The Thin-foil Proton Recoil neutron spectrometer for DT plasmas

BENJAMINAS MARCINKEVICIUS
Abstract


Recent advancements in plasma physics are intensifying the demand for advanced diagnostic techniques in fusion research, particularly for the upcoming ITER fusion reactor. The ITER fusion reactor is projected to be ten times more powerful than its predecessors, imposing higher constraints on operational parameters. To meet ITER's requirements, such as the fuel ion ratio $n_t/n_d$ and fuel ion temperature $T_i$, a High Resolution Neutron Spectrometer System (HRNS) has been proposed.

This thesis focuses on the Thin-foil proton recoil (TPR) spectrometer, an integral part of the HRNS, with an emphasis on its application and validation within the ITER context. The research encompasses two main areas: spectrometer simulations and experimental validation. Through a combination of custom transport code and Geant4 simulations, the study investigates the optimization of the TPR spectrometer's design in terms of efficiency and energy resolution. Additionally, selected design performance under ITER-like conditions has been investigated. These simulations are critical in assessing the spectrometer's capabilities and limitations during operation at ITER. Subsequent experimental validation, conducted using a DT neutron generator and a TPR spectrometer prototype, verified the existing simulation framework in terms of energy resolution and background discrimination methods.

We examined a Tandem neutron spectrometer, used in fusion plasma diagnostics at JET to further investigate TPR spectrometer diagnostic possibilities. Tandem spectrometer was operational during JET's first DT campaign, the spectrometer shares the neutron detection principles of the TPR. The fuel ion ratio $n_t/n_{tot}$ was determined using the Tandem data together with inputs from PENCIL or TRANSP, for previously not analysed JET discharges. Our findings indicate that estimation of $n_t/n_{tot}$ is feasible using either PENCIL or TRANSP. Furthermore, the research demonstrates that TPR based neutron spectrometers can be effectively used in fuel ion ratio determination.

In conclusion, this research significantly advances fusion plasma diagnostics. It validates the TPR spectrometer's design in terms of energy resolution and efficiency for ITER, predicting a signal-to-background ratio of approximately 550 and a maximum count rate of 120kHz. The results from the TPR prototype experiment, replicated with the Geant4 simulation, along with comparative analysis with the JET's Tandem spectrometer, highlight the TPR spectrometer's broad applicability in fusion diagnostics, marking a major advancement in the field.

*Keywords:* fusion, plasma diagnostics, neutron spectrometry, ITER, JET

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   My contribution: Performed simulations and data analysis as well as wrote the paper.
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<th>Description</th>
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<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>BPF</td>
<td>Beam Power Fraction</td>
</tr>
<tr>
<td>BSF</td>
<td>Back Scattering Fraction</td>
</tr>
<tr>
<td>BT</td>
<td>Beam-Thermal</td>
</tr>
<tr>
<td>DSSD</td>
<td>Double-sided Silicon Strip Detector</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
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<td>HRNS</td>
<td>High Resolution Neutron Spectrometer</td>
</tr>
<tr>
<td>ITER</td>
<td>International Thermonuclear Experimental Reactor</td>
</tr>
<tr>
<td>ICRH</td>
<td>Ion Cyclotron Resonance Heating</td>
</tr>
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<td>JET</td>
<td>Joint European Torus</td>
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<td>NBI</td>
<td>Neutral Beam Injection</td>
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<td>NC</td>
<td>Neutron Camera</td>
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<td>NES</td>
<td>Neutron Emission Spectroscopy</td>
</tr>
<tr>
<td>MAST</td>
<td>Mega Ampere Spherical Tokamak</td>
</tr>
<tr>
<td>PHS</td>
<td>Pulse Height Spectrum</td>
</tr>
<tr>
<td>PMT</td>
<td>Photo-multiplier tube</td>
</tr>
<tr>
<td>TH</td>
<td>Thermal</td>
</tr>
<tr>
<td>ToF</td>
<td>Time of flight</td>
</tr>
<tr>
<td>tokamak</td>
<td>toroidal chamber with an axial magnetic field</td>
</tr>
<tr>
<td>TPR</td>
<td>Thin-foil Proton Recoil</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>ROI</td>
<td>Region of Interest</td>
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1. Introduction

“It’s a trap!” – Admiral Ackbar

The concept of fusion emerged in the mid-20th century, alongside the idea of using it to generate energy. However, to this day, the industrial application of fusion for energy remains an unrealised ambition. Fusion energy has the potential to be a sustainable alternative to current fossil fuel-based power plants, as it emits virtually no greenhouse gases. For the first generation fusion power plants the fuel is envisaged to be composed of equal amounts of deuterium and tritium, isotopes of hydrogen. Deuterium can be extracted from water, while tritium can be produced during power plant operation from lithium blankets [1]. The main drawback of such a power plant would be the production of radioactive waste as a result of reactor component activation throughout the plant’s lifetime, but this waste would not be long-lived, and its amount would be significantly lower than the one produced in fission reactors. Despite this potential, due to the plasma instabilities, a harsh radiation environment, high temperatures and magnetic fields, several challenges must be overcome before industrial application is viable. The following chapter provides an overview of the basic concepts of fusion and presents the experimental fusion reactors relevant to this work.

1.1 Thermonuclear Fusion

The concept of thermonuclear fusion was first proposed by Arthur Eddington in 1920 [2]. Within a few decades, in 1934, it was experimentally demonstrated that fusion reactions could be replicated under laboratory conditions [3]. In these experiments, deuteron enriched targets were bombarded with deuterons, which led to fusion reactions:

\[ \text{D}_2^1 + \text{D}_2^1 \rightarrow \text{H}_3^3 + \text{H}_1^1 \]  

\[ \text{D}_2^2 + \text{D}_2^2 \rightarrow \text{He}_3^4 + \text{n}^1 \]

Some years later, Hans Bethe showed that the fusion process drives energy production in stars and demonstrated how to estimate the energy production via reactant binding energies [4]. As the basic theory behind the process was developed, the next step was to harness the fusion reactions for energy production on Earth. James Tuck was one of the first people to propose a possible
design for a fusion reactor in the 1950s. His aspiration led to the construction of the first fusion device, aptly named the "Perhatsatron" [5]. Unfortunately, the plasma proved to be unstable and nuclear fusion was not achieved.

In the following years, Lawson defined the minimal, but not sufficient, criterion for a plasma reactor to be successfully operational [6]. The Lawson criterion, also known as the break-even criterion, requires that the energy released is equal to the energy required to maintain the plasma. A common physical value used is the power gain factor $Q = \frac{P_{\text{fusion}}}{P_{\text{used}}}$, therefore, the break-even criterion is $Q=1$. The power released by fusion reactions in a volume element $V$ can be expressed as:

$$P_{\text{fusion}} = n_1 n_2 \langle v \sigma (v) \rangle E V,$$

(1.3)

Here, $n_1$ and $n_2$ denote the number density of the reacting ions, $\langle v \sigma \rangle$ represents fusion reactivity, and $E$ is the energy released in a fusion reaction. The fusion reactivity can be expressed as integral of the ion species velocity distributions:

$$\langle \sigma v \rangle = \int v_1 \int v_2 f_1(v_1) f_2(v_2) v_{\text{rel}} \sigma (v_{\text{rel}}) d v_1 d v_2$$

(1.4)

where $f_i(v_i)$ denotes the velocity distribution of the ion species $i$, $v_{\text{rel}}$ represents the relative velocity between the two particles and $\sigma$ is the reaction cross section.

Ignition refers to the point where the fusion reaction becomes self-sustaining. This happens when the fusion products provide enough energy to maintain the reaction, eliminating the need for auxiliary heating systems. If the energy production in the fusion plasma is sufficient to maintain the reactions without auxiliary heating, the plasma is in a "burning" condition.

Around the time of the Lawson criterion’s formulation, a new magnetic confinement device, the tokamak, was developed in the Soviet Union. In 1968, the T-3 tokamak achieved higher temperatures [7] than any other fusion device at the time, setting the trend for the upcoming years. Unfortunately, the development of tokamaks for energy production is hindered by challenges related to plasma stability and rapid particle energy loss to the surroundings. As a result, the current record for $Q$ is 0.67 [8] achieved at the JET tokamak during the 1997 deuterium-tritium (DT) campaign. Recently, during the second DT campaign in 2021, JET set a new record for fusion energy, about 60MJ, in a plasma maintained for 5 seconds with a $Q$ of 0.3 [9] and in 2023 it topped the previous record generating fusion energy of 69 MJ [10]. Although the tokamak so far falls short of reaching the Lawson criterion, it is currently the most developed design of a fusion reactor for energy production, and further discussion will be provided in more detail below.
1.2 Tokamaks

Tokamaks are devices that confine fusion fuel within a plasma vessel using strong magnetic fields. The charged fuel ions and electrons are confined in a toroidal vacuum vessel by the bent magnetic field lines, due to the Lorentz force (see figure 1.1). Energetic ions and electrons collide and exchange energy within the plasma, sustaining the plasma temperature. The magnetic field $B$ and plasma current $J$ must be strong enough to balance the outward force of the plasma pressure gradient $\Delta p$:

$$\Delta p = J \times B$$ (1.5)

Figure 1.1. Directions of magnetic field lines, current, and pressure created in the plasma.

Figure 1.2. A - Fusion reaction cross section dependence on the reactant energy in centre-of-mass frame for four different fusion reactions. B - Fusion reactivity dependence on ion temperature in Maxwellian plasmas for four different fusion reactions.

To achieve fusion reactions in a tokamak, it is necessary to confine ions and attain high temperatures. The cross section of the nuclear fusion reaction depends on the temperature (energy) of the reacting ions (see figure 1.2 A). The fusion reactivity (as defined in eq 1.4), which enters linearly into the expression for power production, determines the potential applications of a specific fusion reaction for fusion energy purposes, as shown in figure 1.2 B [11].
The energy released in fusion reactions depends on the reactants, as listed in the following equations:

\[ T + D \rightarrow \alpha + n + 17.6 \text{MeV} \quad (1.6) \]
\[ D + D \rightarrow ^3\text{He} + n + 3.27 \text{MeV} \quad (1.7) \]
\[ D + D \rightarrow T + p + 4.05 \text{MeV} \quad (1.8) \]
\[ D + ^3\text{He} \rightarrow \alpha + p + 18.34 \text{MeV} \quad (1.9) \]
\[ D + ^6\text{Li} \rightarrow 2\alpha + 22.4 \text{MeV} \quad (1.10) \]

The D-T reaction has the highest reactivity at the temperatures currently achievable in tokamaks, making it the most promising reaction for energy production. However, other fusion reactions, such as D-D and T-T, will also occur, along with additional due to reaction products and impurities present in the plasma.

Neutrons produced in the fusion reactions are not confined by the reactor’s magnetic fields and can leave the plasma volume. This property can be used for various purposes, such as neutron diagnostics for investigating different plasma parameters (discussed in Chapter 2); producing tritium fuel in the surrounding lithium blanket via the \( \text{Li}^6(n, \alpha)\text{H}^3 \) reaction [12, 1], and heating the surrounding walls which can be utilised for electricity production [13].

Maintaining sufficient temperature and sustaining plasma confinement require special technical solutions. In the following section, we discuss commonly employed plasma heating techniques and their impact on fast fuel ion distributions.

1.2.1 Plasma Heating

The plasma must be heated to the appropriate temperature to ensure a high probability of a fusion reaction to occur. There are three main heating techniques employed to achieve this: ohmic heating, Neutral Beam Injection (NBI) and radio frequency heating. Once the required conditions for a burning plasma are reached, external heating is no longer necessary, because the fusion process is sustained by the high-energy charged reaction products slowing down in the plasma. The detailed exploration of these heating techniques falls beyond the scope of this thesis; however, a comprehensive overview is available in [14] for interested readers.

Ohmic Heating

In the tokamak plasma, the toroidal current \( \mathbf{J} \), which induces a poloidal magnetic field, crucial for confinement and stability, also provides a source of heating as the drifting electrons and ions collide. Ohmic heating predominantly affects electrons because of their lower mass, but electron-ion collisions transfer
some of the energy to the ions. The heating of plasma can be estimated using Ohm’s law, $P_\omega = \eta J^2$, where $\eta$ is the resistivity and $J$ is the current density. The resistivity is temperature dependent, and therefore, so is the efficiency of Ohmic heating. The efficiency of ohmic heating is proportional to $T_e^{-\frac{3}{2}}$, and thus, the heating is inefficient at high plasma temperatures. In practice, this type of heating is limited by the fuel ion temperature, $T_i$, of up to about 3 keV. For these reasons, additional methods of heating are required to reach higher plasma temperatures [14].

**Neutral Beam Injection**

In Neutral Beam Injection (NBI) heating, a high-energy neutral ion beam is injected into the plasma. Upon reaching the plasma, the particles become ionised through collisions with plasma ions and electrons and deposit their energy in the plasma until they are thermalised or leave the plasma. The particle trajectories depend on the injection energy, injection angle relative to the magnetic field and injection position in the plasma. Three processes dominate the energy transfer between NBI ions and a fusion plasma:

- Charge exchange
- Ionisation by ions
- Ionisation by electrons

The heating efficiency depends on the cross section of these processes, which have different dependencies on the beam ion energy. For instance, for hydrogen beam injection below 90 keV the dominating effect is charge exchange, while for higher energies, ionisation by ions has a stronger influence. Despite its efficiency, the system has engineering drawbacks because the equipment is large, requires direct access to the plasma vacuum chamber and places constraints on the position of the installation to avoid interfering with the magnetic systems of the fusion device.

**Radio Frequency Heating**

Radio frequency (RF) heating involves propagating electromagnetic waves into the plasma to deposit energy inside the plasma. Two effects dominate the wave-particle interaction: resonance absorption and accelerations of particles in an electric field.

Resonant absorption heating is a collision-less process and can produce strong heating due to absorption. Accelerated particles interact with surrounding particles and heat up the plasma. However, as in the Ohmic heating case, the heating efficiency scales as $T_e^{-\frac{3}{2}}$, which is inefficient for hot plasmas. There are three commonly used techniques to implement radio frequency heating for fusion plasmas: ion cyclotron resonance (ICRH), lower hybrid, and electron cyclotron heating. Each of the heating schemes has specific wave frequencies and interacts with different plasma species and at a different po-
sitions in the plasma, since the resonance absorption position depends on the B-field.

1.3 JET

The Joint European Torus (JET) is the largest and most advanced currently operational tokamak fusion reactor, located at the Culham Center for Fusion Energy in Oxfordshire, UK. Operational since 1983, the device has broken the fusion power and energy records [9, 10, 15] and has performed multiple DD and DT plasma campaigns. The DT plasma campaigns were held in 1997, 2021 and 2023 establishing JET as the only current large-scale tokamak capable of utilising tritium fuel [16].

Equipped with NBI and RF plasma heating systems, JET has versatile capabilities. NBI heating has achieved a peak power output of 30 MW while injecting tritium to the plasma, and uniquely, the system can inject both tritium and deuterium through its two available injection boxes. RF heating experiments have been conducted across various plasma modes in JET, reaching up to 5 MW of heating power [17].

Complementing its heating systems, JET features an ITER-like tungsten divertor [18] and a beryllium ITER-like vessel wall [17, 19]. These components make JET’s experimental findings highly relevant for ITER. Additionally, the facility employs an array of diagnostic systems that offer comprehensive insights into the plasma physics of tokamak devices. Specific diagnostics such as charge exchange systems are used for ion temperature measurements [20], and a Penning gauge is available to assess the fuel ion content [21, 22] of the exhaust gases. In this work, these diagnostic tools effectively complement the existing neutron spectrometer-based methods for determining ion temperature and fuel ion content [23, 24, 25].

Of particular note here is the suite of neutron diagnostics that form a crucial part of JET’s scientific arsenal. This includes multiple systems based on different techniques for neutron detection, such as three pairs of fission chambers that act as neutron monitors [26], a pneumatically driven sample delivery system for neutron activation [27], a time-of-flight neutron spectrometer [28, 29], a magnetic proton recoil spectrometer [30], and a neutron camera [31].

In summary, JET’s diverse heating systems, the capability for neutral beam injection of different ion species, ITER-like components, and an extensive array of diagnostic systems enables comprehensive investigation of plasma behavior. This versatility substantially contributes to the advancement of both future plasma devices and the broader field of plasma physics.
1.4 ITER

The International Thermonuclear Experimental Reactor (ITER) is a fusion reactor under construction in France, facilitated by an international consortium including China, the European Union, India, Japan, Korea, Russia and the United States. ITER aims to achieve fusion power operation by 2035. Its core mission is to validate the viability of fusion as a sustainable energy source and to advance the understanding of related physics and technologies.

To realize this vision, ITER has laid out a set of operational objectives. A priority is the attainment of a "burning plasma" state, where the energy of the alpha particles generated through DT fusion reactions is sufficient to sustain the reactor operation. Following this, ITER targets a power gain, Q, of 10, and aspires to produce a fusion power of 500 MW while only using 50 MW for heating. Another key goal is to refine the integrated technologies of heating, control, diagnostics, cryogenics and remote maintenance, which are essential for the development of future energy-producing fusion power plants. The reactor also aims to validate its safety features and demonstrate its capabilities for tritium breeding.

To enable these goals, ITER is designed to have powerful heating systems; currently, it is planned to employ two neutral beam injectors capable of delivering 33.3 MW of power to the plasma [32]. These NBI systems are designed to provide 1 MeV D or 0.87 MeV H beams to the ITER plasma for up to 3600 seconds. This makes them the most powerful neutral beam injectors ever developed, capable of delivering higher energy neutral beams to the plasma in a tokamak for longer duration than any previous systems. There are plans to expand the capabilities of heating during the operation of ITER.

In terms of experimental scope, ITER plans to examine a broad spectrum of plasma states, ranging in fusion power from 0.5 to 500 MW. The reactor is expected to sustain various power-level plasmas for approximately 4700 hours over its operational lifespan [13] and experiment with diverse fuel combinations and heating methods. This will not only test tritium breeding capacities but also lay the groundwork for industrial-scale fusion reactors, as elaborated in a comprehensive research plan [13, 33].

Such ambitious goals require diagnostic systems supporting both research and plasma control. For example, one of the crucial parameters to monitor during the operation of the ITER machine is the fuel ion ratio \( \frac{n_t}{n_d} \) which determines the plasma burning parameters. Additionally, fuel ion ratio and temperature measurements can provide insight into plasma heating efficiency and is important for plasma control and modeling of tokamak physics. A key instrument for diagnosing the ITER plasma is a suit of high resolution neutron spectrometers (HRNS). The Operational requirements of ITER for fuel ion ratio and temperature measurements with the HRNS system are outlined in Table 1.1.
Table 1.1. Requirements for neutron spectroscopy system and roles in ITER

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Measurement Parameter</th>
<th>Accuracy, %</th>
<th>Time Resolution, ms</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Fuel Ion ratio ( n_i/n_d )</td>
<td>20</td>
<td>100</td>
<td>basic machine control</td>
</tr>
<tr>
<td>Supplementary</td>
<td>Fuel Ion temperature ( T_i )</td>
<td>10</td>
<td>100</td>
<td>advanced plasma control</td>
</tr>
</tbody>
</table>

The intensity of neutron emission in ITER will vary by three to four orders of magnitude, necessitating multiple neutron spectrometers, each optimized for specific plasma conditions. Prior studies of neutron spectrometers for ITER have been conducted [34], resulting in the currently proposed design of the HRNS system [33, 35] which is described in the following section.

1.4.1 High Resolution Neutron Spectrometer

HRNS is a spectrometer system proposed for ITER that meets the necessary requirements for all operational conditions. It is composed of four types of spectrometers that have overlapping operating ranges, allowing for a continuous coverage of all plasma scenarios and providing the fuel ion temperature and fuel ion ratio. The conceptual design of the HRNS system is depicted in Figure 1.3.

![Figure 1.3. A figure depicting the HRNS system containing multiple neutron spectrometers. The TPR spectrometer is placed in Cuboid 1.](image)

The main spectrometers that are part of HRNS are the TPR, Diamond, ToF and backToF spectrometers. The TPR and ToF spectrometers have demonstrated their worth by supplying measurement data for the JET fusion device. The TPR system was slightly modified compared to its original version [30]. Due to the space constrains and stray magnetic fields around the ITER tokamak the proposed TPR system does not employ magnetic fields as means of...
spectroscopy and uses annular silicon detectors to measure accurate proton energy deposition instead. The development of diamond spectrometers has been underway and they have been tested for neutron spectroscopy in fusion devices [36, 37]. The backToF [38] spectrometer currently is a concept design which has not been tested experimentally. Overall some of the techniques have been thoroughly validated experimentally in fusion devices and provide routine information for plasma diagnostics while others are conceptual and need additional experimental validation.

The investigation of the spectrometer performance in ITER was based on a reference (Sa2) scenario, which is an H-mode plasma characterized by an output-to-input Q of 10, a plasma current of 15 MA, and a fusion power of 410 MW. Additionally, the production rate for the neutron fusion source is estimated at $2.91 \times 10^{17} \text{ n s}^{-1} \text{ MW}^{-1}$. The scenario requires a NBI of approximately 35 MW, as well as an optional RF heating power of 20 MW. A variety of plasma parameters were investigated using simulations according to the Sa2 scenario. Specifically, the spectrometer’s performance was evaluated over a broad power range, spanning from 0.5 to 500 MW, fuel ion temperatures of 10 and 20 keV, fuel ion ratio and the beam fraction, ranging from 0.001 to 0.9 and from 0.035 to 0.25, respectively. This comprehensive analysis ensures that the system is able to handle all relevant plasma conditions expected during ITER operation.

Each of the spectrometers performance was evaluated by calculating the instrumental response function to the neutron emissivity profile [35]. Using different plasma scenarios and corresponding emissivity profiles a range of spectrometer performance parameters have been determined. The study demonstrated that the currently proposed HRNS design meets the ITER requirements for a wide range of $n_e/n_d$ and fusion powers. As mentioned before, some of the spectrometers employed in the HRNS requires additional validation, and the focus of this thesis is to advance the development of the thin-foil proton recoil (TPR) spectrometer in the context of the ITER. This has been pursued by estimating the operational parameters such as energy resolution, detection efficiency, count rate capabilities and signal-to-background ratio in ITER conditions. Additionally, a spectrometer prototype has been constructed and acquisition software developed to experimentally validate the currently employed simulation framework.
2. Neutron Emission Spectroscopy

“Diamonds are a girl’s best friend” – Leo Robin

Neutron Emission Spectroscopy (NES) is a valuable diagnostic tool for tokamak plasma experiments. Each heating scheme in a tokamak produces a distinct signature in the fuel ion and neutron energy distributions. NES can measure parameters not available through other diagnostic techniques and supplement existing ones. NES can be used to determine plasma temperature, fuel ion density ratio and fusion power [39, 40, 41, 42, 43, 44, 24]. As previously mentioned, multiple neutron spectrometers have been successfully installed at JET and have provided useful diagnostic information [29, 45, 30].

![Diagram of neutron emission spectrometer](image)

*Figure 2.1. Possible neutron paths leading towards interaction in the detector for generic neutron emission spectrometer in a generic fusion device.*

A typical neutron measurement scheme involves collimating the neutrons from the plasma through a slit in a wall before they reach a detector or spectrometer, depending on the diagnostic purpose (see figure 2.1). The resulting neutron flux measured by the detector represents an integral of the neutron emission in the detector’s viewing cone or line-of-sight. Shielding the detector from stray neutrons allows the diagnostics to determine properties of a specific plasma volume. Having multiple lines-of-sight can determine the spatial distribution of neutron emission in the plasma volume; devices with this property are known as neutron cameras (NC).

This chapter reviews different neutron spectral components relevant to a DT plasma in section 2.1; common neutron detectors in section 2.2; spectroscopy techniques used in plasma fusion devices in section 2.3. In addition,
section 2.4 provides a detailed overview of the Thin-foil Proton Recoil (TPR) spectrometer.

2.1 Neutron Spectral Components

The neutron energy spectra in tokamak plasma experiments are composed of three major components, assuming the tokamak is employing ohmic, NBI and RF heating schemes (figure 2.2). The neutron spectrum from thermal (TH) ion fusion is a Gaussian-like distribution with a width determined by the fusing ion energy (temperature). The NBI ions are usually of much higher energy than the thermal ions, such as in JET discharges in the DTE1 campaign, where the NBI energy was approximately 140 keV, while the thermal plasma temperature varied between 3 to 13 keV [25]. As a result, the NBI ions interacting with the thermal plasma create a wider component than TH due to Doppler broadening, which will be referred to as the Beam-Thermal (BT) component in this chapter. The RF heating can give rise to even higher energy ions than the NBI and the resulting neutron emission is therefore skewed towards higher energies than both the BT and TH components.

Unfortunately, collimators are not perfect, and some of the scattered neutrons can reach the detector and create a background signal (referred to as the "scatt" component in figure 2.2). This background signal mostly affects the measurement on the low energy side of the distribution [46] as seen in
In DT experiments this can be a determining factor in the ability to distinguish a DD peak from the scatt component. To address this issue, a method has been developed to determine the fuel ion ratio $n_t/n_d$ for DT plasmas. The method is based on neutron spectroscopy using only the 14 MeV neutron peak, which includes the BT and TH components [39].

Beyond the mentioned major BT, TH, RF and scatt components, there are additional components present in the spectra. For example, NBI fast ions can interact with each other, creating a Beam-Beam neutron component. However such reaction signatures are usually obscured in the experimental measurements due to low reaction rates. Additionally, the neutron spectra can be Doppler shifted to higher or lower energies depending on the position of the spectrometer and the direction of plasma rotation. This energy shift can be corrected for, as plasma rotation data is usually available.

An example of the neutron spectral component decomposition for a DD plasma for the TOFOR spectrometer [29] at the Joint European Torus (JET) tokamak is shown in figure 2.2. The intensities of different heating component signatures in the measured energy spectrum has been determined through fitting experimental data with shapes of energy spectral components derived from TRANSP simulations [47, 48, 49]. The components shown in figure 2.2 represent the best fit found for the experimental data for the 92398 discharge. Similarly, for DT plasmas, when the DD signature is obscured by scattered DT neutrons, it is possible to determine the different components, an example is shown in figure 2.3. The figure shows a measured energy spectrum by

![Figure 2.3. Example of simulated neutron energy distribution from JET DT plasma scenario containing different components. TH - thermal component, BT - component arising due to NBI particles interacting with thermal plasma, scatt - scattered neutrons. Diamond markers represent measured data.](image)

the JET Tandem neutron spectrometer [25] together with the best estimate of
components provided by TRANSP for JET discharge 43011. In this case, no RF heating was present.

In the presented cases it is readily evident that the energy distribution of fast ions can strongly influence the observed neutron spectrum, that is utilized to determine plasma parameters. Such trends can be observed in both DT and DD plasmas, where measurements in DT plasmas may have signatures from both DT and DD fuel ion fusion. A review of techniques used and future prospects of such applications in ITER can be found in [44].

2.2 Neutron Detectors

Though there are different types of neutron detectors, they all share a common feature of detecting secondary particles created by neutron interactions in the detector material or in a neutron scattering target. Some of the most common detectors used for neutron detection in fusion applications include fission chambers, scintillation detectors, solid state detectors, and diamonds. This section will provide a brief review of neutron detectors considered for fusion applications. A broader discussion of different neutron detection methods and techniques can be found in [40, 49, 50].

2.2.1 Fission Chambers

Fission chambers are well-established detectors used in fusion research [51] for neutron flux monitoring. They are based on the principle of the gas-filled ionization chamber with electrodes containing a fissile material. Neutrons induce fission in the electrode, and the energetic heavy fission fragments are then detected. Due to the high energy of the fission fragments, the neutron-induced signal can be discriminated from other types of reactions, making fission chambers useful in mixed radiation fields. However, the influence of neutron energy on the fission fragment energy is insignificant, resulting in the loss of information on neutron energy. Fission chambers typically have an efficiency of approximately 0.1 % and a dependency on the energy-variable fission cross section. Usually, fission chambers are based on $^{235}$U, which is primarily sensitive to thermal neutrons. Therefore, efficient measurements of neutrons from DD or DT fusion reactions requires neutron moderation [50]. Often the $^{235}$U chambers are complemented with $^{238}$U chambers which are selectively sensitive to the high-energy part of the neutron spectrum above approximately 1.5 MeV.

2.2.2 Scintillators

Scintillators can be made of various materials such as plastic, liquid (NE213, EJ301), organic crystals (e.g., stilbene), or inorganic crystals (e.g., NaI). The
basic principle behind neutron detection in scintillators is the neutron’s elastic scattering on hydrogen nuclei (protons) that produces recoil protons, which in turn deposit their energy in the detector media. Recoil charged particles create light in the detector media that is collected, converted to electrons and amplified in the Photo Multiplying Tubes (PMT). The resulting PMT electric signal amplitude is proportional to the scintillation light emitted following the energy deposition of charged particles generated by the interacting neutron.

If the detector response function is known, the collected pulse height spectra can be related to the deposited energy. Scintillation detectors are also sensitive to other types of radiation such as $\gamma$ rays. Fortunately scintillators like EJ301, NE213 or stilbene can discriminate between neutron and $\gamma$ induced electric signals by employing pulse shape discrimination methods [52, 53]. These detectors can have pulse length from few up to 500 ns, which makes them suitable for high particle flux conditions, as for example plastic scintillators employed in ToF spectrometer having typical pulse length of 40 ns [54]. Additionally, they can achieve high neutron detection efficiency. For example, in the Mega Ampere Spherical Tokamak (MAST) fusion reactor the scintillators of the installed neutron camera’s has efficiencies that ranges between 4-12% [55] depending on the set detectors parameters.

![Figure 2.4. Generic NE213 detector response function to 4.5 MeV neutrons. The x axis is electron equivalent energy in MeV.](image)

However, scintillation detectors have some limitations. They have relatively poor energy resolution and the energy resolution is non-linear with respect to particle energy. Furthermore, in many cases, especially when based on n-p elastic scattering, the response function is not suitable for spectroscopic measurements due to its broad shape for mono-energetic neutrons (see figure 2.4). The PMTs are also susceptible to magnetic fields and temperature variations, which is relevant in magnetically confined plasma physics applications [50, 55, 56].

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2.2.3 Diamonds

Diamond detectors for neutron spectroscopy application are typically artificially grown single crystal diamonds that can measure either 2.45 or 14 MeV neutrons. However, the origin of the signal differs. For neutrons up to 5-6 MeV the dominant neutron interaction is via elastic and inelastic scattering on carbon, so the detector can be used in a similar way as a scintillator using the scattered carbon deposited energy. For neutron energies above $\approx 5.7$ MeV a $n,\alpha$ reaction channel in $^{12}$C can be used. The created $\alpha$ and $^9$Be particles are charged and deposit energy in the detector medium, which creates a peaked energy distribution (see figure 2.5). Other threshold reactions like $n,p$ can also be used for spectroscopy purposes. However, the $n,\alpha$ has a very distinct signal, relatively low threshold and high cross section. It would be possible to perform spectroscopy in a similar way to scintillator detectors using reaction $^{12}$C$(n,n'3\alpha)$. An example of simulated diamond detector response to 10 MeV neutrons is shown in figure 2.5. Diamond detectors offer several advantages over other detector materials, such as radiation hardness, as noted in study [57]. Due to their high electron and hole mobility, with values of 2200 cm$^2/(Vs)$ and 1700 cm$^2/(Vs)$ respectively, these detectors can achieve response times of a few ns. Moreover, their relatively large band gap of 5.47 eV allows them to operate in room temperature or even higher temperatures without a significant increase in noise levels. In addition, diamond detectors have a relatively low sensitivity to $\gamma$ radiation. Diamond detectors have been tested in JET and have shown promise as neutron rate monitors and spectrometers [58]. However, diamond detectors do have some drawbacks, including their high cost, relatively small size and challenges in their production. Additionally, the presence of naturally occurring $^{13}$C in the detector can

![Figure 2.5. Generic diamond response function for 10±0.025 MeV neutrons based on Geant4 simulations.](image)
interfere with reactions induced in $^{12}$C. Ongoing research explores possible applications for diamond detectors [56, 59, 60, 61].

2.3 Neutron Spectroscopy Techniques

2.3.1 Time of Flight

In the field of neutron spectroscopy techniques, the time-of-flight (ToF) technique is commonly used to measure particle flight times and relate them to particle speed and energy. This technique is often used in experiments that have a well-defined start time, such as in accelerator target experiments. The energy resolution of ToF spectrometry is heavily dependent on the geometry of the spectrometer, with the length of the flight path and the measured time precision being key factors. For fusion devices that emit neutrons continuously, a double scattering set-up is required, with two sets of detectors measuring the flight time between them. The first detector provides the "start time" of the time-of-flight, while the second detector provides the "stop time".

This technique is common [62, 63] and has been successfully implemented at multiple fusion devices for neutron spectroscopy [29, 28, 64].

2.3.2 Proton Recoil Telescopes

Proton Recoil Telescopes are commonly used in proton accelerators and as neutron spectrometers using a neutron-to-proton converter [65]. The main idea behind this technique shares similarities with neutron detection in scintillators. While scintillators collect energy from scattered protons at all angles, the proton recoil telescope focuses on small-angle elastic neutron-proton scattering in a thin foil. The recoil proton energy ($E_p$) is directly related to the incoming neutron ($E_n$) energy and the n,p scattering angle $\theta_{lab}$ in the laboratory frame of reference:

$$E_p = E_n \cos^2(\theta_{lab})$$

and as a result enables us to determine the incoming neutron energy. Like the time-of-flight technique, the energy resolution is highly influenced by the geometric set-up of the spectrometer, as evident from the equation 2.1. The spectrometer efficiency and resolution can be varied by changing the geometrical parameters such as the distance between the neutron-to-proton converter and the detector. In addition, the spectrometer may need to be placed in vacuum to reduce the influence of proton energy loss and scattering during the transit between the converter and the detectors. While a single detector can be used, it can be advantageous to use multiple detectors (see figure 2.6) in coincidence mode to improve the signal-to-background ratio [50]. A neutron spectrometer using similar techniques has been implemented in JET [45, 66] and new spectrometers are being developed for fusion applications [59].
2.4 Thin-foil Proton Recoil Spectrometer

The TPR spectrometer is similar to the Tandem neutron spectrometer previously implemented at the JET tokamak [45, 66]. Due to size limitations of the silicon detector at the time of construction, an annular polyethylene foil was used as the neutron converter, and a cylindrical silicon detector was employed. Three identical spectrometers were placed one after the other to boost the detection efficiency. Fortunately, with recent improvements in silicon detector production, it is now possible to make larger, thicker, annular detectors which are well suited for proton recoil telescopes. The energy resolution in thin silicon detectors is significantly better than for scintillation detectors, which allows the use of a thin $\Delta E$ detector in coincidence with a thicker $E$ detector for coincidence measurements ($\Delta E - E$ measurements). Additionally, an annular design allows the detector to be placed at $0^\circ$ relative to the neutron beam and avoid direct background induced by the neutron beam. These advantages would make the TPR spectrometer superior to the previously implemented Tandem spectrometer. This set-up also prolongs the lifetime of the silicon detectors, as it minimises the neutron-induced radiation damage. Furthermore, segmented silicon strip detectors allow separate acquisition systems to be used for each detector segment, reducing the effects of pile-up. The detectors used in this work and their properties are described in more detail in Section 3.3. The goal of the TPR spectrometer in the ITER tokamak would be to contribute to the determination of the neutron energy distribution as well as the absolute neutron emission intensity for diagnostic purposes.
3. Silicon Detectors

“The cake is a lie” – Portal

Silicon solid-state detectors have been utilized in nuclear applications for over 50 years, but in recent years their size, quality, and availability have improved rapidly. Silicon detectors possess properties that are suitable for diagnostic applications in fusion devices, such as low sensitivity to magnetic fields, large area, good energy resolution, and a linear energy response for light charged particles [50, 67, 68]. This chapter will present the detection principles of silicon detectors, their sensitivity to gamma radiation, and the electronics necessary for signal detection. Section 3.1 will outline the detection principles, Section 3.2 the pulse handling, Section 3.3 the detectors used in the thin-foil proton recoil spectrometer and Section 3.4 provide a review of radiation hardness of silicon detectors and implications for future use in the ITER tokamak.

3.1 Detection Principles

![Figure 3.1. Principles of inducing a signal in a silicon surface barrier detector. The p-type dopant is shown in golden color at the top, while the bulk is a n-type semiconductor. The applied electric field causes the created free charges to drift accordingly.](image)

The detection principles explained below are common to all solid state detectors, but we will focus on silicon detectors as they are of key importance to this study. The main components of an n-type silicon detector are the n-type silicon bulk and the p-type doped silicon forming an n-p junction, as shown in figure 3.1. The different types of silicon are created by doping it with different atoms, for example p-type silicon can be created by doping with aluminum. An applied bias voltage across the detector depletes the n-p junction of free-charge carriers, thereby blocking the current. When charged particles cross the
detector, they create pairs of electrons and holes in the depleted region. The holes drift towards the p contact (junction), while electrons drift towards the n contact (ohmic). Charge collection generates a current signal at the contacts which can be amplified and detected using suitable electronics. Silicon has an electron mobility of $1350 \text{ cm}^2/(\text{Vs})$, while the hole mobility is $480 \text{ cm}^2/(\text{Vs})$, leading to charge collection times of around 10 ns. The band gap is 1.12 eV, which is large enough to allow for operation of silicon detectors at room temperature (300K). On average, a deposited energy of 3.6 eV will create one ionization event; particles of energies above a few keV can create a large number of charge carriers (electron-hole pairs) with low statistical fluctuations of the current. However, due to impurities and defects in the Si crystal, the depleted region may have remaining charge carriers, leading to a constant current flow (also known as dark current) and increasing the noise in the detection system [68, 69].

3.1.1 Gamma sensitivity

Although our main interest in silicon detectors in this thesis is for proton detection (see the discussion in Section 2.3.2), they are also sensitive to $\gamma$ rays and neutrons. Figure 3.2 compares the $\gamma$ ray sensitivity of various materials used in particle detectors [70]. The total cross section of organic scintillator (NE213) and silicon to $\gamma$ rays above 100 keV is comparable. Although the silicon cross section is lower than that of germanium, especially for energies between 20 keV - 200 keV, silicon has the advantage of operating at room temperature and is often used in X-ray spectroscopy [50]. However, in the current application a lower sensitivity to photons compared to germanium detectors is an advantage.

![Figure 3.2. Comparison of Germanium, Silicon and NE213 total $\gamma$ cross sections.](image-url)
3.2 Signal Shaping

Silicon detectors, as well as other solid state detectors, require dedicated electronic circuits to process the signals induced by charged particles. The following section presents an overview of commonly used equipment in spectroscopy applications.

The intrinsic signal created by solid state detectors is small and requires shaping and amplification to be recorded. Generally, the charge pulses created are amplified by a charge-sensitive amplifier, also known as a preamplifier. The preamplifier integrates the collected charge in the detector, and the resulting signal amplitude is proportional to the total charge collected. The signal decay time is a characteristic of the preamplifier; however, the signal rise time depends on both the preamplifier and detector characteristics. The principle schematic of the charge-sensitive amplifier is shown in figure 3.3, where $A$ is the preamplifier gain, usually in order of thousands, $C$ represents capacitance, $Q$ denotes charge, $U$ denotes voltage and $R$ is resistance. $C_D$ represents the detector, $C_{in}$ preamplifier input capacitance, and $U_{out}$ represents the voltage signal after amplification.

The preamplifier decay time is expressed as:

$$\tau = C_f \cdot R_f$$

(3.1)

where $C_f$ and $R_f$ are feedback capacitance and resistance.

![Figure 3.3. General schematics of a charge sensitive amplifier [68].](image)

The outgoing voltage signal can be expressed using the amplification and the capacitances:

$$U_{out} = -\frac{Q_{in}}{C_f + \frac{C_D + C_f + C_{in}}{A}}$$

(3.2)

If the sum of the feedback, $C_f$, and input, $C_{in}$, coupling capacitors is much larger than the capacitance of the detector, $C_f + C_{in} >> C_D$, the resulting signal
voltage can be approximated as:

\[ U_{\text{out}} \approx -\frac{Q_{\text{in}}}{C_f} \]  

(3.3)

This implies that the charge created in the detector is fully transferred to the preamplifier. If \((C_f + C_{\text{in}}) \ll C_D\) the output signal is inversely dependent on the capacitance of the detector, which can lead to loss of sensitivity and possible crosstalk between neighbouring detector channels. Consequently it is important to match the detector and preamplifier capacitance to ensure that the signal is independent of the detector capacitance and that the signal decay time is as short as possible.

Commonly, the trailing edge of the pulse after the preamplifier is much longer (\(>> 1\mu s\)) than the rise time, see figure 3.4 waveform on the left. To decrease the pulse length and increase the peak rise time, a combination of voltage amplifier with shaping circuit (also known as shaping amplifier) is used, as shown in figure 3.4 [68]. The resulting pulse tail has an undershoot, which can be corrected using a pole-zero restoration circuit that is usually included in the shaping amplifier. The final step in new systems is digitizing the signals using analog-to-digital converters (ADC), which allow the digitization of the full waveform at rates reaching up to 10 GHz [71]. High digitization rate and high ADC resolution enable skipping shaping amplifiers and performing shaping on-line using FPGAs or off-line using personal computers, with little loss of information. Digitised preamplifier pulses have been observed to provide additional information on the impinging particle [72, 73], which may be lost using the shaping amplifier. However, it should be noted that high-resolution fast ADCs are currently more expensive than shaping amplifiers.

![Figure 3.4. Commonly used acquisition scheme for solid state detector signals. Input from the detector goes through a charge amplification step where the current signal is converted to a voltage signal. The shaping stage is responsible for shortening the pulse while increasing the peaking time for better amplitude determination. Pole-zero restoration removes the undershoot after the signal to restore the baseline to a linear trend. Finally, the signal is digitized for further pulse height analysis.](image)
3.3 TPR Spectrometer Detectors

The silicon detectors in consideration for the TPR spectrometer are n-type annular silicon strip detectors. The bulk of the detector is n-type silicon semiconductor which has a thin layer of aluminium deposited as p implant. The silicon detectors used in this study are 0.3 and 1.0 mm thick double-sided silicon detectors (DSSD) of S1 type, purchased from Micron Semiconductor Ltd [67]. Each of the detectors has four quarters, and each quarter is divided radially into 16 segments on the front junction side. Additionally, the thick detector is divided into 16 segments on the rear ohmic side, while the thin detector has only one large segment. An example of a S1 type DSSD is shown in figure 3.5. The detectors have a dead layer of up to 0.5 μm, which is not sensitive to energy deposition on both the junction and ohmic sides [67]. In future applications, we intend to replace the current detectors with thicker ones of 0.5 mm and 1.5 mm, respectively, as they would be more suitable for higher energy neutron detection. For instance, the current TPR spectrometer’s first detector (0.3 mm) would stop protons up to 6.0 MeV, and the combination of both detectors (1.3 mm) would stop protons of 14.1 MeV, approximately corresponding to a neutron energy range of 6.5 - 14.5 MeV. With the indicated thicknesses the future TPR spectrometer should be sensitive to neutrons in the energy range of 9 - 18 MeV and thus suitable for application in fusion experiments.

![Figure 3.5. Drawing of the 1 mm thick silicon S1 detector. The front junction radial segments are depicted on the right side, while the rear ohmic segments are shown on the left side, as indicated by the labels.](image)

3.4 Radiation Hardness

Radiation hardness is a crucial consideration in nuclear physics experiments, where maintaining the properties of experimental equipment is essential for obtaining consistent results.
In this section, we will discuss the various pathways of radiation damage, the dependence of damage on particle fluence, and the effects of radiation damage on silicon detector performance. We will also estimate possible radiation damage to the TPR spectrometer in ITER. While our discussion will focus on silicon detectors, the physical processes are similar in most semiconductor detectors.

Damage pathways for silicon detectors depend on the impinging particle. For neutron spectrometer applications, such as the TPR spectrometer for fusion neutron diagnostics, it is sufficient to consider neutron and proton damage since these particles will dominate the fluence on the detectors and have higher mean energy compared to other particles. There are several main damage pathways induced by impinging energetic particles for silicon detectors:

- Lattice atom displacements
- Nuclear reactions
- Secondary processes from displaced energetic lattice atoms

The displacement of a lattice atom is one of the most straightforward damage pathways. To displace a silicon atom, a minimum energy of approximately 25 eV is required. Recoil silicon atoms of up to 2 keV create point defects, while 12 keV is sufficient to create multiple clusters of displaced atoms. Most of the defects will appear at the end of the recoil silicon or ion track because energy loss increases with decreasing ionised particle energy. A proton and neutron is required to have at least 185 eV to displace a silicon atom via elastic scattering and create a defect. For proton and neutron energies above 35 keV, the displaced silicon creates a cluster of defects. A more in-depth discussion of this subject is beyond the scope of the thesis, and we refer the interested reader to [68, 74] for additional information on radiation damage pathways.

Unfortunately, these effects are difficult to measure experimentally, and these numbers are based on simulations. Most of the created displacements are temporary due to lattice thermal motion at room temperature. However, part of the defects become stable and damage the crystal lattice. An example of a stable defect is the displacement of two silicon atoms next to each other, as thermal motion of the lattice is not sufficient to fill in the created vacancy [68]. Radiation damage leads to multiple macroscopic effects:

- Increase of dark current
- Decrease in charge collection efficiency
- Change of depletion voltage due to changes in crystal energy levels

All the above-mentioned effects directly influence the electronic signal and impact detector performance. For example, the detector energy resolution and pulse height may become dependent on the interaction position, leading to a general degradation of the energy resolution. In more severe cases the resulting radiation damage could lead to inter-strip isolation breakdown, which in turn increases the charge sharing between the neighbouring strips [75, 76].

Fortunately, it is possible to partially restore the performance of a detector even in the presence of stable defects. Annealing at high temperatures can
partially break up such defects. For instance, the previously mentioned double silicon vacancy can be restored at temperatures exceeding 570 K. Another way to compensate for the damage and improve charge collection is to increase the bias voltage \[68, 77, 76\]. Additionally, performing a position-resolved energy calibration can significantly enhance the performance of a radiation damaged detector [75].

Silicon detectors are widely used in nuclear physics applications, and as a result, there have been numerous studies on radiation damage. Previous research has shown that a 2 MeV proton beam with a surface fluence of up to \(10^{11} \text{protons/cm}^2\) does not significantly affect the dark current or energy resolution of silicon detectors. However, for higher proton fluences, the dark current increases linearly with fluence. For example, the detector dark current after proton fluence of \(10^{12} \text{protons/cm}^2\) would rise approximately three times [78]. According to [50] severe detector damage would occur at fluences greater than \(10^{12} \text{protons/cm}^2\). A study [76] has shown that a 12 GeV energy proton fluence of \(4 \times 10^{13} \text{protons/cm}^2\) resulted in a charge loss of up to 30% at the full depletion voltage, although the damage should be somewhat more limited for lower energy protons.

Due to different dominating damage pathways, the neutron fluence limits are lower; as discussed in [50] severe detector damage appears for neutron fluence above \(3 \cdot 10^{11} \text{neutrons/cm}^2\).

3.4.1 Radiation Damage at ITER

The TPR spectrometer is planned to be used as part of the HRNS [79] system in the harsh radiation environment in ITER. Therefore, it is essential to assess the possible influence of radiation damage on the performance of the silicon detector during operation. The particles most likely to induce radiation damage are neutrons and protons. Their intensities can be roughly estimated based on the discussion presented in PAPER I of this thesis. For instance, considering the worst-case scenario for radiation damage and maximum fusion power, we selected one of the optimised TPR spectrometer designs from PAPER I with a detection efficiency of \(\approx 2 \cdot 10^{-5}\) and assumed a neutron intensity of \(10^{10} \text{neutron/s}\) at the spectrometer foil. The area of the detector in question is approximately 5500 mm\(^2\). Assuming ITER operation of 4700 hours [13], this would result in a proton fluence of \(6.2 \cdot 10^{10} \text{protons/cm}^2\) throughout the lifetime of ITER. A similar order of magnitude of neutron fluence is expected to reach the detectors due to scattering in the detector foil.

The TPR spectrometer will be exposed to impinging proton and neutron energies of up to 20 MeV in ITER conditions. On the basis of previous discussions, it can be concluded that proton radiation damage is unlikely to have a significant impact on detector performance. However, silicon detectors may experience performance degradation due to neutron flux, which can be par-
tially mitigated by annealing, increasing the applied bias voltage, or employing more advanced methods [75].

Additionally, as discussed in PAPER I and PAPER II, the TPR neutron spectrometer resolution is mainly defined by the geometrical parameters, and a small degradation of the intrinsic detector energy resolution due to radiation damage would have a negligible influence on the spectrometers performance. The estimated neutron and proton fluences indicate that, during normal operation, the detectors should last the expected lifetime of ITER with only minor degradation of energy resolution. However, it is important to note that this is a first-order estimate, and additional neutron flux sources, such as back-scattering, have not been considered.
4. Designing the TPR spectrometer

“I am always doing what I cannot do yet, in order to learn how to do it.” – Vincent Van Gogh

The purpose of the research presented in this thesis is to demonstrate that a TPR neutron spectrometer can be used to determine the DT neutron spectra in different plasma scenarios at ITER. The development of such a system requires multiple steps involving both experimental work and extensive simulations. The work presented here is divided into separate parts according to topics:

- Simulations of TPR Spectrometer Performance in ITER-like plasmas
- Development of a Prototype TPR Spectrometer and model validation
- Neutron diagnostics using a TPR-like spectrometer in JET DTE1 campaign

4.1 Simulations of TPR spectrometer performance in ITER-like plasmas

Before a spectrometer system is built, it is of high relevance to determine the spectrometer prototype parameters. It is important to estimate diagnostic capabilities of the selected spectrometer design in ITER and determine whether the spectrometer can perform measurements within the required temporal resolution. Furthermore, it is relevant to determine the range of plasma parameters we can expect the spectrometer to perform within the required parameters for diagnostics in ITER. This topic was discussed in detail in PAPER I.

PAPER I results demonstrated the potential of the spectrometer to meet the expected efficiency, resolution, and diagnostic requirements for high-power ITER plasma scenarios. However, the simulations discussed in PAPER I were based on simple assumptions that included only first-order effects. To quantify a more realistic spectrometer response, a dedicated Monte Carlo simulation is necessary. For these purposes, we developed an experiment model using a combination of Geant4 and MCNP6.1. Geant4 was used for the estimation of the spectrometer response while MCNP6.1 was used for estimation of background radiation in a realistic ITER-like experimental set-up. We have selected a worst-case scenario where the access between the two areas (marked cuboids 1 and 2 in figure 1.3) is plugged to create an extensive neutron background signal. Furthermore, we have included the experimentally determined
energy resolutions of each silicon detector and estimated the effects of random coincidences and pile-up events on the measurements. The results are discussed in PAPERS II & III. A more thorough discussion of the main findings is presented in Chapter 5.

4.2 Development of Prototype TPR Spectrometer and experimental measurements

The performed simulations in PAPERS I & II have provided an optimistic outlook of the TPR spectrometer performance at ITER. However, an experimental verification of such simulations would increase confidence in the developed model.

For these purposes a prototype TPR spectrometer has been designed and constructed according to the findings in PAPERS I - III. The prototype TPR spectrometer was tested using a DT neutron generator at Lund University, Department of Applied Nuclear Physics. The generated neutron spectra is peaked around 14 MeV with significant scattered neutron contribution as is also expected in ITER DT plasma conditions. The development of the TPR spectrometer acquisition and analysis system is described in detail in Chapter 6. The results of the experiment are discussed in PAPER IV and an overview of the main findings is provided in Chapter 7.

4.3 TPR like spectrometer neutron diagnostics at JET

An experiment at a DT fusion device using a prototype TPR spectrometer would further increase confidence in such system, however this was not possible in the current time scale. However, a neutron spectrometer [45, 66] based on the same detection principles has been operating in JET during the DT1 campaign [80]. We have reviewed the old data and used a newly developed spectrometer response function in PAPER V to estimate the fuel-ion ratio for certain discharges. The main results are outlined in Chapter 8 which should help to increase confidence in the performance of thin-foil recoil spectrometers in fusion devices.
5. Simulation of the performance of a TPR spectrometer for ITER

"Anything that can go wrong will go wrong" – Murphy’s law

This chapter presents an overview of the main findings published in PAPERS I, II and III, which focused on the design and simulations of a TPR spectrometer for applications in ITER. Two topics were investigated in PAPER I: spectrometer design for maximum efficiency at various resolutions, and analysis of the performance of the selected spectrometer design for ITER-like plasma conditions. Together, the two topics show a path to designing and estimating the performance of a TPR spectrometer specifically for applications at ITER. PAPERS II and III investigated the performance of the previously optimised TPR spectrometer in ITER conditions using dedicated Monte-Carlo particle transport code Geant4. The papers investigated the spectrometer resolution, detection efficiency, signal-to-background ratio, pile-up and coincidence influence on the measured energy spectra and expected detector count rates.

5.1 Spectrometer Design Optimisation

The design of the TPR spectrometer is relatively simple, as shown in figure 2.6. As mentioned, the spectrometer consists of a polyethylene foil and two Si detectors in a proton telescope configuration. For application in ITER the polyethylene foil area was fixed at 10 cm\(^2\) to match the collimator. The spectrometer’s performance parameters depend mainly on the thickness of the scattering foil (f), the distance between the two detectors (D) and the distance between the foil and the first detector (L). Unfortunately, the spectrometer’s energy resolution and efficiency are anti-correlated, and thus the spectrometer requires a purpose-specific optimisation. For applications in ITER, the spectrometer’s energy resolution (FWHM) is required to be below 5% to be comparable to the thermal broadening of the neutron emission from a 10 keV plasma\(^1\) and to provide the required measurement accuracy, as discussed in section 1.4. Since silicon detectors will have an intrinsic energy resolution, a safety margin was left and the designs were optimised for 4.3% FWHM energy resolution. Efficiency-optimised TPR spectrometer designs were found

\(^1\)In the context of DT plasmas, the neutron peak’s broadening \(\Delta E\) (FWHM) correlates directly with the plasma’s temperature, denoted as \(T\) (in keV): \(\Delta E = 177\sqrt{T}\).
Figure 5.1. Panels A and B show design geometrical parameters. $L$ is the distance between the foil and the first detector, $f$ is the thickness of the foil, $D$ is the distance between the two silicon detectors in the telescope configuration. Panel C shows the detection efficiency and resolution relation for non-segmented, while panel D for segmented spectrometer designs. Comparing panels C and D it is obvious that the efficiency using the segmentation of the detector is higher than for non-segmented for the same energy resolution. The labelled points are interrelated between the panels. The blue shaded area marks the spectrometer designs which have a better energy resolution than 4.3%.

using the PROTON code, which was one of the main focuses of PAPER I. The simulation results are shown in Figure 5.1. Each black point in panels A - D refers to an investigated design, while colour coded markers correspond to efficiency optimised designs for specific resolutions and are related in-between the panels. The numbered markers denote a non-segmented spectrometer design, while letter labelled markers denote an 8 channel radially segmented spectrometer design. Note that the colour coded markers correspond to the
designs with the highest efficiency for a specific resolution, as there are no designs above the coloured markers in panels C and D. Consequently, these designs represent a Pareto front [81] for all investigated TPR spectrometer designs. Panels A and B show different relations between geometric parameters (f, D, L) of the TPR spectrometer, while panels C and D show the relation between efficiency and resolution for all investigated spectrometer designs. Two spectrometer designs marked by "case 1" and "case 2" have the highest efficiency and an energy resolution better than 5%. For example, the "case 1" design does not employ detector radial segmentation, has a foil thickness of 0.15 mm and a distance between the foil and the first detector of 240 mm (figure 5.1, panel A) which leads to an energy resolution of 4.3% FWHM for 14 MeV neutrons and an absolute detection efficiency of $2.17 \times 10^{-5}$ (panel C). The "case 2" design employs detector radial segmentation, has a foil thickness of 0.14 mm, a distance between the foil and the first detector of 165 mm and a distance between detectors of 28 mm. This leads to an energy resolution of 4.3% FWHM for 14 MeV neutrons and an absolute detection efficiency of $2.76 \times 10^{-5}$ (panel D). The "case 2" design has higher efficiency for the same energy resolution due to the inclusion of radial segmentation in the analysis of energy spectra. If required, the design can easily be modified to increase efficiency or resolution by, for example, changing the spectrometer foil without the need to change the detectors or data acquisition system. Interchangeable foils have previously been implemented on the magnetic proton recoil spectrometer [30].

5.2 ITER-like plasma analysis

As discussed in chapter 2, NES (Neutron Emission Spectroscopy) can be used to determine different plasma properties, which was the second focus of PA-PER I. For this study, we estimated the number of spectrometer counts required to predict the fuel ion ratio $n_i/n_d$ and the fuel ion temperature, $T_i$, with uncertainties of 20% and 10% respectively, by employing NES. The spectrometer design for this purpose was selected as "case 1" and "case 2" (4.3% FWHM), as described in the previous section and shown in figure 5.1. Both of the selected spectrometer designs have a Gaussian-like response function. During experiments, the determined neutron energy spectra is not sufficient to estimate the fuel ion ratio. There is a necessity of apriori information about plasma parameters, such as fusion reactivity, which is dependent on fuel ion velocity distributions and fusion cross sections. Moreover, the spectrometer’s line of sight must be taken into consideration when determining the neutron emission energy spectrum in the direction of the detection system. However, the major contribution to the uncertainty $n_i/n_d$ is related to neutron emission due to the interaction of beam particles with the thermal plasma. Here, we define it as Beam Power Fraction (BPF), which is a ratio of neutron flux imping-
ing on the spectrometers produced by beam-thermal reactions in the plasma, relative to the total incoming neutron flux. An earlier investigation of \( \frac{n_t}{n_d} \) determination has demonstrated that an uncertainty of 10% in the determination of the BPF corresponds to approximately a 20% uncertainty in the \( \frac{n_t}{n_d} \) ratio [82]. Therefore, the results are presented in uncertainty on BPF rather than \( \frac{n_t}{n_d} \).

Figure 5.2. A - SPEC results on required number of counts to measure BPF with 10% uncertainty; B - SPEC results on required number of counts to measure \( T_i \) with 10% uncertainty.

The simulations of \( \frac{n_t}{n_d} \) and \( T_i \) uncertainty require multiple input parameters on the neutron spectrometer conditions. In this case, the input parameters are the spectrometer response function (simulated using PROTON), the synthetic neutron energy spectrum from a ITER-like plasma and the parameter space of interest. Here, based on the optimised designs discussed above, a TPR design with a Gaussian-like response function with \( \Delta E/E(\text{FWHM}) \) of 4.3% was used. The uncertainties presented solely depend on the number of counts in the synthetic neutron energy spectra and, as a result, are of statistical nature. The results of number of counts in the spectrometer can be seen in figure 5.2 where the plots show the number of counts required to achieve an uncertainty less than 10% for BPF (panel A) and for \( T_i \) (panel B). The x, y axis show plasma scenario parameters, and specifically the BPF and fuel ion temperature \( T_i \) respectively. These results enable to estimate for what kind of plasma scenarios it is possible to determine \( T_i \) and \( \frac{n_t}{n_d} \) within the desired uncertainty for a TPR spectrometer at ITER. No significant differences were observed between "Case 1" or "Case 2" in terms of number of counts required to determine the plasma parameters. However, as "Case 2" detection efficiency is higher, it would be able to achieve a better temporal resolution than "Case 1" spectrometer. In addition, these results can be applied also to other neutron spectrometers with Gaussian-shaped response functions of similar resolution.
5.3 Spectrometer performance in DT plasma conditions

PAPERS II and III concern a possible implementation of the previously optimised TPR spectrometer designs under ITER-like conditions, using realistic neutron spectra and divergent neutron beam as expected in ITER. For these two articles, simulations were performed using a combination of MCNP6.1 and Geant4 and the conceptual design of the HRNS system [33, 35]. Both articles considered an identical foil area of 10 cm² and detector thicknesses of 0.5 and 1.5 mm (as discussed in the section 5.1). The spectrometer design parameters are specified in table 5.1 where \( f \) is the foil thickness, \( D \) is the distance between the two detectors in a proton telescope configuration and \( L \) is the distance between the scattering foil and the first detector. The results on energy resolution for Design 1 vary between the papers as it was decided to slightly increase the margin on error on the FWHM.

<table>
<thead>
<tr>
<th>Design</th>
<th>Paper</th>
<th>( f ) (mm)</th>
<th>( L ) (mm)</th>
<th>( D ) (mm)</th>
<th>Efficiency (%)</th>
<th>FWHM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>II</td>
<td>0.16</td>
<td>250</td>
<td>2</td>
<td>( \times 2.4 \times 10^{-5} )</td>
<td>4.6</td>
</tr>
<tr>
<td>Design 1</td>
<td>III</td>
<td>0.15</td>
<td>245</td>
<td>0</td>
<td>( \times 2.3 \times 10^{-5} )</td>
<td>4.3</td>
</tr>
<tr>
<td>Design 2</td>
<td>II and III</td>
<td>0.14</td>
<td>165</td>
<td>28</td>
<td>( \times 3.0 \times 10^{-5} )</td>
<td>4.3</td>
</tr>
</tbody>
</table>

For PAPER II, we have calculated the coincidence energy deposition in the two \( \Delta E - E \) TPR spectrometer detectors. The main focus of the article was to show that using a region of interest (ROI) on a two-dimensional \( \Delta E - E \) energy deposition map would improve the signal-to-background ratio (s/b) of the determined neutron energy spectra. Furthermore, by combining experimentally determined resolutions of the silicon detectors with the simulation results, we show that the geometry of the spectrometer predominantly determines the energy resolution of the neutron spectrometer.

The simulations were divided into two separate parts to the energy deposition in the TPR spectrometer: i) a direct source neutron contribution and ii) a background contribution. The direct source neutron contribution was estimated using a nearly monoenergetic \( 14 \pm 0.025 \text{ MeV} \) neutron beam, with a Geant4 simulations model of the TPR spectrometer. The neutron background contribution was estimated using a combination of MCNP6.1 and Geant4. The MCNP6.1 model contained a detailed layout of the spectrometer, surrounding systems similar to the presented HRNS spectrometer in figure 1.3.
shielding [79] and a realistic ITER-like neutron spectrum. This combination allowed us to estimate more realistic, than implemented in PAPER I, spectrometer working conditions and possible gamma and neutron background contributions. All background neutron and gamma particles entering the detectors were recorded for further transport using Geant4 to estimate their energy deposition in the TPR spectrometer.

The simulation results yielded an energy resolution for a 14 MeV neutron beam of 4.6% ($\sigma_{\text{sim}} = 276 \text{ keV}$) for both designs; after including the experimentally determined intrinsic detector resolution ($\sigma_{\text{det}} = 120 \text{ keV}$), however, it changed to 5.0 % and 5.1 % for Design 1 and 2 respectively. For Design 1, it was assumed that there was only one segment per detector, while for Design 2 eight radial segments were considered, as discussed previously. In addition to this, the signal-to-background (s/b) ratio was estimated with and without background reduction. By introducing appropriate cuts in the $\Delta E - E$ bidimensional distributions, an improvement of the s/b by more than a factor 10 can be achieved. For Design 1, the s/b without cuts was 3600, while after applying energy cuts the ratio was 94000. Similar results were obtained for Design 2. In addition, the simulations confirmed the PROTON results from PAPER I, suggesting that a Design 2 spectrometer would have higher efficiency compared to Design 1, and be more compact while having near identical resolution. The results are important as they show that the TPR spectrometer would be able to distinguish the signal induced by the collimated neutron beam from the background using $\Delta E - E$ energy cuts.

5.4 Estimates of signal-to-background ratios and count rate limits for ITER like plasmas

PAPER III continues the research presented in PAPER II by including coincidence and pile-up effects that were not accounted for previously. For this purpose, an additional simulation was performed to include effects arising due to random coincidence and pile-up events in the spectrometer’s detectors and assess how these events will affect the resulting energy distribution. The simulation was performed for the worst case ITER scenario, assuming the maximum expected neutron rate of $10^{10}$ neutrons/s impinging on the spectrometer foil. Moreover, in this study Design 1 was modified to take into account 8 radial detector segments, compared to only one discussed in PAPER II, which slightly improved the energy resolution of the Design 1 spectrometer to 4.7% (FWHM). The resulting simulated energy distribution was broadened by the expected intrinsic detector energy resolution and the calculated $\Delta E - E$ coincidence energy spectrum is shown in figure 5.3. An energy threshold of 100 keV was used during the data analysis, because low energy x-rays are likely to influence the baseline rather than create a real detectable pile-up, due to their very low energy deposition and high count rate. Panel A in figure 5.3 shows a
two dimensional histogram of the energy deposition in both of the $\Delta E$ and $E$ detectors, while panel B shows an example of the imposed $\Delta E - E$ energy cuts for Design 1, detector segment 1. The bounds for energy cuts were calculated for each of the segment combinations. The energy cuts were determined from the spectrometer response function simulations performed with Geant4 in a neutron energy range of 8 - 18 MeV. Figure 5.4 shows the total energy deposition $E_{total} = \Delta E + E$ for different source components: $\gamma$ background, neutron background, signal and random coincidence and pile-up. Each of these components was estimated in a separate simulation:

- background - MCNP6.1+Geant4 combined simulation of neutron and $\gamma$ induced energy deposition due to scattered particles interacting in the detectors. The MCNP6.1 model included the HRNS enclosure (cuboids 1&2 as marked in figure 1.3) and was used to produce a background source of scattered particles hitting the detectors and the surrounding shielding. For conservative estimate it was considered that the beam port at the end of cuboid 1 is plugged with boron carbide. This source was then used in a Geant4 simulation to score particle energy deposition in the detectors.

- signal - energy deposition induced by neutron interaction in the spectrometer foil simulated using Geant4 only. The model contained only the TPR spectrometer (foil and the two silicon detectors). Energy deposition is mainly dominated by protons knocked-out from the TPR spectrometer foil. No surrounding structures were modelled to avoid double counting events from the background simulations.

- random coincidence & pile-up - simulation which estimated random double coincidences and pile-ups at a maximum neutron rate of $10^{10}$ neutrons/s impinging on the spectrometer foil using both signal and background simulation results.

Figure 5.3. A - Energy deposition in $\Delta E$ and $E$ detectors, B - The determined energy cuts (two dashed lines) for first inner segments in both $\Delta E$ and $E$ detectors for all neutron energies of interest. The two dashed lines mark the region-of-interest where most of the proton induced energy deposition will take place.
Panel A in figure 5.4 shows the comparison of total energy deposition for different components. The steep change in the intensity at approximately 8 MeV in "signal" (dashed curve) is a consequence of a proton punch through the first 0.5 mm detector. Protons stopping in the first ΔE detector do not induce a proton coincidence signal, consequently only higher than 8 MeV protons would create a coincidence signal. The simulated total energy deposition in both of the detectors with and without ΔE − E energy cuts is displayed in panel B. The high intensity change at 8 MeV is more evident in panel B after applying the energy cuts which effectively removed the events not related to proton coincidence energy deposition. The energy cuts were applied to each possible combination of detector segments in order to select only those events which fall within the two dashed curves shown in figure 5.3 B. Each spectrometer segment combination has a slightly different ΔE − E energy cut due to variations in proton scattering angle and detector area.

Figure 5.4. A - Simulated total energy deposition for different components, B - simulated total energy deposition in the TPR spectrometer detectors (sum of components in panel A) and the same energy deposition after applying the ΔE-E energy cuts.

The main take-away from the paper is presented in figure 5.5 showing signal-to-background ratios as a function of energy deposition for both designs, with and without energy cuts. As shown in the figure, ΔE − E energy

Figure 5.5. A - s/b dependence on energy deposition for the Design 1 spectrometer with and without ΔE - E energy cuts, B - same as panel A but for Design 2 spectrometer.
cuts can significantly improve the s/b ratio. Of particular importance is the region of neutron energy above 15 MeV, where the spectrum is dominated by the beam (NBI) - thermal neutron emission component. Measuring the NBI neutron signature intensity is crucial to determine $\frac{n_c}{n_{th}}$ using the method discussed in [82]. The figure indicates that the currently achieved s/b at expected maximum count rate in ITER is sufficient to perform required NES data analysis to obtain both $\frac{n_c}{n_{th}}$ and $T_i$. In addition, the simulations performed are consistent with the findings presented in PAPER II, showing that TPR spectrometer energy resolution is mainly determined by the geometry and that Design 2 is more compact and has a higher efficiency than Design 1. Furthermore, the simulated maximum count rates are up to 120 kHz per detector segment for both spectrometers Design 1 and 2, which is manageable by the intended acquisition system assuming 8 acquisition channels per detector. From the simulation results it is estimated that the expected pile-up rate is below 5% at a maximum expected count rate.
6. Development and energy calibration of a TPR Spectrometer

“For even the very wise cannot see all ends.” – J.R.R. Tolkien

This chapter is dedicated to the experimental development of the separate parts of TPR spectrometer: acquisition system (Section 6.1), data reduction (Section 6.2) and energy calibration of its silicon detectors (Section 6.3).

The energy calibration was performed at the Uppsala University Tandem laboratory [83] using mono-energetic proton beams. The experimental set-up for the energy calibration of the detectors was kept as similar as reasonably possible to the DT neutron energy spectrum measurement experiment.

6.1 Acquisition System

The acquisition system was developed for the available double-sided silicon detectors as described in Section 3.3. For the TPR spectrometer conceptual tests, it was decided to use only a quarter of the detector’s area, due to limited number of digitizer channels available. This provided sufficient spectrometer detection efficiency to test the TPR spectrometer concept while maintaining the acquisition system relatively simple. Furthermore, this set-up allowed matching the detector capacitance with the preamplifier characteristics and achieving shorter signal rise times for the detector signals.

For these tests, the spectrometer was used in a \( \Delta E - E \) configuration in which the 16 radial strips were connected to groups of 4 strips corresponding to one radial segment. This was done for both of the detectors, and each radial segment was connected to one preamplifier. The preamplifier was placed outside the vacuum chamber as close to the detectors as possible, to minimise pick-up in the cables and cable capacitance. The amplified signal was then sent to the control room via > 10 meter long coaxial cables to the two digitizers. The simplified scheme of signal propagation is shown in figure 6.1. The acquisition system was composed of an 8-channel CAEN A1422 charge sensitive preamplifier [84] and two 4-channel ADQ412 digitizers [71], specifically ADQ412-3920 and ADQ412-0901.

Each digitizer was connected to two segments from each of the detectors. The connection scheme of the detector segments to the digitizers is shown in figure 6.2, this allows recording all channels in one of the digitizers for each trigger event, thus recording waveforms and associated time information.
from each of the digitiser channels. The drawback of this configuration is the following: there is a loss of information as particles can depositing energy in the detector segments connected to different digitizers. This is particularly affecting events with a coincidence between segments E and D (this also corresponds to digitizer channels E&D), such events will create two trigger events, one in each of the two digitizers. Due to lack of synchronisation these separate triggered events cannot be correlated and consequently will be interpreted as two separate particle interactions. The same reasoning holds for events in segments B and G. However, the possibility of the proton of interest interacting in both segments B and G is negligible due to proton kinematics and the geometry of the spectrometer set-up (see figure 6.2). Synchronisation of the digitizers was not possible due to differences in hardware versions.

Figure 6.1. Logical scheme of signal acquisition for the TPR detectors. Preamplifier - CAEN1422, digitizer - ADQ412.

Figure 6.2. Scheme of the detector segment connection to the digitizer channels. Each channel is connected to 4 radial detector strips.

The ADQ412 digitizer has 12-bit amplitude resolution and 800 mV peak-to-peak input range. A control software based on Python 3.6 was used during the acquisition. In general, a large number of parameters can be set for the ADQ412 to match the circumstances of the acquisition. Parameters of relevance, in order to acquire the preamplifier signals for this test set up, (with an indication of their default values) are shown below:

1. Number of records
2. Number of samples per record (2048 samples)
3. Number of pre-trigger samples (512 samples)
4. Sampling frequency (15625 kHz, 64 ns between the samples)
5. Amplitude Offset
6. Acquisition channel
7. Trigger edge (falling)
8. Trigger level
9. Trigger channel

The number of records defines how many triggered events the digitizer will record before terminating the acquisition and saving the data to external storage. For each triggered event, the digitizer records a total of 2048 of samples, of which 512 are before the trigger level crossing. The pre-trigger samples are used for baseline reconstruction.

Trigger amplitude offset capability was used on one of the digitizers (ADQ-3920) while 3dB attenuators were used on the other (ADQ-0901) because the offset capability was not available. This was necessary for the DT experiment to make sure the pulse amplitudes are within the digitizers voltage input range. As a result, the ADQ412-0901 digitizer had an input range from -400 mV to +400 mV, while ADQ412-3920 had input range of -600 mV to +200 mV.

The only difference in the acquisition set-up between the energy calibration at the Tandem laboratory and further experiments at the DT neutron source was the trigger channel and trigger configuration. In the energy calibration each digitizer channel was active to trigger, while in the DT experiment acquisition an additional trigger mode was used. Part of the acquisition was performed with active triggering on the thick E detector only because the main interest was in coincidence signals. An example of the configuration file is attached in APPENDIX A: configuration file for energy calibration measurement and APPENDIX B: configuration file for DT experiment.

6.2 Data Reduction

This section explains how pulse height spectra (PHS) were extracted from the digitised preamplifier waveforms and converted to energy spectra. The recorded waveforms were of negative polarity, however out of convenience they were inverted during the analysis procedure.

The digitized waveforms were analysed to select only waveforms which had little noise, no pileup or lacked other artefacts obscuring the PHS features of interest. The data analysis sequence used in this experiment, as presented below, is followed by a discussion.

1. Baseline restoration subtracting the mean of the first 256 samples.
2. Timing and amplitude estimation
3. Pulse height spectra estimation
4. Fitting pulse height spectra with Gaussian function
Selection of relevant waveforms

Unfortunately the experimental conditions are rarely perfect and there are often waveforms which have been influenced by electromagnetic fields, background loops, pile-ups etc. It was decided to use only waveforms where the amplitude could be determined unambiguously to simplify the interpretation of the results and the analysis of the PHS.

Waveforms that have their amplitude maximum located in the first 256 or last 448 samples were excluded from the analysis because it complicated the baseline correction, determination of rise time, and/or extraction of amplitude.

Waveforms that were below the trigger level after the baseline correction were removed. An example of such rejected waveforms is shown in figure 6.3. The pile-up rate in the energy calibration experiments was negligible, and no explicit pile-up correction was performed.

![Waveform example](image)

*Figure 6.3. Example of waveforms removed from the analysis from the DT experiment. The waveform in the dashed black line contains an inverse polarity pulse which is correlated with the pulse arrival in a neighbouring silicon detector segment. The waveform in blue dash-dot was recorded due to a trigger of the system in one of the other channels. The waveform in red solid line contains multiple pile-ups and energy information is lost.*

Timing and amplitude estimation

The selected waveforms have been interpolated using the sinc interpolation function, otherwise known as Whittaker-Shannon interpolation [85]. The sinc interpolated waveform had a sampling period of 2 ns (equivalent of 0.5 GHz sampling frequency). This enabled to extract the waveform timing information with higher accuracy than from the original data points. The interpolated
waveform was then used to find the maximum amplitude, as well as the rise time and the signal arrival time. It is assumed that the signal arrival time is when the interpolated amplitude reaches 20% of its maximum. The rise time was defined as the difference between the times at 95% and 20% of maximum amplitude.

**Pulse Height Spectra Analysis**

The pulse height spectra were assembled by collecting the extracted maximum amplitude value for each of the accepted pulse waveform into a pulse height histogram. The pulse height spectrum was fitted using a Gaussian function with custom selected boundary region as shown in figure 6.4. An example of pulse height spectrum for a 4 MeV proton beam and used for the energy calibration of the ΔE detector is shown in figure 6.4.

![Example of an experimental pulse height spectrum for the ΔE detector segment A for impinging proton energy of 4 MeV. This corresponds to 3.9 MeV energy deposition due to proton energy loss in gold foil and back-scattering. Left panel shows the total energy spectrum with fit parameters of mean and FWHM, right panel shows a close up of the peak. Red vertical lines mark the boundaries of the fit.](image)

### 6.3 Energy Calibration

**6.3.1 Experiment set-up**

Energy calibration of the detectors was done using a mono-energetic proton beams in the energy range of 3 - 7 MeV at the Uppsala Tandem accelerator. The beam current was around 1 nA to keep pile-up rates at acceptable (low) levels. The ΔE and E silicon detectors were placed inside a vacuum chamber at a pressure of approximately 10⁻⁴ mbar. The proton beam was impinging on a thin 140 ± 14 nm gold foil where some of the protons were back-scattered towards the detectors as shown in figure 6.5 where the proton beam is marked by...
the red line. Placing the detector in the forward direction of the scattered protons was not possible, due to the high count rate and large amount of pileups even at the accelerator lowest current limit. A beam dump was present at the end of the experiment chamber. Steel plates of approximately 1 mm thickness were placed on both sides of the gold foil to block the protons back-scattered from the beam dump from reaching the detectors.

Protons which back-scattered from the gold foil would lose a small fraction of their energy in the gold foil, while the rest of their energy would be deposited in the silicon detector. The detectors in question are DSSD silicon detectors of 0.3 and 1.0 mm thickness discussed in the previous section 3.3. Further subsections cover the details of the conducted experiments.

![Figure 6.5. Energy calibration measurement set-up, distance between gold foil and detector is approximately 30 cm.](image)

The proton’s energy loss due to back-scattering in the gold foil was estimated using the particle transport code SIMNRA [86]. SIMNRA was also used to estimate the proton energy spread due to the solid angle of the detector with respect to the gold foil.

The energy calibration for both of the detectors was done using proton beam energies of 3.5, 4, 5, 6 and 7 MeV. The mean deposited energy in the silicon detectors after taking into account the proton energy loss due to back-scattering in the gold foil should correspond to 3.4, 3.9, 4.9, 5.9, 6.9 MeV respectively. For the thin ΔE silicon detector the 7 MeV proton beam would punch through the detector loosing approximately 4.2 MeV energy, depending on the proton angle.
6.3.2 Waveform Deviations

It was observed that pulses from the thick silicon detector have two distinctly shaped waveforms as shown in figure 6.6. The feature is seen for monoenergetic particles and for a spectrum. The so called "slow" waveform has longer rise time and decay time and a slightly smaller mean absolute amplitude. It was observed that the shape of the waveform is dependent on the detector area where the particles are interacting. The reason behind this difference is not definitively clear, however, there are several viable explanations. First, it has been demonstrated that, when a proton interacts with the silicon detector in the area between the two strips, the charge collection is poorer [87, 88]. Second, defects in the detector crystal can influence charge collection time, and consequently the amplitude. It is important to mention that the ΔE and E detectors have a similar segmentation, with the notable distinction that the waveform differences were only observed in the E detector.

Having two distinct shapes, which may correspond to the same energy, complicates the energy calibration. It was attempted to separate these waveforms and perform energy calibration independently for each shape, but it showed inconsistent results for non-monoenergetic particles. Consequently, the amplitudes were interpreted as is, which led to a slight degradation in energy and time resolution. Such effects could be studied in future research, as in [75].

![Figure 6.6. Example of different waveform shapes from the E silicon detector. Data from neutron experiment.](image)
6.3.3 Results

The energy calibration results for both digitizers and all channels are shown in the figures 6.8 and 6.7. The top panel shows the energy calibration curve for the detector segments while the bottom panel shows experimentally determined FWHM for each of the proton energies. The two top lines in top panel correspond to results for the thick E detector segments, while the bottom two lines represent the energy calibration for the ΔE detector segments. The labels corresponding to the detector segments as described in figure 6.2. The horizontal bars correspond to the experimental data, the error (±σ) was determined from the Gaussian fit to the measured PHS; for example the fit results in figure 6.4 correspond to the bar with amplitude of 659 at energy deposition of 3.9 MeV. The shaded bands around the lines mark the error (±σ) due to the uncertainty in the energy calibration fit. From the figure 6.8 and 6.7 bottom panels it is evident that the ΔE detector performs better: it has an energy resolution below 250keV FWHM at most of proton energies, as well as smaller uncertainties in the energy calibration fit. The relatively large energy spread at 4.2 MeV for the thin detector is due to the specific nature of this particular measurement point; here the energy calibration was achieved from 6.9 MeV protons punching through the detector and depositing only part of their energy. The wider spread is due to the varying proton path lengths in the detector. This is of particular interest as the detector punch through can be used for energy calibration monitoring during neutron experiments. Additionally the energy calibration for E detector is different for 3920 digitizer than for 0901. This is especially visible in the figure 6.8 channel H, which has a larger shaded area due to the poorly aligned measurement point at 4.9 MeV. In addition, the slope of the fit for channels G and H is different, most likely due to the attenuators used for these channels. The poor energy resolution of the thick E detector is the result of having two distinct shape waveforms corresponding to one proton energy. This leads to a wider PHS distribution than for the ΔE detector. A large dark current of the E detector (compared to ΔE detector) was observed during measurements, and a likely cause could be defects in the silicon lattice.
Figure 6.7. Energy calibration results for the channels connected to the ADQ412-3920 digitizer. The energy is given after a subtraction for back-scattering energy loss. Top panel shows the energy calibration fit results with experimentally measured pulse height amplitude. The top two lines correspond to the thick E detector (channels C and D), the lower two lines to the ΔE detector (channels A and B). The bottom panel shows the estimated full-width half maximum for each of the energies and detector segments.
Figure 6.8. Energy calibration results for the channels connected to the ADQ412-0901 digitizer. The energy is given after a subtraction for back-scattering energy loss. Top panel shows the energy calibration fit results with experimentally measured pulse height amplitude. The top two lines correspond to the thick E detector (channels G and H), the lower two lines to the $\Delta E$ detector (channels E and F). The bottom panel shows the estimated full-width half maximum for each of the energies and detector segments.
7. Development of a prototype TPR Spectrometer and model validation

This chapter presents an overview of the main findings of PAPER IV. The performance of the TPR spectrometer under ITER-like conditions is discussed in Chapter 5. Yet, to increase confidence in the simulations performed, experimental validation is necessary. To achieve this, a prototype TPR spectrometer was constructed and tested using a DT neutron generator. A simulation of the experiment was performed using a Geant4 model described in PAPERS II and III.

7.1 Experiment description

The experiment with a prototype TPR spectrometer was carried out at Lund University using a Sodern GENIE-16 type DT neutron generator [89]. The generated neutron energy spectrum has a peak around 14 MeV, as expected in DT fuelled fusion reactors. The neutron generator was absolutely calibrated at the factory and provides a neutron yield of $4.7 \times 10^8$ neutrons per second in a continuous operation mode which was used during the experiment. The generator experimental area has extensive shielding for radiation safety purposes and consequently there is high probability of neutron scattering events which give rise to a high intensity component of scattered, low energy neutrons in the experimental area. Importantly, the possibility to add shielding between the generator and the spectrometer was limited due to space constraints. Such experimental conditions enable us to test the prototype in high intensity neutron background conditions. In contrast, in fusion devices, the neutron spectrometers would be shielded much better, have better neutron collimators and consequently would have lower intensity background component. The ability to determine the measured energy spectra peak FWHM and amplitude under such high background conditions increases the confidence in the implementation of such systems in fusion reactors such as ITER.

The neutron generator is surrounded by water shielding with a circular hole 80.5 mm in radius in the direction of the experimental area as shown in figure 7.1. The circular hole inside the water shielding was used to house a paraffin collimator 320 mm in length with an inner radius of 18 mm. The vacuum chamber containing the TPR spectrometer was placed as close to the
collimator as reasonably possible. With this set-up the TPR spectrometer detectors had some shielding from neutrons impinging directly from the source. The prototype TPR spectrometer follows the schematic in figure 2.6; it uses a low density polyethylene foil which was placed approximately 420 mm away from the neutron source. The weight of the foil was measured to be 0.4531 +-
0.0002 g, with an area of 20.55 ± 0.4 cm². According to the supplier [90], the polyethylene density is 0.92 g/cm³ leading to an estimated foil thickness of 0.239 ± 0.004 mm. The foil is mounted in a steel holder with 21 mm radius opening. The foil is paired with two segmented silicon detectors (as described in Section 3.3) of 0.3 and 1 mm thickness, respectively, and housed in a vacuum chamber. The distance between the converter foil and the ΔE detector is 165 mm, while the distance between the two (ΔE − E) detectors is 8 mm. During the experiment a constant pressure of 0.01 mbar was maintained in the vacuum chamber, to minimise the energy loss and scattering of the protons knocked out of the foil. The vacuum chamber acted as a protection of the silicon detectors from ambient light interference.

The generated detector signals were amplified in a CAEN1422 [84] charge sensitive preamplifier and the preamplifier signals were digitised in the ADQ412 4 channel digitizer [71]. A description of the development of the spectrometer
acquisition system, including the energy calibration, radial detector strip coupling to the digitizer channels and data reduction procedures, is discussed in Chapter 6.

The prototype TPR spectrometer was designed using the same principles as in PAPER I, by optimising the resolution for a specific detection efficiency, which allowed to gain the best performance for the available experimental set-up and source yield. The optimised TPR spectrometer design assuming only first order effects for a collimated neutron beam and using quarter of the detector, is estimated to have an absolute detection efficiency of $3.6 \times 10^{-5}$ and energy resolution of 8.2 % FWHM for 14 MeV neutrons. Using the provided neutron generator yield and the TPR spectrometer prototype parameters we estimated that an expected count rate in the peak of interest would be 4 Hz, leading to a reasonable time of the experiment.

7.2 Results and Conclusions

During the experimental data analysis, nuclear reactions $^{28}\text{Si}(n, \alpha)$ and $^{28}\text{Si}(n, d)$ were observed. Multiple energy deposition peaks corresponding to different excited states were observed between energies 4.7 to 11.4 MeV. Using this observation an energy calibration correction was performed. This has lead to a better match between the experimental and the simulation results. An example of the anti-coincidence energy spectra for the channels A and B (corresponding to the detector $\Delta E$) are shown in figure 7.2, the spectra is including only events which lead to energy deposition in only one of the detector channels.

![Figure 7.2](image)

*Figure 7.2. Experimentally measured anti-coincidence energy deposition spectra for channels A and B corresponding to the $\Delta E$ detector. The plotted energy spectra is after the energy calibration correction has been performed. The energy bin width is 40 keV.*

The experimental results for energy deposition coincidence in the $\Delta E - E$ silicon detectors are shown in figure 7.3. An energy coincidence window of 10000 ns was used during the experimental data analysis. Each of the figure panels represents different channel coincidences (the channel layout is reported in figure 6.2) where each electronics acquisition channel combines 4
radial detector strips. For each of the channel combinations we observe a dis-

Figure 7.3. Energy deposition $\Delta E - E$ histogram in the spectrometer for different channel coincidences. Channel combinations AC, BC, BD contain a prominent peak associated with the 14 MeV neutrons, marked "DT peak". Channel combination AD does not contain this feature. Artefact marks energy cut due to acquisition trigger level. The energy bin width is 100 keV.

tinct "banana" like shape, which corresponds to the proton energy deposition (DT peak) and is the region of interest (ROI) for the purpose of neutron spectroscopy. The ROI contains most of the data required to determine the source neutron energy distribution and intensity. The channel AD stands out as the intensity in the ROI is much smaller. This is because this channel combination for a true proton signal coincidence is very unlikely due to geometrical constraints (see figure 6.2 for clarity).

We used the Geant4 simulation results to approximate the bounds of the ROI and applied this ROI to the experimental measurements to reduce the background contribution. This was performed using the same principles as discussed previously and shown in figure 5.3. The resulting simulated and experimental total energy deposition ($\Delta E + E$) spectra for the coincidence events are shown in figure 7.4. Both of the spectra are normalised to unity at their respective maximum for better shape comparison. The peak position and peak FWHM matches between the experimental and simulated data within the energy resolution of the silicon detectors. However, there are differences between the shapes of the spectra. The energy deposition below 11 MeV is systemically underestimated in the simulations. We assumed that the inte-
Figure 7.4. Total energy deposition from the coincidence events in the Region of interest for channel combinations AC, BC and BD. Comparison of experimental and simulation results together with peak fit results. Both experimental and simulation data are normalised to unity at their respective maximum for better shape comparison. Energy bin width 50 keV.

gral above 11 MeV corresponds to the total counts in the peak. The ratio of peak integrals, calculated by Geant4 over experimental results, is 0.801 (C/E). This is partially due to the background contribution being underestimated in the simulations. The experimental spectra has a different shape for energies above 14 MeV which is due to the previously mentioned poor performance (see Section 6.3.2) of the E detector.

Further investigation was performed by comparing the energy deposition spectra between experiment and simulations for each of the channel combinations shown in figure 7.5. The figure implies a more complex relationship is present in energy deposition for different segment combinations. Channel AD is absent because it does not produce a significant true coincidence peak due to the previously mentioned geometrical constraints. In all three shown cases, the peak position are within 130 keV between the simulation and experiment, with the BD channels showing the best match. The peak FWHM are well reproduced for channels BD; however for channels AC and BC the peak width is underestimated by the simulations by 200 keV compared to the experiment. Furthermore the peak intensity in channels AC is overestimated by the Geant4 simulations while in BC it is underestimated. The exact origin of the intensity mismatch is unclear, as this is outside the statistical uncertainty of the experiment and the simulation results. However, this could be an effect of systemic uncertainties related to the experimental set-up such as, e.g., the collimator manufacturing tolerance, the centring of the foil relative to the de-
Figure 7.5. Total energy deposition from the coincidence events in the Region of interest for all channel combinations containing the peak. Comparison of experimental and simulation results with statistical uncertainty. The simulation results are normalised to the reported source intensity. The energy bin width is 100 keV.

Detectors, or the spectrometer’s alignment with the collimator. Furthermore, the simulations did not include all of the surrounding shielding materials which could contribute to an underestimation of the neutron flux, especially in lower energies. A parameter study could be performed to find the origin of such mismatch and investigate the energy spectra sensitivity; however, this is out of scope of the current research goal. Overall, it can be concluded that the total energy deposition is replicated well by the simulations. However, there is an indication that the energy deposition for the different segment coincidences is more sensitive to the experimental conditions.
8. Fuel ion ratio determination using the 14 MeV Tandem neutron spectrometer at JET

The research work discussed in PAPERS I - III was focused on the design of the TPR spectrometer and estimates of its performance under plasma conditions using synthetic (simulated) data. To comprehensively cover all aspects of the spectrometer’s performance in the context of fusion devices, an exploration of experimental neutron diagnostic data is essential. This was performed in PAPER V which focused on the neutron diagnostics of fusion plasma in the JET fusion experiment. During JET’s first Deuterium-Tritium experimental campaign (DTE1) in 1997, a Tandem neutron spectrometer [45, 66], based on the same principles as the TPR spectrometer, was operational. Since then, neutron diagnostics for the determination of the fuel ion ratio in fusion devices have advanced significantly [24, 39]. In the light of these new developments and their high relevance to the development of a TPR spectrometer, it was decided to revisit the 1997 DTE1 campaign data to estimate fuel ion ratio \( n_t / n_{tot} \) where \( n_{tot} = n_d + n_t \). Furthermore, we estimated \( n_t / n_{tot} \) using two different approaches using the plasma modeling codes PENCIL and TRANSP to determine the fusion reactivities.

8.1 Methods

The method [24, 39] to determine the fuel ion ratio is based on a parameterised model of the neutron emission in terms of the tritium and deuterium fuel ion densities \( n_t \) and \( n_d \). The fuel ion concentrations are varied until a best fit is found to replicate the experimentally determined energy distribution. This procedure requires multiple input parameters: spectrometer line-of-sight information, the spectrometer energy calibration function, the spectrometer response function and fusion reactivities relevant for the studied plasma conditions. In this study, the reactivities were estimated using two different plasma modeling codes, namely TRANSP [91] and PENCIL [92], as further discussed below. First, the Tandem neutron spectrometer energy calibration was performed using an in-built alpha source and the measured energy deposition related to the DT neutron energy peak. The position of this energy
deposition peak was estimated using the Geant4 model of the Tandem spectrometer. The Geant4 model was also used to calculate the Tandem spectrometer response function for a neutron energy range of 8 - 18 MeV in 80 keV steps. The calibrated energy spectra from the Tandem spectrometer were then used to find the most likely plasma fuel ion \(n_t\) and \(n_d\) concentrations which would replicate the measurement results. For the fitting procedure we assumed that the neutron energy spectrum is a parameterised function of the fuel ion \(n_t\) and \(n_d\) concentrations. By varying these concentrations, a model neutron spectrum can be constructed to find the best fit. For an accurate comparison between the constructed neutron energy spectrum and the experimental measurements, the model spectrum is weighted by the line-of-sight information and folded with the response function calculated for the Tandem spectrometer. This converted the calculated energy spectrum of neutrons emitted from the fusion plasma into a model of the energy deposition spectra as measured by the Tandem spectrometer, thus enabling comparisons of modelled and experimental data.

It was assumed that the neutron spectra have three components: beam-thermal (BT), thermal (TH), and scatter, as discussed in Section 2.1. The intensities of the BT and TH component can be related to fuel ion concentrations; for example, the intensity of the thermal DT component can be expressed as an integral over all emission directions \((u)\) and positions \((x)\) in plasma:

\[
I_{TH, dt} = \int \varepsilon(u, x)_{TH, dt} du dx \approx \frac{n_d n_t}{n_e^2} \int n_e^2 \langle \sigma v \rangle_{TH, dt} du dx \quad (8.1)
\]

where \(I_{TH, dt}\) corresponds to the TH component intensity due to DT ion fusion reactions, \(\varepsilon(u, x)\) is the neutron emission from thermal reactions, \(n_t\) is the number density of fuel ion species \(i\), \(n_e\) is the electron density, and \(\langle \sigma v \rangle_{TH, dt}\) is the DT thermal ion reactivity. A similar expression is obtained for \(I_{BT, td}\), the intensity of BT neutron emission for tritium beam:

\[
I_{BT, td} = \int \varepsilon(u, x)_{BT, td} du dx \approx \frac{n_d}{n_e} \int n_e n_{t, NBI} \langle \sigma v \rangle_{BT, td} du dx \quad (8.2)
\]

The electron densities were obtained from LIDAR [93] measurements. The reactivities and beam ion densities, which are necessary to determine the \(I_{BT}\) components, were obtained from PENCIL or TRANSP, depending on the selected analysis method. The tandem spectrometer has not been absolutely calibrated and we used data from the JET fission chambers of the total neutron rate \((R)\) for normalisation. The BT and TH component intensities can be related to \(n_t\):

\[
\frac{n_t}{n_e} = \frac{I_{TH, dt} \cdot c_{NB, td}}{I_{NB, td} \cdot c_{TH, dt}} \quad (8.3)
\]

where \(c_{NB, td}\) and \(c_{TH, dt}\) are the integrals on the right hands side of the equations 8.2 and 8.1. Using a the total neutron rate an expression for \(n_d\) [94] can be derived:

\[
\frac{n_d}{n_e} = \frac{R}{I_{NB, td} + c_{TH, dt} \cdot \frac{n_t}{n_e}} \quad (8.4)
\]
In the TRANSP approach the BT and TH spectral component shapes are provided from the TRANSP output. The scatter component shape is assumed to be an error function which goes to zero above 14 MeV.

Using the PENCIL approach requires assumptions on the spectra component shapes, as PENCIL only provides the reactivity and beam ion densities ($n_t, n_{bi}$). The TH component shape was assumed to be Gaussian with ion temperature and plasma rotation profiles obtained from charge exchange recombination spectroscopy [20] measurements. The BT component is modelled as a simple step function with upper energy defined by the beam injection energy of 150 keV.

Due to the low count rate the analysis was performed on data integrated over a whole discharge, and consequently the derived fuel ion ratio is an average over the whole discharge, biased towards the time period with highest neutron emission.

To perform the fuel ion ratio estimation, it was necessary to select appropriate discharges with available PENCIL or TRANSP simulation data, a sufficient number of counts in the spectrometer energy spectra, no radio frequency heating, and both D and T ion species present. Nine discharges were found matching these criteria, and the results are discussed in the following section.

8.2 Results and Conclusions

The fuel ion ratio $n_t/n_{tot}$ has been calculated for 9 JET discharges using PENCIL or TRANSP. An example of neutron spectra decomposition for 4 analysed JET discharges is shown in Figure 8.1. The neutron component (BT, TH and scatter) intensities were determined by performing a model fit to the experimental data. Both TRANSP and PENCIL show a good match between experimental data and model energy spectra, with TRANSP performing slightly better. TRANSP performs better in recreating the beam-thermal (BT) component width, while PENCIL seems to systematically underestimate it. This result is not surprising since by using the PENCIL framework we have assumed a simplistic BT component shape, while TRANSP provides a more realistic model of the beam ion slowing down distribution.

Using the results of the model fit shown in figure 8.1, along with the reactivity data obtained from the TRANSP and PENCIL simulations, we present the fuel ion ratios determined for selected discharges in figure 8.2. For comparison purposes we have included the time averaged penning gauge [21, 22] measurement data (KT5P), similar to what has been done in previous research [39, 23]. No attempt has been made to account for systematic uncertainties in the simulation. The fuel ion ratios estimated using both TRANSP and PENCIL are consistent within statistical uncertainties. The results demonstrate a better match for plasmas with a higher tritium content. In the case of plasmas dominated by the BT component, such as in discharge 41600, the poor fit of the
Figure 8.1. A comparison of measured energy spectra with model estimates using TRANSP or PENCIL. The legend BT stands for beam-thermal, TH - thermal, scatter - neutron scattering components, total - sum of all three components. The experiment corresponds to the Tandem spectrometer measurements. The title on the right hand side marks the JET discharge number.

PENCIL component significantly contributes to the uncertainty of the $n_t/n_{tot}$
ratio. The KT5P data follows the same trend as \( \frac{n_t}{n_{tot}} \) derived in this research, although it consistently underestimates the ratio. This has been observed in previous studies [39, 23] as well and one of the main arguments is that the penning gauge samples the sub-divertor region and may pick up D ions out-gasing from the tokamak walls. This is in contrast to the neutron-based \( \frac{n_t}{n_{tot}} \) measurements which are biased towards the fuel ion ratio in the core of the plasma. Finally, the presented KT5P values are the ratio of the average over time (\( \tau \)) ion density; for example for the tritium density:

\[
\frac{n_t}{n_{tot}} = \frac{1}{N} \sum_{\tau=0}^{N} n(\tau)_t \propto \sum_{\tau=0}^{N} I(\tau)_{th} \] (8.5)

where \( i \) corresponds to the time interval. However, the neutron based data is the average neutron intensity over time:

\[
n_t \propto \frac{\sum_{\tau=0}^{N} I(\tau)_{th}}{\sum_{\tau=0}^{N} I(\tau)_{nb}} \] (8.6)

Assuming that \( \frac{n_t}{n_{tot}} \) is constant throughout the discharge, the influence of different averaging would be negligible, however this is often not the case. Consequently, the neutron based \( \frac{n_t}{n_{tot}} \) is weighted towards the time period with the highest neutron intensity. For example, the discharge 42840 shows a larger difference between KT5P and TRANSP derived \( \frac{n_t}{n_{tot}} \) than discharge 42992, as shown in figure 8.2. It is likely that the larger difference in discharge 42840 results arise due to different averaging as it exhibits a larger variation of the time dependent \( \frac{n_t}{n_{tot}} \) as shown in figure 8.3.

Figure 8.2. Fuel ion ratio comparison between PENCIL and TRANSP methods for the selected plasma discharges. In addition, the KT5P time averaged data is provided for comparison. The uncertainties plotted correspond to the statistical uncertainty of the measurement. The missing points mean that either TRANSP or PENCIL simulation results were unavailable.
Overall, the results show that the methods previously developed for fuel-ion ratio determination can be successfully applied also to data from the Tandem neutron spectrometer. This increases the confidence of performing $n_t/n_{tot}$ determination using a spectrometer based on the nonmagnetic thin-foil technique for fusion diagnostics in ITER. The PENCIL-based approach is also shown to be a promising method for estimating the average fuel ion ratio $n_t/n_{tot}$ in tritium dominated plasmas. This is advantageous as TRANSP is a more complex and computationally demanding code and this could simplify the $n_t/n_{tot}$ estimation in future discharges. Future work could focus on exploring limits of using PENCIL compared to TRANSP and investigating time-resolved data using higher efficiency neutron spectrometers.
9. Discussion, Conclusions and Future Outlook

The simulations presented in this thesis suggest that a TPR spectrometer based on annular silicon strip detectors can be used as a neutron emission spectroscopy diagnostic at ITER achieving the desired energy resolution of 5% FWHM with a detection efficiency of $(2 - 3) \times 10^{-5}$ for the two investigated designs. The spectrometer design with the higher efficiency was achieved by using the radial segmentation of the detectors to create coincidence energy spectra for each of the segment combinations. The benefits of employing radial segmentation were confirmed in Papers I - III. The TPR spectrometer is expected to have a count rate of up to 120 kHz per acquisition channel for the ITER maximum power scenario and a signal-to-background ratio of around $600 \pm 60$ in the energy range 15-16 MeV. Using the proposed $\Delta E$-$E$ coincidence techniques allowed for the application of energy cuts which can improve the signal-to-background ratio by at least a factor of 7 in the energy range of interest compared to no cuts. The experiments have confirmed that the spectrometer energy resolution is dominated by geometrical parameters even though the current experimental set-up is sub-optimal.

Furthermore, using the calculated response function of the TPR spectrometer, we have investigated the number of counts necessary to achieve the measurement uncertainty of 10% for the $T_i$ and 20% for the $\frac{n_t}{n_d}$ determination in different ITER-like plasma conditions. The result is rather general as the response function used is nearly Gaussian and the results can be used with other spectrometers having similar resolution and Gaussian-like response function.

To increase the confidence in the simulation results, a prototype TPR spectrometer has been constructed and tested at a DT neutron source. The spectrometer design was optimised for efficiency for the experiment using the same procedure as in PAPER I. A Geant4 model of the experiment was created to calculate the measured energy deposition spectra in the detectors. The simulation results were used to estimate the energy deposition in the detectors due to nuclear reactions ($^{28}\text{Si}(n, \alpha)$ and $^{28}\text{Si}(n, d)$). These energy deposition spectra were then used to perform a correction of the silicon detector energy calibration. After applying calibration corrections, the results have shown that both the calculation and the experiment mean energy deposition by 14 MeV neutrons from the DT reaction is within 100 keV. The experimentally determined FWHM of the DT peak is 1.75 MeV, compared to 1.64 MeV from the simulation data. This is a relatively good match for both the mean and FWHM,
especially considering that the experimentally determined energy resolution for the silicon detectors is approximately 200 keV and 600 keV in FWHM for the $\Delta E$ and $E$ detectors, respectively. The simulation underestimates the event count rate in the energy range above 11 MeV by 20%. This discrepancy is partly attributed to the simulation’s underestimation of the scattered neutron contribution to the final energy spectra, a result of model simplifications. Moreover, the uncertainties in the experimental set-up were not accounted for in the simulations.

Overall, the simulations show that a TPR spectrometer based on a segmented silicon detectors could be successfully implemented in ITER for neutron diagnostic purposes while the performed experiment at a DT neutron source validates the developed spectrometer simulation model.

Finally, an analysis of the experimental data collected using the Tandem neutron spectrometer during the 1997 DT experimental campaign at JET has been performed. The results show that proton recoil spectrometers can be successfully employed for fuel ion ratio $n_t/n_{tot}$ determination. Due to low detector efficiency and count rate, an average $n_t/n_{tot}$ was determined over the whole discharge. In addition, the analysis was performed using TRANSP and PENCIL for the fuel ion reactivity estimation and the final results on $n_t/n_{tot}$ match each other within statistical uncertainty between the two methods. This indicates that the fuel ion ratio analysis could be performed using the more simplistic PENCIL code, at least for discharges with high $n_t$ fraction. This has potential to significantly speed up the analysis process and fuel ion ratio determination.

Future work should aim to replicate the neutron experiment under more rigorously controlled experimental conditions, utilising a higher yield neutron source. This would enable the testing of TPR spectrometer set-ups designed for better energy resolution. Subsequently, a thorough sensitivity analysis of the neutron spectrometer’s energy resolution should be conducted. This analysis should specifically explore factors such as the precision of the spectrometer foil’s centring relative to the detectors and the spectrometer’s alignment with the collimator. Furthermore, a preliminary analysis indicates that an energy calibration based on nuclear reactions in the silicon detectors, as performed in this work, should be possible during measurements at ITER. However, this would not be possible to perform at 100 ms temporal resolution, as for example $T_i$ determination, and further analysis is necessary to quantify expected measurement results. The ability to monitor energy calibration during the operation of ITER would be especially advantageous due to limited access to the experimental area.
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Summary in English

The journey to harness energy from fusion reactions began with James Tuck in the 1950s and his aspiration to create a fusion device, prophetically dubbed "Perhapsatron." This device, however, did not achieve a stable plasma. This changed in 1968, when in the Soviet Union a new fusion reactor design called tokamak, demonstrated the achievement to obtaining fusion reactions. At the time the tokamak showed superiority by achieving higher temperatures than any previous fusion device. These breakthroughs inspired the fusion community to further pursue the development of tokamak design reactors, with the most advanced currently being the International Thermonuclear Experimental Reactor (ITER), under construction in France. ITER aims to reach 500 MW of thermal power and demonstrates the capability to produce self-sustained fusion reactions, potentially heralding a new era of development where fusion reactors could fulfil the aspirations of the 1950s. With ITER’s success the next step would be building reactors for energy application, such as the proposed design of a 2000 MW DEMO tokamak.

The current tokamak design still faces multiple technological challenges. The current path for energy production from fusion primarily relies on Deuterium (D) and Tritium (T) gas as fuel. The DT fusion reaction releases 17.6 MeV of energy, producing a helium nuclei and a neutron. The neutron has no charge and with low interaction probability it usually escapes the plasma where it can be utilised, for example, to breed T from lithium to be used as a fuel. The produced helium ions, confined by the reactors magnetic fields, continues heating the D and T ions to sustain the fusion reaction and produce more energetic ions maintaining the fusion process. The intensity of the DT fusion reaction is strongly temperature-dependent. For optimal reactor conditions, the fuel temperature should reach 200 million Kelvin, compared to the sun’s core temperature of around 15 million Kelvin. At these high temperatures, the DT gas mixture becomes fully ionized, forming a plasma, a mixture of an unbound ions and electrons. The positively charged ions create an electromagnetic force, repelling each other and leading to plasma dissipation and the eventual cessation of the fusion reaction. To counteract this force, the plasma is surrounded by strong magnetic fields, which balance out the repulsive force and guide the particles along magnetic field lines, thus maintaining plasma density and temperature while confining the plasma within the reactor. The ability to balance the repulsive force with magnetic fields enables the maintenance of the fusion reaction at higher densities for longer periods, leading to net positive power production and eventually a self-sustained fusion reactions. Beyond the challenge of maintaining plasma within the fusion reactor, it’s crucial to note that direct contact with materials (such as the reactor wall) at such temperatures would adversely affect the longevity of the device. Thus, future fusion reactors must maintain high magnetic fields, high plasma temperatures, and, preferably, high density while preserving the structural integrity of the
device by preventing plasma contact with material surfaces. Given these con-
straints, it is unsurprising that "Perhapsatron" was not a huge success.

To investigate plasma behaviour under various conditions, multiple exper-
imental research fusion reactors have been constructed and are currently op-
erational. Notable examples include the Mega Ampere Spherical Tokamak
(MAST) and its upgrade MAST-U, the Joint European Torus (JET) in the UK,
and the Experimental Advanced Superconducting Tokamak (EAST) in China.
The years of experience gained from these tokamaks have advanced fusion
research and plasma diagnostic techniques. However, the average power pro-
duction of these devices is up to 13.5 MW, a stark contrast to the projected
power for ITER or DEMO. Such developments impose constraints on existing
diagnostic techniques. One of the key diagnostics are based on the neutron
measurements, where escaping neutrons produced in the DT reaction carry
information about internal plasma conditions. Information about the neutron
energy distribution enables inferring the plasma temperature and fuel ion ratio.
Both of these parameters are necessary to accurately monitor plasma reaction
and help in maintaining fuel efficiency and plasma burning conditions. How-
ever the measurement of the neutron spectrum can be challenging. The exper-
iments at ITER cover a wide range of different plasma parameters which will
require a comprehensive neutron spectrometer system, as no single spectrom-
eter can meet the operational requirements. To meet all of the ITER require-
ments a High-Resolution Neutron Spectrometer (HRNS) system is proposed
for operation at ITER.

This thesis advances the existing knowledge on the Thin Foil Proton Recoil
(TPR) spectrometer’s diagnostic capabilities thus contributing to the devel-
opments of the HRNS system to meet ITER requirements. Before deploy-
ing the spectrometer in the ITER experiment, where access and maintenance
will be very limited, a thorough investigation is necessary to foresee the spectrom-
eter’s capabilities in determining plasma parameters such as temperature
and fuel ion ratio. Initially we have investigated spectrometer’s detection ef-
ciciency which lead to two selected designs, one based on radially segmented
silicon detectors an one not taking into account the segmentation. We demon-
strated that detector radial segmentation can be used to enhance the spectrom-
eter design leading to higher efficiency and more compact spectrometer. Both
important factors due to limited space for the diagnostic equipment and effi-
ciency improvements would lead to a higher accuracy measurements.

Subsequently, we evaluated spectrometer’s performance parameters through
dedicated Monte-Carlo simulations. From the simulations it was possible to
determine multiple practical specifications of the spectrometer such as: the
spectrometer’s expected count rate, energy resolution, anticipated detection
efficiency in experimental conditions at ITER and background suppression
methods. We found that the proposed spectrometer design should be able to
successfully perform measurements at ITER high power scenarios. In addition
to this we characterised what kind of diagnostic capabilities such spectrometer
would have in different ITER like plasma conditions. Specifically, we investigated the ability to determine fuel ion ratio and temperature. The results can be applied to other similar type spectrometers. We validated the simulation framework by performing an experiment using a DT neutron source. The findings suggest that the measured spectra shape can be replicated with the developed simulation model with reasonable accuracy. The suggested background suppression methods were effective when applied to experimental data and should significantly improve accuracy of the fuel ion ratio determination. We also demonstrated an energy calibration correction method based on nuclear reactions observed in Silicon detectors.

Finally we investigated experimental results obtained during JET tokamak DT plasma campaign. We have estimated the fuel ion ratio using data from a similar type spectrometer as the TPR. Additionally the findings of the research demonstrated that an alternative computational approach using the code PENCIL may be used for certain plasma scenarios which would significantly simplify the fuel ion ratio analyses. Through a methodical investigation and innovative design proposals, this thesis has advanced the design of the TPR spectrometer as well as demonstrated a working design and validated the simulations performed. The research demonstrated a successful background subtraction methods as well as improved TPR spectrometer’s efficiency and demonstrated an computational pathway for fuel ion ratio determination. The research performed here lays a foundation for future enhancements in spectrometer technology and plasma diagnostics for ITER and beyond.

This thesis is structured into three principal segments: Chapters 1 to 4 provide a overview of the theoretical knowledge on fusion and neutron spectroscopy and methodological approaches applied. Chapters 5 to 8 are dedicated to the primary findings and implications of the research. Lastly Chapter 9 discussed the future outlook.

längd negativt. Således måste framtidens fusionsreaktorer bibehålla höga magnetfält, höga plasmatemperaturer och, helst, hög densitet samtidigt som de bevarar enhetens strukturella integritet genom att förhindra plasma kontakt med materialytor. Med dessa begränsningar är det inte förvånande att Perhapseotron"inte var en stor framgång.


Därefter utvärderade vi spektrometerns prestandaparametrar genom dedikerade Monte-Carlo-simuleringar. Från simuleringarna var det möjligt att bestämma flera praktiska specifikationer för spektrometern, såsom: den förväntade räknehastigheten för spektrometern, energiupplösning, förväntad detekte-
ringseffektivitet i experimentella förhållanden vid ITER och metoder för bak-
.grundsreduktion. Vi fann att den föreslagna spektrometerns design bör fram-
.gångsrikt kunna utföra mätningar vid ITERs högeffektsscenarier. Dessutom ka-
raktäriserade vi vilken typ av diagnostiska förmågor en sådan spektrometer
skulle ha vid olika ITER-liknande plasmaförhållanden. Specifikt undersö-
te vi förmågan att bestämma bränslejonförhållandet och temperaturen. Dessa
resultat kan också tillämpas på andra typer av spektrometrar med liknande
detektionsrespons för neutroner. Dessutom har det utvecklade simuleringsram-
verket för denna typ av spektrometer validerats med hjälp av experiment vid
en DT-neutronkälla.. Resultaten tyder på att experiment data kan replikerats
med den utvecklade simuleringsmodellen. De föreslagna metoderna för bak-
grundsreduktion var effektiva när de tillämpades på experimentella data och
bör avsevärt förbättra mätkvaliteten. Vi demonstrerade också en energikalibre-
ringskorrektionsmetod baserad på kärnreaktioner observerade i kiseldetekto-
er.

Slutligen undersökte vi experimentella resultat erhållna under JET tokamak
DT-plasmakampanjen. Vi har uppskattat bränslejonförhållandet med data från
en liknande typ av spektrometer som TPR. Dessutom visade forskningsre-
sultaten att en alternativ beräkningsmetod med koden PENCIL kan användas
för vissa plasma-scenarier vilket skulle avsevärt förenkla analysen av bränsle-
jonförhållande. Genom en metodisk undersökning och innovativa designför-
slag har denna avhandling framskridit designen av TPR-spektrometer samt
demonstrerat en fungerande design och validerat de utförda simuleringarna.
Forskningen visade framgångsrika metoder för bakgrundsreduktion samt för-
bättrade TPR-spektrometerns effektivitet och demonstrerade en beräknings-
väg för bestämningsbränslejonförhållandet. Den forskning som utförts här
lägger en grund för framtida förbättringar i spektrometerteknik och plasmadi-
agnostik för ITER och bortom.

Denna avhandling är strukturerad i tre huvudsegment: Kapitlen 1 till 4 ger
en översikt över den teoretiska kunskapen om fusion och neutronspektroskopii
samt de metodologiska tillvägagångssätt som tillämpats. Kapitlen 5 till 8 är
tillägnade de primära resultaten och implikationerna av forskningen. Slutligen
diskuterar kapitel 9 framtidsutsikterna.
APPENDIX A: configuration file for energy calibration measurement

NumberOfRecords  10000
SamplesPerRecord  2048
PreTriggerSamples  512
sampleskip       64
TriggerLevel     -300
TriggerLevelreset 0
TriggerEdge      0
ActiveChannels  15
OffsetA          0
OffsetB          0
OffsetC          1000
OffsetD          1000
APPENDIX B: configuration file for DT experiment

NumberOfRecords  10000
SamplesPerRecord  2048
PreTriggerSamples  512
sampleskip  64
TriggerLevel  -300
TriggerLevelreset  0
TriggerEdge  0
ActiveChannels  12
OffsetA  0
OffsetB  0
OffsetC  1000
OffsetD  1000
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