Neutron Spectroscopy

Instrumentation and Methods for Fusion Plasmas

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Abstract


When the heavy hydrogen isotopes deuterium (D) and tritium (T) undergo nuclear fusion, large amounts of energy are released. At the Joint European Torus (JET) research is performed on how to harvest this energy. Two of the most important fusion reactions, d+d→⁴He+n (E_n = 2.5 MeV) and d+t→⁴He+n (E_n = 14 MeV), produce neutrons. This thesis investigates how measurements of these neutrons can provide information on the fusion performance.

The Magnetic Proton Recoil (MPR) neutron spectrometer has operated at JET since 1996. The spectrometer was designed to provide measurements on the 14 MeV neutron emission in DT operation, thereby conveying information on the state of the fuel ions. However, a majority of today’s fusion experiments are performed with pure D fuel. Under such conditions, the measurements with the MPR were severely hampered due to interfering background. This prompted an upgrade of the instrument. The upgrade, described in this thesis, included a new focal plane detector, a phoswich scintillator array, and new data acquisition electronics, based on transient recorder cards. This combination allows for pulse shape discrimination techniques to be applied and a signal to background of 5/1 has been achieved in measurements of the 2.5-MeV neutrons in D experiments. The upgrade also includes a new control and monitoring system, which enables the monitoring and correction of gain variations in the spectrometer’s photo multiplier tubes. Such corrections are vital for obtaining good data quality.

In addition, this thesis describes a new method for determining the total neutron yield and hence the fusion power by using a MPR spectrometer in combination with a neutron emission profile monitor. The system has been operated at JET both during DT and D experiments. It is found that the systematic uncertainties are considerably lower (≈6 %) than for traditional systems. For a dedicated system designed for the next generation fusion experiments, i.e. ITER, uncertainties of 4 % could be attained.

Neutron spectroscopy can also be an important tool for determining the neutron emission from residual tritium in D plasmas. This information is combined with other measurements at JET in order to determine the confinement of the 1 MeV tritons from the d+d→t+p reactions.

Keywords: Neutron spectroscopy, plasma diagnostics, fusion power, fusion, plasma heating, MPRu, JET, triton burn-up, ITER, neutron yield, calibration

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Till min älskade familj
Anna, Alexandra, Lena och Ulf
List of Papers

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


**The New MPRu Instrument for Neutron Emission Spectroscopy at JET**


**Control and Monitoring System of the Upgraded Magnetic Proton Recoil Neutron Spectrometer at JET**


**The thin foil magnetic proton recoil neutron spectrometer MPRu**

*To be submitted to Nuclear Instrumentation and Methods*

**Development and Characterization of the Proton Recoil Detector for the MPRu Neutron Spectrometer**


**Fusion Power Measurement using a Combined Neutron Spectrometer-Camera System at JET**


**Fusion Power Measurement Using a Combined Neutron Spectrometer - Camera System at ITER**


**Triton Burn Up Neutron Emission in JET Low Current Plasmas**


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Abbreviations

ADC  Analogue to Digital Converter
CM-system  Center of Mass system
C&M  Control and Monitoring
D  Deuterium
d  deuteron
FC  Fission Chamber
FWHM  Full Width Half Maximum
I(E_n)  Neutron Energy spectrum
ICRH  Ion Cyclotron Resonance Heating
ITER  International Thermonuclear Test Reactor
JET  Joint European Torus
LOS  Line Of Sight
MCNP  Monte Carlo N-Particle transport code
MPR  Magnetic Proton Recoil neutron spectrometer
MPRu  MPR upgrade
N  Number of counts
NBI  Neutral Beam Injection
PMT  Photo Multiplier Tuber
PSD  Pulse shape Discrimination
Q  integrated charge
ROI  Region Of Interest
S/B  Signal to Background ratio
T  Tritium
t  triton
TFTR  Tokamak Fusion Test Reactor
TOF  Time Of Flight
TOFOR  TOF neutron spectrometer Optimized for Rate
TBN  Triton Burn-up Neutrons
TRC  Transient Recorder Card
TRIGA  Training, Research, Isotopes, General Atomics
UV-light  Ultra violet light
Y  neutron Yield
YAP  Yttrium Aluminium Pervoskite
$\varepsilon_{col}$  photon collection efficiency
$\psi(E_n,q)$  Spectral response function
$\Psi(R,Z,\phi)$  Spatial flux response function
$\gamma(R,Z,\phi)$  neutron emission spatial distribution
1 Introduction

Time is not our friend

Kurt Russell

1.1 Fusion as an energy source

A scientific effort in fusion energy research has been pursued for five decades, with the ultimate aim to deliver clean and safe energy. When fusing light nuclei, the total mass of the nuclei is reduced and a large amount of energy is released as given by Einstein’s famous formula $E=mc^2$ [1].

In general, it is fusion of the lightest nuclei that gives the largest mass reduction and hence the largest energy release. Therefore, the hydrogen isotopes, protium, i.e., regular hydrogen ($^1$H or p), deuterium, ($^2$H or d), and tritium, ($^3$H or t) as well as ‘light’ helium ($^3$He), are suitable candidates for fusion fuel. The fusion power output, $P_{\text{fusion}}$, from a fusion fuel depends both on the fuel density, $n_i$, the energy release from each reaction, $E_{\text{tot}}$, and the fuel’s reactivity:

$$P_{\text{fusion}} = \int_{V_{\text{plasma}}} n_1 \cdot n_2 \langle \sigma v \rangle_{1,2} \cdot E_{\text{tot}} \partial V,$$

where $n_1$ and $n_2$ are the densities of the fuel ion species, $V_{\text{plasma}}$ is the plasma volume and $\langle \sigma v \rangle$ is the fuel reactivity given by

$$\langle \sigma v \rangle_{1,2} = \int \int f_1(v_1) f_2(v_2) |v_1 - v_2| \sigma(|v_1 - v_2|) \partial^3 v_1 \partial^3 v_2,$$

where $v_i$ is the fuel ions velocity, $\sigma(|v_1 - v_2|)$, is the reaction cross section as a function of the relative ions velocity and $f(v_i)$ is the normalized ion velocity distribution. If only one fuel species is present Equation 1 becomes:

$$P_{\text{fusion}} = \int_{V_{\text{plasma}}} \frac{1}{2} n_1^2 \langle \sigma v \rangle_{1,1} \cdot E_{\text{tot}} \partial V.$$

When investigating different possible fusion reactions, one finds that the reactions listed in Table 1 have sufficiently high reactivity and could therefore be used in fusion experiments.
Table 1. Candidate fusion reactions for fusion energy applications. The total energy release is listed, as well as the energy given to charged and neutral particles, respectively.

<table>
<thead>
<tr>
<th>#</th>
<th>Reaction</th>
<th>Fusion product energy [MeV]</th>
<th>Charged ($E_C$)</th>
<th>Neutron ($E_n$)</th>
<th>Total ($E_{tot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$d + d \rightarrow t + p$</td>
<td></td>
<td>4.0</td>
<td>-</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>$d + d \rightarrow ^3\text{He} + n$</td>
<td></td>
<td>0.82</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>$d + ^3\text{He} \rightarrow ^4\text{He} + p$</td>
<td></td>
<td>18.4</td>
<td>-</td>
<td>18.4</td>
</tr>
<tr>
<td>4</td>
<td>$d + t \rightarrow ^4\text{He} + n$</td>
<td></td>
<td>3.5</td>
<td>14.0</td>
<td>17.6</td>
</tr>
</tbody>
</table>

It is interesting to note that the two branches of the dd-reaction, reactions 1 and 2, have approximately the same branching ratios. Regarding reactions 3 and 4 of Table 1, it can be noted that $^3\text{He}$ has a limited natural abundance and is therefore unsuitable as fusion fuel. Tritium is a radioactive isotope with a half life of 12 years and not naturally occurring. It can be produced by neutron capture in deuterium, $n + d \rightarrow t + \gamma$, most commonly done in CANDU reactors [2], which makes it very expensive ($\approx 30 \cdot 10^6$ $\$/kg). The dt-reaction is envisaged for the first generation fusion reactors due to its high reactivity (see Figure 1) and the large energy release per reaction (see Table 1). Consequently, a mixture of deuterium and tritium is used in advanced reactor relevant experiments. The tritium for future reactors will be produced through absorption of fusion neutrons in lithium:

$$n + ^6\text{Li} \rightarrow t + \alpha \quad (4)$$

$$n + ^7\text{Li} \rightarrow t + \alpha + n \quad (5)$$

For the fusion reactions to take place, the two nuclei have to come sufficiently close for the short-range, attractive, nuclear force to act on the nuclei. In order to do so, the nuclei must have sufficient energy to overcome the repulsive Coulomb force. This gives the reactivity a strong positive dependence on the fuel ion temperature as illustrated in Figure 1.
1.2 The Tokamak

At the temperatures of maximum reactivity (i.e., around 60-80 keV for DT plasmas), the fuel nuclei are stripped of their electrons and the fuel is ionized into a plasma mostly consisting of free charged particles. No material walls can withstand these high temperatures, but in a magnetic field the charged particles are forced to spiral along the magnetic field lines due to the Lorentz force as shown in Figure 2.

By bending the B-field in a torus-shaped configuration end losses can be avoided. One such toroidal configuration is the tokamak\textsuperscript{1}. In a tokamak an induced toroidal current produces a poloidal field and together with an externally produced toroidal field a resultant helical field is obtained as shown

---

\textsuperscript{1}The tokamak was invented in the 1950s by Soviet physicists. The term is an abbreviation of the Russian word “toroidal'naya kamera s magnitnymi katushkami”, which translates to "toroidal chamber with magnetic coils".
in Figure 2. It has been found that this field configuration has properties that are beneficial for confining the fuel (plasma) and its energy [3].

Figure 2. The torus-shaped tokamak and its magnetic fields and current. The gyro orbits of magnetically confined ions and electrons are shown. The figure is not to scale. Figure courtesy of EFDA-JET.

The first tokamak to explore the use of high levels of tritium was the TFTR situated in Princeton, USA. Today, however, the Joint European Torus, JET outside Oxford, UK, is the only fusion machine that can handle tritium and hence the only fusion device that can produce MW of fusion power. Due to the high price of tritium and its radioactivity, most fusion experiments operate with pure deuterium. One such example is JT-60U, a Japanese tokamak of similar size as JET.

The next step in fusion research is to build an even bigger fusion experiment, ITER, with a predicted fusion power production of 500 MW. This is of the same magnitude as the electrical output from a midsize nuclear reactor like the Swedish Oskarshamn 1 reactor. In high power experiments ITER will operate with DT fuel; however, in an initial phase ITER will also be operated with pure deuterium plasmas. To set the magnitude of the ITER construction in perspective some of the machine parameters of JET and ITER are given in Table 2.
Table 2. *Machine parameters of JET and ITER.*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>JET</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max current (<em>I</em>)</td>
<td>5 MA</td>
<td>15 MA</td>
</tr>
<tr>
<td>Volume</td>
<td>80 m$^3$</td>
<td>840m$^3$</td>
</tr>
<tr>
<td>Toroidal B-field (<em>B_T</em>)</td>
<td>4 T</td>
<td>5.3 T</td>
</tr>
<tr>
<td>Fusion power</td>
<td>16 MW</td>
<td>500 MW</td>
</tr>
<tr>
<td>Discharge length</td>
<td>20 s</td>
<td>400 s</td>
</tr>
<tr>
<td>Energy confinement time</td>
<td>1 s</td>
<td>4 s</td>
</tr>
</tbody>
</table>

This thesis is concerned with diagnostics and experiments at such magnetically confined fusion plasmas.

### 1.3 Plasma heating

There are several ways the plasma can be heated in order to increase the temperature and thereby reach the point of maximum reactivity (see Figure 1).

- **Ohmic heating**: The plasma current (*I*) in the tokamak heats the plasma through ohmic heating due to the resistivity (*R*) of the plasma. The heating power is proportional to $I^2 \cdot R$, but since $R$ is proportional to $1/T^{3/2}$ it is only possible to reach temperatures of a few keV [3].

- **Neutral beam injection (NBI)** [4]: A particle accelerator outside the tokamak accelerates deuterons or tritons to high energies. The ions are neutralized and can subsequently enter the plasma, where they are again ionized. The ions need to acquire sufficiently high energies to reach the core of the plasma; this is typically $\approx 150$ keV for JET [5] and $\approx 1$ MeV for ITER [6].

- **Ion cyclotron resonance heating (ICRH)**: High frequency electromagnetic waves are generated and launched into the plasma by antennas located on the machine walls facing the plasma. The waves couple to the plasma ions$^2$, which can be accelerated to very high energies.

NBI and ICRH are normally referred to as auxiliary heating schemes. The high-energy particles resulting from the auxiliary heating generally constitute a minority of the plasma ions and they slow down by transferring their energy to the electrons and ions of the bulk plasma. This slowing down

---

$^2$ ICRH heating is similar to what we experience when we heat something in a microwave oven. The dedicated experimentalist can put a lighted candle in a microwave oven and experience how the microwaves heats the plasma (the fire).
process is described by a Fokker-Planck type equation. With a Maxwellian energy distribution of the background plasma, the slowing down of the particle, $dE/dt$, can be written in the following form [7],

$$-\frac{dE}{dt} = \frac{\alpha}{\sqrt{E}} + \beta E,$$

where $E$ is the energy of the particle. The $\alpha$ term describes the slowing down due to ion collisions where $\alpha$ is proportional to the ion density and the $\beta$ term describes the slowing down due to interactions between the particle and the plasma electrons, where $\beta \propto n_e \cdot T_{e}^{3/2}$. Consequently, for a specific plasma, the magnitudes of the parameters $\alpha$ and $\beta$ determine the slowing down time for the energetic ion.

The different heating schemes give rise to different ion velocity distributions. The NBI heating gives a practically square distribution with the maximum energy given by the NBI energy, whereas the ICRH heating gives rise to a quasi-exponential distribution of high energy ions. These high energy particles have an anisotropic velocity distribution. Their motion is normally described by a parallel and a perpendicular velocity component relative to the magnetic field line.

The bulk of the ions, heated either by the ohmic or the auxiliary heating, normally have a Maxwellian energy distribution, i.e., a thermal distribution which can be described with one parameter, its temperature.

Besides the external heating the plasma has a self heating mechanism. This internal heating in a fusion plasma is provided by the charged fusion products ($\alpha$–particles in the case of $dt$-fusion) slowing down and transferring their kinetic energy to the plasma.

For this thesis new instrumentation for studying the effects of plasma heating has been developed.

1.4 Burn Criteria

A high temperature fusion plasma continuously loses energy to the surroundings. In order for the plasma to be in thermal equilibrium the power loss, $P_L$, has to be balanced by internal and external heating:

$$P_e + P_i = P_L,$$

where $P_e$ is the amount of power from external heating and $P_i$ is the power from internal heating. The power losses are due to heat transport and radiation. The power loss due to transport is driven by the temperature gradient
between the centre and the edge of the plasma, whereas the radiation losses are dominated by bremsstrahlung [8], which is produced when the free electrons experience acceleration in collisions with the free ions.

One of the major scientific goals of ITER is to prove that machines of this size can confine the plasma energy sufficiently well for a future reactor to produce a net amount of electricity. To reach this goal the plasma has to reach a condition close to nuclear “ignition”, where the “fusion fire” is sustained by its internal heating, with no or only little externally supplied heating. The internal heating that should balance these losses is proportional to the fusion power, $P_{\text{fusion}}$:

$$P_i = \eta \cdot f_c \cdot P_{\text{fusion}}, \quad (8)$$

where $\eta$ is the fraction of energy from the fusion reactions going to the charged particle(s) and $f_c$ is the fraction of charged particle energy confined by the plasma. Obviously, it is of great importance to determine the different quantities of Equations 7 and 8. The fast charged particle confinement at JET is described in [VII] and a new method for fusion power measurements is described in [V] and [VI]. Instrumentation for providing information on heating effects is described in [I]-[IV]
As can be seen in Table 1, fusion plasmas produce neutrons. These are neutral particles and can therefore escape the magnetic field of the tokamak. The neutron production is both a blessing and a curse for fusion applications. On the one hand, the fusion neutrons cause radiation damage and induce activation in the reactor walls; solving these issues is one of the more challenging quests in fusion research. On the other hand, the neutrons have many positive functions: they breed tritium (see Equations 4 and 5); they deposit their energy into a large volume, thereby reducing the problems of surface heat loads; and they carry important information from the core of the fusion process (which is the main topic for this thesis). Furthermore, a fusion neutron source is an excellent candidate for incinerating the long lived actinides in fission nuclear waste [9] or for breeding fissile material [10] in fission-fusion hybrids. The advantage of such hybrids is that the fission part of the reactor system produces the energy and consequently the burn criterium discussed previously does not have to be fulfilled in order for the system to give a positive energy output. Finally, fusion neutrons can be used in applications outside the energy field, such as medicine through fast neutron therapy and in airport safety through detection of explosives; in these applications small DD or DT sources are used [11].

2.1 Neutron flux

The neutron flux from fusion plasmas originate either from the d+d→³He+n (E_n= 2.5 MeV) or the d+t→⁴He+n (E_n= 14 MeV) reactions, or a combination of the two, and the neutron emissivities, y [neutrons/m³], from the two reactions are given by the reaction rates in the plasma:

\[ y_{14\text{MeV}} = n_d \cdot n_t \langle \sigma v \rangle_{d,t} \]  \hspace{1cm} (9)
\[ y_{2.5\text{MeV}} = \frac{1}{2} n_d^2 \langle \sigma v \rangle_{d,d} \cdot \beta_2 \]  \hspace{1cm} (10)

where \( \beta_2 \) is the branching ratio of the neutron producing reaction number 2 in Table 1. The dd-reaction is also possible in DT plasmas and consequently
DT plasmas emit both 2.5-MeV and 14-MeV neutrons. The fraction of 2.5-MeV neutrons is given by:

\[
\frac{y_{2.5\text{MeV}}}{y_{14\text{MeV}}} = \frac{1/2 \langle \sigma v \rangle_{d,d} \cdot \beta_2}{n_d \cdot n_t \langle \sigma v \rangle_{d,t}} = \frac{n_d \langle \sigma v \rangle_{d,d} \cdot \beta_2}{2 \cdot n_t \langle \sigma v \rangle_{d,t}} .
\]  

(11)

For all realistic temperatures the dd-reactivity is much smaller than the dt-reactivity and consequently the 2.5-MeV neutron emission is roughly two orders of magnitude weaker than the 14-MeV neutron emission.

The fuel density and temperature are functions of the position in the plasma, which results in a spatial distribution of the neutron emission intensity, \( y(R,Z,\phi) \), where \( Z, R, \) and \( \phi \) are the vertical, radial and the toroidal position in the plasma, respectively. Integrating \( y(R,Z,\phi) \), over the plasma volume gives the total neutron emission, \( Y \):

\[
Y = \int_{V_{\text{plasma}}} y(R,Z,\phi) \, \partial V .
\]  

(12)

Tokamak plasmas are toroidally symmetric, and so is \( y(R,Z,\phi) \). Consequently, \( y \) is only a function of \( R \) and \( Z \).

The fusion product energies in Table 1 are given assuming reactants at rest. However, the sum of the energies of the fusion products equals the sum of the energies of the reactants and the reaction \( Q \)-value (\( E_{\text{tot}} \) in Table 1). Moreover, since the fuel ions are moving at high velocities, the CM-system moves in relation to the Lab frame, hence the lab velocity of the neutron is a superposition of the CM-system velocity and the neutron velocity in the CM-system. As a consequence, the fuel ion’s velocity distribution determines the neutron energy distribution, i.e., the neutron energy spectrum, \( I(E_n) \).

Since the ion velocity distribution depends on the heating mechanisms \( I(E_n) \) is closely linked to the type of heating applied. The thermal motion of the ions in the Maxwellian bulk plasma gives rise to a Doppler broadened \( I(E_n) \) [12] which can be described by a Gaussian distribution (see Figure 3). The width of \( I(E_n) \) depends on the ion temperature \( (T_i) \) and the reaction type. For 2.5-MeV neutrons the FWHM=82.5·√(\( T_i \)) [keV] and for 14-MeV neutrons the FWHM=177·√(\( T_i \))[keV] [13], where \( T_i \) is given in keV. The increased energy in the fusion products also gives rise to a kinematical spectral shift. The ion velocity distribution of auxiliary heated plasmas gives a directionally anisotropic \( I(E_n) \) [14] and in D plasma also the neutron emission intensity can be directionally anisotropic [15].
Deuterium plasmas produce mainly 2.5-MeV neutrons, but also neutrons from dt-reactions are present due to a two-step process as illustrated in Figure 9. The 1-MeV triton from the d+d→p+t reaction slows down by collisions with ions and electrons. In the course of this process, there is a probability for a d+t→He+n reaction to occur, where the neutron produced is called a triton burn-up neutron (TBN). The TBN process is illustrated in Figure 4.
The ratio, $\rho$, between the TBN emission and 2.5-MeV neutron emission is normally between 0.005 and 0.015 as can be seen in [VII, Figure 7] and scales as:

$$\rho = \frac{TBN}{Y_{2.5MeV}} \propto T_e \cdot n_d / n_e. \quad (13)$$

From Equation 13 it is clear that information on the deuterium density can be derived by measuring the neutron fluxes and electron temperature and density.

Due to the high energy of the tritons the TBN-emission is associated with a characteristic, very broad, neutron energy spectrum [16], as can be seen in Figure 5. Deuterium plasmas can also contain traces of tritium. Experience from JET has shown that residual tritium from previous DT experiments resides in the fusion machine for very long periods of time and is released back into the plasma during plasma discharges. Additionally, in high power pulses with good particle confinement tritium from the dd-reaction that is not burnt in the triton burn-up process is accumulated in the plasma. Such pulses are expected in the ITER deuterium advanced scenario, when ITER is operated with pure deuterium and high heating power is used. During these experiments the accumulated tritium is expected to contribute to a significant part of the neutron emission [17]. $I(E_n)$ from the residual and accumulated

21
tritium has normally a Gaussian shape characterized by parameters similar to those of the bulk D plasma. The thermal emission, \( Y_{\text{thermal}} \), can therefore be distinguished from the TBN emission using neutron spectroscopy. This is illustrated in Figure 5 and this feature was used in [VII] to account for the residual tritium in the JET machine.

![Figure 5](image)

**Figure 5.** (Color online) Neutron spectrum from TBN (blue thick line) together with the thermal spectrum (red broken line) from residual tritium.

Combining Equation 11 and 13 one finds that the ratio between the emission from residual tritium and the TBN scales as

\[
\frac{TBN}{Y_{\text{thermal}}} \propto T_e \left( \frac{n_d}{n_e} \right) \cdot \frac{n_d}{n_t}.
\]

(14)

As can be seen the ratio is dependent on the amount of impurities in the plasma \( (n_d/n_e) \).

2.2 Scattered and direct neutrons

The neutron flux in and around a fusion device has two components, a scattered flux and a direct flux. Neutrons that have not undergone any reaction constitute the direct flux.

The scattered neutrons have interacted with the fusion machine or surrounding support structures (e.g., diagnostics, walls etc.). Almost all scatter-
ing processes are endothermic, so the scattered flux is degraded in energy. The energy distribution of these neutrons extends from the emission energy all the way down to thermal energies, where the neutrons decay or, more commonly, are absorbed in and around the torus. The scattered neutron flux can be assessed using neutron transport codes such as MCNP [18] or Attila [19].

An example of the scattered flux is shown in Figure 6, where the scattered flux is evaluated with MCNP. It shows the expected energy distribution of the scattered neutron flux from the inner column (the back scattered flux) for ITER when viewed through a radial line of sight (LOS) in the horizontal plane. It has been claimed that the scattered flux in the region 2-5 MeV will be small [20]. This is unfortunately wrong³ as shown by Figure 6. The data in Figure 6 is in good agreement with the results from previous simulations [21].

![Figure 6. (Color online) Scattered flux from ITER’s inner column when viewed through a radial line of sight in the horizontal plane. The structures in the graph are due to structures in the neutron cross section for the different materials (see figure legend) of the inner column. The data was derived using MCNP and a mono energetic 14 MeV neutron source.](image)

³ Ref [20] used a limited toroidal coverage and used reflecting surfaces to compensate for this. From MCNP5 user manual [18]: “Reflecting planes are valuable because they can simplify a geometry setup (and also tracking) in a problem. They can, however, make it difficult (or even impossible) to get the correct answer.”
In order to perform fusion research, plasma diagnostics are crucial for several reasons:

- Plasma control. Accurate knowledge of plasma parameters such as plasma position and magnetic fields is necessary for feedback system to maintain stable plasma condition.
- Machine protection. Phenomena such as disruptions (a sudden loss of plasma confinement) have to be predicted in order to be mitigated.
- Plasma optimization. Information concerning plasma performance parameters, such as temperature, density and fusion power is necessary in order to optimize the operation of the fusion machine.
- Safety and regulatory demands. The amounts of residual tritium and neutron activation are necessary to know in order to meet regulatory demands and maintain a safe operation for the public and operating staff.
- Model benchmarking. Physic models of the plasma behavior have to be tested against information from plasma experiments. This information can only be channelled through diagnostics.

Plasma diagnostics can be divided into five different categories from which important information about the plasma can be derived:

- Passive photon detection. The plasma emits photons from different processes. One example is the bremsstrahlung spectroscopy which measures the radiation emitted from the plasma produced when the free electrons experience acceleration in collisions with the free ions. In [VII] bremsstrahlung spectroscopy [22] is used to determine the effective charge of the plasma, which in turn can be used to determine the deuterium density.
- Active photon detection. By emitting radiation into the plasma and investigating how the radiation is absorbed and scattered information on mainly the plasma electrons can be derived. One example of this is Thomson scattering diagnostics which emits laser light into the plasma. The electron density and temperature can be derived by measuring the amount of scattered light and its Doppler broad-
enabling. Data from the JET Thomson Scattering system, LIDAR [23], was used in [VII], for determining the electron density and temperature.

- Coils [24] are used to measure the magnetic flux outside the plasma and by doing so the magnetic and current profile inside the vessel can be determined.
- Particle detectors measure particles when they have escaped the plasma. Neutron diagnostics, which are described in Section 4, is one example. Faraday cups, scintillator probes or thin-foil methods are examples of diagnostics which measures the escaping charged particles.
- Surface diagnostics are used to investigate how the machine is affected by the amount of material that is deposited on a certain surface or how the surface is eroded through sputtering and other processes.

3.1 Calibration and errors

Independent of the field of science or the type of measurement the output, $q$, from a measurement cannot be related directly to the sought physical parameter, $\lambda$, without the instrument being calibrated. Examples of parameters $q$ are the number of ticks on a ruler, the amount of light from a scintillator or the number of events registered in a detector; examples of corresponding $\lambda$ could be the length of an object, the energy of an incoming particle or the fusion power. The relation $\lambda=f(q)$, where $f$ is the instrumental response function, has to be found. This process is called calibration, and can be divided into cross-calibration, ab initio (from first principles) calibration or direct calibration against a standard. When an instrument is ab initio calibrated, the instrument’s response is characterized from known physical laws (e.g., conservation of momentum), constants (e.g., speed of light) and by measuring physical properties of the instrument (e.g., volume, length etc). However, the instruments response to the sought physical parameter is not directly measured as is done when the instrument is directly calibrated against a standard. On the other hand, in a cross calibration the instrumental response is compared to the instrumental response of a calibrated instrument.

Independent of the type of calibration the concept of traceability is important, which means that it must be possible to trace all quantities that go into the calibration to international standards. In the case of calibration against a standard, the determination of the standard has to be traceable. In an ab initio calibration the measurements of the physical parameters which go into the calibration have to be performed with calibrated instruments.
After a calibration, the instrument is either absolutely calibrated or relatively calibrated. From the measurement of an absolutely calibrated instrument the actual value of the sought parameter can be determined whereas a relative calibration only gives the relation between different objects or events.

The quality of a measurement is not determined by the type of calibration, but rather from the magnitude of its errors. These can be divided into two categories: random errors (precision) and systematic errors (accuracy). The precision of a measurement describes its reproducibility and the accuracy its average error [25] as shown in Figure 7.

![Figure 7. Illustration of the difference between precision and accuracy.](image)

The estimated magnitude of the errors is the uncertainty of the measurement. The systematic uncertainly is determined by careful investigation of the calibration procedure. The random uncertainties, as the name indicates, are given by random effects in the measurement situation. Sources of random uncertainties can be statistical fluctuations in the measurement, instrumental instabilities or a requirement of human input when determining $q$. The size of the random error can sometimes be evaluated by reaped measurements of a single object.
4 Neutron diagnostics

The root of all superstition is that men observe when a thing hits but not when it misses

Francis Bacon

Neutron diagnostics play a prominent part in this thesis and are discussed in detail in this chapter. The neutron emission from a fusion plasma is characterized by its intensity, its spatial distribution and its energy distribution. These are strong functions of the most important reactivity parameters and consequently neutron diagnostics are excellent tools when determining important plasma parameters and benchmarking fusion modelling codes [26]. At large fusion machines such as JET and ITER, each of the neutron emission characteristics has its own diagnostics.

To understand the fundamentals of neutron diagnostics, some principles of neutron detection have to be discussed. The neutron carries no charge [27] and since only charged particles can be detected, the neutral neutron has to undergo a nuclear reaction to be observed. There are in principle three kinds of processes through which the neutron can be detected:

1. Nuclear scattering: Here the neutron transfers part of its momentum to a charged particle, which in turn can be detected. Protons and other light nuclei are preferred, since more energy can be transferred to these (see Section 4.1).
2. Direct charged particle production. When a neutron reacts with a target nucleus a charged particle might be emitted directly. Normally, the charged particle is a proton or an $\alpha$-particle.
3. Nuclear excitation: When a target nucleus absorbs a neutron, the resulting nucleus may be excited above its ground state. The excited nucleus subsequently decays by emitting some kind of radiation. If the nucleus emits a charged particle the reaction can be detected, whereas an emitted photon has to interact with matter in order to be detected. A special case of nuclear de-excitation is fission, where the excited nucleus decays into two charged fission fragments, which can be detected.

While reactions of type 1 or 2 are prompt (e.g., instantaneous on the time scales governing the response of the detector devices), some reactions of type 3 can be “delayed”, taking place on a time scale of seconds or minutes.

Detectors using these different processes are discussed in Sections 4.2 to 4.4 and Chapter 5.
4.1 np scattering

Since neutron scattering on protons is used in many neutron detection applications some further properties of this type of scattering are discussed here. For reactions of type 1 the recoil proton energy \( E_p \), can be related to \( E_n \) by the kinematics of elastic scattering, i.e., for \( n+p \rightarrow n'+p' \):

\[
E_p = 4 \cdot E_n \left( \frac{m_p}{m_n} \right)^2 \cos^2 \theta_{p,\text{lab}}, \quad (15)
\]

where \( m_n \) is the neutron mass, \( m_p \) is the proton mass and \( \theta_{p,\text{lab}} \) is the angle between the incoming neutron and the outgoing proton in the lab frame. For the purpose of this thesis we can assume the proton and neutron masses to be the same, in which case Equation 15 reduces to

\[
E_p = E_n \cdot \cos^2 \theta_{p,\text{lab}}. \quad (16)
\]

The np-elastic cross section in the CM system, \( \sigma_{np,\text{CM}} \), is (approximately) independent of the angle of the outgoing proton. The lab frame cross section \( \sigma_{np,\text{lab}} \) can be approximated with

\[
\sigma_{np,\text{lab}} = 4 \cdot \sigma_{np,\text{CM}} \cdot \cos(\theta_{p,\text{lab}}). \quad (17)
\]

It is important to note that for a given angular segment, \( d\theta \), the solid angle segment, \( d\Omega \), increases with the angle:

\[
d\Omega = 2\pi \sin(\theta_{p,\text{lab}}) d\theta. \quad (18)
\]

Combining 17 and 18 one finds that the maximum number of protons are emitted in \( \theta_{p,\text{lab}} = 45^\circ \). Furthermore combining Equations 16, 17 and 18, one finds that the recoil protons have a uniform energy distribution from the incoming neutron energy and extending all the way down to zero.

4.2 Neutron intensity measurements

From the neutron rates, the reactions’ energy release (see Table 1) and their branching ratios, \( \beta \), the fusion power can be calculated:
where the indices in parentheses relate to the reaction numbers in Table 1.

Besides determining the fusion power the neutron rates have to be measured for several reasons. Regulatory demands require that the neutron intensity is measured, since it determines neutron activation of the machine and hence constitutes both an occupational health problem as well as a waste problem. From the intensity of the 2.5-MeV and 14-MeV neutrons, the ion temperature and densities can be determined. It has been proposed [28] that it should be possible to infer the fuel ion density ratio by measuring the ratio between the 2.5-MeV and 14-MeV emission in DT plasmas (as indicated by Equation 10). However, since the neutron flux around 2.5-MeV is dominated by the scattered flux from the 14-MeV emission (see Figure 6), this measurement is very challenging and can probably only been performed in trace tritium (i.e., $n_t/n_d < 5\%$) experiments. For large fusion machines such as ITER the measurement of the neutron intensity is an important input in the residual tritium calculation. The amount of residual tritium is given by:

$$\Delta t_{\text{residual}} = (t_{\text{in}} - t_{\text{out}}) - Y_{14\text{MeV}} + Y_{2.5\text{MeV}}, \quad (20)$$

where $\Delta t_{\text{residual}}$ [number of atoms] is the change in the residual tritium inventory, $t_{\text{in}}$ is the amount of tritium entering the machine, $t_{\text{out}}$, is the amount of tritium leaving the machine. $Y_{14\text{MeV}}$ is the 14-MeV neutron yield and hence a measurement of the amount of burnt tritium. $Y_{2.5\text{MeV}}$ is the 2.5-MeV neutron yield, which is an approximation of the amount of produced tritium. The amount of residual tritium accumulates over time with the consequence that any systematic errors in the measurement of the parameters in Equation 20 accumulate to a large error in the estimation amount of residual tritium left in the machine. For example, a 10% error in $Y_{14\text{MeV}}$ propagates to approximately 1 kg uncertainty in the amount of residual tritium at the end of the ITER lifetime.

In order to establish the relation between $Y$ and the number of events ($N$) registered by a detector several fundamental processes need to be understood:

1. The energy dependent efficiency $e(E_n)$ of the detector must be known in order to relate the measured count rate to the local flux, $F_n$:

$$N = F_n \cdot A \cdot \int I(E_n)_{\text{detector}} \cdot e(E_n) \cdot dE_n, \quad (21)$$
where $A$ is the area of the detector and $I(E_n)_{\text{detector}}$ is the normalized neutron energy spectrum at the detector. The parameter $e(E_n)$ can be found either by an *ab initio* calibration or through a source calibration using a standard.

2. The spatial flux response, $\Psi(R,Z,\phi)$, has to be identified. This describes how the local neutron emission $y(R,Z,\phi)$ affects the flux at the detector. The flux response is discussed in detail in [V, Equation 13 to 15] and is summarized by the expression:

$$ F_n \cdot A = \int y(R,Z,\phi) \cdot \Psi(R,Z,\phi) dRdZd\phi. \quad (22) $$

$\Psi(R,Z,\phi)$ is normally determined using a neutron transport codes such as MCNP.

3. The normalized function of $y(R,Z,\phi)$ has to be known:

$$ y_{\text{norm}}(R,Z,\phi) = \frac{y(R,Z,\phi)}{Y}. \quad (23) $$

From Equation 22 and 23 the ratio, $p$, between the number of neutrons on the detector and the neutron yield can be calculated:

$$ p = \frac{F_n \cdot A}{Y} = \int y_{\text{norm}}(R,Z,\phi) \cdot \Psi(R,Z,\phi) dRdZd\phi. \quad (24) $$

4. The energy distribution at the detector $I(E_n)_{\text{detector}}$ has to be determined since there normally is an energy dependence in the efficiency of the detector (see point 1). $I(E_n)_{\text{detector}}$ is determined by the ratio between 2.5-MeV and 14-MeV neutrons; the amount of scattered flux; and the initial neutron emission spectrum, $I(E_n)$.

Points 1 and 2 above can be combined into a single calibration step, either by using *in situ* calibration or by cross calibrating the detector against an already calibrated instrument. For *in situ* calibration, a neutron source is placed in the torus and the instrumental response to the source is measured. By moving the neutron source around the torus the product $e(E_n) \cdot \Psi(R,Z,\phi)$ is measured. As neutron source either a dd- or dt-generator is preferred, but alternatively a Californium source can be used. The advantage of *in situ* calibration is that the traceability to international standards is facilitated. However, an *in situ* calibration takes a long time to perform and delays the physics program. Furthermore the calibration has to be redone after any change in the machine hardware. An alternative approach is to use the neutron sources to benchmark the neutron transport calculations.
Finally, the detector can be cross-calibrated to other already calibrated instruments. It is important to note that the systematic uncertainty from the calibrated instrument propagates to the cross-calibrated instrument.

One of the main goals of this thesis is to improve the neutron intensity measurements and a detailed discussion of this is given in Chapter 5. A summary of today’s most common methods in determining the neutron emission intensity is given below.

4.2.1 Activation system

An activation system uses the physical property of certain nuclei to emit gamma rays or delayed neutrons after being excited by neutron absorption. A sample of suitable nuclei is placed in the neutron flux, normally close to the plasma. After irradiation the sample is transported to a measurement station where the induced radiation is measured. Knowing the energy-dependent neutron reaction cross section, the measurement station’s detection efficiency, the half life of the excited nucleus and the time between irradiation and measurement, one can calculate the time-integrated neutron flux at the sample position. The required $\Psi(R,Z,\phi)$ is normally determined using neutron transport codes.

By using foils composed of nuclei with threshold reactions, which are activated only by neutrons with energies above ~5 MeV and therefore discriminating against 2.5-MeV neutrons, an activation system can also be used to measure the 14-MeV yield.

The activation foil technique is an established method in fusion research and is or has been used at both JET [29], JT60U [30] and TFTR [31][32]. There is also a proposed neutron activation system for ITER [33].

Activation foils provide time-integrate yield measurements and other methods have to be used to obtain time resolved data.

4.2.2 Fission chambers

Fission chambers (FC) can be used to determine the time evolution of the neutron emission. A FC consists of a thin foil of fissionable material (normally Uranium) placed around or in an ion chamber. The chamber is further surrounded by hydrogen-rich polythene, where the neutrons are moderated before inducing fission in the uranium. The energetic fission fragments are counted in the ion chamber. In this way, the local neutron flux variation at the FC position can be estimated (i.e., the FC is relatively calibrated). The efficiency of the FC is normally not determined when using FC in fusion applications, so other means are necessary in order to obtain an absolute calibration.
At TFTR *in situ* calibration was performed using both dd-generators, dt-generators and Californium sources [34], and at JT60U Californium sources were used [35]. *In situ* calibrations have also been tried at JET [36]. However, when new hardware was installed the response of the FCs changed and the *in situ* calibration was abandoned. *In situ* calibration is also proposed for ITER [37].

Instead of *in situ* calibration cross-calibration with the activation system is the preferred method at JET and a similar system is also proposed for ITER. The calibration accuracies for the different systems at different machines are given in Table 3.

Table 3. Accuracies in the determination of the neutron yield for different large fusion devices.

<table>
<thead>
<tr>
<th>Method</th>
<th>Measurement</th>
<th>JET</th>
<th>TFTR</th>
<th>JT60 U</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activation</td>
<td>14-MeV</td>
<td>7%</td>
<td>8%[32]</td>
<td>20%[30]</td>
<td>7-10%[41]</td>
</tr>
<tr>
<td>Activation</td>
<td>2.5-MeV</td>
<td>7%</td>
<td>9%[32]</td>
<td>15%[30]</td>
<td>7-10%[41]</td>
</tr>
<tr>
<td><em>In situ</em></td>
<td>14-MeV</td>
<td>NA</td>
<td>13%[39]</td>
<td>NA</td>
<td>10%[37]</td>
</tr>
<tr>
<td><em>In situ</em></td>
<td>2.5-MeV</td>
<td>10%[36]</td>
<td>10%[40]</td>
<td>11%[35]</td>
<td>25%[37]</td>
</tr>
</tbody>
</table>

The accuracies given in Table 3 are for a particular calibration method. It is also possible to combine different independent measurements and make a best estimate of the neutron emission, which reduces the uncertainty. This was done at TFTR and accuracies of 7% were reached [34].

### 4.2.3 Semiconductor detectors

FCs can only be used to determine the total neutron flux, since they have no energy resolution or energy discrimination capability; specifically, they are unable to distinguish between the 14-MeV and the 2.5-MeV neutron emission. Semiconductor detectors, such as silicon (Si) diodes [42], on the other hand, detect charged-particles with good energy resolution, and neutron-induced charged-particle production can therefore be used for neutron flux measurements.

In a Si semiconductor two neutron-induced threshold reactions take place: $^{28}\text{Si}+n\rightarrow^{25}\text{Mg}+\alpha$ and $^{28}\text{Si}+n\rightarrow^{28}\text{Al}+p$. The energy dependence of the reaction cross section, with its abrupt onset at about 5 MeV [43], provides the necessary energy discrimination between the 2.5-MeV and 14-MeV neutron flux. At JET the Si-detectors are used to measure the local 14-MeV flux. The count rate in the Si-detectors is cross-calibrated with 14-MeV activation foils to provide the absolute 14-MeV yield.

---

4 Excluding uncertainties in the cross section of the particular reactions.
One drawback of Si detectors is that they suffer from radiation damage and an alternative is to use diamonds as semiconductors [44].

4.3 Neutron spectroscopy

In addition to the absolute intensity of the neutron emission the energy distribution has to be determined for the neutron emission to be fully characterized. In order to derive the neutron energy spectrum, \( I(E_n) \), a neutron spectrometer is needed. As stated in Section 3.1 a sought parameter, in this case \( I(E_n) \), cannot be measured directly. As a consequence a measurable parameter \( q \) (e.g., pulse height, time, spatial distribution etc.), which can be related to \( I(E_n) \), must be found. The convolution [45] below is a specific type of the response function discussed in Section 3.1:

\[
g(q) = F \cdot A \cdot \int_{-\infty}^{\infty} I(E_n) \cdot \psi(E_n, q) \, dE_n,
\]

(25)

where \( g(q) \) is the distribution of the measured parameter \( q \) and \( \psi(E_n, q) \) is the convolution (response) function relating \( I(E_n) \) to \( g(q) \). In practice \( g(q) \) is normally discretized, \( g[q] \), so it is convenient to express \( \psi(E_n, q) \) and \( I(E_n) \) in matrix form:

\[
g[q] = F_n \cdot A \cdot I[E_n] \cdot \psi[E_n, q],
\]

(26)

where \( \psi[E_n, q] \) is the response matrix, and \( I[E_n] \) is the discretized energy spectrum vector. In principle, \( \psi[E_n, q] \) could be inverted to find \( I[E_n] \):

\[
F_n \cdot A \cdot I[E_n] = \psi[q, E_n]^{-1} \cdot g[q].
\]

(27)

In practice, an inversion magnifies the errors in \( \psi[E_n, q] \) and \( g[q] \), resulting in unacceptably large errors in \( I[E_n] \). More advanced mathematical inversion methods, such as maximum entropy methods, have been tried in order to obtain \( I[E_n] \) [46]. However these methods can introduce large errors [47].

A more feasible method is to fit \( I[E_n] \) to \( g[q] \), but since there is no one-to-one correspondence between \( I[E_n] \) and \( g[q] \), such fitting procedures require assumptions to be made regarding the shape of \( I(E_n) \). One method is to fit spectral components such as those illustrated in Figure 3 to the data. These spectral components are associated with a number of free parameters (e.g., width, energy shift and intensity), and by varying these parameters the \( I[E_n] \) fitted that best describes the data is found [48]; normally Chi-square or C-stat is used as the goodness-of-fit arbiter.
An alternative approach is to calculate the ion velocity distribution from plasma codes such as TRANSP [49], and by coupling these to reactivity codes, such as FPS [14] or Controlroom [50] $I(E_n)$ can be calculated. The calculated $I(E_n)$ is then convoluted with the response function and a simulated measurement result $g(q)_{\text{simulated}}$ is obtained. The distribution $g(q)_{\text{simulated}}$ is subsequently compared to the measured $g(q)$. This method is conceptually simple; a model (hypothesis) of the plasma and its reactivity is constructed and the hypothesis is tested with the measurement. It is also the most inclusive way to treat the problem, since many different aspects of the plasma behavior can be taken into account. However, the method is very computer and manpower intensive, and is therefore not suitable if large data sets are to be analyzed. Moreover, the method does not necessarily find the spectrum that best explains the data, i.e., there is normally an ion velocity distribution that would give a better fit to the data.

4.3.1 Measurement Criteria

Important plasma parameters can be determined from $I(E_n)$. Among these parameters you find such diverse elements as the ion temperature, $T_i$, the collective motion of the main plasma, the fuel ion densities and their velocity distributions [48][51][52]. A spectrometer should determine these parameters with good precision and accuracy in a wide range of plasma scenarios. A number of characteristics that determines the performance of the instrument are listed in [III]. Among those are:

- Accuracy of the response function.
- Rate capability, i.e., the number of useful counts in the spectrometer before saturation effects occur.
- Energy bite, i.e., the energy range covered by the instrument.
- Operational and calibration stability.
- Energy resolution, i.e., the width of the line shape of a mono energetic neutron source.
- Efficiency as defined by Equation 21.
- Immunity to background (see also section 5.1).

Traditionally neutron spectrometers were designed to measure $T_i$ which is closely related to the FWHM ($W$) of $I(E_n)$ (see Section 2.1) and an analytical expression has been derived linking the resolution, $R$, and the number of counts, $N$, in the spectrometer to the uncertainty in the ion temperature determination [53]:

34
\[
\frac{\Delta T_i}{T_i} = 2 \frac{\Delta W}{W} = 2 \left( \frac{R^2 + W^2}{W^2} \right)^2 \left( \frac{1}{2N} + \frac{R^2}{W^2} \right) \left( \frac{\Delta R}{R} \right)^2 ,
\]

where \( \Delta \) is the uncertainty in the different parameters. In case the response function is well known, i.e., \( \Delta R \) is small, Equation 28 simplifies to:

\[
\frac{\Delta T_i}{T_i} = \frac{R^2 + W^2}{W^2} \sqrt{\frac{2}{N}} .
\] (29)

Equations 28 and 29 were derived under the assumption of a Gaussian response function, zero background interference and only counting statistics as the source of error.

In reality, response functions are never completely Gaussian, there are many different sources of error and the uncertainties of other parameters than \( T_i \) have to be assessed. Consequently, today, numerical simulations are done in order to evaluate errors associated with different spectrometers techniques. In order to estimate the errors the following procedure is performed:

1. A plasma model is set up, i.e., a parameterized ion velocity distribution is selected.
2. From the ion velocity distribution a reactivity code calculates a synthetic neutron spectrum. Since the plasma model is well-defined the shape of the neutron spectrum is unambiguous.
3. The synthetic \( I(E_n) \) is convoluted with the response function resulting in a synthetic measured distribution \( g(q)_{\text{synthetic}} \).
4. Measurements of \( g(q) \) are normally associated with a known or assumed error distribution. From this distribution a randomized synthetic error is generated. These synthetic errors are added to \( g(q)_{\text{synthetic}} \). The errors normally come from counting statistics, but other contributions can be included.
5. In a similar way as in step 4 the response function is distorted. Since in general the response function is assumed to be well known, this step is normally omitted.
6. Given \( g(q)_{\text{synthetic}} \) with errors and the distorted response function a \( I(E_n)_{\text{estimated}} \) is derived. From \( I(E_n)_{\text{estimated}} \) an estimation of the sought parameters is derived.
7. Steps 4 to 6 are repeated until enough synthetic data is derived to perform a statistical analysis of the data set.
8. The result is distributions of estimated sought parameters (Figure 7). Ideally these distributions should be narrow and their mean values should be the same as was given by the plasma model in step 1. Systematic differences could be an indication that the method to reconstruct the
neutron spectrum is introducing a bias, but it could also be a feature of the response function. The spreads in the resulting distributions are the total uncertainties in the estimated parameters, i.e., the spreads are the total errors of the sought parameters propagated from the errors in steps 3 and 4. If there is an interest to know whether the found errors are systematic or random the evaluation technique has to be performed twice: once with only random errors as input and once with only systematic errors as input.

The evaluation techniques described above can be used when designing spectrometers, choosing the type of convolution method to derive the neutron spectrum [47] or as decision support when choosing a specific spectroscopic technique for an experiment [54].

Similar techniques can be used when performing error analyses of other types of diagnostic systems. For example the technique above was used when evaluating how the uncertainty in the neutron camera (see Section 4.4) data propagated to the uncertainty in the neutron yield determination in [V] and [VI].

4.3.2 Measurement techniques

In order to make an educated decision on which type of spectrometer to opt for one has to know which measurement techniques are available. Over the years, a number of different spectroscopic approaches have been tested at large fusion machines such as JET [55], TFTR [56][57] and JT60U [58]. Today, there are in principle four different approaches to measuring $I(E_n)$: scintillator, semiconductor, time of flight (TOF) and thin foil proton recoil. The different techniques are illustrated in Figure 8.
4.3.2.1 Semiconductor detectors

Semiconductor detectors are placed directly in the neutron beam. As described in Section 4.2.3 these detectors use charged particle production in order to detect neutrons. The energy of the charged particle(s) is the sum of the energy of the incoming neutron and the reaction Q-value. By measuring the energy of the residuals the neutron energy can be inferred. Si-diodes [42] as well as both artificial [59] and natural diamonds [56] have favorable properties for neutron spectroscopy and have been proposed for ITER [60].

4.3.2.2 Scintillator detectors

As for semiconductors detectors, the scintillator is placed directly into a collimated neutron beam where neutrons scatter on the scintillator protons. The amount of scintillator light is proportional to the amount of energy deposited by the recoil proton, which can be related to the incoming neutron energy (see Equation 16). Thus by measuring the light distribution one can derive \( I(E_n) \). Since normally all scattering angles are allowed, the recoil proton distribution is uniform in the range \( 0 \leq E_p \leq E_n \) (as shown in Section 4.1). This results in a broad response function, which complicates the determination of \( I(E_n) \).

The liquid NE213 scintillator [61] is commonly used for neutron spectroscopy applications due to its ability for pulse shape discrimination between gammas and neutrons; carefully calibrated NE213 scintillators have been exploited at JET for some time [62].

The advantage of scintillator detectors is that they are small in size and conceptually simple. However, the broad response function can introduce
large errors into the analysis and it is therefore difficult to measure weak spectral components. Furthermore, they are sensitive to gain drifts and noise and have limited dynamical range.

4.3.2.3 Time of flight
Time of flight, TOF, measurements are done by measuring the time it takes for a neutron to travel (fly) between two different detectors. This flight time is closely related to the velocity of the particle, which can be related back to its energy. TOF measurement can be performed on 14-MeV neutrons [63] although the technique is best suited for 2.5-MeV neutrons [64]. A recent important addition to the neutron diagnostics of JET is the TOFOR 2.5-MeV neutron TOF spectrometer [65][66].

4.3.2.4 Recoil Proton
In this technique collimated fusion neutrons scatter elastically on hydrogen nuclei (protons) in a thin hydrogen-rich conversion foil, often made of polythene (CH₂). By selecting protons in a limited angular range the proton energy can be related back to the neutron energy. The proton energy can be determined either by direct measurement using, e.g., a semiconductor detector [67][68] or by using a magnetic field to spatially separate the protons by momentum (energy). The later technique is used by the MPR spectrometer described in detail in Chapter 5, and in [I] and [III].

4.4 Neutron emission profile measurements – The Neutron Camera
The final component in characterizing the neutron emission is to determine \( \psi(R,Z,\phi) \); this task can be completed with a neutron camera by measuring the collimated neutron emission from different regions of the plasma. At JET, the camera system [69] consists of a pair of fan-like neutron collimator arrays placed in the torus hall closely coupled to the plasma vessel. One of these is situated above the tokamak (the vertical camera) and the other is located to the side of the torus (the horizontal/radial camera) attached to one of the diagnostic ports. There are nine vertical LOS and ten horizontal ones and all are in the radial direction. Each LOS is equipped with a NE213 scintillator and a plastic scintillator for detecting the incoming neutrons. The detectors’ fields-of-view are defined by adjustable neutron collimators.

By knowing the efficiency of the scintillators, the resulting pulse-height spectrum can be related back to the neutron flux at each detector. In order to relate the neutron emission in a camera’s field-of-view to the evaluated flux at the detector, MCNP calculations are necessary to correct for different scattering processes.
Using the evaluated neutron emission from the cameras’ 19 fields-of-view the \( y(R,Z,\phi) \) can be reconstructed. The problem of reconstructing the \( y(R,Z,\phi) \) is similar to the problem of reconstructing \( I(E_n) \), since they are both underdetermined problems; hence similar techniques can be used in the two cases. At JET the \( y(R,Z,\phi) \) is parameterized and fitted by using a chi-square minimization procedure [70]. It is important to note that only the relative emission in each field-of-view has to be determined in order to find the shape of \( y(R,Z,\phi) \). This facilitates the calibration of the instrument. The absolute level of \( y(R,Z,\phi) \) can then be determined by an instrument absolutely calibrated in flux (see Chapter 6) or against the activation foils system. An independent absolute calibration of the JET neutron camera has been performed [71] and the results were consistent with the JET activation foils.

The NE213 scintillator has the ability to separate 2.5-MeV and 14-MeV neutrons, so in principle both the 2.5-MeV and the 14-MeV \( y(R,Z,\phi) \) can be determined. However, in practice the data from the plastic scintillators are normally used for 14-MeV measurements and the NE213 is used for 2.5-MeV measurements. The 2.5-MeV \( y(R,Z,\phi) \) becomes hard to determine in cases where significant amounts of tritium are mixed into the plasma, because of the broad uniform response function of the detectors and the high level of scattered 14-MeV neutrons.
The Magnetic Proton Recoil (MPR) neutron spectrometer is a thin-foil spectrometer which was installed at JET in 1996 and upgraded (MPRu) 2001-2005. The principle and components of the MPR technique are illustrated in Figure 9. The fusion neutrons are collimated into a neutron beam. At the end of the neutron collimator np-scattering in a thin-foil (CH$_2$) conversion foil takes place. The recoil protons emitted in the forward direction enter the magnetic part of the spectrometer where they are momentum analyzed and focused onto the focal plane. An array of plastic scintillators coupled to photomultiplier tubes (PMTs) register the spatial distribution of the protons. All these steps depend on well-known physical constants (e.g., np cross sections), well-understood physical laws (e.g., the Lorenz force and conservation of momentum) and measurable quantities (e.g., the B-field and the geometry). Consequently an *ab initio* calculated response function can be derived with which the spatial proton distribution can be related back to the neutron energy distribution at the foil. At JET, the MPR has a semi-tangential line of sight through the plasma. The MPR has a 700 mm long cylindrical steel neutron collimator with a 10-cm$^2$ bore. At a distance 170 mm behind the end of the collimator is placed the 10 cm$^2$ polythene conversion foil, defining the active area of the spectrometer. The collimator-foil arrangement defines the spectrometers field-of-view into the plasma.
Figure 9. Schematic figure of the MPR spectrometer and its components together with its radiation shield.

The geometry and the performance of the MPR is discussed in detail in [I], [II], [III] and [IV]. This chapter focuses on the measurement criteria that guided the upgrade of the instrument.

5.1 The background

Close to a fusion machine there are strong levels of radiation (neutrons and gammas) that can constitute a background in the measurement situation. As discussed in Section 2.2 there is a direct, a scattered and a thermal flux of neutrons. Gammas normally originate from neutron induced reactions, but are also produced directly in the fusion plasma. Gammas can produce high energy electrons through Compton scattering. Therefore, besides protons, also gammas, neutrons and Compton electrons impinge on the scintillator array and constitute a background in the measurement. In [V], three criteria were put up for performing measurements despite the background:

- The instrument should be physically shielded from background radiation, so that only few background events are registered. Nor-
mally concrete, preferably borated, is used for neutrons, high Z materials are used for gammas and low Z material are used for Compton electrons.

- Even if detected, background events should be well separated from signal events.
- The background that remains indistinguishable from the signal should be possible to estimate, so that the observed signal can be corrected.

One of the advantages with the MPR technique is that proton detection is well separated from the neutron beam entering the spectrometer, hence limiting the amount of neutrons coming directly from the neutron beam to the detector location. The MPR is shielded using 60 tons of (non borated) concrete around the spectrometer and a lead shield placed close to the scintillators. When particles enter the MPR scintillators, light is emitted, which is converted to charge in a PMT. The amount of charge is registered, either in an analogue to digital converter, ADC, (original MPR) or by a transient recorder card (MPRu). By analyzing the resulting pulse height spectrum a particle identification can be done. The original MPR was designed to operate in DT plasmas and the 14-MeV protons could be distinguished from the background events since they in general deposited more energy. An example of the original MPR pulse height spectrum is given in Figure 10, where the shape of both protons and background is shown. The amount of background under the signal peak was determined by fitting an exponential to the background. It was found that a signal to background ratio (S/B) of 2000 was achieved.
When measuring the 2.5-MeV neutrons in D-operation a S/B = 0.1 was obtained [72]; this is a level that prevents any detailed interpretation of the neutron spectrum. The level and the spectral shape of the background were best explained by penetrating electrons and it was concluded that these were the major cause of background in 2.5-MeV measurements. When constructing the original MPR it was believed that 2.5-MeV neutrons would give rise to less background than 14-MeV neutrons, since they have a lower probability of penetrating the radiation shield. This hypothesis was later tested during the trace tritium experiment and as shown in Figure 11 the level of background does not depend strongly on the neutron source. It is also shown that the shape of the background is independent of the type of neutron emission (see Figure 10). Another hypothesis was that thermal neutrons due to the thermalization of the neutron beam entering the spectrometer cavity were the main source of the background. However, when changing the collimator length and thereby the intensity of the neutron beam entering the neutron spectrometer, no change in the absolute background level was found. The current hypothesis is that thermal neutrons leak into the spectrometer’s cav-

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5 The absolute background is the number of registered background events per emitted JET neutron.
ity, where they induce gammas, which in turn contribute to the background both directly and indirectly through Compton electrons.

![Figure 11. The relative background level (AU) as a function of the 14-MeV emission fraction of the neutron source.](image)

In order to measure the 2.5-MeV neutron spectrum and to improve measurements of weak components in the 14-MeV neutron spectrum (e.g., the $\alpha$ knock-on tail [73]) an upgrade of the spectrometer was performed. The goal of the upgrade was to reduce the background and noise sensitivity of the instrument and to improve the calibration and the control and monitoring system. The full upgrade with its first results is described in [I] to [IV].

### 5.2 The new scintillator array

One of the major components of the upgrade was a new scintillator array. The new array consists of 32 scintillators each coupled to two PMTs. The original MPR used monolithic scintillators, whereas for the MPRu two-layered phoswich scintillators are used. The different timing properties of the two layers make pulse shape discrimination possible. The MPRu scintillators consist of a thin fast scintillating layer which faces the incoming protons and is in optical contact with a thicker slow scintillating layer as illustrated in Figure 12. The thickness is such that 2.5-MeV protons only give signals in the fast layer; this make them distinguishable from penetrating gammas and electrons, which in most cases give signals in both layers. Background neu-
trons interact in the scintillators primarily through np scattering with constituent hydrogen nuclei; the produced recoil protons have a limited energy and range. As a consequence they normally deposit their energy in only one of the two scintillator layers. Only neutrons interacting in the fast scintillator layer give signals with pulse shapes similar to those of incoming signal protons and therefore the background from neutrons scales with the volume of the fast scintillator. Hence by using a thin fast scintillator layer the neutron interference in both 2.5-MeV and 14-MeV measurements are reduced.

![Interaction of different particles in an MPRu phoswich scintillator.](a)

**Figure 12 (Color online)** (a) Interaction of different particles in an MPRu phoswich scintillator. The fast scintillator layer (dark blue) faces the incoming protons is backed with a slow scintillator layer (yellow). (b) Illustration of the timing properties of the two phoswich layers.

5.3 Data reduction and background subtraction

Transient recorder cards (TRC) [74] were installed in order to record the pulse shape of each individual scintillator event. Examples of the difference in shapes between a proton and an electron induced PMT signal are shown in Figure 13. The pulse shape discrimination method used here is a traditional long gate vs. short gate technique where the pulse of each event is integrated over an early short gate and a later long gate as indicated in Figure 13(a).

The corresponding charges from the short gate ($Q_s$) and the long gate ($Q_l$) identify each event. The set of ($Q_s, Q_l$) is used to produce a 2D histogram as illustrated in Figure 13(b). In this 2D histogram the number of events inside a region of interest (ROI) is counted. The ROI is chosen to
include all protons. Background recordings are performed when the spectrometer is operated with zero B-field, preventing any recoil protons from reaching the scintillators. This background recording is used to estimate the background level in subsequent measurements.

Figure 13. (a) The pulse shapes from a proton (blue solid line) and an electron (red broken). The integration intervals used to calculate $Q_S$ and $Q_L$ are indicated with vertical lines. (b) The resulting 2D histogram where the ROI used for proton selection is shown.
To maximize the S/B it is desirable to minimize the width, $\sigma$, of the collected charge, $Q$, distribution. A narrower signal distribution covers a smaller area in the $(Q_S, Q_L)$ space and hence picks up less background. There are in principle three reasons for the broadening of $\sigma(Q)$. Firstly, there is an energy distribution of the protons impinging on a particular phoswich detector. However, in the MPR this is a minor effect, since the energy distribution is only 0.8% and 1.6%, for the two types of scintillators employed. Secondly, photo electron statistics has a significant effect. The number of photo electrons, $n_{PE}$ is given by:

$$n_{PE} = n_\gamma \cdot \epsilon_{col} \cdot q_e,$$  \hspace{1cm}(30)\]

where $n_\gamma$ is the number of photons produced in the scintillator, $\epsilon_{col}$ is the scintillator light collection efficiency and $q_e$ is the quantum efficiency of the PMT. The number of photo electrons can then be related to $\sigma(Q)$:

$$\frac{\sigma(Q)}{Q} = \frac{\sqrt{n_{PE}}}{n_{PE}}.$$  \hspace{1cm}(31)\]

The third contribution to $\sigma(Q)$ is due to the fact that $\epsilon_{col}$ is a function of the position on the scintillator where the protons impinge, which also contributes to the broadening. The parameter $\epsilon_{col}$ normally decreases with the distance to the PMT. This was found to have a quite large effect in the original MPR, and consequently each scintillator in the MPRu was fitted with two PMTs, per scintillator instead of one, which flattened the $\epsilon_{col}$ distribution.

The scintillator’s response to radiation was tested with protons, $\alpha$-particles, electrons and UV-light. The tests are described in [IV]. In Figure 14 an example of the $\epsilon_{col}$ distribution derived with $\alpha$-tests can be seen. Figure 14 shows the achieved $\epsilon_{col}$ distribution when summing the signals from the two PMTs. The $\epsilon_{col}$ distributions when only one of the two PMTs is switched on are also shown.
5.4 Control and monitoring

During the TTE experiments it was found that many of the PMTs experienced gain variations. This complicated the background subtraction. Since the new data acquisition system, using TRCs, enables more advanced post discharge analysis a more advanced gain monitoring system was installed with the MPR upgrade. The new system consists of a YAP [75] scintillator with an embedded $^{241}$Am source attached to the scintillator corresponding to the lowest energy (scintillator 0) and a LED light source coupled to all scintillators. The details of the gain monitoring are described in [II] and it is only briefly summarized here. The gain, $G$, is in this thesis is defined as:

$$G = \frac{Q}{e \cdot \gamma}, \quad (32)$$

where $\gamma$ is the amount of light incident on the photocathode and $e$ is the electron charge. The magnitude of $G$ is given by

$$G = A_{\text{PMT}} \cdot A_{\text{other}} \cdot t \cdot q_e, \quad (33)$$

Figure 14. (Color online) The $\varepsilon_{\text{col}}$ distribution for one of the scintillators with both PMTs active as a function of the position of the incoming radiation. The $\varepsilon_{\text{col}}$ distribution for each individual PMTs is also shown.
where $A_{\text{PMT}}$ is the amplification in the PMT, $A_{\text{other}}$ is amplification in other parts of the system, $t$ is the transmission of charge in the cables and $q_e$ is the PMT quantum efficiency.

Since the output of the YAP source is based on the physical process of alpha particles interacting in the scintillator material, this source provides an absolute stable reference point from which the scintillator 0 can be calibrated. Since the same LED is coupled to all the scintillators the scintillator 0 together with the information from the LED can be used to correct for gain variations in all the scintillators. This method for gain correction is applicable not only for the MPR spectrometer, but for all measurements using a combination of scintillators and PMTs.

5.5 Results and discussion

The MPR upgrade allows for measurements of 2.5-MeV neutrons and such measurements have been performed at JET. With the new scintillator array and transient recorder cards a S/B of 5 was achieved, which is an improvement by a factor of 50 compared to the 2.5-MeV measurements performed with the original MPR and in good agreement with simulations [76].

The gain monitoring system detected significant gain drifts as can be seen in Figure 15(a). In [II] different possibilities for these changes in gain are examined. A reduction in the quantum efficiency could be discarded. It is believed that the loss in gain is due to a reduction in the amplification of the PMTs or some other part of the systems. Due to the large gain variations it would have been almost impossible to analyze the data without gain corrections. It was found that the gain corrections worked adequately as can be seen in Figure 15(b), where the position of the proton peak is restored after the corrections.
Figure 15 (a) Time traces of the gain for one of the MPR scintillator PMT assemblies. The dramatic decrease in gain is not typical, this is the worst case. The spikes in the data are due to PMT over-current trips and subsequent reapplication of the PMT high-voltage. (b) Distribution of the total collected charge per proton event, $Q$, for two different sets of JET plasma discharges (same scintillator as in panel a). The bottom panel shows the gain corrected $Q$-distribution after using the information from panel a. The red full lines are Gaussian fits to the data.

After the background has been subtracted and the gain variations have been corrected for the spatial distribution of the protons, the proton position histogram can be extracted. Examples of the proton histograms from 2.5-MeV neutrons operations are shown in Figure 16 for JET discharge 68569, heated with only NBI, and discharge 68379, subjected to both NBI and ICRH. For the NBI-only pulse the tokamak was operated with a deuterium plasma into which was injected 16 MW of 80+140 keV deuterium beams during a period of 9s. The integrated yield of the discharge was $6.0 \cdot 10^{16}$ neutrons, which resulted in 1770 extracted proton counts in the MPRu position histogram. The ICRH+NBI discharge employed 10 MW of NBI and 9 MW of ICRH (at 55 MHz, e.g., tuned to the fundamental frequency of hydrogen and the 2nd harmonic of deuterium at the centre of the plasma) over a period of 9s into a D plasma. The total neutron yield was $3.5 \cdot 10^{16}$, resulting in a MPRu position histogram with 1183 protons.
One can note that the proton distribution from the NBI case is narrower than for the ICRH+NBI plasma, due to the lower energies of the fuel ions. It was found that the derived neutron energy spectra, if modeled with a Gaussian, had a $\text{FWHM}_{\text{ICRH}} = 476$ keV compared to $\text{FWHM}_{\text{NBI}} = 357$ keV. This is consistent with expectations, since ICRH heating can accelerate the fuel ions to MeV energies while NBI heating is restricted by the maximum energy of the beams (here 130 keV).

The MPRu was also set to measure the 14-MeV neutron spectrum in D-plasmas. As discussed in Section 2.1 the neutron spectrum is composed of both a triton burn-up component and a thermal component as was shown in Figure 5. The neutron spectrum was taken with the MPRu spectrometer and the corresponding proton histogram, with 3139 proton events, is shown in Figure 17.
The TOFOR spectrometer is the key instrument for measurements of 2.5-MeV neutron spectra at JET, due to its high efficiency. However the MPRu has a different LOS than TOFOR and using the dual sight lines of the two instruments can reduce ambiguities in the interpretation of the data [26].

Moreover, the MPRu instrument is *ab initio* calibrated in flux, a characteristic that is used when determining $Y$ as discussed in the next section.
6 MPR -Camera fusion power measurement system

The importance of neutron yield measurements is outlined in Section 4.2. A new independent method for determining the neutron yield has been developed for this thesis, with the goal to increase the accuracy in such measurements. The method is presented in detail in [V] and has the potential to meet the demands of high-accuracy measurements of the fusion power for future fusion experiments such as ITER [VI]. The goal is to correlate the count rate of a spectrometer to the total neutron emission, and hence the fusion power and internal heating as described in Section 3.3.

The method relies on a spectrometer that is absolutely calibrated in flux and energy and a neutron camera. Both of these instruments are present at JET and, consequently, the method has been developed and tested there. The relation between the JET neutron emission, \( Y \), and the spectrometer count rate is given by combining Equations 21 and 24:

\[
Y = F \cdot A \cdot p^{-1} = \frac{N}{e} \cdot p^{-1},
\]

where \( e \) is the average efficiency. The parameter \( p \) has a few different components. The major component to \( p \) is the direct flux from the spectrometer’s field-of-view. The direct flux is estimated with an optical model, where the neutron flux is treated as if it behaved like light (hence the name) and machine structures are either opaque or transparent [V, Section 2]. However, the direct flux has to be corrected for due to the ability of neutrons to penetrate materials without undergoing any interaction. The effective field-of-view is increased due to transmission of neutrons, mainly through the edges of the neutron collimator. On the other hand, neutrons are lost due to attenuation in intervening material. In addition, \( p \) has a component due to the scattered flux. The calculations of the attenuation, transmission and the scattered flux have been done using the neutron transport code MCNP. The attenuation part of the calculations was also checked with a simple exponential attenuation model. The parameter \( p \) depends on the shape of \( y_{\text{norm}}(R,Z,\phi) \) as described in Equation 24. The shape of \( y_{\text{norm}}(R,Z,\phi) \) is determined by using a neutron camera. The schematics of the entire system are illustrated in Figure 18.
Based on this established method a detailed error analysis is performed. It is found that the total systematic uncertainty is 6%, and the random uncertainties are dominated by the counting statistics in the spectrometer.

A performance evaluation for a similar system for ITER has been done [VI], and the different contributions to the uncertainty are given in [VI, Table 1]. It is found that a total systematic uncertainty of 3.0% is achievable, dominated by the uncertainty in the efficiency of the spectrometer. These results rely on the assumption that the centre of the neutron emission profile could be determined with an accuracy of 1 cm. However it has been suggested that the center will be determined with an accuracy of 10 cm [77]. This would increase the total accuracy to 4.2% for the system. It should be noted that the final design of the JET neutron camera is still to be completed and consequently the uncertainty in $\gamma(R,Z,\phi)$ in ITER is still difficult to predict.

6.1 Results

The first application of the method was for data from the 1997 JET deuterium tritium experiments DTE1 and the results are presented in Ref x. During the JET Trace Tritium Experiments, TTE, in 2003 the method was fully developed and it could be applied as a routine control room diagnostic. A comparison of TTE data from the MPR-Camera system and the calibrated silicon diode system (see Section 4.2.3) is shown in Figure 19 where a difference of 9 % between the two systems is found. This difference is within the
uncertainties of the two data sets. Figure 19 also shows the random errors in the MPR-Camera data.

![Figure 19](image)

Figure 19. Comparison of pulse-integrated 14 MeV neutron yield data from the MPR-camera and silicon diode systems for 110 TTE pulses. The random uncertainties for the MPR-camera data are also shown. The silicon diode and MPR data sets are independent and no cross-calibration has been performed.

With the MPRu upgrade it is also possible to measure the 2.5-MeV neutron yield. Time has not permitted to make a detailed analysis of $\gamma(R,Z,\phi)$, so the results presented in [III] uses a fixed $\gamma(R,Z,\phi)$ from the TTE. This increases both the random and the systematic uncertainties. However, an attempt was made to calculate the $\gamma(R,Z,\phi)$ from the neutron camera data available. With this information a preliminary analyses was performed and the integrated neutron yields for 101 pulses were determined. The results can be seen in Figure 20, where a systematic difference of only 2 % between the MPR and the calibrated FCs are found. This is consistent with the results presented in [III] given the increased errors when not using neutron camera data.
Figure 20. Comparison of pulse-integrated 2.5-MeV neutron yield data from the MPRu ($Y_{\text{MPR}}$) and JET fission chambers ($Y_{\text{FC}}$) for 101 JET pulses. Uncertainties due to counting statistics for the MPRu data are also shown.

6.2 Discussion

One of the major reasons that the systematic uncertainties are lower for the ITER system than for JET is that a dedicated, hypothetical, neutron collimator is used. Simulations show that in order to minimize the uncertainty in the calculations the transmission and the scattering should be reduced. To achieve this, a long broad tapered neutron collimator is used for the ITER case Figure 21. Such a collimator, instead of a short cylindrical one (see Figure 9), has many advantages. The flux on the spectrometer increases, since the ratio between the area of the umbra and the penumbra is enhanced. The tapered collimator results in a more well-defined field-of-view, which decreases the uncertainty in the flux. Furthermore, a tapered collimator reduces the amount of neutrons penetrating the collimator. It is also important to have some distance between the collimator and the foil, since this decreases the number of scattered neutrons on the detector. Finally, by increasing the angle of the tapering close to the plasma the amount of scattered neutrons in the collimator is further reduced.
Using a neutron spectrometer-camera system allows the low-energy scattered neutrons to be studied and excluded experimentally. Furthermore, the spectroscopic information makes it possible to correct for any energy dependence in the flux detection efficiency. A collimated neutron flux also decreases the influence of the scattered flux at the detector, which is difficult to model.

The $y(R,Z,\varphi)$ should always be included when neutron yield measurements are performed, independent of the method. However using a collimated neutron flux measurement simplifies the propagation of uncertainties in the $y(R,Z,\varphi)$ to the final result. Furthermore, using a neutron camera for determining the $y(R,Z,\varphi)$ minimizes the associated errors.

Using an MPR spectrometer has some added advantages. The MPR is \textit{ab initio} absolutely calibrated both in flux and in energy, so no \textit{in situ} calibration or cross-calibration of the instrument is needed. This makes the new method independent of other methods for fusion power determination, such as the traditional one based on FCs calibrated with activation foils.

The present system at JET was not optimized for neutron yield measurement. And as shown in [VI], in a dedicated system the uncertainties can be substantially reduced.
7 Charged fusion product confinement measurements

The previous chapter gave examples on how the neutron yield could be determined with an accuracy of 4% when different neutron systems were combined. In this chapter it is shown that a combination of information from a broad range of plasma diagnostics can provide a measurement of the internal heating of the plasma.

The internal heating of the plasma depends both on the released fusion power and the confinement of the charged fusion products (CFP) as shown in Equation 8. In Section 6, [V] and [VI] a new method for measuring the fusion power is outlined. An approach to determine the CFP confinement based on neutron measurements, by measuring the triton burn-up neutrons (TBN) is presented in [VII].

The confinement of 1-MeV tritons has previously been studied by means of TBN measurements [78] for operation in high current mode at JET. Lately, JET has been operated with lower plasma currents in order to investigate new operating scenarios. This thesis describes a set of TBN measurements done under these new operating conditions. There have been previous studies of TBN at low currents at other fusion machines [79]; however this is the first attempt to study the TBN at JET for these conditions.

7.1 TBN model

The TBN model is described in detail in [VII] and is only summarized here. The triton from the d+d reaction is born at an energy of approximately 1-MeV and moves in a gyro-motion orbit where the triton orbits around a magnetic field line. If a triton does not slow down or undergo any collisions, it continues to follow the same gyro-motion orbit as long as the tokamak magnetic field is stable. However, a fraction of the tritons enters into orbits that are intersected by a vessel wall; those tritons are lost. Due to the high velocity of a 1-MeV triton (≈6000km/s), it is lost within a couple of μs after being “born”; this is therefore referred to as a prompt loss. The confined tritons slow down by collisions with the electrons and ions of the background plasma. This slowing down process is described by Equation 6.
After the prompt losses have been estimated, the TBN rate has to be measured and compared to simulated values in order to see if there are any other triton loss processes. The simulated TBN emission is found using the reactivity code TRAPT [78], which simulates the time dependence of the tritons slowing down and reacting with the background plasma.

7.2 Experiments and result

The deuterium experiments at JET in the period October 2000-May 2002 offered an excellent opportunity to study the ion confinement in new operation scenarios. During this period, the ion confinement was studied by means of TBN measurements, prompt loss calculations and TBN simulations.

In these experiments, the 14-MeV neutron rate was monitored by JET’s silicon diodes. In order to calculate the TBN rate from the 14-MeV neutron rate, the residual tritium from previous experiments, namely the major DT experiment in 1997, has to be taken into account. Using the MPR spectrometer the contribution of the neutron flux from the thermal tritons is distinguished from the TBN emission.

It is found that there are significant losses of tritons at low currents. At currents of 3 MA about 10% of the tritons are lost and losses of 60% (mostly prompt losses) were observed at 1 MA current. After correcting for the amount of residual tritium and the number of prompt losses the ratio between the number of measured TBN neutrons and the number of expected TBN neutrons can be derived as shown in Figure 12.
Figure 12 The ratio between the number of measured TBN and the number of expected TBN as function of plasma current.

Furthermore it was found that the ratio, $TBN/Y_{\text{thermal}}$, was affected by the amount of impurities in the plasma as expected from Equation 14.

7.3 Discussion and outlook

The confinement of tritons is a measure on how well $\alpha$-particles are confined. The losses experienced at low currents imply reduced plasma heating in DT-plasmas at low currents (see Equation 8). At currents larger than 2.2 MA, there is no evidence for non-prompt losses; for lower currents other loss-mechanisms could not be excluded. Mechanisms responsible for such losses could be, for example, field ripple diffusion, MHD activity or large-angle Coulomb scattering, but an investigation of this has not been within the scope of this thesis.

In general, the uncertainties associated with the TBN method are to a large degree given by the uncertainties in the input parameters to the simula-
tions. In [VII] the problems to determine the deuterium density were discussed, due to large uncertainties in the effective charge of the plasma. Previously, experiments have shown that the deuterium density can be determined using neutron spectroscopy [80]; a method that could be pursued for current JET experiments. Since the 14-MeV neutron flux is one of the most important input parameters for the ion confinement measurements the developed 14-MeV method outlined in [V], [VI] and in Section 6 could reduce the systematic uncertainties in the TBN-method.
8 Conclusions

The work with this thesis has led to: a MPR neutron spectrometer that is less sensitive to background and gain-drifts; a new method to determine the neutron yield; and a further understanding of the confinement of ions at low currents in large tokamaks.

The results from the confinement study verify findings from other machines, but also highlight the possibilities offered by neutron measurements to supply information outside their traditional field of study. In particular, the ability of a high-resolution neutron spectrometer to separate the triton burn-up and residual triton neutron emission components is of fundamental importance in this context.

The instrumental upgrade allows the MPRu to measure both the 2.5-MeV and 14-MeV neutron spectrum. Consequently, the spectrometer can provide important information on the fuel ion population both in D and DT operation. The possibility to operate in D plasmas allows the spectrometer to be fine tuned and fully characterized prior to the next JET (trace or full) tritium experiment. This possibility is also ITER relevant, since neutron data will be needed from day one of ITER DT experiments. In the planned ITER advanced D experiments and any trace tritium experiments a mixed flux of 2.5-MeV and 14-MeV neutrons is present. The capability to distinguish and measure both these species makes the MPR a rare candidate to study such scenarios.

The results from the developed spectrometer-camera system for yield measurements show that the systematic errors in fusion power measurements can be greatly reduced in comparison to standard methods using activation foils or in situ calibration. Reducing the need of in situ calibration can bring ITER into plasma operation at an earlier date, and consequently speed up the progress in fusion research. The method was originally developed for 14-MeV neutron measurements; however, with the upgraded MPRu spectrometer it is also possible to measure the 2.5-MeV neutron yield. This method has great implications for future fusion power measurements in both D and DT-operation, most notably in that the uncertainty in the residual tritium inventory of ITER can be dramatically reduced.
9 Summary of papers

Paper I
The New MPRu Instrument for Neutron Emission Spectroscopy at JET
This paper presents the upgrade of the Magnetic Proton Recoil (MPR) neutron spectrometer and its improved signal to background capability. This improvement is made possible by the use of a new proton recoil detector in combination with transient recorder data acquisition cards. The importance of these instrumental improvements for extending the use of the MPRu in diagnosis of D and DT plasmas is discussed. Results from the first 2.5-MeV measurements performed with the MPRu during JET’s high level commissioning in April 2006 are presented.

My contribution to Paper I: Building and installing the MPRu at JET. Taking part in the data taking during the JET experimental campaigns. Writing the paper.

Paper II
Control and Monitoring System of the Upgraded Magnetic Proton Recoil Neutron Spectrometer at JET
This paper describes the control and monitoring system of the upgraded MPR neutron spectrometer installed at JET, focusing in particular on a technique for the stabilization of the gain of the photomultipliers coupled to the focal plane scintillator detectors. The technique described is of general interest for all instruments that employ scintillators coupled to photomultiplier tubes.

My contribution in Paper II is participation in the assembly and tests of the different components of the C&M system. I developed and implemented the method for gain corrections, made the data analyses, drew the conclusions and, finally, wrote the paper.
Paper III

**The thin foil magnetic proton recoil spectrometer MPRu**
The paper gives a full description of the completed MPRu spectrometer. Examples are given of its capabilities to measure both 2.5-MeV and 14-MeV neutrons in D plasmas. The new instrument is also used to measure the absolute 2.5 MeV neutron flux.

**My contribution in Paper III** has been constructing and installing the MPRu spectrometer at JET. Paper III has been a true group effort all the way from the design of the spectrometer to the completion of the paper. I have participated in all aspects of this effort.

Paper IV

**Development and Characterization of the Proton Recoil Detector for the MPRu Neutron Spectrometer**
The paper describes the development of the focal plane detector for the MPRu spectrometer. This was partly done by tests of prototype scintillators to reach the final design. The paper reports on the tests conducted and the projected performance.

**My contribution to paper IV** is participating in the design of the test procedure and the actual tests of the phoswich detectors. I also participated in the data analyses.

Paper V

**Fusion Power Measurement using a Combined Neutron Spectrometer-Camera System at JET**
In this paper the principles of collimated neutron flux measurements for fusion plasma power determination are described. A method combining information from a neutron spectrometer and a neutron profile monitor to obtain the neutron yield is presented. Particular care is taken to estimate the uncertainties involved. The method has been put to practical use at JET and results from JET’s Trace Tritium experimental campaign in 2003 are presented.

**My contribution to paper V** is participating in the TTE experiment, developing the method, analyzing the data and writing the paper.
Paper VI

_Fusion Power Measurement Using a Combined Neutron Spectrometer - Camera System at ITER_

In this paper, we present how the system presented in paper V could be implemented on ITER and how well it would perform under different assumptions of plasma scenarios and diagnostic capabilities.

**My contribution to paper VI** is developing the method for error analyses at ITER and building a MCNP model of ITER, interpreting the results, writing the paper and, finally, presenting the paper at the Burning Plasmas Conference in Varenna Italy 2007.

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Paper VII

_Triton Burn Up Neutron Emission in JET Low Current Plasmas_

The paper describes measurements and simulations of the charged particle confinement at JET. By measuring the triton burn-up neutrons and comparing to simulations the amount of lost tritons is estimated for low current plasmas in JET. The level of 14 MeV neutrons due to residual tritium is estimated using data from the MPR neutron spectrometer.

**My contribution to paper VI** is performing preliminary analysis of the data and completing the paper.
En av vår generations största frågor är hur vi ska kunna försörja en växande världsbefolkning med energi. Växthuseffekten begränsar vår vilja att använda olja, gas och kol; i stora delar av värden finns det en folklig rädsla för traditionell kärnkraft; och det finns stora frågetecken kring hur mycket energi som kan levereras från förnyelsebara resurser. Fusionskraft skulle kunna tillgodose vårt behov av en obegränsad mängd med ren och säker energi.

Fusion är den process som driver vår sol. Om denna process kunde kontrolleras på jorden skulle våra energiproblem vara lösta för all framtid. I fusionsprocessen utvins energi genom termonukleär förbränning där lätta atomkärnor slås ihop. I den processen omvandlas en del massa ($m$) till energi ($E$) enligt Einsteins berömda formel:

$$E = mc^2$$

där $c$ är ljushastigheten. Eftersom ljushastigheten är hög (300 000 km/s), behöver bara en liten mängd massa omvandlas för att frigöra en stor mängd energi.

Det mest troliga bränslet i en framtida fusions reaktor är en blandning av två tunga former av väte, deuterium och tritium. När tritium och deuterium slås ihop frigörs stora mängder energi och en heliumkärna och en neutron bildas, vilket visas i Figur 22.

Tritium finns inte naturligt i vår miljö utan måste tillverkas i speciella kärnkraftverk av tungvattentyp. Detta gör tritium väldigt dyrt (ca 200 000 000 kr/kg). Tritium är dessutom radioaktivt och därför används ofta rent deuterium i dagens fusionsforskningsexperiment. Även med rent deuterium bildas neutroner när atomkärnorna slås ihop. Förhoppningen är att i framtidens reaktorer kunna tillverka tritium direkt i reaktorn genom att ”klyva” litium med fusionsneutroner. Litium, i sin tur, är en relativt vanligt förekommande metall i jordskorpan.


I en bilmotor bestämmer trycket och temperaturen bilmotorns effekt. På liknande sätt bestämmer tryck och temperatur den effekt som kan fås ut ur ett fusionskraftverk. För att kontinuerligt kunna kontrollera och förstå förbränningsprocessen måste tryck, temperatur och effekt i ett framtida fusionskraftverk kunna mätas. Eftersom bränslet är väldigt varmt kan inga ”vanliga” mätverktyg (t.ex. en kvicksilvertermometer) föras in i bränslet.
Dessa skulle omedelbart förstöras och förorena bränslet. Bränslets egenskaper måste alltså kunna mätas på distans. Det är i det sammanhanget som forskningsresultaten som presenteras i denna avhandling kommer in.

Oavsett bränslesammansättning kan de elektriskt oladdade neutronerna som kommer från fusionsreaktionerna ta med sig viktig information om förbränningsprocessen ut ur den magnetiska inneslutningen. Genom att mäta neutronernas energi kan man få fram bränslets temperatur och information om hur plasmat är upphettat.


I den här avhandlingen beskrivs också utvecklingen av en ny metod som gör det möjligt att med hjälp av MPR-spektrometern bestämma JETs totala neutronproduktion. Genom att bestämma neutronproduktionen med stor noggrannhet går det att bestämma fusionseffekten och bränslets sammansättning.

För att föra fusionsforskningen vidare har det bestämts att det ska byggas en ny testreaktor, ITER. Den kommer att producera en termisk effekt på upp till 1.5 GW ( motsvarande den elektriska effekten man får ut av ett stort kärnkraftverk) och vid reaktorn kommer forskare att kunna göra experiment som varar i flera minuter. Detta gör att enorma mängder neutroner kommer att produceras. Att kunna mäta dessa neutroner kommer att vara av yttersta vikt för att ITER-projektet ska bli en succé. I avhandlingen visas att det går att bestämma neutronproduktionen med väldigt god noggrannhet med instrumentet och metoden som har utvecklats.
11 Acknowledgments

None of us is as smart as all of us

Japanese proverb

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