipped to CERN and installed for preliminary testing, it was noted during installation the grids showed a non-uniform wire tension and loose wires to the

extent of possible failure. This was confirmed after the detectors failed to achieve operational voltages or produce signals with an α source.

The difficulties associated with winding the fine wire grids clearly became a problem during the construction and it was deemed not possible to manufacture the 10 μm wire design with the required specifications with the equipment available. The considerably thicker 50 μm wire grounding grids also showed significant non-uniformity in the tensions, ‘kinks’ in the wires and a significant ($\sim 50\%$) of the grounding wires were stripped of their gold coating at one or more points along the span. The tungsten substrate was exposed and clearly viable along the wire with wisps of gold protruding from the surface indicating the wire had undergone severe mechanical shear stress during grid production, images of these problems can be seen in Appendix [A.13](#).

The problems discovered with the detectors construction resulted in the backup MWPC detector design, consisting of a 20 μm 3.0 mm gap (with considerable greater tolerance for non-uniformity in wire tensions) to be constructed and installed during the STEFF installation in EAR-2. However, due to time constraints and manufacturing conditions the gap between the anode and cathode planes was 3.2 mm and only a single 20 μm could be produced per stop detector. The final detector arrangement for the stop detector shown in Figure [8.1](#) was a single anode of 20 μm wires with 1 mm pitch with two cathode planes, one PCB and the other a grid of 50 μm wires with 1 mm pitch. The detector constructed for this experiment had significant advantages over the prior PPAC, the detector depth is double the PPAC and the condensed wire pitch improves the detector timing properties significantly. All of these effects we have seen in the detector prototyping work in Chapter [4](#).

It was chosen to use a PCB as one of the cathode planes as time constraints on grid production was pressing and the prior wire grids had shown significant problems.

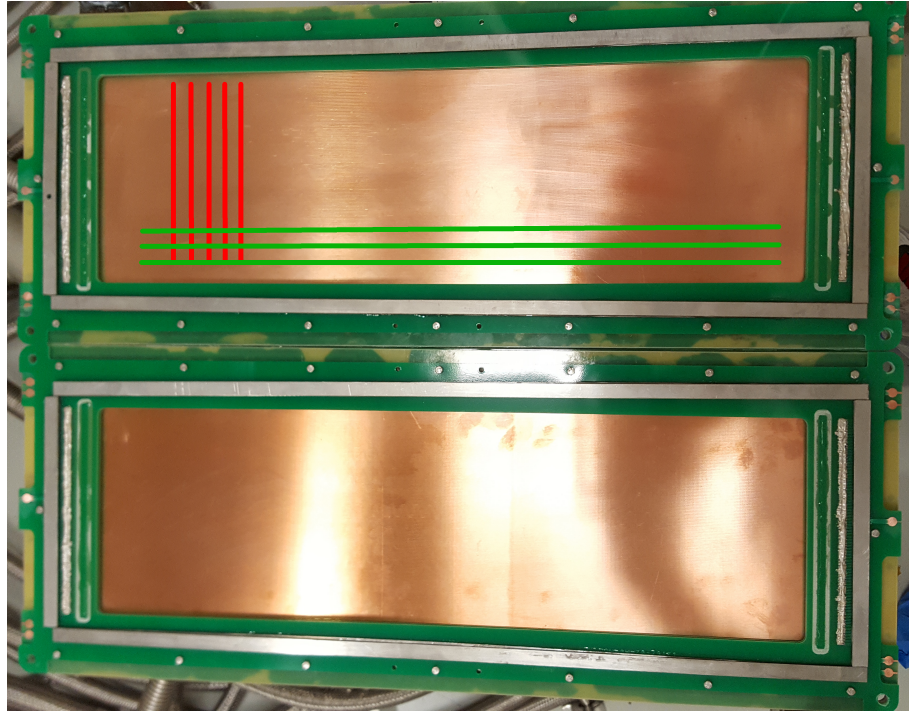


FIGURE 8.1: Two MWPC stop detectors constructed for the second installation of STEFF in EAR-2. The large copper cathode can clearly be seen through the wires, although large area (50×15 cm) it is not used for signal read out. The fine wires are not visible on this image but are indicated with their orientation, the anode wires (red) vertically and the cathode wires (green) horizontally.

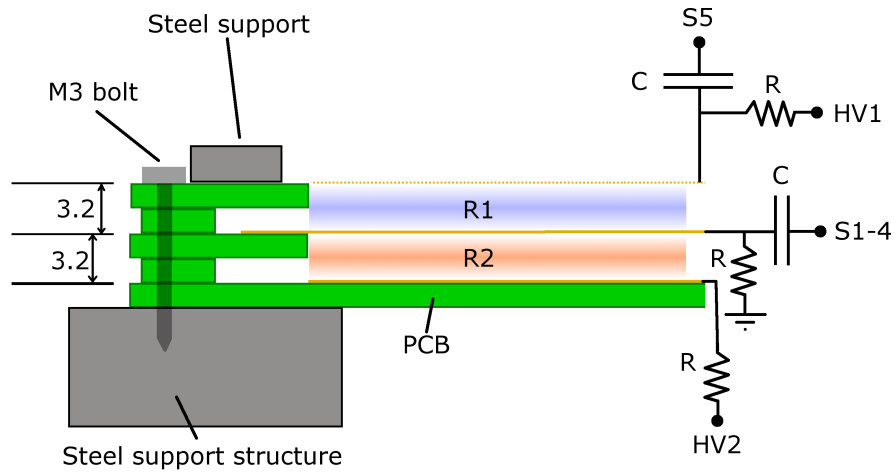


FIGURE 8.2: A schematic showing a side on view of the MWPC stop detector layout for the second run at EAR-2. R1 and R2 are the two independent gas regions utilising a single anode plane split into four sensor regions, S1-4, with the final available feed-through capacitively coupled to the cathode, S5. The resistors, R, are $10 \text{ M}\Omega$ high voltage resistors and the capacitors, C, are 0.47 nF ceramic capacitors.

The cathode PCB and wire planes behave slightly differently with respect to the electrostatic field and ion drift, consequently it was decided to use the cathodes as the source for the electrostatic field by applying a negative potential and grounding the anode. With the appropriate use of $10\text{ M}\Omega$ resistors and 0.47 nF capacitive decoupling, as seen in Figure 8.2, the anode signals could be collected along with a slower (due to the capacitance of the electrode) cathode signal.

The detectors operated at $V(R1) = -640\text{ V}$ and $V(R2) = -630\text{ V}$ for the duration of the second run at a pressure of 9.0 mBar for both the Bragg and Hips arm MWPC's.

8.1.3 Alignment with beam

The wide collimator was installed for this run, it has a considerably larger beam spot diameter of $\phi_{beam} = 7.4 \pm 0.2\text{ cm}$ (FWHM) at the target height of 2 m from collimator aperture and the diameter of the target was 8.1 cm angled at 45° from the horizontal. This gave an effective diameter of the target with respect to beam of 5.7 cm leaving no margin for misalignment before the aluminium frame for target support impinges the beam with the maximum neutron flux. To align the STEFF experiment the method adopted previously in Section 7.1.1 with gafchromic films was used for the X and Y axis, the Z-axis was altered with the jacking screws to minimise the gap between windows. The beam spot produced on the gafchromic film after 12 hours of exposure was processed using the prior methods to direct the necessary adjustments. The difference to the alignment this time was the reduced margin for error for the beam with tolerances of mm precision to prevent beam collision with beam pipes of STEFF and the dump; this was achieved by using hydraulic jacks against the bunker walls and frame of STEFF.

8.1.4 Channel configuration

The data acquisition systems operated with the channel configuration given in Table 8.1, with 67 channels recording over 4 DAQ machines with a time window of 30 ms. The volume of raw data per pulse for the duration of this run was 60 – 95 MByte, depending on primary or parasitic pulse.

Detector	Det. Name [ID]	Channels	Sample rate [GS/s]
Brgg arm Bragg	Brgg [1-15]	15	0.125
Brgg Frisch grid	BrFr [1]	1	0.125
Hips arm Bragg	Hips [16-30]	15	0.125
Hips Frisch grid	HpFr [1]	1	0.125
FiFi anode + Frisch $\times 2$	FiFi [1-4]	4	0.125
FiFi start MCPs	FiSH(B) [1-2]	2	1.800
NaI(Ti) scint.	NaID [0-11]	11	0.450
LaBr scint.	LaBr [1]	1	0.450
Start det. MCP	STRT [1]	1	1.800
Beam Pick up	PKUP [1]	1	0.900
MWPC Hips arm det.	MWPC [1-5]	5	1.800
MWPC Brgg arm det.	MWPC [10-15]	5	1.800
Extraction line pickup	PKUP[1]	1	0.900
Master Trigger channel	MSTR [1-4]	4	N/A

TABLE 8.1: The 67 channel configurations for the n_TOF DAQ for the second of STEFF in EAR-2, with second level triggering.

The data reduction per pulse came from the integration of the second level trigger to the DAQ [111]. This triggered the DAQ to record a discrete section of the trace over every channel unlike the prior channel threshold trigger. This was a significant change to the n_TOF acquisition system and was instigated by the n_TOF collaboration as a result of data-handling issues during the first run with STEFF. Previously, n_TOF detection systems have essentially been un-segmented collections of elements that can essentially be run independently. The large number of elements, and segmentation in STEFF meant that a new approach was needed.

To implement the DAQ trigger across all DAQ machines a logic pulse system was constructed and split into each master channel for each DAQ machine. A definitive trigger for each arm (or group of detectors) was required, the most reliable of these

was the Bragg detectors as they are the most efficient ($\varepsilon = 1.0$ for fission fragments upon entry to detector) and last in the chain of detection. However it was not advisable or feasible to use every anode of the Bragg detectors as a trigger, instead the Frisch grid (that would normally be used purely as a field producing electrode and screen for the anodes) was capacitively coupled to an integrating amplifier and used as a rudimentary trigger. Any charge produced inside the Bragg detectors drifted through the Frisch grid inducing a signal in the anodes, doing so it too induces a bipolar signal in the Frisch grid; additionally the Frisch grid spans the entire array of anodes which made it ideal as a single sensing trigger for the Bragg detectors.

The second level trigger produced an OR logic trigger for the DAQ machines by taking the four signals from the Frisch grids on the four Bragg chambers on STEFF and applying the following analogue procedures. The Frisch grid signals are slow signals with rise-time in the order of $2 - 3 \mu\text{s}$, slow shaping amplifiers are used to amplify and shape the signals with the typical shaping time of $3 \mu\text{s}$. Conventionally a CFD (Constant Fraction Discriminator) would be used as a trigger however the slow rising edge of the signal made their use impossible, leading edge discriminators are used as alternates. The triggered output is fed into a multiplicity logic unit with a constant level on one input. The $N > 1$ output of the logic unit was used to trigger if any one or more of discriminator triggering signals are present; the output was fed into an octal gate-and-delay generator where the resulting trigger signal was copied by daisy-chaining NIM-out to NIM-in on adjacent channels and producing the OR logic between the channels, see Figure 8.3 for layout.

The logic outputs are used as the master channel triggers for the n_TOF data acquisition.

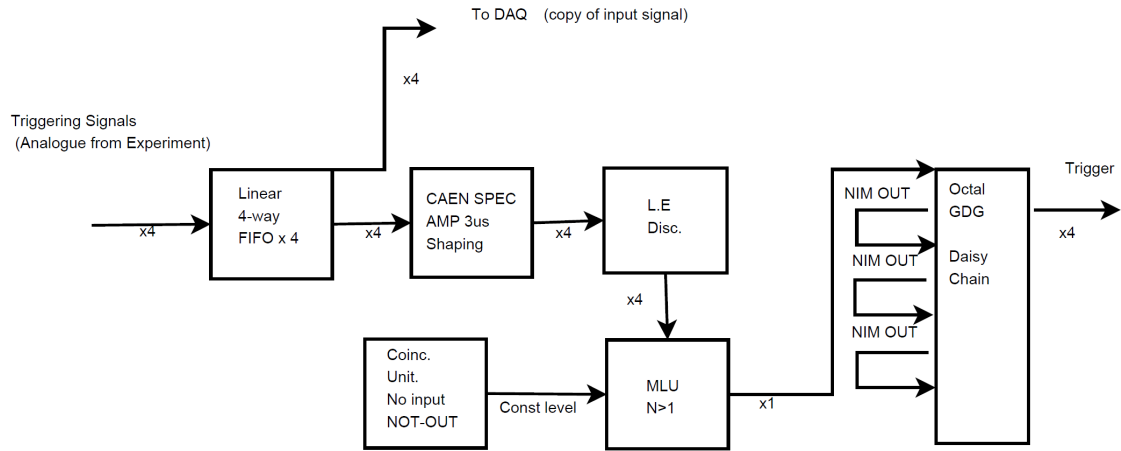


FIGURE 8.3: The second level triggering analogue trigger, FIFO (linear Fan-In-Fan-Out), (L.E) leading edge discriminator, MLU (Multiplicity Logic Unit) and GDG (Gated Delay Generator). Image courtesy of A.G. Smith, University of Manchester.

8.2 Data analysis

The data produced in the *.raw* format were of a different structure to the prior runs data structure (due to the winter shutdown server upgrades and the second level trigger) requiring an additional *ntoflib.lib* modification, this prevented any data processing for the first 10 days of operation. Fortunately the volume of data was more manageable (68 TByte) and some processing directly from the n_TOF DAQ disk server could be established for the preliminary data set, making it possible to begin the *raw2root* processing early in the run to ensure that detectors were functioning correctly and the second level trigger record time windows were set properly over the channels.

As discussed in the previously in Section 7.2, the additional code for handling the Bragg signals (*STEFF_CUT*) was rendered incompatible with the CERN data servers during the winter shutdown and with the new data format would require a complete re-write; this was not time feasible for this work. For the purposes of providing preliminary results to show detector functionality and quantifying the

improvements made to the stop detectors the *raw2root* basic routines for filtering (a running average cosine filter) were applied to the Bragg signals; with no ballistic deficit corrections or signal summing across multiple anodes the fragment total kinetic energy was troublesome to reconstruct.

Post processing on the LXPLUS server, the data were processed using the same routines (with slight modifications), *Tof.it*, with gain matching through an alternate methods, to get the relevant data.

8.3 Results and discussion

The results for the second run of STEFF in the EAR-2 n_TOF facility were significantly improved with the large diameter target and the replacement stop detectors. As with the prior experimental run the γ -ray measurements were not discussed here, the results in this section were for the partially processed data for fission fragment measurements to quantify the improvements made to the STEFF detector systems.

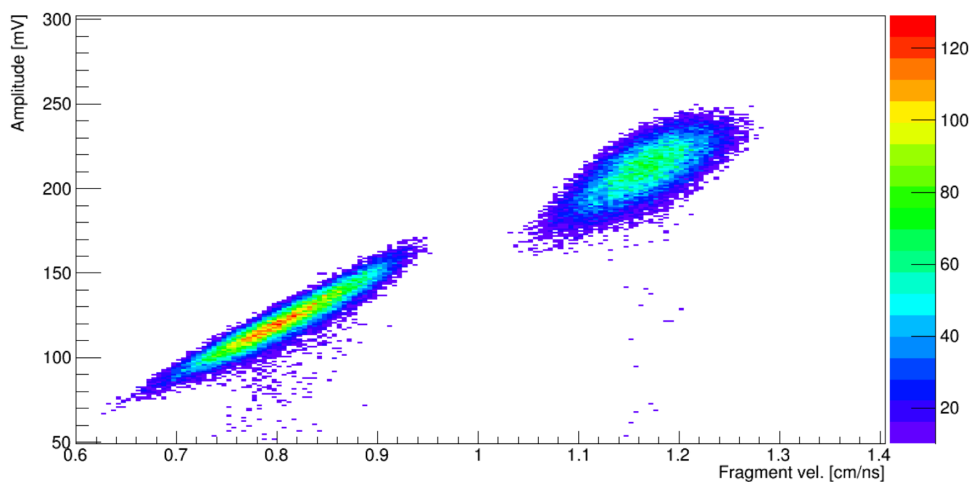


FIGURE 8.4: Fragment velocity and Bragg detector amplitude 2D plot the Bragg arm detector arrays post correction and for 45455 binary fission events.

SRIM calculations were utilised to the simulated energy losses in the new target for a typical light, ^{95}Kr , and heavy, ^{140}Ba , fission fragments for thermal fission with typical fragment energies of $E_L = 100 \text{ MeV}$ and $E_H = 68 \text{ MeV}$, with losses of $E_L = 9.74 \pm 0.01 \text{ MeV}$ and $E_H = 8.78 \pm 0.01 \text{ MeV}$ through the target backing for light and heavy fragments respectively. The energy losses for the fission fragment through the UO_2 , if fission occurs within the target center, were simulated to be $\Delta E_L = 1.438 \pm 0.001 \text{ MeV}$ and $\Delta E_H = 1.326 \pm 0.001 \text{ MeV}$.

As with the prior data set a time offset correction, ΔT , had to be applied to the time-of-flights, $T_{tof} = T_{Str-Stp} + \Delta T$, to correct for electronic and detector delays. The same methods were adopted and applied here. After correction the time-of-flight double gaussian fits gave the light fission fragments time-of-flight as $T_{tof}(L) = 62.90 \pm 0.02 \text{ ns}$ and $T_{tof}(L) = 62.70 \pm 0.03 \text{ ns}$ for the Bragg and Hips arms respectively. The width of light fission fragment time-of-flight peaks was given by σ_{tof} as $\sigma_{tof}(L) = 3.22 \pm 0.02 \text{ ns}$ and $\sigma_{tof}(L) = 3.81 \pm 0.02 \text{ ns}$ for the Bragg and the Hips arm detector arrays respectively for the light fission fragments.

In the previous run the heavy fission fragments lost a considerably large fraction of their total kinetic energy escaping the target. The SRIM simulations showed energy losses in the new target to minimally effect the velocity ($< 1\%$); this can be seen in the comparative results for the heavy fission fragments in the Hips and bragg arms. The time-of-flight distribution for the Heavy fragments were $T_{tof}(H) = 95.64 \pm 0.06 \text{ ns}$ and $T_{tof}(H) = 96.68 \pm 0.02 \text{ ns}$ for the Bragg and Hips arms respectively; with peak widths of $\sigma_{tof}(H) = 9.01 \pm 0.05 \text{ ns}$ and $\sigma_{tof}(H) = 10.29 \pm 0.07 \text{ ns}$ for the Bragg and the Hips arm detector arrays respectively. The time-of-flight peak values and distribution shown in Figure 8.5 for the two main arms of STEFF showed significant improvement over the prior detector system shown in Figure 8.6.

The comparison of the Bragg arm detectors velocity spectra from this data set given

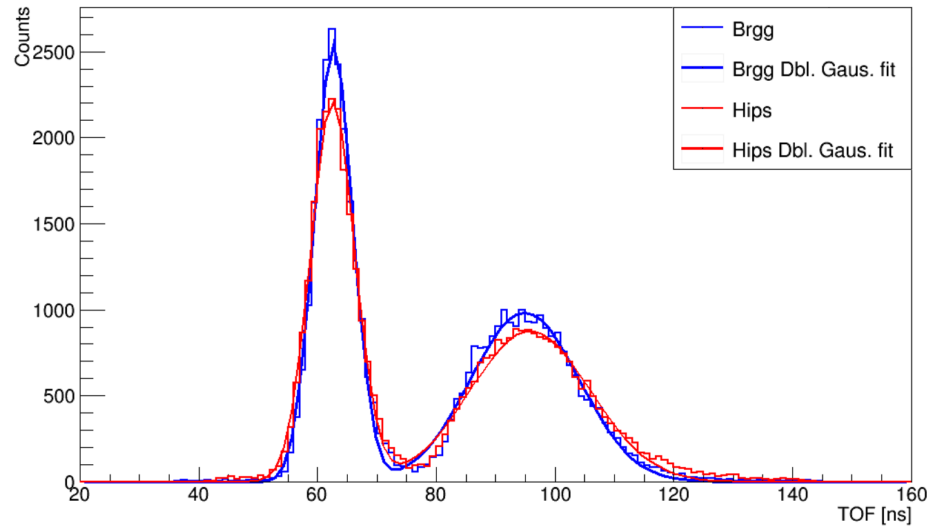


FIGURE 8.5: Time-of-flight distribution for the Brgg and Hips arm detector arrays post correction with the new MWPC stop detector. The identical peaks and the narrowness of the peaks shows significant improvement over the prior detector.

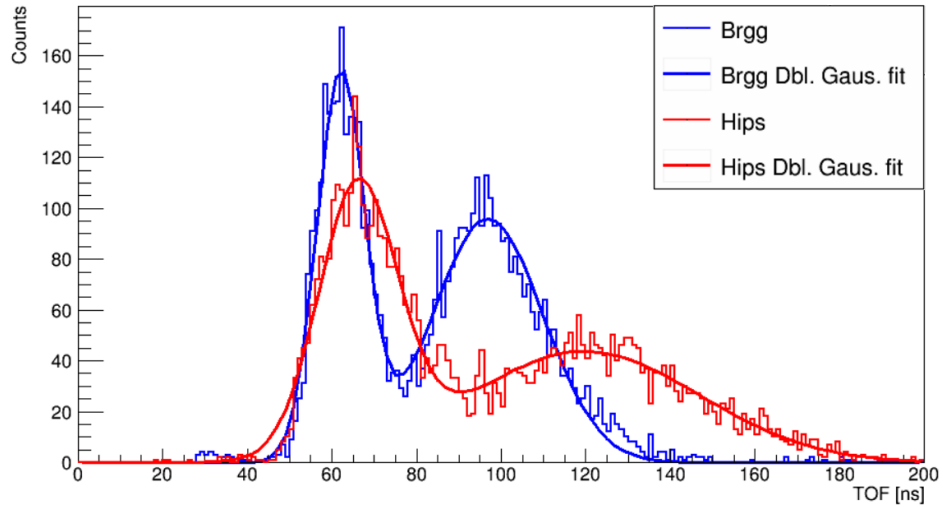


FIGURE 8.6: Time-of-flight distribution for the Brgg and Hips arm detector arrays post correction with the PPAC stop detector from the previous run.

in Figure 8.7 and the prior run given in Figure 8.8 show the influence of the new MWPC detectors, as the velocity peaks have a more defined separation between light and heavy velocities.

The Brgg arm detector array provided the least energy loss from the target with the light fragment peak with $\sigma_v(L) = 0.0749 \pm 0.0002$ cm/ns and for the Hips arm

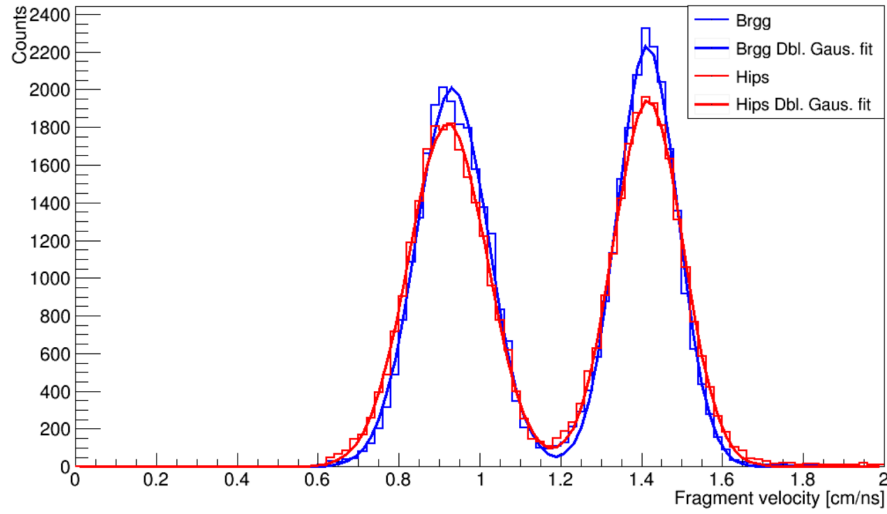


FIGURE 8.7: Fragment velocities for the Brgg and Hips arm detector arrays post correction with the new MWPC stop detector. The identical peaks and the narrowness of the peaks shows significant improvement over the prior detector.

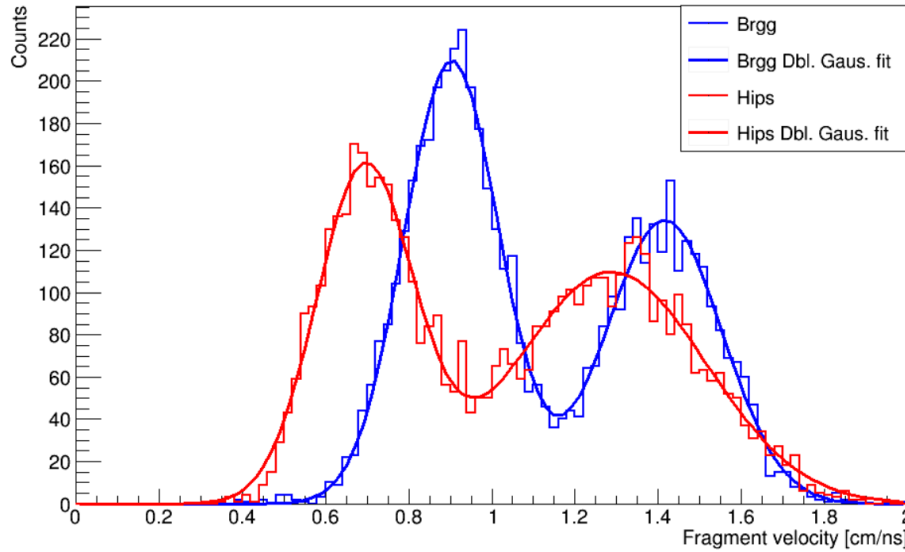


FIGURE 8.8: Fragment velocities for the Brgg and Hips arm detector arrays post correction with the PPAC stop detector from the previous run.

$$\sigma_v(H) = 0.0864 \pm 0.0002 \text{ cm/ns.}$$

By integrating each of the peaks in the dual gaussian fit we observe the ratio of the number of light to heavy (L/H) fragments, for the Brgg arm $L/H = 0.94 \pm 0.01$ and for the Hips $L/H = 0.95 \pm 0.01$. The ratio of light to heavy fission fragment were equal within error for both fragment arms indicating the detector system was

functioning well for binary fission detection and not missing heavy fission events due to the target backing.

The efficiency of the individual MWPC detectors was tested in laboratory experiments with a similar detector gave $\varepsilon \approx 0.6$, the measured efficiency (using the same methods of the prior experiment) gave $\varepsilon_B = 0.67$ and $\varepsilon_H = 0.48$. The efficiency of binary fission detection was determined (with the same method as the prior experiment) as $\varepsilon_{Bin} = 0.19$.

The number of pulses processed in this data set was 76500 (5.01×10^{17} POT), which equated to 71640 nominal pulses processed, this gave the detection of a binary fission per nominal pulse as $N_{Bin} = 0.61$ for the data processed.

The reconstruction of the amplitudes of the Bragg detectors was not possible for this data set in the time scale of this project. The absence of the corrections can be seen when we compared the prior amplitude and time-of-flight plots in Figure 7.7 with this data set in Figure 8.4, the light fission fragment distribution had lower comparative amplitude. The lack of ballistic deficit correction, signal summing and the DSP filtering results in a reduced fidelity on the energy and non linear signal amplitude response with energy deposition (charge collection).

The fission rates of the target were computed for the given energy range with Equation 7.1 using the flux from FLUKA simulations. The computed values were compared to the measured rates in Figure 8.9 for the Bragg arm of STEFF for single fission fragment measurements, providing confirmation of proper operation of the detectors system and gave the ranges at which fission fragment measurements were attained.

Within the thermal neutron region the count rate began to drift away from the expected values, as shown in Figure 8.10 and the prior run Figure 7.11. It also shows a considerable improvement in the stop detector performance with counts

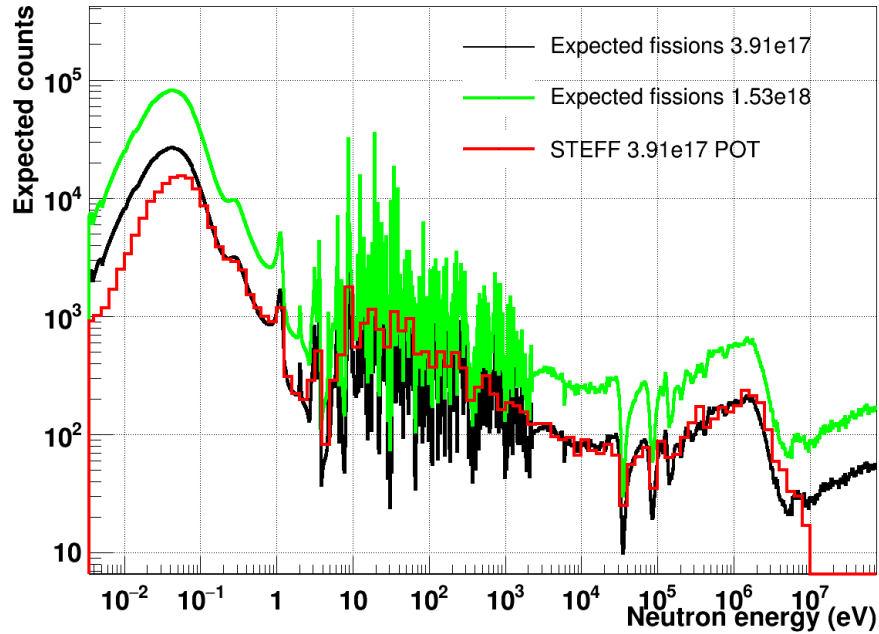


FIGURE 8.9: The fission events vs neutron energy computed for the current number of processed events (black), the predicted number of fissions detected for the entire data set (green) and the fission events detected with STEFF (red) in EAR-2 large diameter target with large collimator.

following the expected fission fragments counts, the start detector does not follow the trend.

The increased count rate in the Bragg detector was due to the *Raw2Root* processing of the data, the signals were not summed and the detection of α from the sample impurities. The reduced fission event count rate in the thermal region was probably due to processing issues with the start detector and signal pileup in the Bragg detectors. The *raw2root* routines were not able to distinguish between the multiple events in the Bragg detectors where the decay tail ($\tau \approx 100 \mu\text{s}$) overlaps to another signal.

8.3.1 Schmitt method

The second data set had considerable statistics with good timing resolution and little energy loss in the target. Preliminary fragment mass analysis was performed

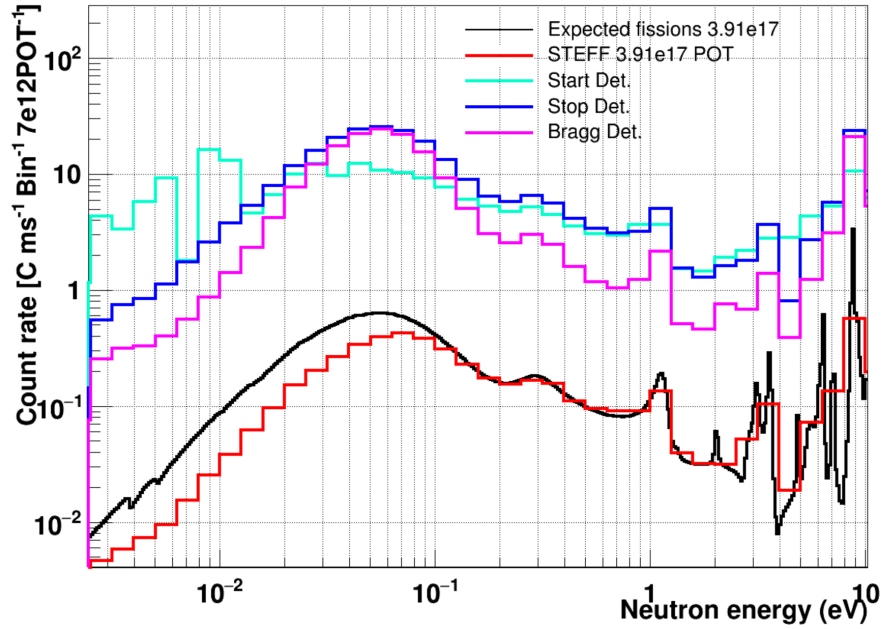


FIGURE 8.10: Counts with neutron energy for the fragment detection systems on STEFF for the thermal neutron region. The expected fission count rate (the black line) compared to the reconstructed STEFF data (red line) follow closely above the thermal neutron region but begins to differ in the thermal neutron region. See text for further information.

on the data based on the Schmitt method [109].

Ideally one would measure the kinetic energy independently from the mass, however in the gas ionisation detectors (Bragg) a small quantity of energy is lost due to non-ionising collisions that result and the variation on charge collection efficiencies within the detector produce variations in the collected signals. The Schmitt method was developed for fission fragment measurements with solid state silicon detectors, these too suffered from mass dependence in the energy calibration.

The Schmitt formalization uses a matrix to transform the raw amplitude and time-of-flight for fission fragments into the calibrated energy and mass. The matrix transformation used a Jacobian matrix to transform the element $\Delta x_e \Delta x_t$ into the

area element $\Delta M \Delta E$. The transformation is given by

$$F(M, E) \Delta M \Delta E = N(x_E, x_t) \begin{bmatrix} x_E & x_t \\ M & E \end{bmatrix} \Delta M \Delta E, \quad (8.1)$$

where the $[]$ brackets denote the jacobian matrix, E is the calibrated kinetic energy, M is the calibrated mass, x_E is the raw energy measurement, x_t is the raw time of flight measurement, $N(x_E, x_t)$ is the counts per bin at x_E, x_t in the raw matrix and $F(M, E)$ is the counts per bin at M, E in the mass energy matrix.

The calibrated time-off-flight, T_{tof} , is given by

$$T_{tof} = c_t + a_t x_t^2 - b_t x_t \quad (8.2)$$

where the constants; a_t , b_t and c_t are determined by the detector. The calibrated energy, E , is given similarly by

$$E = (d + d' M)x + e + e' M \quad (8.3)$$

where M is the calibrated mass and the constants; d, d', e and e' depend on the detector system.

Fortunately, prior work done with STEFF provided a program written by current and prior members of the STEFF group for resolving the constants for the Schmitt method called *mass_analysis*. From this it was possible to create mass and energy distributions for the fission fragments by using a multi-parameter fit to known values of fission fragment distributions. The solutions for the fit provide a secondary means to evaluate some of the main influences on the fission fragment measurements and allow for the production of mass and energy distributions, as shown in Figure 8.11. From the Schmitt method it was possible to estimate the average energy loss for the fission fragment as 16.33 MeV, the timing resolution

for the start-stop coincidence around 1 ns and the ratio of light to heavy fragments as 93.7%.

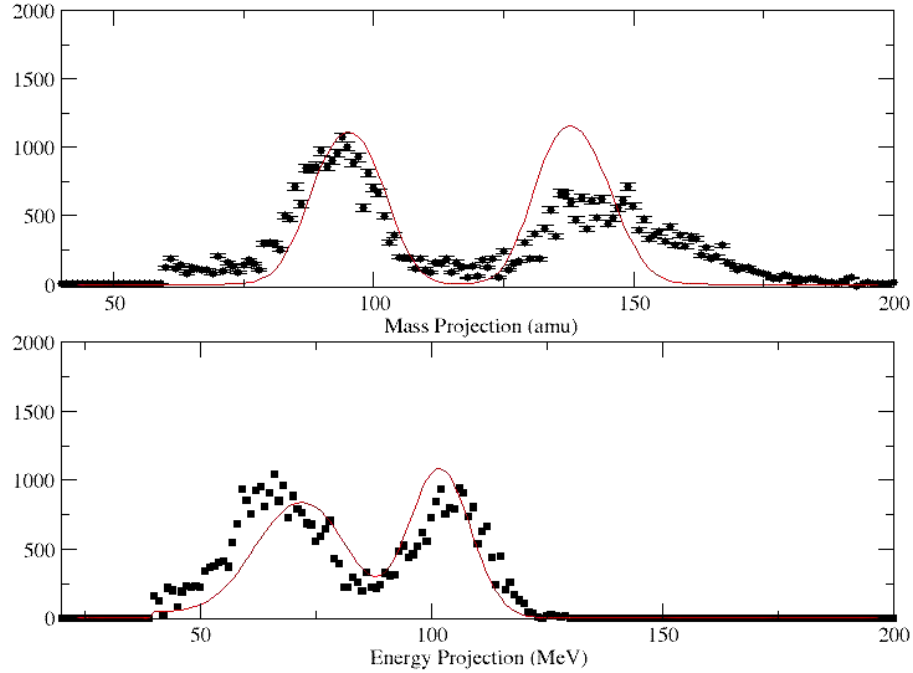


FIGURE 8.11: (Top) Reconstructed fragment masses for fission events. (Bottom) Reconstructed fragment total kinetic energy per fission fragment from the *gavsort* code. The red line represents the known mass/energy distribution for thermal neutron induced fission fragments of ^{235}U that the code attempts to reconstruct. The poor reconstruction of the heavy peak is speculated to be a result of fragment energy deposition reconstruction issues. See text for further information.

Figure 8.11 shows the peak locations to be in the correct positions for the light fragment but the heavy peak is lower in energy than expected and produces an overly wide mass distribution. This is probably due to the non-linear energy response due to the missing corrections to the pulse height. The calculations for the constants and the reconstruction are very sensitive to variations in the time-of-flight or kinetic energy measurements; these values will improve with subsequent improved sort codes. To reconstruct the mass and the energy distribution for the preliminary results shows the detector systems are functioning well.

8.3.2 Stop detector performance comparison and results

The new stop detector performance was a key area of interest with the aims of; improving the stop detector timing coincidence performance, σ_c ; and efficiency, ε , as the main objective of this thesis. To quantify the performance of the detectors the methods developed in the laboratory were applied to the PPAC and MWPC detectors used during the two STEFF installations.

The signal timing resolution, σ_T , gives a good indication into the detectors performance, as shown previously in Section 4. The same methods were applied to get $\sigma_t = 530^{+480}_{-140}$ ps (where the errors have been replaced with the σ of the asymmetric gaussian fit) for the Brgg MWPC compared to the previous PPAC detector value $\sigma_t = 240^{+480}_{-110}$ ps for the Brgg PPAC.

This gave the impression the PPAC detector performed better than the MWPC, however this measure gave an indication to the multiplication of charge in the detector where the timing resolution fluctuations were due to signal properties. It did not indicate the timing resolution due to the geometrical distribution of the deposited energy inside the sensitive volume and consequent collection time.

The Brgg arm light fragments had minimal energy losses escaping the target (exiting the target without traversing the backing) with minimal influence on the fragment velocities. The velocity sigma, σ_v , of the light fragment peaks from the Brgg arm detector array were compared between runs, $\sigma_v(L) = 0.1401 \pm 0.0005$ cm/ns for the PPAC and $\sigma_v(L) = 0.0749 \pm 0.0001$ cm/ns for the new MWPC, an obvious improvement. However one has to be careful on how to interpret the timing performance for the coincidence method with fission fragments between the detectors as there were several influencing factors.

The two main contributions to the timing resolution (other than the detector) were the fragment energy losses from the target and the flight path. We assumed

the fragments were formed at a point source to calculate the contribution to the velocity sigma (due to different possible fragment trajectories and path length) as $\sigma_{v,geo} = 0.017 \pm 0.001$ cm/ns. SRIM calculations of the energy losses of a fission distributed in the target gave $\sigma_{v,\Delta E} = 0.022 \pm 0.001$ cm/ns for the small diameter target and $\sigma_{v,\Delta E} = 0.010 \pm 0.001$ cm/ns for the large diameter target. The contributions of these were subtracted in quadrature from the measured value to provide the fragments velocity sigma, $\sigma_{v,c}$, with the timing of the detector, where $\sigma_{v,c} = 0.137 \pm 0.005$ cm/ns for the small diameter target and $\sigma_{v,c} = 0.072 \pm 0.002$ cm/ns for the large diameter target.

The timing coincidence resolution, σ_c , of the detector array was calculated by comparison to the literature values for the peak width for the light fission fragments with a known timing resolution. Literature values for fragment velocities distribution are given with timing resolution of 1 ns FWHM [3]. By subtracting the major factors for fragment velocity and the measured value for the fragment velocity distribution we attained the timing coincidence between the MCP and the stop detectors as $\sigma_{c,PPAC} = 0.844 \pm 0.085$ ns and $\sigma_{c,MWPC} = 0.442 \pm 0.044$ ns respectively. With the estimated σ_c for the MCP (from a similar MCP coupled to mirror and SEE foil with the same foil coating) we concluded the timing resolution of the stop detectors was $\Delta T_{PPAC} = 0.81 \pm 0.08$ ns and $\Delta T_{MWPC} = 0.40 \pm 0.04$ ns.

The MWPC detectors performed well and with compatible timing properties to the laboratory testing, but they should have performed better. Prior laboratory testing had shown for a 3 mm gap with identical anode plane detector ran with potentials of 670 V, the applied potential for the Stop detectors was $V = 630 - 640$ V, the final 20 - 30 V made a substantial difference to the detector performance. The lower than expected applied potential was suspected to be the result of defects in the construction and uneven wire tensions. Fine wire plane production is by no means an easy task the smaller prototype detector spans 6.4 cm where as

the full scale detector has an anode wire span of 17 cm and cathode span of 50 cm, the inhomogeneity in the wire tension spanning the small prototype has less deformation over the shortened span and consequently greater tolerance for error.

The second main parameter for the replacement stop detector was improved detector efficiency, this was measured using the techniques previously described in Section 7.3, and have shown improvement from the PPAC $\varepsilon = 0.43$ to MWPC $\varepsilon = 0.67$. The improved efficiency came as a result of increasing the gas depth in the detector and these detectors can be stacked to form an additional detector layer working in unison; if the installed detector had the additional layers (as originally designed) it potentially could give $\varepsilon_{dual-MWPC} = 0.89$ detection per fission fragment traversing the SEE foil.

8.4 Conclusion

The second run of the STEFF experiment at the EAR-2 facility was successful with a considerable increase in detector performance, the time-of-flight and fragment velocities were considerably improved from the prior experiment. The large target influenced the binary fragment velocity measurements, both light and heavy fragments closely resembling their identical detector distributions as seen in Figure 8.7. The same can be said for the time-of-flight distributions shown in Figure 8.5. The replacement MWPC stop detectors gave significantly better fragment timing measurements and detection efficiency, we saw an increase in binary fragment detection from the previous value of $\varepsilon_{Bin} = 0.16$ per fission to $\varepsilon_{Bin} = 0.20$ per fission event.

The reduction in data volume through the implementation of the second level trigger has made it possible to process data over a manageable time scale of a few weeks to a month unlike the prior data. The binary fission fragment measurements

made with the n_TOF EAR-2 neutron beam ranged from 20 meV to 10 MeV. The production of a new form of the *STEFF_CUT* program able to operate with the new data structure and servers will enable the full reconstruction of the Bragg detectors providing much greater fragment energy deposition and mass resolution while also reconstructing thermal peak in Figure [8.10](#).

The 68 TByte of data from this experiment will be the subject of the STEFF group for considerable time to come, with 2E2V fragment measurement and complementary γ measurements for individual neutron induced fission events with the n_TOF high flux neutron beam line.

Chapter 9

Conclusion

This work described the development and installation of the STEFF spectrometer for use on the n_TOF EAR-2 beamline with a strong emphasis on improving the detectors mass resolution, ΔA , and fission fragment detection efficiency, ε , through improved time-of-flight detection. Significant modifications to the STEFF spectrometer were made to enable measurements of $^{235}\text{U}(\text{n},\text{f})$ reactions with coincident γ measurements with the high flux pulsed vertical neutron beamline at n_TOF.

The STEFF experiment was successfully operated twice on the EAR-2 pulsed neutron beamline for fission measurements with incident neutron energies ranging from 20 meV to 10 MeV. The first measurement with a narrow aperture collimator in beam with small diameter target and a second measurement with a large aperture collimator in beam with large diameter target; for runs of 1.36×10^{18} POT and 1.53×10^{18} POT respectively.

The success of both these experiments created a large volume of data; 550 TByte and 68 TByte for the two deployments. The volume of data was problematic for the full processing during this work, special optimised routines were written and were implemented to process the data into manageable volume, but due to unforeseen server changes data processing was halted. However, preliminary processing of the

$^{235}\text{U}(\text{n,f})$ data (γ -multiplicity was not discussed in this work) has provided 2E2V measurements of neutron induced fission with preliminary mass reconstruction and velocity resolution of $\sigma_v = 0.072 \pm 0.002$ cm/ns.

Replacement of the stop detectors was preceded by an extensive development phase with the two objectives of improving the timing measurement resolution, ΔT , and efficiency, ε . Multiple prototypes and laboratory testing resulted in a final design of a multi-layered MWPC detector with wire diameter of $10\ \mu\text{m}$ with 1.7 mm gap and 1 mm wire pitch with $\Delta T = 0.42 \pm 0.04$ ns. Problems with construction led to the back-up detector $20\ \mu\text{m}$ with 3.2 mm gap and 1 mm being installed, giving the timing coincidence resolution of $\sigma_c = 0.44 \pm 0.04$ ns with $\Delta T = 0.48 \pm 0.02$ ns for similar small scale prototype in laboratory conditions. Measurements of the full scale replacement MWPC detector installed on STEFF gave the timing coincidence resolution from the start to stop as $\sigma_c = 0.442 \pm 0.044$ ns during the second EAR-2 experiment. The originator PPAC stop detector gave start to stop timing coincidence resolution of $\sigma_c = 0.819 \pm 0.082$ ns measured on STEFF in EAR-2 for the first experiment. The measured efficiencies of each detector were $\varepsilon_{MWPC} = 0.67$ for the installed replacement and $\varepsilon_{PPAC} = 0.43$ for the original stop detector. The modular MWPC design allows for multiple detection layers, the addition of an extra layer will improve the detection efficiency to $\varepsilon_{dual-MWPC} = 0.89$ for the stop detector.

This work has significantly improved the time-of-flight and the efficiency of fission fragment measurements on the STEFF spectrometer, completing the two main objectives for this work.

9.1 Future work

The successful deployment of the STEFF experiment at the n_TOF EAR-2 facility has created two unique 2E2V data sets of $^{235}\text{U}(\text{n},\text{f})$ with coincident γ measurements. The two large volume data sets produced during this work will take significant time to be fully analysed and will be the basis of future work within the STEFF group and the University of Manchester Fission group.

Beyond this experiment the STEFF detector will return to the University of Manchester Schuster laboratories where modifications will be made to further improve the detection systems. Another set of MWPC detectors has been proposed to increase the detector efficiency further via improved construction techniques discussed in this work. Following this there is a proposal for $^{239}\text{Pu}(\text{n},\text{f})$ measurements at the n_TOF EAR-2 facility, where the STEFF spectrometer remains a versatile and unique tool in contributing towards more accurate nuclear data sets.

Appendix A

Appendix

A.1 Detector circuit

Figure [A.1](#) shows the electrical connections for the detector where the anodes are capacitively coupled to the output signal lines via a 1 nF ceramic capacitor (C) and voltage is supplied to the anode via 10 M Ω high voltage resistor (R) to the power supplies (Cooknell HV3). We will be testing the limits of operation, there will be occasional spark discharges. To prevent to the amplifiers fast switching surge protection diodes (D) (1n5711) are paired on the signal lines. In addition to the signal lines there were two test lines for fault finding purposes (T).

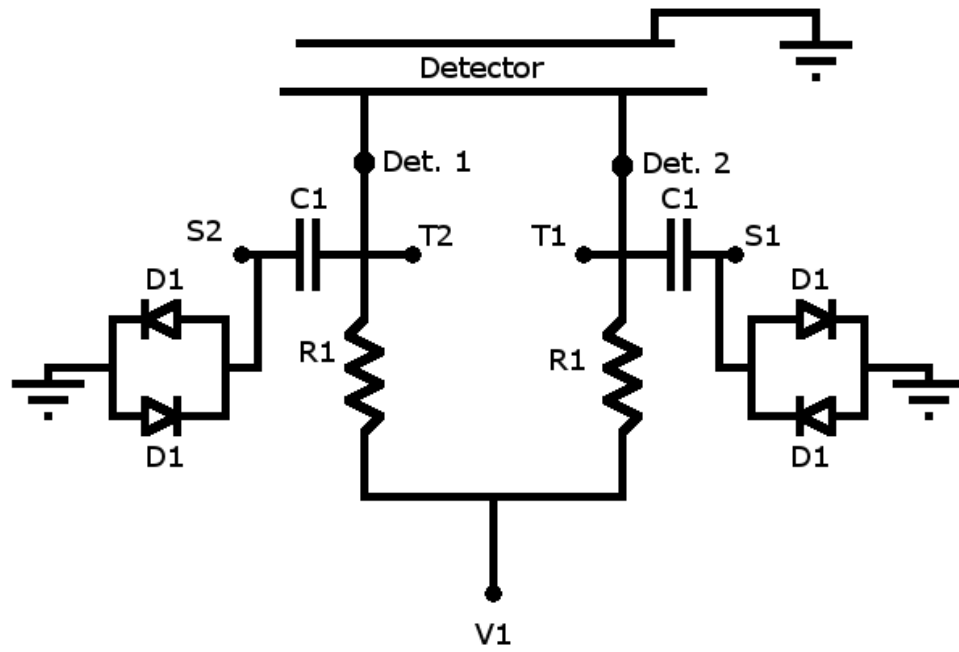


FIGURE A.1: Circuit used for prototyping. D1 is a fast switching surge protection diode (1n5711) for spark protection, C1 is a high voltage 1 nF ceramic capacitor, R1 is a 10 $M\Omega$ high voltage resistor, S1 and S2 are the signal lines to the preamplifier, T1 and T2 are test inputs and V1 is the high voltage source for the detector. There is the possibility to split the voltage source into independent HV feeds per anode.

A.2 Data processing of prototyping

Data processing of the detector development began with a LabView script from Techtroniks capable of interfacing with the TDX3054B oscilloscope, this code was gradually modified to suit the needs of the measurement. The resulting output of the code two histograms of peak to peak amplitude and rise times, which then a asymmetric gaussian can be fitted to get the mean, μ , and the σ variance independently for either rising or falling edge of the fit.

Later the PicoTech 6404D was implemented with significant improvements made to data analysis, no longer restricted to the outputs from a ‘closed’ script it was possible to analyse each trace in raw ADC format. Several codes were written to process the data. A flow diagram, Figure A.2, shows the final version of the processing programs that were applied to all the data recorded with the PicoScope.

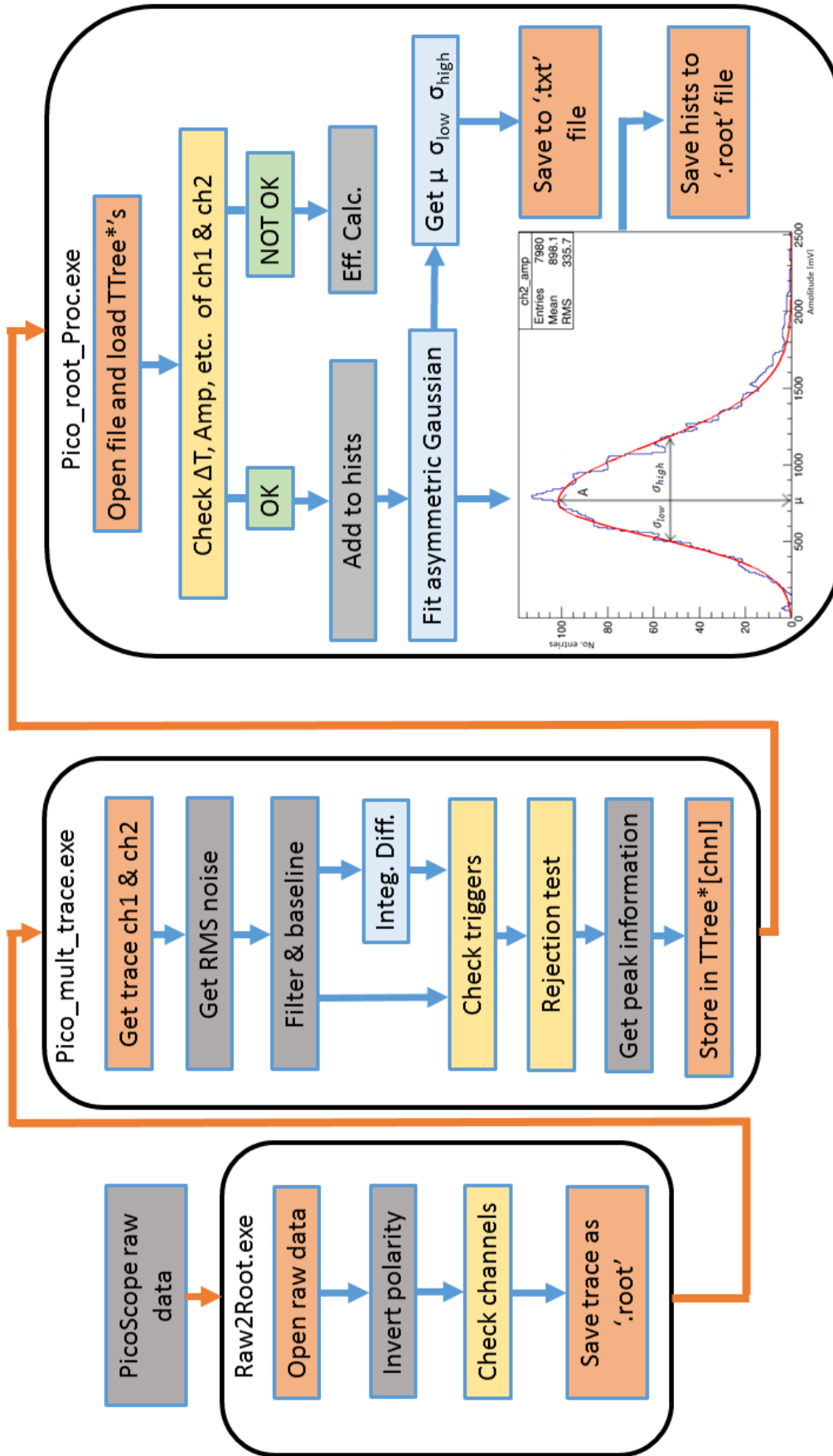


FIGURE A.2: Flow diagram of the several programs developed and implemented over the course of this work to analyse the data. Each program has a specific purpose for converting the raw data into useful data.

The programs shown in Figure A.2 were specifically designed for a single purpose, it was considered packaging all the codes together into one executable but this would seriously hamper debugging and were kept individual and executed using a ‘.bat’ script.

- *Raw2Root.exe* - Converted the PicoScope output data into the root file framework for easy fast access. As well as a performance boost in read/write access it compressed the data to typically 1/2 the disk space.
- *Pic_multi_trace.exe* - Opens the Converted outputs in the form of an array of data points in time, applies a pulse recognition routine (see Section A.5) and begins the first level of rejection removing ‘bad’ events. ‘Bad’ events are events which the signal exceeded the full volt scale of the oscilloscope, a RF pulse from external source or a spark/streamer. The latter is the most difficult to determine as in most cases the initial formation of the streamer is identical to the Townsend avalanche for the first 30 ns then the secondary processes dominate resulting in a discharge. The output of this code is a list of pulse properties - amplitude, rise-time (10 – 90%), FWHM (Full Width Half Maximum), CFD time and other properties related to the event number.
- *Pico_root_proc.exe* - Reads the array of pulse parameters from the prior program to produce histogram distributions. It then fits an asymmetric gaussian to the histograms to extract the σ_{low} , σ_{high} and μ . The program also produces manageable graphical information on the detector performance for each parameter (timing coincidence, rise-time, mean amplitude and efficiency).

A.3 Filter circuit

There was a need to filter the high voltage sources from the CAEN power unit, a strong 50 Hz oscillation was found on the detectors power lines. Figure A.3 shows

the low pas filter was designed with a response cut-off frequency $f_c = 10.26 \text{ Hz}$ at -3 db . Several of these filters were constructed for the STEFF Frisch grid and Bragg anode power supplies.

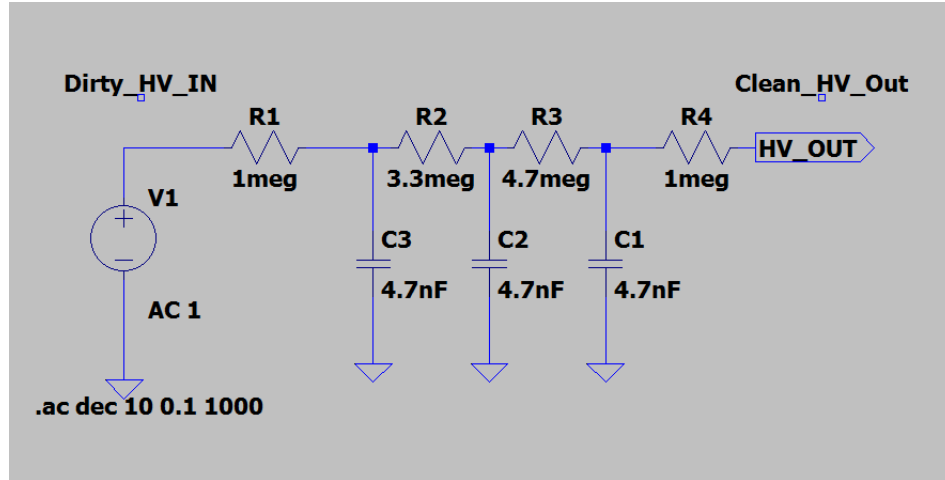


FIGURE A.3: Circuit diagram of the high voltage low pass filter.

A.4 Amplifiers

The previous Ortec vt120C preamplifiers have exceptional gain 200 and a bandwidth of 1 GHz making them a good choice for the fast ($< 10 \text{ ns}$) PPAC and MWPC signals. However the costs associated makes them impractical for the STEFF apparatus and an alternate Texas instruments THS3202EVM with a modification to ‘tune’ to the rise-times and line impedance associated with the experiment. They have a tuned bandwidth for 300 MHz to amplify the signals while minimally amplifying any higher frequency noise and rejecting lower frequency pickups from local RF sources. The amplifiers were tested with a 3.0 ns rising edge pulse generator and the response measured to give a typical gain of 145 ± 5 and rise-time of $3.5 \pm 0.5 \text{ ns}$, there is some bandwidth loss of the signal but this is acceptable at this frequency. The prototype modifications have proven to be a success and a batch of 20 of these were constructed externally to make the necessary set for the new MWPC detectors.

A.5 Data processing - triggering

The data from the PicoScope is in the format of an array of integer values (of 8-bit precision), with a fixed interval of time between each sample combined with a start time. The process of determining if there was a peak is accomplished by first applying a freely available 6th order butterworth DSP filter (from the DSP filters C++ toolkit [112]) to remove digitizer jitter, then splitting the signal into three channels, one remains the original, one is integrated with a time constant $\tau_i(x)$ and the last is differentiated with time constant $\tau_d(x)$. A trigger parameter pre determined for the run is applied to each of the three channels, from this it is possible to determine when the signal begins, reaches its peak and when the signal returns to the baseline or pile up, see Figure A.4.

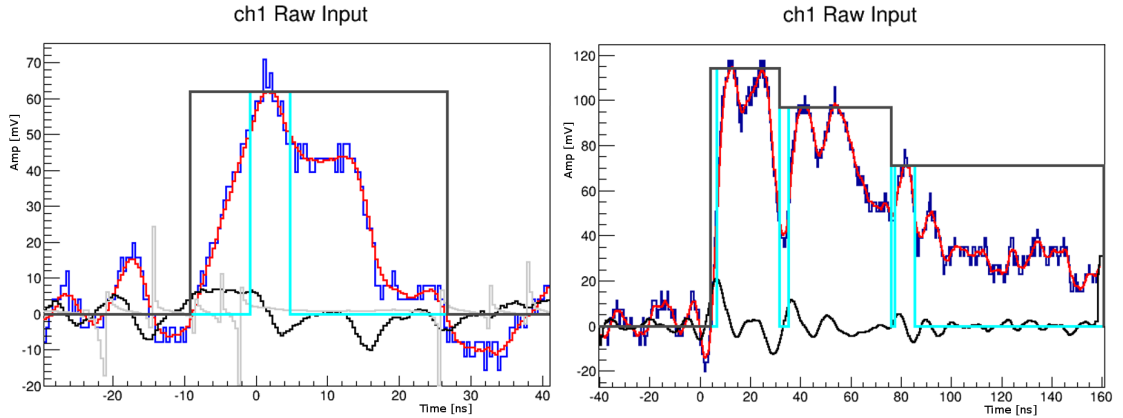


FIGURE A.4: The pulse recognition code on two separate pulses, dark blue is the original signal pre filter, red is the filtered signal, black is the differential signal $\frac{dy(t)}{d\tau_d}$, light blue is the trigger threshold for amplitude only, the dark grey is the window of the full signal and the light grey is the integral over a short time-base. (Left) The routines applied to a low amplitude signal and (right) a high amplitude signal with pile up from multiple signals arriving in quick succession, this would be rejected.

The PPAC and the MWPC detectors are susceptible to spontaneous discharges and induction between planes when in close proximity. Sparking was a common problem during the development phase as we pushed the limits of the detectors operation regions and as changes were made to the grounding planes, this also changed the shielding properties. A C++ logic trigger was implemented into the

processing of the data to prevent the false events influencing the result, see Figure A.6 for the logic.

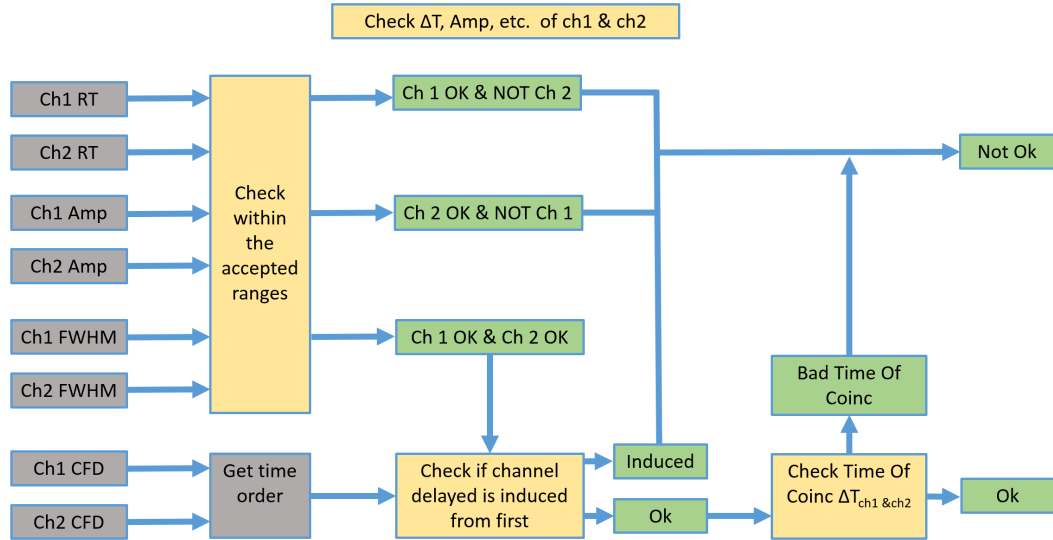


FIGURE A.5: Flow diagram to represent the logic used in the determination of detector coincidence to false or spark coincidences events.

A pulse test was performed to check the reliability of the data processing and the amplifiers through the test points, T1 and T2 in Figure A.1, the results confirmed the code is working properly with the minimum timing coincidence sigma σ_c , attainable of $\sigma_c = 0.46 \pm 0.04 \text{ ns}$ and the detector efficiency test $\varepsilon = 1$.

The limits of the scope have been tested here and the $\sigma = 0.46 \pm 0.04 \text{ ns}$ is larger than predicted but accounted for by the time-base accuracy of the scope of $\pm 2 \text{ ppm}$, after each measurement will have an element of drift in the samples between channels, at the sample rate of 2.5 GS/s this will equate to 0.8 ns per million data points drift.

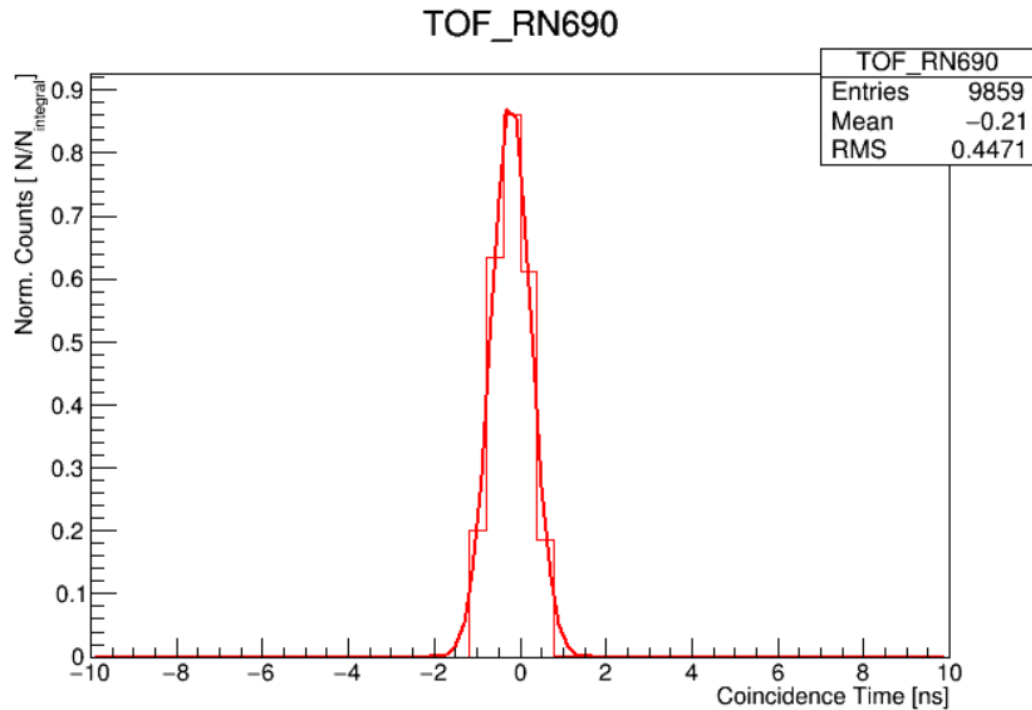


FIGURE A.6: The recorded coincidence time from pulse testing on the T1 and T2 input lines (Figure A.1), the signal has passed through the entire chain of electronics and the C++ codes post processing.

A.6 Wire winding rigs

There were several attempts at producing these wire plains using a winding jig system, the PCB board was fixed to a central perspex plate with jacking screws to raise and lower the PCB, the ends of the plate had two large mandrels situated to support and space the wire as it was wound with 1 mm pitch. At first the wire was tensioned via a friction plate pressed to the wire spool with a M5 steel bolt coated in PTFE free to dangle on the wire, after the wire was wound onto the mandrels and the PCB was raised and presses against the plan of wires to increase the wire tension further, see Figure A.7. This method provided an unknown tension to the wires (T_1 and T_2 will not be identical as the height of the nut changes), additionally the process is entirely manually controlled, with the operator rotating the rig while continuously monitoring the wire on the spool. The manual rotation provided a non-consistent rotation speed and frequently caused the bolt to drop

to the table removing all tension and/or tangle with the wire, causing kinks to form in the wire and in the worst case knot. This method was proven time and time again to be a poor method to produce grids but worked as a starting point and small scale prototypes.

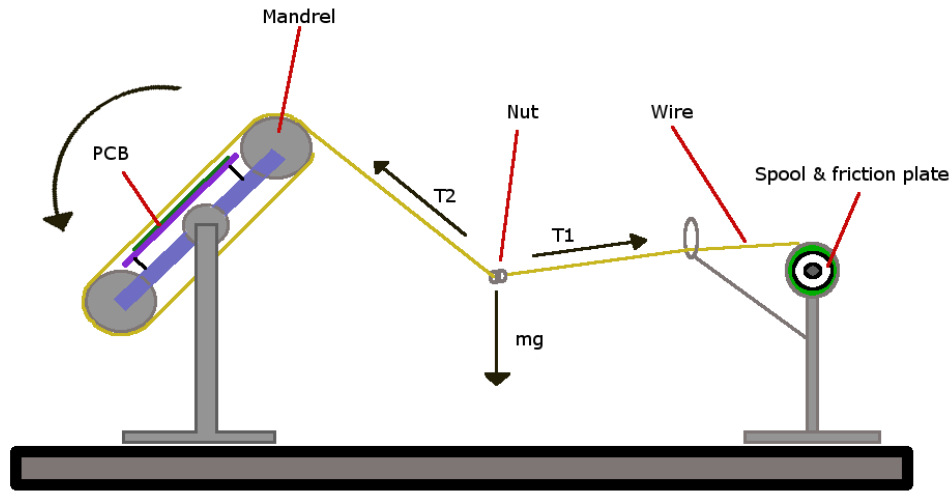


FIGURE A.7: The original wire winding rig used for the early development of the MWPC's. The wire is fed from a the spool where a friction plate provides the tension, T_1 , to suspend the nut on the wire. Depending on where the nut is situated along the length of wire between the mandrel (which is rotating) and the final metal loop from the spool determines the tension for the final wire placement T_2 . Post winding the PCB is lifted with jacking screws to apply additional tension.

A.6.1 Improved winding rig

An automated wire winding rig prototype was constructed using stepper motors to smoothly and constantly drive the rotating mandrels allowing the operator to concentrate closer on the tension where the wire is also mechanically fed out rather than relying on friction plates. The nut for applying tension to the wire was exchanged for two bars supporting the a weight and wire in a U-shaped configuration, see Figure A.8. This was tested in with a $20\ \mu\text{m}$ wire on a large full scale grid, but the electro mechanical components for this prototype did not belong to the University of Manchester. It was only a proof of concept and not used in the final

detector production as materials were not available; this resulted in some serious problems.

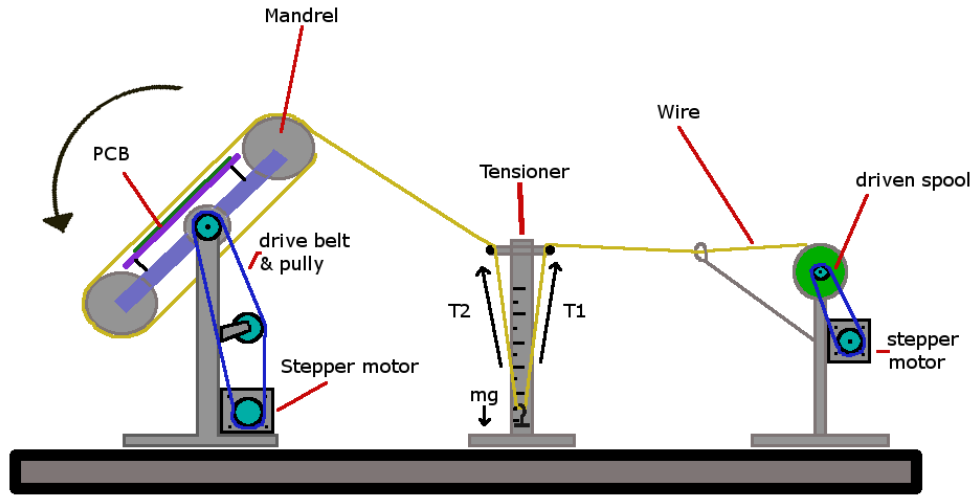


FIGURE A.8: A similar wire winding rig to figure A.7, this version is able to determine the tension on the wires placed as $T1 = T2 = mg/2$, this is possible because the friction plate used in the previous version has been replaced with a stepper motor that fed out wire as it is taken by the rotating mandrels; the operator only has to guide the wire into the channels of the mandrel. Any excess wire spooled out will be taken in on the tensioner to be used later without altering the forces acting on $T2$.

A.6.2 Detector prototype construction notes

The winding of the wire to the spools must be completed in one continuous wire thread, any breaks and loss of tension during production migrates its way around the mandrels and is not possible to recover. Pulling the snapped wire to re-assert tension to propagate back to the previous windings only results in friction around the mandrels preventing the tension to propagate back into prior windings. This occurred several times with the friction plate tension system shown in Figure A.7, with many attempt to recover the grid, with the automated system this did not occur.

Post winding and tensioning, the wires were covered with a sheet of paper (over the active region of the detector to protect from contaminates) then glued in place

along a groove cut in to the PCB surface (to prevent the glue spreading to unwanted locations). Each wire is soldered at both ends onto their respective gold plated pads, the soldering is a particularly difficult process requiring a steady hand and expertise. The gold from the wire can be stripped by the lead in the solder resulting in bare tungsten surface, this makes it difficult to attain good conductivity through the wire and proper wetting of the solder to the wire and can be seen in (C) on Figure [A.13](#).

A.7 Processing of Bragg pulse

The pulse processing of the Bragg detectors is shown in its graphical form in Figure [A.9](#) as the routines of the *Steff_ana* processes, post the signal correction the parameters are quantified as shown in Figure [A.10](#).

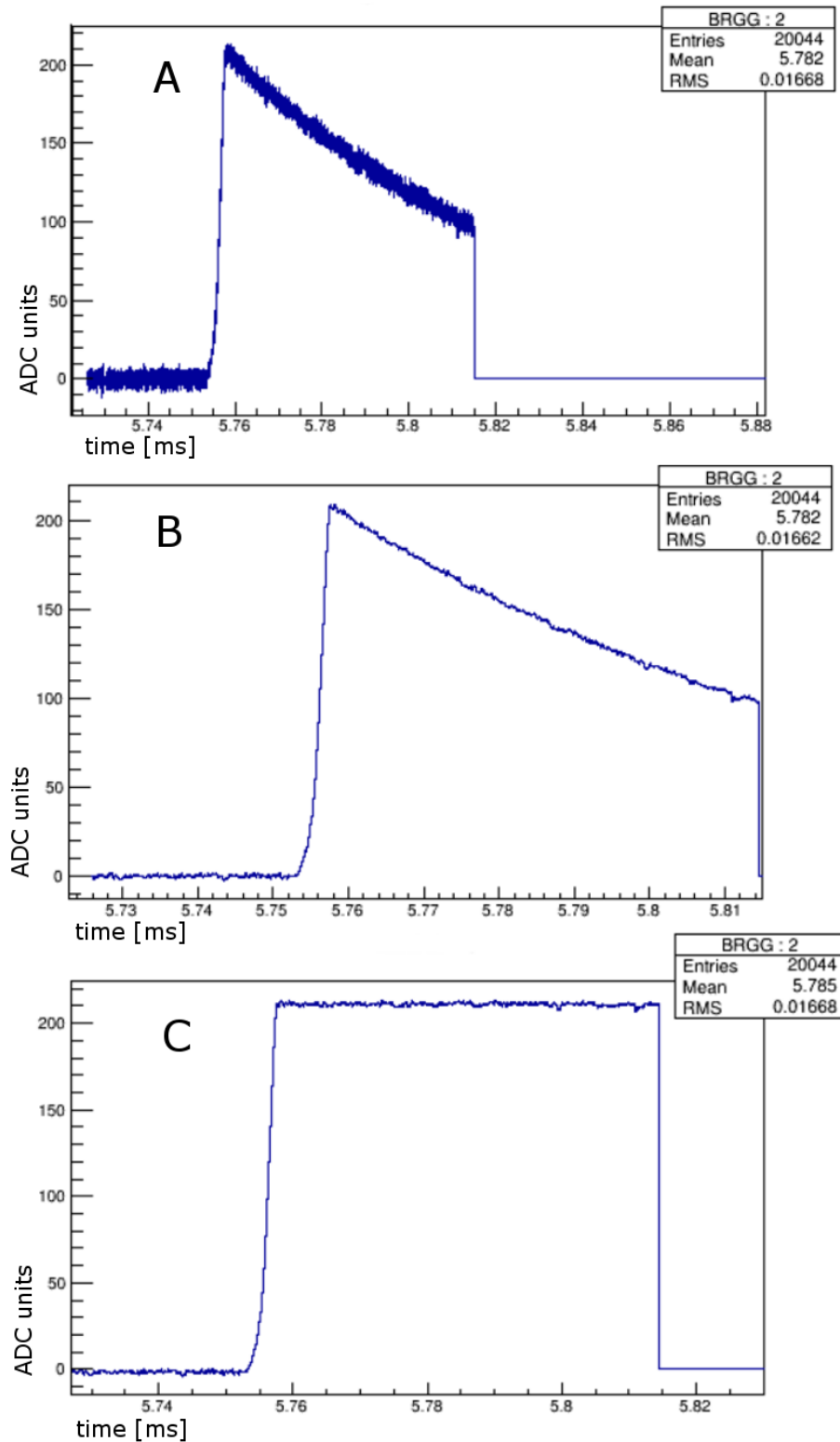


FIGURE A.9: The processing of the raw data to produce the corrected values of charge in the Bragg detectors. A) The raw unfiltered pulse with baseline correction, B) the filtered signal, C) the filtered signal with ballistic deficit correction applied.

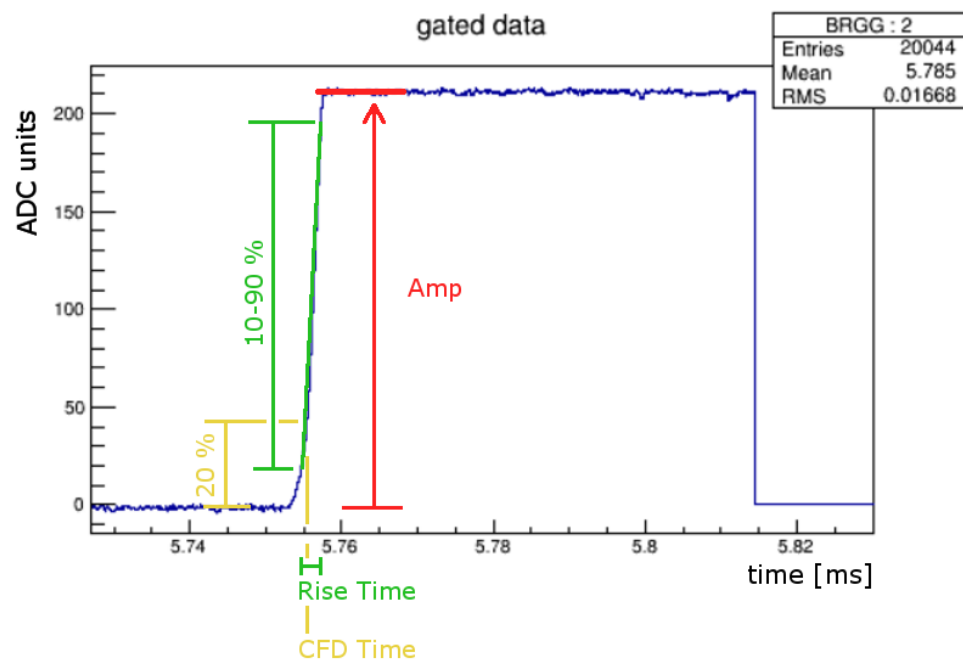


FIGURE A.10: The waveform properties that are recorded for the all Bragg detectors. The amplitude is determined by a linear fit over the plateau (red), from the amplitude it is possible to measure the rise time (10 – 90%) and the CFD time at 20%.

A.8 γ -flash

The influence of the γ -flash on the detectors is shown in Figures A.11 and A.12.

There is a significant count rate caused by the influence of the γ -flash and neutron

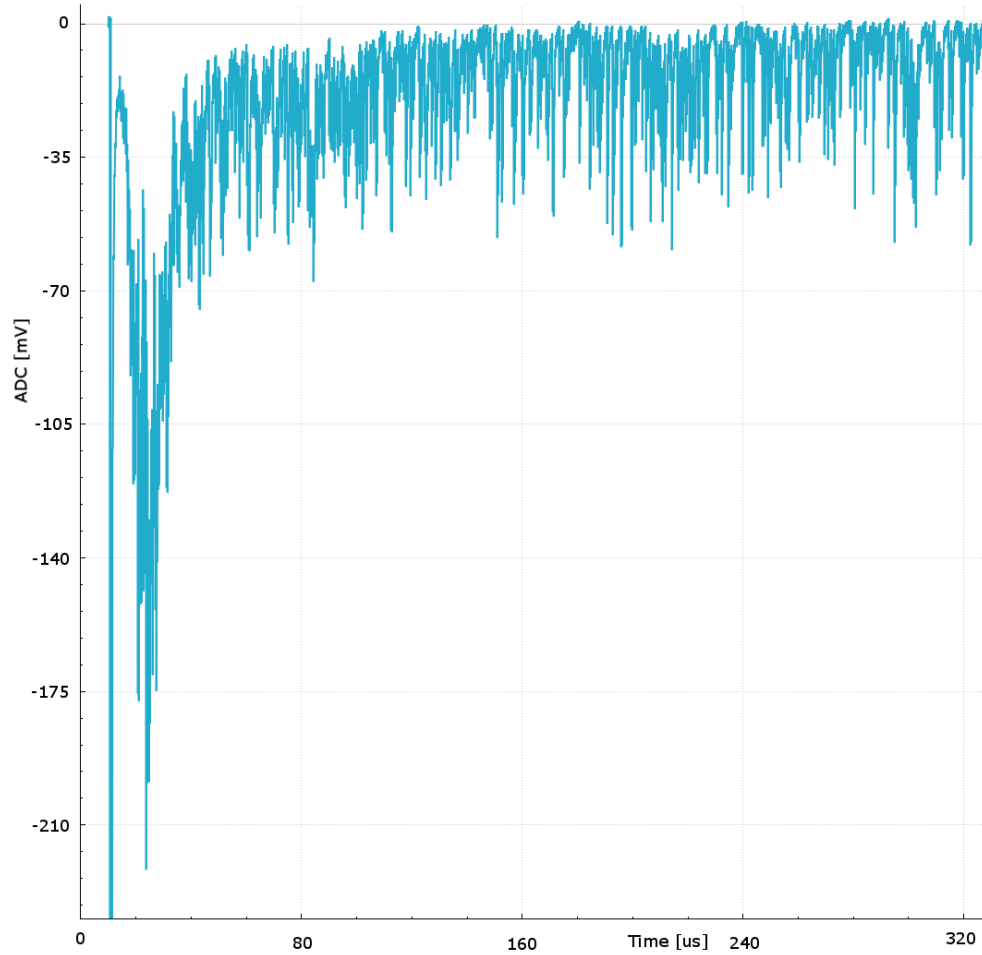


FIGURE A.11: Effect of the γ -flash on the first 500 μs of the beam arrival in EAR-2 for the NaI (Ti) detectors. The proton beam collides with the target at 10 μs

scattering within the EAR-2 experimental area. The influence on the other detectors is moderate in comparison with some detectors experience no such effects, Hips and Bragg Bragg detectors as shown in Figure A.12.

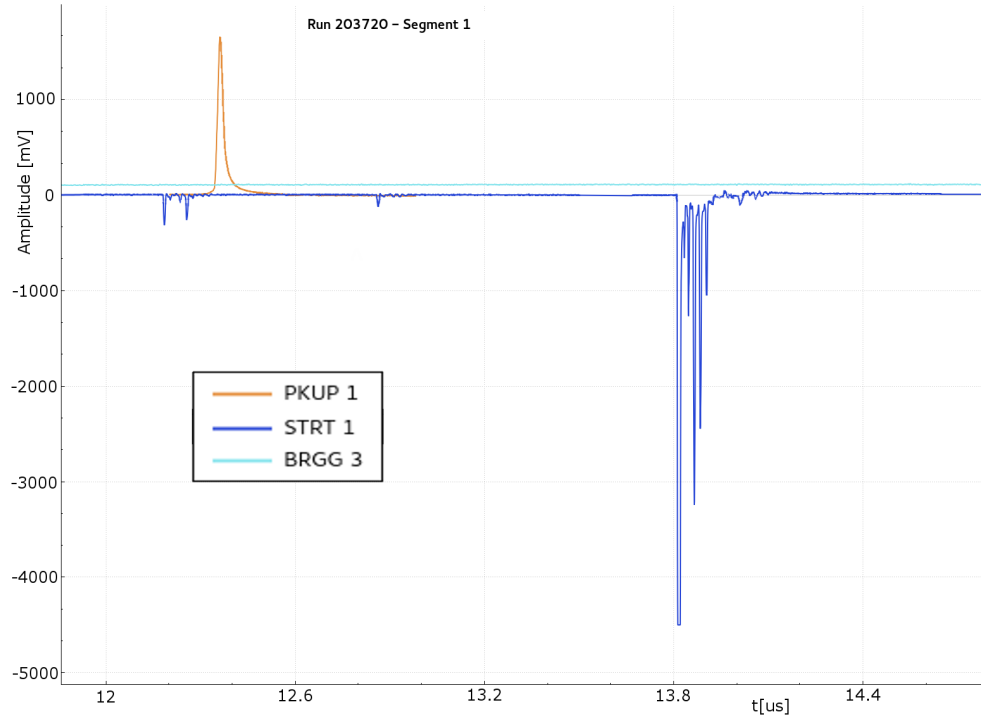


FIGURE A.12: Effect of the γ -flash on the start and Brgg detector for the first $2 \mu\text{s}$ of the beam arrival in EAR-2. The proton beam collides with the target at the time of the PKUP pulse $\approx 12.5 \mu\text{s}$

A.9 Wire problems

During the construction of the final MWPC detectors there were several systematic manufacturing errors discovered in the cathode $50 \mu\text{m}$ and the anode 10 and $20 \mu\text{m}$ grids, Figure A.13 shows some of the typical flaws.

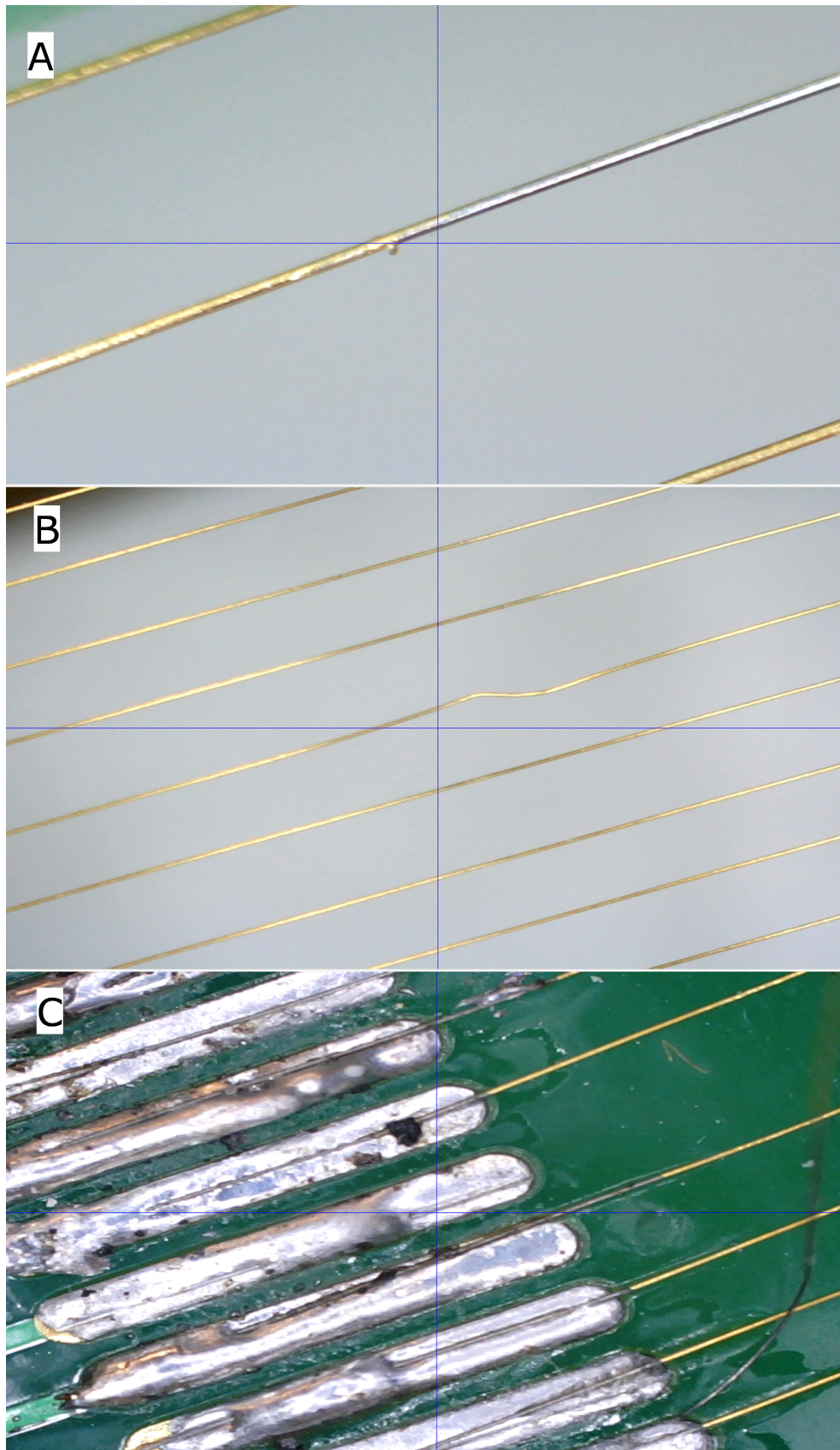


FIGURE A.13: (A) $50\ \mu\text{m}$ wire grounding grid showing the stripped gold surface with gold protrusions on the wires. (B) A typical 'kink' in the wires, several instances were found. (C) A typical poor solder contact, the gold coating can be seen in the soldered stripped from the tungsten substrate.

A.10 Fragment data

For fragment velocity comparison the literature values:

	This Work (Run 1)	This Work (Run 2)	Andritsopoulos	Malton & Fraisure
$V_f(L)$	1.045 ± 0.004	1.369 ± 0.001	1.415	1.409
$V_f(H)$	0.739 ± 0.002	0.907 ± 0.0	0.97	0.966
$\sigma_v(L)$	0.141 ± 0.007	$(7.10 \pm 0.02) \times 10^{-2}$	0.51	0.062
$\sigma_v(H)$	0.129 ± 0.002	$(8.50 \pm 0.04) \times 10^{-2}$	0.086	0.071

TABLE A.1: Values for the velocity before corrections of the Bragg arm time-of-flight detectors compared to other works [3].

A.11 Induction reduction

The signals from the SEE foils set-up had significant cross-talk between the two MCP detectors, such that conventional methods of data processing would have been problematic. To resolve this a C++ script was written to remove the induced signals from the data, Figure A.14 shows the results of the process with pre and post examples.

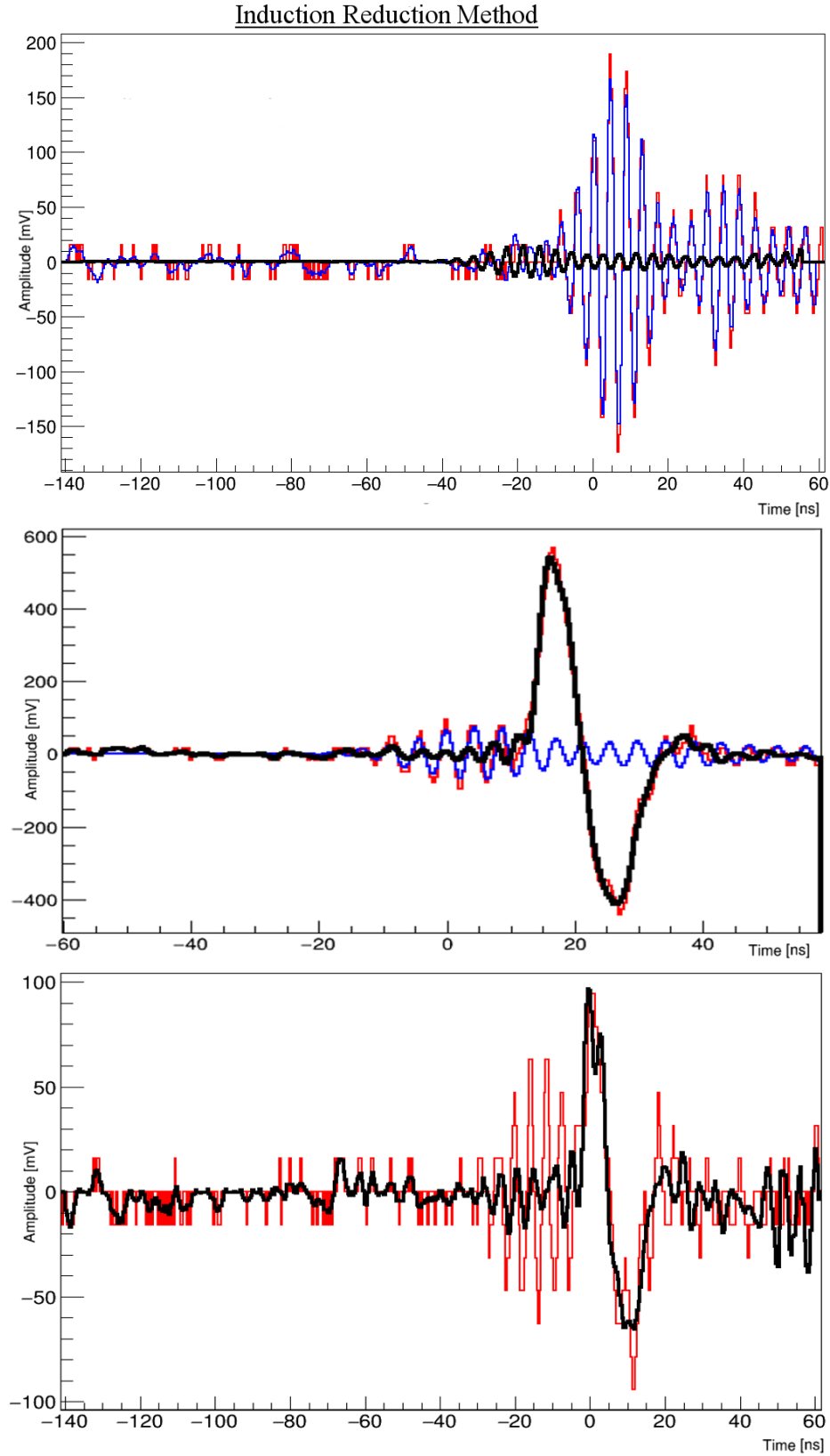


FIGURE A.14: The induction reduction routine shown on three different traces of the raw data. (Top) The raw digitizer values in red, blue the SavitzkyGolay filter and black the signal post induction reduction. (Middle) A moderate signal amplitude with the raw digitizer values in red, the fitted reduced χ^2 fit of the induction profile and black the signal induction reduction. (Bottom) A small amplitude signal with the raw digitizer values in red and black the signal post induction reduction.

Bibliography

- [1] *International Energy Outlook 2016*. U.S Energy Information Administration, 2016.
- [2] N.A.Perfilov. Ternary fission of u^{235} by 14-mev neutrons. *Atomnaya Energiya*, 14:575–577, Aug 1962.
- [3] F Shiraishi and M Hosoe. mass distribution of f on fragments from $235u(n\text{-th}, f)$ by simultaneous measurements of velocity and energy. *NIMA*, 107: 493–500, 1973.
- [4] C. F. v. Weizsäcker. Zur theorie der kernmassen. *Zeitschrift für Physik*, 96(7):431–458, 1935. ISSN 0044-3328. doi: 10.1007/BF01337700. URL <http://dx.doi.org/10.1007/BF01337700>.
- [5] K.S. Krane. *Introductory Nuclear Physics*. Wiley, 1987. ISBN 9780471805533. URL <https://books.google.fr/books?id=ConwAAAAMAAJ>.
- [6] A. Pollitt. *Measurement of prompt gamma-ray energy distribution and multiplicity of ^{252}Cf* . PhD thesis, Physics and Astronomy, 2014.
- [7] C. Wagemans. *The Nuclear Fission Process*. Taylor & Francis, 1991. ISBN 9780849354342. URL <https://books.google.fr/books?id=ERD3yypjgD4C>.

- [8] Niels Bohr and John Archibald Wheeler. The mechanism of nuclear fission. *Phys. Rev.*, 56:426–450, Sep 1939. doi: 10.1103/PhysRev.56.426. URL <http://link.aps.org/doi/10.1103/PhysRev.56.426>.
- [9] *Technology Roadmap Update For Generation IV Nuclear Energy Systems*. the Generation IV International Forum, Jan 2014.
- [10] JEFF-3.2. *Joint Evaluated Fission and Fusion File*. URL <https://www.oecd-nea.org/dbdata/jeff/>.
- [11] ENDF/B-VI ENDF/B-VII. *evaluated nuclear data file*. URL <https://www-nds.iaea.org/exfor/endl.htm>.
- [12] JENDL. *Japanese evaluated nuclear data library*. URL <https://www-nds.iaea.org/exfor/endl.htm>.
- [13] Yukiya Amano. The fukushima daiichi accident. Technical report, International Atomic Energy Agency, 2014.
- [14] W. Stacey. *Nuclear Reactor Physics, Second Edition*. Wiley-VCH Verlag GmbH and Co. KGaA, 2007. URL <http://dx.doi.org/10.1002/9783527611041>.
- [15] R. Billnert, F.-J. Hambsch, A. Oberstedt, and S. Oberstedt. New prompt spectral γ -ray data from the reaction $^{252}\text{cf(sf)}$ and its implication on present evaluated nuclear data files. *Phys. Rev. C*, 87:024601, Feb 2013. doi: 10.1103/PhysRevC.87.024601. URL <http://link.aps.org/doi/10.1103/PhysRevC.87.024601>.
- [16] A. Oberstedt, T. Belgia, R. Billnert, R. Borcea, T. Bryś, W. Geerts, A. Göök, F.-J. Hambsch, Z. Kis, T. Martinez, S. Oberstedt, L. Szentmiklosi, K. Takács, and M. Vidali. Improved values for the characteristics of prompt-fission γ -ray spectra from the reaction $^{235}\text{u}(n_{\text{th}},f)$. *Phys.*

- Rev. C*, 87:051602, May 2013. doi: 10.1103/PhysRevC.87.051602. URL <http://link.aps.org/doi/10.1103/PhysRevC.87.051602>.
- [17] G. Rimpault. Nuclear data high priority request list of the nea (req. id: H.3, h4). URL www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=421.
- [18] E. Murray. *Measurement of prompt gamma-ray energy distribution and multiplicity of ^{235}U following thermal fission using STEFF*. PhD thesis, Physics and astronomy, 2015.
- [19] F. Gunsing et al. Nuclear data activities at the n tof facility at cern. Pre-publication, 2016.
- [20] H. W. Schmitt, J. H. Neiler, and F. J. Walter. Fragment energy correlation measurements for ^{252}Cf spontaneous fission and ^{235}U thermal-neutron fission. *Phys. Rev.*, 141:1146–1160, Jan 1966. doi: 10.1103/PhysRev.141.1146. URL <http://link.aps.org/doi/10.1103/PhysRev.141.1146>.
- [21] Andrew J Pollitt. *Measurements of total gamma-ray energy and multiplicity from the Fission of ^{252}Cf using STEFF*. PhD thesis, Physics and Astronomy, University of Manchester, 2013.
- [22] A. Wahl. *Physics and Chemistry of Fission*. LULU press, 1965.
- [23] Claire Le Naour. private communications, 2016.
- [24] Laurent Tassan-Got. private communications, 2016.
- [25] M.Z.A. Munshi. *Handbook of Solid State Batteries & Capacitors*. World Scientific, 1995. ISBN 9789810217945. URL <https://books.google.fr/books?id=cjG7cjAPDQEC>.
- [26] J.R. Lakowicz. *Volume 1 of Topics in Fluorescence Spectroscopy*. Topics in Fluorescence Spectroscopy. Springer US, 2006. ISBN 9780306470578. URL <https://books.google.fr/books?id=GeHlBwAAQBAJ>.

- [27] K. Oba and P. Rehak. Studies of high-gain micro-channel plate photomultipliers. *Nuclear Science, IEEE Transactions*, 20, 2007.
- [28] *MCP & MCP ASSEMBLY*. Hamamatsu Photonics K.K, jan 2016. URL http://www.hamamatsu.com/resources/pdf/etd/MCP_TMCP0002E.pdf.
- [29] Yasser Assran and Archana Sharma. Transport properties of operational gas mixtures used at lhc. Technical report, CERN, 2011.
- [30] F. Sauli. *Gaseous radiation detectors*. Cambridge University Press, 2014.
- [31] G. C. Montgomery and D. D. Montgomery. Geiger-mueller counters. *J.Frannkline Inst*, 231(447), 1941.
- [32] Jochen P. Ziegler, James F.and Biersack. *Treatise on Heavy-Ion Science: Volume 6: Astrophysics, Chemistry, and Condensed Matter*, chapter The Stopping and Range of Ions in Matter, pages 93–129. Springer US, Boston, MA, 1985. ISBN 978-1-4615-8103-1. doi: 10.1007/978-1-4615-8103-1_3. URL http://dx.doi.org/10.1007/978-1-4615-8103-1_3.
- [33] A. Oed et al. High resolution axial ionization chamber for fission products. *Nuclear Instruments and Methods in Physics Research*, 205(3), 1983.
- [34] James F. Ziegler, M.D. Ziegler, and J.P. Biersack. {SRIM} the stopping and range of ions in matter (2010). *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 268(1112):1818 – 1823, 2010. ISSN 0168-583X. doi: <http://dx.doi.org/10.1016/j.nimb.2010.02.091>. URL <http://www.sciencedirect.com/science/article/pii/S0168583X10001862>. 19th International Conference on Ion Beam Analysis.
- [35] J. R. Young. Outgassing characteristics of stainless steel and aluminum with different surface treatments. *Journal of Vacuum Science & Technology*,

- 6:398, 1969. URL <http://scitation.aip.org/content/avs/journal/jvst/6/3/10.1116/1.1492700>.
- [36] A.G.Smith. private communications, 2015.
- [37] D. Dor, F. Farget, F.-R. Lecolley, G. Lehaut, T. Materna, J. Pancin, S. Panebianco, and Th. Papaevangelou. Falstaff: A new tool for fission fragment characterization. *Nuclear Data Sheets*, 119:346 – 348, 2014. ISSN 0090-3752. doi: <http://dx.doi.org/10.1016/j.nds.2014.08.095>. URL <http://www.sciencedirect.com/science/article/pii/S0090375214006292>.
- [38] H. Kumagai, T. Ohnishi, N. Fukuda, H. Takeda, D. Kameda, N. Inabe, and K. Yoshida. Development of parallel plate avalanche counter (ppac) for bigrips fragment separator. *Nuclear Instruments and Methods in Physics Research B*, 317:717–272, 2013. URL <http://www.sciencedirect.com/science/article/pii/S0168583X13009932>.
- [39] H. Raether. Electron avalanches and breakdown in gases. *Washington, D.C., Butterworth Co*, 1964.
- [40] J. D. Cobine. Gaseous conductors: Theory and engineering applications. *Dover Publications*, 1957.
- [41] James E. Cooley. *Fundamentals of undervoltage breakdown through the townsend mechanism*. PhD thesis, princeton, 2008.
- [42] D. G. Drakoulakos. The first townsend co-efficient and optimisation of the gas gain in mdt muon chambers. *Atlas Internal Notes*, 1997.
- [43] P. Fonte. A model of breakdown in parallel-plate detectors. *IEEE transactions on nuclear science*, 43, 1996.
- [44] J. S. Townsend. The conductivity produced in gases by the motion of negatively-charged ions. *Nature*, 62:340–341, August 1900. URL <http://www.nature.com/nature/journal/v62/n1606/abs/062340b0.html>.

- [45] A.Sharma and F.Sauli. First townsend coefficient measured in argon based mixtures at high fields. *Nuclear Instruments and Methods in Physics Research Section A*, 334(2-3):420–424, october 1993. URL <http://www.sciencedirect.com/science/article/pii/0168900293908020>.
- [46] G.G. Raju. *Gaseous Electronics: Tables, Atoms, and Molecules*. CRC Press, 2011. ISBN 9781439848951. URL <https://books.google.fr/books?id=oHXRQBQAAQBAJ>.
- [47] A. E. D. Heylen. Ionization coefficients and sparking voltages in argon and argon-ethane mixtures. *Journal of Physics D: Applied Physics*, 1(2):179, 1968. URL <http://stacks.iop.org/0022-3727/1/i=2/a=307>.
- [48] Ines Krajcar Bronic and Bernd Grosswendt. Ionization coefficient in propane, propane-based tissue equivalent and dimethyl-ether in strong non-uniform electric fields. *Journal of Physics D: Applied Physics*, 32(24):3179, 1999. URL <http://stacks.iop.org/0022-3727/32/i=24/a=314>.
- [49] W. Shockley. Currents to conductors induced by a moving point charge. *Journal of Applied Physics*, 9(10):635–636, 1938. doi: <http://dx.doi.org/10.1063/1.1710367>. URL <http://scitation.aip.org/content/aip/journal/jap/9/10/10.1063/1.1710367>.
- [50] S. Ramo. Currents induced by electron motion. *Proceedings of the IRE*, 27(9):584–585, Sept 1939. ISSN 0096-8390. doi: 10.1109/JRPROC.1939.228757.
- [51] R. Veenhof. Garfield, recent developments. *Nuclear instruments and methods*, A580:27, 1998.
- [52] R. Veenhof. *GARFIELD: simulation program for gaseous detectors*. CERN, 2015.

- [53] Yu. Ivaniouchenkov, P. Fonte, V. Peskov, and B.D. Ramsey. Breakdown limit studies in high-rate gaseous detectors. *Nuclear Instruments and Methods in Physics Research A*, 422:300–304, 1999. URL https://userweb.jlab.org/~mitras/GEM/GEM_papers/NIMPR_A422_1999_Ivaniouchenkov.pdf.
- [54] T. C. Vivaldini. Measurements of electron drift velocity in pure isobutane. *International Nuclear Atlantic Conference*, Oct 2009.
- [55] S.F. Biagi. Monte carlo simulation of electron drift and diffusion in counting gases under the influence of electric and magnetic fields. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 421(12):234 – 240, 1999. ISSN 0168-9002. doi: [http://dx.doi.org/10.1016/S0168-9002\(98\)01233-9](http://dx.doi.org/10.1016/S0168-9002(98)01233-9). URL <http://www.sciencedirect.com/science/article/pii/S0168900298012339>.
- [56] A. H. Walenta. Performance and development of d e /d x counters. *Physica Scripta*, 23(4A):354, 1981. URL <http://stacks.iop.org/1402-4896/23/i=4A/a=006>.
- [57] E. W. McDaniel and E. A. Mason. The mobility and diffusion of ions in gases. *New York, Wiley & Sons*, 1973.
- [58] T. Yamashita et al. Measurements of electron drift and positive ion mobilities for gasses containing cf4 ii. *Nucl. Inst. and meth.*, A317:213, 1992.
- [59] G. Schultz. Mobilities of positive ions in some gas mixtures used in proportional counters and drft chambers. *Rev. Physique Appliquee*, 12:67, 1977.
- [60] G. Charpak and G. Fisher. Time degeneracy of multiwire proportional chambers. *Nulcear instroments and methods*, 99:279, march 1972.
- [61] Geant4 Collaboration. Geant4a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 503:250–303, july 2003.

- [62] Validation of the geant4 electromagnetic photon cross-sections for elements and compounds. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 618(13):315 – 322, 2010. ISSN 0168-9002. doi: <http://dx.doi.org/10.1016/j.nima.2010.02.112>. URL <http://www.sciencedirect.com/science/article/pii/S0168900210003682>.
- [63] R. Veenhof. Garfield++ simulation of tracking detectors, 2015. URL <http://garfieldpp.web.cern.ch/garfieldpp>.
- [64] T. Zerguerras, B. Genolini, F. Kuger, M. Josselin, A. Maroni, T. Nguyen-Trung, J. Pouthas, P. Rosier, . ahin, D. Suzuki, and R. Veenhof. Understanding avalanches in a micromegas from single-electron response measurement. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 772: 76 – 82, 2015. ISSN 0168-9002. doi: <http://dx.doi.org/10.1016/j.nima.2014.11.014>. URL <http://www.sciencedirect.com/science/article/pii/S0168900214012789>.
- [65] R.Veenhof. Garfield, recent developments. *nuclear instruments and methods*, A419:726, 1998.
- [66] Stephen Biagi. Magboltz2. *Nucl. Inst and Methods*, A421:234–240, 1999.
- [67] D. K. Bajaj. Modelling and exhaust nozzle flow simulations in a scramjet. *journal of Astrophysics & Aerospace Technology*, 3:122, 2015.
- [68] M. Kim. *Finite Element Methods with Programming and Ansys*. LULU Press, 2013. ISBN 9781300777151. URL <https://books.google.co.uk/books?id=BmgwBgAAQBAJ>.

- [69] I. B. Smirnov. Modeling of ionization produced by fast charged particles in gases. *Nuclear Instruments and Methods in Physics Research A*, 554: 474–493, December 2005. doi: 10.1016/j.nima.2005.08.064.
- [70] M. Benoit, R. Cardarelli, S. Dbieux, Y. Favre, G. Iacobucci, M. Nessi, L. Paolozzi, and K. Shu. 100 ps time resolution with thin silicon pixel detectors and a sige hbt amplifier. *Journal of Instrumentation*, 11(03):P03011, 2016. URL <http://stacks.iop.org/1748-0221/11/i=03/a=P03011>.
- [71] Mohammad Nakhostin, Mamoru Baba, and Takuji Oishi. Double-stage low-pressure parallel plate avalanche counter: A high count rate charged particle detector. *NUCLEAR SCIENCE and TECHNOLOGY*, 5:379–382, 2008. doi: <http://dx.doi.org/10.1080/00223131.2008.10875868>.
- [72] *luma metall*, 2016. URL <http://www.luma-metall.com/files/2012/10/LUMA-Gold-Plated-tungsten-wire.pdf>.
- [73] D. C. Faircloth. Technological aspects: High voltage. *CERN Yellow Report CERN*, 007:381–419, may 2013. doi: arXiv:1404.0952.
- [74] G. Miller, G. Presser, and J. Sthler. Heavy particle detection characteristics of an mwpc operating at low (1p30 mbar) gas pressures. *Nuclear Instruments and Methods in Physics Research*, 187(2):605 – 609, 1981. ISSN 0167-5087. doi: [http://dx.doi.org/10.1016/0029-554X\(81\)90396-7](http://dx.doi.org/10.1016/0029-554X(81)90396-7). URL <http://www.sciencedirect.com/science/article/pii/0029554X81903967>.
- [75] A. Breskin. A subnanosecond, low pressure mwpc for heavily ionizing particles. *Nuclear Instruments and Methods*, 141(3):505 – 509, 1977. ISSN 0029-554X. doi: [http://dx.doi.org/10.1016/0029-554X\(77\)90644-9](http://dx.doi.org/10.1016/0029-554X(77)90644-9). URL <http://www.sciencedirect.com/science/article/pii/0029554X77906449>.
- [76] G. Charpack et al. some developements in the operation of multiwire proportional chambers. *nuclear instroments and methods*, 80(13), 1970.

- [77] Pferdekämper, K. E., and H. G. Clerc. Energy spectra of secondary electrons ejected by ions from foils. *Zeitschrift für Physik A Atoms and Nuclei*, 280 (2):155–164, 1977. ISSN 0939-7922. doi: 10.1007/BF01409544. URL <http://dx.doi.org/10.1007/BF01409544>.
- [78] Z. Insepov, V. Ivanov, S.J.Jokela, I. Veryovkin, A. Zinovev, and H. Frisch. Comparison of secondary electron emission simulation to experiment. *NIMA*, pages 155–158, 2010.
- [79] Z. Insepov and V. Ivanov. Comparison of candidate secondary electron emission materials. *Nuclear Instruments and Methods in Physics Research B*, pages 3315–3320, 2010.
- [80] K Kanaya and H Kawakatsu. Secondary electron emission due to primary and backscattered electrons. *Journal of Physics D: Applied Physics*, 5(9): 1727, 1972. URL <http://stacks.iop.org/0022-3727/5/i=9/a=330>.
- [81] J. J. Scholtz, D. Dijkkamp, and R. W. A. Schmitz. Secondary electron emission properties. *Philips J.Res*, 50:375–389, 1996.
- [82] A. Clouvas, H. Rothard, M. Burkhard, K. Kroneberger, C. Biedermann, J. Kemmler, K. O. Groeneveld, R. Kirsch, P. Misaelides, and A. Katsanos. Secondary electron emission from thin foils under fast-ion bombardment. *Phys. Rev. B*, 39:6316–6320, Apr 1989. doi: 10.1103/PhysRevB.39.6316. URL <http://link.aps.org/doi/10.1103/PhysRevB.39.6316>.
- [83] H.P. Garnir et al. Secondary electron emission from thin foils under fast-ion bombardment. *Nuclear Instruments and Methods*, 202:187, Apr 1982. URL <ftp://ftp.mpe.mpg.de/pub/plasma/Presentations/2013-06-Beijing/Workshop/2013-06-Beijing/C-Foil/Garnir-1982-NIM.pdf>.

- [84] E. Bougamonat and P. Bourgeois et al. A large tracking detector for low energy ions. *Nuclear Instruments and Methods A*, 1(19537):1–3, 2003. URL <http://cds.cern.ch/record/798714/files/cm-p00050900.pdf>.
- [85] James B.R. Battat et al. Reducing drift backgrounds with a submicron aluminized-mylar cathode. *Nuclear Instruments and Methods in Physics Research A*, 794:33–46, 2015. URL <http://www.sciencedirect.com/science/article/pii/S0168900215005860>.
- [86] A. Musumarra et al. Measuring total reaction cross-sections at energies near the coulomb barrier by the active target method. *Nuclear Instruments and Methods in Physics Research A*, 612:399–406, 2009.
- [87] T. Nakagawa and W. Bohne. A compact and gridless channel plate start detector. *Nuclear Instruments and Methods in Physics Research A*, 271:523–526, 1988.
- [88] A. Savitzky and M. J. E. Golay. Smoothing and differentiation of data by simplified least squares procedures. *Anal. Chem.*, 36:1627–1639, 1964. URL <http://pubs.acs.org/doi/abs/10.1021/ac60214a047>.
- [89] R. Viswanathan and K. Hilpert. Mass spectrometric study of the vaporization of cesium iodide and thermochemistry of $(\text{csi})_2(\text{g})$ and $(\text{csi})_3(\text{g})$. *Ber. Bunsen-Ges. Phys. Chem.*, 88:125, 1984. URL <http://webbook.nist.gov/cgi/cbook.cgi?ID=C7789175&Mask=20#ref-3>.
- [90] J. Berkowitz, H.A. Tasman, and W.A. Chupka. Double-oven experiments with lithium halide vapors. *J. Chem. Phys.*, 36:2170, 1962. URL <http://webbook.nist.gov/cgi/cbook.cgi?Source=1962BER%2FTAS2170&Units=CAL&Mask=3069>.
- [91] A. Donszelmann and J. H. M. Neijzen. Spectroscopy with rydberg atoms; the neutral spectrum of indium. *Acta Phys. Pol. A*, 63:201–222, 1983.

- [92] V. Kaufman and W. C. Martin. Wavelength and energy level classifications for the spectra of aluminum (al i through al xiii). *J. Phys. Chem. Ref. Data*, 20:775–858, 1991. doi: 10.1063/1.555895.
- [93] M.Gomez, C.Chatillon, and M. Allibert. Thermodynamics of gaseous and condensed indium oxides by mass spectrometry with controlled oxygen pressure. *Chem. Thermodyn.*, 14:447, 1982.
- [94] P.Ho and R.P Burns. A mass spectrometric study of the alo₂ molecule. *High Temp. Sci*, 12:31, 1980. URL <http://webbook.nist.gov/cgi/cbook.cgi?Source=1980HO%2FBUR31&Units=SI&Mask=864>.
- [95] crystals.saint gobain. Csi(tl), csi(na)cesium iodide scintillation material, 2016. URL <http://www.crystals.saint-gobain.com/uploadedFiles/SG-Crystals/Documents/CsI%28Tl%29%20and%20%28Na%29%20data%20sheet.pdf>.
- [96] Andreas Goudelis, Maxim Pospelov, and Josef Pradler. Light particle solution to the cosmic lithium problem. *Phys. Rev. Lett.*, 116:211303, May 2016. doi: 10.1103/PhysRevLett.116.211303. URL <http://link.aps.org/doi/10.1103/PhysRevLett.116.211303>.
- [97] Sara T. Mongelli. Spallation physics and the ads target design. *Brazilian Journal of Physics*, 35, 2005.
- [98] Massimo Tesi. *Measurement of the neutron flux and of the capture cross section of ²³⁶u at n tof*. Phd thesis, Universita Degli Studi di Bari ‘aldo moro’, 2015.
- [99] M. Barbagallo et al. High-accuracy determination of the neutron flux at n tof. *epja*, 49(156), 2013.
- [100] C. Weiss et al. The new vertical neutron beam line at the cern n_tof facility design and outlook on the performance. *NIMA*, 799:90–98, 2015.

- [101] S. Barros, I. Bergstrom, V. Vlachoudis, C. Weiss, and n.TOF collaboration. Optimization of n_tof-ear2 using fluka. *JINST*, 10, 2015. URL <http://iopscience.iop.org/article/10.1088/1748-0221/10/09/P09003/pdf>.
- [102] T.T. Bhlen, F. Cerutti, M.P.W. Chin, A. Fass, A. Ferrari, P.G. Ortega, A. Mairani, P.R. Sala, G. Smirnov, and V. Vlachoudis. The fluka code: Developments and challenges for high energy and medical applications. *Nuclear Data Sheets*, 120:211 – 214, 2014. ISSN 0090-3752. doi: <http://dx.doi.org/10.1016/j.nds.2014.07.049>. URL <http://www.sciencedirect.com/science/article/pii/S0090375214005018>.
- [103] A. Ferrari, P.R. Sala, A. Fasso, and J. Ranft. The fluka: a multi-particle transport code. *CERN 2005-10 (2005)*, *INFN/TC 05/11*, *SLAC-R-773*.
- [104] SP-Devices. Adc412. URL <http://spdevices.com/index.php/adq412>.
- [105] Open source. *GNU Image Manipulation Program (GIMP)*, 2016. URL <https://www.gimp.org/>.
- [106] Open source. *Image Processing and Analysis in Java (ImageJ)*, 2016. URL <https://imagej.nih.gov/ij/index.html>.
- [107] P. Zugec, C. Weiss, C. Guerrero, F. Gunsing, V. Vlachoudis, M. Sabate-Gilarte, A. Stamatopoulos, T. Wright, J. Lerendegui-Marco, F. Mingrone, J.A. Ryan, S.G. Warren, A. Tsinganis, and M. Barbagallo. Pulse processing routines for neutron time-of-flight data. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 812:134–144, 2016.
- [108] P. Zugec et al. Pulse processing routines for neutron time-of-flight data. *physics.ins-det*, jan 2016. URL https://www.researchgate.net/publication/291229383_Pulse_processing_routines_for_neutron_time-of-flight_data.

- [109] H.W. Schmitt, J.H. Neiler, and F.J. Walter. Fragment energy correlation measurements for cf-252 spontaneous fission and. u-235 thermal-neutron fission*. *PRL*, 141(3):1147–1160, Jan 1966.
- [110] Pavel Obloinsk, A.D. Carlson, V.G. Pronyaev, D.L. Smith, N.M. Larson, Zhenpeng Chen, G.M. Hale, F.-J. Hambsch, E.V. Gai, Soo-Youl Oh, S.A. Badikov, T. Kawano, H.M. Hofmann, H. Vonach, and S. Tagesen. Special issue on nuclear reaction data international evaluation of neutron cross section standards. *Nuclear Data Sheets*, 110(12):3215 – 3324, 2009. ISSN 0090-3752. URL <http://www.sciencedirect.com/science/article/pii/S0090375209001008>.
- [111] F. Gunsing, D. Macina, L. Tassan-Got, V. Vlachoudis, and S. Warren. The master channel and calorimetric channel zero suppression method. Technical report, CERN Engineering Department, CERN, Route de Meyrin 385, 1211 Meyrin, Switzerland, jan 2016. EDMS 1569137, rev 0.2.
- [112] Vinnie Falco. A collection of useful c++ classes for digital signal processing, nov 2012. URL <https://github.com/vinniefalco/DSPFilters>.