Study of Collimated Neutron Flux Monitors for MAST and MAST Upgrade

SIRIYAPORN SANGAROON
Abstract

Measurements of the neutron emission, resulting from nuclear fusion reactions between the hydrogen isotopes deuterium and tritium, can provide a wealth of information on the confinement properties of fusion plasmas and how these are affected by Magneto-Hydro-Dynamic (MHD) instabilities.

This thesis describes work aimed to develop neutron measurement techniques for nuclear fusion plasma experiments, specifically regarding the performance and design of collimated neutron flux monitors (neutron cameras) for the Mega Ampere Spherical Tokamak, MAST, and for MAST Upgrade. The first part of the thesis focuses on the characterization of a prototype neutron camera installed at MAST and provides an account of the very first measurements of the neutron emissivity along its collimated fields of view. It is shown that the camera has sufficient temporal and spatial resolution to measure the effect of MHD instabilities on the neutron emissivity. The neutron camera fulfils the requirement on the measurements of the neutron count rate profile with less than 10 % statistical uncertainty in a time resolution of 1 ms. The instrument's more rudimentary capabilities to provide information on the neutron energy distribution are also presented and discussed. The encouraging results obtained with the prototype neutron camera show the potential of a collimated neutron flux monitor at MAST and suggest that an upgraded instrument for MAST Upgrade will provide crucial information on fast ions behavior and other relevant physics issues.

The design of such an upgraded instrument for MAST Upgrade is discussed in the second part of the thesis. Two design options are explored, one consisting of two collimator arrays in the horizontal direction, another more traditional design with lines-of-sight in the poloidal cross section plane. On the basis of the experience gained with the prototype neutron camera and on the exploratory design and estimated performance for the upgraded camera presented here, a conceptual design of a neutron camera upgrade is proposed.

Keywords: Fusion, Plasma diagnostics, Neutron camera, collimated neutron flux monitor, MAST, MAST Upgrade, ITER

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To my mother and father
List of papers

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

I  **Study of the detector efficiency of MAST neutron camera**  
*S. Sangaroon, M. Ceconello, S. Conroy, I. Wodniak, M. Turnyanskiy, G. Ericsson, and MAST team*  
*My contribution:* Participated in the experiment. Performed the simulation and in interpretation of the results and analyzed data. Wrote the paper and presented the material at the conference.

II  **The 2.5 MeV neutron flux monitor for MAST**  
Accepted for publication in Nuclear Instruments and Methods in Physics Research A, March 2014.  
*My contribution:* Participated in the commissioned and calibration, and in interpretation of the results and analyzed data.

III  **Observation of fast ion behaviour with a neutron emission profile monitor in MAST**  
*M. Ceconello, S. Sangaroon, M. Turnyanskiy, S. Conroy, I. Wodniak, R. J. Akers, G. Ericsson and the MAST Team*  
Nuclear Fusion **52** (2012) 094015 (12pp)  
*My contribution:* Participated in the experiment and in interpretation of the results.

IV  **Validation of neutron emission profiles in MAST with a collimated neutron monitor**  
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My contribution: Performed the experiment and interpretation of the results, analyzed data, wrote the paper and presented the material at the conference.

V  A poloidal section neutron camera for MAST Upgrade
Proceedings of the International Conference on Fusion Reactor Diagnostics, Varenna, Italy (2013)
My contribution: Performed the simulation and interpretation of the results, wrote the paper and presented the material at the conference.

VI Conceptual design of the 2.5 MeV neutron flux monitor for MAST Upgrade
In manuscript, to be submitted to Nuclear Instruments and Methods in Physics Research A
My contribution: Performed the simulation and interpretation of the results, wrote the paper.

Proceedings not included in this thesis

VII Characterization of MAST neutron camera detectors and first measurements
S. Sangaroon, M. Cecconello, I. Wodniak, C. Marini Bettolo, M. Turnyanskiy, G. Ericsson, and MAST team
My contribution: Participated in the experiment and in interpretation of the results, analyzed data and wrote the paper and presented the material at the conference.

VIII Conceptual design of a neutron camera upgrade for MAST Upgrade
My contribution: Performed the simulation and interpretation of the results, wrote the paper and presented the material at the conference.

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1. Nuclear Fusion and MAST

1.1 Introduction

Fusion is the process in which two light nuclei fuse to release energy. The released energy can be converted to heat which can be used to maintain a steam cycle for the generation of electricity. Fusion reactions occur naturally in the sun and other stars. On the earth, the ideas of controlled fusion reactions have been investigated for more than 50 years. Fusion reactions happen at extremely high temperature of hundred million degrees Kelvin which corresponds to a mean particle kinetic energy of approximately 10 keV. At these high temperatures, matter is in the plasma state in which atoms are fully ionized.

A number of reactions of relevance for fusion reactors are listed in equations 1.1 - 1.3: these reactions are between the two isotopes of hydrogen, deuterium (D) and tritium (T). Compared to other possible fusion reactions, the DT reaction has a higher energy release and a higher cross section in achievable temperature ranges with a maximum cross section at approximately 100 keV. However, tritium is a radioactive isotope and its use is regulated even for research purposes. Thus, most fusion experiments employ the DD reaction.

\[ {}^2D + ^3T \rightarrow {}^4He + n + 17.6 \text{ MeV} \] (1.1)
\[ {}^2D + ^2D \rightarrow {}^3He + n + 3.27 \text{ MeV} \] (1.2)
\[ {}^2D + ^2D \rightarrow ^3T + H + 4.03 \text{ MeV} \] (1.3)

Since the fuel for fusion reactions consists of charged particles, it can be confined by a magnetic field. Different magnetic confinement configurations exist, among which the tokamak is the most promising one. The tokamak consists of a toroidaly shaped vacuum vessel (reaction chamber), surrounded by electric coils that create a toroidal magnetic field. In addition, a poloidal magnetic field is created by a toroidal electrical current inside the plasma. Those two fields combine to a helical magnetic field confining the plasma. A schematic picture of the toroidal, poloidal and the resulting helical magnetic fields for the tokamak configuration is shown in figure 1.1.

Fusion energy research with tokamaks is currently performed at a number of facilities around the world. The most prominent are JET [1], DIII-D [2], JT-60U [3], ASDEX-Upgrade [4]. A world-wide collaboration is presently constructing the next step device, ITER, in Cadarache, France [5]. ITER is designed to prove the viability of practical fusion energy, and is planned to be followed by design and construction of a demonstration fusion power plant, DEMO [6].
Figure 1.1. Schematic view of a tokamak magnetic confinement fusion device, with poloidal, toroidal and resulting helical magnetics field.

1.2 Mega Ampere Spherical Tokamak

The Mega Ampere Spherical Tokamak (MAST) is a medium sized spherical tokamak (ST) with plasma current up to $\sim 1$ MA [7]. It is located at the Culham Centre for Fusion Energy (CCFE) in Culham, UK. The main scientific goals of MAST are: i) exploring the long term potential of the spherical tokamak as a components test facility (CTF) and/or advanced power plant; ii) giving input to the design of machines like ITER and DEMO; and iii) providing insight into selected aspects of tokamak physics [7, 8]. MAST is designed to study plasmas with a low aspect ratio ($R/a$, $a$ and $R$ being the minor and major radius respectively), high elongation (ratio of vertical and horizontal minor plasma radius), in a low magnetic field with a plasma current in the range of 500 kA to 1 MA. The plasma duration time is $\sim 0.5$ s. The key parameters of MAST are shown in table 1.1.

At MAST, 2.5 MeV neutrons are produced, with a typical neutron rate of $\sim 10^{13}$ n/s, mainly from DD reactions (equation 1.2) when beams of energetic deuterium atoms are injected into the plasma. The injected deuterium atoms are ionized in the plasma and form a population of ions with energies (velocities) much higher than the energy of the ions in the plasma and are therefore called fast ions. At MAST, two Neutral Beam Injectors (NBIs) are the main form of additional plasma heating and are capable of delivering fast ions with energies up to 70 keV and a maximum power of 5 MW [9] for the entire duration of a plasma discharge ($\approx 0.5$ s). The MAST NBI system consists of two injectors (2.5 MW each) named South-South (SS) and South-West (SW) based on their location in the MAST experimental hall. Due to the typical plasma temperatures and beam injection energies in the MAST device, the neutron emission is dominated by interaction of beam fast ions with the thermal bulk plasma (beam-thermal contribution) and between the injected beam deuterons themselves (beam-beam contribution), while the contribution from thermal reactions is typically only about 5% of the total neutron emission.
Table 1.1. Key parameters for MAST [8]

<table>
<thead>
<tr>
<th>MAST parameters</th>
<th>Achieved</th>
</tr>
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<tbody>
<tr>
<td>Minor radius, $a$</td>
<td>0.65 m</td>
</tr>
<tr>
<td>Major radius, $R$</td>
<td>0.85 m</td>
</tr>
<tr>
<td>Elongation, $\kappa$</td>
<td>$\leq 2.5$</td>
</tr>
<tr>
<td>Aspect ratio, $R/a$</td>
<td>$\sim 1.3$</td>
</tr>
<tr>
<td>Plasma toroidal field rod current</td>
<td>$\leq 1.4$ MA</td>
</tr>
<tr>
<td>Toroidal field at $R = 0.7$ m</td>
<td>$\leq 0.62$ T</td>
</tr>
<tr>
<td>Auxiliary heating, $P_{NBI}$</td>
<td>$\leq 5$ MW</td>
</tr>
<tr>
<td>Electron density, $n_e$</td>
<td>$(0.1-1) \times 10^{20}$ m$^{-3}$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>$\sim 0.5$ s</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>10 m$^3$</td>
</tr>
</tbody>
</table>

Thus, detailed observations of the neutron emission can be used as a measurement of spatial the fast ion distribution in the plasma, both energetically and spatially.

1.3 Fast ion physics and MHD instabilities in MAST

In a future fusion reactor, the vast majority of fast ions will consist of $\alpha$ particles produced from $DT$ reactions. These $\alpha$ particles need to be confined for times long enough to transfer their energy to the bulk plasma, thereby sustaining the fusion reactions without the presence of additional external plasma heating. This condition is known as ignition. It is well known, however, that the confinement of $\alpha$ particles is deteriorated by the presence in the plasma by certain Magneto-Hydro-Dynamic (MHD) instabilities. The reduction of the confinement usually takes the form of fast ion transport from the core to the edge of the plasma thereby reducing the fusion power and possibly damaging the first wall of the reactor. The fast ions spatial redistribution is much larger than the one that can be expected by neo-classical diffusion, that is collisional diffusion in toroidal geometry, and it is usually described as the result of an anomalous fast ion diffusion. In particular, some of these MHD instabilities are induced by the presence of the fast ions themselves: for example in MAST the large fast ion pressure from the NBI injection can destabilized modes that causes transport of fast ions away from the plasma core. It is therefore crucial to understand how fast ions interacts with the background plasma and these instabilities in regimes that are relevant for a fusion reactor. In present day devices, operated with deuterium fuel only, some aspects of fast ion physics relevant for ITER and DEMO can be addressed.

MAST is a device that is well suited to address the interplay between fast ions and two specific types of instabilities: the Alfvén Eigemodes (AE) [10, 11] and the Fish-Bone (FB) [10, 12] instabilities. This is because MAST is
characterized by a low toroidal field and highly energetic beams resulting in fast ions with super-Alfvénic velocity and therefore able to drive AE instabilities in a way similar to what α particles will do in ITER. In MAST both AEs and FBs affect the spatial distribution of the fast ions resulting in their transport (redistribution within the plasma volume) and losses (escape from the plasma volume) characterized by a high level of anomalous fast ion diffusion. One particular feature of MAST is the fact that FBs tend to evolve from their intrinsically intermittent behaviour into an almost steady-state, constant-amplitude mode which is called a Long Lived Mode (LLM). The LLM has been observed to also affect the fast ions spatial distribution, especially in the core of MAST plasmas.

The fast ion population is also affected by other instabilities which are present in most tokamaks, namely the sawtooth instability [12, 13, 14]. This instability is caused by the presence, in the plasma core, of current gradients such that a resonant perturbation is destabilized on the \( q = 1 \) surface, where the safety factor \( q \) is defined as \( q(r) = rB_t/(RB_p) \), \( B_t \) and \( B_p \) being the toroidal and poloidal magnetic fields. The resonant perturbation is located inside the plasma at the radial position for which \( q = m/n = 1 \), where \( m \) and \( n \) are the poloidal and toroidal mode numbers respectively. This internal perturbation, also known as internal kink, grows in amplitude and, in the presence of a small and finite resistivity, causes eventually a sudden re-arrangement of the internal magnetic fields known as magnetic reconnection. The reconnection event results in sudden reduction of the plasma energy content and it is accompanied by strong transport of fast ions. The plasma current gradient is temporarily reduced and the \( q = 1 \) surface temporarily removed from the plasma. However due to the continuous plasma current inductive drive, the current gradient is slowly restored leading to the next sawtooth. This cyclic behaviour, the sawtooth oscillation, is regularly observed in many fusion devices.

Since in MAST the fast ions are the main contribution to the neutron emission, their behaviour can be studied by measuring the neutron emission.

### 1.4 Neutron Measurements at MAST

Two neutron diagnostics operate at MAST. First, an absolutely calibrated \(^{235}\text{U}\) Fission Chamber (FC) provides measurement of the total neutron yield with time resolution of 10 \( \mu \)s [15] but no spatial resolution. Second, a collimated neutron flux monitor (in short called a Neutron Camera, NC) provides a spatially localized measurement of the neutron emission profile as a function of time. The main purposes of the NC are: i) to provide information about the fusion source such as its location, shape, intensity, fuel temperature; and ii) to study the behaviour of fast ion in plasmas affected by MHD plasma instabilities.
NCs are available at many fusion research facilities such as TFTR [16], JET [17, 18], JT-60U [19], MAST [20, 21], etc. and is also planned for ITER [22, 23]. A NC based on a parallel multichannel neutron collimator was made for TFTR [16] and provided time-resolved neutron emission profiles from ten vertical collimators. The camera allowed the study of high frequency MHD activity. In 1987, a collimator array (camera) for measurements of the neutron emission profile was installed at JET [17, 18] and it is still in use today. The instrument has ten horizontal and nine vertical channels giving a spatial resolution of 10% of the minor radius and allows for measurements of the time evolution of neutron emissivity poloidal distribution. In 2002, a vertically inclined multichannel collimator was installed at JT-60U [19] for the measurement of the neutron emission profile.

In 2010, a 2.5 MeV neutron collimator array prototype was installed at MAST [20, 21]. The four collimator channels of this prototype allows the study of fast ions with less than 10% statistical uncertainty with a time resolution of 1 ms [20, 21]. Part I of this thesis is focussed on the work carried out with this prototype NC. Part II of this thesis is focussed instead on the conceptual design of an upgrade of the present prototype to a full collimated neutron flux monitor [24, 25, 26] for MAST Upgrade [27].
Part I:  
A prototype neutron camera (Chapter 2 - 4)

A prototype collimated neutron flux monitor for the Mega Ampere Spherical Tokamak (MAST, Culham Science Centre, UK) was designed, built, installed and commissioned in 2008 - 2012. The characterization of this neutron camera (NC) is presented in this section. The camera provides measurements of MAST’s 2.5 MeV neutron emissivity along collimated fields-of-view. The results show that this calibrated prototype NC provides sufficient spatial and temporal resolution to observe the effects of fast ion behaviour and Magneto-Hydro-Dynamic (MHD) instabilities on MAST neutron emissivity. The instrument’s more rudimentary capabilities to operate as a neutron spectrometer are discussed. *(Paper I-IV)*
2. The prototype neutron camera

The MAST NC is a proof-of-principle neutron emission profile monitor with a limited number of sight lines. Figure 2.1 shows an equatorial plane view of MAST and the NC. The two lines-of-sight in the equatorial plane and their fields-of-view are shown. Also, visible in figure 2.1 is the rail along which the camera can be moved to rotate around a pivot point. With this design, even this limited prototype has the flexibility to study the neutron emission and the neutron spectra in different plasma regions.

![Figure 2.1](image)

*Figure 2.1. An equatorial plane view of the MAST tokamak (left) with the NC (right): red lines are the NC sight lines; green lines indicate the extent of the fields-of-view for each sight line; blue bars and arrows indicate the injection directions of MAST’s two NBI systems.*

2.1 Design principle

The proof-of-principle NC has been designed in 2008 considering the performance of MAST plasmas and the available space in the MAST area [28]. The sight lines have been chosen on the basis of the neutron emissivity profiles for different MAST plasma scenarios which were simulated with the plasma transport code TRANSP [29]. An example of a poloidal cross section of the
neutron emissivity of a typical TRANSP simulation (flux surface averaged ($\varepsilon_{fa}$)) on MAST is shown in figure 2.2(a). Four points are indicated by the crossing of the dashed horizontal and vertical lines, each corresponding to the intersection of one line of sight with the poloidal plane. The distance between these points is 20 cm along the major radius, corresponding to a change in neutron emissivity by approximately 50% from the peak emission. The prototype NC consists of four sight lines [20, 21], two lying in the equatorial plane ($Z = 0$ cm), the equatorial channels, and two inclined, intersecting the tangency radius at $Z = -20$ cm, the diagonal channels. The diagonal lines-of-sight are specially designed to study the neutron emissivity in scenarios with off-axis NBI heating as shown in figure 2.2(b). The off-axis current drive provides some density control and, most importantly, a much broader spatial distribution of the fast particles thus reducing the pressure gradient driving the fish-bone instability and therefore increasing their confinement. The equatorial and the diagonal sight lines share the same impact parameters ($p$) where $p$ is defined as the tangential radius of the sight line (figure 2.1). In order to compensate for the limited number of sight lines, the NC is mounted on a rail on which it can be moved to different positions, resulting in different sight lines, thus a full radial neutron emissivity profile can be established on the basis of a series of identical plasma discharges. Also shown in figure 2.1 is the footprint of the NBIs with the arrows indicating the injection directions. With the NC in the position shown in figure 2.1, the lines of sight are said to be in counter beam direction. The NC can also be moved to have the lines of sight in co-beam direction. Co- and counter beam observations of the neutron spectra are expected to differ due to the plasma toroidal rotation. In this way, the observation of the neutron energy distribution, in addition to its intensity, can provide important input for the physics of the plasma scenario under study.

![Figure 2.2](image-url)  
*Figure 2.2.* The flux-surface averaged neutron emission ($\varepsilon_{fa}$) of: (a) a typical MAST discharge; (b) a discharge with off-axis NBI heating.
2.2 Neutron shielding and collimator

The NC is exposed to both direct and scattered neutrons. In order to reduce the contribution from scattered neutrons, the detectors are surrounded by a neutron shielding. Collimators inside this shielding give well-defined lines of sight and limit the direct neutron flux to a level the detectors can handle. The neutron shielding and the collimators were designed using the Monte Carlo code MCNP [30].

The high density polyethylene (HDPE) was selected for the neutron shielding due to its high effectiveness as a neutron moderating material. The 90 cm long collimators embedded in the shielding were designed with a rectangular cross section with a width of 2 cm and a height of 5 cm. The area size was determined on the basis of MAST neutron yield to fulfil the requirement of a 1 ms time resolution with a statistical uncertainty of 10 % at the centre of the plasma. The NC at MAST is shown in figure 2.3. A vertical cut view of the neutron, γ and magnetic shielding as well as the collimators is shown in figure 2.4.

![Figure 2.3. The prototype NC: HDPE radiation shield (white, right front) and MAST vessel: metal (grey, center back). The open volume at the back is where the detectors and other ancillary equipment are installed.](image)

By using specifically designed inserts, the aperture size of the collimator channels can be reduced to an active area of 3 cm$^2$ in order to accommodate different experimental conditions. The "C" shaped collimator inserts have the same length as the original ones. A front view of the collimator with insert is shown in figure 2.5.

In addition, the fractional solid angles that the detector sees from the plasma is evaluated from LINE2 code [31]. The code includes the collimator geometry and splits the MAST vessel volume into voxels and calculates the solid angle seen by the detector for each voxel. The resulting solid angle map (projected on the horizontal and poloidal planes) for the case of collimators without insert blocks are shown in figures 2.6(a) and 2.6(b). The colour intensities...
Figure 2.4. A cut-view model: gray is neutron shielding (HDPE); light gray is equatorial (lower) and diagonal (upper) collimators; red is magnetic shielding (soft iron); yellow is $\gamma$ shielding (lead); green is detector.

Figure 2.5. (a) The front view of the collimator channels with inserts for the equatorial (channel 3,4) and diagonal (channel 1,2) lines of sight. (b) The insert block cross section active area is $1 \times 3$ cm$^2$.

in the figure correspond to the fractional solid angles that the corresponding detector sees from that voxel. The results using collimators with insert blocks are shown in figures 2.6(c) and 2.6(d). The poloidal solid angle projection from LINE2 of sight line $p$, denoted as $\Omega(p;R,Z)$, is used together with the corresponding emissivity projection ($\epsilon_{fa}$) for calculation of the neutron count rate at each $p$ which is then compared to the experimental results.

2.3 Neutron detectors and $\gamma$-ray shielding

Liquid scintillator detectors are widely used in measurements of mixed n/$\gamma$ fields [32, 33] and in fusion applications [34] due to their good n/$\gamma$ discrimina-
Figure 2.6. The toroidal (a) and poloidal (b) projection of $\Omega(p; R, Z)$ of equatorial camera without collimator. The toroidal (c) and poloidal (d) projection of $\Omega(p; R, Z)$ of equatorial camera with collimator insert.

tation capability and neutron detection efficiency. Thus, four liquid scintillator detectors coupled to photomultiplier tubes (PMTs) [35] are installed at the rear end of the collimator channel fitted inside the large shielding. The detectors are placed at a major radius of 4 m. The front, active area of each scintillator is 10 cm$^2$, 2 cm wide and 5 cm high. The thickness of each scintillator is 1.5 cm, chosen to be much larger than the range of 2.5 MeV recoil protons in the scintillator material (of about 0.35 mm). A reference $^{22}\text{Na}$ $\gamma$-rays source with count rate $\sim$ 1 kHz is installed at each detector for energy calibration purposes. The detectors can be used in a wide temperature range (from 5 $^\circ$C to 35 $^\circ$C) and stray magnetic field range up to 13 mT [35]. In order to monitor the detectors’ environment, temperature and magnetic sensors have been installed in the detector’s vicinity (see section 2.5).

The detectors of the NC are exposed to both neutrons and $\gamma$-rays. $\gamma$-rays are emitted from: the plasma itself, interactions of the fusion neutrons in materials of the surrounding structures in the MAST experimental hall and neutron capture reactions in the neutron shield (mainly of energy 2.23 MeV from neutron capture on hydrogen). In order to reduce the number of $\gamma$-rays at the detectors, lead shielding was used. The lead shielding was placed around the detectors, and its thickness (between 5 to 15 cm) was limited by space constraints.
2.4 Magnetic shielding

Although the detectors are placed in a location removed from the central solenoid and the poloidal and toroidal field coils, the stray magnetic field is still not negligible (≈ 30 mT). The PMTs used in this prototype are designed to operate without distortions for magnetic field of 0.1 mT or less. A magnetic field shielding was then designed to reduce the stray magnetic field accordingly. The magnetic shielding consists of double soft iron boxes each one 1 cm thick with \( \mu \)-metal foil in between for further protection. The magnetic shielding was installed inside the neutron shielding and surrounding the \( \gamma \)-rays shielding as shown in figure 2.4. With this design, magnetic field calculations in the poloidal cross section showed that the stray magnetic field at the detectors’ location was less than 0.4 mT in the most extreme MAST operating scenarios and that the perturbations caused by the shielding itself to the plasma confining magnetic fields for radii less than 2 m was nowhere larger than 0.3 mT and therefore posed no concern for MAST operations. The stray magnetic field at each detector was further reduced by individual \( \mu \)-metal shielding surrounding each PMT.

2.5 Monitoring system and environmental system

It is a well known fact that temperature [36, 37], magnetic fields [38] and high count rates [39] affect the operating properties of liquid scintillators and PMTs. In order to monitor the detector properties, a Light Emitting Diode (LED) with pulses of amplitude independent from such environmental effects was therefore included in the NC design. The LED emits a square pulse of blue light of 100 ns duration with a 5 kHz frequency and good stability over the plasma discharge (1 s). The light from the LED is then guided to the PMT of each detectors and LED signals acquired during plasma discharges together with \( \gamma \)-ray and neutron pulses. Any variation of the detector characteristics due to the environment can then be quantified and corrected for by monitoring the LED signal. Variations in the LED signals are directly related to variations in the PMT gains and are correlated to local temperature and magnetic field variations thanks to temperature and magnetic sensors that were installed near the detectors. In order to monitor the magnetic field at the detector’s locations, a 3-axis magnetic field sensor, consisting of three absolutely calibrated linear hall effect probes, was installed. The residual stray magnetic field outside the detectors’ \( \mu \)-metal shielding, in the most extreme MAST regimes, was 0.34 mT [38] and indeed deviations in the PMTs’ gain up to 13 % were observed during plasma discharges. The PMT temperature was measured with a solid state sensor and a time resolution of 1 s [40]. Temperature increases, mainly associated with the PMT power dissipation when high voltage was applied, were measured to be at maximum 5 °C [20]. The gain variations associated with such temperature increase were typically less than 1 %. A more detailed
description of the environmental effect on the detector’s performances are dis-
cussed in section 3.3.

2.6 Data acquisition and analysis

The purpose of the data acquisition system is to collect individual pulses from
the detectors and to store them for further analysis. The acquisition system
consists of two analog-to-digital converter (ADC) cards with 14 bit resolution
and a sampling frequency of 250 MS/s. For each event in the detector,
generating a signal with amplitude above a pre-determined threshold (trigger-
ing event), the ADC collects 64 voltage samples corresponding to a total time
span of 256 ns (a segment) which is sufficiently long to contain the whole
scintillator pulse shape for neutron and γ events as well as LED signals. The
acquisition is operated in multi-trigger mode, that is the input are not sampled
continuously but only when the triggering condition is satisfied. In such a case,
signals from both channel are recorded regardless of which channel caused the
card triggering. The timing of the triggering events (time stamp) is determined
by an internal clock (a counter) that is started at the card arming (typically 0.5 s
before the start of the plasma discharge and running continuously until the end
of the discharge) and whose value is stored for each acquired event. All the
data (segments and time stamps) are stored on the ADC on-board memory and
the acquisition continue until the memory is filled. The on-board memory size
was determined to insure not only the acquisition of the longest MAST pulses
at the highest rate but also the acquisition at the end of each pulse of sufficient
22Na γ-rays and LED pulses for calibration and monitoring purposes.

The data stored in the on-board memory of the ADCs are transferred to a
safe storage at the end of each pulse and then processed to produce, among
many parameters, the neutron count rates. The data analysis,for each plasma
discharge, comprises the following steps: i) baseline correction, preliminary
signal identification and time alignment; ii) PMT gain stability correction;
iii) n/γ pulse shape discrimination; iv) neutron and γ energy calibration; v)
calculation of neutron count rate as a function of (plasma pulse) time; and vi)
pulse pile-up correction [21].
3. Commissioning and characterization of the neutron camera detectors

The neutron detectors used in the prototype neutron camera are liquid scintillators of the NE213 type coupled to photomultipliers. The detectors were commissioned and calibrated both in the laboratory, prior to their installation at MAST, and also once the installation was completed during MAST routine operation. The detectors’ characterization, the data analysis procedures and the necessary corrections to the detectors signals to compensate for environmental effects are discussed in this section.

3.1 Characterization of the neutron detectors

Characterization of the neutron detectors is necessary in order to: 

i) determine the neutron energy threshold of the acquired data; 

ii) determine the detector efficiency; 

iii) determine the energy scale of the acquired data (for neutron spectroscopy). 

In order to characterize the neutron detectors, γ-ray sources are used because of the difficulty of securing mono-energetic neutron sources.

3.1.1 γ-ray energy resolution and calibration

Neutral particles like neutrons and γ-rays produce signals in the liquid scintillator through interactions that generate charged recoil particles. In the case of γ-rays, Compton scattering between the energetic photons and the electrons in the liquid scintillator produces recoil electrons while neutrons interact mainly with the nuclei of the liquid scintillator producing recoil protons (from collisions with hydrogen) and recoil carbon atoms. The charged recoil particles transfer their kinetic energy to the scintillator material, resulting in the emission of light that is then collected by a PMT and converted into an electrical signal whose amplitude and shape depend on the recoil particle and the energy it deposits. In both cases, the scattering collision between incident particles and the liquid scintillator are characterized by a scattering angle that can vary from 0 to 180 degrees resulting in a continuous energy distribution of the recoil particle from zero up to a maximum value. In the case of Compton scattering, the maximum energy for recoil electrons for a incident photon energy $E_\gamma$ is given by:

$$E_C \leq \frac{2E_\gamma^2}{E_{e,0} + 2E_\gamma}$$  \hspace{1cm} (3.1)
where $E_{e,0}$ is the electron rest mass. $E_C$ is known as the Compton edge. In the case of elastic collisions between neutrons and hydrogen nuclei in the liquid scintillators, the recoil proton maximum energy is equal to the incident neutron energy.

An example of the theoretical position of two Compton edges for the $^{22}$Na $\gamma$-rays source ($E_{C,1} = 0.34$ MeV and $E_{C,2} = 1.06$ MeV) is shown in figure 3.1(a). This theoretical Pulse Height Spectrum (PHS) was calculated for the prototype detectors using the neutron-$\gamma$ transport code MCNP [30]. It is worth noting that liquid scintillator, due to their low atomic number $Z$, have an extremely low cross-section for photo-electric absorption and therefore the PHS lacks the characteristic photo-peak that is normally used for the energy calibration and resolution determination. The only features that can be used for the purpose of energy calibration are the Compton edges themselves. However, due to the finite detector resolution, the sharp Compton edges are broadened as can be seen in figure 3.1(b) where an experimental PHS for the same $\gamma$-ray source is shown. As a result of the finite detector resolution, the position of the Compton edge in the experimental PHS is not well defined. Different techniques have been used to determine the position of the Compton edge and the energy resolution [41, 42, 43, 44]. According to these studies, the best estimate of the position of the Compton edge is not at the half height of the PHS, but at 89% of the maximum near the Compton edge [41]. Once the position of the Compton maximum, Compton edge and the half height of the PHS are known from the experimental PHS, both the energy calibration and energy resolution can be calculated. The energy resolution function $\Gamma(E)$ can be parametrized as follow:

$$\Gamma(E) = \sqrt{\alpha^2 + \frac{\beta^2}{E} + \frac{\gamma^2}{E^2}}$$ (3.2)

where $\alpha$ represents the contribution due to the position dependent light transport in the detector material to the PMT, $\beta$ takes into account the statistical nature of the process generating photoelectrons and their multiplication in the PMT dynode chain and $\gamma$ is linked to the electronics noise in the PMT [43].

In this thesis, the energy resolution function was obtained without determining the position of the Compton edges. Instead, the following procedure was followed. For any given Compton scattering angle, recoil electrons were assumed to have an energy distribution $R(E)$ described by a Gaussian distribution centred around $E'$ according to:

$$R(E) = \frac{A}{\sigma(E')\sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{E - E'}{\sigma(E')} \right)^2 \right]$$ (3.3)

where $\sigma(E')$ is related to the energy resolution function $\Gamma(E)$ according to the relation:

$$\sigma(E') = \frac{1}{2\sqrt{2\log(2)}} \Gamma(E')$$ (3.4)
and where the normalization factor $A$ is determined by the condition:

$$\int_{E_{\text{min}}}^{E_{\text{max}}} R(E)dE = PHST(E)$$  \hspace{1cm} (3.5)$$

where $PHST(E)$ is theoretical pulse height predicted by MCNP for a $\gamma$-ray of energy $E_\gamma$ giving rise to a recoil electron of energy $E'$ and $[E_{\text{min}}, E_{\text{max}}]$ is the energy interval in which $PHST$ is calculated. By summing together the integrals above calculated for each $E'$, the theoretical PHS folded with the detector energy resolution function is obtained. The predicted PHS depends then on the energy resolution parameters $\alpha$, $\beta$ and $\gamma$ which were determined by a least square minimization fit to the experimental PHS. In particular, for the PHS shown in figure 3.1(b) the fitting procedure resulted in $\alpha = 16.47 \pm 1.06$, $\beta = 16.19 \pm 0.58$ and $\gamma = 4.03 \pm 0.41$ with a reduced chi-squared of $\chi^2_{\text{rad}} = 1.24$ [38].

![Figure 3.1](image.png)

Figure 3.1. (a) The PHS of $^{22}\text{Na}$ simulated with MCNP (solid line - blue) folded with the resolution (response) function (dashed line - red). Three examples of the resolution function at various energies are given. (b) The simulated pulses height spectrum (red) as fitted to the experimental calibration data from a $^{22}\text{Na}$ source (blue).

3.1.2 Detector efficiency

An accurate estimate of the liquid scintillator’s neutron detection efficiency $\varepsilon_D$ is very important to link the measured count rates to the neutron source strength in the plasma. For this purpose, the Monte Carlo code NEFF from Physikalisch-Technische Bundesanstalt (PTB) [43] was used. This Monte Carlo code includes a description of the detector geometry and material composition (liquid scintillator, light pipe and metallic casing), of the neutron source (geometry and energy), of the different neutron scattering processes in the detector, of the neutron transport, of the generation of secondary charged particles (electrons and protons) and of the associated light output function as...
well as a description of the energy resolution function. Estimates of the detector’s efficiency obtained with NEFF were also compared to theoretical predictions which include multiple neutron scattering on $H$ and $C$ [45] and good agreement was found as shown in figure 3.2. According to these calculations, the detector efficiencies for mono-energetic neutrons with $E_n = 2.5$ MeV, with energy thresholds $E_{TH} = 0.7$ MeV and $E_{TH} = 1.5$ MeV, are $\varepsilon_D = 0.13 \pm 0.01$ and $\varepsilon_D = 0.07 \pm 0.01$ respectively, paper I, [46].

![Figure 3.2](image)

Figure 3.2. The detector efficiency for NC detector calculated with NEFF, NRESP as well as with a theoretical model for two different settings of the detection threshold, $E_{(TH,p)} = 0.7$ MeV and $E_{(TH,p)} = 1.5$ MeV, respectively. Vertical line represent the neutron detection efficiency for mono-energetic neutrons ($E_n$) of 2.5 MeV.

### 3.1.3 Neutron response function

The response function of liquid scintillators to mono-energetic neutrons is, in an ideal case with scattering on hydrogen only and infinite resolution, a recoil proton energy pulse spectrum with a constant amplitude extending from the incident neutron energy all the way to zero as shown in figure 3.3. In practice, distortions to this ideal spectrum are introduced due to neutron scattering on carbon and to the finite energy resolution of the scintillator. The situation if further complicated in fusion devices by the fact that the neutron source energy spectrum is not mono-energetic and that the flux at the detector contains different components both of direct and scattered neutrons, as will be discussed in section 4.2. In order to obtain information on the neutron energy spectrum it is therefore necessary to determine the detector response function to neutrons in an energy region that covers the range of interest, for MAST typically from 0 to 5 MeV. The neutron response function for the detectors used in the neutron camera prototype was determined using the Monte Carlo code NRESP also from PTB [43]. NRESP is an extension of NEFF which calculates the recoil proton PHS, $R(E_p,E_n)$, as a function of mono-energetic incident neutrons $E_n$. An example of the response function $R(E_p,E_n)$ for mono-energetic neutrons...
with $E_n = 2.5$ MeV is shown in figure 3.3(a) with and without the contribution of the energy resolution, while figure 3.3(b) shows the 2D response function for neutrons with energies in the range 0 to 10 MeV. Finally, NRESP can be used to calculate also the detector efficiency by introducing different energy thresholds $E_{TH}$ (the threshold was assumed as a sharp cut in the proton recoil energy distribution) by combining the detector response function matrix $R(E_p, E_n)$ with the neutron energy spectrum $\Gamma(E_n)$ according to:

$$\varepsilon_D(E_{TH}) = \sum_{E_p=E_{TH}} R(E_p, E_n) \Gamma(E_n)$$  \hspace{1cm} (3.6)

and, as expected, agreement is found with NEFF calculations as shown in figure 3.2.

Figure 3.3. (a) The theoretical (black) and NRESP simulated detector response function ($E_p$) for $E_n = 2.45$ MeV. The simulated results are for the cases without (red) and with (blue) the effect of detector resolution included. (b) The $R(E_p, E_n)$ folded with the experimental resolution function in the range 0.2-10 MeV in steps of 50 keV. The intensity scale is relative, logarithmic.

### 3.2 Pulse shape discrimination

Liquid scintillators are sensitive to both neutrons and $\gamma$-rays but the light output yield and the pulse decay time are different depending on the incident particle type. In particular, the difference in the decay time is exploited to separate neutrons from $\gamma$-rays. The acquired data however do not contain only single neutron and $\gamma$-ray pulses but also LED and pile-up pulses. The separation of all these events into separate categories is carried out in three three steps: i) preliminary event identification in which LED pulses are separated from neutron and $\gamma$-rays; ii) pile-up event identification; and iii) single event neutron and $\gamma$-ray pulse shape discrimination. Note that before step iii), single neutrons and $\gamma$-ray events are treated as signals of the same type (as distinguished from LED pulses for example) and referred to as neutron-$\gamma$-ray events.
Any triggering event in the acquisition system results in a signal consisting of 64 samples (a **segment**) with 16 pre-trigger and 48 post-trigger samples respectively: each segment is 256 ns long. The offset on each individual signal is removed by baseline subtraction using the first 12 samples of the pre-trigger. Once the offset has been subtracted, a preliminary event identification is carried out. The first step consists in the separation of LED from neutron-γ-ray events: this is easily done thanks to their different pulse shape as can be seen in figure 3.4(a). Single events and pile-up events are distinguished by comparing each individual signal with reference neutron-γ-ray and LED signals obtained as averages of many events collected after each plasma discharge when the count rate is low (few kHz, due to the LED and $^{22}$Na calibration source) so that the probability of contamination from pile-up events is negligible. This comparison is based on the correlation coefficient between reference and individual signals: signals with a correlation coefficient below a certain threshold are considered pile-up events. The correlation coefficient thresholds have been chosen based on experimental observations of the correlation coefficient for neutron-γ-ray and LED signals as shown in figure 3.4(b). A signal is classified as: i) single LED event if the correlation coefficient between signal and LED reference is higher than 0.96; ii) single neutron-γ-ray event if the correlation coefficient between signal and neutron-γ-ray reference is higher than 0.85; iii) non-single event in all other cases (see section 3.3.3).

![Figure 3.4](image.png)

**Figure 3.4.** (a) Average normalized signal pulse amplitude ($V$) of neutrons and γ (red) and LED (blue) versus the sample number. (b) The correlation coefficient of both neutron-γ-ray and LED pulse shown in red and blue respectively. The vertical lines represent the thresholds on the correlation coefficient $r$.  

### 3.2.1 Neutron and γ pulse shape discrimination

Once single neutron-γ-ray events have been identified, neutrons can be discriminated from γ-rays events employing a number of different pulse shape discrimination methods (**PSD**) methods [47, 48, 49, 50, 51]. The charge com-
parison method is most commonly used for neutron-\(\gamma\)-ray discrimination and is also the one used here. The charge comparison method exploits the different decay times of neutron and \(\gamma\)-ray pulses by calculating for each individual event the following quantity:

\[
PSD = \frac{Q_{\text{long}} - Q_{\text{short}}}{Q_{\text{long}}}
\]  (3.7)

where \(Q_{\text{short}}\) and \(Q_{\text{long}}\) are the integrals over the pulse voltage values for two time intervals, \(\Delta t_{\text{short}}\) and \(\Delta t_{\text{long}}\) as shown in figure 3.5. A 2D histogram of single neutron-\(\gamma\)-ray events plotted against \(Q_{\text{total}}\) (identical to \(Q_{\text{long}}\) and PSD is shown in figure 3.6(a): two different regions can be distinguished, one that is associated with neutrons (PSD \(\gtrsim 0.1\)) one associated with \(\gamma\)-rays (PSD \(\lesssim 0.1\)). The separation of these two regions depends on the incident particle’s energy (proportional to \(Q_{\text{total}}\)) and on the choice of the integration time intervals \(\Delta t_{\text{short}}\) and \(\Delta t_{\text{long}}\). In order to quantify the neutron-\(\gamma\)-ray separation, the 2D histogram is divided in narrow energy (\(Q_{\text{total}}\)) intervals and a 1D histogram of the single events in each interval is calculated as a function of PSD. An example of such an histogram is shown in figure 3.7(a). The quantity:

\[
FOM = \frac{DIST_{n\gamma}}{FWHM_{\gamma} + FWHM_{n}}
\]  (3.8)

known as the figure-of-merit (FOM) provides a measure of the neutron-\(\gamma\)-ray separation. In the equation above, \(DIST_{n\gamma}\) is the distance between the centroids of the neutron and \(\gamma\)-ray peaks and FWHM\(_{\gamma}\) and FWHM\(_{n}\) are the full widths at half maximum of the neutron and \(\gamma\)-ray peaks, respectively. Higher FOM values indicate a better separation and a FOM \(\approx 1\) is typically observed [52]. The time intervals for \(Q_{\text{short}}\) and \(Q_{\text{long}}\) that provide the best separation on average for different energies have been determined to be \(\Delta t_{\text{short}} = 44\) ns and \(\Delta t_{\text{long}} = 104\) ns, respectively. Examples of the FOM dependency on the recoil electron energy, with these time intervals, is shown in figure 3.7(b) for the four detectors used in the prototype neutron camera. Three energy intervals with recoil electron energies of 0.3 MeV < \(E_e\) < 0.4 MeV; 0.5 MeV < \(E_e\) < 0.6 MeV; and 0.7 MeV < \(E_e\) < 0.8 MeV (corresponding to neutron energies of 1.42, 1.90 and 2.34 MeV) are shown. All four detectors have a FOM between 0.8 to 1.1 with the higher values for higher energies. This pulse shape discrimination capability is sufficient for the present application. The \(\gamma\)-ray contamination of neutron events has been determined to be less than 2 % in the most performing MAST discharges [21].

30
Figure 3.5. Average n/γ pulse shapes. The short and the long time gates used in the analysis are also shown as $\Delta t_{\text{short}}$ and $\Delta t_{\text{long}}$, respectively.

Figure 3.6. An example of pulse shape discrimination for plasma discharge 27202. (a) Two dimensional intensity distribution of PSD versus $Q_{\text{total}}$ of n/γ pulses. (b) The same for the LED signal. The color bar gives the logarithm of the number of entries in the 2D-histogram.

3.3 Photomultiplier gain variations and correction

3.3.1 Gain variations

It is a well known fact that a PMT’s gain depends non linearly on the count rate due to space charge effects between dynodes and anode and that this effect depends on the PMT’s operating voltage [53, 54]. In the case of the prototype neutron camera, total count rates as high as $1.5 \times 10^6$ Hz are observed and PMT gain variations are clearly seen [38]. A systematic study of the PMT gain dependency on the applied voltage and count rate was carried out in the laboratory for the prototype detectors using LED signals with frequencies between 200 Hz and 2 MHz and for applied voltages between 600 V and 1000 V. The results of this study are shown in figure 3.8(a). As expected, for total count rates above $5 \times 10^5$ Hz, the gain depends not only on the count rate but also on the applied high voltage. For example, gain variations as high as 20
Figure 3.7. (a) An example of a distribution histogram of measured neutron and γ. Red and blue are the Gaussian distributions calculated by a fit to the measured neutron and γ data, respectively. The quantities used for the calculation of the figure-of-merit (FOM) are indicated. (b) The FOM of three different ranges in energy (derived from $Q_{\text{total}}$) and for all four detectors of the NC.

% are observed for applied voltages higher than 900 V. Since the PMTs are operated at voltage in the range 780 - 825 V, the gain of the PMT will change during a plasma discharge as shown in figure 3.8(b) where the gain variation for detector SEK468 is plotted versus the count rate indicating a gain variation of 25 % for count rates higher than 1 MHz.

Figure 3.8. (a) An example of gain variation with different count rate and supply voltage of a NC detector. (b) The gain variation during plasma discharge 27144, 27202, 27298 due to high count rate for detector SEK468.

The PMT gain is also affected by the detector’s environment. The relative gain is reduced by 13 % by the stray magnetic field at the detectors’ location (0.34 mT) [38] while relative gain reduction of the orders of 1 % °C$^{-1}$ are observed [20]. All the factors described above (high count rate, magnetic stray field and operating temperature) will affect the PMT gain which in turn affects the amplitude and charge of each pulse and therefore the efficiency and
pulse shape discrimination. It is therefore necessary, before the pulse shape
discrimination is carried out, to correct for the resulting gain variations. This
is described in the following section.

3.3.2 Gain correction
Since the LED light pulse used to illuminate the photomultiplier has an ampli-
tude that does not depend on the environment on the time scale of the data ac-
quision, any variation in the measured LED pulse from the detector is due the
combined result of count rate, magnetic stray field and temperature. All these
three effects are corrected for simultaneously by introducing the so called cor-
rection factor $\alpha_{\text{LED},i}$:

$$
\alpha_{\text{LED},i} = \frac{Q_{\text{LED,ref}}}{\langle Q_{\text{LED},i} \rangle} \tag{3.9}
$$

where $Q_{\text{LED}(\text{ref})}$ is the average total charge in the LED pulses measured after
the end of the plasma discharges when the count rate is very low (a few kHz)
and therefore not affecting the PMT gain and when no stray magnetic field is
present. In the above equation $\langle Q_{\text{LED},i} \rangle$ is the $i$-th LED event total charged
smoothed on a running window consisting of 100 LED pulses: this is neces-
sary to remove the LED light amplitude intrinsic fluctuations. The correction
factor of each $j$-th event between two consecutive LED pulses, that is between
t$_{i}$ and $t_{i+1}$], is calculated as the linear extrapolation of the correction factors
$\alpha_{\text{LED},i}$ and $\alpha_{\text{LED},i+1}$ at the time of the event $t_{j}$ with $t_{i} \leq t_{j} \geq t_{i+1}$, i.e.:

$$
\alpha_{j} = \frac{\alpha_{i+1} - \alpha_{i}}{t_{i+1} - t_{i}} \cdot t_{j} + \frac{\alpha_{i}t_{i+1} - \alpha_{i+1}t_{i}}{t_{i+1} - t_{i}} \tag{3.10}
$$

Figure 3.9 shows the time traces of plasma discharge 27047 global param-
eters: (a) NBI power; (b) plasma current; (c) neutron count rate measured by
the fission chamber; and (d) the total count rate measured by one detector of
the neutron camera. The red curve in panel (e) of figure 3.9 shows the rel-
ative gain variation of LED signals as a function of time during the plasma
discharge. The dependency of the PMT gain variation on the detector count
rate between 0.15 and 0.28 s is clearly seen. The same panel shows the PMTs
gain (in black) corrected with the method described above. The effect of the
gain correction on the recoil proton pulse height spectrum is shown in panel
(f) of figure 3.9.

Once the PMT gain has been corrected for, it is possible to carry out a
neutron calibration using the relation between the light output functions for
recoil electrons and protons. In the energy range of interest here, the light
output from a scintillator can be assumed linearly proportional to the energy
of recoil electrons. However, due to quenching effects, this is not the case for
recoil protons. Therefore, the energy calibration for recoil protons is derived
from a calibration for recoil electrons using data available in literature for the
same type of liquid scintillators used here [35, 55]. Pulse height spectra for recoil electrons and protons plotted against the corresponding energy scale are shown in figure 3.10(a) and figure 3.10(b).

**Figure 3.9.** Time traces of plasma and NC parameters for MAST pulse 27047: (a) NBI power, (b) plasma current, (c) neutron yield measured by FC; (d) neutron yield measured by the NC; and (e) the PMT gain variation observed via LED signal (red) and the results of gain compensation (black). (f) The uncompensated and compensated recoil proton PHS.

**Figure 3.10.** (a) Recoil electron PHS. (b) Recoil proton PHS.
3.3.3 Pile-up compensation

During the highest performing plasma discharges, the detector’s count rate is so high that pile-up events becomes a significant fraction of the total events that are recorded. These pile-up events contain any possible combination of LED, neutron and γ-ray event. LED events polluted by neutrons and γ-rays events contribute little to the true neutron or γ-ray count rates due to the LED low frequency (5 kHz). Pile-up events containing any combination of two or more neutron and γ-rays however contribute significantly to the true neutron and γ-rays count rates and therefore they must be taken into account. The first step in analysing pile-up events consists in the separation of double pile-up events (that is signal containing two superimposed events) from multiple (3 or more) pile-up events. It has been observed experimentally that on MAST, even in the highest performing plasma discharges, multiple pile-up events constitute less than 1% of the total events.

Ideally, pile-up due to $n$ events recorded during a single signal acquisition (segment) would require the reconstruction of $n$ independent signals which could then be classified as neutron or γ-rays events with the PSD method described before. This however is not possible in the prototype neutron camera due to the limited sampling frequency of the ADC. A simplified pile-up corrections is instead used based on the assumption that the fractional contribution of neutrons and γ-rays to the pile-up events at any given time is equal to their fractional contribution to single events (i.e. non pile-up events). In the case of double pile-up events, the “true” neutron count rate $CR_n'(t)$ is then the sum of the count rate for single neutron events $CR_n(t)$ plus the contribution from those neutron events in which pile-up occurs $D(t)$:

$$CR_n'(t) = CR_n(t) + D(t)$$  \hspace{1cm} (3.11)

where $D(t)$ is estimated as:

$$D(t) = F_n CR_p(t)$$  \hspace{1cm} (3.12)

where $CR_p(t)$ is the count rate of pile-up events and $F_n$ is:

$$F_n(t) = \frac{CR_n(t)}{CR_n(t) + CR_\gamma(t)}$$  \hspace{1cm} (3.13)

where $CR_\gamma$ is the count rate of single γ events. Signals characterized by triple pile-ups events are treated in a similar way while signals containing four or more pile-up events are neglected. Pile-up events can not be simply ignored as shown in panel (b) of figure 3.11 where it is clear that the neutron count rate measured by the neutron camera without taking them into account starts to saturate as the total neutron rate measured by the fission chamber increases. When pile-up events are taken into account, linearity between the count rates from the neutron camera and the fission chamber is restored.
Figure 3.11. (a) Comparison of neutron count rate measured with FC and NC (without - dash-dotted, black line - and with - dashed, red line - the pile-up correction) for plasma discharge 26086. (b) Neutron count rate of NC versus FC.
4. Experimental results

The neutron camera (NC) on MAST has been used to measure a number of important plasma parameters, including: i) Neutron count rate as a function of time; ii) time resolved neutron emissivity profiles; and iii) the neutron spectrum with different temporal and spatial resolution during different plasma scenarios. The measurements have been analyzed by comparing them with predictions and results from independent diagnostics as a way to validate the NC results. This chapter deals with the modelling of the experimental neutron emissivity, the comparison with the fission chamber (FC) measurements and preliminary results on the spectroscopic capabilities of the NC.

4.1 Neutron emissivity profile and MHD activity

On MAST, the neutron emission is primarily caused by the fast ion (NBI) population and therefore the measurement of the neutron emissivity profile as a function of time can be used to study the interplay between fast ions and the MHD activity. Since for each plasma discharge only 2 radial positions can be measured, a series of similar plasma discharges, typically 4 - 6 discharges, is needed for sufficient radial coverage. An example of similar plasma discharges (26448, 26451, 26453 and 26458) is shown in figure 4.1. The global plasma parameters for this set are: (a) a plasma current of 0.5 MA; (b) a NBI power of 2 MW; and (c) a neutron rate, measured by the fission chamber, of \(0.5 \times 10^{14}\) n/s. The corresponding neutron count rates measured by the neutron camera for impact parameters \(p\) in the range 0.24 - 1.2 m are shown in figure 4.2. The neutron count rate profile as a function of the impact parameter is shown in figure 4.3(a) for two time intervals, \(\Delta t_1\) (0.25 - 0.27 s) and \(\Delta t_2\) (0.37 - 0.39 s).

The interpretation of these experimental observations is based on the convolution of the plasma neutron emissivity \(\varepsilon_n\) with the solid angle for each impact parameter \(\Omega(p;R,Z)\). Under the assumption of toroidally and poloidally symmetric neutron emissivity, the plasma neutron source depends only on the plasma minor radius. Its projection on a poloidal cross section, expressed as function of the radial and longitudinal coordinates \(R\) and \(Z\), is therefore representative of the neutron emissivity in every point of the plasma. This poloidal projection can be therefore combined with the poloidal projection of the detector solid angle and the detector efficiency to predict the count rate that should be measured at any given impact parameter. This interpretative method
Figure 4.1. Time traces for MAST plasma pulse 26448 (green), 26451 (blue), 26453 (red) and 26458 (black). Plasma parameter: (a) plasma current; (b) NBI power; (c) neutrons yield as measured by FC; and (d) soft x-ray.

Figure 4.2. Neutron count rate in function of time as measured by NC for $p$ in the range of 0.2 - 1.2 m from plasma discharge 26448, 26451, 26453, 26458.

is known as forward modelling since the experimentally measured quantity is predicted from the modelling of the plasma discharge. One advantage of this procedure is that the comparison between model and experiment is done on the level of actual measured quantities (here, counts per impact parameter). This facilitates for example the assignment of uncertainties to the extracted param-
MHD instabilities such as fish-bones, sawteeth and long-lived modes (LLM) cause spatial redistribution or losses of fast ions which are seen by the neutron camera as changes in the neutron count rate profiles. An example is given in figure 4.3(b), where the neutron count rate profile is shown before \( t = 0.374 \) s and after \( t = 0.378 \) s the sawtooth crash for these plasma discharges (26448, 26451, 26453 and 26458). As typically observed in MAST, sawteeth cause fast ion losses rather than redistribution since the drop in the neutron count rate is observed at all radial positions, paper I and III, [12, 46]. In the case of a LLM, the neutron count rate profile is only slightly reduced while the entire profile is slightly shifted inward indicating some level of fast ion redistribution [12].

A preliminary comparison between the total neutron yield estimated by the neutron camera \( Y_{\text{model}} \) and the one measured by the absolutely calibrated fission chamber \( Y_{\text{FC}} \) has been performed for these plasma discharges (26448, 26451, 26453 and 26458) in the time interval 0.32 s - 0.39 s. This comparison has been carried out by integrating the synthetic neutron emissivity profile over the whole plasma volume and including the detector efficiency \( \epsilon_D \) as determined in section 3.1.2, the solid angles of the lines of sight and the
attenuation of the neutrons escaping the plasma and passing through the ob-
ervation flange. The results show that the average proportionality constant
between $Y_{model}$ and $Y_{FC}$ is $Y_{model}/Y_{FC} \approx 0.94 \pm 0.05$ [46]. This result supports
the conclusion that the $\epsilon_D$ calculated in section 3.1.2 is correct within the ex-
perimental uncertainty.

4.2 Neutron spectroscopy
Neutrons incident on the liquid scintillator will give rise to recoil proton pulse
height spectra as a function of the recoil proton energy $E_p$. This recoil proton
PHS depends on the neutron energy. In fusion plasmas, the neutron source
is not mono energetic and therefore the recoil proton PHS measured by liq-
uid scintillators will be a complex function of the neutron energy spectrum
at the detector and its response function. This complex process can be sim-
ulated numerically to produce a simulated recoil proton $PHS_{sim}$ which can
then be compared with the experimentally measured one. In order to calculate
$PHS_{sim}$, it is necessary to know the neutron energy spectrum at the detector
which consists of a scattered and a direct neutron component. The scattered
neutron component has been estimated with MCNP assuming a Gaussian neu-
tron energy source in the plasma volume and including models of the proto-
type neutron camera, of MAST (vessel, central column, coils, etc.) and of
the MAST experimental hall. Some structures external to the MAST vessel,
such as the neutral beam boxes and the other diagnostics, were not taken into
account. MCNP also provides the direct neutron component at the detector
which has been used to calculate the ratio between direct and scattered neu-
trons as a function of the impact parameter $p$. This ratio is shown in figure
4.4(a) and shows that the signal from the detectors includes a component due
to scattered neutrons that varies from about 6 to 50 % depending on impact
parameter ($p$). The shape of direct and scattered neutron energy spectra, for
the case $p = +0.64$ m, are shown in panels (b) and (c) of the same figure.
The direct neutron energy spectrum obtained from MCNP, however, is only a
crude approximation of the real neutron spectrum at the detector. This is so
since in reality the energy spectrum of the neutron source contains different
components due to the different fusion reactions that occur in a plasma with a
significant fast ions population. On MAST in particular, the beam-thermal and
beam-beam contribution dominate over the thermal fusion reaction contribu-
tion. In addition, the direction of observation of the neutron source might alter
the neutron spectrum seen by the detector due to plasma rotation and the direc-
tion of injection of the fast ions. These complex physical processes have been
modelled for MAST plasmas using a combination of three codes: TRANSP,
LINE2 and ControlRoom [56]. TRANSP is used to calculate the thermal and
fast ion distribution in space and energy for a given plasma scenarios. LINE2
is used to calculate the solid angles of the detectors of the neutron camera for
a given impact parameter $p$. Finally ControlRoom combines the outputs from TRANSP and LINE2 to provide the energy spectrum of direct neutrons at the detector by calculating the fusion reactions for all components taking into consideration the plasma properties (such as its rotation). For a typical NBI heated plasma scenario at MAST, the direct neutron energy spectrum calculated by ControlRoom is peaked and slightly asymmetric with a mean energy that depends on the line of observation with respect to the injection direction of the beams, reflecting the fact that the neutron emission is highly dominated by beam-thermal reactions. By combining the scattered neutron energy spectrum estimated by MCNP and the direct neutron energy spectrum obtained by ControlRoom the total neutron energy spectrum at the detector is obtained.

![Figure 4.4](image)

**Figure 4.4.** (a) Ratio of direct to scattered neutrons from simulations. (b) Direct neutron component. (c) Scattered neutron component.

### 4.2.1 Modelling of experimental spectra and the sight lines observation

Once the total neutron energy spectrum is known, a simulated pulse height spectrum as given by the detector, $PHS_{sim}$, is calculated according to:

$$PHS_{sim}(E_p, p) = \sum_{E_n=E_{TH}} R(E_p, E_n) \times \Gamma_{total}(p)$$

where $R(E_p, E_n)$ is the response function matrix of the liquid scintillator detector (see section 3.1.3); $E_p$ is the recoil proton energy; $E_{TH}$ is the threshold energy (in this work, $E_{TH} = 1.5$ MeV); and $\Gamma_{total}(p)$ is the total neutron energy spectrum.

In paper IV, Ref. [57], an analysis of the recoil proton PHS as a function of the viewing direction (impact parameter) was presented. Here we revisit this work, applying the full simulation and analysis machinery presented above. In particular, for plasma discharge 27043, the NC was positioned such that $p = 0$ m, i.e., viewing radially straight into the MAST central column. The
direct neutron energy distribution was calculated with ControlRoom resulting in a direct neutron energy spectrum centred at $E_n = 2489.60$ keV. A component of scattered neutrons was added, with an energy distribution according to figure 4.4(c) and with an intensity fixed relative to the direct component as given by figure 4.4(a) (also at $p = 0$ m). The direct and scattered neutron energy components (figure 4.5(a)) were then multiplied with the response function matrix $R$ (as shown in Eq. 4.1) and added to produce the simulated pulse height spectrum. This spectrum was finally fitted to the experimental data (figure 4.5(b)) where only two free parameters were used: a common normalization factor, and an energy shift of the direct component. The best fit to the data gives a mean energy of the direct neutron emission of $2487.38$ keV $\pm 7.17$ keV, with a $\chi^2_{red} = 1.67$. Note the good agreement between the fit and the value calculated with ControlRoom, where the small difference of $-2.22$ keV is well within the statistical uncertainty. These results give confidence in the performed energy calibration and also in the modelling done, both of direct and scattered components.

![Figure 4.5](image)

**Figure 4.5.** (a) The simulated neutron energy spectrum for $p = 0$ m that gives the best fit to the experimental data: curve (a) is the scattered neutrons component; curve (b) is the direct neutron component; curve (c) is the total neutron energy spectrum ($\Gamma_{total}(p)$). (b) The experimental $PHS_{exp}$ (curve (a) - histogram) and the simulated: curve (b) is $PHS_{sim}(E_p, p)$; curve (c) is $PHS_{direct}(E_p, p)$; and curve (d) is $PHS_{scattered}(E_p, p)$.

For discharge 27047 one camera sight line was at $p = +0.64$ m looking in counter beam direction, i.e., with beams moving towards the detector. Again using ControlRoom, a simulated direct neutron energy spectrum centred at $E_n = 2626.59$ keV was obtained as shown in figure 4.6(a). The scattered neutron component is the same as in the previous analysis for $p = 0$ m and the ratio of direct to scattered components was fixed to the value presented in figure 4.4(a) ($p = +0.64$ m). Fitting the simulated components to the experimental data (figure 4.6(b)), with the common amplitude and the energy shift of the direct component as the two free parameters, gave the (direct) energy spectrum centred at $2615.00$ keV $\pm 4.80$ keV, with a $\chi^2_{red} = 1.67$ resulting in a
difference of $-11.6$ keV ControlRoom result. This is significantly outside the reported statistical uncertainty. However, it should be noted that systematic uncertainties of a few percent (few tens of keV) should be expected, for example from the modelling, energy calibration and gain correction procedures. Thus, the small discrepancy between the theoretical and the experimental results is insignificant. Rather, this example corroborates the result from the $p = 0$ m study, and gives further confidence in the ability of the neutron camera to also provide information on aspects of the neutron energy distribution. In addition, measurements with a line of sight set at $p = -0.64$ m, i.e., with the beam moving away from the detector (co-beam), gave further support to this; in this case a strong down-shift of the neutron energy distribution is expected and indeed also observed experimentally.

Figure 4.6. (a) The simulated neutron energy spectrum for $p = +0.64$ m (counter beam): curve (a) is the scattered neutrons component; curve (b) is the direct neutron component; curve (c) is the total neutron energy spectrum ($\Gamma_{\text{total}}(p)$). (b) The experimental $PHS_{\exp}$ (curve (a) - histogram) and the simulated: curve (b) is $PHS_{\text{sim}}(E_p, p)$; curve (c) is $PHS_{\text{direct}}(E_p, p)$; and curve (d) is $PHS_{\text{scattered}}(E_p, p)$.

To experimentally study the influence of scattered neutrons in the neutron emission measurements data from the equatorial channels of the neutron camera were collected in the range $0.35 \leq p \leq 1.20$ m in a series of six similar plasma discharges (26856, 26884-26889) as can be seen in figure 4.7.

For these plasma discharges, an experimental neutron count rate profile was obtained in the time interval $0.15 - 0.29$ s as shown in figure 4.9 as black dotted. Each experimental point in this plot corresponds to the sum of the counts in the recoil proton pulse height spectrum during the entire time interval under study, shown in figure 4.8, and is the combination of both direct and scattered neutron contributions. A software threshold at $E = 0.2$ MeVee was imposed, as indicated in figure 4.8. The individual contribution from scattered and direct neutrons has been estimated from the simulated components with the method described above for each individual experimental spectrum, that is for each impact parameter $p$, as is also shown in figure 4.8. The simulated neutron count rate profile is shown for comparison with the experimental measurements in
Figure 4.7. Global parameters for pulses 26856, 26884 - 26889: (a) line-integrated electron density; (b) plasma current; (c) NBI power; (d) neutron rate from the fission chamber. Blue bar shows the analysis time interval.

Figure 4.9 (note that due to the forced normalization of the pulse height spectra, the total simulated counts exactly overlaps with the experimental data), as well the direct and scattered neutron count rate profiles. It can be noted that the results for the scattered count rate forms a basically constant level, irrespective of impact parameter, with small increases for the highest and lowest impact parameters. This result is in nice agreement with the MCNP results presented in Paper II, figure 3, and corroborates the modeling and analysis methods described here. As a final check that the detector has been properly characterized and of the correctness of the procedure described in this chapter, the direct neutron count rate profile obtained with ControlRoom and the one obtained using the flux-averaged neutron emissivity predicted by TRANSP (in combination with LINE2) for these plasma discharges is shown in figure 4.9. The agreement is good.
Figure 4.8. The experimental $PHS_{exp}$ (black - histogram) and the simulated: $PHS_{sim}(E_p, p)$ (red); $PHS_{direct}(E_p, p)$ (green); $PHS_{scattered}(E_p, p)$ (blue) for 14 different impact parameters in the range $0.35 \text{ m} < p < 1.20 \text{ m}$.

Figure 4.9. Comparison of neutron count rate profiles for: (a) experimental data for pulses 26856, 26884-26889, time slice 0.15-0.29 s, impact parameters in the range $0.35 \text{ m} < p < 1.20 \text{ m}$ (black-dotted); (b) simulated total neutron rate (red-up triangles); (c) simulated direct neutron rate (ControlRoom)(green-squares); (d) simulated scattered neutron rate (blue-down triangles); and (e) neutron rate given by a multiplication of $\epsilon_f a$ and $\Omega(p,R,Z)$ (black-circles).
Part II:
A neutron camera upgrade (Chapter 5 - 6)

The encouraging results obtained with the prototype neutron camera clearly show the potential of a collimated neutron flux monitor at MAST and suggest that an upgraded instrument for MAST Upgrade could continue to provide crucial information on important physics issues, such as the interplay between Magneto-Hydro-Dynamic (MHD) instabilities and fast ions. On the basis of the results presented in the previous sections and on the gained experience, a conceptual design of a neutron camera upgrade has been initiated. This section focuses on the simulation of the conceptual design of the neutron camera upgrade. (Paper V-VI)
5. The conceptual design of the neutron camera upgrade

MAST has contributed to the understanding of different aspects on tokamak physics which is relevant for ITER and future devices such as DEMO and has provided insights on the potential of spherical tokamaks as Component Test Facilities (CTFs). CTFs are a necessary part of the fusion programme whose aim is to test and develop components able to withstand the high neutron fluxes and fluences expected in future fusion power plants. In order to extend MAST operating scenarios, an upgrade program was developed and it has now entered the its realization phase: MAST ended its operation in September 2013 and first plasmas on MAST Upgrade are expected for early 2016.

5.1 MAST Upgrade

The aims of MAST upgrade are [27]: i) to demonstrate the physics viability of the spherical tokamak concept with off-axis current drive; ii) to test different plasma stability scenarios; iii) to investigate fast ion physics and their interplay with MHD instabilities; and iv) to test and develop divertor solutions such as the Super-X and the “snow-flake” divertors. The major components of the upgrade are:

1. an increased toroidal magnetic field;
2. a doubling of the central solenoid flux;
3. an increased number of poloidal field coils;
4. additional power supplies;
5. increased additional heating capabilities (power and duration);
6. a new divertor design;
7. new plasma shaping and control systems.

MAST Upgrade will retain the same vacuum vessel of MAST, while most of the ancillary systems, diagnostics included, will be upgraded to cope with longer and more performing plasma discharges. MAST Upgrade program is divided in different stages which will allow, among other things, to increase the additional heating by adding more NBIs. The first of these stages, known as “core scope”, will retain the same NBIs heating power of MAST but with a modified geometry for one of the NBIs allowing off-axis heating. The off-axis NBI will inject fast deuterium atoms in tangential direction in a plane that is vertically displaced above the equatorial plane by 65 cm. The combination
of the on- and off-axis NBIs will allow more flexibility in controlling the fast ions spatial distribution (and thereby the stability of a specific class of MHD instabilities) and in providing off-axis heating for non-inductive current drive studies. The “core scope” stage will be followed by “stage 1” in which one more off-axis NBI will be installed bring to the total NBI power to 7.5 MW. Further stages are envisaged which will rise the NBI power even further. Figure 5.1 shows a poloidal cross-section of MAST and MAST Upgrade while their plasma parameters, for the “stage 1” case, are compared in table 5.1.

Different operating regimes, labelled A to G, have been studied for MAST Upgrade (scenario B has been dropped) [27]:

- Scenario A high \( q \) \((q > 2)\) plasmas for stability and confinement studies of a ST-CTF like q-profile; this scenario is further divided in scenarios A.1 and A.2 for high and low density, respectively;
- Scenario C steady state operations with off-axis current drive and \( q_{\text{min}} \approx 1 – 1.5 \);
- Scenario D scaling and confinement at high plasma current;
- Scenario E baseline scenario (close to current MAST plasmas);
- Scenario F effect of triangularity on MHD stability, confinement and performance;
- Scenario G thermal and total normalized plasma pressure effect on MHD stability.

Of particular interest are scenarios A, C and D. Scenario A is important since the two variants with high and low density illustrate the key flexibility of MAST Upgrade in achieving stationary conditions at different plasma pa-
Table 5.1. Parameters of MAST upgrade, compared to MAST [27]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>MAST</th>
<th>MAST-U (Stage 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elongation, $\kappa$</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Plasma and toroidal field current, $I_p, I_{TF}$ (MA)</td>
<td>1.5, 2.0</td>
<td>2.0, 3.2</td>
</tr>
<tr>
<td>Normalised pressure, $\beta_N, \beta_T$</td>
<td>4.5, 15%</td>
<td>5.5, 40%</td>
</tr>
<tr>
<td>Aux. heating power, $P_{aux}$ (MW)</td>
<td>3.8</td>
<td>7.5 (max)</td>
</tr>
<tr>
<td>Normalised density, $n/n_G$</td>
<td>0.15-0.8</td>
<td>0.15-1</td>
</tr>
<tr>
<td>Non-inductive and Bootstrap Current, $f_{NI}, f_{BS}$ (%)</td>
<td>&lt;30, &lt;30</td>
<td>≤100, ≤40</td>
</tr>
<tr>
<td>Pulse length, (s)</td>
<td>0.6</td>
<td>5</td>
</tr>
</tbody>
</table>

Parameters. Scenario C is designed to study long plasma discharges with fully relaxed $q$-profiles where non-inductive current drive is dominant. Scenario D will allow to study the scaling of confinement with plasma current at high normalized magnetic pressure. In all these scenarios, the fast particle pressure is large compared to the thermal one and therefore fast ion redistribution is expected as a result of the destabilization of energetic particle modes. TRANS simulations, based on plasma parameters likely to be achieved, have been carried out for different level of anomalous fast ion diffusion in the range $0 – 2$ m$^2$/s [58] and the corresponding flux surface averaged ($\epsilon_{fa}$) and non-flux surface averaged ($\epsilon_{nfa}$) neutron emissivity on a poloidal cross section were obtained [59].

MAST Upgrade focus on fast ion physics will require a suite of fast ion diagnostics. One of the key diagnostics is a collimated neutron flux monitor. The prototype described in part I of this thesis will be upgraded to provide a full radial profile of the neutron count rates in a single plasma discharge, to cope with the expected higher neutron flux expect during “stage 1” and possibly beyond it, and to probe both the on-axis and off-axis NBIs. An important aspect in the design of the neutron camera upgrade is the transport of neutrons generated by the deuterium-deuterium fusion reactions to the detectors. In order to simulate this, a MCNP model has been obtained from the MAST Upgrade team which includes the full geometry and material composition of the MAST Upgrade main components (vacuum vessel, magnetic field coils) and of the experimental hall (floor, ceiling and so on). This MCNP model has been then modified as described in the following sections to include the model of the different conceptual designs of the neutron camera upgrade.

5.2 Neutron Camera Upgrade

One of the primary goals of the MAST Upgrade is the study of fast ion physics and off-axis neutral beam current drive in order to design and access high performance and advanced plasma scenarios. Thus the study of the neutron emission, which can observe the fast ion activity, is important. Even for MAST
Upgrade the neutron emission is dominated by interaction between beam fast ions and ions of the thermal plasma (beam-thermal contribution). Therefore, details of the neutron emission can be used as a measurement for the fast ion distribution in the plasma and plasma MHD activity. In combination with the MAST Upgrade, and upgrade of the existing prototype neutron camera is envisaged. The upgraded neutron camera (NC Upgrade) will measure the neutron emission through a number of sight lines viewing different plasma regions and it will therefore provide information on the neutron emissivity profile in a single plasma discharge.

The design of the NC Upgrade is based on desired properties like spatial resolution or time resolution as well as an engineering and interfacing issues like available space and possible port plugs. Camera parameters like the position of the camera, the number of sight lines, the collimator dimensions and the shielding material have been determined on the basis of results from simulations with the neutron transport code MCNP [30]. Details of the calculations, such as the neutron source or the models used for MAST and the neutron cameras, are described in paper VI [26].

One of the results from the prototype NC is the observation that fast ion redistributions and losses induced by MHD activities result in a significant modification of the radial distribution of the neutron emissivity. Thus, one possibility for the design of the upgraded camera is to retain the principles of the prototype NC, with all sight-lines in the horizontal plane, a horizontal camera [24, 26]. The horizontal camera presented here consists of an equatorial camera \((Z = 0)\) with twelve sight lines and a down-shifted camera with eight sight lines in a plane with \(Z = -65\) cm. The investigation of the horizontal camera is discussed in section 6.1.

The second camera studied here is a poloidal section camera [25, 26] that measures the neutron emission in a poloidal section plane. It is designed on the basis of the camera design at exists that many tokamaks such as TFTR [16], JET [17, 18], JT-60U [19] and is also planned for ITER [22, 23]. The poloidal section camera presented here consists of a radial camera with twelve sight lines, viewing the plasma through a port in the equatorial plane. The radial camera is complemented by a diagonal camera with nine sight lines, viewing the plasma through a port at \(Z = +135\) cm. Due to the considerable value in detecting the radial gradient of fast ion redistribution, a poloidal camera system with a radial and vertical camera would be more favorable than the design suggested here. However, due to space limitations and interfacing constraints at MAST Upgrade, a vertical camera can not be realized here. The investigation of the poloidal section camera is discussed in paper V and VI and in section 6.2.

The sight lines of the four cameras view the plasma through a common pivot point located in the respective port. Due to the diverging sight lines beyond the pivot point and due to the large distance of the cameras from the vessel
Table 5.2. Camera dimensions. Note that the equatorial and the down-shifted camera share the same shielding structure.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Dimension(cm³)</th>
<th>Pivot point(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial</td>
<td>~ 215 × 260 × 250</td>
<td>[212,-49,0]</td>
</tr>
<tr>
<td>Down-shifted</td>
<td>~ 215 × 260 × 250</td>
<td>[212,-49,-65]</td>
</tr>
<tr>
<td>Radial</td>
<td>~ 80 × 191 × 340</td>
<td>[204,-54,0]</td>
</tr>
<tr>
<td>Diagonal</td>
<td>~ 80 × 191 × 390</td>
<td>[204,-54,135]</td>
</tr>
</tbody>
</table>

(see below), the instruments become quite large. The camera dimensions are summarized in table 5.2.

5.3 Design criteria

For the NC Upgrade, the following design criteria have been set [26]:

1. The camera has to allow profile measurements for neutron rates of \( \sim 10^{14} - 10^{15} \) n/s, which is the expected range for MAST Upgrade;

2. The camera has to allow measurements with a time resolution of 1 ms and a statistical uncertainty of not more than 10 % on the neutron emission from the plasma core for a typical MAST Upgrade discharge;

3. The camera has to provide a spatial resolution of 6 - 8 cm while covering the whole plasma cross section.

Design criteria (1) and (2) relate neutron fluxes to count rates and hence specify the detector efficiency. The efficiency can be adjusted within some limits once the camera position and design have been determined. Design criterion (3) defines the number of sight lines for a given plasma cross section and even the overlap between neighbouring sight lines. For a horizontal camera, the spatial resolution is given by the distance between neighbouring sight lines in the plane perpendicular to the central sight line and spanned by the MAST central solenoid. For a poloidal section camera, the spatial resolution is measured in the plane perpendicular to the central sight line and going through the plasma center (minor radius \( a = 0 \)). At the same time, the spatial resolution is affected by the overlap between the viewing cones for neighbouring sight lines. Sight lines without overlap provide good spatial resolution, but on the expense of a poorer neutron count rate due to the narrow viewing cones. Large overlap caused by wider viewing cones gives higher count rates, but deteriorates the spatial resolution. For the camera designs presented here, a radial overlap of 50 % of the full penumbra footprint was set as a target value.

5.4 Magnetic shielding

The magnetic field at different distances from the MAST vessel was calculated in order to decide the position of the camera detectors and to design the
thickness of the required magnetic shielding. The design is the result of simulta-
neously reducing the impact of magnetic stray field on the detector PMTs to a tolerable level and perturbing effect of the magnetic shielding on the original MAST magnetic field. At the same time, the camera design has to allow sufficiently high count rates, excluding too large distances from the MAST vessel. In this work, the calculations were performed with the Matlab\textsuperscript{©} partial differential equation toolbox [60]. The magnetic field in MAST Upgrade is generated by the poloidal and toroidal field coils, the central solenoid and the plasma itself. In a worst-scenario study we used the maximum coil currents and no plasma current. The magnetic shielding used is a combination of a soft iron box (thickness in the range of 2 - 6 cm) and a thin $\mu$-metal layer (thickness range 1 - 2 mm) [26]. Figure 5.2(a) shows the results for a combination of 6 cm thick soft iron and 2 mm thick $\mu$-metal at different distances of 350, 400, 450 and 500 cm. The resulting magnetic stray field at the detector position was found to be 0.64, 0.50, 0.41 and 0.35 mT, respectively. The “spikes” in the figure are due to the magnetisation of the metallic materials. A reduction of the shielding material to 4.8 cm thick soft iron and 2 mm thick $\mu$-metal at detector position 5 m results in a magnetic field at detector position of less than 0.39 mT, slightly below the value inside the shielding of the prototype camera of 0.4 mT [38] and low enough for the operation of PMTs. Figure 5.2(b) shows the magnetic field in the vicinity of the detectors for this magnetic shielding geometry and at 5 m in major radius. The perturbation of the original MAST magnetic field caused by the camera magnetic shielding for radii less than 2 m is nowhere larger than 0.32 mT. Again, this value can be compared with the prototype NC that perturbs the original MAST magnetic field with less than 0.3 mT [21]. Based on these finding, a detector position at a major radius of 5 m and a shielding consisting of 4.8 cm soft iron and 2 mm $\mu$-metal is proposed. Moreover, the ratio of between neutron and $\gamma$ flux for difference thick soft iron is evaluated (figure 5.3) which shows that thickness of the soft iron magnetic shielding box has only a small effect on the level of background $\gamma$-rays.

5.5 Number of sight lines

The number of sight lines for each camera should fulfill the following criteria:

1. Provide a sufficient spatial resolution for measuring changes in the neutron emission due to e.g. off-axis heating and trapped ions, required is about 7 cm;
2. Allow a detailed reconstruction of the neutron emission profile;
3. Grant a sufficient neutron count rate in the detectors;
4. Fit in the available space at MAST.

Calculations were performed for cameras with 10, 12 and 14 sight lines. The spatial resolution of the camera is the distance between neighbouring sight
Figure 5.2. (a) Magnetic stray field around MAST without shielding and with a shielding consisting of 4.8 cm soft iron and 2 mm μ-metal at different detector distances \(R\). (b) Magnetic field inside the shielding box for a detector position at \(R = 5\) m. The boxes consists of two double soft iron boxes (2.4 cm each) with 2 mm μ-metal in between.

Figure 5.3. Ratio between neutron and \(\gamma\) fluxes with and without the magnetic shielding.

lines along a plane perpendicular to the viewing cones, that is 7.8, 6.4 and 5.4 cm for an equatorial camera with these numbers of sight lines. The collimator dimensions are chosen to give a radial overlap of about 50 % between neighbouring sight lines (full penumbra footprint) in a plane perpendicular to the viewing cones (figure 5.4). A comparison between the simulation and the line integrated results is shown in figure 5.5. The line integral describes the neutron emissivity along the central sight line of the respective viewing cone, representing a very small field-of-view. The number of sight lines affects the level of detail with which the neutron emission profile can be reconstructed. As an indicator of this capability we use the figure of merit \((FOM)\) defined as:
\[ FOM = \frac{1}{N} \sum \frac{|X_i - Y_i|}{X_i} \]  

(5.1)

where \( N \) is the number of sight lines, \( X_i \) is the simulated neutron counts for sight line \( i \) and \( Y_i \) is the normalized line integrated neutron counts of sight line \( i \). Here, the lower \( FOM \) means a better capability to reconstruct the emission profile. The \( FOM \) for 10 to 14 sight lines is \( \sim 0.06 \), indicating that an increased number of sight lines does not improve the camera’s reconstruction capability. With the demand on the spatial resolution better than 7 cm, an equatorial camera with twelve sight lines is chosen. A similar procedure has been performed for all four cameras; the results are discussed in chapter 6.

![Figure 5.4](image_url)  

Figure 5.4. (a) Top view of three viewing cones for the equatorial camera, illustrating the overlap in the plane indicated by the line through the central column. (b) Poloidal view of the viewing cones in the plane drawn in (a).

![Figure 5.5](image_url)  

Figure 5.5. Comparison of line integrated neutron profile and the MCNP results for the equatorial camera and plasma scenario \( C \) (normalized).
5.6 Neutron and $\gamma$-rays shielding

In order to provide good collimation of the sight lines and to reduce the contribution from scattered neutrons, the camera detectors have to be surrounded by a neutron shielding. In paper VI the same shielding material as for the prototype NC was used (HDPE). Here we present an extended study where the following materials were selected for the neutron shielding:

1. High density polyethylene (HDPE) is a common shielding material and has been used in the prototype NC. HDPE has a density of 0.92 g/cm$^3$. Due to its high hydrogen content, neutrons are efficiently moderated, however, the level of 2.23 MeV $\gamma$-rays emitted after neutrons capture in hydrogen is a concern;

2. 5 % borated polyethylene with a density of 1.08 g/cm$^3$. Neutron are absorbed in the boron which improves the attenuation and reduces the level of 2.23 MeV $\gamma$-rays from absorption in hydrogen. However, 0.42 MeV $\gamma$-rays are emitted after neutron capture in boron;

3. 7.5 % lithium polyethylene with a density of 1.06 g/cm$^3$. This is an effective neutron shield which uses lithium instead of boron. There is no $\gamma$ radiation following the neutron capture in lithium;

4. Boran frits-baryte concrete with a density of 3.10 g/cm$^3$. Concrete has been selected for this study due to its high density; it has also been used in other camera, for example at JET [17, 18].

The different shielding material have been studied for the equatorial camera. The neutron fluxes along the major radius, displayed in figure 5.6 show that the neutron flux at the detector position ($R \approx 500$ cm) is reduced by 3 - 4 orders of magnitude. The figure shows that the neutron flux is drastically decreased by the HDPE shielding, for the $\gamma$-rays, however, additional lead shielding is required, see below. For the polyethylene based shields, a material thickness of about 40 cm is sufficient to reduce the neutron flux to insignificant levels; concrete requires about 2.5 times that thickness for a comparable result. Figure 5.6(b) shows that the $\gamma$ fluxes inside the shielding based on polyethylene are somewhat higher than inside the concrete shielding. For this reason, additional $\gamma$-ray shielding is required, see below.

Figure 5.7 shows the MCNP results for the $\gamma$ flux for different thickness of lead shielding in the case of the equatorial camera detectors. With a lead thickness of $\geq 10$ cm the reduction of the $\gamma$ flux intensity at the detector is about one order of magnitude. In this work, a 15 cm thick lead shielding is used in MCNP model for each camera.

Figure 5.8(a) shows the ratio between scattered and direct neutrons flux which shows that the concrete performs slightly worse than the HDPE based materials. Figure 5.8(b) shows the ratio between neutron and $\gamma$ fluxes. The results show that the ratio of neutron to $\gamma$-ray fluxes is significantly worse (by a factor of about 7 at $p \sim 90$ cm) when using concrete shielding. Thus, a polyethylene based shielding is suggested for the NC Upgrade; due to its con-
Figure 5.6. (a) The neutron fluxes; and (b) $\gamma$ fluxes; along the major radius in the equatorial plane for different neutron shielding materials: (a) HDPE; (b) 5% Borated polyethylene; (c) 7.5% Lithium polyethylene; and (d) boran frits-baryte concrete.

Figure 5.7. $\gamma$-ray flux for different impact parameters and thicknesses of the lead shielding. Note that the tests were done for the 10 sight line camera.

siderably lower cost we will use the pure HDPE in this design and performance study.

5.7 Collimator geometries

The collimator length is determined by the thickness of the neutron camera shielding. The shielding quality is described by the ratio between scattered neutrons (reaching the detector after having passed through the shielding) and direct neutrons (going through the collimator). This scattered to direct ratio is shown in figure 5.9(a) for HDPE and collimator lengths between 85 cm and 135 cm. Note that the neutron shielding is 19.8 cm thinner than the collimator length due to the required shielding against $\gamma$-rays (see section 5.6) and the magnetic field (see section 5.4). From figure 5.9(a) it can be seen that the ratio between scattered and direct neutrons is not affected by the collimator length.
This results indicate that the scattered neutrons emerge mainly from scattering on the MAST vessel and reach the detector through the collimator (back scattering) and that only a small factor of the scattered neutrons is scattered in the shielding material and reaches the detector this way. This interpretation is corroborated by an additional simulation where the collimators have been blocked; here, a further reduction of the scattered neutron flux by some orders of magnitude has been observed.

Apart from the contribution from scattered neutrons, the detectors are sensitive to $\gamma$-rays (see even section 3.2). The ratios between neutron and $\gamma$ flux are evaluated (figure 5.9(b)). The ratio is low at the plasma edge due to the low neutron count and at $p$ between 70 - 80 cm due to the intersection of the fields-of-view with the toroidal field coil at the opposite side of the camera resulting in high $\gamma$-rays count rates. The results show that a larger collimator length results a better neutron to $\gamma$ ratio. Based on these results, the collimator dimensions are chosen as discussed in chapter 6 and in paper VI [26].
6. Investigation of two camera designs

In this chapter, the horizontal and the poloidal section camera are investigated and compared. Both cameras are based on the design criteria and physics considerations discussed in chapter 5.

6.1 Horizontal camera

The design of the horizontal camera is based on the experience from the prototype NC, but adapted to the expected off-axis heating scenarios for MAST Upgrade. The horizontal camera consists of two detector arrays, an equatorial camera at \( Z = 0 \) cm and a down-shifted camera in the \( Z = -65 \) cm plane.

6.1.1 Equatorial camera

As discussion in chapter 5, a design with twelve sight lines has been chosen for the horizontal camera (figure 6.1), given the spatial resolution of 6.4 cm. The impact parameter, \( p \), has a range of \( 50 \, \text{cm} \leq p \leq 120 \, \text{cm} \).

The procedure for determining the collimator dimensions is described in paper VI and ref. [26] and can be summarised as follow:

1. The detector distance from the MAST vessel is determined on the basis of the magnetic fields at the detector position and the impact of the camera on the magnetic field at MAST;
2. The collimator length is given by the required thickness of the shielding material, which in turn is chosen in order to suppress the \( \gamma \) flux on the detector;
3. With the detector position and collimator length, the collimator radius is determined so that the radial overlap between neighbouring sight lines is 50 %;
4. The detector thickness and hence its efficiency is selected to allow for appropriate count rates for the expected neutron fluxes.

For the equatorial camera, there are a detector distance of 5 m from the central solenoid, a collimator length of 115 cm, a collimator radius of 1 cm (giving an overlap of 49 %) and detector thickness of 2.5 cm, corresponding to an efficiency of 11 %. Table 6.1 summarizes the neutron statistics for this design of the equatorial neutron camera and different MAST Upgrade plasma scenarios, as simulated for a measurement time of 1 ms. The numbers show that the
camera fulfils the design criterion of 10 % statistical uncertainty for the sight lines through the plasma core.

The conducted performance tests for the equatorial camera are presented in paper VI. The comparison of the simulated profiles with the line integrals (compare section 5.5) prove that the proposed design allows a detailed reconstruction of the emissivity profile. Due to its orientation in the equatorial plane, the camera is sensitive to both shifts and broadenings of the emission profile.

In addition to the results discussed in paper VI, figure 6.2 shows the neutron emissivity profile as calculated with TRANSP and the expected neutron count profile for the equatorial camera. On the inboard side, the observed neutrons originate mainly from the intersection of the sight lines with the plasma core before and after reaching the minimum radius that is given in the figure. This indicates that the equatorial camera is not sensitive to changes in the neutron emission at small major radii even if the whole field of view can be modeled in the data analysis process. On the outboard side the camera results reproduce the emissivity profile well. This, in combination with the performance tests described in paper VI proves that the equatorial camera is a highly useful design for a neutron camera at MAST Upgrade.

### 6.1.2 Down-shifted camera

The down-shifted camera has been designed to study the neutron emissivity in scenario with off-axis NBI heating. The Z position of the down-shifted camera has been chosen set to match the MAST Upgrade off-axis NBI deposition, located at $Z = +65$ cm. Due to interfacing constraints it was not possible to install the camera in an up-shifted position. The redistribution of the injected fast particles is however very fast and therefore the down-shifted lines-of-sight will still provide relevant information as shown in figure 6.3. The figure shows the results of line integrated neutron emission profiles at $Z = +65$ cm and $Z = -65$ cm for plasma scenarios A.1, A.2, C and D. It is clearly seen from these

<table>
<thead>
<tr>
<th>Camera</th>
<th>Plasma core (Counts)</th>
<th>Plasma edge (Counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Equatorial</td>
<td>519(22)-C</td>
<td>113(10)-A.1</td>
</tr>
<tr>
<td>Down-shifted</td>
<td>370(19)-D</td>
<td>110(10)-A.1</td>
</tr>
<tr>
<td>Radial</td>
<td>412(20)-D</td>
<td>104(10)-A.1</td>
</tr>
<tr>
<td>Vertical</td>
<td>818(28)-D</td>
<td>220(14)-A.1</td>
</tr>
<tr>
<td>Diagonal</td>
<td>493(22)-D</td>
<td>134(11)-A.1</td>
</tr>
</tbody>
</table>

**Table 6.1.** The neutron counts measured in 1 ms at plasma core and plasma edge measured with the suggested NC Upgrade geometries. The maximum and minimum are evaluated for plasma scenarios A.1, A.2, C and D.
Figure 6.1. (a) Toroidal view of the equatorial camera. (b) MCNP model of the MAST Upgrade vacuum vessel and the equatorial camera. Color code: MAST vessel: white is vacuum; dark blue is stainless steel, light blue is copper. The purple dots represent the neutron source. Cameras: dark blue is polyethylene; light blue is lead; dark green is soft iron. Green is the air and red is iron.

Figure 6.2. (a) The non-flux surface averaged neutron emissivity profiles ($\varepsilon_{\text{nfa}}$) plasma scenario C. Dashed line represents the mid-plane. (b) The MCNP simulation results of the proposed equatorial camera (solid line) and the neutron emissivity profile at mid-plane (dashed line) of plasma scenario C.

results that the down-shifted camera still provides the possibility to measure the fast ions behaviour of the off-axis NBI.

The proposed down-shifted camera has eight line of sight, viewing the plasma in the range of $60 \ cm \leq p \leq 110 \ cm$ and resulting in a spatial resolution of $7.2 \ cm$, see figure 6.4.

Following the same procedure as described for the equatorial camera, the resulting dimension are: a collimator length of 115 cm, a collimator radius of 1.15 cm (giving an overlap of 52 \%) and detector thickness of 4 cm, corresponding to an efficiency of 16 \%. The expected neutron statistics are given
Figure 6.3. The line integrated neutron particle flux profile for the set of arrays in horizontal plane at upper-shifted plane of \( Z = +65 \) cm (open symbols) and at down-shifted plane of \( Z = -65 \) cm (solid symbols) for plasma scenario: (a) A.1; (b) A.2; (c) C; and (d) D.

Figure 6.4. (a) Toroidal view of the down-shifted camera. (b) MCNP model of the MAST Upgrade vacuum vessel and the down-shifted camera on \( Z = -65 \) cm plane. Color code: MAST vessel: white is vacuum; dark blue is stainless steel, light blue is copper. The purple dots represent the neutron source. Cameras: dark blue is polyethylene; light blue is lead; dark green is soft iron. Green is the air and red is iron.

in table 6.1 and show that even this camera fulfils the design criterion of 10 % statistical uncertainty at plasma core sight lines.

The results discuss in paper VI and show that the down-shifted camera is sensitive to radial shifted of the emission profile. The capability to measure broadening, however, is constrained by the lower neutron statistic at \( Z = -65 \) cm. For the same reason, the contribution from scattered neutrons is higher than for the equatorial camera. Furthermore figure 6.5 shows that the agreement between the observed neutron count profile and the neutron emissivity is moderate only, even for the outboard side of the plasma.
Figure 6.5. (a) The non-flux surface averaged neutron emissivity profiles ($\epsilon_{nfa}$) plasma scenario C. Dashed line represents the $Z = -65$ cm plane. (b) The MCNP simulation results of the proposed down-shifted camera (solid line) and the neutron emissivity profile at $Z = -65$ cm plane (dashed line) of plasma scenario C.

6.2 Poloidal section camera

As an alternative to the horizontal camera, we explore a design of the NC Upgrade with the cameras viewing the poloidal section of the plasma on the basis of the camera design which exists at many tokamaks such as TFTR [16], JET [17, 18], JT-60U [19] and is also planned for ITER [22, 23]. A radial, a vertical and a diagonal camera are discussed.

6.2.1 Radial camera

Twelve sight lines are suggested for the radial camera, see figure 6.6, which results in a spatial resolution of 8.4 cm. Note that due to the interfacing with the poloidal field coils, the radial camera does not view the whole plasma section in the vertical plane through the plasma center. The camera dimensions become: a collimator length of 115 cm, a collimator radius of 1.25 cm (giving an overlap of 47 %) and detector thickness of 2.5 cm, corresponding to an efficiency of 11 %. The expected neutron statistics are given in table 6.1 and show that even this camera fulfils the design criterion of 10 % statistical uncertainty at plasma core sight lines.

The performance tests for this camera show its low capacity to measure radial shifts of the neutron emission, as expected for a camera with mainly radial sight lines. A broadening of the profile can be observed well and the profile reconstruction capability, as seen from the comparison between simulated profile and line integrals, is high. The radial camera demonstrates a low contribution from scattered neutron.
Figure 6.6. (a) Poloidal cross section view of the radial (blue-lines) and diagonal (red-lines). (b) MCNP model of the MAST Upgrade vacuum vessel and the poloidal section camera. Color code: MAST vessel: white is vacuum; dark blue is stainless steel, light blue is copper. The purple dots represent the neutron source. Cameras: dark blue is polyethylene; light blue is lead; dark green is soft iron. Green is the air and red is iron.

The comparison between the simulated and the emission profile (figure 6.7) show that the radial camera reproduces the emission well, but only in a limited field of view. Therefore, additional sight lines are needed to measure the emission from the plasma edges. For this purpose, a vertical and diagonal camera are studied in the following section.

Figure 6.7. (a) The MCNP simulation results of the proposed radial camera (solid line) and the neutron emissivity profile histogram in horizontal projection of plasma scenario C.

6.2.2 Vertical camera
A feasibility study of a vertical camera with six lines of sight and a spatial resolution of 7 cm has been carried out. The camera is shown in figure 6.8
and the dimensions are given by: a collimator length of 100 cm (plus 150 cm of concrete roof), a collimator radius of 1.75 cm and detector thickness of 1.5 cm, corresponding to an efficiency of 7%. Note that the concrete roof above the MAST tokamak is used both for defining the collimator channels and as neutron shielding.

Figure 6.8. (a) The poloidal cross section view of the poloidal section camera and their intersection with the neutron emissivity of plasma scenario C. (b) The MCNP model of the MAST Upgrade vacuum vessel and vertical camera.

Figure 6.9(a) shows the total neutron counts during measuring time of 1 ms for the different plasma scenarios. The count rates are higher than for the other camera designs, but still well within the operational range for scintillator detectors. Despite of the good statistics, the ratio between scattered and direct neutrons, see figure 6.9(b), is higher than for the equatorial camera, mainly due to the interaction of the sight lines and the lower divertor plate. The expected neutron statistics are given in table 6.1, the camera clearly fulfils the design criterion of 10% statistical uncertainty for the counts from the plasma core.

The vertical camera is very valuable for detecting in/out asymmetries in the fast ions redistribution. Unfortunately, these vertical sight lines require a large opening (~ 14 × 30 cm²) in the divertor and first wall which makes them not compatible with MAST Upgrade operations. Thus, the vertical camera is not proposed for the NC Upgrade at MAST Upgrade.

6.2.3 Diagonal camera

Due to the constraints concerning a vertical neutron camera, a diagonal camera with vertically inclined sight lines and a pivot point at Z = + 135 cm on an
existing port is studied. The proposed design contains nine sight lines, see figure 6.6, and gives a spatial resolution of 7.5 cm. The geometry is given by: a collimator length of 115 cm, a collimator radius of 2 cm (giving an overlap of 56 %) and detector thickness of 2.5 cm, corresponding to an efficiency of 11 %. The expected neutron statistics are given in table 6.1 and show that even this camera fulfils the design criteria of 10 % statistical uncertainty at plasma core sight lines.

The performance tests in paper VI show that the diagonal camera is sensitive to broadenings of the plasma profile, but that it is difficult to measure profile shifts with diagonal sight lines. Even the profile reconstruction capabilities are worse than for the other cameras.

In conclusion, all cameras fulfil the design criterion concerning the statistical uncertainties, the performance tests, however, show that a combination of two horizontal cameras in the equatorial and down-shifted plane is superior to a combination of a radial and a diagonal camera.

6.3 Neutron count rate profiles in MAST Upgrade

As discussed in the previous section, a camera design with two horizontal arrays of neutron detectors, one in the equatorial and one in a down-shifted ($Z = -65$ cm) plane, have been found to give the best suited for MAST upgrade [26]. This section provides some examples of the expected performance of this neutron camera upgrade using the plasma scenarios described in section 5.1.

As described before, TRANSP calculates, among other plasma parameters, the neutron emissivity on a poloidal cross-section either as a flux-surface averaged quantity and a non-flux averaged one. These two neutron emissivities are indicated as $\varepsilon_{fa}$ and $\varepsilon_{nfa}$ [58, 59]. It has been shown that the non-flux
averaged neutron emissivity gives a better agreement when compared with the measurement carried out at MAST with the prototype neutron camera [59], the reason being a significant poloidal asymmetry in the fast ion spatial distribution due to a significant population of trapped fast ions on the plasma outboard side where the magnetic field is lower compared to the inboard side. In MAST Upgrade the trapped fast ion population is also expected to be very large, especially when the additional heating power will be increased from the “core scope” phase to the “stage 1” one. For this reason, in the following study most of the attention will be given to results obtained using the non-flux averaged neutron emissivity: the flux-averaged one is used just for reference.

The plasma scenarios that have been studied include scenarios A.1, A.2, C and D with and without anomalous fast ion diffusion. In this section, only results from the A.1 scenario without anomalous fast ion diffusion ($D_{an} = 0 \text{ m}^2/\text{s}$) are presented. Scenario A.1 is a high-density, high temperature H-mode plasma with an expected neutron rate of approximately $3 \times 10^{14} \text{ n/s}$. The poloidal projection of the neutron emissivity is presented in figures figure 6.10: panels (a) and (b) show $\varepsilon_{fa}$ and $\varepsilon_{nfa}$ while panel (c) their difference. The poloidal asymmetries are clearly visible.

Expected count rate profiles from the equatorial and down-shifted cameras are shown in figures 6.11(a) and 6.11(b), respectively. The importance of using the non-flux averaged neutron emissivity is particularly evident for the down-shifted neutron camera which is viewing the plasma at $Z = -65 \text{ cm}$ which will be strongly affected by the fast ions population from the off-axis neutral NBI.

![Figure 6.10. The TRANSP-simulated poloidal cross-sections of: (a) $\varepsilon_{fa}$; (b) $\varepsilon_{nfa}$; and (c) $\varepsilon_{nfa} - \varepsilon_{fa}$; of plasma scenario A.1 with $D_{an} = 0 \text{ m}^2/\text{s}$.](image)

Previous MAST experiments have shown that fast ions are spatially redistributed as a results of their interaction with MHD instabilities. Their spatial redistribution is usually modelled in TRANSP assuming a certain level of anomalous fast ion diffusivity whose amplitude correlates with the amplitude
of the MHD instabilities [61]. This correlation was determined as a result of a comparison of the TRANSP predicted neutron count rate profiles with the ones measured with the prototype neutron camera and the fission chamber.

The precise level of anomalous fast ion diffusivity on MAST Upgrade is not known and therefore a systematic mapping of its effect on the expected fast ion distribution was carried out for all the scenarios for $D_{an}$ in the range 0 - 5 m$^2$/s. In this section, only scenario C is discussed, in particular for an $D_{an}$ of 0, 1 and 5 m$^2$/s. The corresponding TRANSP-simulated neutron emissivities ($\varepsilon_{nfa}$) are shown in figure 6.12.

The corresponding MCNP simulated neutron count rate profiles are shown in figure 6.13(a) and 6.13(b) for equatorial and down-shifted camera respectively. The results show that the cameras are able to distinguish different plasma scenarios within the expected anomalous fast ion diffusivities. However, in order to do so it might be necessary to relax the 1 ms requirement.
on the time resolution if a 10% statistical uncertainty on the count rate is required.

Figure 6.13. The MCNP simulated neutron count rate profile of: (a) the equatorial camera; and (b) the down-shifted camera; for the plasma scenario C with $D_{an} = 0$ m$^2$/s (black - circles), $D_{an} = 1$ m$^2$/s (red - squares) and $D_{an} = 5$ m$^2$/s (blue - triangles). Dashed lines are neutron emissivity at: (a) midplane; (b) $Z = -65$ cm. The neutron counts are measured in 1 ms.
7. Summary and outlook

In part I of this thesis the neutron detectors used in the prototype neutron camera diagnostic on MAST have been fully characterized both in the laboratory and at MAST. The characterization included the determination of their energy resolution for $\gamma$-ray sources, their response function matrix for neutrons with energies in the relevant range for deuterium-deuterium fusion reactions and their efficiencies. The effect of temperature and magnetic field on the detectors were studied and it was shown how these effects can be compensated for in the data analysis due to the availability of a reference signal in the form of a pulsed LED source. Optimal pulse shape discrimination time intervals where determined. The pulse shape discrimination dependence on the temperature was also studied and shown not to be degraded during normal MAST operations. The pulse shape discrimination allowed the determination of the neutron count rates as a function of time even in the presence of a strong background of $\gamma$-rays and scattered neutrons. In these cases, the total count rate of the detectors was so high that non-linearities in the output signals were observed and later corrected during data analysis. Finally, a pile-up correction was performed on the acquired data to provide a neutron count rate that scaled linearly with the neutron rate measured independently by an absolutely calibrated fission chamber. Comparison between fission chamber and neutron camera measurements agreed within the experimental uncertainties when the proper solid angles, detector efficiencies and the plasma neutron emissivity were taken into account. The achievable time resolution of the neutron count rate was 1 ms with a statistical uncertainty on the neutron counts of less than 10%. Neutron count rate profiles have been measured and interpreted in light of plasma global parameters and fast ion populations. Although the prototype neutron camera has a much lower time resolution than the fission chamber, the results presented in this thesis show that the neutron camera provides information that can not be captured by the fission chamber alone and complements it thanks to the camera’s spatial resolution capabilities, in particular in the presence of strong MHD activity. Sawtooth and long-lived mode instabilities have been investigated: redistribution of fast ions due to such MHD instabilities is manifested in significant changes in the amplitude and shape of the measured neutron emission profiles. First attempts have been presented in modelling the neutron emissivity using both synthetic and TRANSP neutron emissivity profiles. Finally, the neutron energy spectroscopic capabilities of the prototype neutron camera has been assessed providing further support to the correctness of the detectors characterization and of the modelling tools.
used to simulate the recoil proton pulse height spectra. Although limited in energy resolution, large changes in the neutron energy spectrum due to the direction of observation with respect to the direction of the NBI injection agree with model predictions. One major limitation of the current neutron camera is obviously the limited number of lines of sight (2 each for the equatorial and the diagonal views) which imposed the necessity of repeated and reproducible plasma discharges in order to measure accurately the neutron count rate profiles. Although MAST plasmas are highly repeatable, as has been shown in this thesis, some features of the MHD activity can not be exactly reproduced from discharge to discharge, as for example in the case of the fish-bones, thus restricting the usability of the neutron camera only to some scenarios or making the analysis of these phenomena more difficult. A way to overcome these difficulties is to redesign the current system to allow for more lines of sight. Notwithstanding these limitations, the neutron camera has become one of the key diagnostics on MAST for fast ions physics studies together with the Fast Ion D-Alpha and the proton diagnostics.

Currently, an upgrade of the MAST device that is in progress. Part II of this thesis describes the conceptual designs that have been investigated of a neutron camera for this upgrade. MAST Upgrade will address many physics issues that are relevant for both ITER and DEMO, in particular in the area of fast ion physics. The proposed neutron camera upgrade has been largely based on the experience gained and the results obtained from the prototype neutron camera described in part I of this thesis. An increase in the number of the lines of sight, improved collimation and better shielding are the key features of the neutron camera proposed for MAST Upgrade to take into account the longer and more performing plasma discharges, with neutron rates well into the $1 \times 10^{14} - 1 \times 10^{15}$ n/s range. The proposed design will allow studies of the fast ion spatial redistribution in a single plasma discharge. The study presented in part II of this thesis focussed on two camera designs both consisting of two array of collimated neutron flux monitors based on liquid scintillators where one is looking tangentially to the plasma while the other had the lines of sight lying in the poloidal cross-section. Both cameras have been designed so that they allow measurements of the neutron count rate profile with a time resolution of 1 ms and with a statistical uncertainty of no more than 10 % for the sight lines looking mainly at the central region of the plasma. The performance of of the two designs in resolving spatial shifts and broadening of the neutron emissivity was investigated. The results indicated that the overall performance of the tangential neutron camera system is superior to the cameras looking at the poloidal cross-section. Based on these results, two horizontal neutron cameras looking at the plasma in the tangential direction with respect to the plasma current are suggested for MAST Upgrade. Of these two cameras, the equatorial one has clearly been demonstrated as the most performing instrument that can be installed with the interfacing constraints at MAST. The down-shifted camera appears poorer in resolving quality, but gains value from the fact that its
position at $Z = -65$ cm will be sensitive to the fast ion population in operating scenarios employing off-axis NBI. It is anticipated that the proposed system will operate without problems during the “core scope” and “stage 1” phases of the MAST Upgrade project. Later phases of the MAST Upgrade project envisage a further increase of the NBI power to 12 MW which will beyond the operating regime of the currently proposed design. In order to cope with the higher neutron rates expected, the collimator channels of the neutron camera will then have to (and can) be equipped with inserts, decreasing their cross section and thereby the neutron flux on the detectors, which could in principle also be segmented, so that the time resolution could be maintained without a too high count rate on each individual detector. The design proposed in this thesis for a neutron camera upgrade for MAST Upgrade will be consolidated during 2014, with procurement of the system beginning early in 2015. The aim will be to install and commission the new diagnostics towards the end of 2015, early 2016 to be ready for the first plasma discharges of MAST Upgrade.
Fusionsenergi frigörs vid sammansmältning, fusion, av lätta atomkärnor. Fusion är den process som ger energi åt solen och alla stjärnor. Den fusionreaktion som har den största potentialen att kunna användas som bränsle i eventuella framtida fusionskraftverk här på jorden är den mellan de två tunga vätekärnorna deuterium ($^2D$) och tritium ($^3T$). Vid dessa reaktioner bildas en heliumkärna ($^4He$) och en neutron samt en stor mängd energi frigörs:

$$^2D + ^3T \rightarrow ^4He + n + 17.6 \text{ MeV} \quad (8.1)$$

Denna $DT$-reaktion har den största energiutvinningen och den största reaktionshastigheten bland de reaktioner som kunde vara tänkbara för en fusionreaktor på jorden. Precis som för annan kärnkraft är de frigjorda energimängderna per fusionsreaktion enorma jämfört med t ex kemisk förbränning av fossilbränslen eller biomassa; man kan grovt säga att ca 1 miljon gånger mer energi frigörs per reaktion. Dock används tritium idag relativt sparsamt inom fusionsenergiforskningen då denna väteisotop är radioaktiv och dyr. De flesta experiment utförs istället med endast deuterium som bränsle, varvid två olika “kanaler” för fusionsreaktionen är möjliga:

$$^2D + ^2D \rightarrow ^3He + n + 3.27 \text{ MeV} \quad (8.2)$$

$$^2D + ^2D \rightarrow ^3T + H + 4.03 \text{ MeV} \quad (8.3)$$

Dessa reaktioner sker med samma sannolikhet i reaktorn. För att utveckla fusion till en användbar energikälla utfors forskning inom en rad delområden, såsom plasmafysik, materialteknik, atomfysik samt utveckling av avancerade mät- och analysmetoder. Fusionsforskningens mål är alltså att ta fram en ny energikälla som kan leverera elektricitet till elnätet. På det internationella planet är ett världsomspännande samarbete etablerat för att bygga forskningsreaktorn ITER i Cadarache, Frankrike. Målet med ITER är att:

- Visa att fusionsenergi är tekniskt möjligt genom att uppnå ett stort energiöverskott.
- Testa en rad delsystem nödvändiga för fusionsenergi, som t ex “breeding” av nytt bränsle.
- Bereda vägen för byggandet av en första fusionsreaktor ansluten till elnätet; DEMO.

Byggandet av ITER är nu i full gång, och reaktorn beräknas stå klar för första testköningar ca år 2020 och sedan för drift med optimalt kärnbränsle och vid full effekt, ca 500 MW, kring år 2026.
För att förbereda det vetenskapliga och tekniska arbetet vid ITER och för DEMO utförs idag forskning vid en rad experimentreaktorer världen över. En av dessa är MAST (“Mega Ampere Spherical Tokamak”) belägen vid forskningscentret Culham Centre for Fusion Energy, utanför Oxford i Storbritannien. MAST är en reaktor av typen tokamak, precis som ITER, men med en mer kompakt design och av betydligt mindre dimensioner. Denna avhandling handlar om experiment med och utveckling av avancerade neutronmätinstrument för MAST, närmare bestämt den typ av diagnostik som går under namnet neutronkamera. Neutronmätningar är viktiga inom fusionsforskningen av flera skäl. Som framgår av reaktionerna i formlerna (1) och (2) frigörs neutroner vid alla de relevanta fusionsreaktioner som studeras inom fusionsforskningen. Intensiteten hos neutronstrålingen ger direkt den utvunna fusionseffekten från reaktorn, och de utskickade neutronerna kan också viktig detaljkunskap om förhållandena i reaktorn och hos dess bränsle.

Vid Avdelningen för tillämpad kärnfysik, Uppsala universitet, har ett prototypinstrument av typen neutronkamera designats, byggts och installerats vid MAST som en del av detta avhandlingsarbete. Avhandlingen beskriver uppbyggnaden av detta instrument och de principer som styrt designen. En viktig aspekt för all diagnostik kring en fusionsreaktor är t ex att skydda känsliga instrument från störningar av olika slag. Därför har stor möda lagts ner för att utrusta neutronkameran med skydd mot icke önskvärd strålning samt mot de starka magnetfält som omgärder MAST. En annan viktig aspekt är att etablera arbetspunkter för och karakterisera de detektorer som ingår i neutronkameran. Dessa detektorer är i detta fall av typen flytande scintillatorer, och de är kopplade till fotomultiplikatorrör vilka producerar elektriska signaler som kan registreras och slutligen lagras av instrumentets datainsamlingsystem. Avhandlingen går igenom hur detektorerna testats med olika typer av strålningskällor (gammastrålare) och även hur de svarar vid bestrålning av neutroner. För att kunna dra riktiga slutsatser av de data som neutronkameran levererar måste man förstå detektorernas respons till både det sökta signalen, d v s neutronerna från fusionsreaktionerna, men också hur de svarar på bestrålning från olika typer av bakgrundskällor. Genom noggrann karakterisering och dataanalys kan på så sätt resultat levereras som berättar om hur bränslet i reaktorn uppför sig under olika körszenarii för reaktorn. Prototypkameran vid MAST har varit aktiv under ett flertal experimentkampanjer och levererat data som varit av stort värde. Det gäller fr a vid studiet av snabba partiklar i bränslet, alltså deuterium- och tritiumjoner som har betydligt högre kinetisk energi än det övriga bränslet. Populationer av sådana partiklar kan koppla till speciella störningsfenomen i bränslet, s k magnetohydrodynamiska moder, vilket kan orsaka flera olika problem vid driften av reaktorn. T ex kan dessa störningar orsaka att stora mängder bränsle kastas ut från reaktorns kärna, varvid den utvecklade reaktoreffekten minskar. Dessa utkastade partiklar kan dessutom kollidera med reaktorns väggar vilka kan ta skada av ett sådant bombardemang. MAST är en maskin där studier av dessa fenomen är särskilt
gynnsamma, och lärdomarna från dessa experiment blir viktiga för att i ett senare läge köra t ex ITER-reaktorn på ett säkert och stabilt sätt.

Vid MAST har nu ett uppgraderingsprojekt startats som syftar till att göra reaktorn än mer relevant för den framtida fusionsforskningen. I samband med detta genomförs också en studie för att designa en ny och förbättrad neutronkamera för ”MAST Upgrade”. Denna studie, genomförd med simuleringsprogrammet MCNP, beskrivs i viss detalj i denna avhandling. Två olika designmodeller har modelerats med stor omsorg och sedan studerats för att försöka avgöra vilken typ av neutronkamera som bäst kan svara mot de nya förhållandena vid MAST Upgrade, och därmed leverera relevanta resultat av god kvalitet. Den ena designen bygger på den framgångsrika prototypkameran och består av två detektorarrayer som tittar in i reaktorn horisontellt, den ena arrayen i mittplanet, den andra något förskjuten nedåt. Den andra designen är av mer traditionell typ och liknar de neutronkameror som installerats vid andra fusionsanläggningar. Denna kamera tittar in mot bränslet i radiell riktning, med en array av detektorer placerad vid sidan av reaktorn och en annan som tittar in snett uppifrån (den optimala lösningen med två detektorarrayer med ortogonala siktlinjer är tyvärr inte möjlig p g a geometriskt/mekaniska begränsningar kring MAST-reaktorn). Den genomförda utredningen har tittat på alla relevanta faktorer för uppbyggnaden av de två kamerasystemen och slutligen försökt avgöra vilket av systemen som kan leverera de bästa resultaten utifrån de tänkta körscenarierna vid MAST Upgrade. Det visar sig att, bl a p g a de geometriska begränsningarna för den traditionella designen, den horisontella lösningen ger de bästa förutsättningarna och detta är den rekommendation som kommer ut som ett resultat av denna avhandling. För att summera kan vi konstatera att neutronmätningar spelar en viktig roll inom fusionsforskningen, och denna avhandling har visat hur experiment med en neutronkamera vid experimentreaktorn MAST har bidragit med viktig information om hur snabba bränslepartiklar uppför sig i en fusionsreaktor. Dessa resultat förväntas ha stor betydelse när verksamheten kring nästa generations fusionsexperiment, ITER, planeras och genomförs om 5–10 års tid. Ett annat viktigt bidrag som denna avhandling gett är de rekommendationer som framkommit för hur framtidiga neutronkameror ska designas, och då speciellt en uppgraderad kamera för MAST Upgrade. En sådan uppgraderad instrument skulle kunna ge många viktiga resultat och bidra till att göra hela MAST-uppgraderingsprojektet till en framgång.
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