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PHD THESIS

Secondary Emission Monitor (SEM) optimisation at the CERN fixed target beamlines

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Abstract

Understanding the effects of ageing instrumentation on the measurement of various beam properties is key to fixing undesired behaviour. The aim of this thesis was to conduct an investigation into the unexplained observations presented by Secondary Emission Monitor (SEM) instrumentation in the North Area (NA) fixed target beamlines at European Organization for Nuclear Research (CERN). First installed in the late 1970s, last calibrated in the 1990s and still in use today, SEM monitors are ubiquitous in these beamlines and responsible for measuring quantities such as the Protons on Target (POT), the transmission efficiency and beam position, used for steering the beam.

The main objectives were: to understand and separate the contributions to signal caused by foil ageing due to proton dose, changes in the vacuum conditions and additional secondary charged particles, created in interactions with the bias foils or surrounding equipment; to perform the absolute calibration of the Beam Secondary Emission Intensity monitor (BSI)s in the NA target locations; and to improve the signal to noise ratio of the Beam Secondary Emission Grid (BSG)s in the NA, thus improving the steering accuracy within the beamlines.

To understand the contributions to the BSI signal from additional secondary charged particles, simulation work was conducted comparing different positions of the beam relative to the BSI geometry. The energy, vertex location, generating process and type of particle created by the simulations and their effect on the signal generation for the BSI monitors was studied.

The absolute calibration measurements for the BSIs, positioned at the primary target locations in the NA, were carried out using the activation method, and as a result, new calibration factors were established for all BSIs at these locations, affecting POT measurements for all fixed target experiments in the NA and improving the reliability of the transmission efficiencies measured. The results, stability of the measurements and the impact that these have on the operation of these devices was discussed.

A solution for improving the signal to noise ratio of BSGs, using autoencoders to reduce the background noise, was investigated. An autoencoder model was trained on available BSG data and tested on new data. The results and performance of this model were evaluated.

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Acronyms

ADC Analog-to-Digital Converter.

ALARA As Low As Reasonably Achievable.

BCT Beam Current Transformer.

BSG Beam Secondary Emission Grid.

BSI Beam Secondary Emission Intensity monitor.

CERN European Organization for Nuclear Research.

EA East Area.

LHC Large Hadron collider.

ML Machine Learning.

NA North Area.

POT Protons on Target.

PS Proton Synchrotron.

PSB Proton Synchrotron Booster.

RF Radio Frequency.

RP Radioprotection.

SEC Secondary Emission Chamber.

SEE Secondary Electron Emission.

SEM Secondary Emission Monitor.

SEY Secondary Emission Yield.

SPS Super Proton Synchrotron.

TBID Target Box Instrumentation Downstream.

TBIU Target Box Instrumentation Upstream.

XPS X-ray Photon Spectroscopy.

XSEC Secondary Emission Chamber.

Chapter 1

Introduction

The European Organization for Nuclear Research (CERN) experimental complex was built to answer a range of fundamental physics questions, concerning matter/antimatter asymmetry, the search for dark matter, neutrino physics, among many others. Since its construction, it has been responsible for validating the standard model theory, through the discovery of the W, Z and Higgs boson, the first creation of antihydrogen, among many other important feats [1]. These discoveries have driven incredible technological innovation, such as the invention of the World Wide Web [2].

At the heart of the experiments conducted at CERN are particles. The experiments rely on high energy particles, arriving at the right location and at the right time. Accelerating and guiding these particles is achieved via interconnected accelerators and beamlines. These rely on a large number of instruments in the beam, to understand where the particles are, how many of them exist and if they are on track to arrive at the correct location. Feedback systems are designed around these to guide the particles towards the ideal conditions, ensuring that they arrive at each location in the right conditions.

Since its creation CERN has expanded greatly, and state of the art solutions have been custom built for the latest accelerators. But alongside these huge new developments and upgrades there are also many older beamlines and accelerators, some of which have been repurposed, some retired and others that have been in operation for many years, still containing older equipment, that has been functioning, but in unexpected and inconsistent ways.

The CERN North Area is one such beamline, containing ageing instrumentation, some of which has been in place since the construction of the beamline in the late seventies. This thesis, covering the topic of Secondary Emission Monitor (SEM) optimisation, is the result of a four year project, realised in collaboration with CERN and the University of Liverpool. The objective was to investigate the ongoing issues with the SEM instrumentation present in the beamlines, perform calibration measurements and create simulations of the beam interaction with the SEM monitors, to understand the origin of these

problems and find solutions for optimising their measurement capabilities.

The remainder of this chapter will describe the CERN accelerator complex, giving details about the project location, a brief introduction to the physics of particle matter interaction, followed by presenting the an insight into the history and motivation behind this project. Chapter 2 will introduce important accelerator physics concepts, as well as the relevant beam instrumentation. Chapter 3 shows simulation work conducted in Geant4 investigating the interaction between the beam and the Beam Secondary Emission Intensity monitor (BSI) monitor. Chapter 4 presents the calibration measurements conducted for the BSIs at the target stations in the North Area. Chapter 5 will cover the the topic of machine learning used for optimisation of SEM grids. Chapter 6 presents the final considerations and plans for future work.

1.1 CERN Accelerator Complex

CERN is home to a number of accelerators, most of which are a part of the injection chain for the Large Hadron collider (LHC), the largest collider built to date, measuring 27 km.

The accelerator complex is capable of accelerating protons and heavy ions and provides particle beams for a large variety of experiments located on several locations along the trajectory of acceleration. Figure 1.1 shows the CERN accelerator complex and associated experiments.

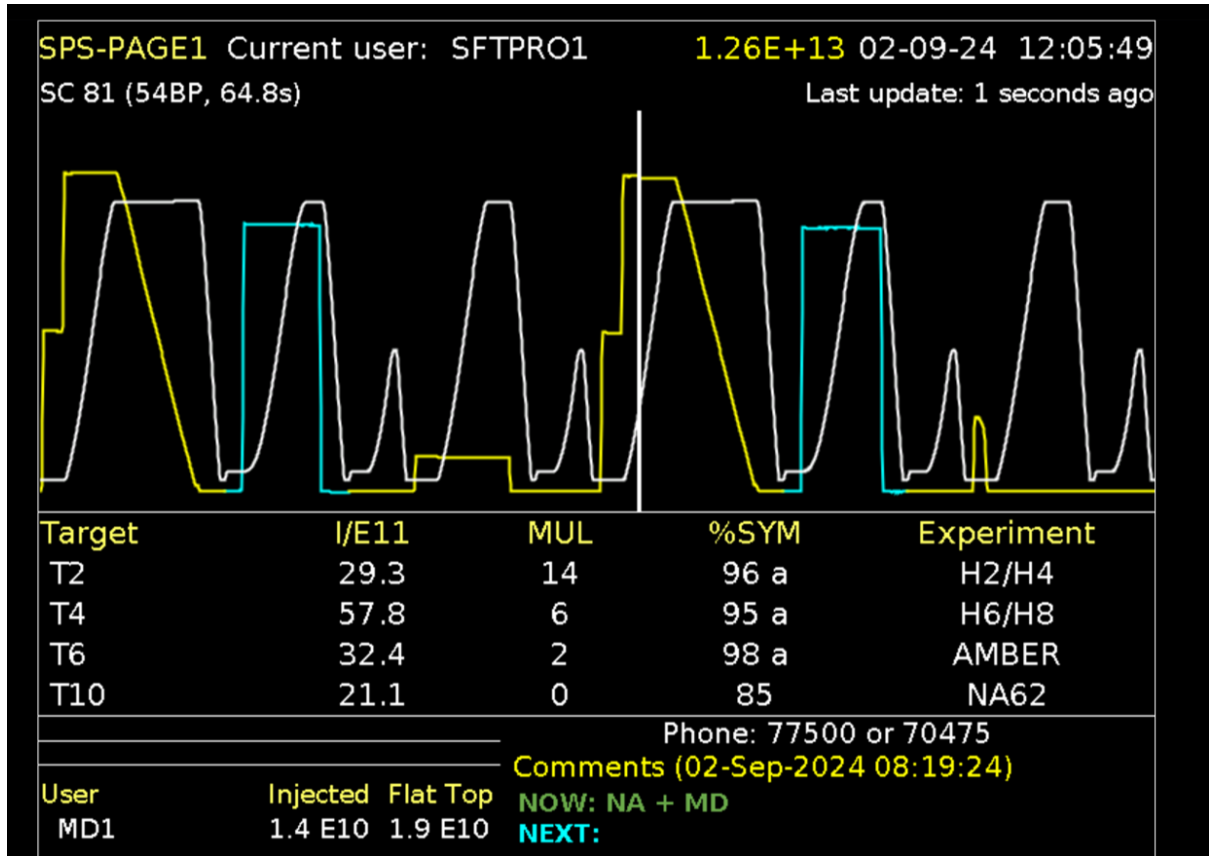


Figure 1.2: SPS Page 1 Screenshot

Each time the yellow line goes up, it means that the SPS is receiving protons, this is known as the injection phase. When the yellow line goes down it means that protons are leaving the SPS and being sent somewhere, this is called extraction. The time from the beginning of the injection to the end of the extraction is called a cycle. In Fig. 1.2 you can see multiple cycles. All the cycles that can be seen in this image make up what is called a Super-cycle and the vertical white bar shows the current position in the Super-cycle. Each cycle will correspond to a different user and the Super-cycle pattern will keep repeating until modified. The user indicates where the beam is being sent and beam parameters, such as intensity and duration of the extraction may differ for different users. For example, in Fig. 1.2 the current user is SFTPRO1. This means that the beam is being sent to the North Area. Other North Area users include SFTPRO2 and SFTION.

The North Area, in operation since 1978, is home to many fixed target experiments, that compliment the collider based experiments at CERN. Fixed target experiments are those in which the protons, instead of colliding with other protons, collide with a target, producing secondary beams of other particles.

The TT20 beamline receives a slow extracted beam from the SPS, which it transports to the experiments in the North Area. The North Area is home to many SEM, of different types, measuring beam intensity, beam position and beam profile. These instruments are described in more detail in Section 2.3.1.

Looking at Fig. 1.2 it is possible to see that the extraction to the North area is a slow extraction. The yellow line goes down diagonally, showing that it is reducing slowly over time. In contrast the turquoise line, representing an AWAKE experiment cycle, is vertical at extraction, indicating a fast extraction.

Differently to the beam in most accelerators at CERN, which is generally bunched, the slow extracted beam in the North Area is continuous, having a fixed intensity and a typical pulse duration of 4.8s. This pulse of DC beam is known as the spill. The slow extracted beam is distributed towards the different targets in the North Area. The intensity of the beam at each target is measured by BSIs positioned upstream of each of the Target stations. The proton intensity at each target is displayed in the SPS Page 1, below the plots of the super-cycle, as seen in Fig. 1.2. Information displayed on SPS Page 1 is crucial for beam operation. Both Operation and North Area experiments rely on BSI data collected by various BSIs positioned along the lines, to measure the proton current.

1.2 Interaction of particles with matter

Understanding the interaction between the particle beam and objects placed in and around it is of crucial importance in the field of beam instrumentation. This section will give an introduction to some of the main processes that govern the interaction between the proton beam, extracted from the SPS, and the BSI monitor described in Section 2.3.1.

The interaction of particles with a medium is often described in terms of energy loss. There are different mechanisms for energy loss, that will vary according to the type of particle, the kinetic energy of the particle and the type of medium. The probability of a particle interacting with a target, or another particle, is known as a cross-section σ . Different types of cross-sections exist for different types of particles and processes. The differential cross-section $\frac{d\sigma}{d\Omega}$ for a photon is described by Eq. (1.1), where $d\Omega$ represents the solid angle in the direction of the photon scattered [4].

$$\sigma = \int_{4\pi} \frac{d\sigma}{d\Omega} d\Omega \quad (1.1)$$

The proton beam, being made up of charged particles, is affected by Coulomb forces and will interact with the electrons present in the target material. A number of Coulomb interactions may happen, such as elastic or inelastic scattering, radiative emission and absorption. Elastic scattering, where the total kinetic energy is conserved, does not lead to much energy loss, as the target tends to be much larger than the incoming particle, and as such will not recoil much, but will cause the incoming particle to change direction. Inelastic scattering occurs when the incident particle transfers some of its energy to an electron in the target, causing the excitation of atoms and ionisation.

In addition to electromagnetic interactions, the particles can also undergo hadronic and nuclear interactions, which although not the main method responsible for the signal generation in SEMs, could be responsible for other background processes that may affect the measured signal. In particular if these interactions create products that are also charged particles, that could lead to the amplification of the signal being measured. It is beyond the scope of this thesis to give a comprehensive description of all possible interactions of particles with matter. This section will cover the processes most relevant to the understanding of signal generation in SEM detectors, such as ionisation and the Bethe-Bloch equation, the semi empirical theory of secondary electron emission, and also processes relevant for the calibration of SEM monitors such as nuclear Spallation, which is the key process responsible for the Activation Calibration Method, described in Section 4.2.

1.2.1 The Bethe Bloch Equation

The inelastic collisions taking place between the proton beam and the electrons in the target, result in the deposition of energy along the particle track. The energy deposition changes according to particle momentum, and different models are used for each momentum range. Fig. 1.3 shows the mean energy loss for a positive muon in copper at various momenta. The vertical blue lines represent the boundaries in which different models best apply.

For moderately relativistic heavy charged particles¹ the mean rate of energy loss when a particle passes through a material, or stopping power, in units of $MeVg^{-1}cm^2$, is best described by the Bethe-Bloch equation:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (1.2)$$

Here K is a constant of value $0.307075 MeVmol^{-1}cm^2$ given by $4\pi N_A r_e^2 m_e c^2$, z is the charge number of the incident absorber, Z is the atomic number of the absorber, m_e is the electron mass, r_e is the classical electron radius, N_A is Avogadro's number, I is the mean excitation energy in eV, A is the atomic mass of the absorber, β and γ are the relativistic kinematic variables, W_{max} is the maximum transfer of energy from a single collision, given by Eq. (1.3) and $\delta(\beta\gamma)$ is the density effect correction to ionisation energy loss.

$$W_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + \frac{2\gamma m_e}{M} + \left(\frac{m_e}{M}\right)^2} \quad (1.3)$$

¹particles with momentum between $0.1 \lesssim \beta\gamma \lesssim 1000$

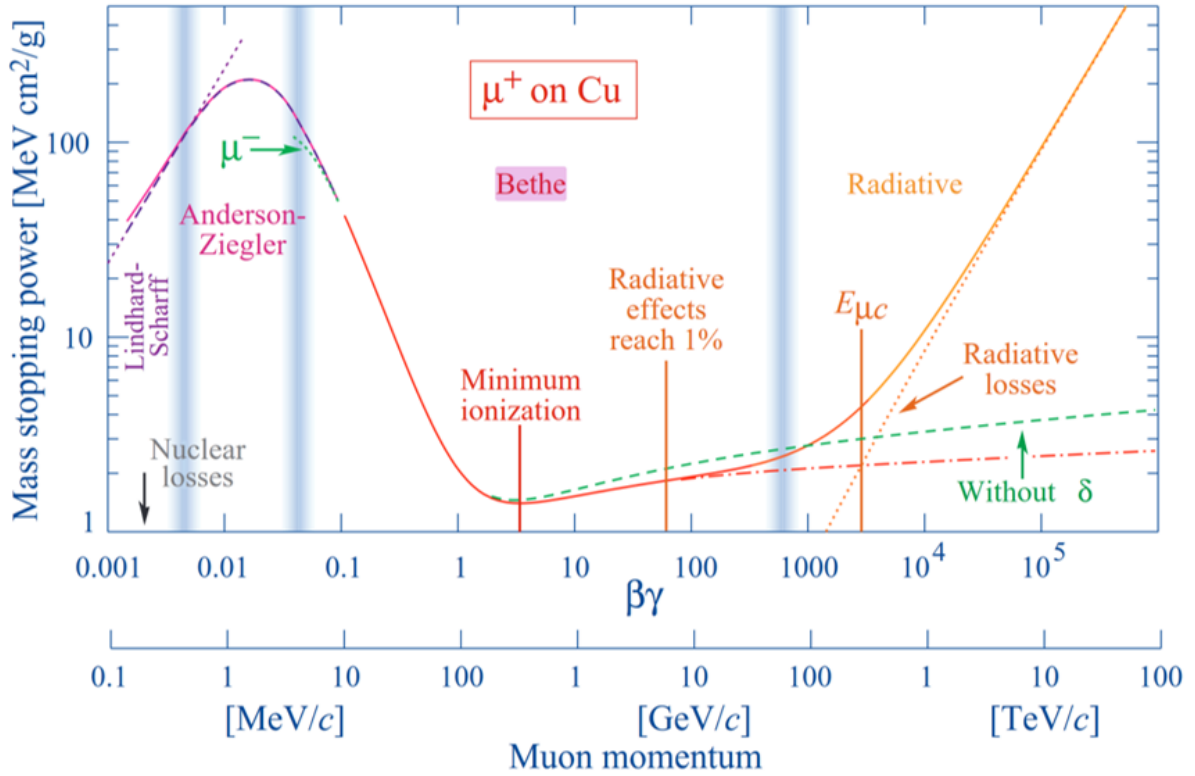


Figure 1.3: Stopping power for positive muons on copper as a function of momentum. From [5]

Where M is the mass of the incident particle. Further information about the derivation of this equation and the different terms it contains can be found in [5, 6]. Fig. 1.4 shows the stopping power for protons in a range of different target material between the energies of $1\text{keV} - 10\text{GeV}$.

Energy loss for electrons at lower energies is described by a similar version of the Bethe-Bloch equation, but as their energy increases, ionisation ceases to be the main mechanism for energy loss and more and more energy is lost to radiation, with Bremsstrahlung being the dominant process. The point at which the energy lost via ionisation equals the energy lost through radiation is called the critical energy (E_c). Expressed in units of MeV E_c for electrons is given approximately by Eq. (1.4) [8].

$$E_c = \frac{800}{Z + 1.2} \quad (1.4)$$

The critical energy exists also for other particles such as muons and pions, but for these the value of E_c is much higher. This can clearly be seen in Fig. 1.3 which shows the E_c for muons in copper is hundreds of GeV.

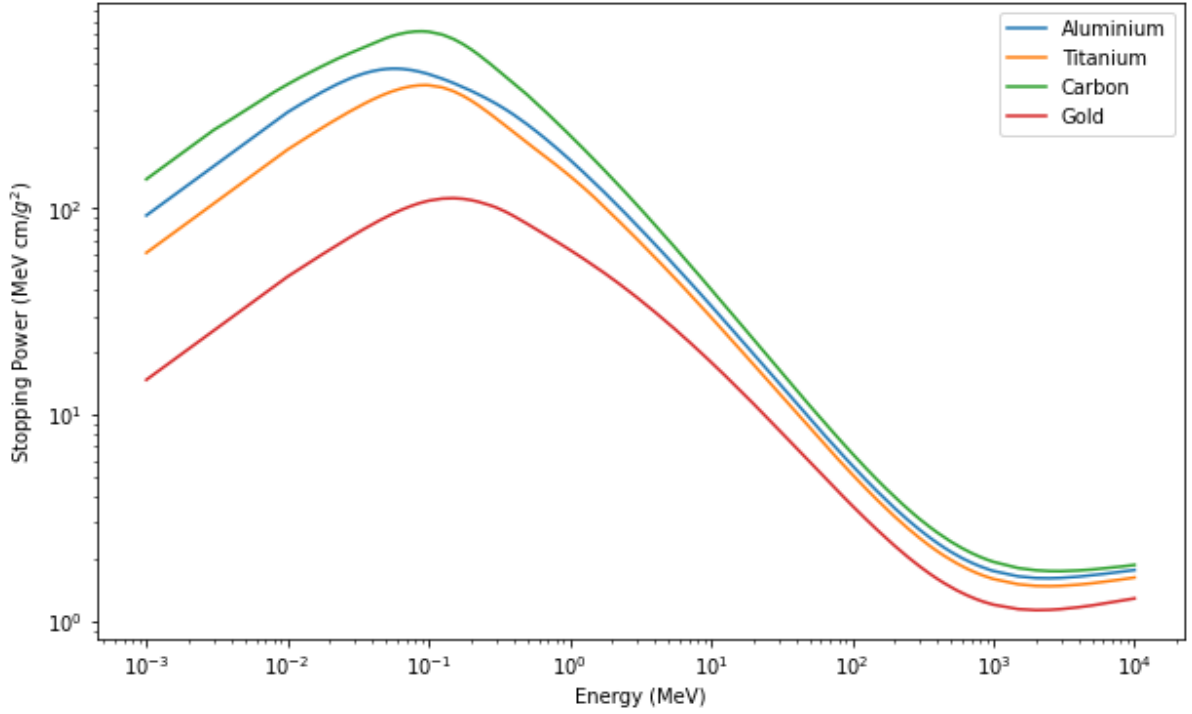


Figure 1.4: Stopping power for protons incident on various materials. Using data from [7]

If a particle passes through a composite material, then we can imagine the medium being made up of j thin slices, then the energy deposited per slice $\frac{dE}{dx_j}$ can be summed to give the total energy deposited:

$$\left\langle \frac{dE}{dx} \right\rangle = \sum w_j \left\langle \frac{dE}{dx_j} \right\rangle \quad (1.5)$$

1.2.2 Particle Range and straggling

Charged particles depositing energy in a material lose energy continuously according to the Continuous Slowing Down Approximation (CSDA), at a rate equal to the mean energy loss of the particle in that particular medium. The mean path travelled by these particles in the material according to the CSDA description is defined as the CSDA range R_{CSDA} , given by Eq. (1.6).

$$R_{CSDA} = \int \left(\frac{dE}{dx} \right)^{-1} dE \quad (1.6)$$

However, in reality, particles do not deposit exactly the mean energy at every step they take in the material, their actual energy loss will vary around the value of the mean energy loss. This variation in energy loss has an impact on the range of the particles, and this variation in both range and energy loss is known as straggling. This definition of range applies to particles that lose energy predominantly

according to the Bethe-Bloch equation. As particles start to lose energy predominantly via radiation, this definition no longer applies[6].

As well as not taking straggling into account, the CSDA range does not consider the effects of multiple scattering. Alternatively one can define the mean forward range or R_{mf} , also sometimes called projected range, as the mean forward path of the particle, including both straggling and multiple scattering effects. This is normally shorter than the CSDA range.

1.2.3 Theory of Secondary Electron Emission

Secondary Electron Emission (SEE) is defined as the emission of an electron, created by the interaction of a charged particle with matter. A theory for secondary emission was developed by E. J. Sternglass in [9]. Here he describes the derivation of a semi-empirical formula for the secondary emission process. This is a process involving three main stages: excitation, diffusion and emission.

In the first stage the charged particle interacts with the electrons in the solid, transferring some of its energy to them. If the energy is sufficient then ionisation can occur. This ionisation can be either the ionisation of the electrons in the solid, or the ionisation of electrons in the charged particle passing through it (if this is a charged particle containing electrons). The majority of electrons generated will be low energy electrons, but there is also a small probability of creating higher energy δ electrons. This type of electron is the result of a close interaction between the projectile particle and an atomic electron, in which a large amount of energy is transferred to that electron.

Once created, the electrons can travel in the material and create further interactions, this is the diffusion stage. Here, Sternglass compares the motion of the excited electrons in the solid to the motion of electrons in a gas, and uses diffusion theory in order to describe the motion of these particles. Low energy electrons are unlikely to travel far from where they are originally created, but δ electrons, can travel further and contribute significantly to the production of secondary electron emission. For this reason, in Sternglass' description of the SEE process he specifically distinguishes between two types of secondary electron generation processes: the secondary electrons created by direct interaction with the primary charged particle ($n_{se}^{(1)}$), described by Eq. (1.7) and those created by interactions with δ electrons ($n_{se}^{(2)}$), described by Eq. (1.8).

$$n_{se}(x, v)^{(1)} = \frac{1}{\bar{E}_0} \left\langle \frac{dE}{dx} \right\rangle^{(1)} \quad (1.7)$$

Here x represents the depth, $\bar{E}_0$ is the mean energy lost per secondary creation and $\left\langle \frac{dE}{dx} \right\rangle^{(1)}$ is the mean energy lost in creating low energy secondaries.

$$n_{se}(x, v)^{(2)} = f(x, v) \frac{1}{\bar{E}_0} \left\langle \frac{dE}{dx} \right\rangle^{(2)} \quad (1.8)$$

Similarly to the previous equation $\left\langle \frac{dE}{dx} \right\rangle^{(2)}$ is the mean energy lost in producing δ electrons and $f(x, v)$ is the energy available for the generation of δ electrons at a certain depth. The combined contributions of secondary and δ electrons $n_{se}(x, v_i)$ is given by Eq. (1.9), which is the sum of Eqs. (1.7) and (1.8).

$$n_{se}(x, v_i) = \left(\frac{1}{\bar{E}_0} \right) \frac{1}{2} \left\langle \frac{dE_i}{dx} \right\rangle [1 + f(v_i x)] \quad (1.9)$$

The third stage is the emission of the electron. The probability of emission of an electron at a depth x from the metal is described by Eq. (1.10), is dependent on a constant related to the distribution of initial velocity of the secondaries A , the surface transmission coefficient τ , given by Eq. (1.11) and the characteristic length of diffusion of low energy electrons L_s , given by Eq. (1.12).

$$P(x) = \tau A \exp\left(\frac{-x}{L_s}\right) \quad (1.10)$$

In his paper [9] Sternglass argues that τ , in the context of bombardment by fast ions, is independent of the work function and the Fermi Energy and can be expressed in terms of the surface dipole potential Φ_D . Assuming evenly distributed electron velocities τ can be shown to be given by Eq. (1.11)

$$\tau = 1 - \left(\frac{\Phi_D}{\bar{E}_s + \Phi_D} \right)^{\frac{1}{2}} \quad (1.11)$$

Here Φ_D originates from the difference in electrostatic potential for the electrons inside the metal (where they are created) and the vacuum to which they escape and $\bar{E}_s$ is the secondary electron energy, measured relative to the vacuum level. Φ_D is expected to be small in comparison to the average energy of the secondary electrons.

$$L_s = (\alpha' N \sigma_g)^{-1}, \quad (1.12)$$

The characteristic length of diffusion of low energy electrons L_s is related to the number of atoms per unit volume N , the geometric area of the outermost filled shells σ_g and constant α' , which is assumed

to be similar for all metals, considering the atom is described as a collection of free atoms [9]. σ_g was experimentally observed to agree with the empirical formula given by Eq. (1.13), in which Z represents the atomic number.

$$\sigma_g = 1.6 \cdot 10^{-16} Z^{1/3} \quad (1.13)$$

The quantity of electrons generated for each proton is called the Secondary Emission Yield (SEY). This can be determined by integrating the number of secondary electrons produced in a thin slice dx , at a depth x , by the probability of emission of the electron at that depth.

$$SEY = \int n_{se}(x, v_i) P(x) dx \quad (1.14)$$

Solving the integral in Eq. (1.14) leads to Eq. (1.15), in which L_δ is the effective penetration depth for delta electrons.

$$SEY = \frac{1}{2} \left(\frac{1}{\bar{E}_0} \right) \left\langle \frac{dE_i}{dx} \right\rangle \tau A L_s \left[1 + \frac{1}{1 + \frac{L_\delta}{L_s}} \right] \quad (1.15)$$

The angle of incidence of the incoming projectile can have a significant effect on the SEY, as particles with an angle θ with respect to the normal, would have a larger range and thus more opportunities for interaction. In [9] the relationship between the SEY measured at an angle of θ to the normal (SEY_θ) and the SEY measured at an angle of 0 to the normal (SEY_0) is described by:

$$\frac{SEY_\theta}{SEY_0} = \sec(\theta) \quad (1.16)$$

However after further experimental investigation [10] this relationship in Eq. (1.16) was later found to better described by Eq. (1.17), In which α is the secondary electron absorption coefficient and x is the penetration depth.

$$\frac{SEY_\theta}{SEY_0} = e^{\alpha x (1 - \cos \theta)} \quad (1.17)$$

Fig. 1.5 shows the spectra of energies for secondary emission electrons produced by 500 keV protons for various different materials. It is clear that the majority of secondary electrons have quite a low energy peak, in the order of eVs.

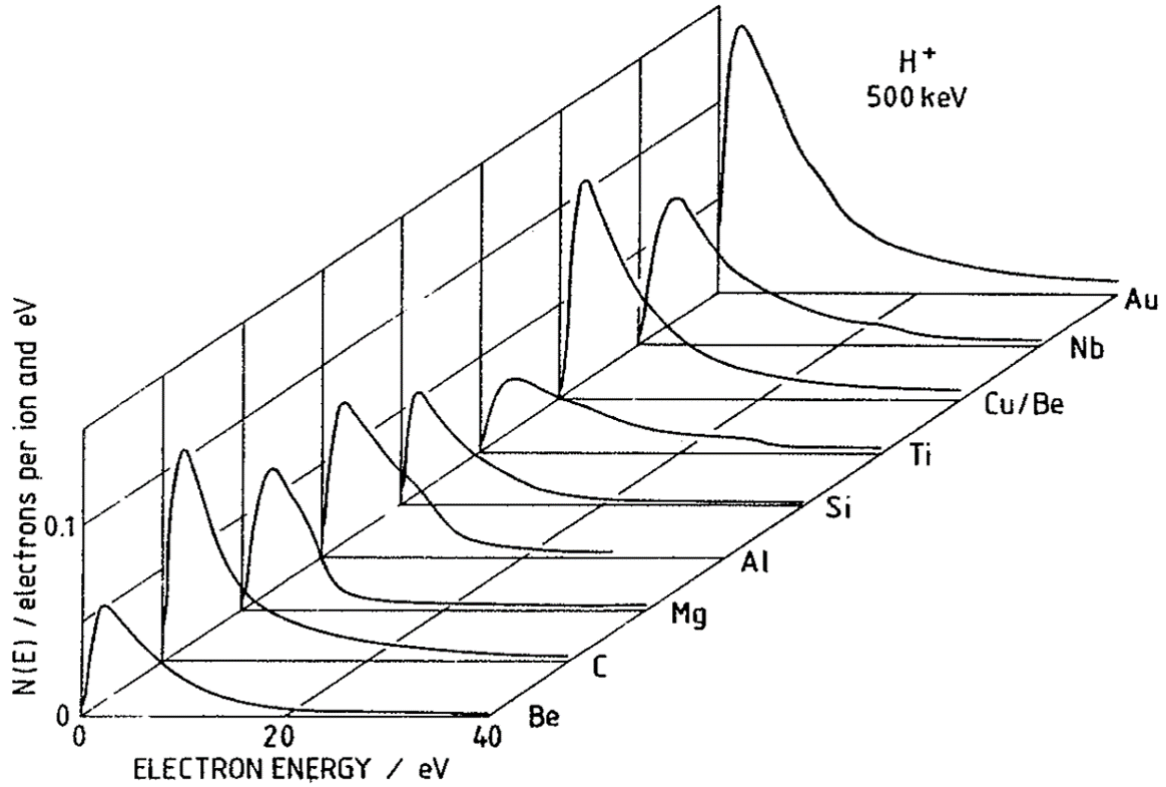


Figure 1.5: SEY Spectra, taken from [11]

1.2.4 Spallation

A collision between a high energy projectile and target can produce a type of nuclear reaction known as spallation, in which the projectile interacts with atomic nuclei, removing nucleons and causing some lighter nuclei to be expelled [12, 13]. This process occurs in steps, which are illustrated in Fig. 1.6. In the first step the projectile collides with a nucleon, knocking it out and provoking a series of knock on collisions between nucleons, with further nucleons being ejected. This is called intra-nuclear cascade. Some nucleons may also interact with nucleons from another nucleus, this is known as internuclear cascade. The remaining nucleus is thus highly excited, from all of the repeated collisions [15, 16].

In the second step the excited nucleus decays by evaporation of neutrons and light charged particles, leading to a variety of nuclei of mass number smaller than that of the target being formed.

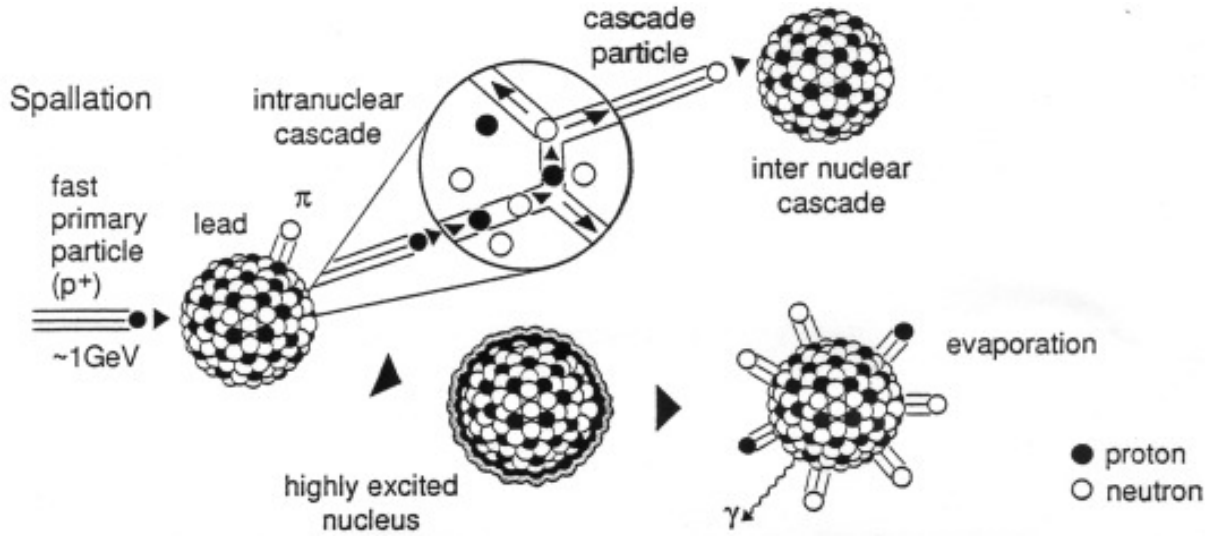


Figure 1.6: Steps in spallation process, from [14]

1.3 History and motivation

The CERN North Area, as described in Section 1.1.1, has been in operation since 1978 [17] and is home to various fixed target experiments such as COMPASS/AMBER, NA61/SHINE, NA62, NA64, the neutrino platform, as well as being used for R&D and testing of detectors and instrumentation [18].

The beam for this area, coming from the SPS, is carried towards the target beamlines, via the TT20 beamline. Most of the SEMs in the TT20 area were installed in the late 1970s [19]. The last calibration of these instruments was performed in 1996 [20]. Apart from the renovation of the target box instrumentation in 2014, which is described in [21], very little documentation exists to indicate that any changes have occurred to the BSIs since their last calibration. These instruments, despite their limitations, survived the best part of four decades with minimum changes and interventions.

In 2016 the Physics Beyond Colliders (PCB) initiative began, with the intention making full use of the infrastructure available at CERN. The proposal, detailed in [22], was to explore the creation of fundamental physics research experiments, complimentary to those being conducted in colliders. This led to the evaluation of existing facilities, including the North Area beamlines, and the proposal of many ambitious projects. The stringent requirements of many of these projects brought to light the limitations of the NA instrumentation, which was not originally designed with these experiments in mind.

A key issue that has been mentioned [23, 24] is the high activation level detected in the slow extraction area of the TT20 beamline. The number of Protons on Target (POT) has been increasing over time and future experiments will demand even higher POT. If left unchanged, increased POT would result in more

losses, and higher activation, since the activation is caused by predominantly by the slow extraction losses.

Slow extraction is a beam extraction process which transforms a pulsed beam into a continuous beam, with a DC current with a longer duration. This DC pulse in the TT20 beamline typically lasts around 4.8 seconds.

Determining the extraction efficiency is key for adequate protection measures to be taken for both staff and equipment, since the extraction efficiency is proportional to the induced radioactivity [25, 26]. The extraction efficiency can be determined from the ratio between the extracted beam intensity and the intensity measured when the beam is circulating (before extraction). Calibration errors between different beam intensity monitors, even if they are small, can have a significant impact on this efficiency.

In addition to extra protection from radiation, future experiments would also like to improve the precision of the devices, with plans to either significantly improve the current detector design or to replace the currently installed monitors with a better performing device during Long Shutdown 3 (LS3). Cryogenic current comparators have been mentioned in [19] as a possible, albeit costly solution, but the preferred solution would be to understand problems occurring with the SEM devices and optimise them, in order to achieve the required performance at a lower cost. Key priorities for improvement include beam position and intensity measurement, which present distinct challenges to be addressed.

BSP monitors are used in some parts of this beamline for measuring the beam position, but they have known saturation issues. Other monitors used to monitor steering include BBS and BSG monitors, which use thin metallic strips instead of foils to measure the beam position. Because multiple measurements of position are being taken and these are relative measurements, absolute calibration is not a big problem for the smooth operation of these devices. However the small size of the strips means less of the beam passes through them, resulting in much lower secondary emission currents. Low signals can be amplified, but this can create noise. Signal to noise ratio here becomes an important consideration. Chapter 5 presents work done using machine learning to improve signal to noise ratio for BSG monitors in the beamline.

In the NA, due to the low DC beam current extracted, it is not possible to use conventional beam pick-ups (which can normally be calibrated to 1% error) to measure the beam intensity. Instead, proportional counting instruments, such as SEMs and ionisation monitors are employed [27]. Many SEMs are used for beam current measurements between the SPS and the target stations.

However SEMs in particular are prone to degradation over time, due to environmental factors such as radiation, vacuum and conditioning history. This degradation leads to the secondary emission yield

changing over time. Although we know this degradation is happening, it is unclear to which extent each one of these factors is contributing to the degradation, and over what time scales these changes occur.

These changes in Secondary Emission Yield (SEY) are of great importance for SEM monitors that measure beam intensity, because they measure the current from a single foil and rely on devices being calibrated to work properly. Any change to the SEY would have an impact in the accuracy of the signal being measured therefore absolute calibration is crucial for these instruments.

Some studies [20, 28] looking at the stability of SEM foils and evaluating their degradation over time were conducted. The longest study [28] was conducted over a year between 1995 and 1996. A range of different foil materials were tested, including aluminium, titanium, gold, and gold-plated aluminium and titanium. It was observed that in most foils, including aluminium, which was commonly used in BSIs at the time, the SEY decreased significantly during the testing period. Titanium was the best performing material, showing a slight increase in the measured SEY in the beginning, and returning close to its original SEY value over time. This resulted in all the target station BSI monitors having their foils replaced with titanium foils. However the timescale of the studies conducted is relatively short, compared to the lifetime of the BSI monitors and it is not clear whether the results observed can be directly attributed to one factor.

A more recent analysis [29], including SEY and X-ray Photon Spectroscopy (XPS) measurements, was conducted at CERN in 2016, examining old aluminium BSI foils. This study found significant differences in the SEY of the aluminium foils measured at different locations, and the presence of additional elements on the surface of the foils. These results are complimentary to the previous SEY study [28] and demonstrate the combined ageing effects, resulting from the beam conditions these foils were exposed to. It would be interesting to see similar studies conducted on titanium foils.

Studies [30–33] have also been conducted to study the impact of vacuum, surface treatments and conditioning on the SEY of certain materials, such as carbon, copper, aluminium and stainless steel. In [32] the effects of exposure to high vacuum and air were studied for amorphous carbon coatings on stainless steel. Exposure to either air or high vacuum were found to increase the SEY, although interestingly not all samples subjected to similar conditions aged at the same rate. It was found that annealing the coating in air lead to a decrease in SEY. In [30], many ways of lowering the SEY were discussed including making grooves, coating surfaces, blackening of the surface of materials using a laser, and conditioning of materials through electron bombardment.

Most of these studies were conducted in the context of electron cloud, aiming to study how to reduce the SEY with the application of various coatings. It is possible to gain an insight into some factors that can impact the SEY, but difficult to draw any direct conclusions, since the materials in question

are not the same as the material of the BSI foils. In [34] the effect of ion bombardment on the surface of untreated titanium and copper was studied, as well as its effect on the SEY. It found that titanium that had been treated by bombardment with low pressure, 1500 eV argon ions, significantly decreased the SEY in titanium, when tested for a range of electron energies between 200 and 2000 eV. Here, although the same material was used, as that of the BSI foils, the beam type was different and the energy range is orders of magnitude lower when compared to the beam in the CERN North Area (NA). Most SEY studies found, focus on the SEY values measured close to the SEY peak, but little data exists for higher energy values, far from this peak.

Problems with the calibration of SEM devices were highlighted in 2016, when a large difference was noted between beam intensity measured by a SEM monitor (BSI.210279) in the TT20 beamline and the beam current transformer (BCT) in the SPS. There was also a difference between the current measured between two foils located within the same device. The BSI.210279 monitor being comprised of two measurement foils A and B, sandwiched between bias foils: foil A being upstream of foil B. According to [27], at the end of the physics run in 2016, foil A was removed from TT20 and installed in TT10 in order to investigate this issue, as the TT10 line had a fast-BCT, enabling the direct measurement of beam current. The foil at position B in TT10 and both foils in BSI.210279 were replaced with new foils at this time. This paper mentions that after moving foil A between TT20 and TT10 a signal increase of 10% was recorded for this foil, which was attributed to its exposure to air and that a 15% discrepancy was measured between the two foils (A and B) in the same device.

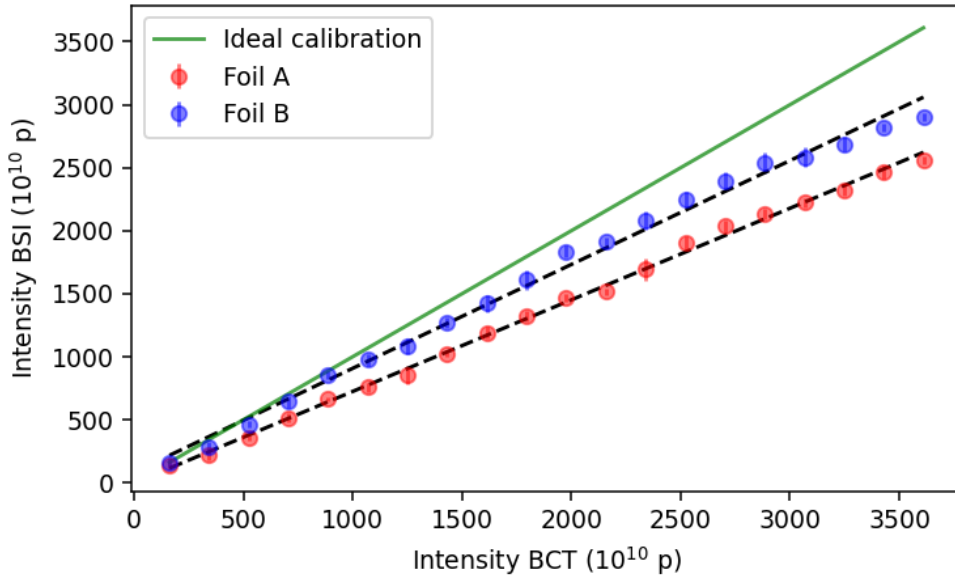


Figure 1.7: Intensity measured in by BSI as a function of intensity measured by BCT for two foils in BSI.210279 during 2017

Fig. 1.7 shows the beam current intensity as measured by the two foils of BSI.210279, compared to the beam current intensity measured by the BCT in the SPS ring, for the period between May and October 2017. The green line represents the ideal calibration, in which the intensity measured by the BSI foils and the BCT are the same and the slope is equal to 1.

In reality the measurements of the BSI foils deviate from the green line, due to a few different factors. Firstly, the extraction from the SPS is not lossless, and secondly the calibration of the BSIs is not perfect. The difference between the ideal slope and the slope of the measured BSI values could suggest systematic errors in the calibration of the device - such as the DAQ gain, or SEY- it could also indicate secondary emission losses between the BCT and BSI.

The difference in current measured between the two foils could be due to charged particles, created in the first foil or bias foils, reaching the second foil and creating an additional secondary emission signal. The bias foils, in theory should help to prevent this from happening, but they wouldn't be able to stop higher energy particles. However it is also possible that the signal difference could be due to localised ageing of the foil or contamination due to changes in vacuum conditions. The latter being a possible consequence of the lack of reliability the of the vacuum system in the NA beamlines, reported in various documents [18, 35–37] between 2015 and 2021. The problems derive from the high levels of radiation damage the equipment is subjected to, which lead to the degradation vacuum components over time, resulting in failures, compromising the reliability of the system.

The relationship between the beam current measured by the two BSI foils is non-linear. This could be caused by the losses varying according to beam intensity, the SEY changing over time, or the DAQ relationship with signal level. In Fig. 1.8, which shows the progression over time of the signal measured by the two BSI foils, normalised by the signal measured by the BCT in the ring, we can see the non-linearity even more clearly.

It is evident that not only is the signal fluctuating over time, but that the difference between the two measured signals is also varying, with the signal values for the two foils converging more towards the end of 2017, than they did at the beginning. The exact reason for this remains unclear. Similar mechanisms could be responsible for this that cause the non-linearity effects described, or perhaps it could be linked to the stability of the beam operation.

This is however quite a complex problem, with multiple factors to consider. Is there an increase in signal due to secondary particles, coming from losses or contact with other instrumentation in the vicinity? It is important to note here that the SEM instruments have bias foils that contain a hole at the centre. If there were any problems with the beam steering, or if the beam was larger than the bias foil

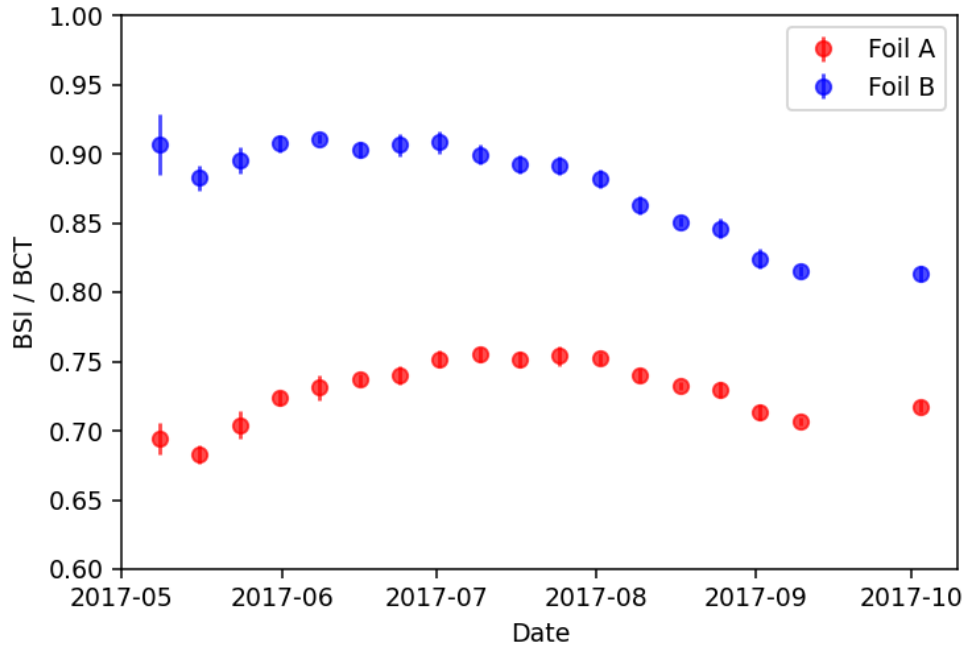


Figure 1.8: Ratio of BSI to BCT Intensity as a function of time

hole this could be an important issue to think about. Additionally, as already discussed, we know that bombarding foils with particles, changes the material properties of the foils, so do changes in vacuum conditions. These effects have been studied for various materials, but are not well understood in the context of high energy proton beams impinging on titanium foils. Could localised damage to the BSI foils, caused by such effects be the best explanation for what was observed? If so then is there a dominant contribution from either of these effects? How large is the contribution to the SEY from the bias foils? Different operating conditions could lead to changes in the beam size and intensity, with varying effects on each of the factors mentioned.

The challenge is how to isolate these effects in order to understand the underlying physics mechanisms behind the strange behaviour observed and to what extent each one contributes to what we see. Chapters 3 and 4 were dedicated to answering some of these questions, the former consisting of investigating the relationship between the beam and the bias foil geometry and the latter presenting work done on absolute calibration measurements at the BSIs in the NA beamlines.

Background information on some of these problems and other related issues is discussed in more detail in [19, 38]. These documents discuss the observed issues and highlight the need for calibration of the SEMs in the TT20 as a priority.

Chapter 2

Accelerator Physics Concepts

2.1 Particle Motion in Accelerators

The understanding of particle motion in accelerators underpins what we observe with beam instrumentation. The movement of particles in an accelerator is described by both the position and the momentum of the particles, as both have corresponding x, y and z components. This results in a 6D system for describing particle motion. This motion can be described in terms of two planes: the longitudinal plane, which is along the direction of motion, and the transverse plane, which is perpendicular to the direction of motion. As the instrumentation referred to in this thesis is transverse beam instrumentation, this section will describe the basics transverse motion of particles in accelerators. For more detailed information on both transverse and longitudinal particle motion, please refer to [39, 40].

When describing an ideal accelerator we assume that the accelerator has a constant energy and stable beam trajectory. The accelerator components chosen ensure that particles travel following the ideal reference path and are accelerated until they reach the required energy, before being delivered to the relevant experiment.

The coordinate system used for describing transverse particle motion is shown in Fig. 2.1. This system is described in relation to the ideal path, also known as design orbit, represented by s , with radius of curvature ρ . At any given point s along the design orbit there is an orthogonal plane, which can be used to describe the trajectory of the particle, in relation to s . This is known as the Frenet-Serret coordinate system.

The particle motion is controlled via the use of electromagnetic fields. Longitudinal electric fields produced by Radio Frequency (RF) cavities accelerate the beam, whilst transverse magnetic fields are used to control the direction of motion. If the magnetic field $\vec{B}$ is oriented vertically then the charged particle will experience a force $\vec{F}$ in the horizontal plane given by Eq. (2.1).

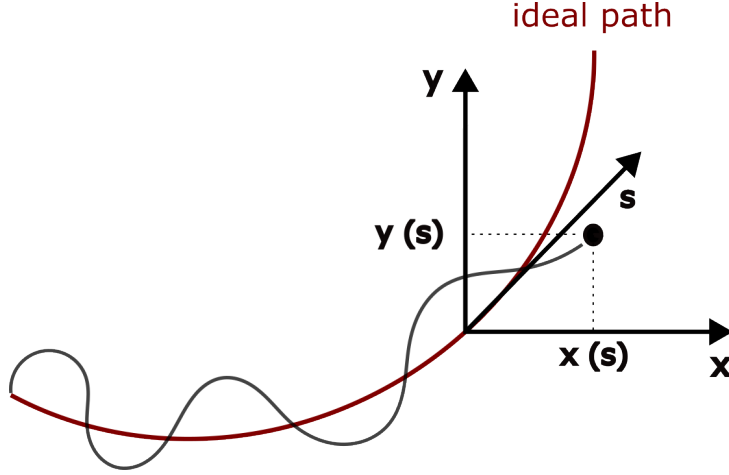


Figure 2.1: Coordinate system for transverse motion of a particle in an accelerator

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2.1)$$

Where q is the particle charge and $\vec{v}$ is the particle velocity tangential to the particle's path. Magnets used for bending are called dipoles, so named because they have two magnetic poles. For an ideal orbit the momentum p of a particle is related to the radius of curvature ρ and magnetic field B according to Eq. (2.2).

$$B\rho = \frac{p}{q} \quad (2.2)$$

Where $B\rho$ is known as the beam rigidity and represents the constraints in both size and magnetic field for achieving a certain momentum in a storage ring. Particles with momentum p travelling through a dipole of length L will be deflected according to the bending angle θ given by Eq. (2.3) [40], as is evident from the geometric relationship shown in Fig. 2.2.

$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{LB}{2B\rho} \quad (2.3)$$

In reality not all particles in a beam travel along the ideal path. Instead, particles with non-zero starting position and momentum coordinates start to diverge from the design orbit and need to be focused. Dipole magnets produce a weak focusing effect on the horizontal plane, restoring particles back towards the ideal orbit.

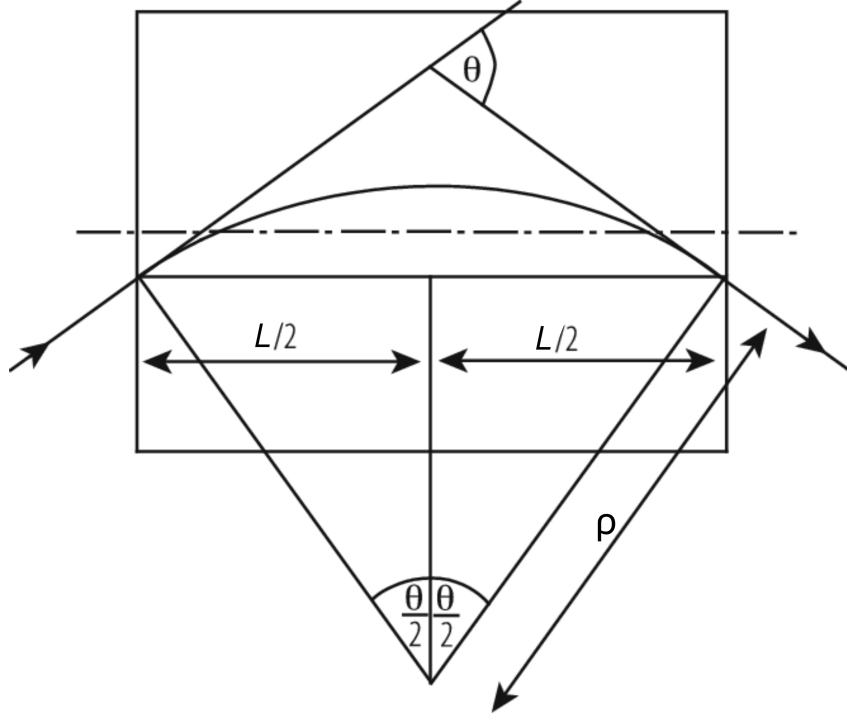


Figure 2.2: Bending angle for dipole, from [40]

Stronger focusing can be achieved via the use of quadrupole magnets, shown in Fig. 2.3. Quadrupoles are made up of four poles and provide focusing, but do not bend. These magnets are only able to focus the beam in one direction, whilst the other direction becomes defocused. To focus in both transverse directions, quadrupoles that focus in each direction need to be combined. These magnets are aligned in structures called FODO cells, which can be repeated throughout the accelerator. Each cell is made up of two quadrupoles F and D, where F is horizontally focusing and D is horizontally defocusing, interspaced with a drift space (O) [39].

A particle with displacement x and angle x' , given by Eq. (2.4), experiences a restoring force of strength $k(s)$, as it passes through a quadrupole of length L . This force creates a small change dx' in the angle x' , which is given by Eq. (2.5)

$$x' = \frac{dx}{ds} \quad (2.4)$$

$$dx' = Lkx \quad (2.5)$$

where $k(s)$ is given by Eq. (2.6)

$$k(s) = \frac{1}{B\rho} \frac{dB_y}{dx} \quad (2.6)$$

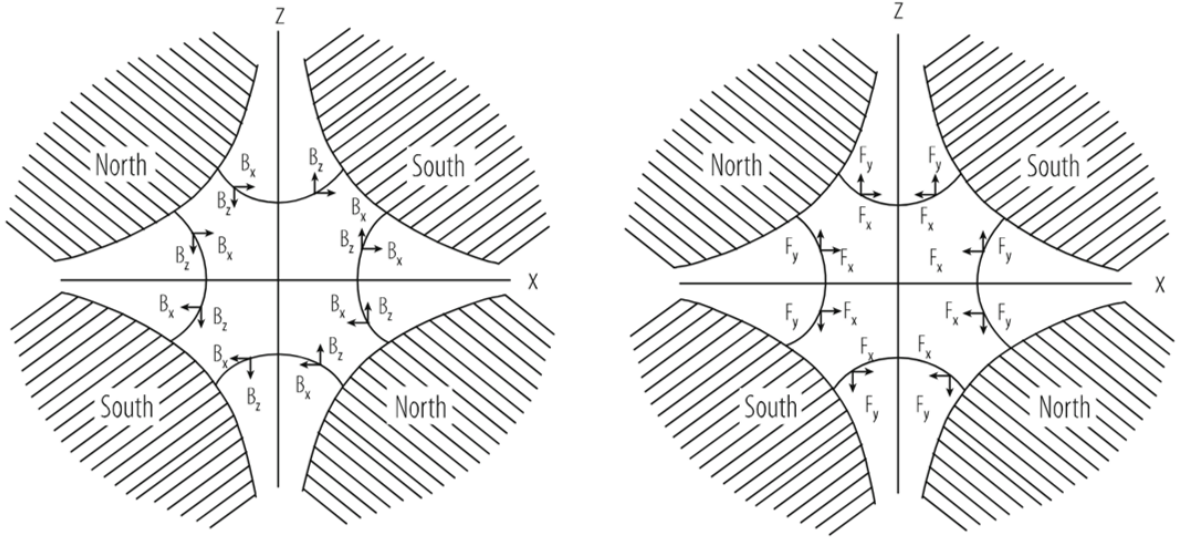


Figure 2.3: Magnetic field of quadrupole magnet, from [40]

$K(s)$ is the sum of the contributions from the quadrupole and the dipole¹, which is described by Eq. (2.7), for both horizontal and vertical planes.

$$K(s) = \begin{bmatrix} \frac{1}{\rho^2} + k(s) \\ -k(s) \end{bmatrix} \quad (2.7)$$

As such we can write an equation of motion [39], similar to one used in simple harmonic motion, for both transverse coordinates, given by Eq. (2.8), where u can represent either x or y .

$$u'' + K(s)u = 0 \quad (2.8)$$

The equations for both coordinates (x and y) given by Eq. (2.8) are referred to as Hill's equations and can be expressed in the form of a matrix. For each optical element in the beamline, a matrix M can be determined, that applied to a vector of starting coordinates $[u_0, u'_0]$, will give a new set of coordinates $[u(s), u'(s)]$ for the particle at position s , after traversing the element. In this way matrices can be applied in succession to track the evolution of particle coordinates within the accelerator.

$$\begin{bmatrix} u(s) \\ u'(s) \end{bmatrix} = \begin{bmatrix} C(s) & S(s) \\ C'(s) & S'(s) \end{bmatrix} \begin{bmatrix} u_0 \\ u'_0 \end{bmatrix} = M(s) \begin{bmatrix} u_0 \\ u'_0 \end{bmatrix} \quad (2.9)$$

¹In the linear approximation.

Here $C(s)$ and $S(s)$ are given by Eq. (2.10) and Eq. (2.11) respectively.

$$C(s) = \begin{cases} \cos(\sqrt{K}s) & \text{for } K > 0 \\ \cosh(\sqrt{|K|}s) & \text{for } K < 0 \end{cases} \quad (2.10)$$

$$S(s) = \begin{cases} \frac{1}{\sqrt{K}} \sin(\sqrt{K}s) & \text{for } K > 0 \\ \frac{1}{\sqrt{|K|}} \sinh(\sqrt{|K|}s) & \text{for } K < 0 \end{cases} \quad (2.11)$$

2.2 Beam Properties

As we cannot directly observe the particles in the beam, we must measure the beam properties in order to understand what is happening to the beam at any given time. The beam properties allow us to understand the conditions of the beam and make decisions affecting it. The beam properties that are most relevant to this PhD thesis are described here.

2.2.1 Beam Current

The beam current refers to the number of charges passing per second through a measuring device. Given by Eq. (2.12), it is proportional to the number of charged particles passing through. This is an important quantity for accelerator operation because it can allow operators to know if particles have been lost along the way and exactly how many particles are arriving at a certain location, and is also used by experiments for their data. It is of particular importance at locations in which the beam is split into different beamlines, at extraction points, before collision points and around target locations.

$$I(t) = \frac{dq}{dt} \quad (2.12)$$

The way of measuring beam current depends on the structure and type of the beam. At CERN most accelerators² have bunched beams, with the number of particles highly concentrated around certain regular intervals in time, resulting in high beam currents. In between the bunches there are spaces and these form part of a train. It is common to speak of bunch intensity in this scenario. For this type of beam, where there are high beam currents, it is common to use a Beam Current Transformer (BCT) for beam current measurements, which measures the induced magnetic field generated by the passing beam.

There are also some transfer lines where the beam is slow extracted, such as the NA and East Area

²including PS and SPS

(EA). Here there are no longer bunches. The particles in these are spread out in time, distributed evenly in what is known as a spill. In this context we may speak of spill intensity. Fig. 2.4 shows the Intensity measured as a function of time in the spill. The spill intensity is given by the integral of the shaded area underneath the curve. Here the intensity is low, as the particles are no longer concentrated in

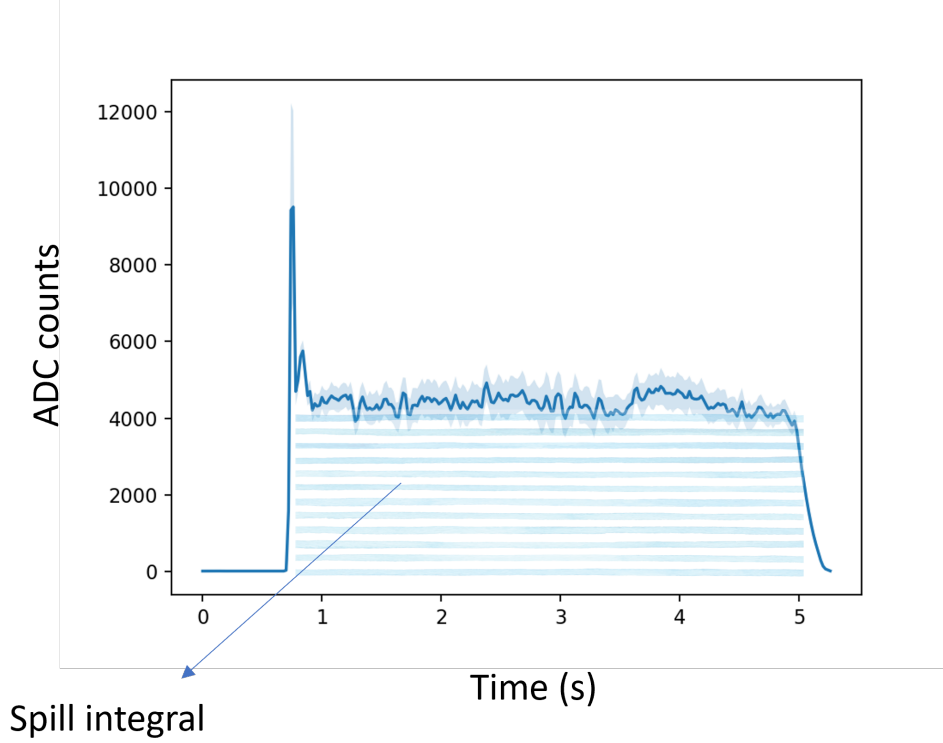


Figure 2.4: Beam intensity measured, as a function of time in the spill

time, which makes beam current transformers no longer practical. In these areas proportional counting devices such as SEMs and ionisation chambers are used. These instruments also have limitations: ionisation chambers have very low outputs, and SEMs, although they can be amplified, present issues with surface degradation [41].

There are however not really viable alternatives for online monitoring of the beam, since particle detectors, such as scintillators, which measure the energy loss of particles traversing a material, are not radiation resistant and present saturation issues. Faraday cups, which collect the beam in a cup and measure its electrical charge, although they provide very accurate measurement, are destructive and present problems with peak power.

2.2.2 Beam Profile and Emittance

The particles that make up the beam are distributed in space, their position changing over time as they interact with guiding magnetic fields. The beam profile contains information about the beam shape,

and the number of particles at a particular location. Fig. 2.5 shows the an example of a beam profile. The particles in a beam are generally distributed according to Gaussian distribution³, which is described by Eq. (2.13) [42].

$$f(x) = \frac{N_0}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \quad (2.13)$$

Where μ is the mean and σ is the standard deviation. Eq. (2.13) refers to the distribution for one coordinate. It is common for the spread of particles and the mean value to change in different parts of the accelerator, as these get bent in different directions, focused or defocused by magnets. Dipoles act on individual transverse coordinates, whereas quadrupoles, focus in one direction, whilst defocusing in the opposite transverse direction. This can lead to differences in the values for μ and σ for each of the transverse coordinates (x,y).

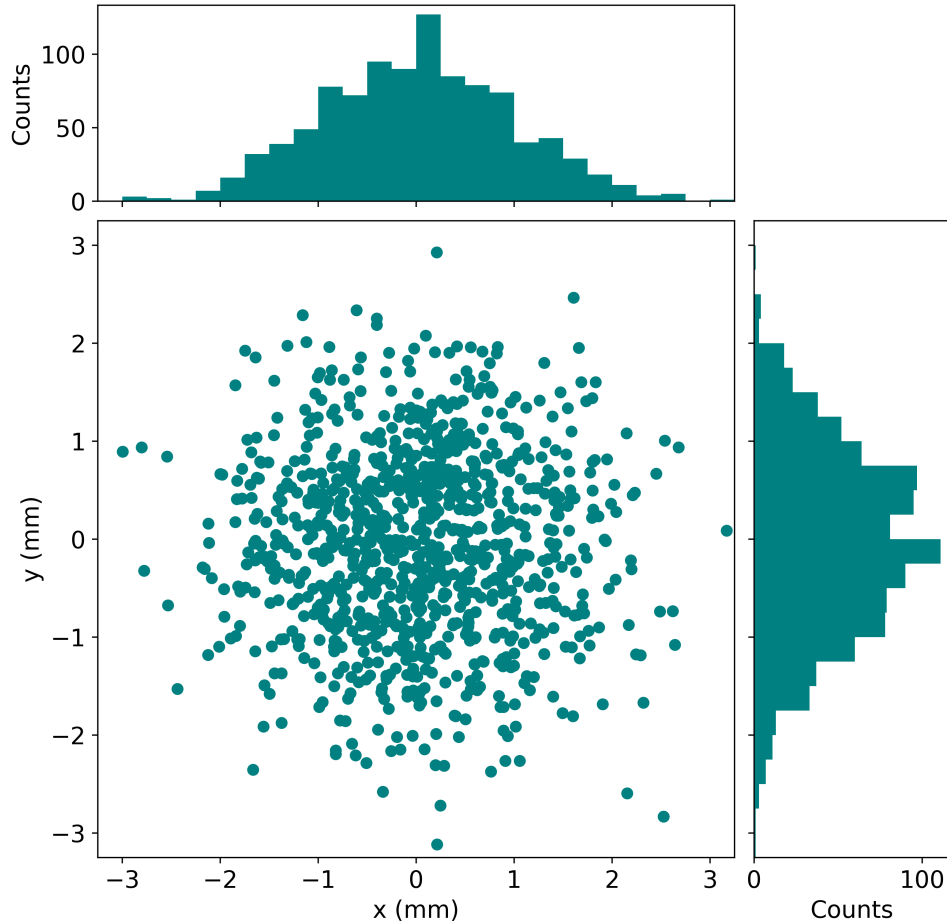


Figure 2.5: Example of transverse beam profile, showing particle distribution in transverse space coordinates(x,y), including projections

³at first approximation

As well as giving information about the particle position in space, one can define a set of coordinates that contains information about the particles' position and motion, by relating the transverse space coordinates (x, y) to the transverse dispersion coordinates (x', y') . By doing this we get a set of phase space⁴ coordinates for each axis: (x, x') and (y, y') [40, 42, 43]. Plotting the particle distribution according to these coordinates, produces a phase space diagram. Particle distribution in phase space occurs within an ellipse, shown in Fig. 2.6.

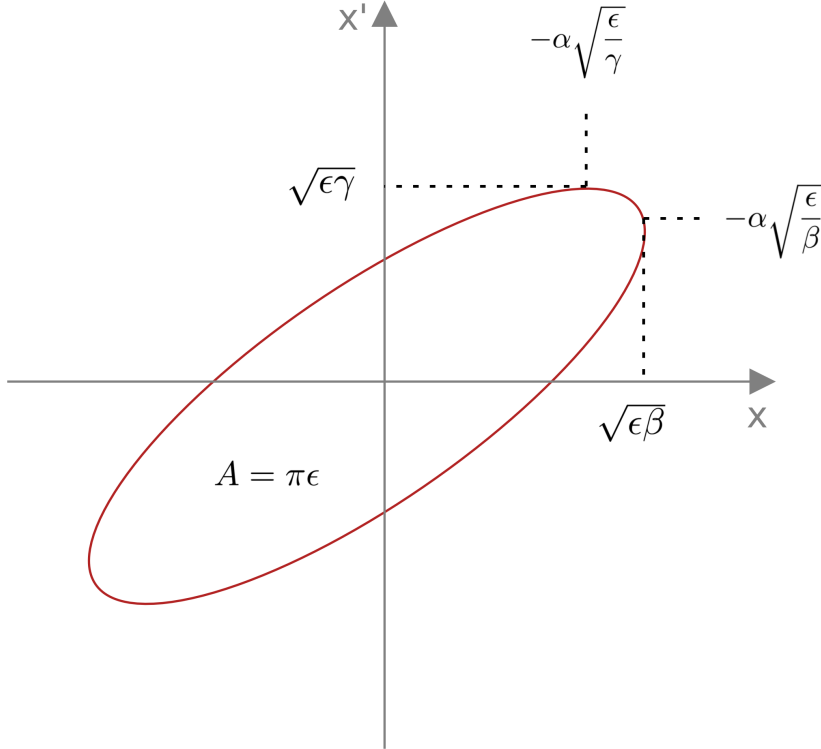


Figure 2.6: Phase space diagram

Here we can see the particles form an ellipse, which is described by Eq. (2.14).

$$\epsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2 \quad (2.14)$$

Where α, β and γ are geometric parameters of the ellipse shown in Fig. 2.6, known as Courant-Snyder variables. γ is related to α and β via Eq. (2.15).

$$\gamma = \frac{1 + \alpha^2}{\beta} \quad (2.15)$$

⁴According to [40] "phase space" refers specifically to position and momentum coordinates and the name "trace space" should be used when referring to position and dispersion coordinates, but this distinction is not always evident in literature

The area A of this ellipse is defined by Eq. (2.16), where ϵ is the emittance, given in units of mm mrad, and represents the distribution of particles in phase space.

$$A = \pi\epsilon \quad (2.16)$$

Eq. (2.14) can also be written using the matrix formalism to give the beam matrix [44, 45], shown in Eq. (2.17)

$$\Sigma = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \quad (2.17)$$

Here the terms $\langle x \rangle$, $\langle x' \rangle$ represent the mean distribution of particles in the x and x' axis respectively. And the square root of the determinant of this matrix gives the rms emittance ϵ_{rms} defined by Eq. (2.18).

$$\epsilon_{rms} = \pi \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \quad (2.18)$$

The shape of the ellipse changes in time according to whether the beam is converging or diverging, but the area remains constant, if there is no acceleration. This conservation law is known as Liouville's Theorem [40].

If the particles are being accelerated then the geometric emittance ϵ is no longer conserved, instead we can define the normalised emittance ϵ_n according to Eq. (2.19), which is invariant even under acceleration.

$$\epsilon_n = \beta_r \gamma_r \epsilon \quad (2.19)$$

Where β_r and γ_r are the relativistic parameters, which are different to the previously described Courant-Snyder parameters.

If we take Eq. (2.9), solve for x_0 and x'_0 , and substitute into Eq. (2.14) then we can get a set of simultaneous equations for the Courant-Snyder variables shown in Eq. (2.20), where C and S are given by Eqs. (2.10) and (2.11). More details on this can be found in [39].

$$\begin{bmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{bmatrix} = \begin{bmatrix} C^2 & -CS & S^2 \\ -CC' & CS' + C'S & -SS' \\ C'^2 & -2C'S' & S'^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{bmatrix} \quad (2.20)$$

2.3 Beam Instrumentation

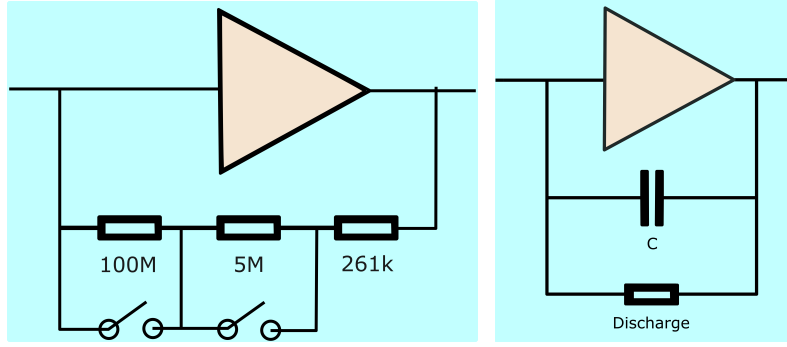
Understanding what is happening to the beam is crucial for accelerator operation and control. This is done by measuring beam properties throughout the machine. Some measurements might be taken only during commissioning, others might be a vital part of day to day operation of the accelerator. Which beam properties are measured and the requirements and constraints of each accelerator, impact the choice of beam instrumentation. As a result there is a wide variety of beam diagnostic devices to meet these needs [46]. This chapter is dedicated to describing the main instruments used in the North Area beamlines that are of relevance to this PhD project.

2.3.1 Secondary Emission Monitors

Secondary Emission Monitors (SEMs) are a type of beam instrumentation that use the process of secondary emission to measure various properties of the beam. Secondary emission occurs when charged particles come into contact with a metallic surface. The energy of these particles is transferred to the material, exciting and sometimes liberating electrons from the material. This generates a secondary electron current, in which the number of secondary electrons is proportional to the number of incident particles [47–50]. A more detailed description of the secondary emission process can be found in [9].

Most of the instruments in the TT20 beamline are SEMs. There are over 100 SEMs in this beamline and many of these devices have been in long term use since the beginning of the NA operation. All of them use the same Data Acquisition System (DAQ). The DAQ for the SEM monitors consists of a VME card, with 32 readout channels, connected to amplifiers (shown in Fig. 2.7) with individual amplification control. Multiple detectors can connect to one card. The amplifiers are connected to an Analog-to-Digital Converter (ADC) and the digitised signal is sent to a computer, where the recorded data is transferred to the NXCALS database.

The DAQ has two main modes of operation: linear mode, for use with slow extraction and integrator mode, for use with fast extraction. The linear mode uses linear amplification, sampling spill signal data every 20 ms. For noise reduction the linear mode uses subsampling to reduce 50Hz to 300Hz components and offset correction Integrator mode, which uses active integrators and applies noise reduction using a reference sample taken just before beam.



(a) Linear mode: operational amplifier, connected to 3 resistors, two which have switches, allowing for 3 different gain values to be set (b) Integrator mode: operational amplifier, connected to resistor and capacitor

Figure 2.7: Electronics of SEM DAQ, sourced from [51]

Different types of SEM devices exist: for measuring beam position, beam profile, beam halo and beam intensity. Fig. 2.8 shows the distribution of these devices along the different beamlines in the North Area. In the figure the beamlines are numbered, with the number appearing above each one in black. The different SEM types are colour coded according to their function. The instruments in the beamline are numbered according to their position within it. For example a BSI in the beamline 250 will be named BSI.250.XXX, where XXX will be a 3 digit number indicating its distance along the beamline, with the lowest values corresponding to the start of the beamline, and proceeding in ascending order towards end of the beamline. For all other SEM instruments shown in Fig. 2.8 a similar naming convention is used. The black rectangles are target boxes (described in Section 2.3.1.2) containing various instruments inside. Instruments inside the target boxes follow the same naming convention, but are usually preceded by the target number. For example, the BSI at target T10 is T10-BSI.045914. The locations of the calibration measurements conducted during this thesis are highlighted in red and green, for the first two measurements and the third respectively.

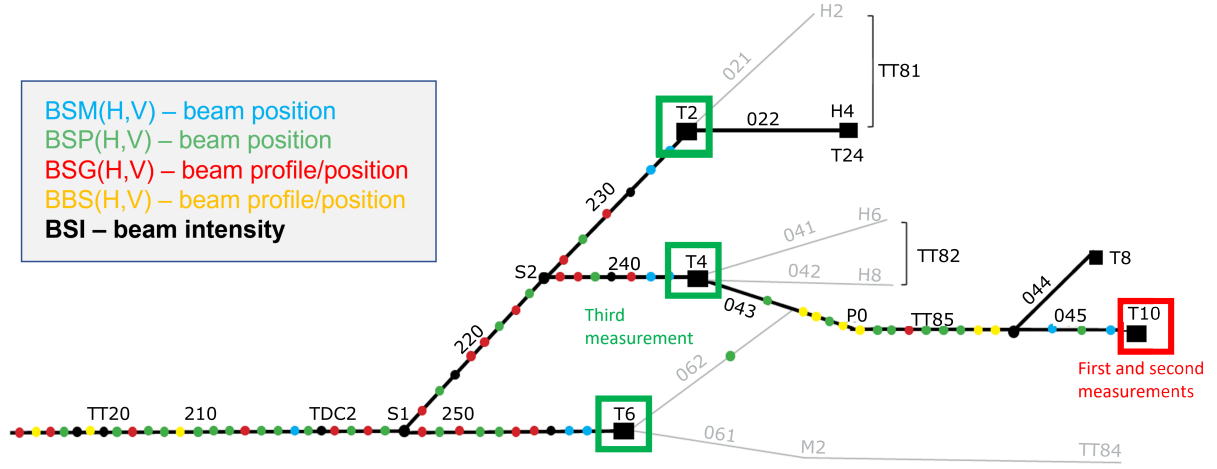


Figure 2.8: Distribution of SEM Monitors in North Area Beamlines. From [52]

There are two types of beam position monitor: BSPs (non-motorised), and BSMs (motorised), made up of two half foils. These are often used for steering, but are prone to saturation issues and as such not always the most reliable.

There are two types of beam profile monitors, which can also be used to measure position: wire strips (BBS) and SEM grids (BSG) [53]. They are formed of either a single (BBS) or multiple (BSG) wire strips and obtain the profile by combining the measured current with the position information. The position information is obtained either from reading data for multiple strips at a fixed location, or by displacing the strip and taking multiple measurements at different positions.



Figure 2.9: Picture of SEM Grid.

The Beam Intensity Monitors (BSI) used in the TT20 beamline are composed of thin titanium foils, placed in between bias electrodes, made of aluminium (see Fig. 2.10).

The bias electrodes produce an electric field, to ensure the electrons generated are promptly collected, thus preventing the formation of an electron cloud near the titanium foil which would contribute to the signal measured. They each have a hole in the centre to enable particles to flow through, without interacting with the bias plate [20].

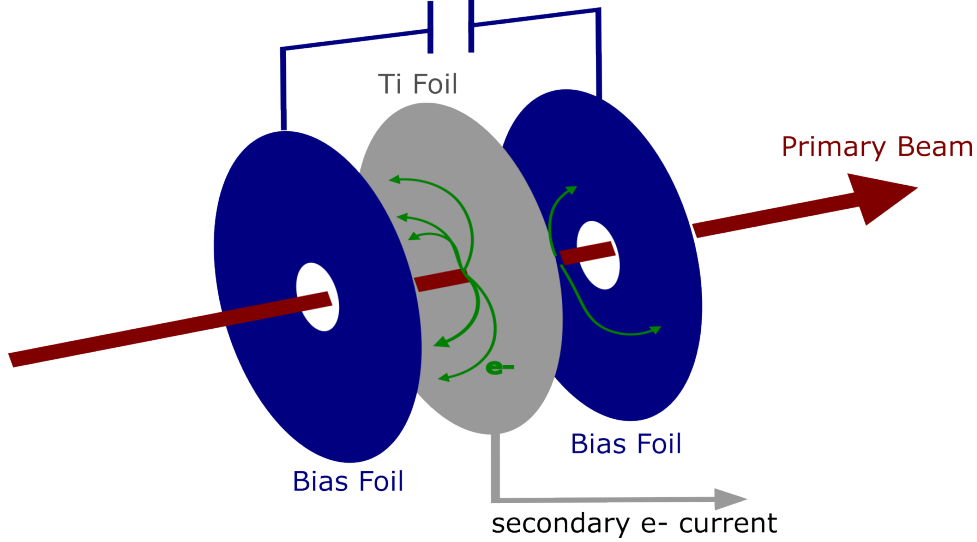


Figure 2.10: Diagram of BSI monitor - titanium foils measuring secondary emission current are positioned between bias plates

The secondary emission signal in the foil can be related to the number of protons via a calibration factor, described by Eq. (2.21). Over time ageing effects that stem from multiple sources may lead to changes in the SEY and hence the calibration factor. It is therefore vital to perform an absolute calibration measurement when ageing effects start to become apparent, since at this point the device is no longer capable of accurately measuring the proton current. More details on the calibration process can be found in Chapter 4.

$$C_f = \frac{N_P}{N_{SEM}} \quad (2.21)$$

Here N_P represents the number of primary protons incident on the BSI and N_{SEM} is the current measured in the BSI monitor.

It is worth mentioning that the term BSI is used for SEM devices measuring proton intensity in the NA at CERN. Another term encountered in literature to refer to this type of monitor is Secondary Emission Chamber (SEC). In fact, such devices in the CERN EA are referred to as Secondary Emission

Chamber (XSEC). The exact geometry and materials used for the measuring foils of SECs in other locations may vary. Often they have multiple measuring foils, interspaced with bias electrodes, instead of a singular foil, as is more common in the BSI design used in the CERN NA.

2.3.1.1 Signal Generation in SEM

As explained in Section 1.2 there are many processes involved in the production of charged particles. Charged particles passing through a metallic foil can lead to the emission of secondary electrons, creating a secondary electron current, which can be measured. Sternglass has produced a semi-empirical formula (Eq. (1.15)) which is able to describe the behaviour of these secondary electrons (including high energy delta electrons). However this equation is assuming one type of incident charged particle, with a certain value for kinetic energy.

As a first approximation this should be sufficient to quantify the SEY of a BSI monitor, but in reality at higher beam energies many different types of charged particles can be created, and these particles could potentially contribute to the signal, generating additional SEY. This is especially true for particles created outside of the Ti foil, that have enough energy to overcome the bias potential and reach the Ti foil. Whether this contribution is significant or not is one of the questions to be answered by this thesis.

Fig. 2.11 illustrates some of the main scenarios that could potentially contribute to signal generation in SEM. Here the primary proton beam is shown in red. Blue represents secondary electrons, where dotted blue lines represent electrons that are not emitted and solid lines represent electrons that have been emitted. Purple tracks represent an undefined secondary charged particle and they are labelled a-d, representing different possible scenarios.

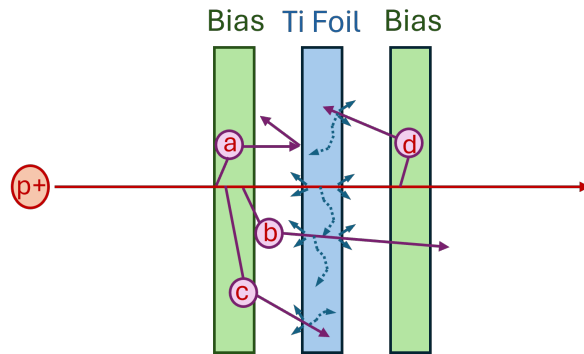


Figure 2.11: Mechanisms for signal generation by secondary particles in SEM monitor: a) elastic backscattering, without entering Ti foil; b) secondary particle traverses the Ti foil; c) secondary particle enters Ti foil; d) secondary particle backscatters and enters the Ti foil

In the case of scenario a, no signal is being generated, as the particle scatters elastically, without entering the foil, but if the scattering were inelastic, a secondary electron may have been created. In scenario b a highly energetic secondary particle, created in the bias foil crosses the Ti foil. Each time this particle passes close to the boundary between the Ti foil and vacuum, there is a probability it could lead to secondary emission. As it crosses the boundary twice, it is twice as likely to produce secondary particles than in scenario c, in which a secondary particle, produced in the bias foil, enters the Ti foil and does not exit. In scenario d the charged particle in the bias electrode backscatters, entering the Titanium foil. Here as it travels close to the boundary between materials, there is a possibility of electron emission.

It is worth noting that one particle could undergo the same process multiple times or combine multiple processes and this could lead to additional signal being created in the monitor. Additionally if there was a problem with the steering of the beam and there were beam losses somewhere in the vicinity of the beam, the particles created from the beam loss could also generate additional signal.

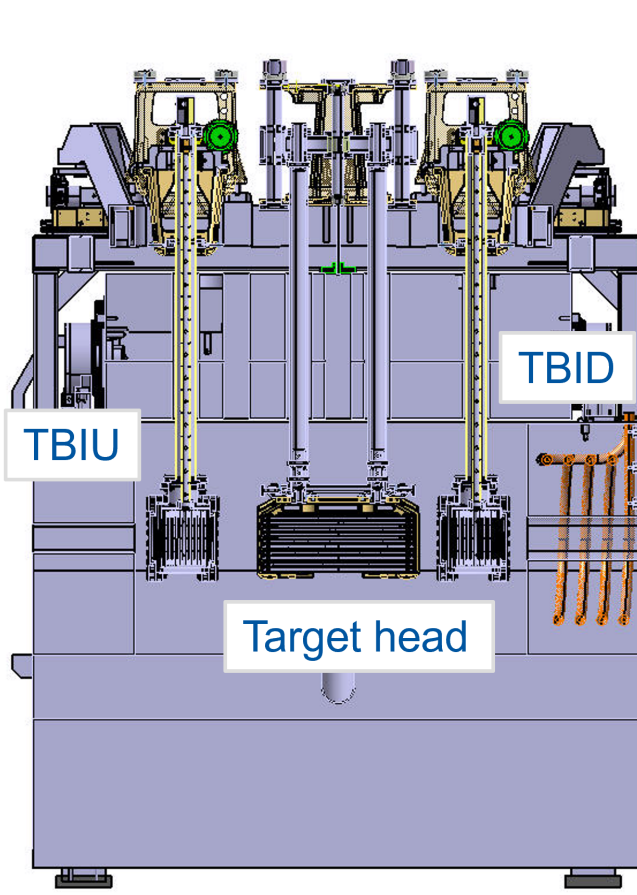
The signal generated in the SEM would be proportional to the net charge deposited in the foil q_{net} , given by Eq. (2.22)

$$q_{net} = \sum_i \eta_i N_i = q_{in} - q_{out} \quad (2.22)$$

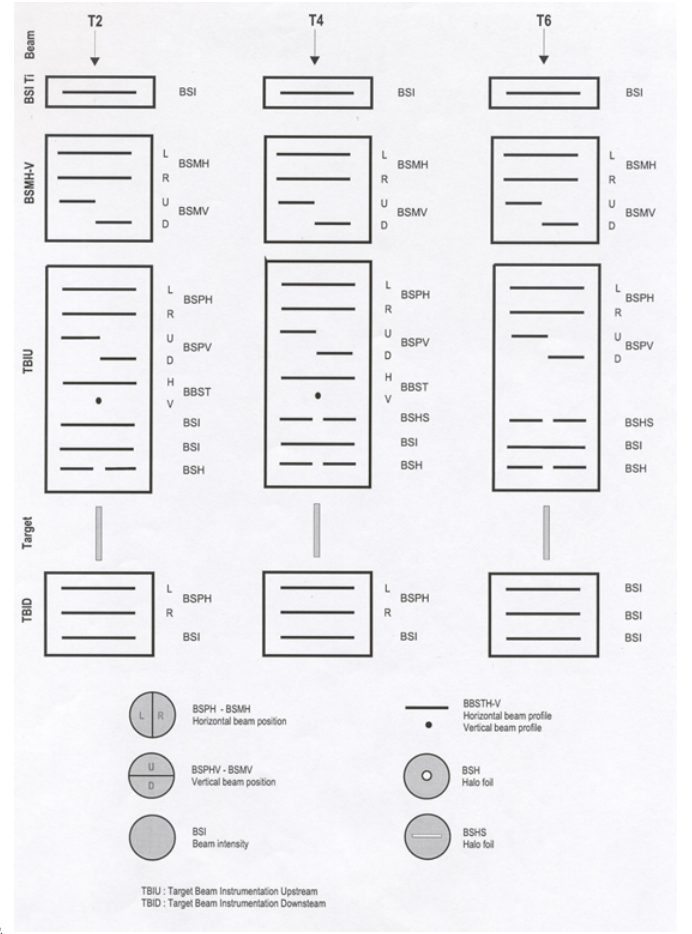
Where i is the charged particle index, η_i represents the fraction of the i th type of charged particle that is deposited in the foil and N_i is the total number of charged particles of the i th type.

2.3.1.2 Target boxes

At the target stations, many different types of SEM devices are installed inside target boxes. These boxes, positioned either side of the targets, contain SEM instruments separated by bias foils. The boxes preceding the targets are called TBIU and those after the targets are called TBID. Fig. 2.12 shows the positioning of the target boxes around the target (Fig. 2.12a), as well as the instrumentation contained inside them (Fig. 2.12b).



(a) Cross-section showing the TBIU and TBID instrumentation positioning around target



(b) Instrumentation inside the target boxes

Figure 2.12: Instrumentation at target stations [51]

2.3.2 Beam Current Transformers

Beam current transformers (BCTs) are a commonly used non-invasive method for measuring beam current in accelerators. At CERN they are used in various accelerators for monitoring beam loss occurrences and beam transfer efficiencies between different accelerators and beamlines.

They generally consist of a torus, with wire wrapped around it, that is positioned around the beam pipe. This can be visualised as a transformer, in which the beam is the primary winding and the wire wrapped around the torus is the secondary winding. The beam current I_{beam} , passing through the torus is described by Eq. (2.23).

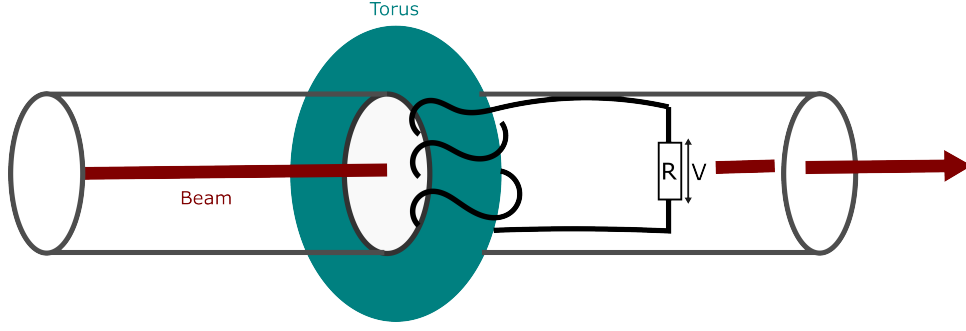


Figure 2.13: Diagram of BCT

$$I_{beam} = qe \frac{N}{t} = qe\beta c \frac{N}{l} \quad (2.23)$$

Where q is the beam charge e is the electron charge, N is the number of particles and t is time. Equivalently this can also be written in terms of the particle velocity β/c and the length l . The magnetic field created by the beam induces a current in the secondary winding. This current is proportional to the beam current and can be used to measure it. In the case of an ideal transformer the current in the secondary winding I_2 is described by Eq. (2.24)

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \rightarrow I_2 = \frac{1}{N_2} I_{beam} \quad (2.24)$$

Here $I_1 = I_{beam}$, N_1 is 1 and N_2 is the number of windings around the torus.

$$U = LI \quad (2.25)$$

In reality the voltage induced in the secondary winding U will depend on the inductance L of the torus, defined by Eq. (2.26) and the rate of change of the beam current I .

$$L = \frac{\mu_0 \mu_r}{2\pi} l N^2 \ln \frac{r_{out}}{r_{in}} \quad (2.26)$$

Where μ_0 is the permeability of free space, μ_r is the permeability of the torus and r_{in} and r_{out} are respectively.

Chapter 3

Simulating particle interaction with SEM monitors

Testing beam time at accelerators can be limited and difficult to secure and some tests can be too disruptive to be practical. Furthermore, in some cases it might be impossible to isolate and study independent factors leading to observed effects. In these cases simulations can help test a variety of different scenarios and help to inform planning and decisions for future real life tests and upgrades.

In the case of the BSI monitors it is difficult to remove these from the beam area and test different configurations, as they are directly in the path of the beam, in high radiation areas. Changing them would require stopping the beam and waiting for a certain cooldown period. Also many of these are vital for beam operation, so they may need to be replaced before re-starting the beam.

With problems in the BSI calibration in TT20 being brought to attention in 2017, the need arose to investigate what was causing the discrepancy in the current being measured by two BSI foils of the same material, positioned one after each other in the same vacuum vessel. Initial investigations were conducted at the time, which left open questions. This work is briefly discussed in Section 3.1. The work carried out in this chapter is a follow up to that work, looking into possible explanations for the differences in signal being measured. Section 3.2 contains an introduction to the simulation toolkit used to conduct the simulation, Section 3.3 details the simulation of the BSI monitors using the Geant4 toolkit and Section 3.4 presents the results obtained from this simulation.

3.1 Previous Simulations

Initial studies, investigating the Secondary Emission Yield (SEY) of the BSI monitors in the TT20, were originally conducted in 2017 by Federico Roncarolo. One of the problems identified was that for the same primary protons traversing the BSI tank, the signal was higher in the downstream foil compared to the upstream one. The mechanism behind this discrepancy between the two BSI foil measurements was not fully understood, but two situations were thought of as possible causes: secondary electrons from the first BSI foil reaching the second foil, or other types of secondary particles being generated when protons hit the foil. Contributions from these other particles could be the cause of the higher secondary emission current detected in the second foil. Preliminary simulations were conducted by Federico to test these theories.

The first simulation, made in CST Particle Studio [54], tested a range of different voltages applied to the bias plate, to investigate if it was possible that some secondary electrons generated in the first foil were reaching the second foil. Another simulation was conducted in FLUKA [55], to investigate what types of secondary particles, other than electrons were likely to be generated and whether these were contributing to the higher secondary emission yield in the downstream foil. The results and discussion for these simulations can be found in [56]. More extensive work is needed to conclusively understand what is at the heart of this problem and how to fix it. This was one of the purposes of this PhD project.

3.2 Introduction to the Geant4 Toolkit

Simulations were conducted using the GEANT4 toolkit [57]. Geant4(GEometry ANd Tracking) is an object oriented C++ simulation toolkit provided by CERN, used for Monte Carlo simulations of particles passing through matter.

Monte Carlo simulations are based on the principle of random sampling. They are generally used for complex problems that are difficult to solve analytically. These simulations use random numbers as inputs to mathematical models, that attempt to recreate the processes of interest to be studied. This process can be repeated multiple times to accumulate a large number of statistics [58]. The toolkit provides different classes allowing the user the flexibility to model a diverse range of scenarios. These are described in more detail in [59]. A typical Geant4 application will be made up of the main code which invokes these classes.

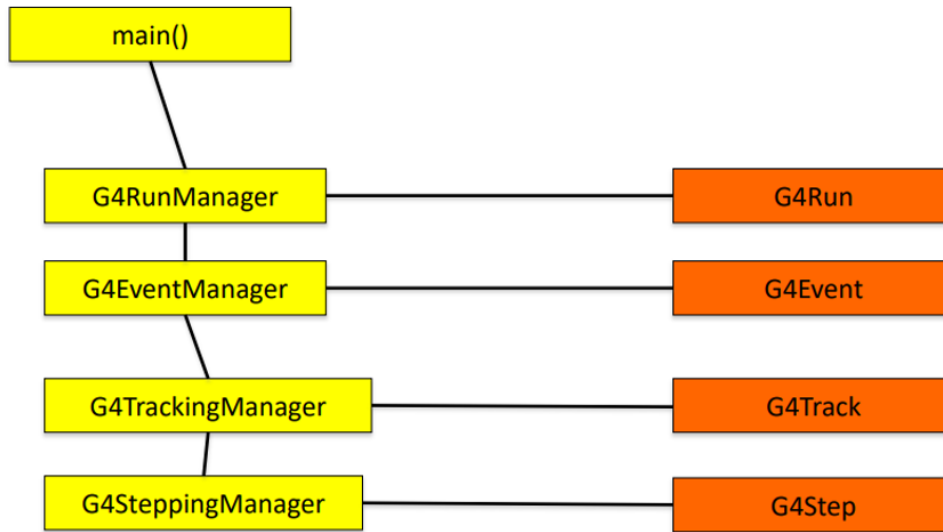


Figure 3.1: Key Geant4 Classes and objects, taken from [60]

In Fig. 3.1 the classes (shown in yellow) manage the creation of the objects (in orange). A Run object is created with the command "runBeamOn()" and is made up of a series of Event objects. Each event contains many Track objects and a Track is made up of many Step objects. In order for the RunManager to create a run it must first be given a description of the geometry to simulate, the particle beam and the physics to be applied.

The geometry is described in the G4VUserDetectorConstruction class, which is a mandatory class for any Geant4 simulation. It starts with a world, which contains all the physical geometries of objects in the simulation. The description of the world and these objects, as well as the materials that they are made of, are given in this class.

The particle beam description is done in the PrimaryGeneratorAction class, which contains information such as the number and type of particles that make up the primary beam, the beam shape and position inside the world, the energy and momentum of the beam.

The various interactions of particles with matter are modelled via a physics list. The physics list contains information about the particle types, cross-sections, physics processes, and models used to simulate the interactions. The user may either choose to create their own physics list, or choose from one of the pre-compiled reference physics lists that Geant4 has to offer [61].

A process is defined by the physics list and describes the interaction of particles with materials. It can occur at the beginning, at the end or along the step of a track and lead to effects such as the creation

of new particles, energy loss, or change in the trajectory of the particle. Geant4 models both continuous and discrete processes.

As mentioned earlier a run is made up of events. A new event begins with the "generatePrimaryVertex()" method that is called from the PrimaryGeneratorAction class. An Event creates a number of primary particles, according to the description given in the PrimaryGeneratorAction. These primary particles are described by the Track class in Geant4.

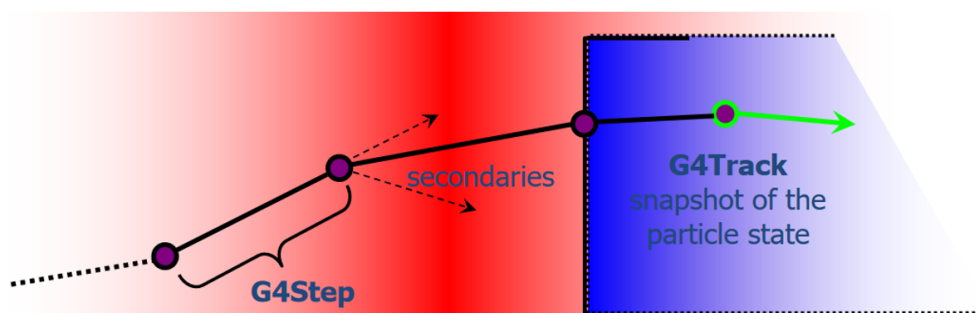


Figure 3.2: Particle Tracks in Geant4, from [62]

A Track, illustrated in Fig. 3.2, contains the current information of a particle, such as its current position, type of particle and energy, but it does not contain information about previous states/locations of the particle. At the beginning of an Event primary Tracks are put in a stack and then each Track is propagated through the world in a number of Steps.

At each Step the program will take information about the particle such as its location, particle type, material through which it's traversing, and use the Physics list in order to determine the next step. The step has two reference points, pre-step, which refers to the beginning of the step and post-step, which refers to the location of the particle after having taken the step.

Having generated data the user can select the information that is of interest, record and export the data for further analysis. Simulations can be run via scripts, in batch mode - useful for large simulations - or there is also the possibility of running the program in visualisation mode, which is especially useful when visualising the geometry and debugging, but slow when simulating more than just a limited number of particles. Geant4 also provides a range of different example projects, with varying levels of complexity.

3.3 Modelling the BSI

The current design for the BSI is described in details in Section 2.3.1. It contains a bias plate with a circular hole in the centre to allow the primary beam to pass through with minimum disturbance (refer to Fig. 2.10). The aim of the simulation was to model this detector and explore the impact of the materials and geometry on the signal generated in the BSI monitor. Some key questions being asked were:

- Does the displacement of the beam from the centre cause significant change to the signal measured?
- Could there be additional charged particles besides secondary electrons?
- Could these contribute significantly to the signal generated in the SEM foil?
- What energies would these particles have?
- Would they be contained by the bias foil?

3.3.1 Bias Foil Geometry Simulation

This simulation was constructed based on Geant4 example codes provided with the installation of the software. It consists of a modified version of example B1 [63], combined with the tracking inspired by example B4a [64].

The detector was modelled as one circular titanium foil, 10 μm thick and radius of 72.5 mm sandwiched between two circular aluminium electrodes, with the same radius, 20 μm thickness, and a central hole, 10 mm in diameter, contained in a cube shaped envelope of vacuum, with a side of 10 cm. The envelope itself being contained within a cube shaped world of air, with a 12 cm side. Each one of these objects is referred to as a volume in Geant4. Each volume has associated material properties such as density and mass, as well as its geometric properties. Volumes are used during particle tracking: particles take steps within volumes and interact with the material of the volume, through the processes that occur during the steps taken.

The beam was modelled as a gaussian proton beam consisting of 10^7 particles and energy of 400 GeV (the same energy as the SPS NA beam) incident on the detector. The particles' starting position was fixed in the z direction and drawn from a Gaussian distribution centred around zero (for the centred beam) and 7 mm (for the off-centred beam). The starting angle was also randomly generated from a Gaussian distribution. In reality beam parameters for the SPS are of the order of 10^{11} protons per bunch during commissioning and 10^{13} during normal operation [65, 66], as described in Section 1.1.1. However it is computationally intensive to simulate a beam with such a high number of particles, therefore a smaller number of protons were used in the simulation and the statistics obtained assumed to be in proportion to the the number of particles in the beam.

Fig. 3.3 shows a visual representation of the geometry of the simulation, created using the Geant4 toolbox.

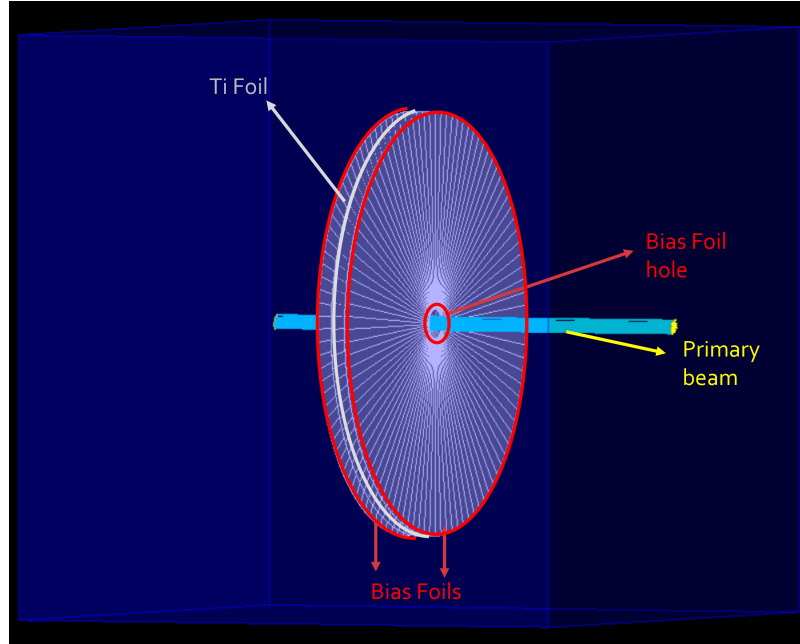


Figure 3.3: Geant4 simulation of BSI monitor with primary beam centred, passing through the hole in the bias foils

Note that in Fig. 3.3 the beam (shown in blue) crosses the BSI monitor without producing any secondary particles. This is due to the low number of statistics generated for visualisation purposes. When executing the code in batch mode, secondary particles are generated, although in fairly small numbers when compared to the number of primary particles.

For comparison, another simulation was run with the beam displaced from the centre so that, instead of passing through the bias foil hole, the beam hit both bias foils in full, in addition to the central titanium foil (see Fig. 3.4). This was done in order to see what effect an extreme beam displacement could have on the generation of current in the BSI.

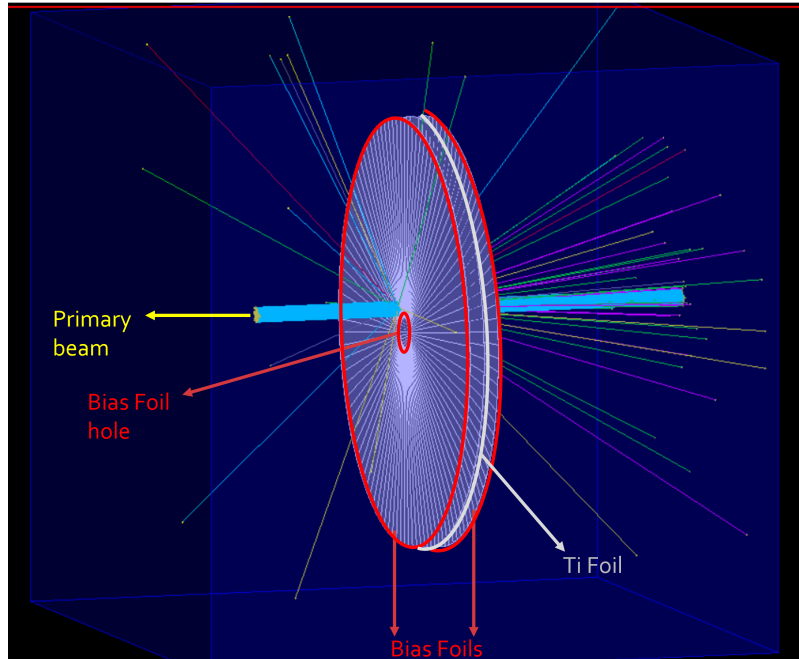


Figure 3.4: Geant4 Simulation of BSI monitor with primary beam off-centred, hitting both bias foils

In Fig 3.4 it is possible to see that the beam is clearly incident to the side of the bias foil hole, thus passing through the both bias foils. We can also see some secondary particles generated in this image.

3.3.2 Physics List

For the purpose of the simulation of SEY in the BSI foils the physics list chosen was "QGSP_BERT_HP". This is a physics list generally recommended for high energy physics tracking, LHC neutron fluxes and shielding applications, among others. It uses a combination of the Quark-Gluon String (QGS), Fritiof parton (FTF) Bertini cascade (BERT) and Precompound(P) models for simulating hadron-nucleous interactions.

The Bertini cascade is used for protons, neutrons, pions, kaons and sigma, lambda, omega and xi baryons between the energies of 0-6 GeV. The QGS model is used for protons neutrons, pions and kaons above 12GeV. Whereas the FTF model is used between the energies of 3-25 GeV for the same particles as the QGS. A number of antimatter particles and ions in the 0 to 100 Tev range are also modelled by the FTF. Both the QGS and FTF models use the precompound model to deal with de-excitation of any excited nucleus.

When energy ranges overlap a probability is used to select the model to be used. This physics list also includes the high precision neutron package for dealing with neutrons below 20 MeV, until they reach thermal energies. Fig. 3.5 shows the energy ranges for some of the main models that are included in the Geant4 reference physics lists. In this figure the Quark Gluon string, Fritiof string, BERT, Pre-

compound and High precision neutron, all form a part of the "QGSP_BERT_HP" physics list used in the simulation, which produced a variety of different charged particles, which are relevant to the signal being measured by the SEM monitor.

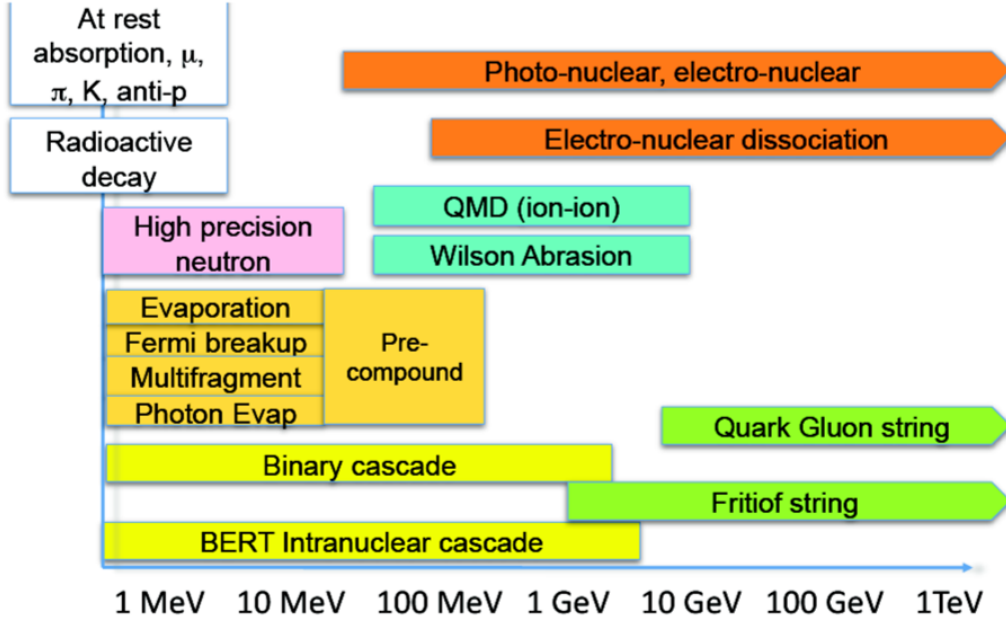


Figure 3.5: Geant4 Physics models and energy ranges, from [67]

For the electromagnetic interactions EM standard physics option 4 was used. This option uses a combination of models and is recommended [59] for use in high accuracy simulations. For more detailed information about the Physics list and models described in this section please consult [68], which gives an overview of different standard physics lists available in Geant4 and lists the models used in each physics list. Detailed information on the physics behind the implementation of these models can be found in [69].

3.3.3 Step size and production cuts

It is important to understand some of the limitations of the Geant4 toolkit. One of the tricky aspects of simulating many particles and particle decays is that at lower energies particles may interact more easily with objects and generate more particles, quickly multiplying and consuming many computing resources to simulate. In addition to this, having a very large world or taking many small steps in an environment, can quickly render a simulation computationally infeasible. Geant4 has inbuilt methods to deal with this, but it also requires the user to specify what is important. It might be necessary to sacrifice some detail in order to gain speed in the simulation, otherwise more time might be necessary for the simulation to run, or more computational resources.

In order to limit the complexity of the simulation, in Geant4 each particle has a threshold below which no secondary particles are generated, instead the particle undergoes continuous energy loss, depositing its energy in the material at that point [59, 61]. This threshold is given as a range, in units of length, and is internally converted to an energy threshold by Geant4. The threshold is called a production cut and is usually set automatically by the Physics list. The default value is 1.0 mm [59], although it is possible to alter this value if needed.

Another important concept is the step size. This is particularly relevant when dealing with thin film detectors, as the step size could be larger than the detector itself. If tracking the trajectory of particles within the material is important, then the step size can be adjusted accordingly. Geant4 will model energy deposition differently depending on the step size and production cuts, as is explained in Section 3.3.4. It is recommended [69] that very small steps are used in order to guarantee accuracy in the simulation, but there is a trade-off between step size and computing time.

To effectively manage competing demands for resources it is possible to create regions, linked to Geant4 volumes, where the user can set specific rules that apply only to the region in question. This allows the simulation to get more detail in the areas of interest and dedicate fewer resources to other areas.

For this simulation a region was created for the detector, including the bias plates and Titanium foil. In the detector region the maximum step size within was set to 2.5 μm . The production cuts were also changed, limited to 500 nm. A separate simulation with maximum step size of 1 μm was run to test the effect of changing the step size.

The data, including particle ID, particle type, position, kinetic energy, energy deposited in the material, volume of origin, current volume, step length, process of creation of the particle (if not primary particle) was saved for all steps within the detector region for all particles that were not a part of the primary particle beam. This data is presented in section 3.4.

3.3.4 Energy Loss in Thin Absorbers

The continuous energy deposition due to electromagnetic processes in Geant4 results from both excitation and ionisation and is modelled differently for thin and thick absorbers. For thin absorbers, such as the foils in this simulation, where the steps are small, the model makes the assumption that the cross-section is constant along the step and that there are only two energy levels, resulting in two possible values for the energy loss due to excitation E_1 and E_2 [69]. The energy lost due to excitation is therefore calculated according to Eq. (3.1).

$$\Delta E_{exc} = n_1 E_1 + n_2 E_2 \quad (3.1)$$

Where n_1 and n_2 are two numbers sampled from a Poisson distribution. The energy loss due to ionisation is calculated according to Eq. (3.2).

$$\Delta E_{ion} = \sum_{j=1}^n \frac{E_0}{1 - u_j \frac{T_\delta - E_0}{T_\delta}} \quad (3.2)$$

Where T_δ is the energy production threshold for delta electrons, E_0 is the ionisation energy of the atom and n is the number of ionisations, sampled from a Poisson distribution and u is a number, also sampled from a Poisson distribution. Combining Eq. (3.1) and Eq. (3.2) we get the mean continuous electromagnetic energy loss for a track segment ΔE , given by Eq. (3.3).

$$\Delta E = \Delta E_{exc} + \Delta E_{ion} \quad (3.3)$$

3.3.5 Secondary Emission in Geant4

It is important to note that Geant4 was not originally designed to simulate the secondary emission process. This is a very low energy process and most Geant4 physics lists are designed to simulate higher energy interactions, with the toolkit being optimised for some of its main use cases such as high energy particle tracking, nuclear interaction, or medical physics.

Most available pre-compiled physics lists have models that are accurate for higher energy simulations and high values for the production cuts. This would mean that all particles below the production cut would not be produced and their energy would be deposited in the material. In practical terms only delta electrons would be simulated as individual particles, all the lower energy electrons would exist only as part of the energy deposited in the detector.

The Sternglass semi-empirical formula includes contributions from both delta electrons and low energy secondary emission electrons. In theory one could calculate the low energy part of the SEY, using part of the SEY equation and the energy deposited in the detector, then add the number of delta electrons produced in the simulation. However it is difficult to separate which part of the energy deposited in the material would be resulting from electromagnetic deposition, and what part of that energy could be the result of a production cut for a different type of process. Secondary emission has been previously

simulated in Geant4, for example in [47]. Here, a custom built secondary emission particle generator was created and invoked in the Stepping Action class, in order to simulate the SEY, as no predefined physics list describing secondary emission was available with Geant4 at the time.

However, since then there has been an experimentally developed physics list called Microelec, based on Geant4-DNA extension for low energy physics, which was developed for microdosimetry and Single-Event applications in Silicon. This has recently been extended to include materials such as Titanium and Aluminium, according to [70] and now includes surface processes. One of the applications targeted by the creators was the simulation of the SEY. It is not mentioned in [68], but it is briefly referred to in [69]. It is also included in one of the Geant4 extended examples [71]. Based on its use in the Geant4 example and what is written in [70] it was assumed that this physics list was the most appropriate for this simulation.

In practice the Microelec physics list lowers the production threshold for electrons and includes some additional processes that are activated specifically when a particle crosses a material boundary. This makes this physics list much more resource intensive. However this problem was minimised via the use of a detector region (described in Section 3.3.3), which encompassed the bias and the titanium foils. The Microelec physics list was used only in the detector region, in addition to other previously mentioned physics lists, in order to make the simulation run faster.

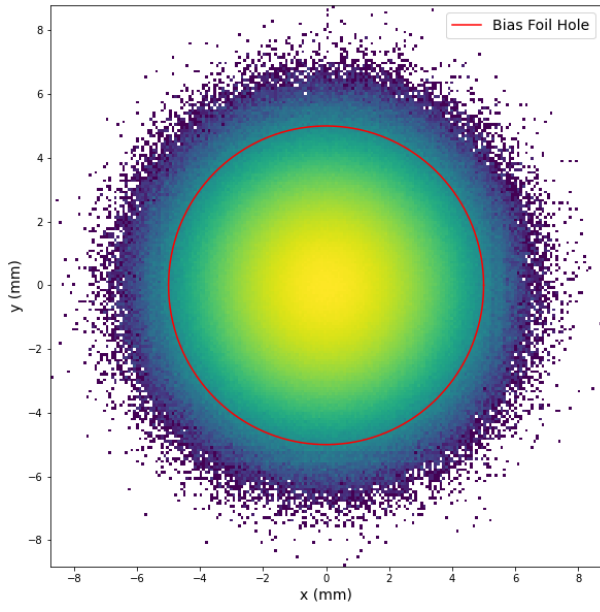
3.4 Simulation Output

In this section we will discuss the results produced by the Geant4 simulation described in Section 3.3. Here we will focus on comparing two cases for which the simulation was run with the beam centred on the BSI device and the beam displaced from the centre of the BSI device.

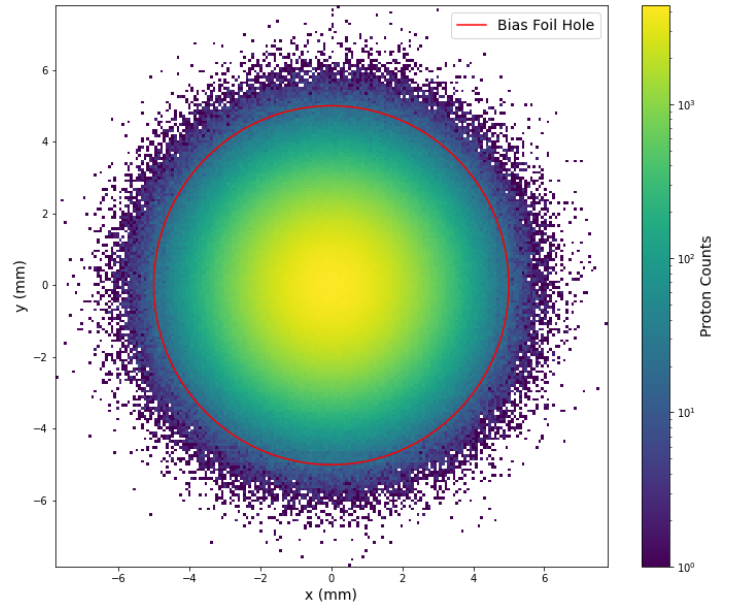
The centred beam represents the ideal scenario, where the beam is perfectly steered along the beam line. However, this is not always the case due to trajectory bumps off-axis in both the horizontal and vertical directions. These bumps can occur intentionally or unintentionally during commissioning and operation of the accelerator facility. Different beamline settings can also result in larger than nominal beam sizes at the location of the BSI monitors. Consequently, it's possible that all or part of the primary beam falls outside the bias foil's central hole, generating secondary particles that can affect the BSI signal. The purpose of this simulation was to quantify the impact of this effect. If this is significant then it could help explain some of the non-linearity previously observed in the BSI signal, which is discussed in Section 1.3.

Fig. 3.6 shows the relationship between the beam size parameters and the position of the primary beam

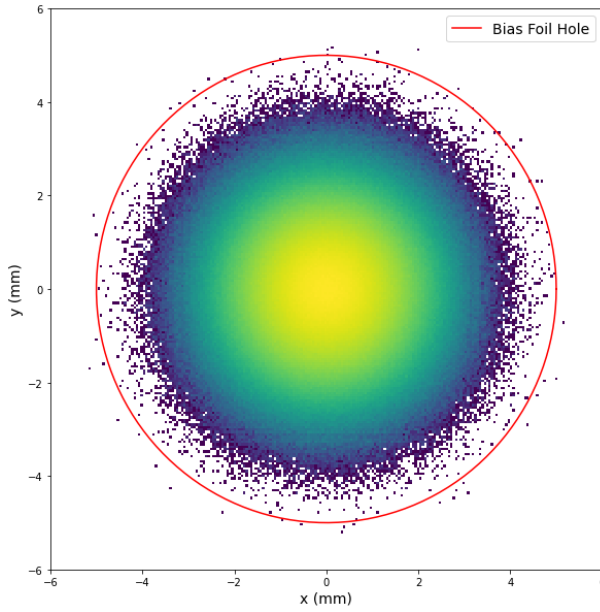
particles in relation to the bias foil hole for a centred beam. These plots were created using Geant4 to simulate the different beam parameters. Each plot consists of 10^7 protons, and the origin of the beam was arbitrarily chosen to be 5 cm away from the first bias foil in the simulation.



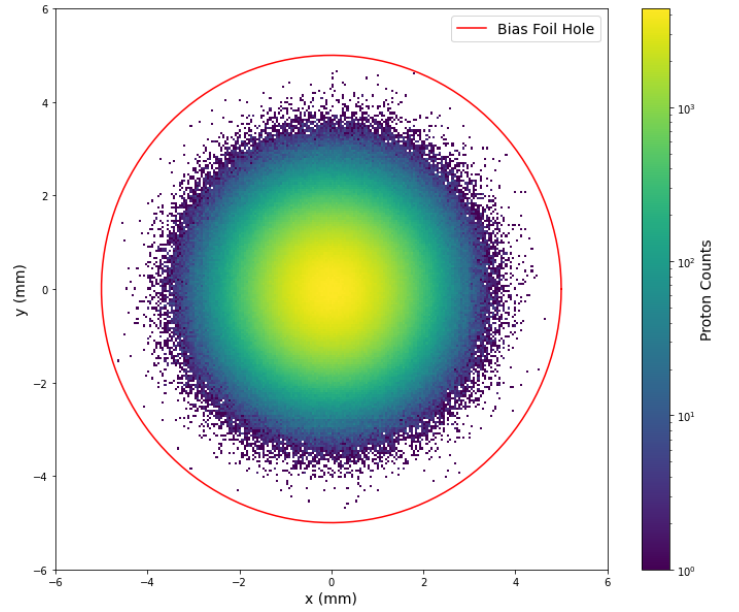
(a) $\sigma_x = \sigma_y = 1.69\text{mm}$, $\sigma'_x = \sigma'_y = 0.1\text{mrad}$



(b) $\sigma_x = \sigma_y = 1.5\text{mm}$, $\sigma'_x = \sigma'_y = 0$



(c) $\sigma_x = \sigma_y = 1\text{mm}$, $\sigma'_x = \sigma'_y = 0$



(d) $\sigma_x = \sigma_y = 0.9\text{mm}$, $\sigma'_x = \sigma'_y = 0$

Figure 3.6: Primary beam particle distribution for Gaussian beam for a range of beam sizes

In Fig. 3.6a the beam has a σ' of 0.1 mrad, whereas in Figs. 3.6b to 3.6d the beam is parallel. It is evident that even at relatively small beam sizes there are some particles that hit the bias foil. At 1 mm beam size the number of particles not going through the hole is very minimal. 0.9 mm was the largest size tested for which no particles hit the bias foil, this was therefore selected to be the size for the beam in the final simulation. However in reality the beam is not perfectly parallel, and often the beam shape resembles more of an ellipse than a circle.

This CERN document ([66]) contains the beam specifications for the beam extracted from the SPS towards the NA, including a table of beam sizes at different locations of interest in the NA beamlines. Fig. 3.7 shows a Gaussian beam, simulated with Geant4, using the beam sizes specified by [66] for some key areas in the transfer lines, including the target locations. It is important to note that the Gaussian beam is an approximation and in reality the shape of the beam may differ. It was beyond the scope of this PhD project to make an accurate simulation of the beam itself. The purpose of these plots is to give an idea of the range of beam sizes compared to the bias foil hole, and what fraction of the beam is likely to be hitting the foil at these locations.

The large variation in beam size at different locations is evident from Fig. 3.7. At the centre of the targets (Figs. 3.7a to 3.7d) the beam size was generally quite small, and the beam would be expected to pass through the centre of the bias foil hole if the beam was centred. However, at some of the other locations (Figs. 3.7e and 3.7f) if the beam were to pass through a BSI monitor, a large portion would be hitting the bias foil, even if the beam was perfectly centred. It is important to note however that not all BSIs are placed close to these locations, so the beam size could be different when passing through some of the BSIs. The locations were chosen to showcase the expected variation in beam size throughout the transfer lines in the NA, based on the information available in [66]. Beam size can vary depending on operating conditions.

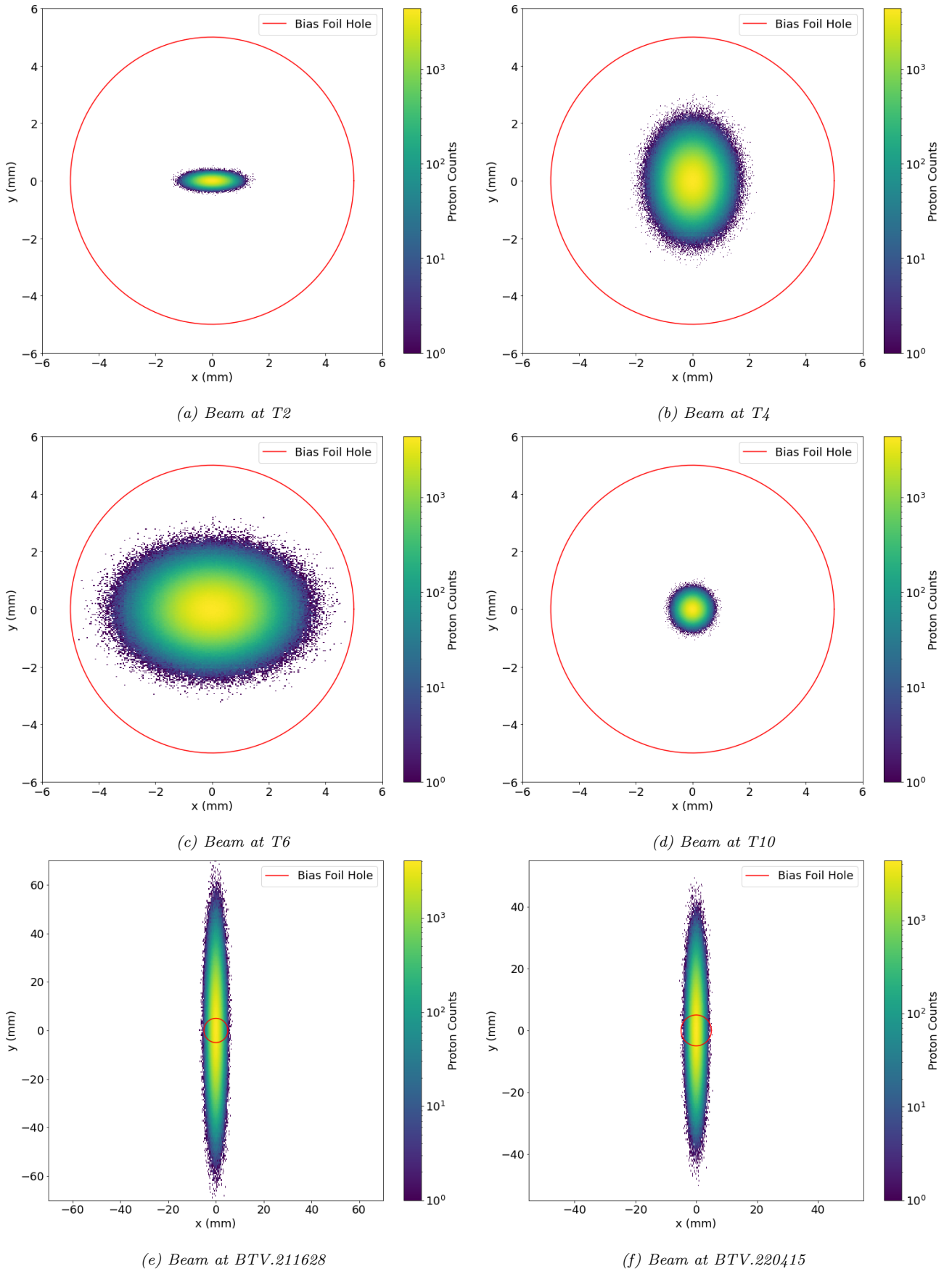
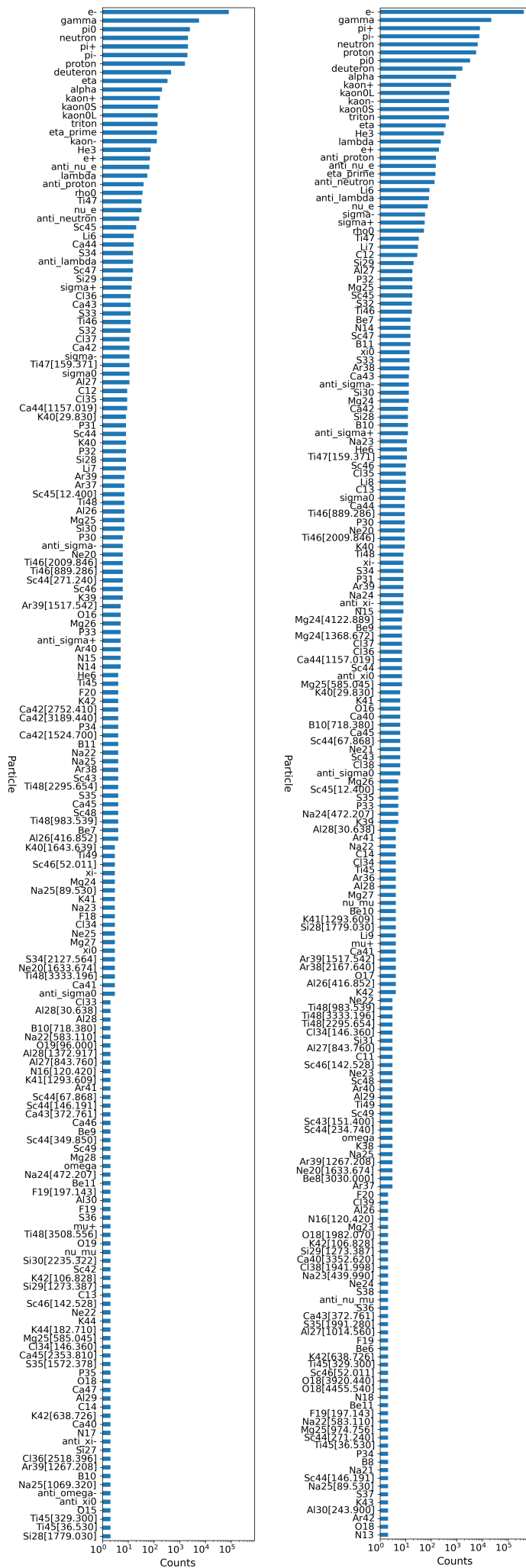


Figure 3.7: Gaussian beam simulated with beam sizes for various locations in NA beamlines, found in [66]



(a) Centred Beam

(b) Off-centred Beam

Figure 3.8: Particles generated in simulation

Fig. 3.8 shows all the secondary particle counts registered by the Geant4 simulation. Here more secondaries may have been generated, but some of these tracks may have scattered at different angles and missed the detector. Only data for the particles inside the detector region was saved, in order to make the simulation more efficient. Data for all particles, crossing, ending or originating in the titanium foil was saved, as well as data for any particles moving between two different volumes, if one of those volumes is the bias foil. All other data was not saved.

A large variety of secondary particles were retrieved from the simulation for both centred and off-centred beam. As might be expected, the off-centred beam simulation produced both higher particle counts and more particle variety.

Fig. 3.9 shows the volume in the Geant4 simulation in which these secondary particles were generated. Here B1 and B2 correspond to bias foil 1 (before the titanium foil) and bias foil 2 (after the foil) and envelope is just the environment surrounding the BSI detector, which in this case is vacuum.

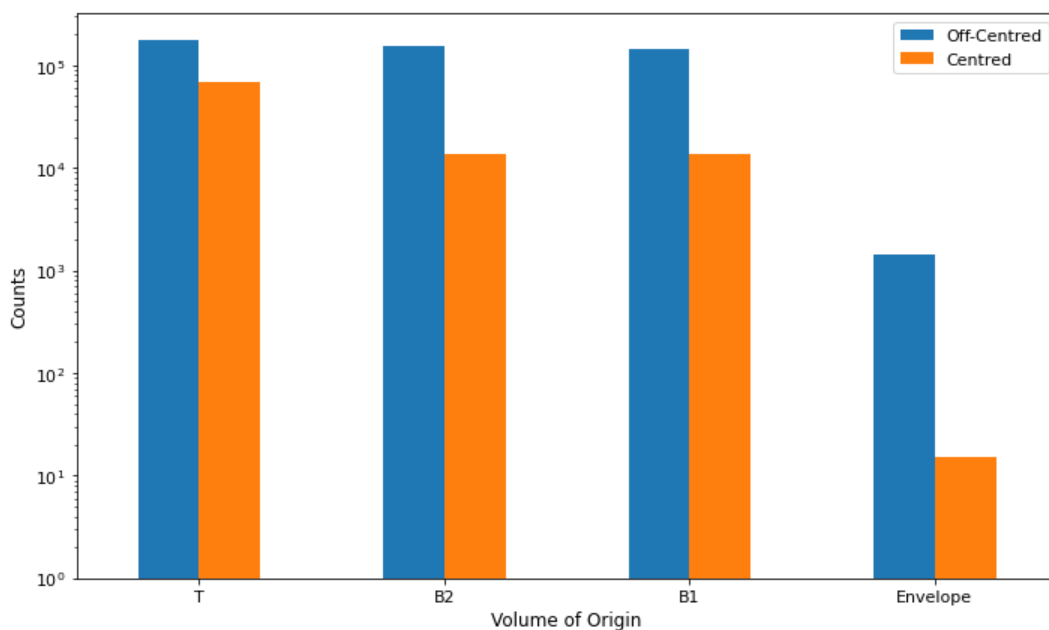


Figure 3.9: Particle Tracks in Geant4

We can see that for the off-centred beam very similar quantities of particles originate from both bias foils and the titanium foil, with significantly fewer originating in the envelope. This is possibly because the envelope is made of vacuum, the step size, physics list and production cuts are different in the envelope and the filter on saving the data prioritises saving data for the BSI detector region. For the centred beam we can see overall lower counts for all volumes, with the majority of particles produced in the titanium foil, although still a considerable amount of particles being created in the bias foils and very few in the envelope. These particles that are being created in the envelope are predominantly gamma rays resulting from the decay of particles. The particles which generate the decays, are being produced by

the interactions between the beam and the detector foils, but some of these particles may escape the foils and decay whilst travelling in the envelope. As more particles are being produced during the off-centred simulation, there is a higher probability that some of these particles will decay whilst travelling in vacuum.

To determine which particles in the simulation are contributing significantly to the SEY we should focus on the charged particles, as these will be the ones creating secondary emission electrons when they cross the surface of the foil. It is interesting to investigate both the particles crossing the foil, as well as those that get stopped by the foil.

Fig. 3.10 shows the number of secondary charged particles produced outside of the titanium foil, grouped by particle type, that pass through the titanium foil for centred and off centred beam. Passing through is defined as entering and exiting the titanium foil.

The only type of secondary charged particle crossing the foil for the centred case and the most common secondary charged particle crossing the foil in the off-centred simulation is the electron. The off-centred beam simulation also produces a larger variety of particles. Other particles commonly crossing the foil when the beam is off-centred include pions, protons and deuterons. The counts for all particles types are higher for the off-centred beam.

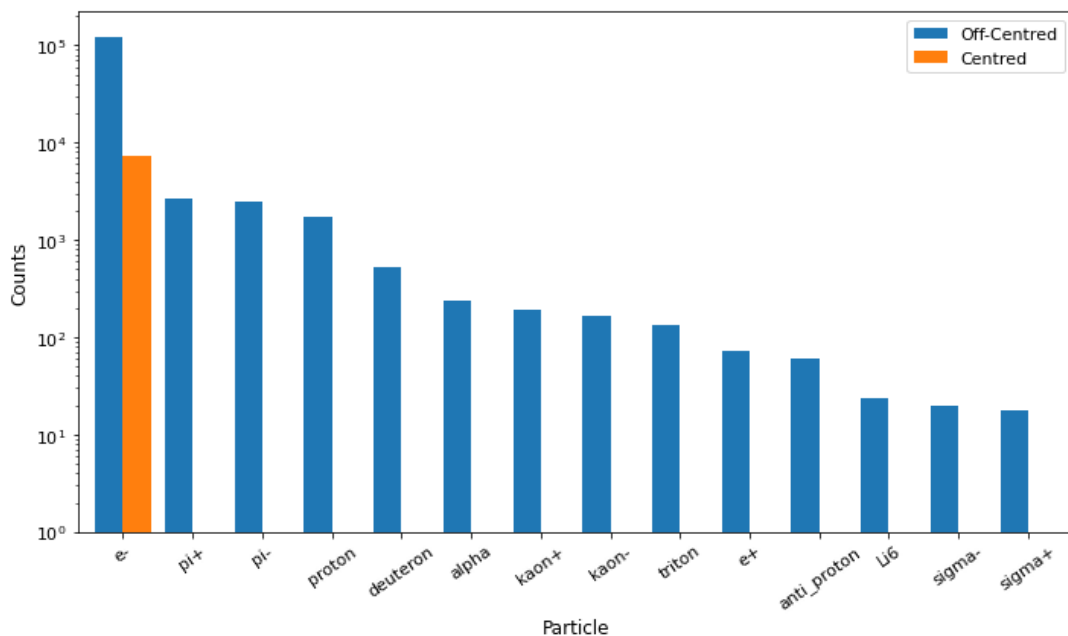


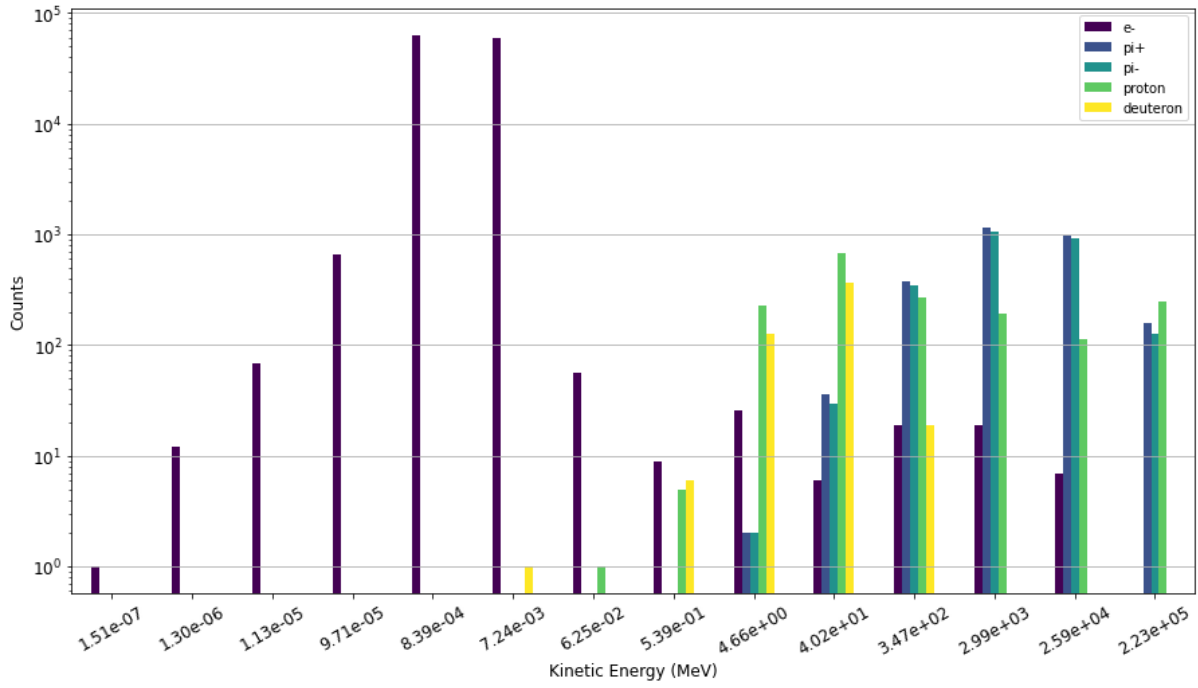
Figure 3.10: Types of charged secondary particles passing through Ti foil

These results are not surprising, considering that in the centred beam simulation the primary beam only has the opportunity to interact with the titanium foil (as the bias foils have a holes in them). In the off-centred beam simulation, the primary beam passes through both bias foils and and the titanium foil.

This means that there is a much higher probability of production of secondary particles in the off-centred case. Once produced the particles must cross the titanium foil. In the centred beam case, as can be seen in Fig. 3.9, most secondaries are being produced in the titanium foil, it is therefore less likely that they will cross the titanium foil. In the case of the off-centred beam secondary particles are produced in similar amounts from the bias foils and the titanium foil, therefore it is easier for them to cross the titanium foil. Higher statistics also lead to a higher variety of particles being produced.

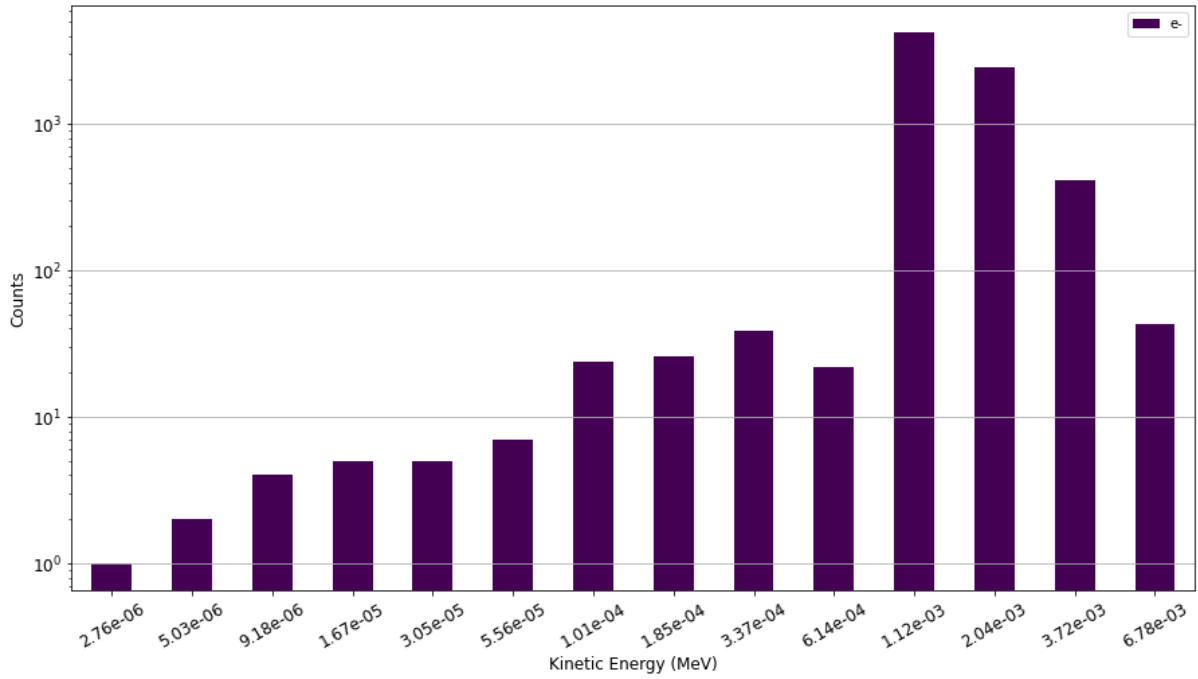
In reality the BSI monitor itself is not the only source of secondary charged particles, there could be many others. There are locations with lots of equipment close together (such as the target stations), where multiple types of instrumentation exists inside the target boxes. There could easily be cross-talk between different instruments in this case. Additionally in areas with any significant losses, the secondary particles could be coming from interaction of those losses with the walls of beam pipe and surrounding instrumentation. These secondary particles, if charged, could add to the signal directly and/or generate additional ionisation when interacting with the monitor.

Having looked at the types and quantity of secondary particles being generated that cross the foil, it is also important to consider their energy, and whether they are affected by the bias potential, which is applied to the bias foils to stop secondary electrons from escaping. This was done by looking at the distribution of secondary particle energies and deducing which particles were likely to overcome the potential.



(b) Off-centred Beam

Figure 3.11: Kinetic energy distribution of particles crossing titanium foil, when leaving foil



(a) Centred Beam

In Fig. 3.11 we can see the energy distribution of the 5 most abundant particles that cross the titanium foil, at the point where they leave the foil. For the centred beam the electrons in the higher energy bins (which have significantly higher counts) would most likely be unaffected by the 200 V potential applied to

the bias foils, however there are a number of lower energy bins (with fewer counts), containing electrons of an energy that would be affected by the bias potential. For the off-centred beam there are a number of lower energy bins that contain electrons that could be affected by the bias potential (around 0.65% of charged particles crossing).

We are not only interested in the particles crossing the foil, but also those that get stopped and deposit all of their energy in the foil. In Fig. 3.12 we can see the number of particles produced outside of the titanium foil that get stopped in the foil, separated by particle type, for both centred and off-centred beam. Here we can see that very few particles coming from outside of the titanium foil, get stopped in the foil. For both the centred and off-centred beam simulations the most commonly stopped in the foil is the electron.

In the off-centred beam the only types of particles other than electrons generated by this simulation were alphas, deuterons and pi- mesons. This is most likely because the foil is very thin and the majority of particles simulated would have enough energy to exit the foil. Alpha particles and deuterons, due to their higher mass will loose energy faster and thus are more likely to deposit all of their energy in the material and pions, although lighter, were the second most abundant charged particle simulated.

In the centred beam case, as most secondary particles are being produced in the titanium foil, there are no other types of secondary particles, coming from other volumes, stopped the foil, apart from electrons. This is because the primary beam does not interact with the bias foils when the beam is centred, it only interacts with the titanium foil. For a charged particle to be produced in another volume, one of the secondaries¹ produced in the titanium foil would have to interact with one of the bias foils, producing another secondary charged particle, that would then have to travel back towards the foil and have enough energy to reach the titanium foil, but not so much energy that it would exit the other side. This improbable scenario is reflected in the statistics shown.

¹or a daughter particle of one of these secondaries

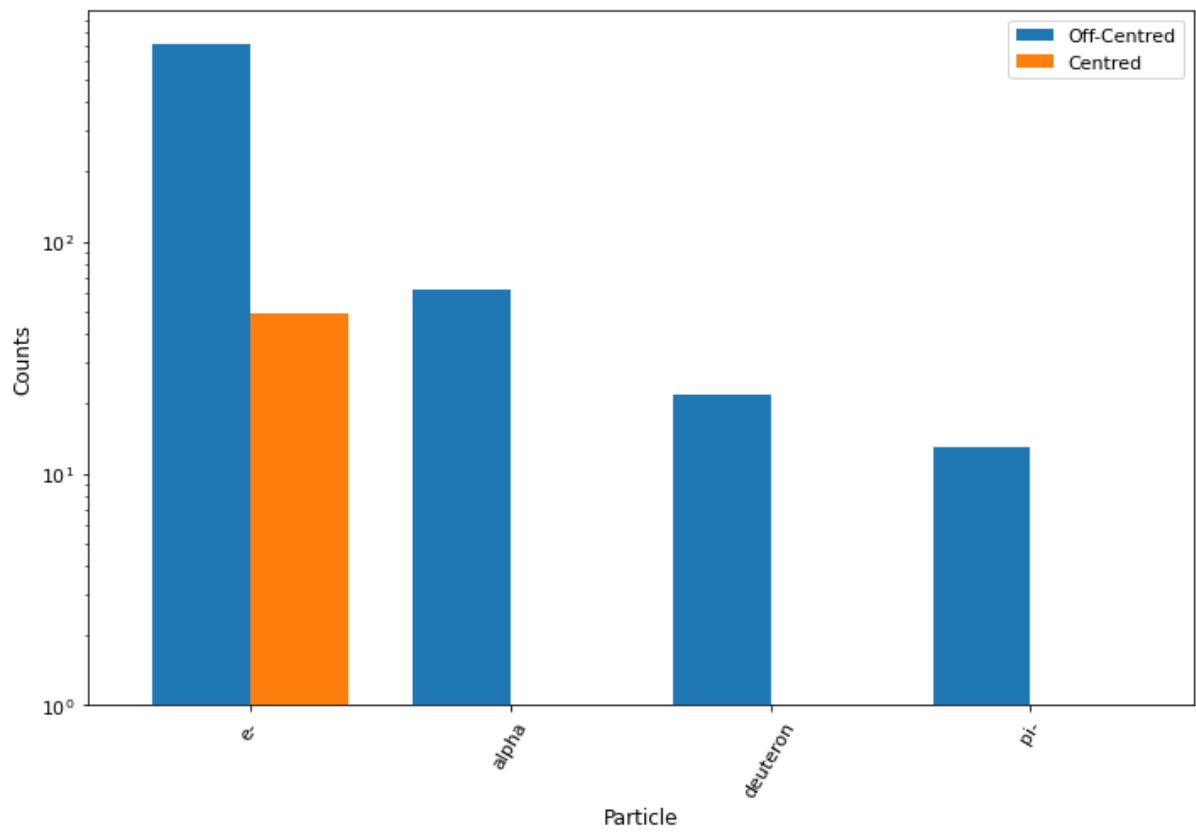
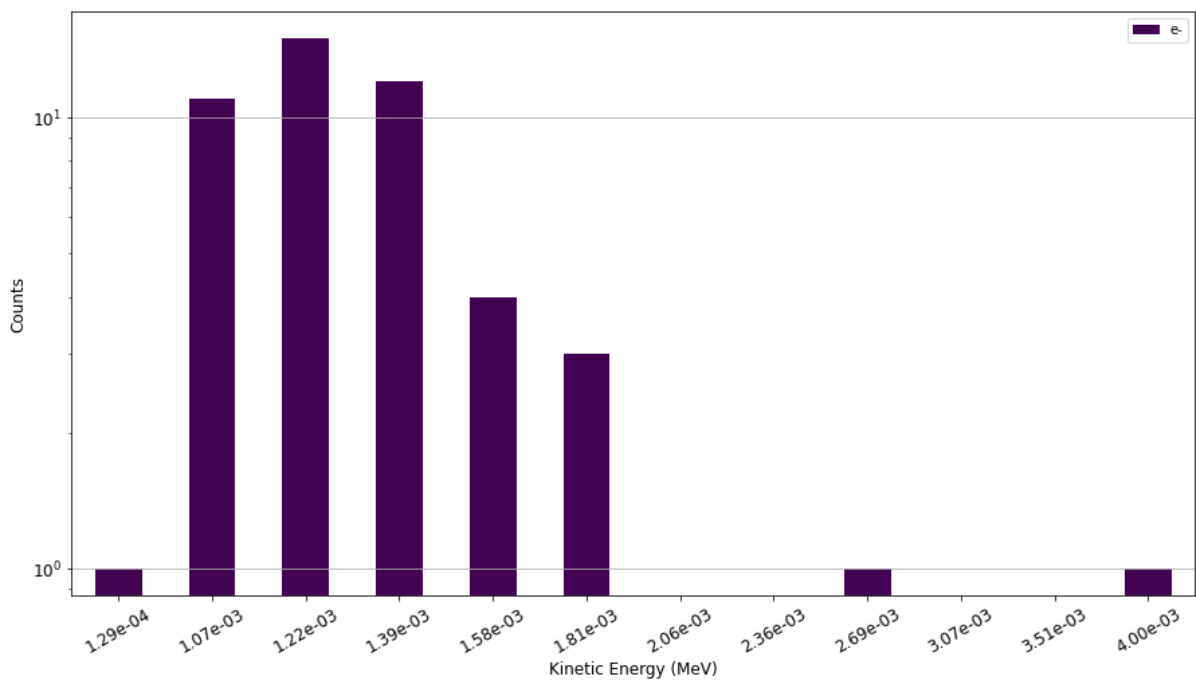
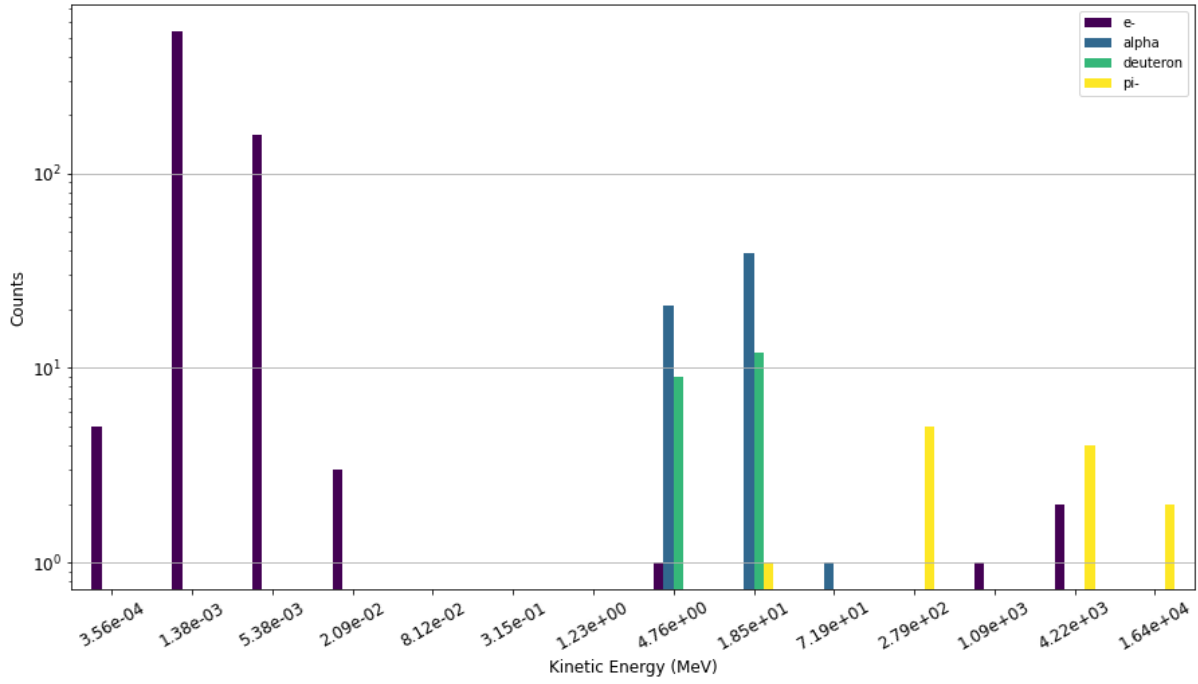


Figure 3.12: Distribution of charged particles produced outside Ti foil stopped in the foil



(a) Centred Beam

Fig. 3.13 shows the distribution of energy for secondary particles, at the beginning of the particle track for



(b) Off-centred Beam

Figure 3.13: Kinetic energy distribution of particles ending in titanium foil at beginning of track

the particles that were stopped in the titanium foil. Considering the very low number of statistics present in the histograms it is not possible to make any definitive conclusions about the energy distribution. Most electrons that get stopped appear to be in the keV range at the start of the track for both centred and off centred beams. For the off-centred beam simulation alphas and deuterons appear around the MeV- tens of MeV range. With most pions having higher starting energies between hundreds of MeV to tens of GeV.

If a particle created were to fall below the energy production cut, this particle would not be generated, instead the energy would be deposited in the material. Here it would not possible to distinguish which process generated the energy deposition. For the centred beam only a small number of electrons are stopped in the foil and the energy of these particles is too low to deposit any energy in the foil. Because of this it was not possible to plot the energy deposition of particles stopped in the foil for the centred beam.

Fig. 3.14 shows the distribution of the energy deposited in the titanium foil per particle track for the five most common particles with the off-centred beam. This figure includes a zero value bin which contains particles that deposited either zero or negligible amounts of energy. This bin was created because the Geant4 software often registers a very small energy deposition, which is calculated according to Eq. (3.3), but for very low energy electrons this can result in values for energy deposition that are unphysical.

It is important to remember that the step size has been modified for this simulation, so that the particle

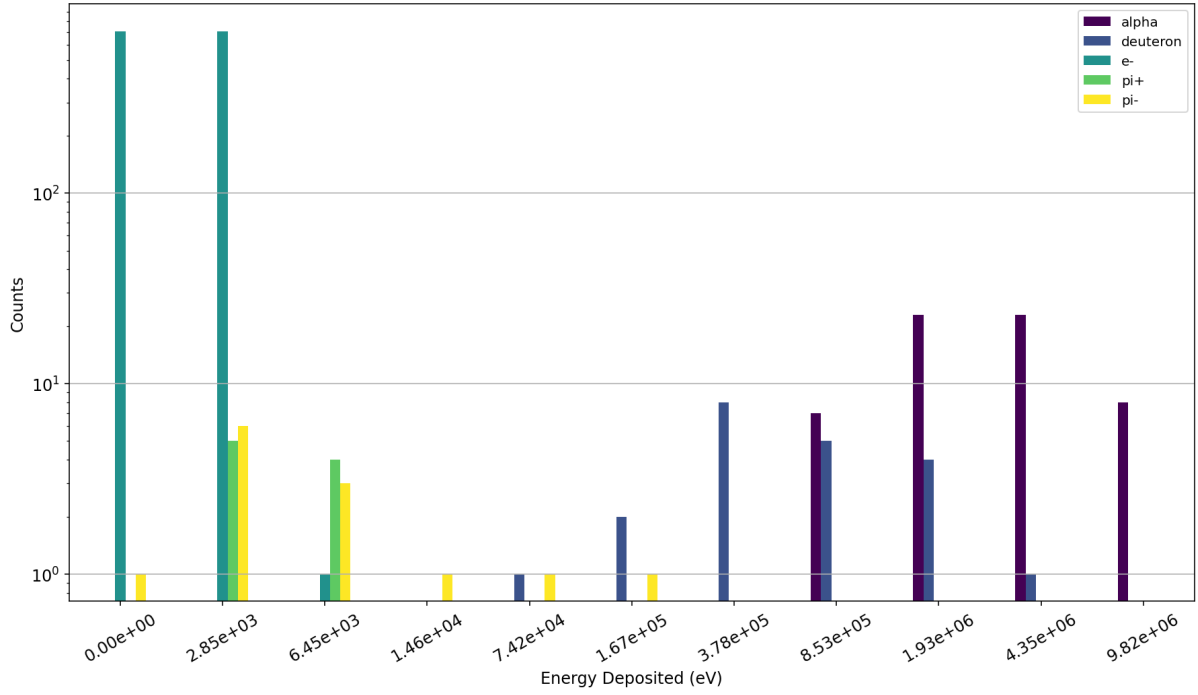


Figure 3.14: Energy deposited in Ti foil per particle for particles stopping in foil, with off-centred beam

takes a number of steps inside the detector, but as explained in Section 3.3.4 the number and size of steps has an impact on the way that the energy loss is calculated and a large amount of steps is required to ensure accuracy. Geant4 does not include physics models for condensed matter physics processes, therefore the lower energy electron interactions in thin absorbers may be at the limit of the Geant4 simulation capabilities.

In Fig. 3.14 a large number of electrons deposit no energy and the peak in deposited energy for electrons appears to be around 3 keV. We also see energy deposited in the titanium foil by other particle types, but this peaks at higher energies: around 3-6 keV for pions, 0.4 MeV for deuterons and 2-4 MeV for alpha particles.

Fig. 3.15 shows the total energy deposited by charged particles, separated by particle type, ending in the titanium foil. The total energy deposition correlates with the particle counts seen in Fig. 3.12 and the amount energy deposited per particle track seen in Fig. 3.14. Although electrons are the most abundant particle stopping in the titanium foil, they deposit such a small amount of energy per track, that collectively they are responsible for the lowest energy deposition of all particle types shown in Fig. 3.15, in the off-centred beam case.

For the off-centred beam the energy deposition is highest amongst alpha particles and deuterons, which although less abundant are also heavier, thus depositing more energy in the titanium foil. For the cen-

tered beam there are only electrons ending in the titanium foil. Because of the small number of electrons produced in the off-centred simulation and the low energy per track of these electrons, the total energy deposited by all electrons in the titanium foil for the centred beam ($2.89 \times 10^{-15} \text{eV}$) is too low, compared to the total energy deposited by electrons in the off-centred beam case, to be visible on the graph.

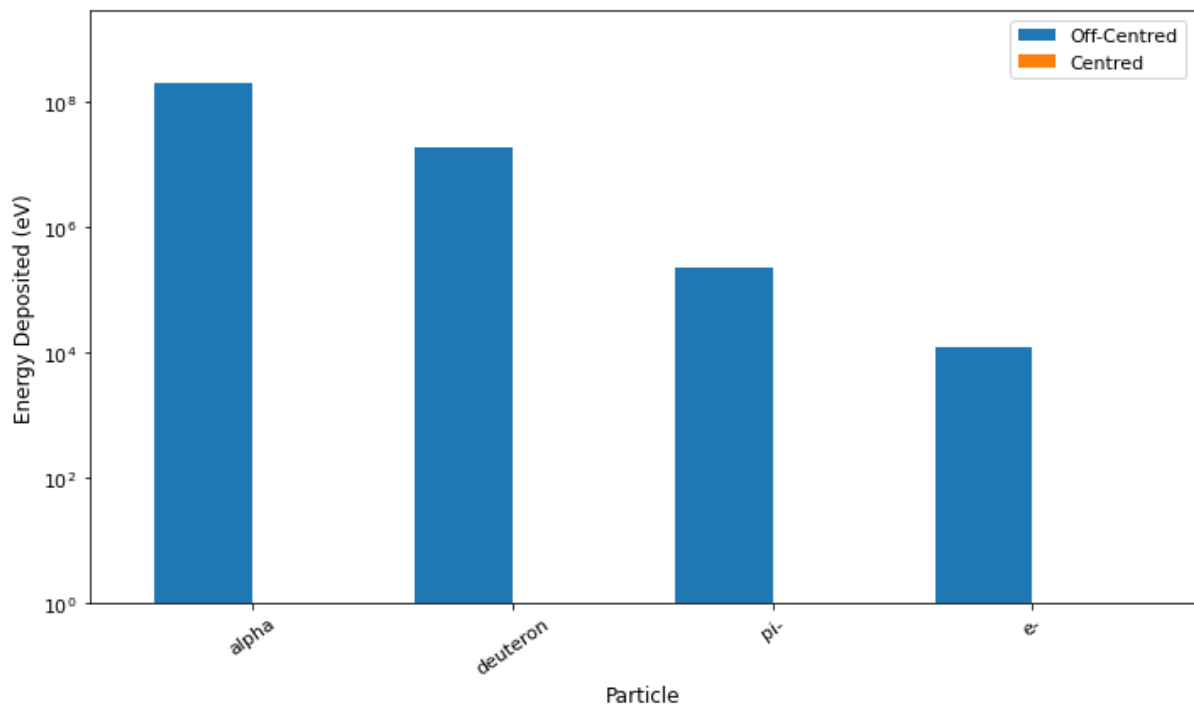


Figure 3.15: Total energy deposited by charged particles stopped in the foil

Another scenario of interest is when charged secondary particles produced in the titanium foil have enough energy to leave the foil. Fig. 3.16 shows the most common particle types created in the foil that then escape for centred and off-centred beam. The number and type of particles being produced is similar for centred and off-centred beam simulations, although the off-centred beam produces slightly more electrons compared to the centred beam. Electrons are the most abundant, followed by pions, protons, and deuterons.

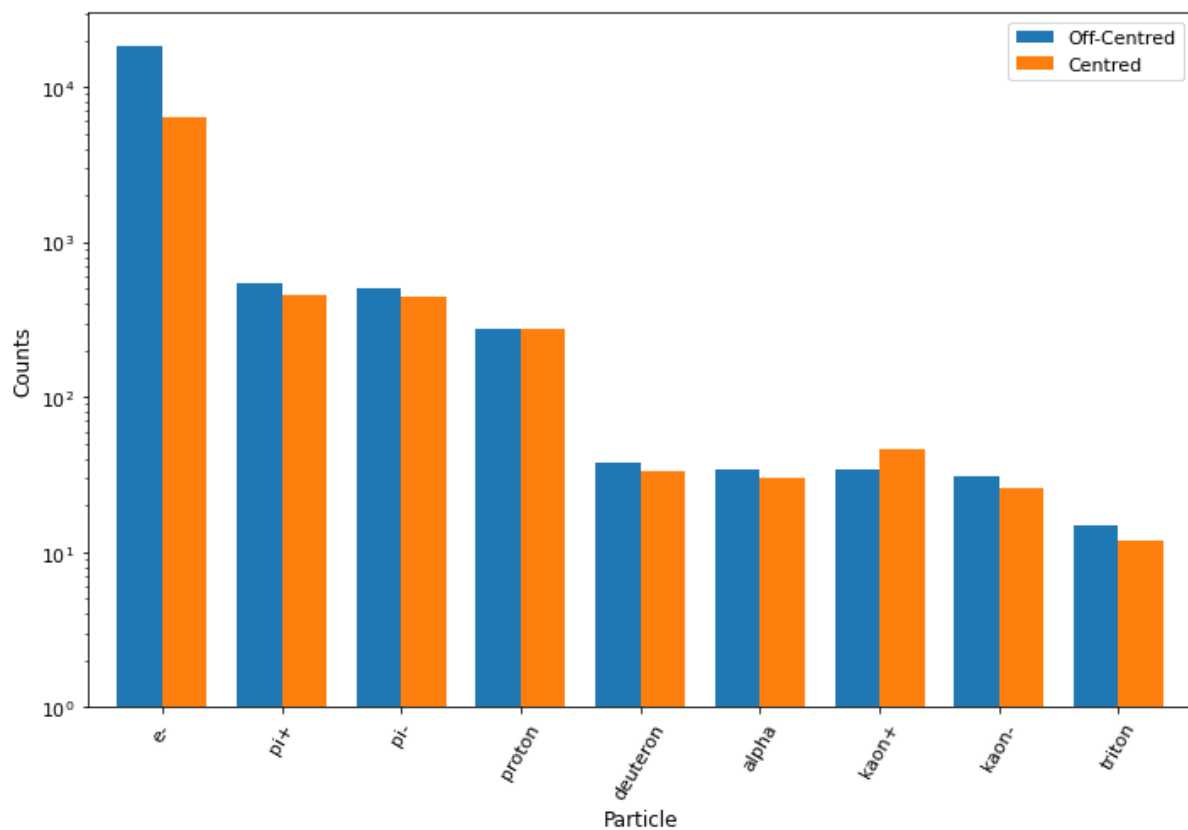
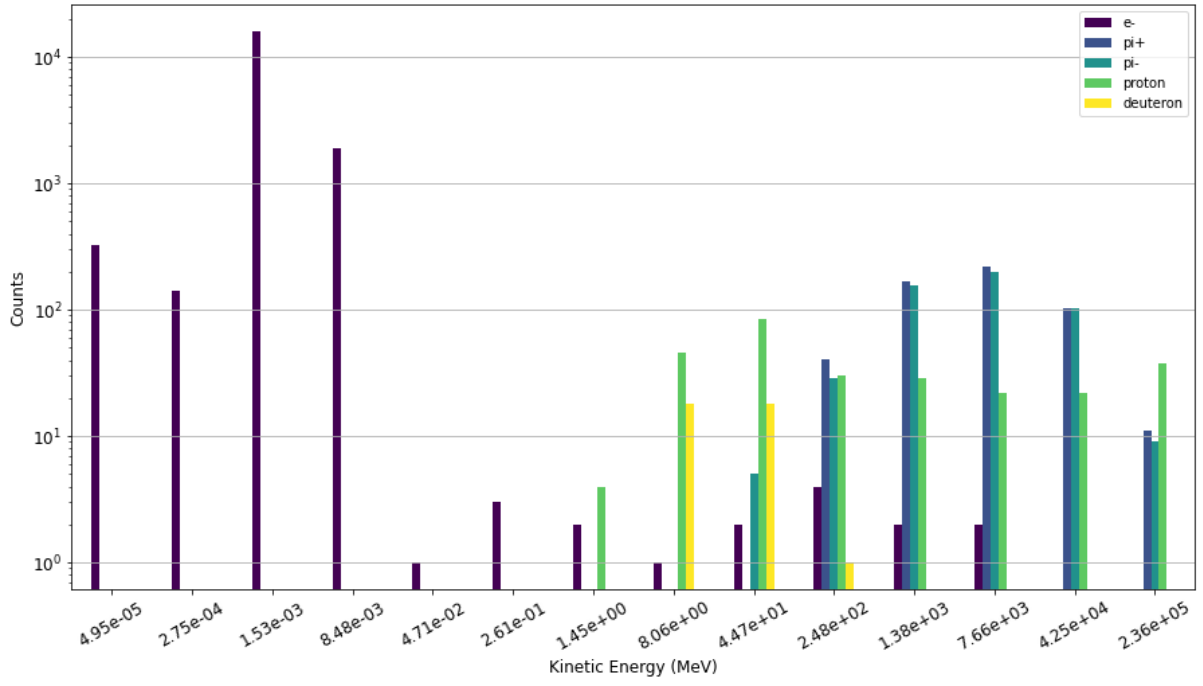


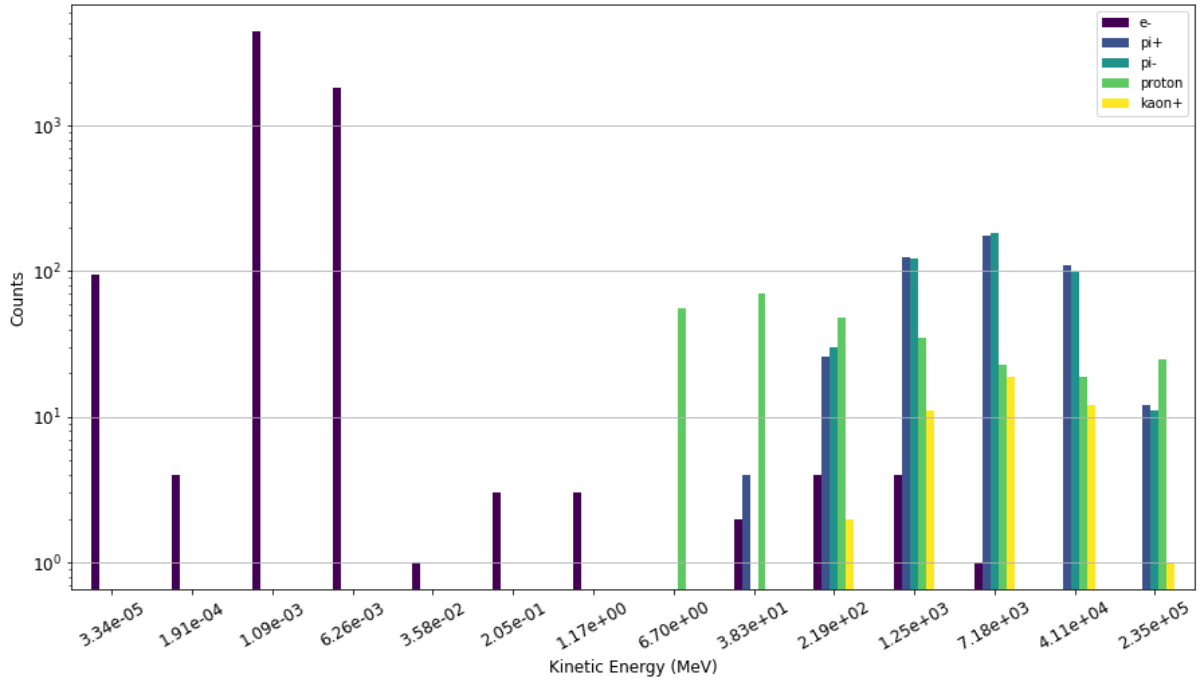
Figure 3.16: Charged particles created in titanium foil leaving foil

Fig. 3.17 shows the energy distribution of the particles created in the titanium foil as they leave the foil. For both centred and off-centred beam cases there are a number of electrons contained in the two lower energy bins that would most likely be affected by the bias voltage. The rest of the particles would most likely be unaffected by the voltage.



(b) Off-centred Beam

Figure 3.17: Kinetic energy distribution of particles created in titanium foil, when leaving foil



(a) Centred Beam

In order to investigate the effect of the maximum step size on the particle generation, a separate simulation was run, changing the step size from 2.5 μm to 1 μm for both centred and off-centred beam cases. The comparison between the number of secondary charged particles ending in the titanium foil, generated us-

ing the different step sizes, can be seen in Fig. 3.18 and the comparison between the number of secondary charged particles created in the titanium foil, which then exit, for both step sizes can be seen in Fig. 3.19.

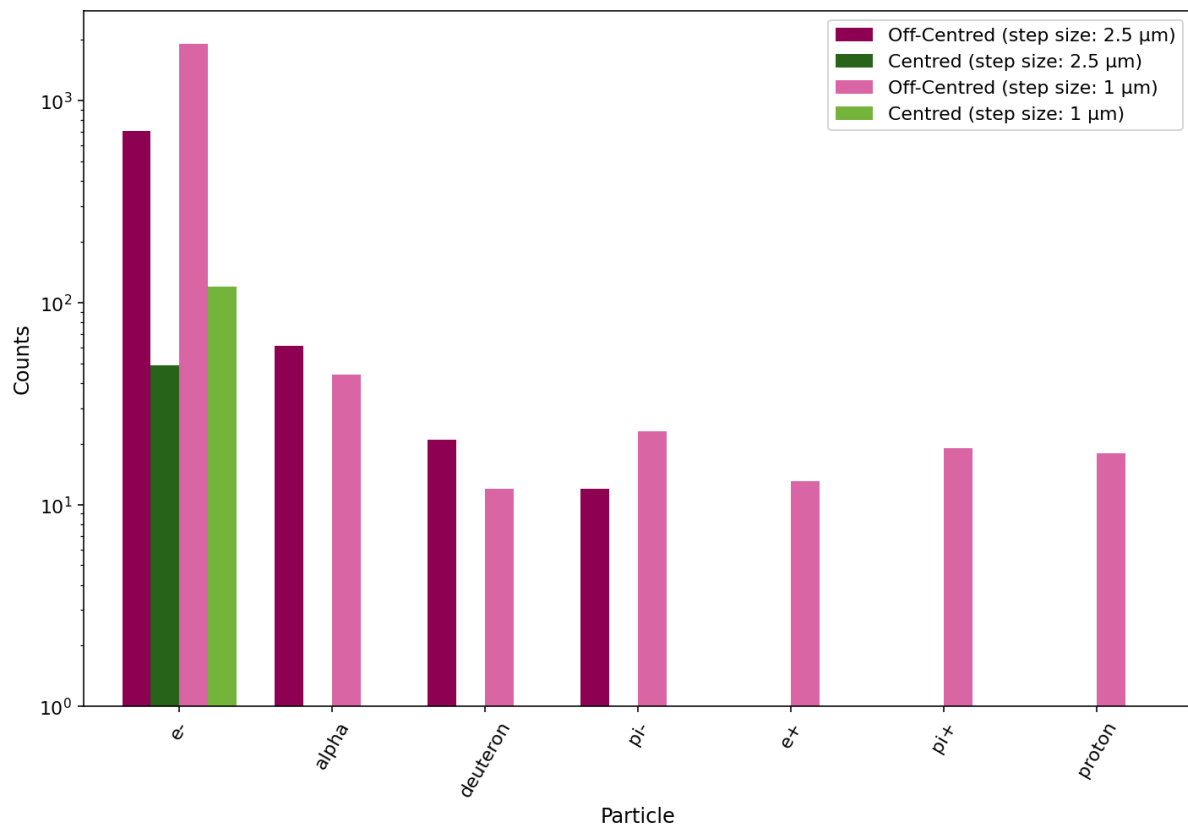


Figure 3.18: Comparison of charged particles entering titanium foil for different step sizes

In Fig. 3.18 there appear to be more electrons that end in the titanium foil for the 1 μm step size, compared to the 2.5 μm step size, this appears to be the case for both centred and off-centred beam. For the other particle types the differences between the number of particles generated that end in the foil using different step sizes are less pronounced. There are also much lower statistics, so the differences could be caused by statistical fluctuations. The reason there is such a noticeable difference between the electron counts, could be due to a combination of low electron production cuts, set by the micro-elec physics region in the detector, combined with the smaller step size, resulting in more steps within the detector, causing a larger number of electrons to stop within the material when the step size is smaller.

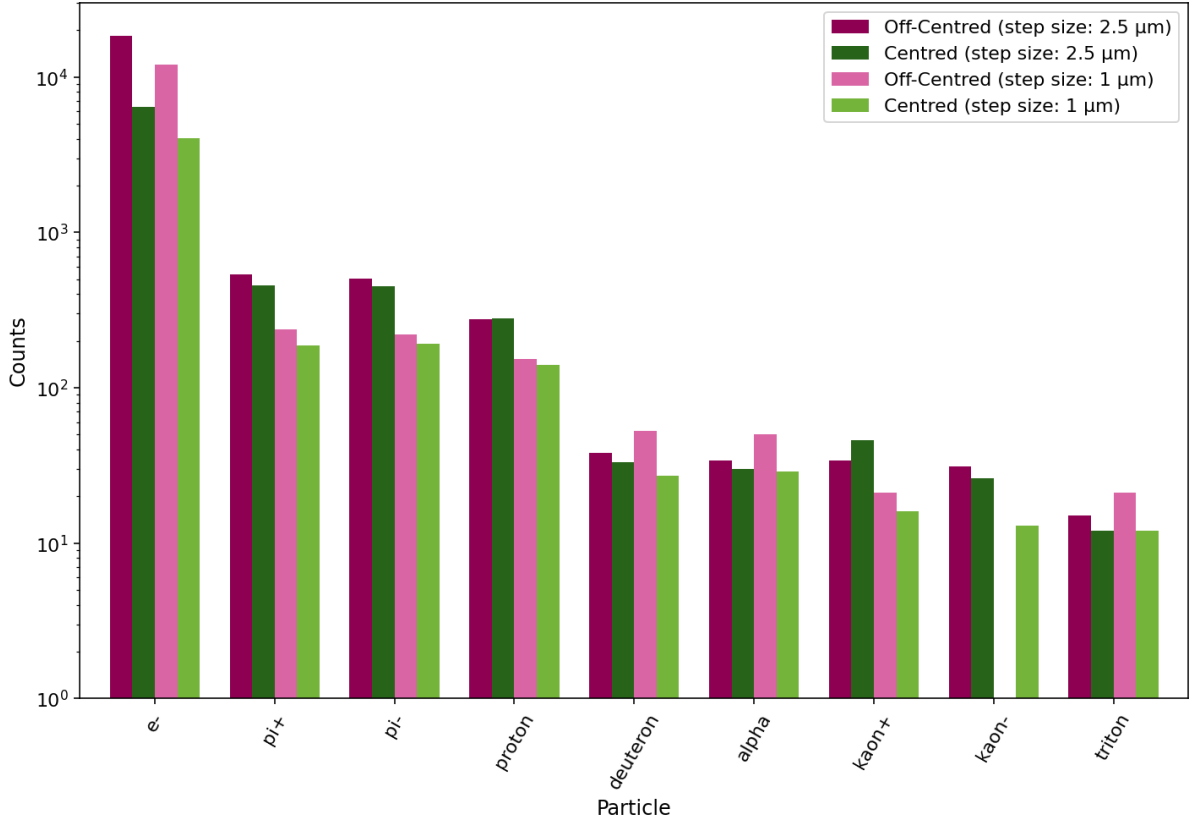


Figure 3.19: Comparison of charged particles created in titanium foil leaving foil for different step sizes

When looking at the particles created in the titanium foil that escape, as shown in Fig. 3.19, we can see that there appear to be a slightly larger amount of electrons, pions and protons that leave the foil for the larger step size and this appears to be the case for both centred and off-centred beams. Some of this might be explained by more particles getting stopped in the foil if there are a higher number of steps being taken. Another possible explanation is that there is some statistical variation between each iteration of the simulation, which caused the observed differences.

Fig. 3.20 shows the processes that have generated the secondary particles in the simulation, whereas Fig. 3.21 shows more specifically the processes responsible for creating secondary electrons in the simulation. The most common process of secondary particle and electron production for both centred and off-centred beam is ion ionisation, which makes sense, since the protons should be the main source of particle generation in the detector. Other relevant processes include hadron ionisation, proton inelastic scattering (which is responsible for creating many secondary particles, but does not generate secondary electrons) and decay. Ionisation by electrons, which is caused by high energy delta electrons passing through the material, is quite low as a percentage of the total number of interactions, accounting for just 0.018% of all processes creating secondary particles even when the beam is off-centred.

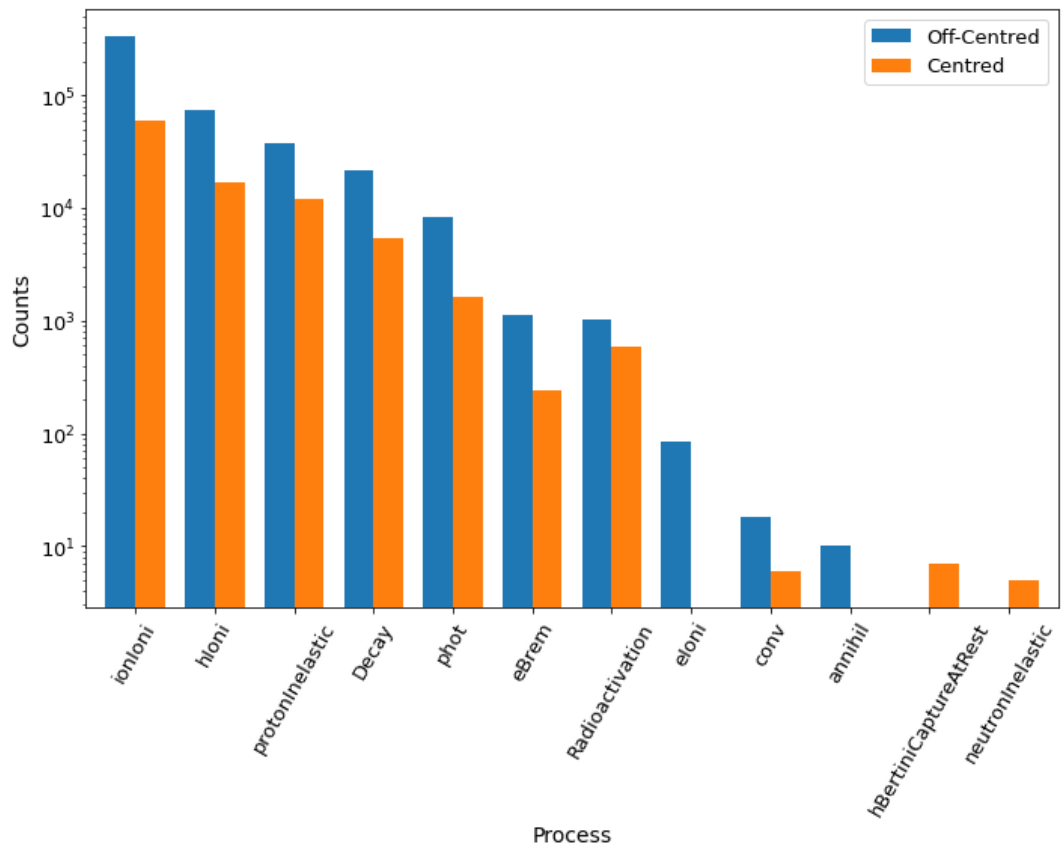


Figure 3.20: Processes involved in the creation of secondary particles

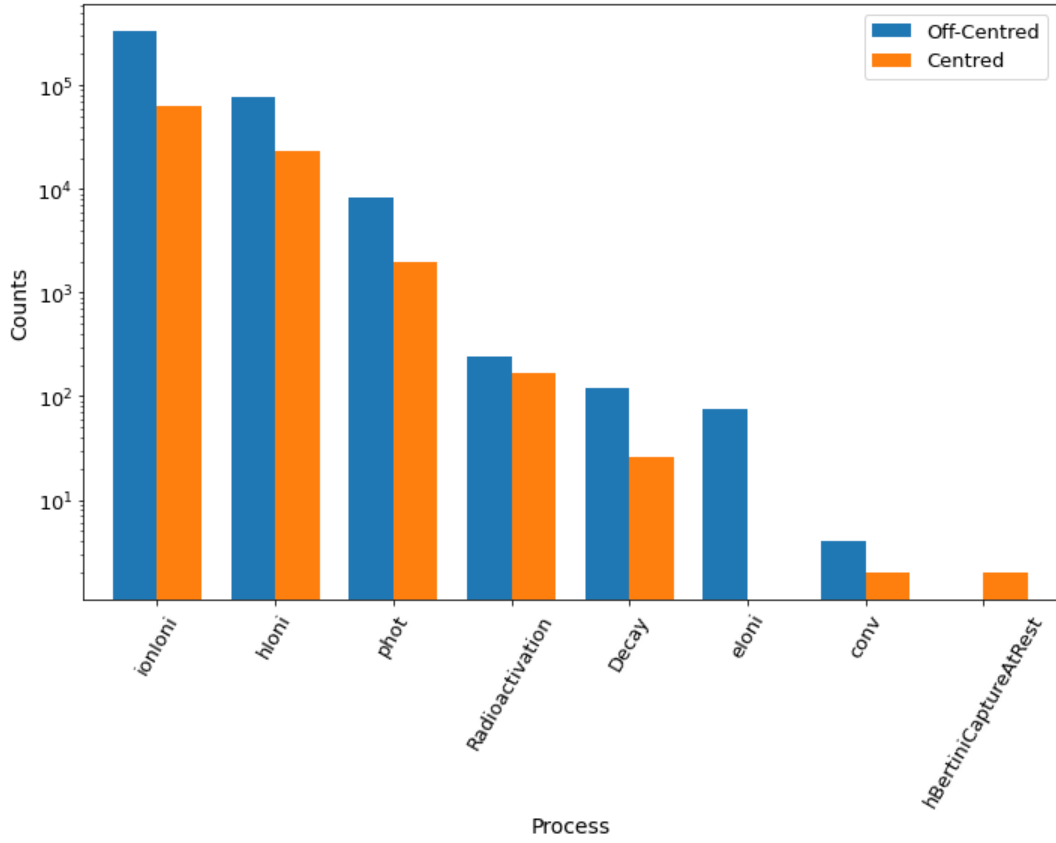


Figure 3.21: Processes involved in the creation of secondary electrons

The number of secondary particles produced in the off-centred beam simulation as a percentage of the primary protons was 4.76%. Of these secondary particles 66.39% had some interaction with the titanium foil and 61.58% were charged secondary particles interacting with the titanium foil.

The number of secondary particles produced in the centred beam simulation as a percentage of the primary protons was 0.77%. Of these secondary particles 79.16% had some interaction with the titanium foil and 67.88% were charged secondary particles interacting with the titanium foil.

Here secondary particles refers to any particles that are not a part of the primary beam, but not all of these are direct products of the primary beam. Many secondary particles originate from other secondary particles. And due to the filtering added to the simulation more secondaries may have been produced for which the data was not saved, as they did not interact with the detector. These particles are not of direct interest to the simulation, but they may have produced some of the secondary particles that did interact with the detector. Fig. 3.22 shows the distribution of secondary electrons, grouped according to their ParentID for both centred and off-centred beam simulations. Here ParentID refers to a Geant4 defined property of the particle track object, which defines how far descended from the primary beam the particle track is. Where a ParentID of zero indicates that the particle is a part of the primary beam, a ParentID of 1 indicates a secondary particle created directly from a particle in the primary beam, and

so on.

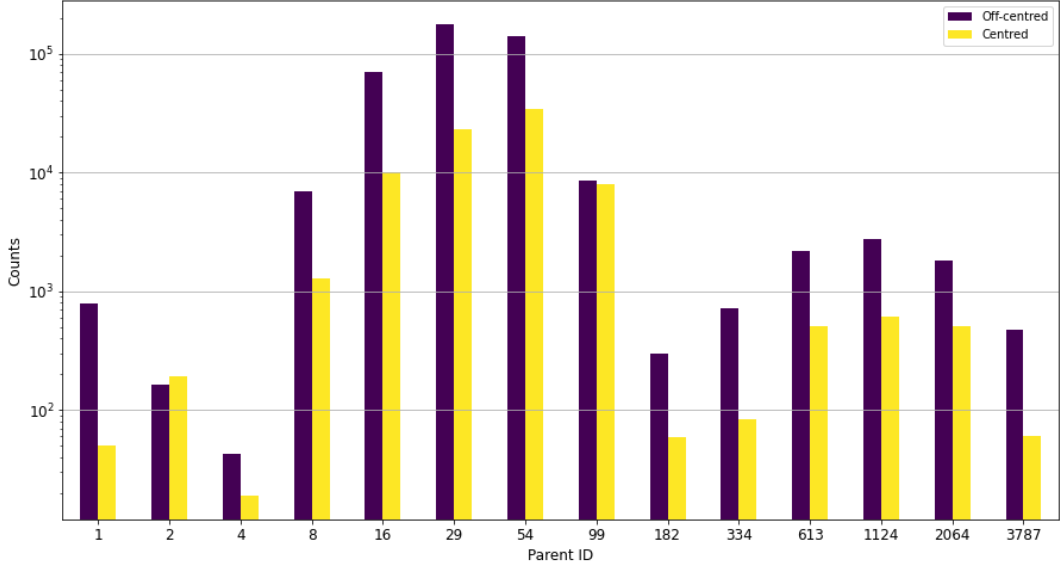


Figure 3.22: Electrons grouped by ParentID

It is interesting to see that there are relatively few secondary particles with a ParentID of 1, and there appears to be a peak occurring of particles with a ParentID of between 20-70. This means that the majority of electrons that we see in the simulations are created indirectly, most likely from other secondary particles (not electrons). Taking into account Fig. 3.21, the secondary particles creating electrons are most likely ions or hadrons. This would suggest that if there were to be a significant increase in ions or hadrons there would also be an increase in the number of secondary electrons being created, although not all of these would contribute to the secondary emission current.

If we look at the distribution of particle IDs among all types of particles in the simulation, as shown in Fig. 3.23, the number of particles with ParentID of 1 increases substantially, compared with Fig. 3.22. This suggests that the majority of secondary particles produced from direct interaction with the primary beam, and that have some sort of interaction with the foils, are not electrons. This means that either the electrons produced directly from the primary beam are produced outside of the detector region, and thus no data for these was saved or that the majority of electrons are produced through intermediary particles.

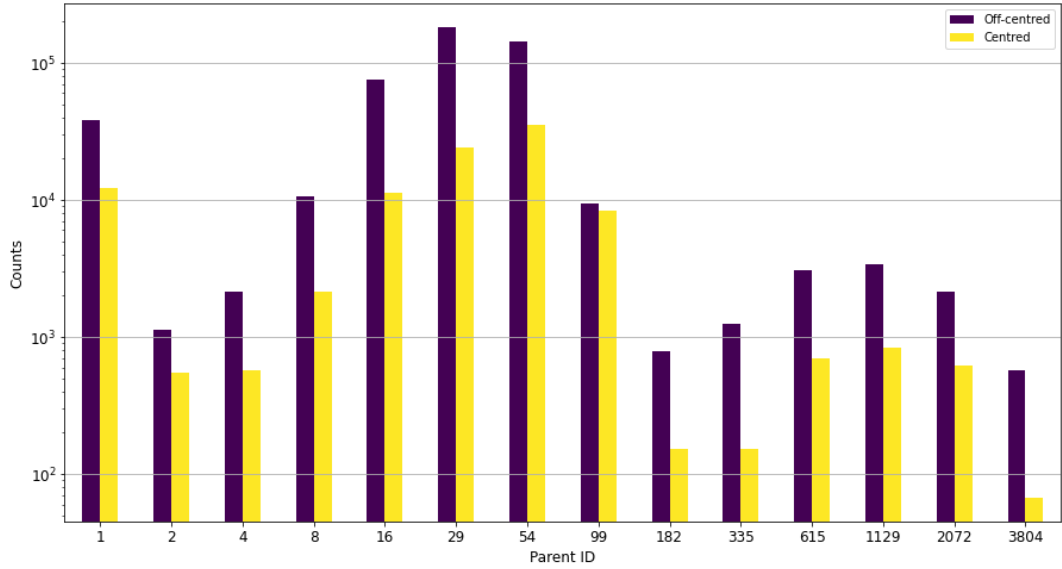


Figure 3.23: Particles grouped by ParentID

Due to the many particles being produced from other secondaries, and these numbers quickly growing, it is difficult to distinguish which secondary particles originate indirectly from the interaction of a primary proton with one of the bias foils and those that originate indirectly from interactions of the primary beam with the titanium foil.

Also, as shown in Fig. 3.15, it is not known exactly how many and what type of particles may have not been produced due to range cuts. Due to these uncertainties we cannot provide the exact value of the increase in signal that might be observed, but we can provide a rough estimate of how this signal might scale if the beam were to be displaced from passing through the centre of the bias foils.

Comparing the off-centred and centred beam simulations, the off-centred beam produced a factor of 4.9 times more secondary particles when compared to the centred beam. The off-centred beam produced 4.1 times more particles that interact with titanium foil and 4.4 times more charged particles that interact with the titanium foil.

A calculation of the net charge of the foil was done, according to Eq. (2.22), filtering on particle energy, in order to account for the effect of the bias foil. The net charge of the centred beam simulation was +16408 and the net charge in the off-centred beam simulation was +44227, resulting in a 170% difference between the net charge in the two simulations.

Although this is a considerable difference, it is important to point out that this simulation compared two extremes. In real operation, it would be unlikely for 100% of the primary beam to hit the bias foil. It is more likely that a small fraction of the beam might hit the bias foils, either due to increased beam

size, or problems with steering. In these cases only a small fraction of the beam would hit the bias foil, resulting in a much smaller difference in the measured beam current, between spills. This could even help to explain some of the non linearities observed between the ratios of the BSI to BCT signal.

Limitations of the simulation are also important to consider: as this is a simulation over a large energy range, it is possible that some of the physics, at the extremes of the range is not well captured; the detector is very thin and perhaps not enough steps were taken inside it to produce accurate results; the bias foil potential field was not simulated.

3.5 Conclusion and Future work

In this chapter simulations were conducted to investigate the strange behaviour observed in the proton current measured by BSI devices. These devices are made of thin foils, with the secondary emission current in the central foil being used to determine the number of protons passing through. Bias foils with a central hole are placed either side. The objective of these simulations was look into the relationship between the geometry of the setup and the inconsistencies in signal measurement: whether there were a significant amount of secondary charged particles produced due to the interaction with the primary beam and the bias foils; what type of particles these were; whether these were able to overcome the bias potential and add to the signal being measured.

The BSI monitor was simulated in Geant4 and two separate simulations of 10^7 primary protons were conducted: one with the beam centred on the BSI device, passing through the hole in the bias foils and the other where the beam was off-centred so that 100% of the primary beam passed through all three foils.

In the simulation it was observed that direct contributions of secondary particles stopping in the foil were relatively low, most secondary particles passed through both sides of the central foil. However, it was also observed that due to the large number of charged secondary particles being produced from interaction of the beam with the bias foils, that many of these had enough energy to cross the foils and in doing so, they contributed to an increase in ionisation, resulting roughly in a 170% increase in signal between the centred and off-centred beam. It is worth pointing out that it is extremely unlikely for 100% of the beam to be hitting all 3 bias foils. In reality any problems with the size or steering of the beam are likely to result in only a fraction of the beam hitting the bias foil, and the variation in signal measured would be considerably smaller than the 170% variation seen in this simulation.

Additionally it is worth considering the limitations of the simulation itself, which is simulating a factor of 10^6 fewer particles compared to the number of particles in one spill and is taking a relatively small number of small steps inside a very thin detector. A combination of physics lists has been used including

"QGSP_BERT_HP", EM option 4 and Microelec (inside the detector region) to try to capture a very large energy range and combination of different processes from the incident proton energy of 400 GeV down to the eV range for the simulation of SEY. Although only particles with high enough energy to overcome the bias potential were included in the signal calculation, the bias potential itself was not simulated.

The simulation was focused on investigating the effect of the bias foils' interaction with the primary beam, but similar observations might be made for closely positioned foil stacks, or any other closely located instrumentation. More simulations would be necessary to quantify whether the contributions from these would be significant, as additional instrumentation would have a bias foil in between it and the previous instrument, so the distance between consecutive current measuring foils would be greater. However, if they were found to contribute, then this could explain the difference in signal measured by the two foils placed at a similar location, which was highlighted in 2017.

Further considerations include the small amount of experimental data available for the SEY of high energy protons. SEY data measured at CERN with these devices could be subject to a systematic error, if the interaction of the primary beam with the bias foils were to produce a significant increase in the measured ADC current. As the previous SEY measurements were also made with BSI devices the true SEY for protons in titanium could be lower. Furthermore it is hard to separate differences in signal caused by additional particles, resulting in localised ageing damage to the foils, from those caused by changes to the vacuum conditions that may have occurred over time, leading to contamination of the foil surfaces and changing the SEY.

Further work could include simulating a partially displaced beam, simulating different bias foil hole sizes and including an electromagnetic field to simulate the bias foil potential on the particles. Further simulations could explore using different material thicknesses, number of foils, and inter-foil spacings. It would be interesting to test measuring the SEY without the bias foils, with different bias foil hole sizes, and using bias foils without holes, as this could reduce the variation in signal, while still applying the bias potential. It would also be interesting to conduct dedicated vacuum studies and study the changes in the SEY due to vacuum. Finally it would be interesting to study the effects proton dose on ageing, and how this affects the SEY over a long period of time. Only by controlling for each one of these variables separately will we truly understand in what measure each one of these factors impact the BSI performance and how often these need to be recalibrated or replaced.

Chapter 4

Calibration of NA BSIs

This chapter describes the experimental measurements carried out for the calibration of the BSIs in the NA. Starting with an introduction of the previous calibration history at this location and challenges involved, it will then describe the main method used for calibration of BSIs - the activation method, before detailing the measurement campaign: including the setup for each of the measurements and the experimental results.

4.1 Calibration Challenges

As discussed in Section 1.3 the last known calibration of the BSIs was performed in the 90s and recent data investigations, starting in 2016 have drawn attention to strange behaviour displayed by these devices, such as non-linearities and discrepancies between the signal measured by the BCT before extraction and the BSIs in the TT20 beamline. These have highlighted the need for absolute calibration of these devices, in order to provide an accurate number for the POT to all experiments in the North Area. This calibration is of extreme importance, as the uncertainty on the POT has a direct impact on all the experiments using this number in their calculations. Both absolute and relative BSI calibration are vital for accurately measuring transmission efficiency along the NA lines. Poor transmission leads to losses and equipment activation, making maintenance more difficult under As Low As Reasonably Achievable (ALARA) principles.

However, the absolute calibration of the SEM devices in the North Area is not trivial, due to this being a slow extracted beamline. This means that the protons are spread out along a spill, resulting in a lower intensity, making the use of BCTs (which are very precise and used in most of the other accelerators and beamlines) infeasible. Using a fast extracted beam to measure the beam current directly with a BCT (as done when extracting beam from the PS into the East Area), is not possible in the North Area, as such a device is not currently installed, nor are there any plans to install one at the present moment. In any case, the current SPS slow extraction system cannot produce beam parameters that

are measurable by present-technology BCTs. This applies specifically to the combination of minimum charge numbers within maximum pulse lengths.

The closest beam intensity monitor that can be used to compare to BSI in the NA primary lines is the BCT in the SPS ring. However, the large distance between it and the closest BSI, combined with the uncertainty in quantifying the slow extraction losses, results in high uncertainty in the absolute calibration results. Another method must then be employed for this purpose. Historically, previous device calibrations in the NA [20, 72] and more recent calibration of similar devices in the East Area [73, 74] have been carried out using the *activation method*.

This method has performed well in the past, however it is not an online measurement and requires dedicated time for installation, irradiation and retrieval. During this time experiments in the area cannot operate. The high demand for beam time in this area, due to its diverse experimental program, increases the challenge for calibration. Beam time for testing accelerator device instrumentation is limited and often shared with other maintenance and commissioning projects.

4.2 The Activation Method

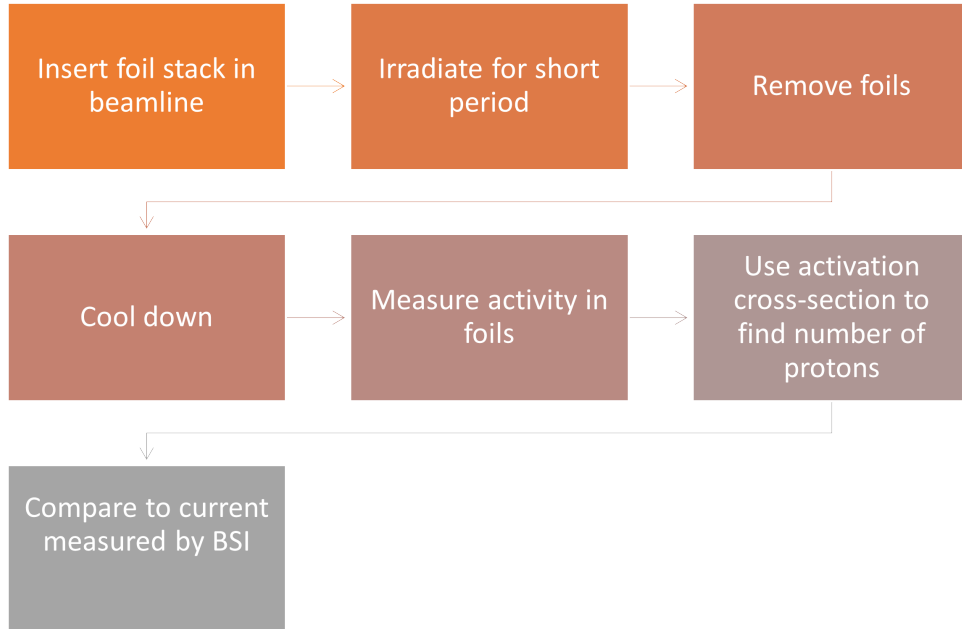


Figure 4.1: Calibration via activation process

Fig. 4.1 shows the steps in the calibration process. In order to perform calibration via activation it is necessary to temporarily introduce a stack of foils in the beam line. Once the foil stack has been inserted, the beam is then switched on, allowing protons to pass through. As they pass, some protons will cause

a nuclear spallation reaction, resulting in the production of radioisotopes [41].

The production of radioisotopes has been extensively studied and documented for various materials, particle types, and energy ranges. Using published cross sections for protons at 400 GeV (NA energy), we can accurately determine the number of protons that traversed the foil stack by measuring the induced radioactivity in the foils.

The activity is measured offline, via gamma spectrometry analysis. For this reason it is also necessary to stop the beam after irradiation of the foil stack. Once stopped a period of cool down is also necessary before the foil removal is possible. Once removed, the foils are disassembled and left to cool, before being transported for measurement. The proton flux ϕ' is related to the activity A via Eq. (4.1).

$$\phi' = \frac{A}{N_x \sigma (1 - e^{-\lambda t_{irr}}) e^{-\lambda t_{wait}}}. \quad (4.1)$$

Here σ is the cross section, λ is the decay constant, t_{irr} , is the irradiation time, t_{wait} is the time between the end of the irradiation and the beginning of the gamma spectrometry measurement and N_x is the surface atomic density, defined as:

$$N_x = \frac{N_{av}}{M} \rho \Delta x. \quad (4.2)$$

Where N_{av} is Avogadro's number ($6.022 \times 10^{23} \text{ mol}^{-1}$), M is the molar mass, ρ is the density and Δx is the thickness of the foil. The POT can be calculated from the flux ϕ' by multiplying it by t_{irr} .

4.2.1 Material Considerations

There are a few considerations to make when choosing the material of the foils and the reaction to be observed. Materials produce different isotopes, with varying cross sections, which also depend on the energy of the beam. Some materials also have additional reactions that produce backgrounds that must be accounted for during calculation.

The purity of the material could influence the resulting isotope production, depending on the quantity and cross section of the isotopes produced by the impurities contained within the material. A high percentage of impurities, or impurities which produce isotopes with a large cross section, could introduce uncertainties in the measurements.

Another important consideration is the half-life of the isotopes produced in the spallation reaction. Ideally it is important to have one or more isotopes with a relatively short half-life, so that the activity measured is high, but not too short that the isotope decays completely before the gamma spectrometry measurement has started. Furthermore it is important to choose a material for which cross sections for isotopes at a similar beam energy have already been measured and reported in literature, which can be harder to find at higher energies.

With these considerations in mind the ideal material for the foils would be one which produces a range of isotopes with large cross sections, short, but still measurable half-life, with minimum background contributions, that have been measured at the appropriate energy and are well documented in literature. Unfortunately no material is perfect and one must consider the pros and cons of different reactions in order to pick the most suitable material.

Reactions commonly used for calibration via activation are the $^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ and the $^{nat}\text{Cu}(p, x)^{24}\text{Na}$. The former has cross section reported over a wide energy range and has a large cross section, but also has background contribution from competing reaction $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$. The latter has no major contributing background reactions, however it also has a lower cross section [41].

Another process contributing to uncertainty in the measurements is the nuclear recoil effect. This occurs during the spallation process, when the energy of the reaction causes a part of the resulting nuclei to be ejected from the foil. This uncertainty can be mitigated by placing catcher foils either side of a central foil. In this case, the nuclei ejected from neighbouring foils would compensate each other and the middle foil would be in equilibrium. In this case only the activity measured in the middle foil would be used for the calibration.

4.3 The Measurement Campaign

Among the various BSI monitors installed in the SPS NA lines, 4 are used as reference to infer the integrated protons on the 4 targets (T2, T4, T6 and T10). These were considered as the most important to calibrate.

The calibration process was carried out in stages. The BSI upstream of the T10 target was the first to be calibrated. Due to this area being a branch towards the end of the NA beamlines, it was easier to gain access to this beamline for measurements. The objective of the first measurement was to reduce the uncertainty on the protons on target being measured at T10 and to act as a pilot measurement to test out best practice for subsequent measurement.

Up until this point the POT, measured by the BSI just before T10, had a very large error, which was one of the main sources of uncertainty for the NA62 measurements. Other experiments also had interest in reducing the uncertainty on the POT in their beamlines.

Having successfully carried out the first measurement, 2 other measurements followed: a second calibration measurement for the T10 BSI and a calibration measurement for BSIs before targets T2, T4 and T6. This section is split according to measurement location: Section 4.3.1 will discuss the measurements at target T10 and Section 4.3.2 will describe the simultaneous calibration of the T2, T4 and T6 targets.

4.3.1 Measurements at Target T10

Two measurements were performed at target T10, the setup for each of these can be found in Section 4.3.1.1. The method for processing the data collected and calculating the calibration factor can be found in Section 4.3.1.2. The results for both measurements are discussed in Section 4.3.1.3.

4.3.1.1 Setup

Different experimental setups were used for each measurement. Here we will describe each one of the different setups, stating the changes made and why these were made.

4.3.1.1.1 First Measurement

For the first measurement a foil stack was assembled with 99.5 % purity aluminium foils, as shown in Fig. 4.2. Three 100 μ m thick foils were used to construct the stack, as well as 2 GAFChromic films (GAFChromic HD-V2 and FWT-60-20F).

On the 16th of September 2022 the foil stack was placed in the beamline, upstream of T10 and irradiated for approximately 26 minutes, corresponding to 109 shots. To check the stability of the beam during the calibration measurement, the intensity was measured by the closest SEM devices to the BSI being calibrated and by the BCT in the SPS, before extraction to the NA. Fig. 4.3 shows the integrated intensity per spill measured by these devices ¹. Please refer to Fig. 2.8 for the position of these instruments in the beamline. The instruments that start with T10, are positioned inside the target box and T10-BSI.045914 was the instrument being calibrated.

From the raw data for each spill, an average of the intensity measured by the T10 BSI for all of the spills during the measurement was taken, for each point in time during the spill, and can be seen in Fig. 4.4. Here the solid blue line represents the average intensity as a function of time during the spill and the light blue shaded area is the standard deviation across all spills for each point in time during the

¹more details on how the data is processed can be found in Section 4.3.1.2

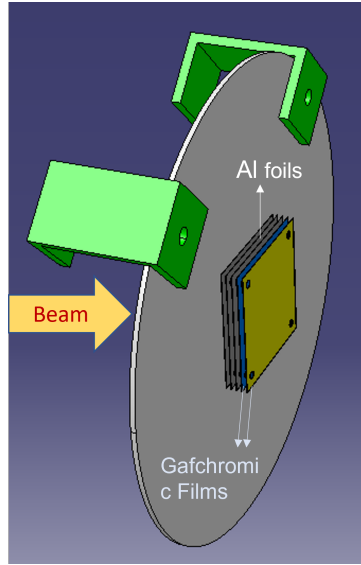


Figure 4.2: Experimental setup for first set of measurements

spill. Apart from a short peak towards the beginning of the spill, the signal remains constant throughout the spill. From Figs. 4.3 and 4.4 it is clear that the intensity remained stable throughout the calibration measurement.

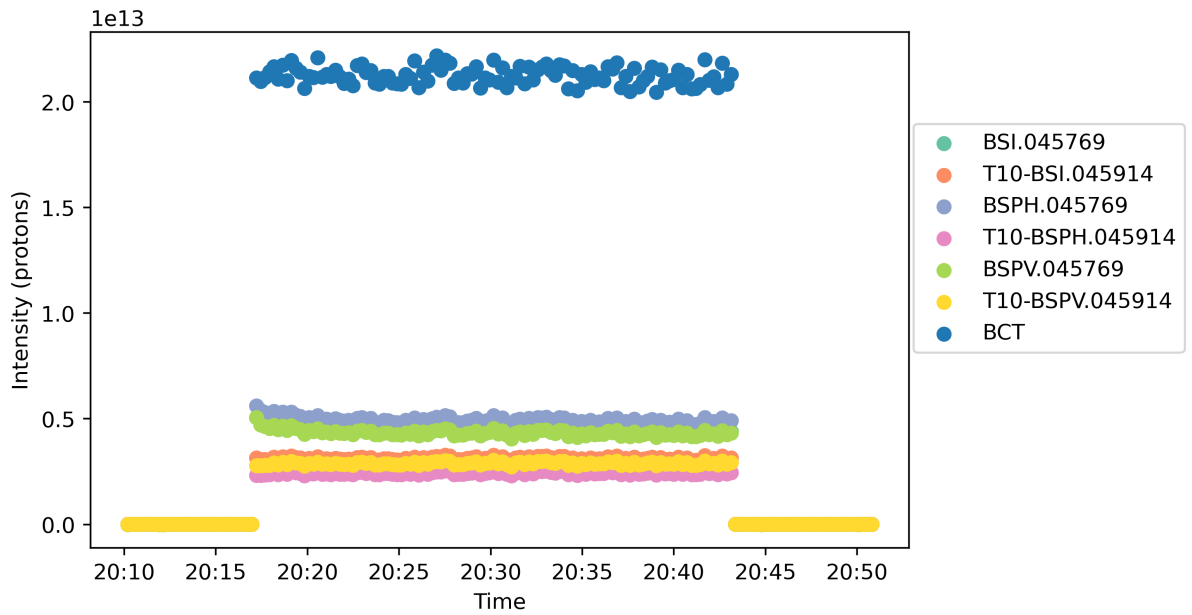


Figure 4.3: Intensity integrated per spill, measured by SEM monitors near target T10 and BCT in SPS, during first calibration measurement

After 2 days of cooldown the foils were retrieved and taken for gamma spectrometry measurements.

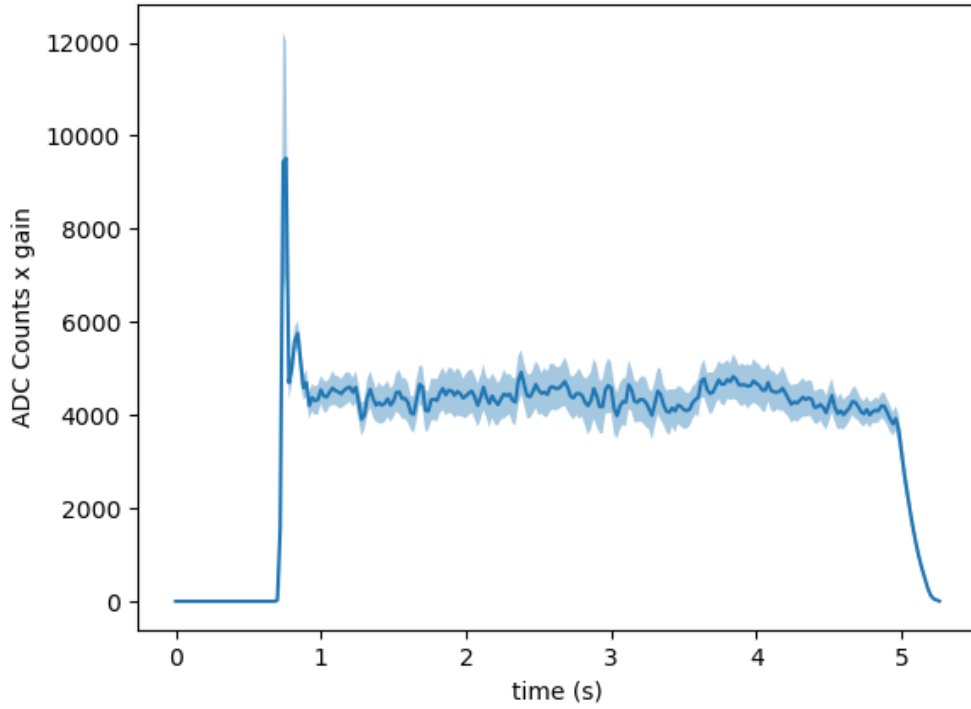


Figure 4.4: Average intensity during the spill for 109 Spills measured by T10 BSI during the first calibration measurement

These measurements were conducted by the CERN Radioprotection (RP) group, using high purity germanium detectors from Mirion Technologies (Canberra). The RP group measured the activity of various different isotopes generated in the spallation process (described in Section 1.2.4), when the high energy proton beam hit the foils. The activity for various isotopes, measured by the RP group, can be found in Table A.1 in Appendix A, and was used to calculate the proton flux. Section 4.3.1.2 shows how the POT and calibration factor were calculated using the aforementioned data. The results of these calculations are presented in Section 4.3.1.3.

4.3.1.1.2 Second Measurement

As a follow on from the first pilot measurement, a second measurement was conducted, with improved setup. The improvements were driven by a couple of considerations arising from the analysis of the data for the first measurement. Firstly a large discrepancy on experimentally measured cross sections found in literature for Aluminium was noted. The values reported in literature were measured at both Fermilab and CERN, but there was a significant difference between them. This discrepancy introduced a large uncertainty on the proton flux calculated, and one of the main aims of the calibration of the BSIs was to reduce the uncertainty in the POT being delivered to the experiments in the NA.

It was noted that the cross section values reported for copper in literature were in much better agreement. Furthermore, the copper foils had the advantage of not having any significant background reactions, thus needing no background corrections. Because of this, a new foil stack, similar to that described in section 4.3.1.1.1, was created. The new stack contained 3 copper foils and 3 aluminium foils. The aluminium foils were replaced with 99.99% purity aluminium foils to avoid any possible contributions from impurities to the measurement. The metal spacers present in the first setup were also replaced with plastic ones, in order to avoid contributions from impurities interfering with the measurements.

A second calibration measurement was performed on the 26th of October 2022 using the updated

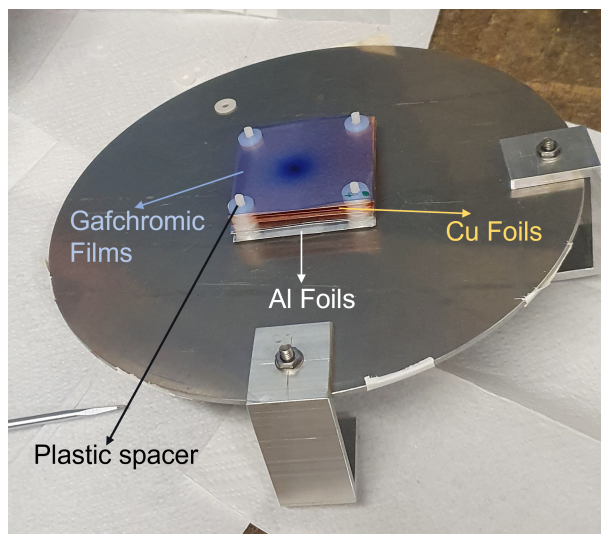


Figure 4.5: Experimental setup for second set of measurements

foil stack. A picture of the foil stack can be seen in Fig. 4.5. The stack of foils was then irradiated for 32 minutes (109 shots). A plot of the integrated intensities per spill² measured by the SEM devices closest to the T10 target, during the second calibration can be seen in Fig. 4.6.

The average intensity per time in the spill, measured by the T10 BSI across all 109 spills during the second measurement can be found in Fig. 4.7. The blue line represents the average intensity value during the spills and the lighter blue shaded area the standard deviation, calculated for each point in time across all spills. It is clear from both Fig. 4.6 and Fig. 4.7 that the intensity was stable throughout the measurement.

The foils were then left to cool for approx 5 days, before being collected for measurement. The additional cool down time was due to the higher level of activation of the copper foils. The foil dose rate was measured several times over the course of the cool down, for future use when estimating the cooldowns.

²more details on how the data is processed can be found in Section 4.3.1.2

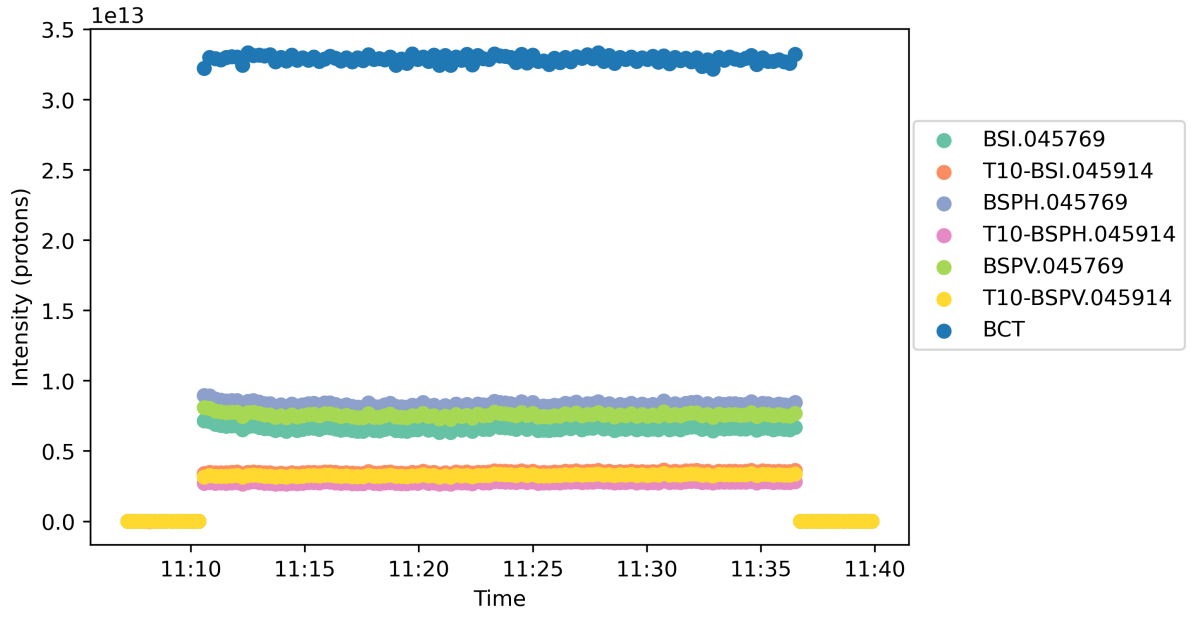


Figure 4.6: Intensity integrated per spill, measured by SEM monitors near target T10 and BCT in SPS, during second calibration measurement

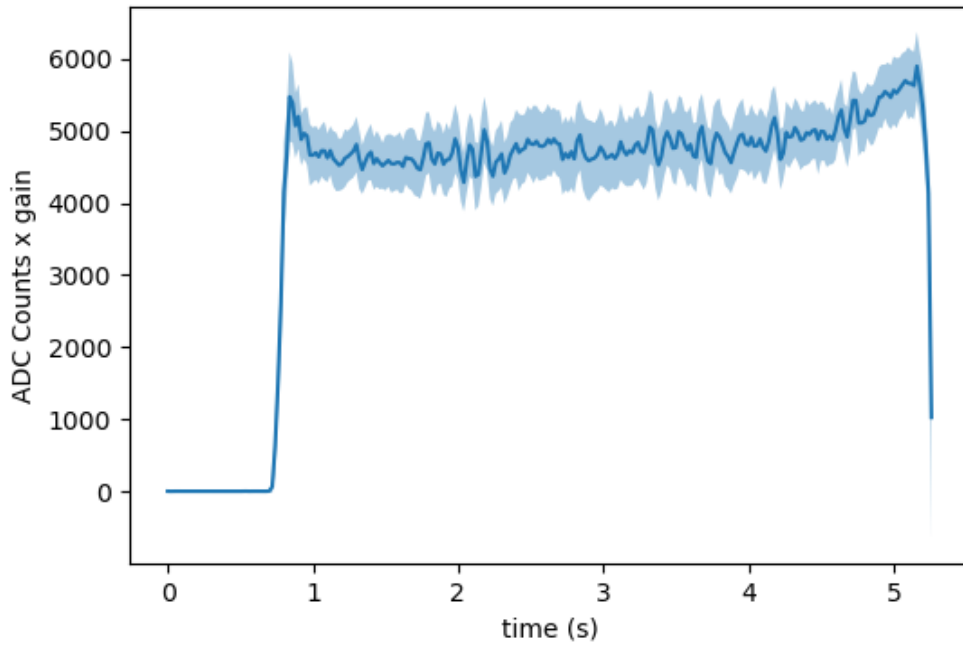


Figure 4.7: Average intensity during the spill for 109 Spills measured by T10 BSI during the second calibration measurement

The activation measurements taken by the CERN RP team can be found in Table 4.1.

Foil Description	Dose rate($\mu\text{Sv/h}$)				
	26/10 16h30	27/10 9h30	27/10 14h00	28/10 10h00	31/10 9h30
Alu 1	63	33	30	10	0.6
Alu 2	73	31	23	9	0.6
Alu 3	77	30	23	10	0.6
Cu 5	280	38	38	20	8
Cu 6	217	40	35	21	8
Cu 7	250	45	44	21	8

Table 4.1: Measured dose rate of foils during cooldown period for second measurement (before gamma spectrometry measurements)

After cooldown gamma spectrometry measurements for the foils were taken and the activity measured was used to calculate the proton flux, following the same procedure as for the first measurement.

4.3.1.2 Calculating the Calibration Factor

In order to obtain a value for the POT and subsequently the calibration factor, it was necessary to combine the data from the offline gamma spectrometry measurements, provided by the CERN RP team, with the online BSI signal measurements stored in the CERN NXCALS database. The BSI raw data was retrieved from the NXCALS database via the CERN SWAN platform. Here timestamps were selected based on the BCT signal. The timestamps for the BSI were selected when the BCT signal was active. Each timestamp contained the raw data for the signal measured during one spill, consisting of 264 datapoints.

Some basic corrections were applied to the raw signal: first the offset was calculated, using average of the first 28 points in the spill. This offset was subtracted from all datapoints. Any points below 10% of the mean value of the signal were set to zero (to avoid counting background fluctuations caused by noise in the electronics). These corrections can be visualised in Fig. 4.8. The 264 individual corrected signal datapoints for each spill were added together, and divided by the amplifier gain (G) to give the integrated current (I) for each spill in ADC counts, as shown in Eq. (4.3).

$$I(t) = \int q(t)dt = \frac{\sum_i q(t)}{G} \quad (4.3)$$

There were a total of 109 spills for the first and second measurement at target T10. Figs. 4.3 and 4.6 show these values multiplied by the calibration factor, to give the proton intensity (also referred to as POT) during the measurement. Once the integrated current values for each spill measured by the BSI

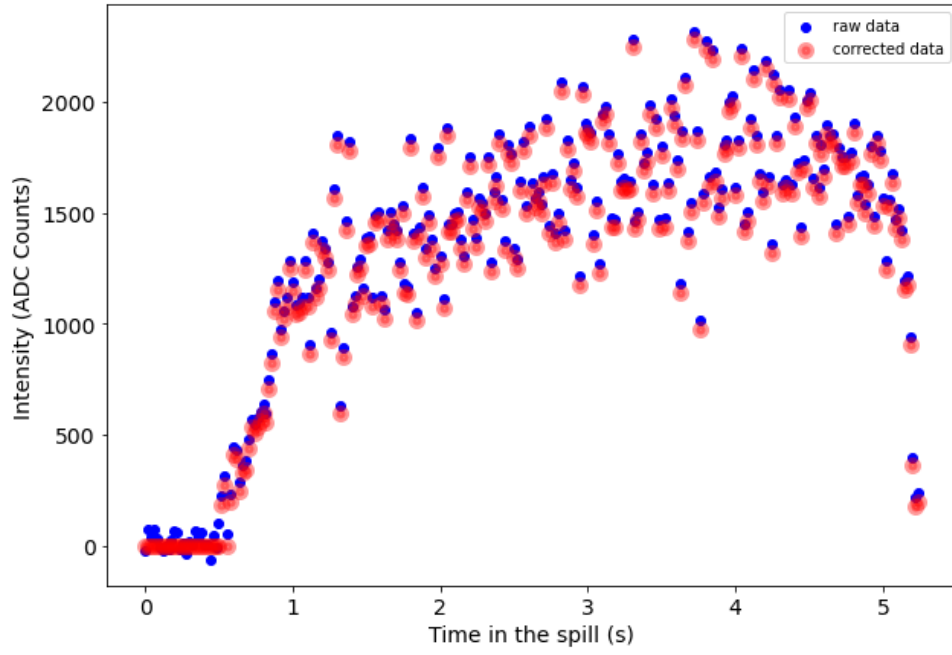


Figure 4.8: Corrections applied to raw data for BSI signal during the spill

were obtained, all spills were added together to give the total intensity measured by the BSI over the course of the calibration. This intensity value will be referred to as I_{BSI} and it can be used in combination with the intensity measured via the activation method I_{Act} to determine the calibration factor (c_f), according to Eq. (4.4).

$$c_f = \frac{I_{Act}}{I_{BSI}} \quad (4.4)$$

The activation method used for calculating the proton intensity from the measured activity (I_{Act}) for different isotopes is described in detail in Section 4.2. First a value for the proton flux was determined from the activity measured by the CERN RP team (shown in Table A.1 in Appendix A), using Eq. (4.1). The half-life ($t^{1/2}$) values, taken from [75], can be found in Table 4.2, were used to calculate the decay constant λ according to Eq. (4.5)

Table 4.2: Half life values for Isotopes

Isotope	Half-Life (s)	Δ Half-Life(s)
7Be	4598208	5184
${}^{22}Na$	82104810	69425
${}^{24}Na$	53989	43

$$\lambda = \frac{\ln(2)}{t^{1/2}} \quad (4.5)$$

The cross-section values for the production of various isotopes in copper and Aluminium, used in the calculation of the proton flux, were taken from published measurements [72, 76–78] and are shown in Table 4.3. Only values for cross-sections measured at energies close to 400 GeV were used in the calculations. Values for cross-sections at these energies were measured at CERN and Fermilab.

Table 4.3: Cross section values (including 1σ error) for production of isotopes from protons in Aluminium and Copper

Institution	Mat.	Isotope	E(GeV)	$\sigma(b)$
Fermilab	Al	7Be	300	8.7 ± 0.7
Fermilab	Al	${}^{22}Na$	300	9.4 ± 0.8
Fermilab	Al	${}^{24}Na$	300	8.04 ± 0.58
CERN	Al	${}^{24}Na$	400	8.82 ± 0.18
CERN	Cu	${}^{24}Na$	400	3.96 ± 0.10
Fermilab	Cu	${}^{24}Na$	30-800	3.59 ± 0.02
Fermilab	Cu	${}^{24}Na$	400	3.90 ± 0.11

Care was taken when measuring the thickness of the foils (Δ_x), used in the calculation of the proton flux for the activation measurement. Due to the thin nature of the foils, instead of measuring the thickness directly, it was estimated from measurements their mass m and sides Δ_y and Δ_z , according to Eq. (4.6). Before assembly, the foils were individually weighed and repeated measurements of each side of the foil were taken, in order to reduce random error. The data for these measurements can be found in Appendix A, as well as the material properties for copper and aluminium.

$$\Delta x = \frac{m}{\rho \Delta y \Delta z}. \quad (4.6)$$

To obtain the value for I_{Act} , the proton flux was multiplied by the irradiation time. This was then used to determine the calibration factor using Eq. (4.4). A value for the calibration factor was calculated, using each of the measured isotopes. Where multiple cross-section values were found in literature a calibration factor was calculated for each cross-section value. The results for the absolute calibration performed at T10 can be found in Section 4.3.1.3.

4.3.1.2.1 Corrections

As discussed in Section 4.2.1, when using aluminium foils, the spallation reaction ${}^{27}Al(p, 3pn){}^{24}Na$ is susceptible to background contributions from neutrons and other high energy hadrons. This effect scales

with the foil thickness. In [73] measurements of the proton intensity were taken with aluminium foils, at varying thicknesses, using the activation method. They were able to establish a relationship between the mass thickness and the additional background contributions. This was found to be 1.4% per 100 mgcm^{-2} . This correction was applied to the activity measured by the aluminium foils, taking into account the thickness of all foils positioned upstream of the foil used for measurement plus the vacuum window upstream of the target box.

In addition to the corrections to the activity, corrections were also applied to some of the cross-section values in Table 4.3, as there were a few differences in the way the measurements of these cross-sections were carried out. The cross-sections measured for isotopes produced in aluminium at Fermilab were measured at 300 GeV. The ^{24}Na cross-section in aluminium measured at Fermilab was corrected for the background $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$ reaction. The value measured for the same cross-section at CERN was measured at 400 GeV, but did not correct for any background contributions. The CERN measured cross-section value for $^{27}\text{Al}(p, 3pn)^{24}\text{Na}$ reported in [72] was modified to account for this effect.

Separate corrections were applied to the activity measured by copper foils, to correct for additional contributions to the activation by secondary hadrons, affecting the productions of ^{24}Na in copper. These corrections are based on work done at Fermilab, described in [78], where they related the apparent cross-sections for the $^{63,65}\text{Cu}(p, x)^{24}\text{Na}$ reaction to the mass thickness (t) and found that the value for the cross-section(σ) changed according to Eq. (4.7). Where the mass thickness is in units of mgcm^{-2} .

$$\sigma = \sigma_0[1 + (7.3 \pm 1.5) \times 10^{-5}t]. \quad (4.7)$$

All cross-sections in Table 4.3, for ^{24}Na in copper, were measured at 400 GeV. The background contribution for ^{24}Na measured copper, although taken into account in the measurements done at Fermilab, was not mentioned in the CERN measurement. A correction for this background was therefore applied to the cross-section value for ^{24}Na in copper, measured at CERN.

4.3.1.2.2 Error calculations

Errors accounted for by the RP team include statistical errors on the measured activity and systematic uncertainties related to the gamma ray intensity. Systematic uncertainties due to the to the sample geometry were not included, as the beam was close enough to a point source, that these were estimated to be relatively small. The values and associated errors (quoted to 1σ) can be found in Appendix A.

Errors for the half-life and cross-section values are shown in Tables 4.2 and 4.3 respectively. The errors on the material properties of the foil can be found in Appendix A. The errors on the irradiation time and the wait time were assumed to be negligible in comparison with other errors.

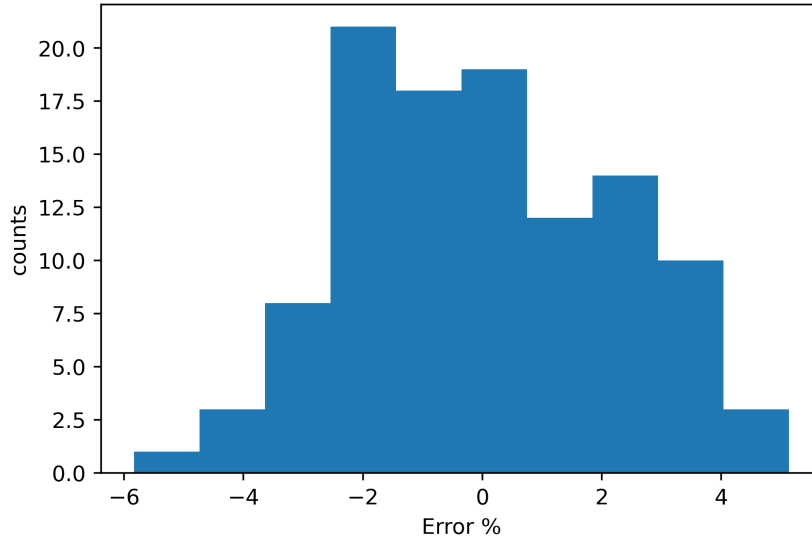


Figure 4.9: Variation from the mean for BSI ADC counts

Most errors were propagated by adding the fractional errors according to Eq. (4.8).

$$\Delta value = value \sqrt{\sum_i \left(\frac{\Delta v_i}{v_i}\right)^2} \quad (4.8)$$

The error on the proton flux ϕ' , determined using Eq. (4.1), was calculated according to Eq. (4.9)

$$\Delta\phi' = \phi' \sqrt{\left(\frac{\Delta c}{c}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta N_x}{N_x}\right)^2 + \left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left[(t_w - \frac{t_i e^{-\lambda t_i}}{1 - e^{-\lambda t_i}})\Delta\lambda\right]^2} \quad (4.9)$$

Where c is the correction factor applied to the measured activation as described in Section 4.3.1.2.1 and all other terms were previously defined.

In order to determine the statistical uncertainty on the measurement of the BSI values the percentage difference from the mean value measured was calculated for all BSI values collected during the measurement. This plot can be seen in Fig. 4.9. From Fig. 4.9 the error on the intensity measured for one spill was estimated to be approximately 2%. Because multiple measurements of the spill intensity were taken and then added together to give the total ADC counts, the error on the ADC counts was calculated using the standard error on the mean, calculated according to Eq. (4.10).

$$\Delta value = \frac{\sigma_{std}(value)}{\sqrt{N}} \quad (4.10)$$

Where σ_{std} is the standard deviation and N is the number of samples. The result was an error of 0.002%,

which was considered to be negligible when compared to other sources of error and therefore was not included in the final error calculations.

4.3.1.3 Results

Fig. 4.10 shows the calibration factor, normalised to the old calibration factor for the first and second TBIU calibrations, performed on target T10. The larger errorbars on some of the measurements are due to the low statistics measured for certain isotopes, which is related to how quickly the isotopes decay. The value for the calibration factor for T10 was calculated via a weighted mean and found to be $99 \pm 2\%$.

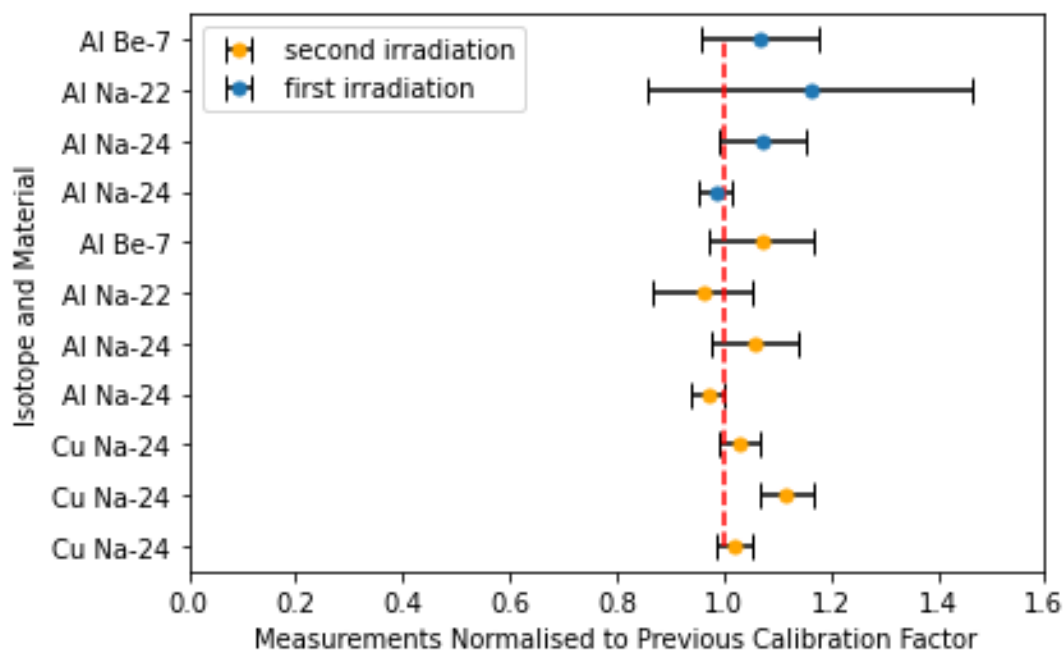


Figure 4.10: Calibration factor obtained during first and second measurements

The results for this calibration are in excellent agreement with the calibration factor determined in 1996. This is a surprising result, showing excellent stability for this particular device, however this does not apply to all devices.

4.3.2 Measurements at Targets T2, T4 and T6

Following on from the promising calibration results obtained in T10, a wider measurement campaign was proposed, extending the calibration measurements to targets T2, T4 and T6 (please refer to Fig. 2.8 for the calibration location). The Setup for these measurements is described in Section 4.3.2.1, the method to determine the calibration factor for each of the BSIs at the target stations is the same as described in Section 4.3.1.2 and the results obtained are shown in Section 4.3.2.2.

4.3.2.1 Setup

The foil configuration used was similar to that of the setup for measurement 2: 3 Aluminium + 3 copper foils, but new foil holders were created, especially optimised for placement in the new target locations. One additional GAFChromic film was used at the beginning of the stack, to monitor the beam alignment and size during the measurement. The new holders can be seen in Fig. 4.11.

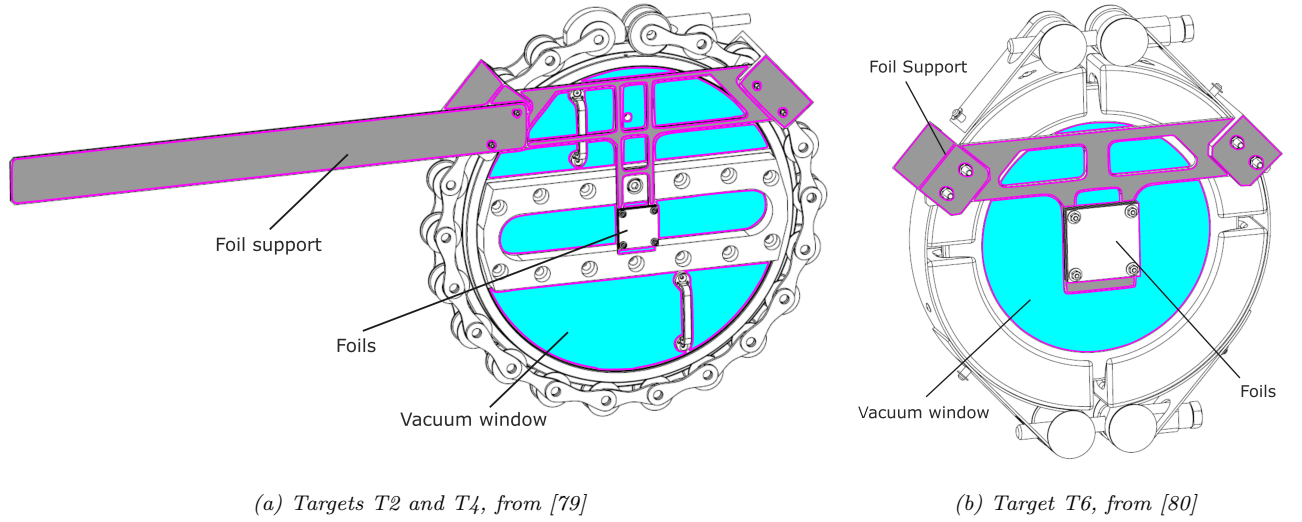


Figure 4.11: Experimental setup for third set of measurement

A total of 3 separate foil stacks were positioned at 3 different target locations: T2, T4 and T6 on the 14th of April 2023. The targets were removed and the foils were irradiated for approximately 25 minutes (corresponding to 229 shots). Fig. 4.12 shows the intensity measured by the BSIs at targets T2, T4 and T6 during the third calibration measurement, as well as the BCT in the SPS. The intensity during this measurement did not remain stable throughout the measurement. The beam was lost at a certain point, but only spills in which there was beam were used in the final calculation. Figs. 4.13 to 4.15 show the average of 209 spills, measured over the course of the calibration by the BSIs at targets T2, T4 and T6. The blue line represents the average TBIU BSI signal and the orange line the average TBID BSI signal, both as a function of time in the spill. The shaded area around the lines represents the standard deviation across all spills measured for that point in time.

With the exception of a couple of kinks at the beginning of the spill, it remains fairly square and constant throughout the activation measurement for all targets. A larger variation in signal intensity is observed across the measured spills towards the end of the spill. We can see that the intensity is slightly different at each target, with the T4 target measuring the lowest signal value and T6 the highest. The most consistent values for signals measured by TBIU/TBID are for target T4 with the other targets showing a larger separation between these measured signals.

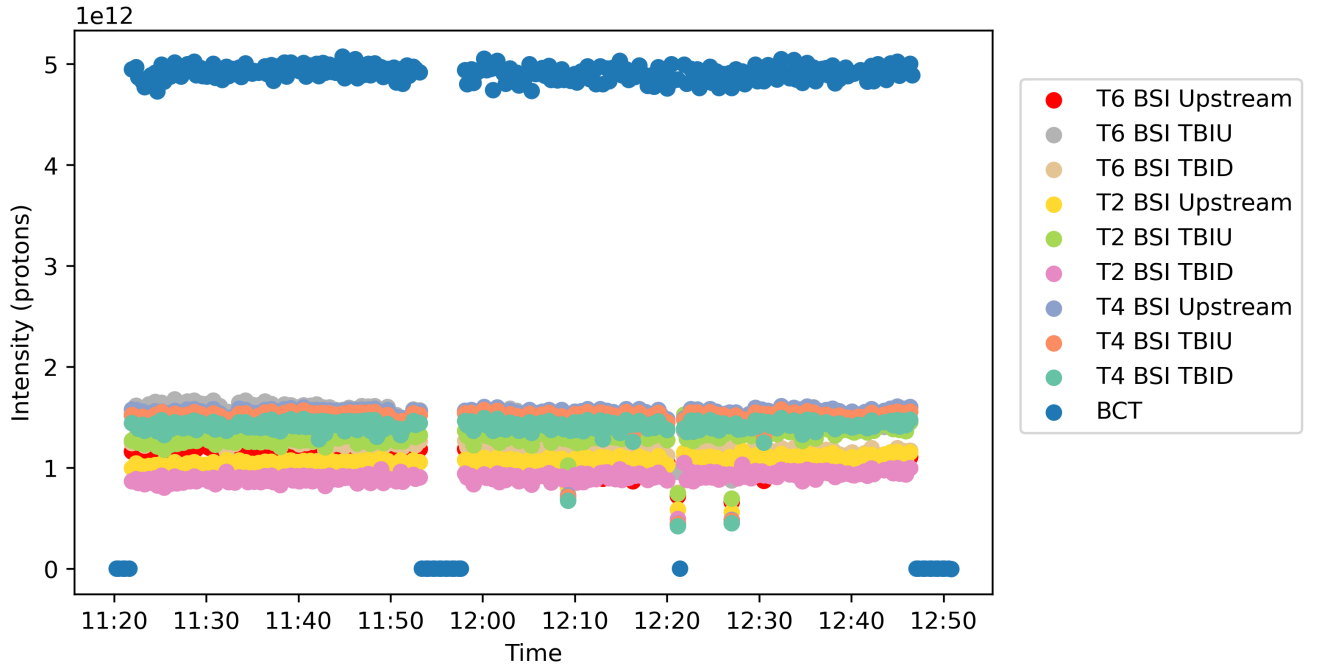


Figure 4.12: Intensity integrated per spill, measured by BSI monitors near targets T2, T4 and T6 and BCT in SPS, during third calibration measurement

The foils were then left to cool for 5 days. Gamma spectrometry measurements were then carried out by the CERN RP team, as done in previous measurements. These measurements can be found in Table A.3 in Appendix A. Due to the large number of foils being measured simultaneously, the spectrometry measurements obtained had lower statistics compared to previous measurements, resulting in larger error bars. Please refer to section 4.3.2.2 for more details on the results and analysis of this calibration measurement.

4.3.2.2 Results

For the third set of measurements, performed at targets T2, T4 and T6 simultaneously, three different sets of calibration factors were calculated. One set for the BSIs located upstream of each of the targets, one for the target TBIUs and one for the target TBIDs.

Fig. 4.16 shows the calibration factor, normalised to the old calibration factor for the third measurement, performed at the BSIs upstream of targets T2, T4 and T6. The values for the calibration factor measured for each target, as a percentage of the existing calibration factor are shown in Table 4.4. Compared to the measurements done in T10, here we see a worse agreement between the measured and previous calibration value. Furthermore the agreement changes depending on the target location, with target T2 being the closest to the previous calibration value.

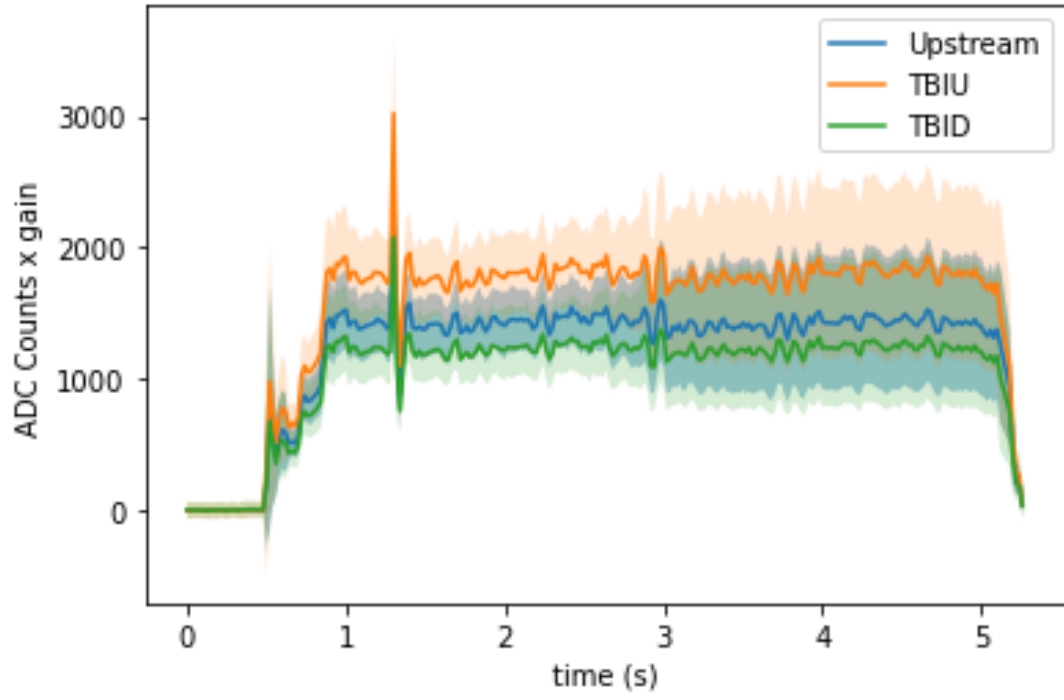


Figure 4.13: Average of 209 Spills for BSIs at Target T2, during the calibration measurement

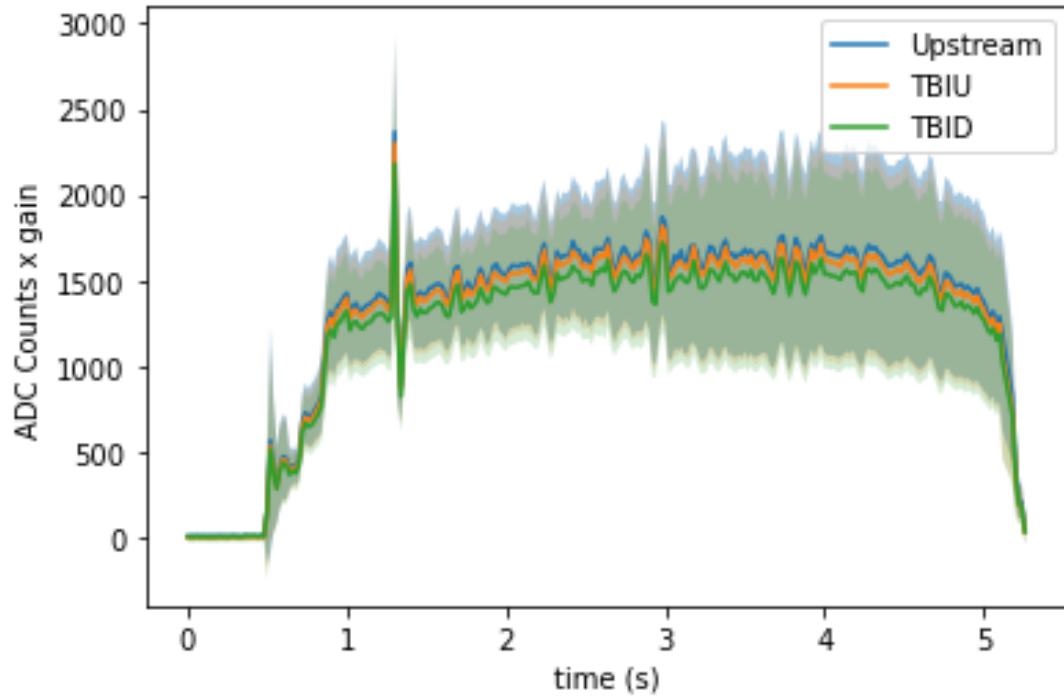


Figure 4.14: Average of 209 Spills for BSIs at Target T4, during the calibration measurement

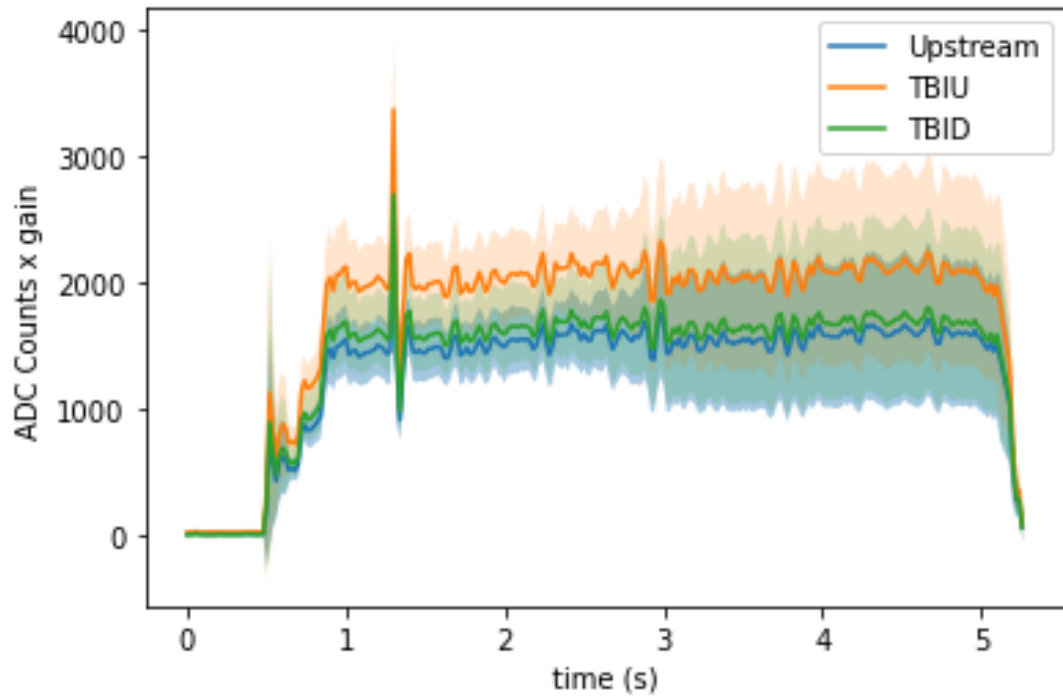


Figure 4.15: Average of 209 Spills for BSIs at Target T6, during the calibration measurement

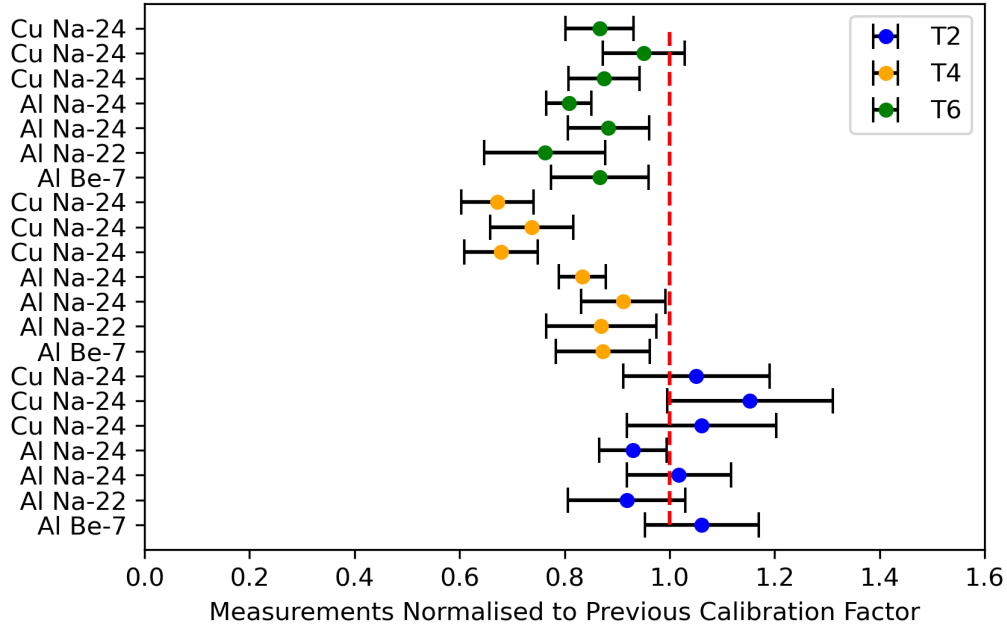


Figure 4.16: Calibration factor for upstream BSIs at targets T2, T4 and T6

Fig. 4.17 shows the calibration factor, normalised to the old calibration factor for the third measurement, performed at the TBIU BSIs at targets T2, T4 and T6. The values for the calibration factor

measured for each target, as a percentage of the existing calibration factor are shown in Table 4.4. This set of measurements also shows a worse agreement between the measured and previous calibration value, when compared to the measurements done in the T10 line. What is interesting is that in this set of measurements, it is the BSI at T4 that measures the closest value to the original calibration factor.

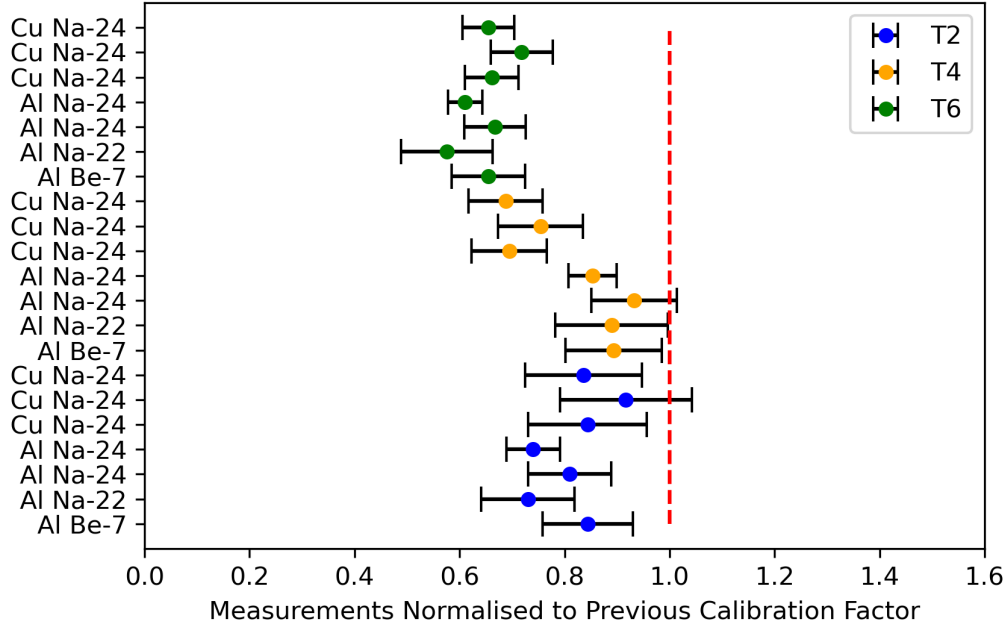


Figure 4.17: Calibration factor for TBIU BSIs at targets T2, T4 and T6

Fig. 4.18 shows the calibration factor, normalised to the old calibration factor for the third measurement, performed at the TBID BSIs at targets T2, T4 and T6. The values for the calibration factor measured for each target, as a percentage of the existing calibration factor are shown in Table 4.4. Here again we see T4 as the closest value to the original calibration factor. The measured value for T4 remains similar across Upstream, TBIU and TBID BSIs, but it is interesting to see that the variation in measured calibration factor across T2 and T6 BSIs varies massively between BSIs located at the same target station.

It is unclear why the results for the third measurement showed such discrepancies from the original calibration, when the previous measurements at T10 showed such good agreement, but there were some key differences regarding the measurements. The first two measurements were performed at the T10 target, which has only a TBIU and no TBID. During this measurement the beam was not split between different targets, the full beam being sent towards T10. During the third measurement the beam was split between targets T2, T4 and T6, all of which have a TBID in addition to the TBIU. During this measurement the targets were removed. The measurement took longer, because less intensity was avail-

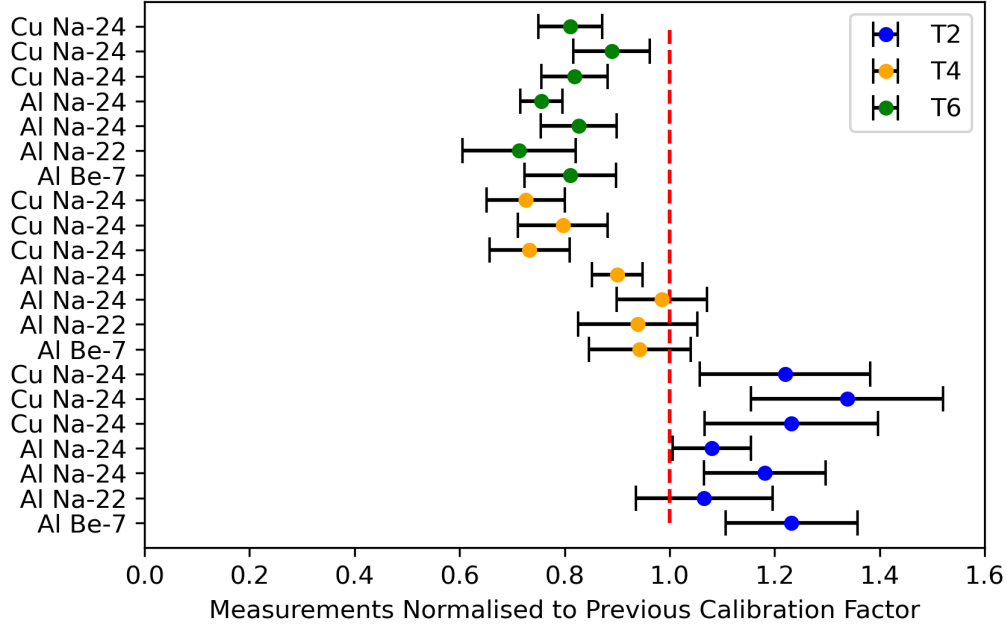


Figure 4.18: Calibration factor for TBID BSIs at targets T2, T4 and T6

	T2		T4		T6	
	value(%)	error(%)	value(%)	error(%)	value(%)	error(%)
Upstream	104	3	80	4	86	2
TBIU	83	2	82	4	65	2
TBID	120	4	87	4	80	2

Table 4.4: Results for BSI Calibration at targets T2, T4 and T6

able per target. There was also an increased wait time between the end of the irradiation and collection of the foils for measurement, which increased the uncertainty on the measurements, but the scale of the discrepancy cannot be explained by this uncertainty alone.

Perhaps the most important factor here could be the splitting of the beam after the targets. A series of magnets can be used to alter the angle of the primary beam and create several secondary beams from the same target. More details on this can be found in [81, 82]. This process is generally referred to as "wobbling". Some of the "wobbling" magnets are actually located before the targets and affect the incidence of the beam on the BSI devices [83]. The target boxes are designed to move to compensate for the "wobbling", but even with this movement the beam still varies its position of incidence on the BSI foil. Because the SEY is a surface phenomenon, as the beam hits a different part of the foil, it could be experiencing a different SEY at each point it hits.

To investigate the relationship between beam position on the BSI and its effects on the measured signal a test was run on the 12th of November 2021, in the T10 beamline. Here the beam was displaced across the surface of BSI.045914 and the signal for the BSI was measured, alongside the signal for upstream device BSI.045769. The downstream signal, after the target, was measured by the XION device, which measures the current of ions downstream from the target. Fig. 4.19 shows the results of this test.

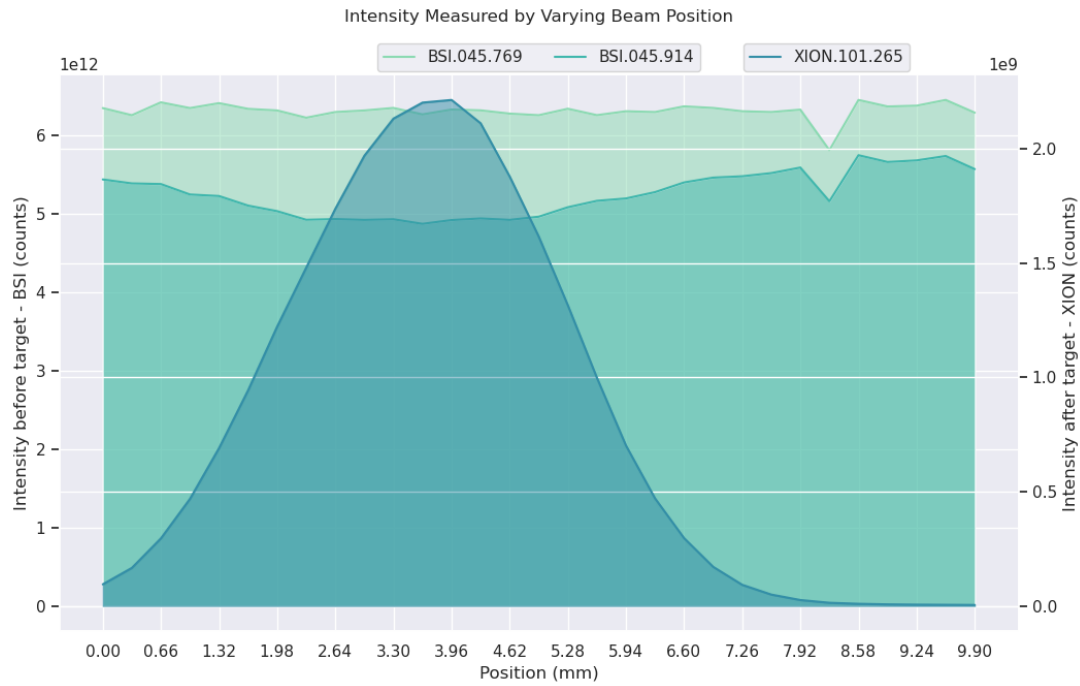


Figure 4.19: Intensity measured during beam displacement test

It is clear from this image that there is a dip in the signal for BSI.045914, that coincides with the centre of the intensity peak measured by the XION device. The same dip is not seen by BSI.045769, upstream, where the beam has been incident at a fixed location. This plot shows the correlation between the beam position and signal intensity, with the localised dip possibly representing a sign of localised damage on the surface of the SEM monitor, which has led to a change in the SEY at that location. Once the beam moves away from that location the signal in the BSI starts to increase.

This plot illustrates the sensitivity of the BSI to position of the beam on the surface of the foil. When a calibration is performed, this is valid for a particular foil positioned at a certain location in relation to the beam. If we move the position of the beam or change the foil this could easily affect the calibration. Furthermore if the beam is regularly being moved and hitting different sections of the BSI foil then the damage to the foil would be varying too. If this were the case it would be extremely difficult to accurately calibrate the BSI devices for when the beam is being used with different "wobbling" settings, as it might

need to be calibrated for different locations at which the beam is incident and this is highly impractical.

It is possible that the changes in the position of the beam due to wobbling could distribute the dose over a larger area of the BSI. Both T2 and T4 have wobbling stations, whereas T6 does not. This could mean that the BSIs around target T6, might concentrate a higher dose in a more localised area, when compared to other targets. Whether the variation in measured calibration factors can be solely attributed to the wobbling remains unclear. Possibly other factors may also be contributing. Not all targets receive exactly the same amount of protons/ions and the relative dose received in a localised spot could lead to changes in the SEY. This could be particularly relevant for TBID foils, as different targets will produce different types of particles, but also the number of particles produced could change quite significantly between targets. Fig. 4.20 shows the cumulative POT measured by the upstream BSIs at each target station, delivered over a number of years. It is interesting to note that T6, which produced

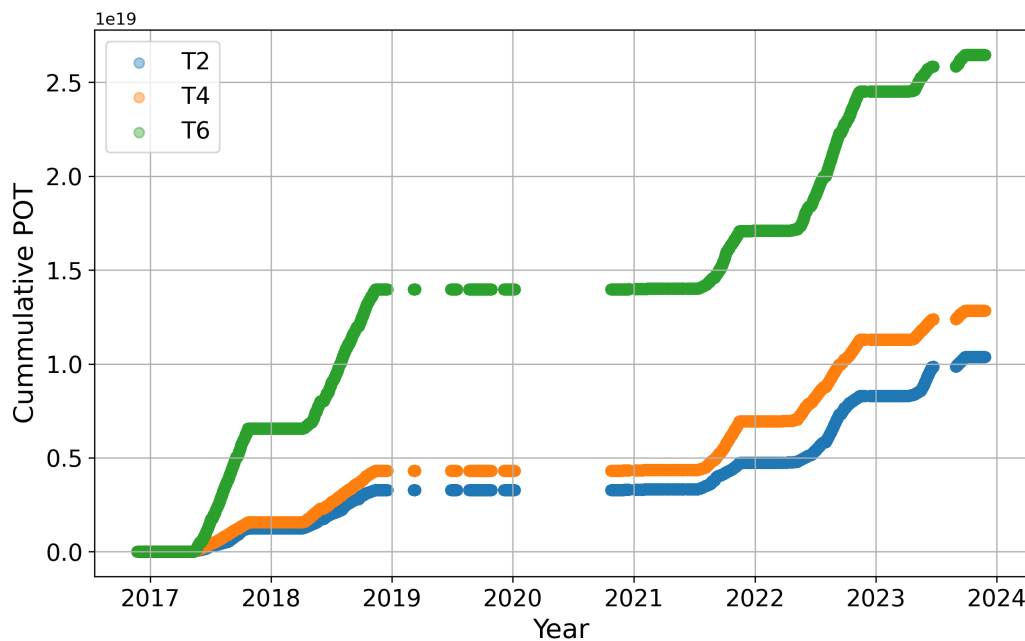


Figure 4.20: history of POT for Upstream BSIs

on average the results least consistent with the original calibration, is also the target receiving the most protons between the years of 2017 and 2024. However it is difficult to isolate the effects of dose from other effects taking place in the same time frame.

These changes in dose received by each foil, coupled with possible changes in vacuum conditions between targets over a long time period, could possibly help explain the variation in measurement that we see in BSIs positioned at the same target.

In order to better understand the individual factors responsible for the results we see, we would need to carry out experiments with foils in controlled environments, isolating each factor, to understand exactly in which way each factor contributes to the ageing process. This kind of experiment would be interesting to do, as a future investigation, but is difficult to carry out in practice, in beamlines with high user demand. Time for beam instrumentation experiments is often limited and many times carried out in parallel with other tests, that make it harder to isolate variables.

4.4 Conclusions and Outlook

One of the key problems identified in Section 1.3 was the uncertainty on the absolute value for POT in the NA fixed target beamlines. The POT value was being measured by BSI instruments that had not been calibrated since the 90s. In this chapter the activation method for absolute calibration of proton intensity measurement was described and the absolute calibration of BSIs at targets T2, T4, T6 and T10 was performed. These are the instruments responsible for measuring the POT in the NA, which affect all of the fixed target experiments in the NA. A new value for the calibration factor for the BSIs at each of these targets was determined.

Two initial measurements were conducted at target T10. These measurements were found to be within a few percent of the old calibration factor, which was remarkable considering the amount of time elapsed since the previous calibration. After the success of these two measurements the calibration campaign was extended to other target stations.

A third measurement was conducted to calibrate targets T2, T4 and T6 simultaneously. However, differently to T10, there were 3 BSIs being calibrated at each of the 3 targets, substantially increasing the number of activation foils to be measured within a short time window, when compared to the previous two measurements. The increase in the number of foils being measured simultaneously, lead to a decrease in time taken per foil measurement, which resulted in lower statistics and consequently higher errors. But also there was a large variation in the calibration factor values measured, compared to the old values at each target station. The largest discrepancy was a 35% difference from the original value, measured in the T6 Target Box Instrumentation Upstream (TBIU). The closest to the original value was found to be the Upstream BSI for target T2, with only a 4% difference. The values across all T4 BSIs were found to be the most consistent with each other.

It was unclear why there was so much variation in the difference between old and newly measured calibration factors at the BSIs at targets T2, T4 and T6. One possible explanation relates to the splitting of the beams after the targets, known as "wobbling". For target T10 there is no "wobbling", but targets T2 and T4 have "wobbling". Despite measures to counteract the motion of the beam due to

”wobbling”, such as moving the target station and instrumentation in sync with the beam position, there is still a small movement in the position of the beam. The changing position of the beam could lead to it hitting areas with different SEY in the foil. If the beam hits an area with localised damage and one without, the SEY could change significantly between measurements. This could also lead to different rates of ageing at different locations in the foil. In addition to this, depending on the movement and size of the beam it could be hitting the bias foil and creating additional signal in the BSI.

Measurements taken by displacing the beam around target T10 show a 10% to 20% difference in the current measured when displacing the beam horizontally and vertically across the surface of the BSI. It is unclear whether this measurement is the result of ageing, or interaction with the bias foils, as the beam is displaced, or even a combination of both.

Other factors affecting the differences in measurement could include the type of particles being produced at each target and the intensity being measured at each BSI. The T6 target has the highest cumulative POT measured since 2017. These points could help explain the differences between the newly measured and the previously measured calibration factors.

Achieving one of the key objectives of this project, the absolute calibration of the BSIs in the NA, has brought to light many questions still to be answered. One of the most challenging aspects of the research conducted in this thesis is the lack of recent calibration data and the difficulty in isolating a combination of effects leading to changes in the measured BSI signal: the increase in signal due to additional secondary particles, the effect of changes in vacuum on the SEY and the effect of the proton beam on the surface of the foils.

It is clear that further research is necessary to fully understand the impact of each of these factors. This research could include: beam displacement measurements, at each one of the target stations, to see the difference in intensity measured, as the beam is displaced across the surface of the foil; comparison measurements of foils with the bias foils completely removed or replaced with foils with no hole; comparison measurements between aged and new foils. This may allow us to gain an insight into how much of the change in the signal is caused by additional signal from secondary particles and how much is due to ageing effects.

Another avenue for investigation could include conducting regular calibrations and noting how quickly the calibration changes over time. Having a record of this could help improve our understanding and help us to correlate changes in the calibration factor with changes in the physics being carried out and beam conditions. Or even investigations of how the proton dose affects the foils. Furthermore when the

foils get replaced with new foils it would be interesting to carry out surface roughness measurements of the old foils and inspect the foils for damage and keep the findings for future reference. As mentioned in the previous chapter, investigations into vacuum contamination of foils would also be of value.

Chapter 5

Optimisation of SEM Grids with Machine Learning

This chapter covers the the work done optimising the SEM grids with Machine Learning. Section 5.1 will give a brief introduction to Machine Learning techniques and discuss how these are being applied in the field of accelerator physics. Section 5.2 will detail machine learning used for image processing, focusing on the autoencoder model and its applications. Section 5.3 will cover the issues with the SEM grids and how the autoencoder model was used to optimise it.

5.1 Machine Learning and Accelerators

Machine learning (ML) refers to a type of algorithm that is not expressly programmed, but instead uses data to extract information, learning patterns and adjusting itself in the process. There are many machine learning methods, which can be split into a number of different categories. Two of the most common categories are: supervised and unsupervised learning.

Supervised machine learning requires labelled data. The algorithm goes through a process of “training” where it reads in labelled data and learns patterns, making a series of self adjustments in order to reproduce the target labels better. This training can then be tested on new data to see if the patterns that the model has learnt perform well when applied to new data.

Unsupervised learning is performed when the data is unlabelled. Here features in the data can be used to identify underlying patterns. This type of learning can be used for clustering and dimensionality reduction.

The beginning of the field of machine learning is generally associated with the creation of the per-

ceptron machine by Frank Rosenblatt in 1958 [84] and definition of the term “machine learning” by Arthur Samuel in 1959 [85]. In the early years some important advances in this field were made but at this time the computing resources needed to effectively run the algorithms, rendered them time consuming and impractical [86–89].

The first uses of machine learning in accelerators were in the late 1980s and early 1990s. Although some applications proved to be experimentally successful, these were ultimately not used for everyday accelerator operations at the time due to limitations in hardware, software and data collection capabilities [90].

The beginning of the 21st century brought with it key technological advances, such as Big Data, a reduction of the cost of parallel computing and memory and the use of Graphical Processing Units (GPUs) for machine learning purposes, which resulted in a surge in popularity and rapid growth of Machine Learning and its application to a vast number of fields [86].

In the field of accelerator physics, traditional methods that have worked well for linear corrections and optimisation problems with a limited number of optimisation parameters, have shown limitations when dealing with more complex problems [91]. Accelerator designs have grown in cost and complexity, with many applications requiring solutions involving either a very large number of parameters to be optimised, or non-linear behaviour. Solving these problems with traditional methods has become impractical.

Given recent technological advances that have enabled successful application of machine learning in other areas (including better availability of data), these techniques are being re-introduced to the field of accelerators for a number of different applications, where the complexity of the problems means that allowing the computer to learn the rules from the data is more efficient than explicit programming. They have been applied to problems such as: optimisation and prediction, for example in the optimisation of undulator tapering at LCLS [92]; anomaly detection, used to detect quenches in superconducting magnets at the LHC [93]; correction of lattice imperfections, such as the orbit correction strategy used at DELTA [94]; automation of operation, like the detection of spikes for collimator alignment in the LHC [95].

The collimator alignment in the LHC builds a strong case for the application of ML in accelerator operation. Until recently this system was semi-automated. An algorithm would move the collimator jaws towards the beam, stopping at a threshold value. The operators would then analyse the beam loss monitor signals and classify the collimator’s alignment, based on the shapes of the spikes in the data. With a total of 98 collimators protecting the LHC (which require alignment at least once a year) manually distinguishing between alignment and non-alignment spikes was a very time consuming task. Having

achieved a precision of over 95% with the trained models, the fully automated system was successfully deployed in the LHC where it has operated since 2018, greatly improving control efficiency.

Projects such as this one showcase the potential for machine learning methods to improve the control and operation of accelerators, reducing the time needed for repetitive processes such as collimator alignment.

5.2 Autoencoders and Image Processing

Machine learning is a vast and fast advancing field of research, with new models constantly being developed to target specific types of data and use cases. As the work being conducted as part of this thesis was linked to profile images of the beam, a model was chosen that was commonly used for processing image data. In this case a type of neural network called an autoencoder was used. This section will give a brief explanation of what a neural network is (Section 5.2.3), introduce the concept of an autocencoder (Section 5.2.3.1), before touching on a few relevant autoencoder models that were used as reference in this work.

5.2.1 Digital Image Representation

The information contained in an image can be described in terms of the spatial distribution of intensity within the image. This intensity information for a 2-D image can be digitally represented as pixels arranged in a matrix containing M rows and N columns (as shown in Fig. 5.1) , each pixel containing intensity information for a rectangular region of the image. For 3-D images an additional dimension is added to the matrix representation and the smallest volume element is known as a voxel [96].

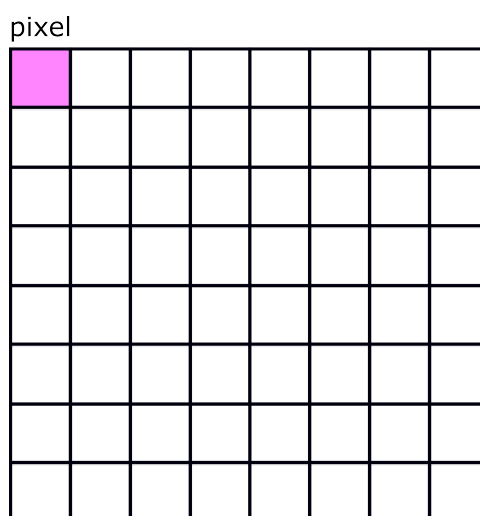


Figure 5.1: Digital representation of a 2-D image. Squares represent pixels in an $M \times N$ matrix

Information in digital format is quantised. Each pixel/voxel contains discrete information for the intensity at that point. The intensity values usually have a numeric representation for the greyscale that varies between 0 and 255. The higher the number of pixels the higher the resolution of the image and the less it is possible to distinguish individual pixels/voxels.

5.2.2 Common Image Filtering Techniques

Digital image representations, may contain defects, that have become a part of the image at some point in the acquisition or processing of the image. Many techniques have been developed in for getting rid of unwanted noise and enhancing image quality. These techniques often rely on a filter, which transforms the image. Various types of filters exist that tackle specific types of noise.

Some common filters that do not include machine learning will be briefly discussed in this section, including the mean, median, low-pass, Gaussian and bilateral filters. For more in depth information about this topic please refer to [97–99]. Fig. 5.2 contains examples of these filters applied to an image to demonstrate the effects of each filter. None of these filters is perfect, some of the filters are good at removing the background noise, such as Figs. 5.2d and 5.2f, but the signal is also a bit blurred and some of the information is lost, others such as Figs. 5.2b and 5.2e blur both the signal and the background, but don't effectively remove the noise and Fig. 5.2c even creates artifacts in the image. Each filter and effects will be described separately below.

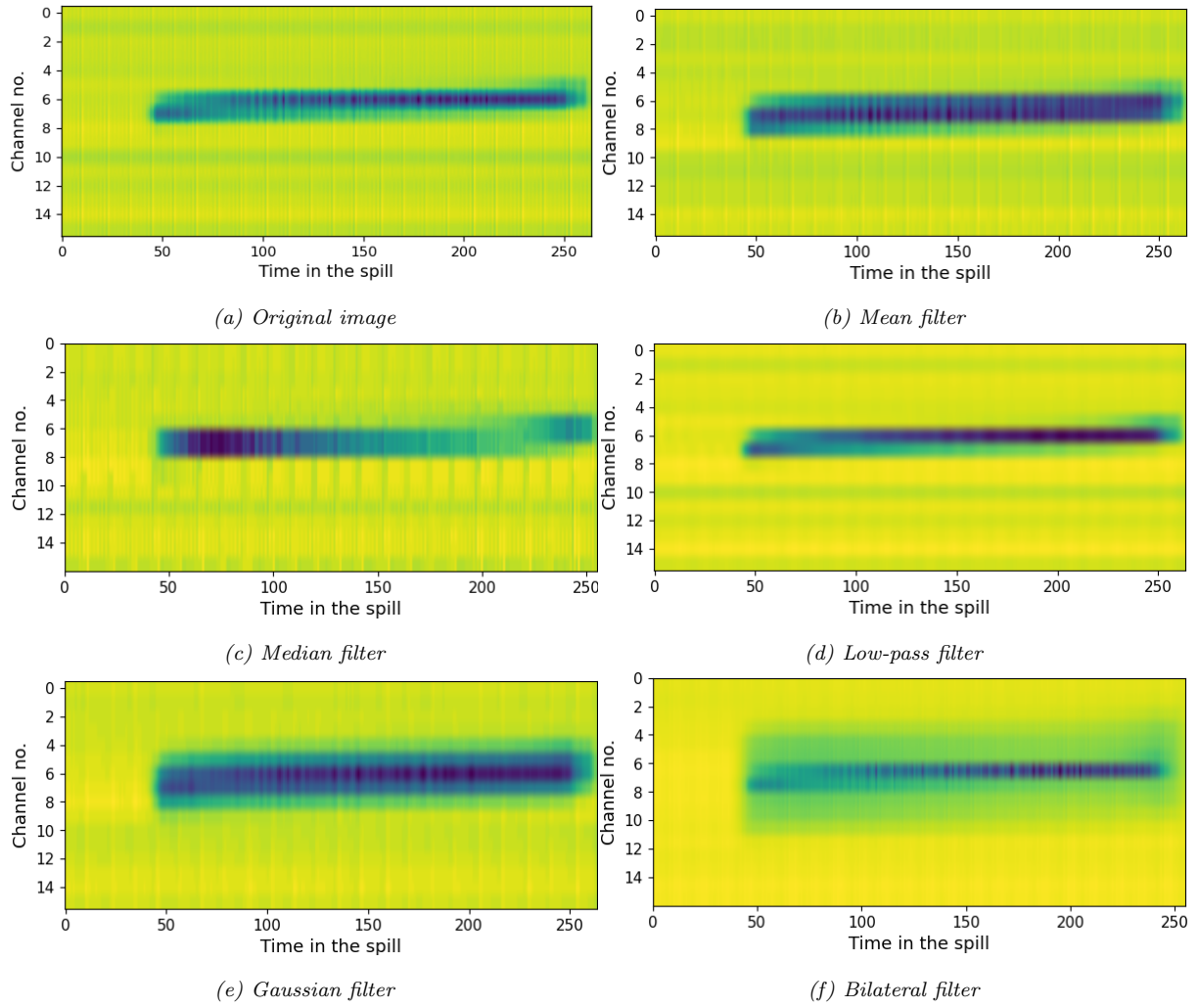


Figure 5.2: Comparison of different filters applied to original image

5.2.2.1 Mean Filter

The mean filter is a type of linear spatial filter that replaces a pixel with the mean of its neighbouring pixels, according to Eq. (5.1) [97]. Here N is the number of pixels that make up the Neighbourhood W .

$$I_{avg}(m, n) = \frac{1}{N} \sum_{(i,j) \in W} I(m+i, n+j) \quad (5.1)$$

It is usually employed to reduce uniform Gaussian noise and as a result has a tendency to create a more blurry image. An example of this filter can be seen in Fig. 5.2b. Here we can see that the features are a little bit blurred, the edge sharpness having decreased a little, when compared to the original image in Fig. 5.2a

5.2.2.2 Median Filter

The median filter is a non-linear filter which replaces each pixel with the value at the centre of the array W of neighbouring pixels, according to Eq. (5.2) [97]. If the array is odd the central value is chosen. If

the array is even, an average of the two central values is returned.

$$I_{med}(m, n) = median\{I(m + i, n + j), \quad (i, j) \in W\} \quad (5.2)$$

This type of filter performs well on binary noise but is not the best choice for Gaussian noise [99]. If the number of noise pixels is equal to or above half the pixels in the neighbourhood the performance of this model is negatively impacted.

5.2.2.3 Low-pass Filter

This frequency domain filter, relies on the transformation of the spatial information into the frequency domain, via a Fourier Transform. A discrete Fourier transform is given by Eq. (5.3) [100].

$$f(\omega) = \frac{1}{N} \sum_{t=0}^{N-1} F(x) \exp\left(\frac{2i\pi\omega x}{N}\right), \quad \omega = 0, 1, \dots, N-1 \quad (5.3)$$

Here ω is the spatial frequency sampled at regular discrete intervals, x is the spatial coordinate, also sampled at regular discrete intervals and N is the number of samples. Once converted into the frequency domain, a threshold is applied that filters out all frequencies above it. After the filter is applied a reverse Fourier Transform, given by Eq. (5.4) [100], can be used to retrieve the result in the spatial domain.

$$F(x) = \frac{1}{N} \sum_{\omega=0}^{N-1} f(\omega) \exp\left(\frac{2i\pi\omega x}{N}\right), \quad x = 0, 1, \dots, N-1 \quad (5.4)$$

The result is an image with the high frequency spatial components filtered out, as can be seen in Fig. 5.2d. The effect is a blurring of the signal and the background.

5.2.2.4 Gaussian Filter

This type of filter is a weighted mean of the intensity, given by Eq. (5.5) [98], with the weight at a point q being determined by the spatial distance from the central point p , via a Gaussian kernel $G_\sigma(x)$ given by Eq. (5.6).

$$I_{Gaus} = \sum_{q \in S} G_\sigma(\|p - q\|) I_q \quad (5.5)$$

Here S represents all pixels in the spatial domain of the image, $\|p - q\|$ is the Euclidean distance and I_q is the intensity at point q .

$$G_\sigma(x) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right) \quad (5.6)$$

Here σ represents the neighbourhood size. An example of this filter being applied can be seen in Fig. 5.2e. The effect of this type of filter is to blur the image that it's applied to. It's best for removing Gaussian noise, but comes at the cost of losing edge definition.

5.2.2.5 Bilateral Filter

This filter combines the benefits of Gaussian smoothing, with improved edge definition. This is achieved by combining the Gaussian filter(Eq. (5.5)), which acts in the spatial domain, with a range component, which compares the intensity between pixels, resulting in Eq. (5.7) [98].

$$I_{Bilateral} = \frac{1}{W_p} \sum_{q \in S} G_{\sigma_s}(\|p - q\|) G_{\sigma_r}(|I_p - I_q|) I_q \quad (5.7)$$

Here G_{σ_s} represents the Gaussian weighting in the spatial domain and G_{σ_r} represents the Gaussian weighting in the range domain, I_q is the intensity at point q , I_p is the intensity at point p , and W_p is a normalisation factor given by Eq. (5.8)

$$W_p = \sum_{q \in S} G_{\sigma_s}(\|p - q\|) G_{\sigma_r}(|I_p - I_q|). \quad (5.8)$$

An example of the effect of this filter applied to Fig. 5.2a can be seen in Fig. 5.2f. The improvements on edge definition around the centre of the signal and background smoothing can clearly be seen, in comparison with Fig. 5.2e, but the transition between signal and background is blurred over a larger area in Fig. 5.2f.

5.2.3 Neural Networks

A neural network (NN) is a type of machine learning structure devised to mimic the human brain. Fig 5.3 shows a pictorial representation of a NN. The basic building block of a NN is called a node. A node has a certain number of inputs, a bias and an output. Nodes are arranged in layers and connected to other nodes via weights.

The input values fed to the nodes are multiplied by the weights connecting them. All input values, having been multiplied by the weights to the node are added together to give the output. Mathematically this can be written as shown in Eq. (5.9). The output becomes the input to the next layer in the network.

$$f(x) = \sigma(\sum_i W_i * x_i + b) \quad (5.9)$$

During the training phase the model is fed data from which it tries to make predictions. The predictions are then judged using a loss function, which measures how far the predictions are from true value. The type of loss function used varies depending on the specific model. After each iteration the weights of the

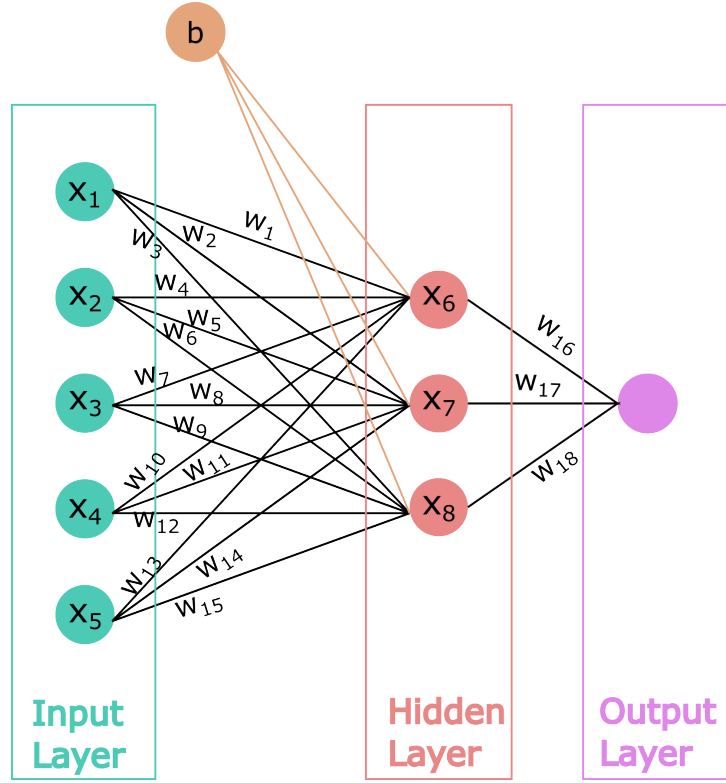


Figure 5.3: Graphical representation of a neural network

neural network are adjusted, based on its previous performance and the learning rate. The learning rate is a hyperparameter which defines how quickly the weights change when they are updated. New data is fed to the model and it will repeat the process, adjusting the weights as it learns new information. This iterative process is repeated until the model reaches the desired performance.

5.2.3.1 Autoencoders

An autoencoder, illustrated in Fig. 5.4 is a type of comprised of two sections, that mirror each other: an encoder that takes an input layer and compresses the information, mapping it to a lower dimension representation and a decoder that takes the compressed information and tries to reconstruct the original input. In its simplest form it is made of 3 fully connected layers: one input layer, one hidden layer - also referred to as latent space - and one output layer [101] .

An activation function can be used in the encoder and decoder in order to introduce non linearity. Some common activation functions include the ReLU and sigmoid functions, but many others also exist, more information on these can be found in [102]. The choice of activation function will vary depending on the type of data, model and application.

A sigmoid function is described by Eq. (5.10), in which x is the input to the activation function. A

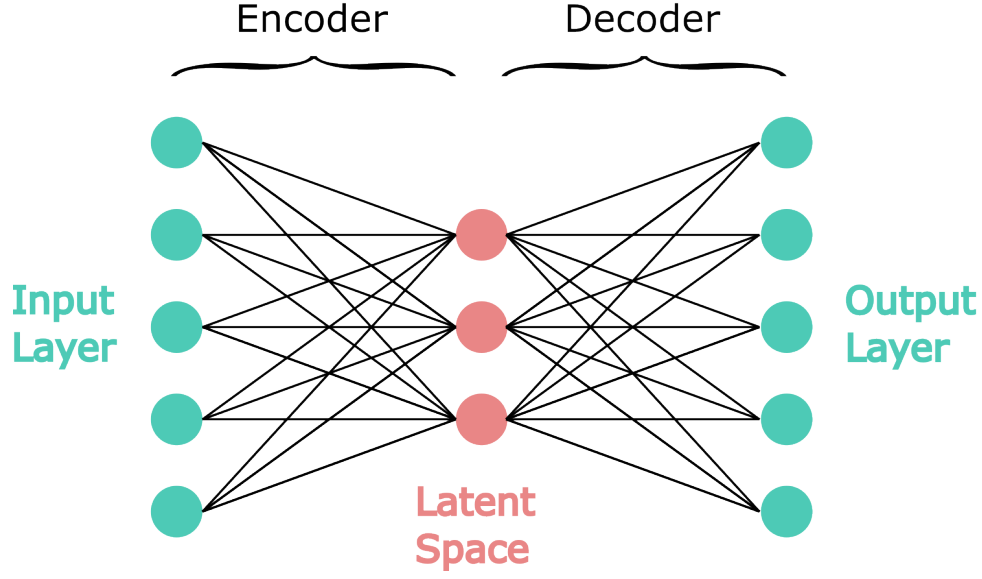
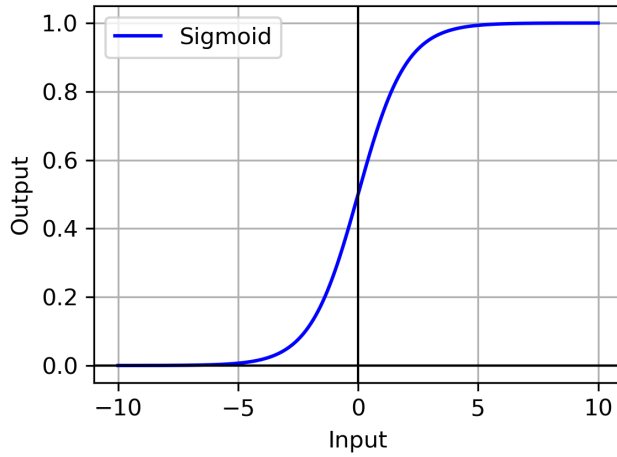


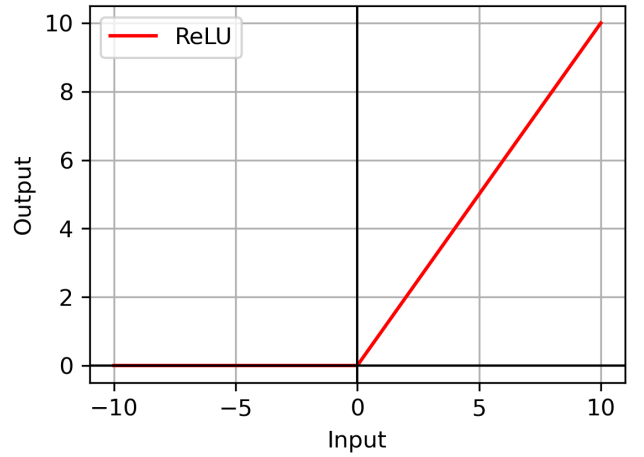
Figure 5.4: Schematic representation of autoencoder

visual representation of this activation function can be seen in Fig. 5.5a. It can be thought of as a rounded step function and produces results that are in the $[0,1]$ interval.

$$f(x) = \frac{1}{1 + e^{-x}} \quad (5.10)$$



(a) Sigmoid



(b) ReLU

Figure 5.5: Examples of activation functions used in autoencoders

The ReLU (Rectified Linear Unit) function, given an input x produces an output described by Eq. (5.11). In practice this means that it will return any positive values unchanged, but return 0 for the negative

values, as can be seen in Fig. 5.5b.

$$f(x) = \frac{x + |x|}{2} \quad (5.11)$$

In addition to this simple autoencoder, a variety of other autoencoder models exist, with varying levels of complexity, depending on the application. A detailed description of all autoencoder models and applications is beyond the scope of this thesis, but further information on this topic can be found in [103, 104]. Further descriptions will focus on types of autoencoder relevant to understanding the research conducted in this thesis.

5.2.3.1.1 Denoising Autoencoders

A denoising autoencoder is an autoencoder which is trained to reconstruct a cleaned image from a noisy image. For this purpose it is given both noisy and cleaned versions of the same image, and as it trains it learns to map patterns in the noisy image and reconstruct the image without the noise. An example of this can be seen in Fig. 5.6.

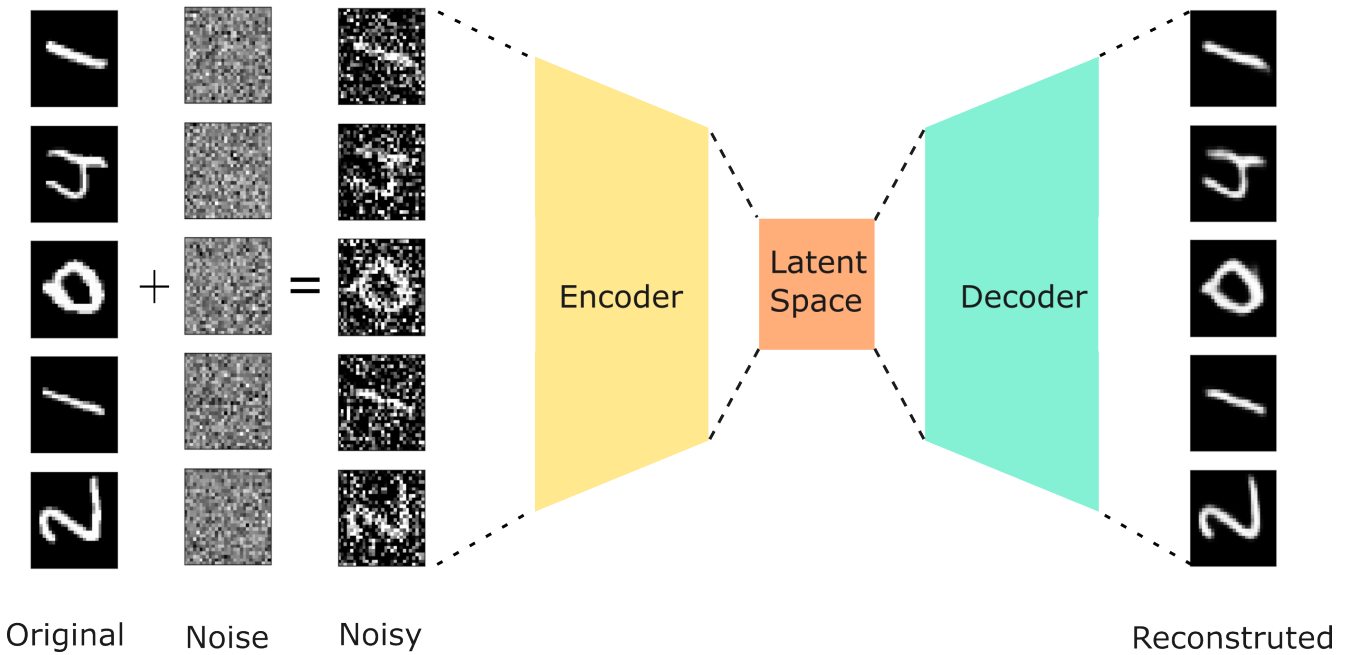


Figure 5.6: Graphic representation of denoising autoencoder, made using mnist dataset

Denoising autoencoders have been proven to work very successfully, however they require training and testing data that have cleaned and noisy examples of the same image. In cases where access to cleaned data is not available this type of model cannot easily be trained. In most cases models are trained using noise that has been artificially added to a clean image. Here it is important for the artificially added noise to be similar to the type of noise we are expecting to remove, otherwise the trained model may not generalise well when used on real data.

5.2.3.1.2 Convolutional Autoencoders

A convolutional autoencoder is a type of autoencoder in which the encoder/decoder parts consist of a convolutional neural network (CNN). This is a type of deep learning network, so called because it uses hidden layers to process information. It uses pooling and convolution layers to map image features to a lower dimensionality.

A convolution layer, illustrated in Fig. 5.7, takes a sample of input elements and performs a convolution operation, as defined in Eq. (5.12), using a kernel, defined by the user. This convolution creates a feature map of the image, allowing for pattern recognition.

$$(f * k)_n = \sum_m f_m k_{(n-m)} \quad (5.12)$$

Here f and k are two matrices being convolved. In this particular case f represents the input data and k is the kernel.

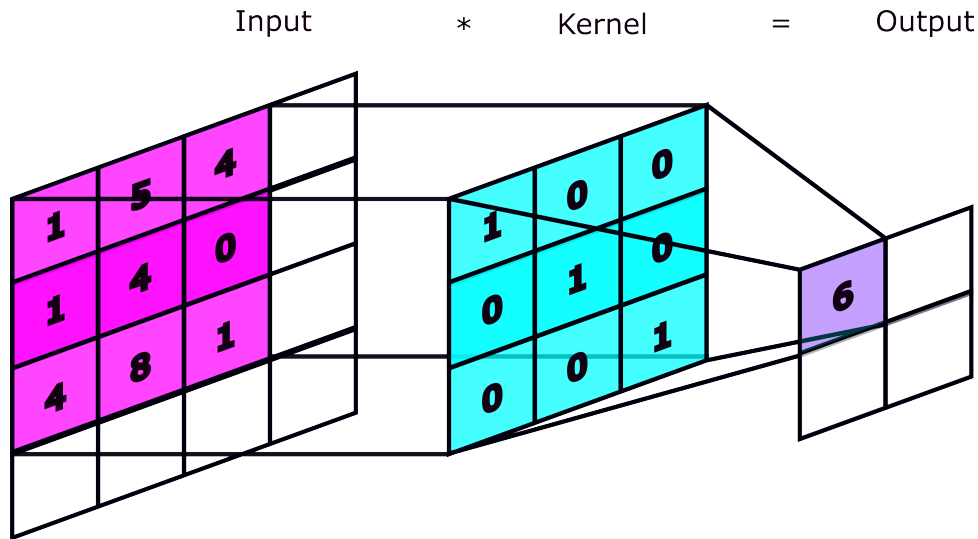


Figure 5.7: Illustration of Convolution layer

A pooling layer (Fig. 5.8), condenses information, by selecting a group of elements from input data, according to the shape of the filter specified by the user, and extracting a single value to represent the group, taking for example the average or the maximum value of the group. The example in Fig. 5.8 is a max pooling layer, so it will extract the maximum value from a group of elements.

In the example shown in Fig. 5.8 a 2x2 filter was chosen, so the pooling layer will sample the ele-

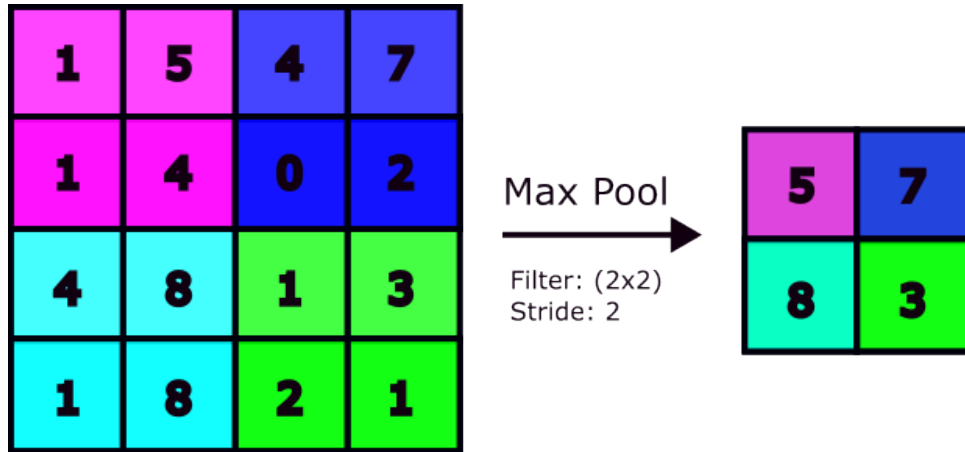


Figure 5.8: Illustration of Max Pooling layer

ments in the data in groups of 2x2. The stride parameter tells the model how many steps to take in relation to its current location to sample the next group of elements. In this example a stride of 2 was chosen.

Layers of pooling and convolution can be used in combination for selecting important features. They allow for the drastic change in the dimensions of the original data, retaining a representation of certain features, which can be used to make predictions. This allows for more efficient pattern matching, due to the reduced dimensionality.

In the decoder part of convolutional autoencoder, the compressed representation is returned to its original dimensions. This is achieved by reversing the pooling and convolution steps. In order to reverse the pooling, we use what is called an upsampling layer. This layer takes each element from the compressed representation and extracts from each element a group of elements with the shape of the filter, by performing an interpolation using a function specified by the user. The simplest option is simply to make all the elements in the output group equal to the element in the input. This option is called "nearest" in the keras library, but other interpolation functions also exist. More information on these options can be found in [105].

The autoencoder will also have convolutional layers in the decoder that will mirror the convolutional layers of the encoder. The mirrored upsampling and convolutional layers will restore the image to its original dimensions.

5.3 Denoising the SEM grids

The NA slow extraction lines use BBSs and BSGs to measure the beam profile and position. These instruments are described in more detail in Section 2.3.1. They are made up of vertically or horizontally oriented metal bands that measure the secondary emission current, produced by the incoming proton beam. Each band has its own dedicated DAQ channel and the data is stored for all channels over the course of one spill. The data for the BSGs is stored for every spill. Each spill consists of a matrix with dimensions 264×16 . Where the first number corresponds to the number of data points per spill (1 point per 20 ms) and the second corresponds to the total number of DAQ channels of the SEM grid.

For this type of device the absolute calibration is not an important factor in the determination of either the position or the profile. Only a fraction of the beam is passing through each band, and it is possible to retrieve profile and position information independently of the calibration factor. However due to the small amount of particles passing through the bands, the signal generated is low. This makes the SEM grids particularly susceptible to sources of electronic noise. Improving the signal to noise ratio is therefore of utmost importance for these devices and consequently for the smooth steering of the beam.

An example of a noisy beam profile image can be seen in Fig. 5.9. The objective of this research was to improve the signal to noise ratio by removing some of the random noise present in the image, thus improving the profile measurements made by the BSGs in the NA slow extraction lines. Since most BSGs in beam, continuously collect data, during operation, the availability of data was vast. Given the random variation in the noise patterns, and the difficulty in explicitly programming a correction for this type of variation, a Machine Learning (ML) solution was explored. The autoencoder model, described in section 5.2, was chosen, due to its versatility in handling image processing.

Originally a denoising autoencoder was considered, but due to difficulties in determining clean im-

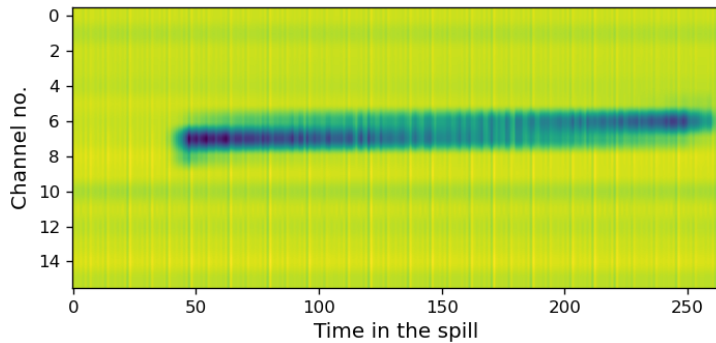


Figure 5.9: Example of noisy beam profile image acquired with BSG

ages and without a clear pattern for the noise, it would have been difficult to select clean images and

artificially replicate noise. Instead, the focus of this research was to attempt to exploit the loss of resolution when compressing the image to the latent space, in order to learn what the general shape of the signal should be, retaining important features, but smoothing out small bits of noise.

A convolutional autoencoder was chosen for this purpose. It was developed using the TensorFlow [106] and Keras [107] libraries. The architecture of the model used in this project is shown in Fig. 5.10, where the yellow represents the dimensions of the output at each step and the blue and green represent different types of layers in the autoencoder. The encoder section was comprised of one 2D convolutional layer, with a ReLU activation function and one 2D max pooling layer and the mirroring decoder, constructed with one 2D upsampling layer, one 2D convolutional layer, with a sigmoid activation function.

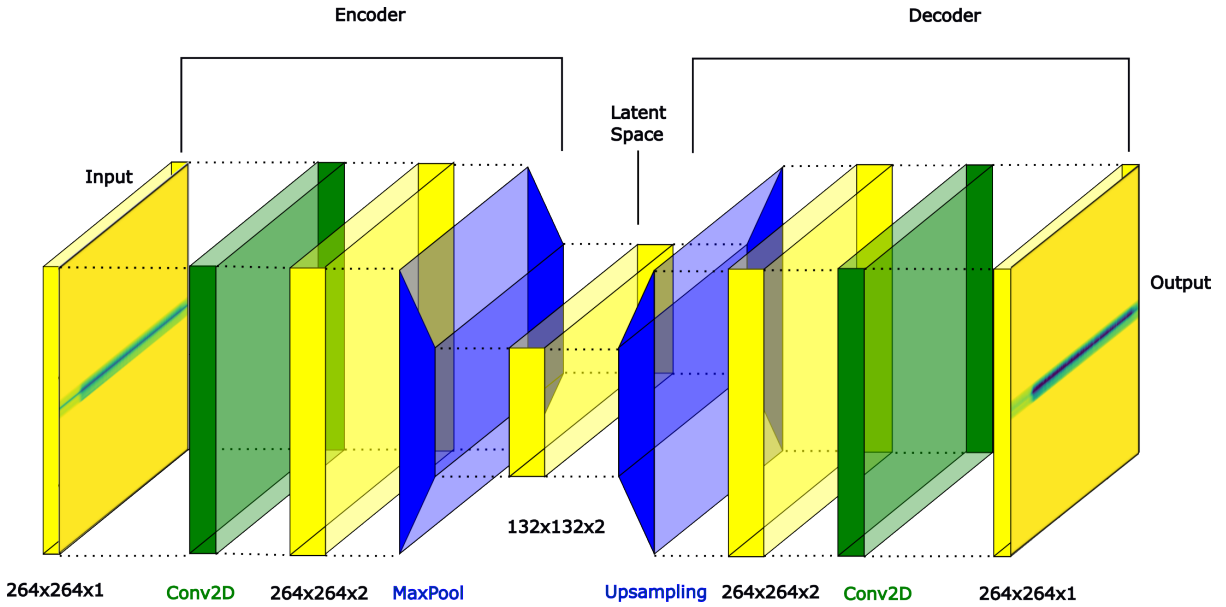


Figure 5.10: Representation of autoencoder model: yellow shows dimensions at different steps within the model, green and blue represent different types of layers in the model

The 2D convolutional layer (represented in green in Fig. 5.10) takes the input matrix of images and performs a convolution operation with the kernel, according to Eq. (5.12), creating a feature map of the input data matrix, as demonstrated in Fig. 5.7, transforming the input dimensions from 256x256x1 to 256x256x2. The convolved distribution is then passed into a MaxPool pooling layer (represented in blue in Fig. 5.10), which selects the maximum value for each group of numbers, using a 2x2 kernel. In the pooling step the dimensions change from 256x256x2 to 128x128x2. These first two layers of the model form part of the encoder, which creates a compressed representation of the input data, also known as latent space.

The compressed representation is passed on to the decoder, responsible for reversing the encoder transformations. The decoder has an upsampling layer (represented in blue in Fig. 5.10) which transforms the matrix dimensions from 128x128x2 to 256x256x2, followed by a convolutional layer (represented in green in Fig. 5.10) which transforms the matrix back to its original dimensions (256x256x1).

Before training the autoencoder model, a few pre-processing steps were required to adjust the data to the correct format required for training. For optimum performance while training, the data should have equal x and y dimensions and be normalised. The x and y dimensions were matched by adding padding, changing the matrix dimensions from 264x16 to 264x264. The normalisation was achieved by subtracting the mean from each of the data points and then dividing each one by the standard deviation. Fig. 5.11 shows the preprocessing steps.

Once pre-processed the data was split between training and testing groups, each containing 3117 and 1040 sample signals respectively. Once split, the training data, consisting of a matrix of 3117 samples of 264x264 beam profile signals, was provided to the autoencoder model to train. The training was carried out using random batches of training data, containing 240 samples each, over 19 epochs. Each sample within a batch, contained multiple numeric values arranged in a matrix. These values were multiplied by the weights connected to them in the model and propagated through each layer according to Eq. (5.9), to compute an output.

At each step in the training, the output was compared to the expected value and the model weights were adjusted accordingly, to minimise the loss function. This was done using the Adaptive Moment Estimation (Adam) optimiser, a stochastic gradient based optimisation algorithm, described in [108], which employs exponential moving averages of the gradient and squared gradient of the loss function in order to efficiently optimise the weights in the neural network. The loss function used by the optimiser was Binary Cross Entropy, given by Eq. (5.13), with a learning rate of 0.6×10^{-3} .

$$Loss = \frac{1}{N} \sum_{i=1}^N (y_i \log \hat{y}_i + (1 - y_i) \log (1 - \hat{y}_i)) \quad (5.13)$$

Where N represents the class number, $y_i \in [0, 1]$ is the target value and $\hat{y}_i \in [0, 1]$ is the predicted value [109].

Once trained, the model was used to reconstruct the test data. The preprocessing steps were then reverted to retrieve the final reconstructed image. The results of this reconstruction are presented and discussed in section 5.4.

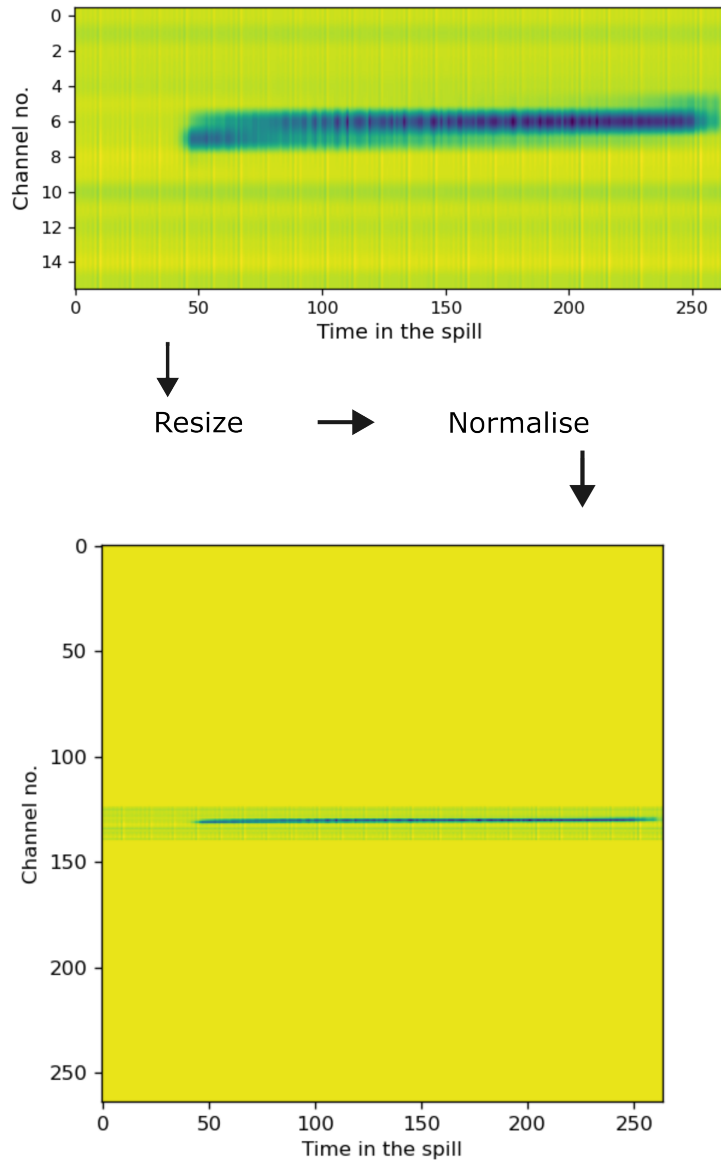


Figure 5.11: Preprocessing steps

5.4 Results and Discussion

Fig. 5.12 shows an example of an autoencoder prediction based on the trained model, where Fig. 5.12a shows the original image and Fig. 5.12b shows the autoencoder reconstruction. Making a qualitative comparison between the original and the reconstructed image it is clear that the reconstructed image is smoother, however the beam profile itself is wider in the reconstructed image. The noise does not appear to be completely removed, instead both horizontal and vertical noise stripes appear broadened and less frequent.

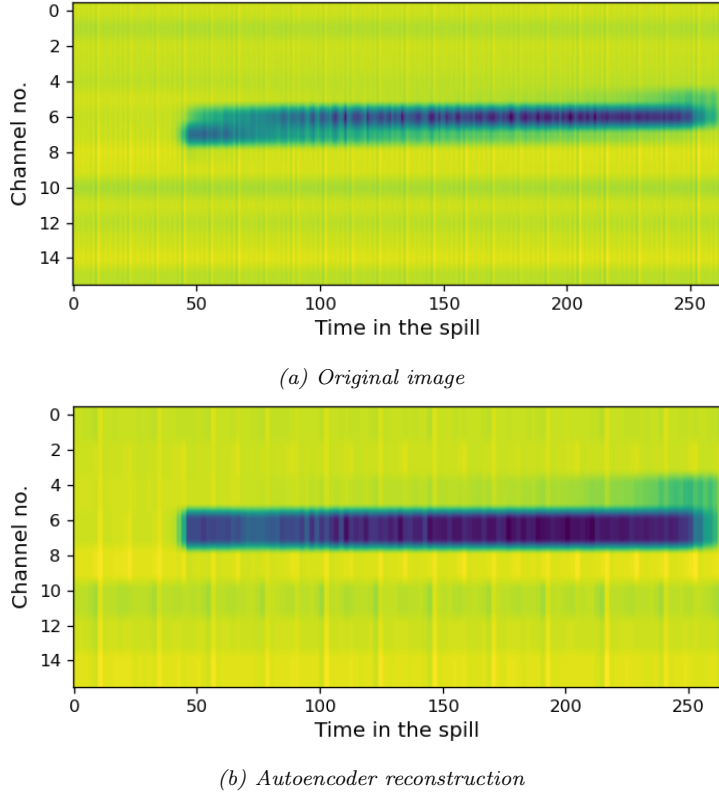


Figure 5.12: Example of autoencoder reconstruction

In order to compare the intensity values between the original and reconstructed image, an integral of the BSG signal was performed. This was accomplished by adding the signal from the different channels, at every point in the spill for both images. The data was grouped together in bins and the error on each bin was determined from the standard deviation of the data points in each bin. The results are shown in Fig. 5.13. It can be seen that the error bars on the original data are larger than those in the reconstructed data. This can be interpreted as a reduction in the noise, since the spread of the data (implied by the error bars) is less in the reconstructed data, when compared to the original data.

A plot of the beam profile is shown in Fig. 5.14. This plot shows the normalised intensity, measured at a single timestamp plotted as a function of channel number. The plot shows overall a smoother profile for the autoencoder reconstructed image, when compared to the original image, especially when comparing the tails of both distributions. However this smoothing effect comes at the cost of the possible artificial widening of the beam profile. It is noticeable from the plot that signal signals close to the top intensity value, are brought closer to that value, achieving a more homogenised profile, but in doing so it is possible that some information might be lost. Even with this drawback, this result could still be helpful in a lot of situations, considering that during operation the beam profile is determined from the distribution mean and standard deviation. This means that reducing the noise at the tails could have a positive overall impact on the beam profile measurement.

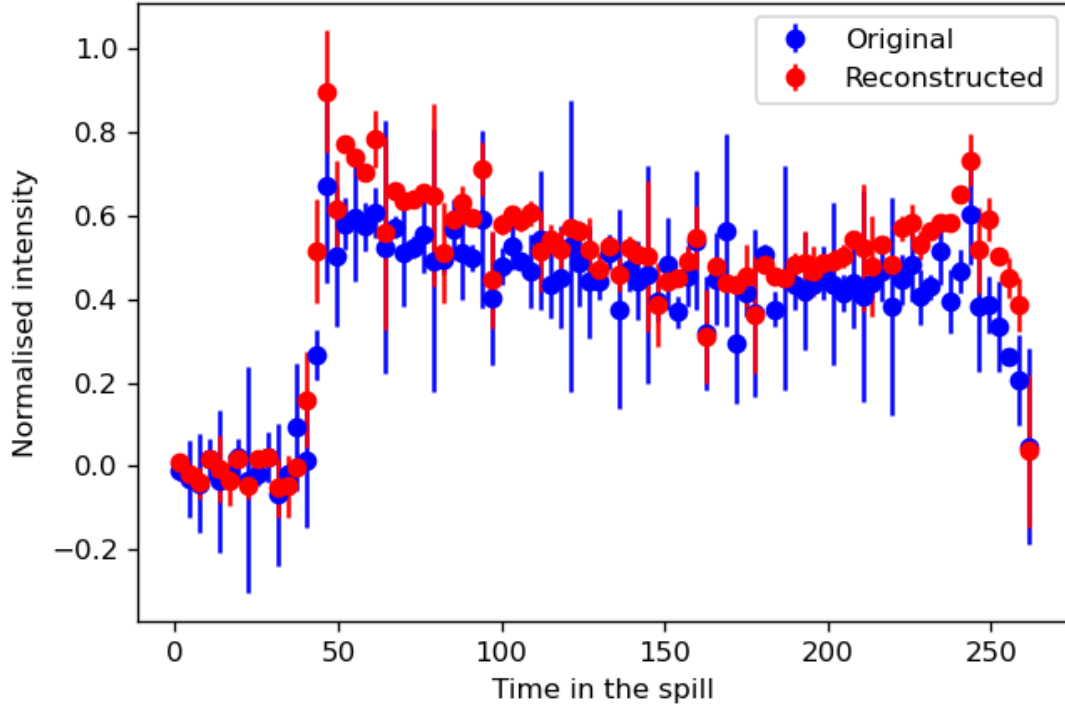


Figure 5.13: Normalised intensity as a function of time in the spill

These are promising initial results, however more work would be required for actual use during beamline operation. Looking closely at the original image we can see that in some areas it is difficult to distinguish the beam from the periodic horizontal background stripes. Since both horizontal and vertical stripes appear in the autoencoder reconstruction, this would be a promising feature to try and remove, that could result in better model performance.

5.5 Conclusions and Outlook

In this chapter work was done to address the problems with signal to noise ratio experienced with Beam Secondary Emission Grid (BSG) monitors in the NA. These devices have rows of thin metallic strips that interact with the primary proton beam, but this leads to a lower current being measured, which is why the signal to noise ratio becomes an issue. For these devices it is the relative, not the absolute calibration, which is of importance, since the profile is measured from the standard deviation of the integrated current in different strips.

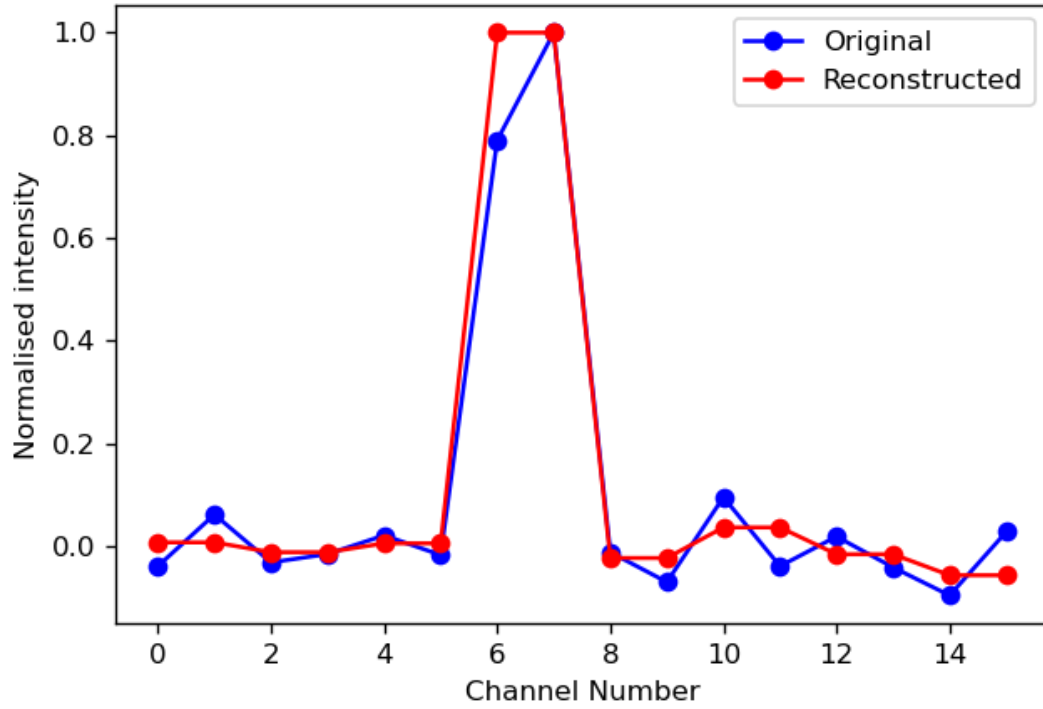


Figure 5.14: Normalised intensity as a function of channel number

With this in mind the data for all BSG channels was combined into a matrix, preprocessed and fed to an autoencoder. This autoencoder was trained on a variety of BSG data and used to try and reconstruct the original image minus the noise. The idea was to exploit the reduction in dimensionality to retain important features and exclude random noise observed. The trained model was then trialled on new data.

The results obtained were promising, with the autoencoder able to successfully re-construct important features and noticeable noise reduction achieved, however this came at the cost of the broadening of features, including some of the periodic noise in the background, which was not able to be completely removed. It remains unclear whether the benefits of the noise reduction would outweigh the smoothing and broadening of features observed, but further work could be done to optimise this.

Future improvements could include interpolating the noise from the areas surrounding the beam and subtracting it from the raw image. This could then be used to train a denoising autoencoder with noisy and clean samples. Another option could be to use other noise filtering techniques in the pre-processing stage, such as Fourier transforms, to remove periodic noise before re-training the model.

Further optimisation of the autoencoder model itself could also impact outcomes. This could be achieved by systematic testing of different sizes of kernels, alternative activation functions, more layers and their

effects on the model performance. Another possible avenue for exploration could be to measure beam profiles with another instrument to use as the ground truth when training the model. This of course relies on there being beam profile monitors of different types in close proximity, which is not always the case.

Ultimately, even with a fully optimised model producing better results, it would be important to robustly test the noise filtering in real operation, under a range of different beam conditions, in order to validate it before actual use in the machine. Correctly steering the beam is of vital importance and any mistakes could be dangerous to both personnel and equipment. It would have to be shown that the filtering provides clear improvement and generalises well to different conditions for it to be worth using. It would also be important to retrain the model if there were any significant changes to beam operation, as this could affect the results.

Chapter 6

Conclusion

Monitoring beam properties within an accelerator is of utmost importance to ensure the safe delivery of the beam to its desired location. Without appropriate monitoring, the beam could cause severe damage to expensive equipment and personnel, and introduce large errors in experimental measurements. The monitoring of the beam relies on instruments, some of which were designed long ago, and that have been adapted for new purposes. Over time, as the experimental programs in accelerators evolve, more ambitious operating targets are set, and instruments get used in ever more challenging conditions, the effects of ageing instrumentation start to become evident.

This thesis was dedicated to investigating ongoing issues existing with CERN NA beam instrumentation, in particular concerning the SEM devices measuring beam current and beam profile present throughout these transfer lines. These devices had been presenting odd behaviour, that was first noted in 2017, but although some initial studies had been carried out, they were inconclusive and unable to account for the behaviour observed.

Problems included: inconsistent measurements of the beam current between closely positioned monitors of the same material; discrepancies between the signal measured before extraction from the SPS by the BCT in the ring and the BSIs in the NA slow extraction transfer lines; non linearities in the ratio between BSI and BCT measured currents; and signal to noise problems with BSGs measuring beam profile and position, due to noise from the electronics, affecting the low signal passing through each of the BSG channels.

It was unclear whether these problems were caused by changes in the vacuum conditions, damage to the foils caused by exposure to the beam, or additional secondary particles contributing to the signal, coming from losses, or interactions with the bias foils, placed either side of the measuring foil, and nearby equipment. The last calibration of these devices had been conducted in the 90s, and since then the foils and electronics had been replaced and there was a large uncertainty on the absolute calibration of the

BSIs measuring the beam current.

To investigate the potential contribution of additional secondary particles to the BSI current, Geant4 simulations of the detector were conducted, which are described in Chapter 3. These simulations included the central measuring foil and two bias foils, with a central hole, placed either side of it, to attract low energy secondary electrons, once they exit the foil. Simulations were conducted with all of the beam passing through the hole in the bias foils, and with the beam displaced to the side of the hole, so that it hit all three foils in full.

The simulation results showed that, although there were not many secondary particles produced in the bias foils, directly contributing to the current measured in the BSI, many additional high energy charged particles were created that passed through the foils, creating additional signal due to ionisation. There was found to be an 170% difference in the signal measured between the two cases. However it is worth pointing out that if the beam were displaced, it would be unlikely to hit 100% of the bias foils, as was the case in the simulation. Therefore the fluctuations in beam current observed experimentally would be much lower. This was a challenging simulation, covering a wide range of energies from 400 GeV down to a few eVs, including many different types of processes, and tracking that occurred inside a very thin detector. These parameters were pushing the Geant4 toolkit close to its limits. Additionally, although the particles counted as part of the signal were only counted if they had high enough energy to overcome the bias potential, the bias potential itself was not simulated.

To tackle the problem with the absolute calibration of the BSI monitors, the BSIs at the main target stations (T2, T4, T6 and T10) in the NA were calibrated using the activation method. This work was described in Chapter 4. The absolute calibration of these devices was challenging to achieve due to there being no other online current measuring device positioned anywhere near the BSIs in question, the closest instrument being located in the SPS ring before extraction to the NA. Because the losses occurring between extraction from the SPS and the targets were not known to a high degree of precision, this would make calibration using the current measured by the BCT unreliable. The only known available method for calibration was the activation method, but this is an off-line method, which requires beam time to be diverted from experiments and other essential maintenance, in order to be performed.

Activation foils were positioned upstream from the target locations and irradiated with protons for a short time period. The foils were then collected, after cooling down for a number of days and gamma spectrometry measurements made. The proton flux was calculated from the measured activity of different isotope found in the foil, and compared to the proton current, measured by the BSI, to determine a new calibration factor for the BSIs at each of the target stations.

The measurements at target T10 were found to be within 2% of the original value, indicating quite good stability over a long period of time. However the same was not true for the measurements conducted at the other target stations, some of which differed up to 35% from the original value. This was attributed to different beam conditions existing at the location of these targets. Targets T2 and T4 are subject to "wobbling", which is used to split the beam into different beamlines after the targets. Some wobbling magnets affect the beam before the targets and although the target stations are set to move with the beam, some of the beam could be hitting different parts of the detector, possibly even the bias foils. Damage to the foils could be happening at different rates, depending on factors such as the wobbling, the intensity of the beam at each target and the types of particles being produced at the targets. All of these factors could be causing the differences in reliability observed between the different BSI locations. Open questions remain on whether the main factor driving these discrepancies is ageing of the foils due to dose, additional secondary particles contributing to the signal or differences in vacuum conditions.

Finally, in Chapter 5, a solution for problems with signal to noise ratio using autoencoders was tested. This is a problem affecting the BSG devices, used for measuring beam profile and position in the NA. The solution tested was to train an autoencoder model, using data from the BSG signals, with the aim of reproducing the data without the noise. The idea behind the noise reduction, was that if the dimensionality of the data was sufficiently reduced at the autoencoder bottleneck, that the autoencoder might be able to learn the main features in the BSG data, but the noise would be smoothed over. When tested on new data the model was able to reconstruct the main features, and reduce the noise, however it resulted on a broadening of the key features. Furthermore, there was still some periodic noise included in the reconstruction.

These initial results seem promising but additional work would be needed to verify their effectiveness for use during operation. Future work could include: further optimisation of the parameters of the existing model; subtracting the noise from the background, using a noise filtering technique such as Fourier transforms and training a denoising autoencoder model, by feeding it samples of noisy and clean images; or acquiring clean images using another type of beam profile instrument and using these as examples of clean images to train a denoising autoencoder.

It would be important to train the model with a wide variety of data before it could be used during routine operation, as it would need to perform well under a range of different scenarios. A well trained and tested model would have the potential to improve the signal to noise ratio and consequently the beam steering capabilities not only in the NA, but also any of the many other accelerators and beamlines that use SEM grids for steering. Better steering results in fewer losses, which results in safer and more efficient control of the beam.

With regards to the BSI monitors, it is clear that fully understanding the causes of the behaviour observed is a complex task, requiring much thought and effort to isolate each of potential factors contributing to the additional signal observed. This could be achieved by further developing the Geant4 simulation: implementing the bias potential field and simulating a variety of different sized bias foil holes; simulating different material thicknesses and inter-material spacings, simulating more of the surrounding equipment. More experimental measurements would also be beneficial. Future work could include: beam scans of the surface of the BSI at different target locations; measurements of the SEY of old foils compared to new foils, measurement of the SEY of BSIs with bias foils with no holes in them, or no bias foils; dose studies of foil degradation over time; Studies of changes to the foil composition due to changes in vacuum; inspection of the surface roughness of old foils.

This thesis has presented some insights into possible causes of discrepancies observed in the measured signals of the NA BSIs, but there is clearly still more to be learned about underlying causes of foil ageing in BSIs. Considering the tolerance that these instruments have to high radiation environments and the longevity of these instruments, it is worth spending the time to properly understand the underlying mechanisms for these problems, as they could not only lead to significant improvements the performance of the instruments themselves, but could also provide insight into the ageing of other types of beam instrumentation.

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Appendix A

Raw Data for BSI Calibration

Table A.1: Raw data for gamma spectrometry measurements of activation foils placed at target T10, taken by CERN RP team

Foil	Assay Date	Creation Date	Update Date	Isotope	Activity (μCi)	Δ Activity (μCi)	Measurem. ID
1	19/09/2022 16:00:17	19/09/2022 16:00	21/09/2022 16:33	Na-22	0.000434241	0.0000433	1st
1	19/09/2022 16:00:17	19/09/2022 16:00	21/09/2022 16:33	Na-24	0.032138739	0.000667599	1st
1	19/09/2022 16:00:17	19/09/2022 16:00	21/09/2022 16:33	Sc-44m	0.000225532	0.0000622	1st
1	19/09/2022 16:00:17	19/09/2022 16:00	21/09/2022 16:33	Sc-47	0.0000946	0.0000149	1st
1	19/09/2022 16:00:17	19/09/2022 16:00	21/09/2022 16:33	Mn-52	0.000190239	0.0000217	1st
1	19/09/2022 16:00:17	19/09/2022 16:00	21/09/2022 16:33	Te-123m	0.0000769	0.0000121	1st
2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Be-7	0.008024435	0.000500488	1st
2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Na-22	0.000545995	0.000134588	1st
2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Na-24	0.031380843	0.000687663	1st
2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Sc-44m	0.000176552	0.0000192	1st
2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Sc-47	0.0000695	0.0000156	1st

2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Mn-52	0.000144266	0.0000201	1st
2	19/09/2022 16:24:48	19/09/2022 16:24	21/09/2022 16:22	Te-123m	0.0000565	0.0000126	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Be-7	0.006155923	0.000408013	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Na-22	0.00041002	0.0000408	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Na-24	0.02719056	0.000584628	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Sc-44	0.000142119	0.0000341	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Sc-44m	0.000147627	0.0000195	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Sc-47	0.000072	0.0000162	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Mn-52	0.0000845	0.0000137	1st
3	19/09/2022 16:06	19/09/2022 16:05	21/09/2022 16:08	Te-123m	0.0000585	0.0000131	1st
9	19/09/2022 16:31	19/09/2022 16:31	21/09/2022 15:41	Be-7	0.009761195	0.00046948	1st
9	19/09/2022 16:31	19/09/2022 16:31	21/09/2022 15:41	Na-24	0.000154353	0.00000801	1st
1	31/10/2022 10:58:15	31/10/2022 10:58:10.693000	04/11/2022 15:02:06.457000	Be-7	0.007830418	0.000332654	2nd
1	31/10/2022 10:58:15	31/10/2022 10:58:10.693000	04/11/2022 15:02:06.457000	Na-22	0.000549584	0.0000385	2nd
1	31/10/2022 10:58:15	31/10/2022 10:58:10.693000	04/11/2022 15:02:06.457000	Na-24	0.002995382	0.0000819	2nd
1	31/10/2022 10:58:15	31/10/2022 10:58:10.693000	04/11/2022 15:02:06.457000	Ra-226	0.0000416	0.0000153	2nd
2	31/10/2022 10:23:06	31/10/2022 10:23:02.033000	04/11/2022 15:05:28.697000	Be-7	0.008147429	0.000378085	2nd
2	31/10/2022 10:23:06	31/10/2022 10:23:02.033000	04/11/2022 15:05:28.697000	Na-22	0.000469672	0.0000199	2nd
2	31/10/2022 10:23:06	31/10/2022 10:23:02.033000	04/11/2022 15:05:28.697000	Na-24	0.003038364	0.0000661	2nd

3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Be-7	0.007385591	0.000342927	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Na-22	0.000419569	0.0000167	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Na-24	0.002689322	0.0000588	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Sc-44	0.0000432	0.00000666	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Sc-44m	0.0000377	0.00000813	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Sc-47	0.0000143	0.00000284	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Sc-48	0.0000237	0.00000298	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Mn-52	0.0000209	0.00000253	2nd
3	31/10/2022 11:02:38	31/10/2022 11:02:34.903000	04/11/2022 05:08:51.017000	Te-123m	0.0000115	0.00000228	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Be-7	0.015336763	0.000692056	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Na-22	0.00020911	0.0000146	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Na-24	0.001419002	0.0000422	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Mg-28	0.00063433	0.0000245	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	K-42	0.000553866	0.0000657	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	K-43	0.002103767	0.0000557	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Sc-44	0.057540748	0.001387451	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Sc-44m	0.031085717	0.001081423	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Sc-46	0.004515541	0.0000936	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 05:13:14.627000	Ca-47	0.000607771	0.0000656	2nd

5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Sc-47	0.018600438	0.001015942	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Cr-48	0.000330491	0.0000165	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Sc-48	0.003149117	0.000105107	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	V-48	0.02797894	0.0004394	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Cr-51	0.033775616	0.00164047	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Mn-52	0.031961925	0.000449354	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Mn-54	0.002857158	0.0000888	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Co-55	0.000618829	0.0000312	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Co-56	0.004414856	0.0000823	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Co-57	0.004356892	0.000173921	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Ni-57	0.002245321	0.0000668	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Co-58	0.019002395	0.000555391	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Fe-59	0.002286994	0.0000757	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	Co-60	0.000366896	0.0000223	2nd
5	31/10/2022 16:34:44	31/10/2022 16:34:40.120000	04/11/2022 15:13:14.627000	U-238	0.001159907	0.000155766	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Be-7	0.017671373	0.000783543	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Na-22	0.000216992	0.0000216	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Na-24	0.001489517	0.0000346	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Mg-28	0.000652508	0.0000204	2nd

6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	K-42	0.000487772	0.0000771	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	K-43	0.002243738	0.0000633	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Sc-44	0.044646095	0.001123217	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Sc-44m	0.034166094	0.001112286	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Sc-46	0.004871557	0.000117731	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Ca-47	0.000685034	0.0000749	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Sc-47	0.020427018	0.001115185	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Cr-48	0.000405401	0.00002	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Sc-48	0.003342929	0.000101705	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	V-48	0.028838409	0.000507572	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Cr-51	0.037613899	0.001889123	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Mn-52	0.033414602	0.000439326	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Mn-54	0.003350032	0.000103771	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Co-55	0.000603717	0.0000347	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Co-56	0.00453713	0.0000697	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Co-57	0.004680485	0.000179356	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Ni-57	0.002372927	0.0000555	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Co-58	0.021271728	0.000620837	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 15:20:20.657000	Fe-59	0.002473542	0.0000821	2nd

6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 05:20:20.657000	Co-60	0.000382617	0.0000225	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 05:20:20.657000	Zn-65	0.000224377	0.0000408	2nd
6	31/10/2022 16:31:59	31/10/2022 16:31:55.147000	04/11/2022 05:20:20.657000	Au-198	0.0000976	0.0000135	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Be-7	0.015294038	0.000835105	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Na-22	0.000188529	0.0000121	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Na-24	0.001345073	0.0000333	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Mg-28	0.000602724	0.0000205	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	K-42	0.000445056	0.0000451	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	K-43	0.001929869	0.0000597	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Sc-44	0.043883301	0.001165725	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Sc-44m	0.027549926	0.00084541	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Sc-46	0.004263023	0.000100624	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Ca-47	0.000563859	0.0000643	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Sc-47	0.0177671	0.000973829	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Cr-48	0.000340963	0.0000181	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Sc-48	0.002813031	0.0000964	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	V-48	0.02605083	0.000407199	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Cr-51	0.033444997	0.001775699	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Mn-52	0.029763376	0.000420288	2nd

8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Mn-54	0.002856318	0.0000869	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Co-55	0.0004215	0.0000225	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Co-56	0.00408331	0.0000692	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Co-57	0.003981421	0.000175719	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Ni-57	0.002083603	0.0000466	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Co-58	0.018767184	0.000560707	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Fe-59	0.002255595	0.0000987	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Co-60	0.000325077	0.0000158	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	Zn-65	0.000167774	0.0000255	2nd
8	31/10/2022 16:54:25	31/10/2022 16:54:22.317000	04/11/2022 04:50:13.837000	U-238	0.001730571	0.000448843	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Be-7	0.002810662	0.000127272	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Sc-44	0.0000157	0.0000022	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Sc-44m	0.00000907	0.000000952	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Sc-46	0.0000151	0.00000142	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Sc-47	0.00000583	0.000000773	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Sc-48	0.0000187	0.00000914	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	V-48	0.0000376	0.00000804	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Cr-51	0.0000648	0.0000203	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Mn-52	0.0000215	0.000000851	2nd

10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Mn-54	0.00000664	0.000000819	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Co-56	0.00000387	0.000000718	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Co-57	0.00000462	0.000000498	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Co-58	0.0000147	0.00000111	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Te-123m	0.00000447	0.000000593	2nd
10	10/11/2022 15:26	10/11/2022 15:26	16/11/2022 10:43	Eu-152	0.0000138	0.00000149	2nd
9	10/11/2022 15:25	10/11/2022 15:25	16/11/2022 10:15	Be-7	0.008442723	0.000374974	2nd
9	10/11/2022 15:25	10/11/2022 15:25	16/11/2022 10:15	Ra-226	0.00000964	0.00000124	2nd

Table A.3: Raw data for gamma spectrometry measurements of activation foils placed at targets T2, T4 and T6, taken by CERN RP team

Foil	Assay Date	Creation Date	Update Date	Isotope	Activity (Bq)	Δ Activ- ity (Bq)	Target
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Be-7	383.1183361	123.0258248	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Na-24	35.93040502	2.651927352	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Mg-28	15.55432187	2.334410608	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	K-43	46.5858056	3.020069656	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Sc-44	706.5391168	31.17675183	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Sc-44m	699.0193501	38.75633923	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Sc-46	103.0532881	4.333870675	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Ca-47	20.29684698	6.926844173	T6

6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Sc-47	442.407243	31.50339454	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Sc-48	79.41295952	5.99789212	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	V-48	651.3226014	18.83519371	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Cr-51	846.6485962	54.86739043	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Mn-52	772.3113	14.96667319	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Mn-54	75.3083576	13.38782508	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Co-56	94.04576547	4.373995682	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Co-57	99.36041874	5.783442321	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Ni-57	55.5159162	4.719379474	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Co-58	494.3355145	27.05602744	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Fe-59	48.14733809	6.459947675	T6
6	19/04/2023 15:36	19/04/2023 15:36	20/04/2023 14:31	Te-123m	359.7192373	25.5858865	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Na-24	32.25967771	3.892660083	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Mg-28	14.93482021	2.729838197	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	K-43	44.1176499	5.740253429	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Sc-44	736.1511271	27.77395997	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Sc-44m	725.8655485	35.64121056	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Sc-46	102.6603011	5.939820738	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Sc-47	442.4110679	25.00248165	T6

4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Cr-48	9.468372096	1.917085443	T6
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4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Cr-51	785.5686173	57.06206278	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Mn-52	797.80595	17.10839078	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Mn-54	71.84225821	6.287513548	T6
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4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Co-57	105.0526989	6.187135747	T6
4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Ni-57	55.14176108	6.907030285	T6
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4	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:18	Fe-59	48.1461708	9.932577028	T6
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5	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:26	Cr-51	807.3794693	132.8404015	T6
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5	19/04/2023 14:16	19/04/2023 14:16	20/04/2023 14:26	Mn-54	66.2595015	4.849720935	T6
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4	20/04/2023 08:20	20/04/2023 08:20	21/04/2023 10:12	Co-57	91.4865348	9.653970075	T4
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5	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:22	Cr-51	707.789287	66.82983134	T4
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5	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:22	Mn-54	70.06724831	6.193501496	T4
5	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:22	Co-56	99.05419941	5.572107824	T4
5	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:22	Co-57	105.7650857	7.729694829	T4
5	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:22	Ni-57	54.2221081	5.701767644	T4

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6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Sc-44	731.798619	27.57218352	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Sc-44m	699.3021201	34.38783786	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Sc-46	108.6870225	5.922185839	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Sc-47	425.0383889	24.04781838	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Sc-48	70.52403595	7.969413797	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	V-48	669.1845972	21.09968633	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Cr-51	882.6889209	61.36454944	T4
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6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Mn-54	72.86658883	6.805840545	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Co-56	112.9049254	6.408916684	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Co-57	102.2215011	6.040643813	T4
6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Ni-57	51.02678272	6.116831981	T4

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6	19/04/2023 16:41	19/04/2023 16:41	21/04/2023 10:33	Fe-59	42.06258792	9.41450955	T4
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2	19/04/2023 15:34	19/04/2023 15:34	21/04/2023 10:55	Na-24	57.15907761	2.699462377	T6
2	19/04/2023 15:34	19/04/2023 15:34	21/04/2023 10:55	K-40	19.85761186	9.465028503	T6
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6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Na-24	14.80391287	2.555113897	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Mg-28	10.80901851	2.940946018	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	K-43	31.5338627	3.053687578	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Sc-44	574.0785562	23.17037544	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Sc-44m	600.3400553	29.70493102	T2

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6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Sc-47	400.0993893	22.69276598	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Sc-48	52.30670387	7.152524893	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	V-48	706.8073452	20.65980725	T2
6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Cr-51	817.899093	57.73679027	T2
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6	20/04/2023 09:40	20/04/2023 09:40	21/04/2023 09:39	Co-56	108.0616531	6.045696355	T2
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5	20/04/2023 09:39	20/04/2023 09:39	21/04/2023 09:27	Sc-46	100.5959783	4.189558538	T2

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5	20/04/2023 09:39	20/04/2023 09:39	21/04/2023 09:27	Mn-54	67.69127457	11.88478232	T2
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4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Sc-46	102.5111715	7.646130834	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Sc-47	361.6561741	27.02281118	T2

4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Sc-48	56.37374555	4.986869651	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	V-48	637.2364089	19.70843051	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Cr-51	748.0145805	50.16537826	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Mn-52	718.5938172	13.44811529	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Mn-54	65.1869413	4.672457173	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Co-56	94.88658071	4.449183463	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Co-57	95.87507835	10.20224189	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Ni-57	37.52269642	3.718098924	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Co-58	458.3242731	22.26871648	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Fe-59	41.28523311	4.2463789	T2
4	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:17	Te-123m	294.0609409	21.94923908	T2
3	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:09	Be-7	218.5811414	21.36790176	T2
3	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:09	Na-22	12.35644869	1.446987091	T2
3	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:09	Na-24	24.58925225	1.708622345	T2
1	20/04/2023 12:07	20/04/2023 12:07	21/04/2023 08:54	Be-7	191.8882336	12.06569388	T2
1	20/04/2023 12:07	20/04/2023 12:07	21/04/2023 08:54	Na-22	12.94561895	1.102462551	T2
1	20/04/2023 12:07	20/04/2023 12:07	21/04/2023 08:54	Na-24	22.08488452	1.172482636	T2
2	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:03	Be-7	223.6535139	13.63073796	T2
2	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:03	Na-22	12.59697528	1.085691145	T2

2	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:03	Na-24	25.1808411	1.624340905	T2
2	20/04/2023 10:52	20/04/2023 10:52	21/04/2023 09:03	Ra-226	2.371592338	0.971742244	T2

Table A.5: Raw data for foil thickness measurements for second calibration measurement

Foil	Mass (g)	Side1 (cm)	Side2 (cm)
Alu 1	0.6789	5.05	5.1
		5.05	4.95
		5.05	5
Alu 2	0.6501	4.85	5.05
		4.95	4.95
		4.9	5
Alu 3	0.6621	4.97	4.95
		4.978	4.985
		5.025	4.969
Alu 4	0.6772	4.9	5.05
		4.9	5.15
		4.9	5.15
Cu 5	2.2365	5	4.9
		5.1	5.1
		5.05	5
Cu 6	2.1908	5.1	4.9
		4.95	4.85
		5.05	5
Cu 7	2.2795	5.05	5
		5.1	5.1
		5.2	5.1
Cu 8	2.2039	4.95	5.05
		5.1	4.95
		5	5.05

Table A.7: Raw data for foil thickness measurements for third calibration measurement

Foil	Mass(g)	Side1(cm)	Side2(cm)	Material	Target
1	5	5	0.6796	Al	T2
2	5	4.95	0.6761	Al	T2
3	4.95	4.95	0.6845	Al	T2

4	5	4.95	2.1926	Cu	T2
5	5	5	2.218	Cu	T2
6	4.9	4.9	2.1246	Cu	T2
1	4.9	4.95	0.6505	Al	T4
2	5	4.95	0.6806	Al	T4
3	4.95	5	0.6868	Al	T4
4	5	5	2.1817	Cu	T4
5	5	4.95	2.1584	Cu	T4
6	5	4.95	2.17	Cu	T4
1	5	4.95	0.6838	Al	T6
2	5	5	0.6889	Al	T6
3	5	4.95	0.6906	Al	T6
4	5	5.05	2.2028	Cu	T6
5	4.9	5.05	2.198	Cu	T6