Liquid scintillators as neutron diagnostic tools for fusion plasmas

System characterization and data analysis

FEDERICO BINDA
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**Abstract**


The neutrons produced in fusion devices carry information about various properties of the ions that are reacting in the machine. Measurements of the neutron flux and energy distribution can therefore be used to study the behaviour of the plasma ions under different experimental conditions.

Several neutron detection techniques are available, each having advantages and disadvantages compared to the others. In this thesis we study neutron measurements performed with NE213 liquid scintillators. One advantage of NE213s compared to other neutron detection techniques is that they are simple to use, small and cheap. On the other hand, their response to neutrons makes the extraction of information about the neutron energy less precise.

In the thesis we present the development of methods for the characterization and the data analysis of NE213 detectors. The work was performed using two instruments installed at the Joint European Torus (JET) tokamak in the UK: the “Afterburner” detector, which is an NE213 installed on a tangential line of sight, and the neutron camera, which is a system composed of 19 NE213 detectors installed on different lines of sight (10 horizontal and 9 vertical). The analysis of data from the Afterburner detector was focused on resolving different features of the neutron energy spectra which are related to different properties of the ion velocity distribution.

The analysis of data from the neutron camera was directed towards the investigation of the spatial distribution of ions in the plasma. However, the individual characterization of the camera detectors allowed the inclusion of information about the energy distribution of the ions in the analysis.

The outcomes of the studies performed indicate that the methods developed give reliable results and can therefore be applied to extract information about the plasma ions. In particular, the possibility of performing neutron emission spectroscopy analysis in each line of sight of a neutron camera is of great value for future studies.

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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I  **Generation of the neutron response function of an NE213 scintillator for fusion applications**
F. Binda, J. Eriksson, G. Ericsson, C. Hellesen, S. Conroy, M. Nocente, E. Andersson Sundén, JET Contributors
My contribution: Developed the method for the calibration, performed the data analysis, wrote the paper.

II  **Forward fitting of experimental data from a NE213 neutron detector installed with the magnetic proton recoil upgraded spectrometer at JET**
F. Binda, G. Ericsson, J. Eriksson, C. Hellesen, S. Conroy, E. Andersson Sundén and JET EFDA Contributors
My contribution: Performed the calibration, performed the data analysis, wrote the paper.

III  **Dual sightline measurements of MeV range deuterons with neutron and gamma-ray spectroscopy at JET**
*Nuclear Fusion* **55** (2015) 123026
My contribution: Took part in the data analysis for the NE213 detector.

IV  **Absolute calibration of the JET neutron profile monitor**
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My contribution: Contributed to the development of the calibration technique, performed the data analysis, wrote the paper.
V  Calculation of the profile-dependent neutron backscatter matrix for the JET neutron camera system  
F. Binda, G. Ericsson, S. Conroy, E. Andersson Sundén, JET Contributors  
Fusion Engineering and Design 123 (2017) 865-868  
My contribution: Performed the simulations and the analysis, wrote the paper.

VI  Study of the energy-dependent fast ion redistribution during sawtooth oscillations with the neutron camera at JET  
F. Binda, J. Eriksson, C. Hellesen, G. Ericsson, E. Andersson Sundén, S. Conroy, JET Contributors  
Manuscript (2018)  
My contribution: Performed the data analysis, wrote part of the paper.

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### Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>JET</td>
<td>Joint European Torus</td>
</tr>
<tr>
<td>NES</td>
<td>Neutron Emission Spectroscopy</td>
</tr>
<tr>
<td>NBI</td>
<td>Neutral Beam Injection</td>
</tr>
<tr>
<td>ICRH</td>
<td>Ion Cyclotron Resonance Heating</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>MPRu</td>
<td>Magnetic Proton Recoil (spectrometer) upgrade</td>
</tr>
<tr>
<td>TOFOR</td>
<td>Time Of Flight (spectrometer) Optimized for Rate</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier Tube</td>
</tr>
<tr>
<td>PSD</td>
<td>Pulse Shape Discrimination</td>
</tr>
<tr>
<td>PHS</td>
<td>Pulse Height Spectrum</td>
</tr>
<tr>
<td>TF</td>
<td>Thermal Fraction</td>
</tr>
<tr>
<td>DD</td>
<td>Deuterium-Deuterium (reaction)</td>
</tr>
<tr>
<td>DD</td>
<td>Deuterium-Tritium (reaction)</td>
</tr>
<tr>
<td>JPN</td>
<td>Jet Pulse Number</td>
</tr>
</tbody>
</table>
Disclaimer

The first two parts of this thesis are largely based on the introductory chapters of my licentiate thesis [1]. The material has been adapted to better fit into this work, but some portions of the text and some figures may have remained identical to the original.
Part I:
Introduction

“Irrigation of the land with seawater desalinated by fusion power is ancient.
It’s called rain.”
– Mike McAlary
1. Nuclear Fusion

1.1 Introduction to nuclear fusion

The growing world energy demand calls for technologies that can provide clean and virtually unlimited energy. Nuclear fusion has the potential to fulfill such requirements [2], and is therefore subject to thorough investigation by scientists and engineers, in the attempt to find an efficient and practical way to obtain a net energy output from it.

The basic principle of fusion is, as the word says, the merging of two nuclei (the reactants). The products of this process are a heavier nucleus and a light particle. If the total mass of the products is lower than the total mass of the reactants, the reaction gives a positive energy output, according to the famous relationship:

\[ E = \Delta m \cdot c^2. \] (1.1)

Table 1.1 presents the most relevant fusion reactions for energy production. Reaction number 4, i.e. the deuterium-tritium (DT) reaction, is considered the best candidate for future reactors, because it has a higher energy release and a higher cross section than the other candidates at reactor relevant conditions (Figure 1.1). However today’s research reactors work mostly with pure deuterium fuel, to avoid practical issues related to the handling of tritium, which is radioactive. For this reason, the neutrons measured in this thesis come almost exclusively from reaction number 1, which we refer to as the DD reaction.

Table 1.1. Fusion reactions relevant for energy production.

<table>
<thead>
<tr>
<th>#</th>
<th>Reactants</th>
<th>Products</th>
<th>(E_N) (MeV)</th>
<th>(E_{TOT}) (MeV)</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(d + d) (\rightarrow) (^3)He + n</td>
<td>2.45 3.27</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(d + d) (\rightarrow) p + t</td>
<td>- 4.03</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(d + ^3)He (\rightarrow) (^4)He + p</td>
<td>- 18.4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(d + t) (\rightarrow) (^4)He + n</td>
<td>14.0 17.6</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fusion can only occur if the nuclei get close enough so that the strong nuclear force overcomes the Coulomb repulsion. In the sun, for example, this is accomplished thanks to the very high pressure generated by the gravitational field.

One possibility to achieve controlled fusion in a laboratory environment is to heat the fuel to very high temperatures. This transforms the fuel into a
plasma, a state of matter which can be described, in a very simplistic way, as a gas made of charged particles.

The temperatures reached are so high that the fuel would melt any containing material with which it came into direct contact. One way to deal with this problem is to use magnetic fields to confine the fuel in a defined region of space and keep it away from the material walls of the surrounding vacuum vessel. The plasma particles are charged, therefore they are forced to follow the magnetic field lines.

Another way to obtain controlled fusion which is important to mention is inertial confinement. In inertial confinement fusion, the fuel is made into a small pellet that is heated and compressed using laser beams [3]. Currently the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in the US is the most important centre for research on inertial confinement fusion. NIF has the world largest laser system, with 192 beams that deliver a total energy up to 1.8 MJ [4].

![Cross section versus center of mass energy for some of the reactions in Table 1.1: reaction 3 (solid), reaction 1 (DD reaction, dashed) and reaction 4 (DT reaction, dash-dotted).](image)

**Figure 1.1.** Cross section versus center of mass energy for some of the reactions in Table 1.1: reaction 3 (solid), reaction 1 (DD reaction, dashed) and reaction 4 (DT reaction, dash-dotted).

### 1.2 Magnetically confined fusion

Magnetic fields can be used to control the trajectories of the ionized particles that form a fusion plasma [5]. The Lorentz force makes the charged particles
follow helical orbits centered around the magnetic field lines, as shown in Figure 1.2. Therefore an appropriate choice of the field lines can trap the plasma particles in a defined region of space.

![Figure 1.2. Trajectory of a charged particle (dashed) in a magnetic field (solid arrow).](image)

One way to obtain magnetic confinement is by using magnetic mirrors. In a magnetic mirror the field lines are arranged in a cylindrical shape, parallel to the axis of the cylinder, with the intensity of the field increasing at the ends. A charged particle moving towards one of the ends of the cylinder experiences an increasing intensity of the magnetic field. It can be shown that the magnetic field gradient generates a force acting on the particle, with direction towards the lower field region in the center of the cylinder. This means that the parallel velocity of the particle will decrease and eventually change sign, trapping the particle within a well defined region of space. However this mechanism is not perfect, since particles that have a parallel velocity high enough will not be reflected and will escape at the end of the cylinder.

To improve this idea it was proposed to bend the lines to form a toroidal shape, so that there are no ends where the particles can escape. This is the basis point for the development of the tokamak [6], which is currently the primary focus of magnetic fusion developments.

An alternative concept, the stellerator, is also actively researched [7, 8], but not further discussed here.

1.2.1 The tokamak

The word tokamak comes from the Russian acronym “toroidal’naya kamera s magnitnymi katushkami”, which translated to English is “toroidal chamber with magnetic coils”. The configuration of the magnetic field in a tokamak is depicted in Figure 1.3. The toroidal coils produce the toroidal component
of the magnetic field. The poloidal component of the field is produced by inducing a toroidal current in the plasma by transformer action. The resulting magnetic field is helical, i.e. composed of twisted toroidal lines (Figure 1.3). The twisting is necessary to avoid the creation of electric fields that could destroy the confinement of the plasma.

Figure 1.3. Configuration of the magnetic field in a tokamak. Figure from www.eurofusion.org

The work presented in this thesis was carried out at the Joint European Torus (JET). JET is currently the largest tokamak in the world [9], with a major radius (i.e. the radial distance from the centre of the machine to the centre of the plasma) of about 3 m and a total plasma volume of about 100 m$^3$. It was built in the end of the 70s near Culham, a small village outside Oxford in England; it started operations in 1983 and in 1997 achieved the world record of fusion power produced, 16 MW [10]. Figure 1.4 shows the JET torus hall and the interior of the JET vacuum vessel.

The next step towards a fusion tokamak reactor is ITER, which is currently being built in Cadarache, France, and is expected to start operations in 2025 [11]. The ITER tokamak will have a major radius of 6 m and a plasma volume of 840 m$^3$ and the goal is to produce 500 MW of fusion power over extended periods of time (minutes) [12].
1.2.2 Heating methods

Looking at the cross sections in Figure 1.1 one can understand that the deuterium ions need energies in the keV range or higher to fuse efficiently. Therefore various heating methods have been developed in order to raise the thermal energy of the plasma particles.

Before going into the discussion of the heating methods, it is convenient to introduce the definition of temperature that is commonly used in plasma physics:

\[ T[eV] = kT[K], \]

where \( k \) is the Boltzmann constant and \( T[K] \) is the temperature in Kelvin. With this definition the plasma temperature is given in eV. As an example, a temperature of 1 eV corresponds to about 11600 K.

There are three main methods for external heating of the plasma and one internal heating mechanism. The internal heating is due to the \( \alpha \) particles generated in the DT reaction. If the \( \alpha \) particles are well confined they can heat the plasma by transferring their high energy to the fuel deuterons, electrons and tritons.

The external heating methods are: ohmic heating, neutral beam injection (NBI) [13] and radio frequency (RF) heating [14]. There are different types of RF heating, but in this thesis we will deal only with ion cyclotron resonance frequency heating (ICRH).

Ohmic heating consists in driving a current through the fusion plasma, which dissipates heat because of the resistance of the plasma. However the resistance of the plasma is proportional to \( T^{-3/2} \) [13], therefore this technique becomes less efficient when high temperatures are reached. At JET ohmic heating can raise the temperature to about 2 keV. NBI and/or ICRH, which are commonly referred to as auxiliary heating, are necessary to reach higher temperatures.

The principle behind NBI heating is the injection of highly energetic neutral fuel particles in the plasma. The particles must be neutral to avoid any deflec-
tion of their trajectory by the strong magnetic fields of the tokamak. Once inside the plasma they get quickly ionized and get thermalized, transferring their energy to the plasma particles and becoming plasma particles themselves. Thus, NBI heating also serves the additional purpose of fueling the device.

Finally ICRH is based on the transfer of energy from radio-frequency waves to ions, thanks to the resonance between the frequency of the injected electromagnetic wave and the ion cyclotron rotation frequency. ICRH also induces highly energetic ions (up to a few MeV) in the plasma.
Part II:  
Fusion neutrons measurements

“Neutron spectrometers never measure the neutron energy.”  
– Erik Andersson Sundén and Sean Conroy
2. Neutron diagnostics

The detection of subatomic particles relies almost exclusively on electrical measurements. Since neutrons are neutral, they cannot be detected directly. The techniques used to detect neutrons rely on the transfer of energy from the neutron to a charged particle, normally a proton or a heavier ion, which is charged and can therefore be detected, for example, in a scintillator or a semiconductor. In the case of energy measurements, the quantity directly detected by the spectrometer is not the neutron energy but some other quantity that is related to it. For example in the time of flight technique the time of flight of the neutron, which depends on the neutron energy, is what is actually measured (more on the time of flight technique in Section 2.1). The following sections give an overview of some of the neutron diagnostic installations at JET and the detection techniques that they employ.

2.1 TOFOR

The Time Of Flight spectrometer Optimized for high Rate (TOFOR) was installed in the JET roof lab (above the tokamak) by the Uppsala group in 2005 [15]. A similar instrument has been later installed at the EAST tokamak in China [16]. TOFOR is optimized as a 2.5 MeV spectrometer, but it is in fact a broadband spectrometer capable of measuring all neutron energies above 1 MeV. The principle behind this spectrometer is the measurement of the time that it takes for a scattered neutron to cover a certain distance, which can be related to the energy of the incident neutron as explained later in this section.

The geometry of the TOFOR instrument is shown in Figure 2.1. The neutrons from the plasma are formed into a collimated “neutron beam” through a 2 meter long aperture in the JET roof laboratory floor. Some of the incoming neutrons scatter in a first set of detectors (S1) which gives the start time. Some of the scattered neutrons are subsequently detected in a second set of detectors (S2), that gives the stop time. The S2 detectors are placed at an angle $\alpha \neq 0$ with respect to the incoming neutron flux. The time of flight measured is therefore that of a scattered neutron with scattering angle $\alpha$ and energy $E'_n$. The energy of the scattered neutron is given by the following equation:

$$E'_n = \frac{1}{2} m_n \frac{L^2}{t_{tof}^2}, \quad (2.1)$$
where \( m_n \) is the neutron mass and \( L \) is the length of the flight path (see Figure 2.1). Noticing that \( E'_n = E_n \cos^2(\alpha) \) and \( L = 2r \cos(\alpha) \) (where \( r \) is the radius of the sphere shown in Figure 2.1), Equation 2.1 can be modified to obtain the original neutron energy:

\[
E_n = 2m_n \frac{r^2}{t_{tof}}. \tag{2.2}
\]

Figure 2.1. Geometry of the TOFOR spectrometer. From [15].

2.2 The magnetic proton recoil technique

The magnetic proton recoil (MPR) technique is based on the transfer of energy from neutrons to protons via \((n, p)\) elastic scattering on hydrogen in a thin plastic foil and the subsequent momentum separation of the recoil protons in the spectrometer’s magnetic field.

An instrument based on this technique was installed by the Uppsala neutron diagnostics group at JET in 1996 [18], inside the torus hall, and it was upgraded (MPRu) with new detectors and a digital acquisition system in 2005 [19]. An instrument based on the same measurement technique is used at NIF [20].

The MPR is optimized for 14 MeV neutrons (from the DT reaction) measurements, but it can also be used to measure 2.5 MeV neutrons (from the DD reaction).
reaction). The main components of the MPRu spectrometer are shown in Figure 2.2. The neutrons emitted by the plasma are formed into a "neutron beam" by a collimator. They then enter the spectrometer's vacuum chamber through a thin steel window and impinge on a thin polythene foil, where they may interact with the foil's hydrogen nuclei (protons) via elastic scattering. Some of the recoil protons are scattered in the forward direction (same direction as the incoming neutrons) and they pass through the proton collimator. The relationship between neutron and proton energy is \( E_p = E_n \cos^2 \theta \), where \( \theta \) is the angle between the trajectory of the incoming neutron and the trajectory of the proton in the laboratory system. Thus a proton scattered in the exact forward direction (\( \theta = 0^\circ \)) has the same energy as the original neutron. The neutron and proton collimators ensure that the scattering angle is restricted to a small range close to zero. Inside the vacuum chamber two magnetic dipoles (D1 and D2) generate a magnetic field that bends the trajectories of the protons towards the hodoscope, the instrument's proton detector composed of an array of plastic scintillators. The bending radius of the protons in the magnetic field is proportional to their velocity (in case of a uniform magnetic field \( B \),
\( r = \frac{mv}{Bq} \), thus the position distribution of protons on the hodoscope is a reflection of the initial energy distribution of neutrons.

### 2.3 The Afterburner

The MPRu spectrometer has a pre-prepared cavity in the back, before the beam dump (see Figure 2.2), where different detectors can be tested. A liquid scintillator (manufactured by SCIONIX [21]) was installed in this cavity. The installation was named “Afterburner”, since it measures neutrons after they have gone through the thin conversion foil, as well as the entrance and exit windows of the vacuum chamber of the MPRu. The characterization and data analysis of the Afterburner is the topic of Papers I, II and III.

Liquid scintillators are usually made of organic compounds, therefore they contain mainly hydrogen and carbon atoms [22]. At the energies of interest for DD fusion, neutrons interact with hydrogen (proton) and carbon nuclei via elastic scattering. Other reaction channels on carbon such as \(^{12}\text{C}(n, \alpha)^{9}\text{Be}\), \(^{12}\text{C}(n, p)^{12}\text{B}\), and \(^{12}\text{C}(n, d)^{11}\text{B}\) become important only for neutron energies above about 7 MeV, because of their reaction thresholds.

The scattered proton is charged, therefore it is slowed down by interacting with the electrons in the material, which results in the excitation of molecular levels in the scintillator. The subsequent de-excitation produces light in the visible range, with a total intensity which depends on the energy deposited by the recoil nucleus. The light pulse produced can then be converted into a current pulse using a Photomultiplier Tube (PMT). The PMT is composed of a photo-cathode that converts photons into electrons through the photoelectric effect, and then a series of dynodes that multiply the electrons, which are finally collected by an anode. The integral of the current pulse (total charge) is directly proportional to the intensity of the light collected by the photocathode, therefore it is related to the energy deposited in the scintillator. The spectrum constructed from the distribution of the total charge of the events is referred to as a pulse height spectrum (PHS). Notice that for a given transferred energy the light produced from recoil carbon is much less than that from protons, and therefore it contributes only to the low energy part of the measured spectrum [23].

There are several factors that contribute to the resolution of a detector based on (liquid) scintillation and PMTs:

1. spatial variations in the light collection efficiency from different parts of the scintillation volume;
2. statistical fluctuations in the number of photo-electrons produced and in the multiplication process in the PMT;
3. electrical noise on the signal.

These three effects are represented in the following empirical equation by the terms \( \alpha \), \( \beta \), and \( \gamma \) respectively [24]:

22
\[ R(E) = \frac{FWHM(E)}{E} = \sqrt{\frac{\alpha^2}{E} + \frac{\beta^2}{E^2} + \frac{\gamma^2}{E^2}}, \quad (2.3) \]

where \( R \) is the relative resolution, \( E \) is the light yield, and \( FWHM \) stands for full width at half maximum.

Furthermore, if the pulses are recorded using a waveform digitizer, the resolution could be deteriorated if the bit resolution and sampling frequency of the digitizer are not chosen appropriately [25, 26].

In a similar way to that for neutron detection, liquid scintillators can also detect gamma rays, the difference being that the gammas interact with electrons (mainly via Compton scattering in the energy range relevant for this thesis) instead of protons. However some scintillators give pulse shapes (i.e. the time evolution of the light pulse) that depend on the interacting particle, which allows for the identification of the type of particle that produced a specific pulse. The reason for this is that different particles excite different molecular levels, which have slightly different de-excitation times. This is reflected in the scintillation pulse shapes as shown in Figure 2.3: the tail of the neutron (proton) pulse shapes is longer than the one of the gamma (electron), a difference that can be exploited using various techniques to distinguish between neutron and gamma events.

![Figure 2.3. Average proton (neutron) and electron (gamma) pulse shapes for a NE213 liquid scintillator.](image)

Several organic liquid scintillators have been developed over the years. The Afterburner is a scintillator of the NE213 type (a.k.a. BC-501A or EJ-301 de-
pending on the manufacturer), which provides excellent performance in terms of pulse shape discrimination [27]. Some of the properties of NE213 scintillators are shown in Table 2.1.

Table 2.1. Properties of NE213 liquid scintillators [28].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Output (% Anthracene)</td>
<td>78</td>
</tr>
<tr>
<td>Scintillation Efficiency (photons/1 MeV e-)</td>
<td>12000</td>
</tr>
<tr>
<td>Wavelength of Maximum Emission (nm)</td>
<td>425</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>0.874</td>
</tr>
<tr>
<td>Flash Point (°C)</td>
<td>26</td>
</tr>
<tr>
<td>No. of H Atoms per cm$^3$</td>
<td>4.82 · 10$^{22}$</td>
</tr>
<tr>
<td>No. of C Atoms per cm$^3$</td>
<td>3.98 · 10$^{22}$</td>
</tr>
</tbody>
</table>

It is important to know that the light emission from electron signals is linearly proportional to the energy deposited in the detector (in the energy range of interest for this work), but the same is not true for protons [22, 23]. The non-linearity makes the analysis of neutron pulse height spectra more complicated than that of gammas. Furthermore, the light output from a proton that deposits a certain energy is generally lower than that of an electron that deposits the same energy.

The Afterburner detector consists of a cylindrical cell with 12.3 mm diameter and 8.4 mm height, for a total active volume of about 1 cm$^3$. The cell is optically connected to a PMT (Hamamatsu R5611 [29]) and the whole assembly is embedded in an aluminium casing. The PMT is shielded against magnetic fields by a 1 mm thick μ-metal layer. The detector is held in position by a soft iron cylinder which also serves as additional magnetic shielding. A $^{22}$Na gamma source used for energy calibration and monitoring of the gain drift of the PMT is placed in front of the scintillator volume. Three cables are connected to the PMT: a cable with SHV connector for high voltage supply, a cable with BNC connector to transmit the signal, and an optical fiber to send external light signals such as LED pulses to the photocathode of the PMT. Figure 2.4 shows the detector and the holder before the installation at JET.

The full PMT pulses are recorded digitally using a SP Devices ADQ214 digitizer (14 bit, 400 MSPS) [30] and stored on a local computer.

2.4 Other compact neutron detectors

Liquid scintillators fall in the category of compact neutron detectors, which, in contrast with complex systems like the MPRu and TOFOR, are simple and have small size. However, their performance in terms of neutron energy measurements is usually worse than that of the non compact spectrometers. Other than liquid scintillators, also semiconductors (silicon [31] and diamonds ([32]) and solid scintillators [33] are used as compact neutron detectors. Two further
NE213 scintillators are installed at JET at different locations [34], and two instruments based on diamond detectors are also present [32, 35]. One of the diamonds [32] is installed in the MPRu shielding, behind the Afterburner, and it is used for a part of the data analysis presented in Paper III.

2.5 The JET neutron camera

The JET neutron camera [36, 37], or neutron profile monitor, is a system composed of 19 lines of sight (10 horizontal, 9 vertical), each equipped with an NE213 liquid scintillator, used for measurements during DD plasma discharges, and a BC418, used for measurements in DT plasmas.

Figure 2.5 shows a model of the neutron camera system together with the field of view of each detector. The box on the left of the figure is the horizontal camera, the box on top is the vertical camera; the structure on the bottom right is a poloidal cross section of the tokamak vessel. The numbers indicate the different channels of the camera: channels 1 to 10 are the horizontal channels, from top to bottom, and channels 11 to 19 are the vertical channels, from the inboard to the outboard side of the vessel.

The neutron camera is used to provide information on the spatial distribution of the neutron emission from the plasma. Papers IV, V and VI are devoted to the characterization and data analysis of the neutron camera.
Figure 2.5. The neutron camera system (horizontal camera on the left, vertical camera on top) and the JET tokamak vessel (bottom right) shown in a poloidal cross section. The field of view of each detector is shown inside the vessel. The numbers indicate the neutron camera channels, with the numbering direction going clockwise from 1 to 19. The figure was obtained from a MCNP model of the JET tokamak and neutron camera.

2.6 Fission chambers

The total neutron yield at JET is measured with fission chambers [38]. Two types of chambers are used: $^{235}\text{U}$ and $^{238}\text{U}$. The neutrons that enter the chambers can induce fission of the uranium isotopes, and the fission products are detected in a gas ionization chamber. 6 chambers (3 of each type) are placed outside the tokamak vessel at 3 different positions. With a proper calibration, the total neutron yield can be deduced from the fission chambers measurement [39].
3. Neutron emission from the plasma

Reactions 1 (DD) and 4 (DT) from Table 1.1 produce neutrons. The DD reaction emits neutrons at about 2.45 MeV while the DT reaction neutrons have an energy of about 14.0 MeV. One must be aware that even with a pure deuterium fuel there will be tritons generated by the second reaction in Table 1.1. These tritons can interact with the deuterons and produce 14 MeV neutrons which are commonly referred to as triton burn-up neutrons (TBN). TBN usually account for about 1% of the total neutron emission from a pure D plasma [40].

Neutrons are not charged, therefore they are not trapped by the magnetic field, and they leave the plasma unaffected. The number of neutrons emitted depends on the number of fusion reactions occurring in the plasma. Since to each reaction is associated an energy release, a measurement of the total neutron yield in a pure D plasma can be related to the total power produced in the tokamak, using the following relationship:

\[
P = Y_{n,DT} \cdot Q_{DT} + Y_{n,DD} \cdot \left( Q_{n,DD} + Q_{p,DD} \cdot \frac{BR_p}{BR_n} \right), \tag{3.1}
\]

where \(Y\) denotes the neutron yield, i.e. the total number of neutrons produced by the reaction, \(Q\) denotes the total energy release of each reaction, \(BR\) denotes the branching ratio of a reaction, and the subscripts \(n\) and \(p\) stand for the neutron and proton producing branch of the DD reaction. The fact that the DD reaction has two branches, of which only one produces neutrons, needs to be taken into account in the multiplicative factor for \(Y_{n,DD}\) as done in the equation above. Notice that, in the case of a DT plasma, if significant amounts of tritium are present, then also reactions between two tritons (TT), that also produce neutrons, should be considered in Equation 3.1. This is however beyond the scope of this thesis, since we deal only with pure deuterium plasmas.

Since a neutron is generated in the reaction between two ions in the plasma, its energy is related to the velocity of the reactants. The relationship is given by the formula [41]:

\[
E_n = \frac{1}{2} m_n v_{cm}^2 + \frac{m_r}{m_n + m_r} (Q + K) + v_{cm} \cos \theta \left( \frac{2m_nm_r}{m_n + m_r} (Q + K) \right)^{1/2}, \tag{3.2}
\]

where the subscripts \(cm, n, r\) denote respectively centre of mass, neutron and residual nucleus, \(K\) is the relative kinetic energy of the reactants, \(Q\) is the total
energy released in the reaction, and θ is the angle between the velocity of the emitted neutron and the relative velocity of the reactants in the center of mass frame (Figure 3.1). Notice that the second term of equation 3.2 is made of quantities which are independent of the measurement reference frame, which comes into the first and third terms via $v_{cm}$ and θ.

![Figure 3.1. The kinematics of a fusion reaction in the centre of mass reference frame. $v_1$ and $v_2$ are the velocities of the reacting ions, $v_r$ is the velocity of the residual nucleus and $v_n$ is the velocity of the neutron.](image)

The velocity of the ions is represented in the equation through the terms $K$ and $v_{cm}$. Therefore measuring the energy distribution of the neutrons means diagnosing indirectly the velocity distribution of the ions in the plasma.

Equation 3.2 is the basis for neutron emission spectroscopy (NES) analysis. One way to approach NES analysis is with the forward modeling technique: one starts from a model of the plasma and after passing through a series of steps obtains modeled neutron measurement data; the model is dependent on a number of parameters that can be left free to vary when fitting the model to the experimental data. Some typical examples of such parameters are the plasma ion temperature and the intensity of the neutron spectrum components.

The following sections are devoted to a description of the modeling steps required to perform NES analysis on neutron data: modeling of the plasma ion velocity distribution, modeling of the neutron emission, modeling of the detector signal.

### 3.1 Modeling of plasma ion velocity distribution

The ion velocity distribution in the plasma, and therefore its modeling, can be very different depending on the plasma scenario. For the simple case of Ohmic plasmas, the plasma ion velocity distribution can be described as a
Maxwellian distribution with temperature \( T_i \). Neutrons are generated by the interaction between these ions, and an analytical expression for the resulting neutron energy spectrum, which is approximately a Gaussian with a broadening that is proportional to \( \sqrt{T_i} \), was derived in [41].

In the case when auxiliary heating is applied (NBI and/or ICRH), one way of describing the time evolution of the ion velocity distribution is with a Fokker-Planck equation:

\[
\frac{\partial f}{\partial t} = C(f) + Q(f) + S(v) + L(v),
\]

where \( v \) is the ion velocity, \( f \) is the ion velocity distribution function, \( C \) is a collision term that represents collisions between fast ions and thermal ions, \( Q \) describes the interaction between the ICRH waves and the fast ions, \( S \) and \( L \) are terms that represent sources and losses of particles.

In some cases it is possible to solve equation 3.3 analytically by making simplifying assumptions, for example about the distribution of the direction of the fast ion velocities (as it was done in Paper III). When it is not possible to make such assumptions, it is necessary to use numerical tools that, e.g., employ Monte Carlo methods to simulate the transport of the fast ions in the plasma (as it was done in Papers I, II and IV). For the modeling of NBI heated plasmas, TRANSF [42] is a code which is commonly used, while for ICRH modeling some common codes are PION [43] and SELFO [44].

Often it is convenient to separate ions into different populations, based on their origin and history. For example, in an NBI heated plasma, it is convenient to consider two ion populations: thermal ions (the ions already thermalised inside the plasma) and beam ions (the ions introduced by the beams which have not been thermalised yet). Why this is convenient will become clear in the end of the next section.

### 3.2 Modeling of the neutron emission

Starting from a model of the ion velocity distribution, it is possible to calculate the corresponding neutron spectrum in the detector reference frame. The calculation is usually performed either analytically [41], when possible, or with Monte Carlo simulation codes such as FPS [45], ControlRoom [46] and DRESS [47]. In the DRESS code, the velocities of the reacting ions are sampled according to their velocity distribution, then the energy of the emitted neutron is calculated by solving a relativistic version of Equation 3.2 for a given direction of emission; the code also computes the reaction rate for the selected ion velocities. After repeating this procedure multiple times, the energy values are collected in a binned histogram, where each value is weighted according to the corresponding reaction rate.
The field of view of the detector also needs to be taken into account. In this work we model the field of view using the Monte-Carlo code LINE2.1, which is described as part of Paper IV. In the code the plasma volume is divided into voxels. Hindering surfaces such as the collimator front and end are defined. After sampling a random point inside the voxel and another one on the detector surface, the code checks if the two points are optically connected, i.e. if the line connecting the two points does not cross any hindering surface. This is done multiple times for each voxel, and from the fraction of connected lines, the expected number of neutrons at the detector position for a given neutron emissivity from the voxel is computed:

\[ N = F \cdot \varepsilon = \frac{N_C A \cdot \cos \theta}{N_T 4\pi L^2 V} \cdot \varepsilon, \]  

(3.4)

where \( \varepsilon \) is the neutron emissivity from the voxel \((n/m^3s)\), \( F \) is the “optical weight” of the voxel, \( N_C \) is the number of optically connected lines, \( N_T \) is the total number of lines checked in the simulation, \( A \) is the detector surface area, \( \theta \) is the angle between the normal to the detector surface and the line connecting the centre of the voxel to the centre of the detector surface, \( L \) is the distance between the voxel and the detector surface, \( V \) is the voxel’s volume.

The two codes (DRESS and LINE2.1) are used together to obtain the neutron spectrum at the detector position. The ion velocity distribution in each voxel is used by DRESS to evaluate the neutron spectrum reaching the detector directly from that voxel, and then the results are summed up with the optical weights \( F \) from the LINE2.1 calculation.

Usually, instead of immediately calculating one total neutron spectrum, we calculate spectrum components. Each spectrum component is the result of interactions of pairs of ions belonging to two specific ion populations (see Section 3.1). For example, in an NBI heated plasma, one has three components: the thermal component (interaction between two thermal ions), the beam-thermal component (interaction between a beam and a thermal ion) and the beam-beam component (interaction between two beam ions). The advantage of modeling each component separately can be seen for example in Paper II, where the intensities of the components were separate free parameters of the fit (for more details, see Section 8.2).

3.3 Modeling of the detector signal

The response of the detector to neutron interactions is the last link of the chain that permits to compare a model of the ion velocity distribution in the plasma with a neutron measurement. Starting from a model of the neutron spectrum at the detector position, the model of the detector signal \( D \) is given by:

\[ D = \bar{R} \times S, \]  

(3.5)
where \( \overline{R} \) is the neutron response matrix, \( \overline{S} \) is the neutron spectrum at the detector position. The response \( \overline{R} \), and therefore the detector signal \( \overline{D} \), differs depending on the detector type. For TOFOR, \( \overline{D} \) is a time of flight spectrum, for the MPRu it is a position spectrum, while for NE213 detectors it is a pulse height spectrum.

Some care needs to be taken before applying equation 3.5, because the neutron spectrum at the detector position is not just the direct spectrum calculated as explained in the previous section. It is also necessary to include the contribution to the spectrum due to scattered neutrons, i.e. neutron that enter the collimator and reach the detector after scattering on various tokamak structures. Usually the great majority of the scattered neutrons come from scattering on the far wall opposite the detector, therefore we refer to them as backscattered neutron (see the left panel of Figure 3.2). This contribution is evaluated by means of neutron transport codes such as MCNP [48], and it is usually treated as a component of the neutron spectrum [49]. Other secondary effects like transmission through the collimator, scattering in the collimator and attenuation of the neutron flux are shown in the right panel of Figure 3.2. These effects may also be relevant and can, if required, be evaluated with neutron transport simulations.

![Diagram of neutron flux contributions](image)

**Figure 3.2.** Left panel: direct (solid) and backscatter (dash-dotted) contributions to the neutron flux at the collimator entrance. Left panel: secondary effects that affect the neutron flux at the detector position. Figure from Paper IV.

### 3.4 Absolute comparison

The comparison between model and measurement can be performed on an absolute level, i.e. without any arbitrary scaling of the intensity of the modeled spectrum. To achieve that, all of the steps in the modeling chain, from the ion distribution to the detector response, must be calculated in absolute units. In
Paper IV we made an absolute comparison of the neutron camera measurement with a model of the neutron emission. The results of such comparison are presented in section 9.1.
Part III:
Characterization of NE213 scintillators

“A sword by itself does not slay; it is merely the weapon used by the slayer.”
– Seneca
4. Data processing

The raw data collected during experiments have to be processed to obtain something that can be compared to theoretical models or simulations. In the case of NE213 detectors, when a digital acquisition system is in place, the raw data is a collection of digitized pulses, and the end product of the processing is a pulse height spectrum.

The steps in the processing are:
1. baseline restoration;
2. pulse integration;
3. pulse shape analysis (event type identification and selection);
4. gain drift correction.

The following sections describe the processing steps in a general fashion. Details about their implementation for specific systems are given in Chapter 6, in Paper I (Afterburner) and Paper IV (Neutron camera).

4.1 Baseline

An example of a raw digitized pulse is shown in Figure 4.1. By looking at the Figure one can notice that the baseline, i.e. the samples before the start of the pulse, have an amplitude which is not, on average, zero. If no action is taken, the integration of the pulse would give biased values, depending on the baseline level. The problem is overcome by calculating the average amplitude of the baseline samples before the onset of the signal pulse and then subtracting the average from all the samples. This procedure is called baseline subtraction. In some cases the baseline might be affected by pick-up noise which requires a more elaborate handling in the restoration step (see e.g. [17]). This is however not the case in this work.

4.2 Pulse integration and pulse shape analysis

After the baseline is restored it is possible to perform the integration of the pulses to obtain the total charge (or pulse height) values. However the pulses also need to be classified into neutrons, gammas, LED (if present) and pile-up events. It is possible to classify the events based on the different shapes of the pulses induced (see Figure 2.3). The classification can be done in a number of different ways [27]: comparing the gradients of the tails [50], shaping the
pulse so that it crosses the zero level and comparing the time of zero crossing [51], etc. Here we use the charge comparison method [52], which consists in integrating the pulses in two different time intervals and extracting a classification coefficient from the integral values. The integration intervals must be chosen in a way that maximizes the separation between the various types of events.

4.3 Gain drift correction

The photomultiplier tube coupled to the NE213 detector can be subject to changes in its gain over time. Depending on the time scale of the change, the gain drift can be classified as long term (days-months) or short term (below seconds) [53].

The first type is caused by temperature changes and degradation of the materials in the PMT, especially in the photocathode and the last dynode steps. Long term drifts are usually monitored with a gamma source, because the gamma rays produced by the source have fixed energies that depend only on the source element and do not change over time. The PHS derived from the interactions of the gammas from the source with the detector can be used to estimate the gain of the PMT. However, since for safety and operational reasons such a calibration source must be limited in rate, in order have a good counting statistics, the measurement has to be performed for a relatively long period of time, which depends on the source activity and on the desired precision of the
gain estimate. Even with a fairly high rate source and a low requirement in the precision, the measurement takes at least some seconds. This means that gamma sources cannot be used to monitor short term gain drifts.

The short term drifts occur when the current flowing in the PMT is comparable to the current in the voltage divider circuit of the PMT. This can happen for example if the counting rates in the detector are high. For the correction of short term drifts an LED pulser can be used as reference. The advantage with the LED pulser is that it emits light pulses with an intensity that has a Gaussian distribution around a mean value. As a consequence, even single pulses can be used to estimate the gain of the PMT, thus pushing the time scale of the correction down to the repetition period of the pulses, which can be of the order of milliseconds. The drawback of the LED pulser is that the mean value of the light intensity can itself drift over time, therefore it cannot be used to monitor long term gain drifts [54].
5. Gamma and neutron response

5.1 Gamma energy calibration

The gamma source mentioned in the previous chapter can also be used to estimate the energy calibration of the detector. In this context the expression “energy calibration” means the conversion from the total charge value obtained from the integration of the pulse to the energy deposited by the recoil electron that produced it. To be precise, the total charge value is a measurement of the light emitted by the scintillator. Therefore it would be more accurate to call this procedure “light yield calibration” but since for electrons the relationship between the deposited energy and light emitted is linear (for energies in the keV - MeV range), it is traditionally referred to as “energy calibration”. However, the unit of measurement to which the total charge is converted to is called electronvolt electron equivalent (eVee), a name which bears a reminder that the quantity is related to energy in a somewhat restricted sense. As the name says, one unit of electronvolt electron equivalent is the light emitted by the scintillator from the interaction of an electron that deposited 1 eV of energy. The equation used for the calibration is a simple linear relationship:

\[ L = k \cdot Q + m, \]

where \( L \) is the calibrated light yield (eVee), \( Q \) is the total charge, \( k \) and \( m \) are the calibration coefficients. Notice that the coefficient \( m \) is added to compensate for non-linearities of the relationship in the low energy range.

One way to perform the energy calibration is to simulate the response of the detector to the gamma energies emitted by the source. This can be done for example with a MCNP model of the detector. The result of the simulation does not include the resolution of the detector, therefore the MCNP response must be convolved with a Gaussian function, whose broadening depends on the energy as described by Equation 2.3. The output of this calculation can then be fitted to the measured gamma PHS, using the resolution \((\alpha, \beta, \gamma)\) and calibration \((k, m)\) parameters as free parameters of the fit. An example of an energy calibration with a Bismuth-207 gamma source (3 gamma peaks at 569 keV, 1063 keV and 1770 keV) is shown in Figure 5.1. Each of the three edges in the PHS shown in the Figure corresponds to one gamma energy. Since the dominant mechanism of energy transfer is Compton scattering, the maximum energy of the Compton edges is lower than the gamma energy, and it is given by the formula [22]:

\[ E_{\text{Compton}} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_{\text{eV}}} \rho}, \]

where \( E_{\gamma} \) is the gamma energy, \( m_{\text{eV}} \) is the atomic mass of the element, and \( \rho \) is the density of the element.
where $E_C$ is the energy of the Compton edge, $E_\gamma$ is the energy of the incoming gamma, $m_e$ is the electron mass and $c$ is the speed of light. For the Bismuth-207 gamma energies, the Compton edges correspond to 392 keV, 857 keV and 1547 keV.

Figure 5.1. Example of a gamma calibration with a Bismuth-207 gamma source. Bismuth-207 produces 3 gamma energies: 569 keV, 1063 keV, 1770 keV. This figure is used here only to illustrate the gamma calibration procedure; the data comes from a detector that was not used in this thesis.

5.2 Neutron response

The response of the detector to neutrons can be measured at an accelerator facility with mono-energetic neutron beams [55], [56], or it can be simulated with particle transport codes such as MCNP or NRESP [57]. These particle transport codes cannot simulate the production of scintillation light. There are two options to solve this problem: coupling the transport code with a code that can simulate the scintillation part, or adopting a proton light yield function from the literature. In the second case, which is the option chosen in this work, it is necessary to perform a calibration of the response to correct for the differences between the real light yield function and the one assumed in the simulation.
5.2.1 Simulation of the response matrix

The neutron response matrix $\overline{R}$ (see Equation 3.5) can be obtained from MCNP simulations with mono-energetic neutrons. Each of the mono-energetic neutron simulations gives a light yield spectrum which constitutes one row of the response matrix.

The MCNP model comprises the detector geometry and its surroundings. It is possible to obtain the light yield distribution as output of the simulation by using an F8 tally in coincidence with an F6 tally. The F6 tally gives the conversion from proton deposited energy to light yield. For this to work, the Russian roulette has to be switched off.

As in the case of the calculation of the gamma response, the output does not include the resolution of the detector, which needs to be included by convolving the response with a Gaussian distribution whose broadening is given by Equation 2.3.

An example of a response calculated with MCNP before the addition of resolution broadening is shown in Figure 5.2. Notice that the response to mono-energetics neutrons is a “box-shaped” broad spectrum which extends from the maximum possible deposited energy down to zero.

![Simulated NE213 neutron response](image)

*Figure 5.2.* Response of an NE213 detector to 3, 4 and 5 MeV neutrons calculated with MCNP. The proton light yield function used in the simulation was taken from [58].

5.2.2 Calibration of the response

If the neutron light yield function used in the simulation of the response was not measured specifically for the detector in consideration, the response ob-
tained might be inaccurate. To improve the accuracy it is possible to perform a calibration of the response, using data for which the neutron spectrum is well known. Such well known spectra in a fusion tokamak can be measured for example during Ohmic plasma discharges.

The calibration factor used in this work is a simple multiplication (stretching) factor for the proton light yield axis of the neutron response:

\[ L' = \lambda L, \]  

(5.3)

where \( L \) is the light yield function used in the simulation, \( L' \) is the corrected light yield function and \( \lambda \) is the calibration factor. An estimate of \( \lambda \) can be obtained by fitting a model of the neutron emission to the experimental neutron pulse height spectrum measured during Ohmic plasma discharges. The neutron spectrum from Ohmic plasma discharges is simple to model (see Section 3.1). However, the neutron rates from such discharges are low compared to discharges with auxiliary heating. Therefore it is often necessary to sum over many discharges to reach a number of counts in the detector that allows to estimate the calibration parameter with good precision (say 1% or better).
6. System-specific characterization

6.1 Afterburner

A detailed description of the characterization of the Afterburner system (see Section 2.3), and in particular of the way its neutron response is evaluated, is given in Paper I. Here we present some details on the treatment of the raw data and we give an overview of the detector characterization.

6.1.1 Processing of raw data

The raw data is stored in the digitizer in 256 samples long records, with 64 pre-trigger samples. Figure 6.1 shows an example of a digitized pulse with the different gates used for averaging and integration. The average of the first 60 samples are used as baseline level, and it is subtracted from the pulse. The total gate is defined starting from sample 61 and is 65 samples long, while the start of the long gate is 14 samples after the start of the total gate and is 50 samples long.

The PSD factor is defined as $PSD = Q_L / Q_T$, where $Q_L$ is the integrated charge (sum of baseline subtracted sample amplitudes) in the long gate and $Q_T$ is the total charge, which is integrated in the total gate. Figure 6.2 shows a 2D histogram with events distributed according to their total charge (x axis) and PSD factor (y axis). There are 4 distinct types of events, labeled in the figure:

1. neutron;
2. gamma;
3. pile-up;
4. LED.

Once the events are sorted, it is possible to perform the gamma and neutron calibrations, and the LED events can be used to estimate the gain drift during plasma discharges.

6.1.2 Gamma calibration

The $^{22}Na$ gamma source installed in front of the Afterburner detector produces gammas with energies of 511 and 1275 keV. The response of the detector to these energy was simulated with MCNP. A fit to the data was then used to determine the resolution (Equation 2.3) and calibration (Equation 5.1) parameters. In this case the resolution parameter $\alpha$, which represents resolution
Figure 6.1. Example of an Afterburner pulse with the baseline and integration gates delimited by the red vertical lines and indicated by the horizontal arrows.

Figure 6.2. Example of an Afterburner PSD histogram, where the clusters corresponding to the different types of events are indicated.

broadening due to non-uniform light collection in the detector, was set to 0, because the detector size is small, so that these effects are negligible.
An example of the results of such a fit are shown in Figure 6.3. Notice that, since Compton scattering dominates, the edges of the PHS correspond to the Compton electron maximum energies of 341 and 1062 KeV (see Equation 5.2). The resolution is about 10% at 1 MeVee.

6.1.3 Neutron response calibration

The neutron response matrix was calculated as described in Section 5.2.1 with MCNP simulations using the proton light yield function from [58]. The impact of the proton light yield function chosen on the data analysis was investigated in Paper I and it is described in Part IV.

To calibrate the neutron response matrix, data from the Ohmic phase of about 600 plasma discharges were summed up. In the model of the neutron spectrum that was fitted to the data, the ion temperature of the plasma was assumed to be 2 keV.

The result of the fit is presented in Figure 6.4. The value obtained for the calibration parameter was $\lambda = 0.967 \pm 0.002$.
6.1.4 Gain drift estimate

The gain drift due to high counting rates in the detector was estimated using signals from the LED source that shines into the photomultiplier tube of the detector. A plot of the relationship between gain and counting rate (Figure 6.5) shows that the drift is lower than 1% up to about 60 kHz. The relationship between gain drift and current in the PMT is expected to be linear, therefore the relationship between gain drift and counting rates is also expected to be linear, provided that the distribution of the light intensity of the events is about the same for all rates.

6.2 Neutron camera

Each of the 19 NE213 detectors present in the neutron camera is characterized independently, in a similar way to what was done for the Afterburner. The characterization of the Neutron camera detectors is described in Paper IV. Here we give some details on the processing of the raw data and present an overview of the characterization.
6.2.1 Processing of raw data

The raw data from each detector are digitized in records that have variable length. The sampling frequency in this case is 200 MSPS, and the resolution is 14 bit. The integration gates in this case are defined dynamically using the maximum amplitude of the pulse as a reference point. The total charge is obtained by integrating the pulse over the entire record length. The short integration gate includes the maximum and the sample before it, while the long gate is 8 samples long and starts from the third sample after the maximum. The PSD factor is defined as $PSD = Q_L/Q_S$, and the events can be displayed in a 2D histogram and separated into types in a similar way as it was done for the Afterburner.

A difference from the Afterburner detector is that in this case there are no LED events, since the detectors are not equipped with LED pulsers. This implies that an alternative method needs to be used to evaluate gain drifts due to high count rates in the detectors. The gamma data from the plasma discharges can be used to get an estimate of the relationship between count rate and gain drift, as described in Section 6.2.4 and in Paper IV.

6.2.2 Gamma calibration

Each of the detectors is equipped with a $^{22}Na$ source, so the gamma calibration is analogous to the one for the Afterburner detector. However, since the
Figure 6.6. Template pulse for a neutron camera detector. The circles indicate the samples used for the short charge integration, while the squares indicate the samples used for the long charge integration.

detectors are bigger than the Afterburner, it is not possible to neglect the parameter $\alpha$ in the resolution Equation 2.3. An example of a gamma calibration for channel 5 is shown in Figure 6.7

6.2.3 Neutron response calibration

For the calibration of the neutron response of the camera detectors, the data collected during a series of 10 Ohmic discharges was used. Since there was no additional heating for the whole duration of the discharges, the spectra were sufficient to obtain estimates of the $\lambda$ calibration parameter with uncertainties ranging from 0.5\% in the central channels to about 2\% in the edge channels. Examples of the fits obtained for a central (5) and an edge (2) channel are shown in Figure 6.8. The estimated $\lambda$ for each channel and their uncertainty are shown in Table 6.1.

6.2.4 Gain drift estimate

Since the NE213 detectors of the neutron camera are not equipped with LED sources, an alternative method must be used. Here we obtain an estimate of the gain drift due to high counting rates by using the gamma pulse height spectra collected during plasma discharges. These gamma spectra are not expected
Figure 6.7. Example of a gamma calibration of the neutron camera detector in channel 5. Points with error bars are pulse height data, the dashed line is the fitted 511 keV component; the dash-dotted line is the fitted 1275 keV component; the solid line is the sum of the two components.

Figure 6.8. The results of the fit of the Ohmic PHS measured by the detectors in channel 5 (left) and channel 2 (right). In both panels, the dashed line is the backscatter component, the dotted line is the direct component, the solid line is the sum of the two components and the dots with error bars are the experimental points.

to change significantly, therefore changes in the measured gamma PHS correlated with counting rates are likely due to gain drift of the PMT. This correlation was investigated by summing up gamma PHS in different counting rate ranges and comparing them visually (see Figure 6.9) and quantitatively.

A two samples Kolmogorov-Smirnov test, which indicates if 2 samples are likely to be drawn from two different probability distributions or not, was performed on the spectra to obtain a quantitative comparison. A p-value of
Table 6.1. Values and uncertainties of the calibration parameter $\lambda$ obtained from the calibration procedure.

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<th>$\sigma_\lambda$</th>
<th>Ch</th>
<th>$\lambda$</th>
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<td>0.005</td>
<td>10</td>
<td>0.74</td>
<td>0.01</td>
<td>17</td>
<td>0.88</td>
<td>0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.888</td>
<td>0.004</td>
<td>11</td>
<td>0.76</td>
<td>0.02</td>
<td>18</td>
<td>0.95</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>0.952</td>
<td>0.004</td>
<td>12</td>
<td>0.94</td>
<td>0.03</td>
<td>19</td>
<td>0.92</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
<td>0.882</td>
<td>0.005</td>
<td>13</td>
<td>0.94</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.86</td>
<td>0.01</td>
<td>14</td>
<td>0.910</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6.9.** Gamma PHS measured by the neutron camera detector in channel 16 during periods with different counting rates ranges: 40-60 kHz (solid line), 120-140 kHz (dashed line), 200-220 kHz (dash-dotted line).

0.34 was obtained when comparing the data in the 40-60 kHz and 200-220 kHz ranges, which indicates that there are no significant differences in the 2 data sets. Therefore no rate dependent gain correction was imposed on the data.
Part IV:
Data analysis

“You know my methods. Apply them.”
– Sherlock Holmes
7. Fitting procedure and uncertainty estimate

Before going into the description of the data analysis, I will briefly describe how the best values for parameters and their uncertainties have been estimated. A more detailed description of the procedure was given in [59, 60]. The procedure was used not only for the data analysis presented in this part of the thesis, but also for the calibration procedure presented in Part III.

7.1 Fit and statistical uncertainty

Typically we have binned data (PHS for the Afterburner and the neutron camera, or time of flight spectra for TOFOR) and a model which depends on some parameters (see Chapter 3). The goal is to find the set of model parameters that best describe the data. If, as in most of the cases in this thesis, the data in each bin represents the number of counts in the bin interval, then the function that is minimized to obtain the best values for the parameters is the Cash statistic (C-stat) [61]. Otherwise a standard $\chi^2$ function is used.

If we consider $N$ bins, each having an expected number of counts $e_i$ and a measured number of counts $n_i$, the Cash statistic is given by [61]:

$$C = 2 \sum_{i=1}^{N} (e_i - n_i \ln e_i + \ln n_i!).$$

(7.1)

Notice that, if the number of counts in each bin is high (say $> 10$), then the Cash statistic is equivalent to the $\chi^2$ statistic.

An initial fit of the model to the data is performed by applying a standard minimization procedure. This method is quick, but does not provide an estimate of the uncorrelated uncertainty on the parameters. Thus, after this first fitting procedure, sets of values for the free parameters are randomly sampled. The range for the sampling of the parameter is centred at the best values obtained from the first fitting, and it extends over a pre-defined parameter range. The log likelihood $\log \mathcal{L}$ of the fit, i.e. the opposite of Equation 7.1, is calculated for each set of values. A scatter plot of $\log \mathcal{L}$ vs parameter value for each parameter (see Figure 7.1) is then used to estimate the best value and its uncertainty by fitting a second order polynomial envelope to the upper boundary of the plot. The maximum position of the envelope is the best value, the range of the parameter where the amplitude of the envelope is decreased by half is the statistical uncertainty $\sigma_{\text{STAT}}$ on the parameter, which corresponds to...
a 68.3% probability confidence interval. An example of such scatter plot with the fitted envelope is shown in Figure 7.1.

Notice that this method allows to evaluate also correlations between the parameters, as shown in Figure 7.2. For a given pair of parameters (P1, P2), one can make a scatter plot of P1 vs P2 and plot the likelihood contours. The contour is usually elliptical, and the correlation can be deduced from its slope. For example, it can be deduced from Figure 7.2 that P1 and P2 are positively correlated.

Figure 7.1. Example of a scatter plot used to extract the best estimate (dash-dotted lines) and the uncertainty (dashed lines) for the value of a free parameter of the fit. The solid lines is the polynomial envelope, while the points represent sampled values and their respective log $\mathcal{L}$.

7.2 Systematic uncertainties and error propagation

The calibration parameters give systematic uncertainties on the estimates of the parameters of the model (e.g. the intensity of the spectral components). These systematic uncertainties can be estimated by reiterating the fitting procedure after changing the value of the relevant calibration parameter by ±σ. If we take a parameter P and its best estimate $P_{\text{BEST}}$, after changing a calibration parameter we obtain two new best values $P_{\text{BEST}}^+$ and $P_{\text{BEST}}^-$. The difference between the new best values and the original best value gives the systematic uncertainty from the calibration parameter:

$$\sigma_{\text{SYS}}^± = \left| P_{\text{BEST}}^± - P_{\text{BEST}} \right|.$$  \hspace{1cm} (7.2)
Figure 7.2. Example of a scatter plot of 2 parameters P1 and P2, where the lines indicate the contours of constant log $\mathcal{L}$ and the solid line indicates the contour for which $\log \mathcal{L} = \log \mathcal{L}_{\text{MAX}} - 0.5$. The inclination of the contours gives the correlation between the two parameters.

The total uncertainty is obtained by applying the standard procedure of error propagation:

$$
\sigma_{\text{TOT}}^{\pm} = \sqrt{\sigma_{\text{STAT}}^2 + \sum (\sigma_{\text{SYS}}^{\pm})^2},
$$

(7.3)

where $\sigma_{\text{STAT}}$ is the statistical uncertainty obtained by applying the method described at the beginning of this chapter, and the summation is performed over all the systematic uncertainties that have been estimated. Notice that in the analysis that comes, the only calibration parameter that gives a significant contribution to the systematic uncertainty is the calibration parameter of the neutron response matrix $\lambda$ (see Section 5.2.2).
8. Afterburner

Papers I, II and III include analysis of Afterburner neutron pulse height spectra. The main focus in the analysis is to extract parameters related to the plasma state such as the thermal fraction (Paper II, see Section 8.2), a parameter related to the RF absorbed power $C_{RF}$ and the RF wave number $k_{\perp}$ (Paper III, see Section 8.3).

In Paper I we discussed the method for simulating and calibrating the neutron response function of the Afterburner detector. Details about this procedure are given in Part III. Furthermore, in the paper we discussed the impact that the choice of a specific proton light yield function has on the results of NES analysis of neutron PHS. This part of the paper will be discussed in the following section.

Paper II is mostly a proof of principle. In the paper we investigate how reliably we can separate neutron spectral components with the Afterburner detector, comparing the results with those obtained with the TOFOR neutron spectrometer.

In Paper III data from the Afterburner were analysed in conjunction with the data from TOFOR, a diamond neutron spectrometer and gamma spectrometers. In the paper it is shown that the analysis of the Afterburner and diamond data, which look through the plasma along a different line of sight than that of TOFOR and of the gamma spectrometer, adds information that is otherwise not possible to obtain with just one line of sight.

8.1 Sensitivity of the data analysis on the choice of light yield function in the simulation of the detector response (Paper I)

The neutron response matrix of the detector is used to perform a comparison between a model and the measured data (see Equation 3.5). Systematic uncertainties in the response affect the result of the comparison. The choice of proton light yield function that is necessary in the method that we use to evaluate the response matrix of the detector introduces a systematic uncertainty. This uncertainty is partly compensated by performing the calibration of the response as described in 5.2.2. To estimate the magnitude of the uncertainty that is left after the calibration, we produced three different neutron response matrices for the Afterburner. Each of the matrices was obtained from
MCNP simulations in which the only difference was the proton light yield function used: Verbinski [23], Hawkes [58] and “ED” (a function taken from the database of the simulation code NRESP [57]). The three matrices were calibrated separately, using the same Ohmic data set for the calibration. The calibrated matrices were then used to compare a model of the discharges from the 3rd harmonic RF experiment (which are discussed in Section 8.3) to the measured data. In this case, differently from what was done in Section 8.3, the parameters of the model (except the total normalization of the PHS) were fixed from the TOFOR data analysis. Figure 8.1 shows the results of the comparison of the measured and modeled PHS for discharge 86459, while Table 8.1 gives the reduced C-stat values obtained for all of the three discharges analyzed. As can be seen from the Figure and the values in the Table, the choice of proton light yield function has a small impact on the result.

![Figure 8.1](image)

**Figure 8.1.** Comparison between the measured PHS for discharge 86459 and the model using the three different response matrices, generated from different proton light yield functions. Figure from Paper I.

<table>
<thead>
<tr>
<th>Discharge number</th>
<th>Hawkes</th>
<th>ED</th>
<th>Verbinski</th>
</tr>
</thead>
<tbody>
<tr>
<td>86459</td>
<td>1.29</td>
<td>1.27</td>
<td>1.40</td>
</tr>
<tr>
<td>86461</td>
<td>1.38</td>
<td>1.27</td>
<td>1.21</td>
</tr>
<tr>
<td>86464</td>
<td>1.47</td>
<td>1.54</td>
<td>1.77</td>
</tr>
</tbody>
</table>

**Table 8.1.** Reduced C-stat values obtained for the three discharges analysed, using the three different response functions.
8.2 Thermal fraction estimate (Paper II)

The thermal fraction, i.e. the fraction of neutrons emitted from fusion reactions between ions from the thermal ion population, can be estimated by NES analysis. We define the thermal fraction as:

\[ TF = \frac{I_{th}}{I_{tot}}, \]  

(8.1)

where \( I_{th} \) is the intensity of the thermal neutron emission, \( I_{tot} \) is the total intensity of the neutron emission. The thermal fraction can be seen as an indicator of the performance of a plasma: a high thermal fraction means that the fusion device is less dependent on external heating to sustain the fusion reactions.

In an NBI heated plasma, the ions can be divided into two populations: beam ions and thermal ions. Neutrons can be produced by the interaction of two ions belonging to any of these populations: thermal-thermal, beam-thermal and beam-beam. These interactions produce neutron spectra of different shapes, and the total neutron spectrum is the sum of all such neutron spectrum components. The components can be modeled as described in chapter 3, and a fit to the data can be performed to estimate their relative intensities.

The data analysis was performed on plasma discharges that were selected applying the following criteria:

1. Afterburner and TOFOR data available;
2. NBI heated discharges only;
3. high electron density (\( n_e \approx 10^{20} \)).

The last point allows us to make some assumptions that simplify the modeling: first of all it can be assumed that \( T_i \approx T_e \), and second, the beam-beam component can be neglected. Six data sets which fulfill these criteria were selected for the analysis. The discharges were modeled with TRANSP, and ControlRoom was used to calculate the beam-thermal and thermal neutron spectrum components. These two components, together with the backscatter component, were multiplied with the Afterburner neutron response matrix (see Equation 3.5) and then fitted to the data, with their intensities as free parameters. From the fitted intensities the TF was calculated as in equation 8.1. The same analysis was performed with TOFOR data and the results are compared in Figure 8.2.

The error on the Afterburner results is 4 to 7 times higher than the error on the TOFOR results. This difference is partly due to the uncertainties in the response function of the Afterburner detector. However, the intrinsic shape of the response of the Afterburner also plays a role: TOFOR has a peaked response, while the Afterburner has a box-shaped response. The TOFOR response is better suited for NES analysis, since the features in the neutron spectrum are better represented in the measured spectrum.

From the comparison, one can conclude that the thermal fraction estimates from the two spectrometers are correlated, but there seems to be a system-
Figure 8.2. Comparison between the TOFOR and Afterburner estimates of the TF for all the plasma discharges analysed. The dashed line represents the fitted straight line, the solid line represents the ideal 1 to 1 relationship. Modified figure from Paper II.

atic difference between the two. One possible explanation for this is that the plasma rotation induced by the NBI, which was not included in the TRANSP modeling, affects the measurements of the two instruments in a different way, because of their different sight-lines. However, it must be pointed out that the TF value, as it is defined here, should depend on the LOS of the instrument used for the estimate, hence we do not necessarily expect the same value from the two instruments.

8.3 3rd harmonic RF experiment (Paper III)

In Paper III we analysed plasma discharges heated with a combination of NBI heating and RF heating tuned to the 3rd harmonic frequency of deuterium. This scenario can produce very energetic deuterium ions, reaching energies up to some MeV. The fusion reactions between such ions and the thermal deuterons can produce neutrons with energies well above the “cold plasma” reaction neutron energy of 2.45 MeV, therefore the neutron spectrum presents a characteristic high energy tail.

The Fokker-Planck equation 3.3 can be used to model the velocity distribution of NBI and RF ions. With this heating scheme, the ICRH accelerates ions mainly in the direction perpendicular to the magnetic field lines, therefore it is
possible to assume that for the fast ions \(v_\perp >> v_\parallel\). This leads to a 1-D form of
the Fokker-Planck equation [62]:

\[
\frac{\partial f}{\partial t} = \frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} \left[ -\alpha v_\perp f + \frac{1}{2} \frac{\partial}{\partial v_\perp} (\beta v_\perp f) + \frac{1}{4} \gamma f + \frac{1}{2} D_{RF} v_\perp \frac{\partial f}{\partial v_\perp} \right] + S(v_\perp) + L(v_\perp),
\]

(8.2)

where \(\alpha\), \(\beta\) and \(\gamma\) are the Spitzer coefficients [63], which determine the slowing down of fast ions, and \(D_{RF}\) is the RF diffusion coefficient, which describes the interaction between the RF waves and the ions. The latter can be expressed as:

\[
D_{RF} = C_{RF} \left| J_{n-1} \left( \frac{k_\perp v_\perp}{\omega_c} \right) + \frac{E_-}{E_+} J_{n+1} \left( \frac{k_\perp v_\perp}{\omega_c} \right) \right|^2
\]

(8.3)

where \(C_{RF}\) is a constant related to the RF absorbed power, \(k_\perp\) and \(v_\perp\) are the RF wave number and the ion velocity in the direction perpendicular to the magnetic field, \(\omega_c\) is the ion cyclotron frequency, \(E_\pm\) are the left-handed and right-handed components of the electric field at the resonance frequency, \(J\) denotes the Bessel function, and \(n\) indicates the harmonic number of the resonance (3 in this case).

The values of the Spitzer coefficients can be set from measurements of plasma parameters such as ion and electron temperatures, electron density and effective charge. The fraction \(E_+/E_-\) can also be calculated by using the equations from [64]. Finally, in stationary conditions, Equation 8.2 becomes an ordinary differential equation and can be solved for \(f\) analytically. The result is a function of \(v_\perp\), hence of the deuteron energy, since \(E_d \approx \frac{mv_\perp^2}{2}\). The other two variables that remain in the distribution function are \(C_{RF}\) and \(k_\perp\). The value of \(C_{RF}\) affects the intensity of the high energy tail in the distribution, while the value of \(k_\perp\) affects the extent of the tail, since it determines the cut-off energy, i.e. the energy where the distribution function crosses zero.

Three discharges were selected for the analysis: JET pulse number (JPN) 86459, 86461 and 86464. The first two were very similar, while JPN 86464 had a different lower NBI power, higher RF power and higher electron density compared to the other two.

The model of the neutron spectrum was obtained from the Fokker-Planck model of the fast ion distribution. The direction of the fast ion velocity was not assumed to be exactly perpendicular to the magnetic field. Instead, the pitch angle of the ions (the angle between the ion velocity and the magnetic field), was assumed to have a Gaussian distribution around 90 degrees, with a standard deviation of 10 degrees.

The model of the neutron spectrum was fitted to the TOFOR and Afterburner data, with \(C_{RF}\) and \(k_\perp\) as free parameters of the fit. The results for discharge 86459 are shown in Figure 8.3.
Figure 8.3. Measured spectra with fitted model (left) and corresponding neutron spectra (right) for discharge 86459 for TOFOR (upper panels) and the Afterburner (lower panels). Figures from Paper III.

The fast ion distributions corresponding to the fitted values of the parameters for all of the 3 discharges are shown in the left panels of Figure 8.4. It can be noticed that the cut-off energy in the distribution estimated from the Afterburner data is systematically higher than that from TOFOR. The two dashed lines are obtained by recalculating the distribution with the fit parameters shifted by $\pm \sigma$: one with $C_{RF} + \sigma_C$ and $k_{\perp} - \sigma_k$, the other with $C_{RF} - \sigma_C$ and $k_{\perp} + \sigma_k$. They do not represent the uncertainty of the distribution function, but they give a feeling for the range of possible distributions for the given estimates of the parameters and their uncertainty.

The two distributions were checked against data from the diamond detector, which shares the line of sight with the Afterburner, and the gamma spectrometer, which shares the line of sight with TOFOR. It was found that there was good agreement between instruments with the same line of sight. This points to the conclusion that the 1 dimensional modeling of the fast ion distribution is insufficient to describe properly the neutron emission consistently on different lines of sight. In particular, the assumption on the pitch angle distribution can play a role in explaining the difference between the two sight-lines. The Afterburner sight-line, which is tangential to the magnetic field, is more sensitive to changes in the pitch angle distribution, while the TOFOR sight-line, which is vertical and radial, is less affected by assumptions in the pitch angle. In
Figure 8.4. Fast ion distribution obtained from the fitting of the model to the TOFOR data (blue) and to the Afterburner data (red - labeled “NE213” in the legend). The left panels show the distributions obtained under the assumption of a pitch angle between 80 and 100 degrees, the right panels show the distributions obtained under the assumption of a pitch angle between 70 and 110 degrees. The dashed lines are the distributions obtained by shifting the fit parameters by $\pm \sigma$. Figure from Paper III.

In the right panel of Figure 8.4 it is shown that changing the standard deviation of the pitch angle distribution from 10 to 20 degrees improves the agreement between the TOFOR and Afterburner estimates of the fast ion distribution.

A more detailed description of the ion velocity distribution can be obtained from Monte Carlo codes. A simulation of discharge 86459 using the ASCOT-RFOF code [65] was performed, and the fast ion velocity distribution from the code was used to calculate the neutron and gamma emission and compare that with the measurements from the different instruments mentioned before. Figure 8.5 shows the comparison with TOFOR (a) and Afterburner data (b). The agreement was good for all of the measurements, except for TOFOR ($\chi^2_{\text{RED}} \approx 2.3$). However, it is important to notice that even in the TOFOR case, the cut-off energy estimated by the code is in good agreement with the measurement. This points to the fact that a more detailed modeling of the fast ion distribution is indeed what is required to properly describe consistently all the measurements on different lines of sight.
Figure 8.5. Comparison of the model of the neutron emission obtained from the fast ion velocity distribution from the ASCOT-RFOF code for discharge 86459 with data from TOFOR (a) and the Afterburner (b). Figure from Paper III.

In conclusion, the results presented here show that having neutron emission spectroscopy analysis of data from spectrometers on different lines of sight can provide a more complete picture of the plasma conditions than if just one spectrometer is used.
9. Neutron camera

Papers IV, V and VI are devoted to the analysis of data collected with the JET neutron camera. In Paper IV we make an absolute comparison between a model of the neutron emission and the neutron camera measurement. In Paper V we perform MCNP simulations to study the dependence of the backscatter intensity on the neutron emissivity profile of the plasma. In Paper VI the focus of the analysis is on the energy dependence of spatial redistribution of the fast ions during sawtooth oscillations.

9.1 Absolute measurement of the neutron emission (Paper IV)

The objective of the analysis and modeling presented here is to perform a comparison on absolute levels between a model of the neutron emission and the neutron camera data. We do this in the forward modeling framework described in Chapter 3. The absolute aspect here means that we compare a modeled detector count rate with the actual experimental count rate. The modeling starts from absolute plasma quantities and involves no normalization steps.

For the analysis we selected JET discharge number 84792 in the time interval 5.1-5.6 seconds. The discharge was heated with NBI heating only, and the time interval was chosen because of the good agreement between the neutron yield estimated by the TRANSP code and the one measured by the fission chambers (see Figure 9.1). TRANSP overestimated the neutron yield by about 8%, which we consider to be a fairly good level of agreement compared to the levels of disagreement seen in many other discharges [66].

9.1.1 Modeling

The ion velocity distribution was also modeled with the same TRANSP simulation, and it was used as input for DRESS to calculate the neutron emission intensity and energy spectrum on each line of sight of the neutron camera. The DRESS code is set up so that the output neutron spectrum is given on an absolute scale of neutrons per second. The DRESS output does not include the backscatter component, which is calculated separately as mentioned in Section 3.3. In Paper V (see next Section) we showed that it is generally speaking a good approximation to consider the intensity of the backscatter component
as independent of the neutron emissivity profile. Thus, the backscatter component obtained from an MCNP simulation can be expressed on an absolute level by multiplying it with the total neutron yield from the plasma. Here we decided to use the total neutron yield estimated by TRANSP as the multiplying factor, to keep consistency with the modeling of the neutron spectrum. Since both the direct and the backscatter components of the neutron spectrum are expressed on absolute levels, the term $S$ in Equation 3.5, which is the sum of the two, is also expressed on an absolute level.

The other term in Equation 3.5 which needs to be expressed on an absolute level is the detector response matrix $R$. The matrix is obtained from MCNP simulations and then for each detector it is calibrated as described in Section 6.2.3. In the simulation, the neutron source emitted neutrons in a cone towards the detector. The cone covers an area larger than the area at the end of the collimator (which is larger than the detector area), in order to include secondary effects such as scattering inside the collimator. Therefore, it is necessary to rescale the output of the simulation according to the ratio $A_S/A_E$, where $A_E$ is the area of the collimator end, and $A_S$ is the area of the emission cone at the collimator end. This way, also the detector response is expressed on an absolute level, and therefore the result of Equation 3.5 can be compared to the data on an absolute level without any fitting or normalization of the intensity.

![Figure 9.1](image_url)

Figure 9.1. Total neutron yield for JET discharge 84792. The solid line is the fission chambers measurement, the dashed line is the TRANSP simulation result. The vertical lines indicate the time interval considered in the analysis. Figure from Paper IV.
9.1.2 Comparison with data

Figure 9.2 shows the comparison between the modeled and the measured PHS for two camera channels.

\[ \text{Recall proton energy [MeV]} \]

\[ \text{Light Yield [MeV ee]} \]

\[ \text{Counts/MeV ee} \]

\[ \text{Direct} \]

\[ \text{Backscatter} \]

\[ \text{Total} \]

\[ \text{Data} \]

Figure 9.2. Absolute comparison between the measured data and the model of the PHS for discharge 84792, channel 5 (left) and 8 (right). The points with error bars represent the experimental data, the dashed line is the model of the direct component, the dash-dotted line is the model of the backscatter component, the bold line is the sum of the components. The vertical lines indicate the 2 MeV integration thresholds. Figure from Paper IV.

All the modeled and measured PHS were integrated above an energy threshold corresponding to 2 MeV deposited proton energy in the detector, to produce the neutron camera profiles shown in Figure 9.3. In Figure 9.2 the vertical red line indicates the integration threshold. Notice that the 2 MeV deposited proton energy corresponds to a different light yield for different channels. This is because each detector has a different proton light yield function, as defined by the calibration.

It can be noticed from the Figure 9.3 that the model overestimates the data, especially for the central channels. Integrating the counts in the entire profile, we find that the model overestimates the measurement by about 9%, which is consistent with the 8% difference in the neutron yield mentioned above.

From this comparison one can conclude that, in this case, the neutron camera measurement agrees with the fission chamber measurement, since they show a similar difference with the models. However, the analysis of more discharges would be required to draw definitive conclusions about the agreement between the two instruments.

9.2 Dependence of the backscatter component on the neutron emissivity profile (Paper V)

The backscatter level in each neutron camera channel has been previously considered to be independent of the neutron emissivity profile [36]. The aim of
this paper was to investigate the limits of validity of this assumption. The investigation was carried out by producing a profile-dependent backscatter matrix for the neutron camera, which was then used to test the backscatter intensity in the camera channels for different neutron emissivity profiles. Before proceeding in the description, to avoid possible confusion, it should be clarified that in the text we call “neutron emissivity profile” the spatial distribution of the neutron emissivity in the plasma volume, while we call “neutron camera profile” the distribution of neutron counts in the 19 camera channels.

The backscatter matrix was obtained by performing MCNP simulations with a complete model of the JET tokamak [49] and of the neutron camera assemblies, which is shown in Figure 2.5. A plasma volume was defined and divided into 387 toroidal voxels (“toxels”), each having a square poloidal cross-section of 10 cm x 10 cm and a cylindrical ring concentric to the torus of JET. The neutron source was moved from one toxel to the other and the neutron flux at the detector position was recorded separately for each toxel and for each of the 19 detectors of the neutron camera. The MCNP point flux tally also registers separately the direct and total flux. The total flux is the sum of the direct and scattered flux. Since most of the scattered flux actually comes from backscattered neutrons, the backscattered flux is obtained
by subtracting the direct flux from the total flux. The backscatter matrix for each camera channel is made from the 387 estimates of the backscattered flux. The matrices for channel 5 and 15 integrated above a 1 MeV neutron energy threshold are shown in Figure 9.4, where one can see that neutrons generated in the region of the plasma close to the wall opposite to the detector contribute the most to the backscatter signal of that detector. Similarly we can obtain a matrix for the direct flux which can be used later in the analysis in parallel with the backscatter matrix to obtain the direct neutron camera profile.

\[ s(\rho) = S_0 \left[ (1 - \Delta) (1 - \rho)^\alpha + \Delta \right], \quad (9.1) \]

where \( S_0 \) is the total emissivity, \( \Delta \) is a pedestal level, which is constant over the entire plasma, \( \rho \) is the normalized minor radius and \( \alpha \) is a factor that regulates the peaking of the emissivity profile. Two of the three profiles that were tested were obtained from this equation, by setting \( \alpha \) to 5 (broad) and 30 (peaked). The third emissivity profile was obtained from a more complex parametrization given in [67], and it describes the neutron emissivity given by NBI heated ions.

We then obtain the backscatter (and direct) neutron spectra by multiplying the emissivity profiles with the backscatter (direct) matrix. After that we find
the expected PHS in each channel by multiplying the neutron spectra with
the response matrix of the detector. Finally we produce the backscattered and
direct neutron camera profiles by integrating the PHS above a defined energy
threshold.

Figure 9.5 shows the comparison between the neutron camera profiles ob-
tained from the two thermal emissivity profiles for a high (1.8 MeV) and low
(1.0 MeV) neutron energy integration threshold. Figure 9.6 shows the same
type of comparison, but this time between the neutron camera profile obtained
from the two broad thermal emissivity and the one obtained from the NBI
emissivity.

Figure 9.5. The neutron camera profiles for a $\alpha = 5$ and a $\alpha = 30$ thermal emissivity
profile, calculated for an energy threshold of 1.8 MeV (a) and 1.0 MeV (b).

Figure 9.6. The neutron camera profiles for a thermal ($\alpha = 5$) and an NBI emissivity
profile, calculated for an energy threshold of 1.8 MeV (a) and 1.0 MeV (b).

In Figure 9.5, for both of the energy thresholds the difference in the backscatter
level is negligible, especially if compared with the intensity of the direct
emission. In Figure 9.6 instead, the difference in the case with low (1.0 MeV)
threshold is significant.

Measured neutron camera profiles at JET mostly resemble the profiles ob-
tained from the thermal parametrization, and only in rare cases they get close
to a pure NBI parametrization [67] like the one shown in Figure 9.6. We can
then conclude that when using low integration thresholds one should be aware of the possible dependence of the backscatter component on the emissivity profile, but that in general such dependence is weak and can be disregarded.

9.3 Fast ion redistribution during sawtooth activity
(Paper VI)

Sawtooth oscillations are periodic variations of plasma parameters such as electron and ion temperature and density. It has been shown theoretically that sawteeth affect the ions in the plasma by redistributing them in space, and that ions with higher energies are less affected [68]. This energy dependence has also been observed experimentally at the DIII-D [69] and ASDEX Upgrade [70] tokamaks, but never at JET.

The calibration of the neutron response performed in this thesis (see Section 6.2.3) allows to set arbitrary integration thresholds on the PHS for the production of neutron camera profiles, a fact which can be exploited to investigate this energy dependence. However, for a correct interpretation of the observations from such neutron camera profiles, it is necessary to fully understand their non-trivial connection with the ion energy distribution. The integration threshold used to produce the profile is a light yield threshold, since it is applied to the PHS measured by the camera detectors. However, one would like, ideally, to have an ion energy threshold. This is not possible, but the relationship between the fast ion energy and the light yield integration threshold can be understood as explained in the following section.

9.3.1 Fast ion energy and integration threshold

First of all we start with a general discussion about the relationship between neutron and ion energies which is independent of the detection technique used for the measurement. Let’s consider the fusion reaction between a fast ion and an ion from the bulk plasma. The generated neutron has an energy which is given by equation 3.2. Under the assumption that the velocity of the fast ion is much higher than that of the bulk plasma ion, the centre of mass velocity becomes $v_{cm} \approx v_i/2$, where $v_i$ is the fast ion velocity, and the relative kinetic energy of the reactants becomes $K = E_i/2$. If we look for the maximum neutron energy for a given fast ion energy, we obtain it by setting $\cos(\theta) = 1$, therefore Equation 3.2 becomes:

$$E_{n,max} = \frac{1}{4} \frac{m_n}{m_i} E_i + \frac{m_r}{m_n + m_r} \left( Q + \frac{E_i}{2} \right) + \frac{m_nm_r}{m_i(m_n+m_r)} E_i \left( Q + \frac{E_i}{2} \right)^{1/2},$$

(9.2)
where the maximum neutron energy has been expressed as a function of the fast ion energy \( E_i \). This means that if a certain neutron energy has been measured, the fast ion that generated the neutron had a minimum energy given by the inverse of function 9.2, which is shown in Figure 9.7.

![Figure 9.7. Minimum deuterium ion energy \( E_i \) that is required to give a fusion neutron of energy \( E_n \).](image)

The reasoning that was just presented should be used as a guide for the interpretation of neutron measurements that are integrated above a certain energy threshold. However, another level of complication is added when one considers the fact that in the analysis of experimental data, the threshold for the integration is set in the units of the measurement (e.g. light yield for NE213 scintillators), not in units of neutron energy. This implies that the effect of the detector response to neutrons should be considered, as it affects the way the threshold excludes or includes neutrons of different energies.

In the NE213 case, if we consider only single elastic scattering interactions between neutrons and protons in the detector, the probability distribution of the energy transfered from the neutron to the proton is uniform, ranging from zero to the neutron energy. Therefore, when one sets a threshold in the PHS, even if we say that this threshold corresponds to a certain neutron energy, in reality it also affects the analysis of neutrons with energies above the threshold. Notice that considering other effects like multiple scattering, scattering on carbon, non-linear proton light yield function, resolution broadening etc. changes the
shape of the distribution, but does not affect the reasoning presented above. Figure 9.8 illustrates how the integration threshold acts on the response of an NE213 detector. From the figure it can be seen that a 3 MeV threshold excludes almost all of the 3 MeV neutron response, except for a small part that remains above threshold due to the resolution of the detector. A 3.5 MeV threshold instead excludes the 3 MeV response completely. Looking at the 4 MeV response instead, one can see that the 3.5 MeV threshold, despite being lower than 4 MeV, excludes a big part of the 4 MeV response.

![NE213 neutron response](image)

Figure 9.8. NE213 response to 3 MeV neutrons (solid line) and 4 MeV neutrons (dashed line), together with indications of the position of the 3 MeV and 3.5 MeV neutron energy integration thresholds.

In conclusion, if we try to tie everything together, we can say that it is possible to set a lower threshold which excludes the effect of ions below a certain energy from the neutron camera profile, but it will have a non-trivial effect on ions with energy above the threshold. Due to the box-like response function, the effects of events with neutron energies higher than the threshold are never fully included in the analysis.

To keep the experimental data separated from the modeling of the ion distribution, the thresholds in the neutron camera profiles will be given in units of recoil proton energy.

9.3.2 Neutron camera profiles observed in the 3rd harmonic RF experiment

JET discharge 86459, which was analysed in section 8.3, presented sawtooth oscillations, as shown in the electron temperature measurement in Figure 9.9.
To investigate how the fast ions are redistributed we selected the 6 sawtooth crashes which are indicated in the Figure with numbers from 1 to 6. We then integrated the camera data in two time intervals around each crash, one before and one after it, as shown in the inset of Figure 9.9. The two time intervals have the same length (90 ms) and there is 4 ms time in between them. To have a higher number of counts, we summed up the data from all 6 crashes, and produced the summed neutron camera profiles before and after the sawtooth crash, as shown in Figure 9.10.

The top left panel shows the neutron camera profile obtained with a proton energy integration threshold of 2.0 MeV. One can notice that the neutron emission in the core decreases substantially after the crash, while the emission at the edges increases. This is in line with what is predicted by theory: ions are expected to redistribute from the core towards the edge regions. The ion redistribution is also expected to have an energy dependence, with higher energy ions being less affected by the sawtooth.

The energy dependence can be verified by looking at neutron camera profiles with higher energy thresholds. The right top panel of Figure 9.10 shows the profiles before and after the sawtooth obtained with a threshold of 4.0 MeV. This threshold corresponds to a minimum ion energy of about 0.9 MeV.
Figure 9.10. Top panels: measured neutron camera profiles before (solid line) and after (dashed line) the sawtooth crash. Bottom panels: relative difference between the before and after profiles. The plots on the left were obtained with a proton energy threshold of 2.0 MeV, the panels on the right were obtained with a proton energy threshold of 4.0 MeV. Figure from Paper VI.

From the figure it can be observed that the change in the emission is smaller compared to the case with the 2 MeV threshold. The bottom panels of Figure 9.10 shows the relative difference of the profile between before and after the sawtooth for the two thresholds. If one considers the central channels (3, 4, 5 for the horizontal camera, 14, 15, 16 for the vertical camera) the change is well beyond error bars compared to 0 for the 2 MeV case, while it is close to 0 in the 4.0 MeV case.

Figure 9.11 shows the relative counts change for channel 4 (left) and 15 (right) for different integration energy thresholds. In the figure it is possible to notice that the reduction of the neutron emission in channels 4 and 15 follows the expected trend, i.e. the relative difference between after and before is smaller at higher energies.

An estimate of the critical energy, i.e. the ion energy at which a 50% decrease in the number of ions redistributed is expected, is given in [71]. For the conditions of this experiment the estimated critical energy is about 150-200 keV. Looking at Figure 9.7 we can see that this corresponds roughly to a 3 MeV neutron energy. If we then look at Figure 9.11, we can see that the relative difference at 2.0 MeV is about -0.17 for channel 4 and -0.10 for channel 15, and the difference decreases by about 50% close to the 3 MeV energy threshold, which is consistent with the expected critical energy.
Figure 9.11. Relative difference in counts in channel 4 (left) and 15 (right) between after and before the crash, averaged over the 6 crashes that were selected for the analysis.

However, it is important to notice that the interpretation of the results from these measurements are not straightforward. In fact, practically all of the measured neutrons are produced by the interaction of 2 ions. The interactions that produce the most neutrons are those that occur between a fast ion and a bulk ion. Even if the fast ions are not redistributed, the thermal ions, which have low energies, still are. Therefore the energy dependence of the redistribution measured in the neutron emission cannot be interpreted exactly as a measurement of the energy dependence in the redistribution of ions.
Part V: Conclusions and outlook

“A conclusion is simply the place where you got tired of thinking.”
– Dan Chaon
The main aim of the work presented in this thesis was to extensively study the capability of liquid scintillators (NE213) as tools for diagnosing fusion plasmas.

Papers I, II and III are devoted to the characterization and analysis of data from a single NE213 detector, the Afterburner, installed with the MPRu spectrometer at JET.

The first step was to carefully characterize the detector response to neutrons. In Paper I we performed such characterization for the Afterburner detector using a method which involves simulations and in-situ measurements for the calibration of the light yield. Despite the fact that a measurement of the response at an accelerator facility has been generally preferred until now, the method presented in this thesis was shown to provide reliable results and can therefore be employed with confidence in future works.

In Paper II we studied the performance of the Afterburner detector in separating the neutron spectral components, to estimate the fraction of thermonuclear neutron emission from the plasma. The results were compared with the estimates from the TOFOR spectrometer, and were found to be correlated. However the uncertainties on the Afterburner estimates were significantly larger than those on the TOFOR ones. This is generally expected, due to the less favorable response function of the liquid scintillators. Furthermore, the analysis of the Afterburner data systematically estimated the thermal fraction to be higher than the same analysis of TOFOR data. The difference could be a consequence of the imperfections in the modeling that affect the neutron spectra in the Afterburner line of sight differently from the way they affect the neutron spectra in the TOFOR line of sight.

In Paper III the Afterburner was used in conjunction with other neutron and gamma spectrometers to study the fast ion distribution during discharges heated with ICRH tuned on the 3rd harmonic resonance of deuterium. In the paper it was shown how the measurement from instruments on a tangential line of sight, like the Afterburner, were more sensitive to changes in the pitch angle distribution assumed in the ion velocity distribution, while this was not the case for the instruments on a vertical line like TOFOR. The consequence is that measurements of diagnostics on different lines of sight can provide more detailed information on the plasma parameters that are probed.

Papers IV, V and VI are instead devoted to the characterization and analysis of data from a set of 19 NE213 detectors which are part of the JET neutron camera.
Paper IV describes the characterization of the detectors of the neutron camera, together with the modeling steps used to perform an absolute comparison between a model of the neutron emission and the neutron camera measurement. The comparison showed a level of disagreement between the model and the data that was comparable to the level of disagreement between the model of the total neutron yield obtained from the same TRANSP simulation and the measurement of the fission chambers. This is an indirect indication that the measurement of the camera and that of the fission chambers are in agreement. However, at present this indication is based on the analysis of a single discharge and the issue should be studied further in future works.

Paper V gives a technical description of the calculations performed to estimate the backscattered neutron flux in the neutron camera lines of sight. Scattered neutrons are an unavoidable background in collimated neutron measurements and detailed knowledge of their distribution is necessary for the type of analysis presented here. The result showed that the flux depends very weakly on the neutron emissivity profile. Therefore, for most plasma scenarios, the scattered neutron background can be considered as a fixed component in the analysis, only depending on the given total neutron yield.

Finally in Paper VI we used the neutron camera to investigate the energy dependent redistribution of ions in the plasma due to a sawtooth crash. The neutron camera data show that, in line with theoretical predictions, high energy ions are less affected by the crash.

The overall conclusion of this work is that the energy information present in the PHS recorded by NE213 liquid scintillators can be exploited to provide neutron emission spectroscopy analysis. The analysis provided by the NE213 does not match the performance of the more complex instruments which are designed for spectroscopy measurements such as TOFOR. However, using dedicated spectrometers in a neutron camera is both impractical and expensive, therefore NE213 detectors are a relevant option when multiple line of sight measurements are required, and should be considered in the design of plasma diagnostics for future fusion devices.

Future work

This thesis can be seen as the starting point for future studies of plasma physics which involve multiple line of sight measurements with NE213 detectors and energy resolved neutron emission analysis.

The method for the simulation and calibration of the neutron response of the detector is applicable to NE213 installations on any fusion device, even though some small modifications might be necessary to adapt it to different machines. Applications of the method to other fields than nuclear fusion could also be possible, provided a well known neutron spectrum is available for the calibration.
Acknowledgments

Even though only my name is on the cover, I was not alone in performing the work presented here. Many people have dedicated time and energy to contribute to this final product, which otherwise would have never seen the light of day. I will try in this section to thank all the relevant people, but before that, I would like all of you to know that my gratitude goes way beyond the few words written here.

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I en fusionsreaktion sammanfogas två lätta atomkärnor till en tyngre atomkärna samt en eller flera lätta partiklar. Forskare försöker utnyttja fusionsreaktioner mellan de två väteisotoperna deuterium (D) och tritium (T) för att utnyttja energin som frigörs i dessa. I dagsläget är dock energin som krävs för att starta och upprätthålla reaktionerna i en fusionsreaktor större än energin som produceras.


En bra karakterisering av neutronresponsfunktionen är grundläggande för att få pålitliga resultat av dataanalysen. En del av avhandlingen beskriver en metod för att simulera neutronresponsfunktionen med MCNP, som är en Monte Carlo kod. Sen kalibreras responsfunktionen med hjälp av experimentella mätningar. Metoden testades först med ”Afterburner”-detektorn, en NE213 scintillator, som är installerad på JET. I avhandlingen visas att metoden är robust då resultaten av dataanalysen inte beror på några antaganden vid framtagandet av responsfunktionen.


Även om dedikerade spektrometrar som TOFOR presterar bättre skulle det vara för dyrt att använda sådana i varje siktlinje i en neutronkamera. Istället används NE213-detektorer som är billiga och små. Metoderna som presenteras visar att NE213-detektorer kan användas för att undersöka egenskaper hos bränslejoner i plasmat.
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