Characterization of $\gamma$-rays at MAST

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Abstract

The $\gamma$-ray characterizing possibility of the neutron collimated flux monitor (in short, Neutron Camera) at the Mega Ampere Spherical Tokamak (MAST) is explored. Typically used to monitor neutron emission, the Neutron Camera has excellent neutron/$\gamma$-ray discrimination properties and thus presents the opportunity to measure spatially and temporally resolved $\gamma$-ray emission - a possibility of an additional fusion diagnostics method with already existing equipment. An Online Data Analysis (ODA) code was used to analyze the data on $\gamma$-rays from several plasma discharges with similar plasma parameters. A high statistics temporal distribution of the $\gamma$-ray emission and a lower statistics spatial distribution were analyzed. However, the low energy resolution and range for the Neutron Camera $\gamma$-ray measurements revealed few conclusive results on the origin of the higher energy $\gamma$-rays. Detection systems with higher energy resolution and range are suggested for an extensive analysis of $\gamma$-ray emission at MAST Upgrade.

Sammanfattning

Möjligheten att karakterisera $\gamma$-strålnings med en "neutron collimated flux monitor" (eller Neutron Kameran) vid Mega Ampere Spherical Tokamak (MAST) undersöks. Neutron Kameran användes generellt sett till att undersöka neutronstrålnings, men med dess utmärkta förmåga att urskilja neutroner och $\gamma$-strålnings erbjuder Neutron Kameran således en möjlighet att mäta $\gamma$-strålnlingen både rumsligt och temporalt upplöst - en möjlighet till ytterligare fusionsdiagnostik med redan existerande instrument. En "Online Data Analysis" (ODA) kod användes för att analysera $\gamma$-strålningsdata från flertalet plasmaskott med liknande plasma parametrar. Analysen av $\gamma$-strålningen skedde med hög statistik på tidsutvecklingen och lägre statistik på rumsfördelningen. Neutron Kamerans låga energiupplösning och -omfång för mätning av $\gamma$-strålnings ledde till få slutgiltiga resultat angående ursprunget till hög-energi $\gamma$-strålningen. Ett detektorsystem med högre energiupplösning och -omfång rekommenderas för en mer ingående analys av $\gamma$-strålningen vid MAST Upgrade.
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1 Introduction

1.1 Fusion and the tokamak

Fusion is the process in which atomic nuclei join together to form heavier nuclei resulting in a release of energy. Fusion reactions that involve lighter elements release substantial amounts of energy that can be used to generate electricity in a safe and clean way. Thus, research on controlling fusion has been conducted for over 60 years focusing mainly on reactions involving deuterium (D) and tritium (T) (see reactions (1) - (3)) [1].

\[ \text{D} + \text{T} \rightarrow ^{4}\text{He} (3.5 \text{ MeV}) + \text{n} (14.1 \text{ MeV}) \]  
\[ \text{D} + \text{D} \rightarrow ^{3}\text{He} (0.82 \text{ MeV}) + \text{n} (2.45 \text{ MeV}) [50\%] \]  
\[ \text{D} + \text{D} \rightarrow \text{T} (1.01 \text{ MeV}) + \text{p} (3.02 \text{ MeV}) [50\%] \]  

Above are examples of reactions used in fusion reactors. The energy of the products are in parentheses and the branching ratios in brackets.

Controlling nuclear fusion comes with great challenges. The fusion reactions demand extremely high temperatures as high as a hundred million degrees Kelvin, hence the fuel is fully ionized in what is called a plasma state. Once heated, the hot plasma can be confined by a magnetic field that keeps it from contact with the reactor walls, where heat loss and material damage are inevitable. One of the most promising magnetic confinement configurations is the tokamak, which exploits toroidal geometry and a helical magnetic field to confine the plasma. The largest tokamak to date is JET (Joint European Torus) and there is an ongoing project to construct a larger tokamak, ITER (International Thermonuclear Experimental Reactor), with the aim of achieving a net power production from fusion.

1.2 The spherical tokamak and MAST

A certain type of tokamak is the spherical tokamak (ST) which has a lower aspect ratio (the ratio between the torus’ major and minor radius) which gives it its more spherical shape and a smaller central column. One such spherical tokamak is the Mega Ampere Spherical Tokamak (MAST) at the Culham Centre for Fusion Energy (CCFE) which explores the potential of the ST as well as physics relevant for the ITER project [2]. MAST operates on the D-D reactions (reactions (2) and (3)) and has provided important developments in fusion research since its 1999 start-up.

1.3 Diagnosing the fusion reactions

In order to gain understanding of the properties of the plasma and and its interplay with the reactor and surrounding materials, a mapping of the spatial and temporal distribution of fusion reactions is vital. From the D-D reactions used at MAST emerge \(\gamma\)-rays and high energy neutrons (2.45 MeV, see reaction (2)) that can interact with the reactor walls and surrounding materials to produce additional \(\gamma\)-rays [3, 4]. An analysis of these neutrons and \(\gamma\)-rays can reveal information about the plasma and the fusion reactions inside the reactor. This information includes where and to what extent the fusion reactions occur and how surrounding materials respond to the radiation it sustains during a plasma discharge. A Neutron Camera (NC) [5] is used to detect both neutrons and \(\gamma\)-rays and it has the capability to discriminate between the two types of radiation. The NC is primarily used to identify and analyze neutron emission while this thesis focuses on characterizing the \(\gamma\)-ray emission. The thermal neutron capture on the hydrogen (\(\text{H}(\text{n},\gamma)\text{D}\)) of the NC shielding provide the main source of \(\gamma\)-rays of 2.23 MeV and it is particularly the \(\gamma\)-rays with energies higher than this that are of interest in this thesis. These high energy \(\gamma\)-rays potentially originate from the plasma itself or from so-called run-away electrons that can damage the reactor walls [6]. A comparison of the time evolution of these high energy \(\gamma\)-rays with the time evolution of typical plasma parameters (such as plasma current, applied heating power, neutron emission, etc.) during a plasma discharge can provide further information on the source of said \(\gamma\)-rays.
2 Measurements of $\gamma$-rays at MAST

This section begins by an introduction to MAST and its goals followed by a more in-depth description of the NC, radiation characterization and the data acquisition system. Finally, observed sources of $\gamma$-rays in tokamaks will be discussed followed by a description of the MAST data analyzed in the thesis.

2.1 MAST

The spherical tokamak design shows potential as a cost-efficient fusion reactor [2]. Successful results from the Small Tight Aspect Ratio Tokamak (START) in the 1990s inspired the construction of new STs, one of which was MAST [7]. MAST objectives were to further explore the potential of the STs as power plants or test facilities but also to provide a deeper understanding of conventional tokamaks such as ITER. The heating of the plasma is achieved by Neutral Beam Injection (NBI) where neutral high-energy deuterium, unaffected by the reactor’s magnetic field, is injected into the reactor. Here it is ionized by the plasma and subsequently transfers parts of its energy to it by interactions with the ions and electrons. The NBI power was about 3.5 MW for plasma durations of approximately 0.5 s. Key parameters of MAST are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major and minor radii $R$, $a$ (m)</td>
<td>0.85, 0.65</td>
</tr>
<tr>
<td>Elongation $\kappa$</td>
<td>2.45</td>
</tr>
<tr>
<td>Aspect ratio $A = R/a$</td>
<td>1.3</td>
</tr>
<tr>
<td>Plasma current $I_p$ (MA)</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>Auxiliary heating $P_{NBI}$ (MW)</td>
<td>$\leq 3.5$</td>
</tr>
<tr>
<td>Plasma duration (s)</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>Density (particles/m$^3$)</td>
<td>$\leq 10^{20}$</td>
</tr>
<tr>
<td>Toroidal field at $R = 0.7$m (T)</td>
<td>0.45 - 0.65</td>
</tr>
</tbody>
</table>

One key feature of MAST was its high reproducibility, i.e. it can achieve plasma discharges with similar plasma parameters such as NBI power, plasma current, etc. This high reproducibility was exploited by the NC to observe the neutron and $\gamma$-ray emission at different parts of the plasma over several similar discharges. It was thus possible to obtain both neutron- and gamma emissivity profiles to analyze the plasma activities and Magneto-Hydro-Dynamic (MHD) instabilities. Neutron emissivity profiles have previously been used to probe the behaviour of fast ions [9].

2.2 The Neutron Camera

The neutron collimated flux monitor (or Neutron Camera (NC)) at MAST was designed to measure high energy neutron emission (2.45 MeV) with measurements every millisecond that are separated 20 cm apart [5]. Among other neutron monitoring detectors at MAST was the fission chamber (FC) which measured the total neutron yield with a higher temporal resolution but no spatial resolution [10]. The NC consists of four detectors, radiation shielding and collimation, shielding from the reactor’s stray magnetic fields and systems for calibration and environment monitoring. The four detectors are identical and positioned to look along four different lines of sight: Two looking in the equatorial plane with an impact parameter (closest distance from line of sight to the center of the tokamak, see figure 1a) 20 cm apart. The other two detectors have the same impact parameter but are looking in an inclined, diagonal view with respect to the equatorial plane (see figure 1b) ([5] again). The detectors consist of an aluminium chamber containing the EJ-301 liquid scintillator coupled to a photomultiplier tube (PMT). Additionally, a $^{22}$Na $\gamma$-ray source for calibration and an LED for gain corrections (see section 2.4) are attached to each detector. The line of sight collimation is achieved by blocks of high purity and high density polyethylene (HPDP) that also provide shielding against scattered neutrons. However, this hydrogen-rich shielding enables the thermal neutron capture nuclear reaction $H(n,\gamma)D$ and therefore additional shielding against the emerging 2.23 MeV $\gamma$-rays is required. For this reason, lead blocks are placed between the HPDP shield and the detector. However, the lead blocks do not entirely shield the detectors which results in a significant $\gamma$-ray contribution to the NC measured signals. The NC is mounted on a rail, which
Ch 0
Ch 1

Figure 1: Sketches based on the design principles of the NC detectors’ lines of sight [5]. The Neutron Camera is represented by the blue rectangle and the lines of sight in dashed blue lines.

allows the camera to move, thus varying the detectors’ impact parameters in between discharges. (figure 1a again)

2.3 Radiation characterization

In order to correctly identify the energy and type of the radiation detected, corrections, calibration and characterization of the detected pulses are required. Incident radiation excites the scintillator molecules that emit visible light by subsequent de-excitation [11]. This light output is converted into a voltage that is recorded into a digital Analog-to-Digital Converter (ADC) with 250 MHz sampling frequency.

Different types of radiation are characterized by different pulse decay times due to the characteristic lifetimes of the different excited states. This crucial property allows the discrimination between neutrons and γ-rays using Pulse Shape Discrimination (PSD) techniques. This is done by calculating the integral of the pulse for two different time intervals (see figure 2) to obtain the so called fast charge, \(Q_F\) (interval of the quick rise and quick decay), and total charge, \(Q_T\) (interval of the quick rise, quick decay and subsequent slow decay). The pulse shapes of neutrons and the pulse shapes γ-rays are distinguished by having a different value of the quantity

\[ F_{PSD} = \frac{Q_T - Q_F}{Q_T}. \] (4)

A visual representation of this property is provided by a 2D histogram of counts over \(F_{PSD}\) and \(Q_T\) (see figure 3) which can be used for neutron/γ-ray discrimination (See section 3.1) as the neutrons have a value of \(F_{PSD}\) in the range of approximately 0.1-0.2 and γ-rays in the range of approximately 0-0.1. A Region Of Interest (ROI) is chosen manually to separate the neutrons from the γ-rays.

The total charge \(Q_T\) and the maximum amplitude of the pulse are important characteristics of the type and energy of the detected radiation. The pulse amplitude is calculated after baseline subtraction, which the analysis software performs by first calculating the average amplitude value of the segments before the \(Q_T\)-region and then subtracts this value from every sample. Additionally, due to the random nature of nuclear reactions, more than one pulse can be detected during a sampling period. This causes pile-up events with overlapping pulse shapes, which must separated from single-event pulses.

High count rates in the detectors cause a variation in the PMT’s gain and consequently an undesired variation in the amplitudes and \(Q_T\) of the recorded pulses. The LED attached to the detector provides a source of reference pulses that can be used to correct for this variation. These
pulses have significantly different values of $F_{PSD}$ than the values for typical neutron or $\gamma$-ray pulses and are therefore easily discriminated.

Typically, $\gamma$-ray spectroscopy is performed with high density, high Z-value detectors, thus taking advantage of the photo-peak for better energy calibration and good energy resolution [11], whereas the liquid scintillators are preferred for high energy neutron detection. Yet, the NC scintillators’ good discrimination properties provide the opportunity to study the temporal evolution and spatial profile of the $\gamma$-ray emission although with very low energy resolution.

Energy calibration is done by relating the pulse amplitudes of $\gamma$-rays to their energy. An important property of the organic scintillator is that the scintillation efficiency depends on type of particle and the energy of the particles. The notion of MeV electron equivalent (MeVee) is introduced to compare the light yield of different particles: 1 MeVee is the light yield of a 1 MeV electron that has deposited its entire energy in the detector, while the same light yield can require the deposition of several MeV for heavier particles. For $\gamma$-rays, the relationship between recoil electron energy and the light yield is linear which allows a simple calibration.

It is important to note that each detector has a unique high voltage setting that ultimately affects the proportionality constant between energy and amplitude. As mentioned in section 2.2, there are $^{22}$Na-sources attached to each detector for calibration purposes. The data acquisition time extends beyond the duration of the plasma to obtain the recoil electrons’ Pulse Height Spectra (PHS) which are then used to calibrate the detectors. However, the low Z-value liquid scintillator detectors of the NC have a negligible cross-section for photo-electric emission and thus the Compton edges must be used for energy calibration which is not ideal [11]. The Compton edge depends on the energy of the $^{22}$Na $\gamma$-rays:

$$E_{edge} = \frac{2E_\gamma^2}{m_e c^2 + 2E_\gamma},$$

(5)

where $E_\gamma$ is the energy of the $\gamma$-ray and $m_e c^2$ is the electron rest energy. Equation (4) gives Compton edges at 0.341 MeV and 1.062 MeV (from the 0.511 MeV and 1.275 MeV emission [13]). There exist different views on how to evaluate the Compton edges from the PHS and a greater uncertainty in this type of calibration is expected [14, 15, 16].

2.4 Data acquisition

Data from the NC are recorded in two ADC cards, each with two channels where Card 0 contains the data from the two diagonal detectors and Card 1 contains data from the two equatorial detectors. This means that the channel 0 detectors, irrespective of card, have the same impact parameter and similarly for the channel 1 detectors. When the voltage input to one channel goes above a threshold, data acquisition for both channels of that card is triggered and a segment is recorded. Each segment lasts for 256 ns during which 64 samples of the input signal are recorded as well as the triggering time. Data acquisition starts approximately 0.5s before the plasma discharge and
Table 2: \(\gamma\)-ray producing fusion reactions in plasmas with corresponding Q-values to the left. \(\gamma\)-ray producing reactions from plasma impurities with corresponding \(\gamma\)-ray energies to the right [3].

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Q-value (MeV)</th>
<th>Reaction</th>
<th>(E_\gamma) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D(p,\gamma)^3\text{He})</td>
<td>5.5</td>
<td>(^9\text{Be}(d,n\gamma)^{10}\text{Be})</td>
<td>2.88</td>
</tr>
<tr>
<td>(D(^3\text{He},\gamma)^3\text{Li})</td>
<td>16.38</td>
<td>(^{12}\text{C}(d,\gamma)^{13}\text{C})</td>
<td>3.09</td>
</tr>
<tr>
<td>(D(t,\gamma)^3\text{He})</td>
<td>16.63</td>
<td>(^9\text{Be}(d,\gamma)^{10}\text{Be})</td>
<td>3.37</td>
</tr>
<tr>
<td>(T(p,\gamma)^4\text{He})</td>
<td>19.7</td>
<td>(^{12}\text{C}(p,p'\gamma)^{12}\text{C}) (1st level)</td>
<td>4.44</td>
</tr>
<tr>
<td>(D(d,\gamma)^4\text{He})</td>
<td>23.8</td>
<td>(^{12}\text{C}(p,p'\gamma)^{12}\text{C}) (2nd level)</td>
<td>3.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^9\text{Be}(^4\text{He},n\gamma)^{12}\text{C})</td>
<td>4.44</td>
</tr>
</tbody>
</table>


does not bargain anything of the cards’ memories are full. It is important to note that the ADC has a 14 bit input range (positive and negative) that can be mapped to different input voltage ranges. Signals above the maximum allowable range are indicated as saturated and their recorded amplitude corresponds to the value 8192.

### 2.5 \(\gamma\)-rays in tokamaks

There are a number of potential sources of \(\gamma\)-rays in tokamaks, both directly from nuclear reactions in the plasma and from neutrons interacting with the surrounding structures (such as the 2.23 MeV \(\gamma\)-ray producing reaction H(n,\(\gamma\))D mentioned in section 2.2) [3, 4]. The latter produces a continuous \(\gamma\)-ray background in the \(\gamma\)-ray spectrum of the NC detectors. The charged rest products of the initial D-D reactions, such as tritons \(^3\text{H}\), protons, \(^3\text{He}\)-ions, are confined in the tokamak to contribute to fusion reactions that produce \(\gamma\)-rays (see table 2). Experiments at JET have identified several \(\gamma\)-ray producing nuclear reactions that involve \(^9\text{Be}\) or \(^{12}\text{C}\) (some of these are shown in table 2). The latter reactions are due to plasma impurities and cause energy losses in the plasma [17]. Beryllium is not used for MAST walls and thus the plasma impurity reactions that involve beryllium are not relevant in this context. Carbon is present in MAST first wall and divertor as well as in the stainless steel structures of the tokamak and thus the carbon reactions are potentially relevant.

High energy run-away electrons of up to 20 MeV can be generated during plasma discharges in tokamaks. In larger tokamaks these electrons can be accelerated to energies (possibly up to 100 MeV) where they can cause serious damage the reactor structures and result in the emission of \(\gamma\)-rays [6]. The Frascati Tokamak Upgrade performed experiments on runaway electrons using plasma currents between 0.3-1 MA, particle density of up to \(10^{20}\) and toroidal magnetic field of 5-7 T [6]. It was observed that the runaway electrons typically emerge during start-up or the dramatic shut-down of the plasma discharge and show no significant production during the more stable flat-top period. Also, Run-away electron production was observed to be greater towards the center of the plasma.

### 2.6 The plasma discharge data from MAST

Two sets of plasma discharges were considered for studying \(\gamma\)-ray emission: the scan discharges and the high statistics discharges. The scan discharges consisted of MAST discharges 29132, 29181, 29207-29210 and 29359 that have similar plasma parameters (NBI power within 3.28-3.50 MW, \(I_p\) in the range of 900-930 kA, \(Y_n\) in the range of 1.59-1.80 \(\times 10^{14}\) n/s) but different impact parameters (see table 3) which allowed the measurement of the \(\gamma\)-ray emission from different regions of the plasma (profile information).

The high statistics discharges consisted of MAST discharges 29383-29385 all characterized by the NC located at the same impact parameter and with equal plasma parameters (NBI power = 3.50 MW, \(I_p = 430\) kA, \(Y_n = 0.45\times10^{14}\) n/s) (again, table 3) to provide \(\gamma\)-ray measurements with better statistics.
The time evolution of relevant plasma global parameters are presented in 4a and 4b for the two sets of discharges respectively. The neutron yield provides information about the activity in the plasma for comparison with the $\gamma$-ray emission time evolution.

### Table 3: Discharge parameters. IP = impact parameter.

<table>
<thead>
<tr>
<th>Discharge #</th>
<th>Ch 0, IP (mm)</th>
<th>Ch 1, IP (mm)</th>
<th>NBI power (MW)</th>
<th>$I_p$ (kA)</th>
<th>$Y_n(10^{14}$ n/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29359</td>
<td>-1215</td>
<td>-1025.2</td>
<td>3.50</td>
<td>930</td>
<td>1.80</td>
</tr>
<tr>
<td>29132</td>
<td>-636.11</td>
<td>-425</td>
<td>3.50</td>
<td>900</td>
<td>1.25</td>
</tr>
<tr>
<td>29210</td>
<td>711</td>
<td>501</td>
<td>3.40</td>
<td>905</td>
<td>1.67</td>
</tr>
<tr>
<td>29209</td>
<td>814</td>
<td>607</td>
<td>3.40</td>
<td>909</td>
<td>1.70</td>
</tr>
<tr>
<td>29181</td>
<td>937</td>
<td>735</td>
<td>3.28</td>
<td>900</td>
<td>1.59</td>
</tr>
<tr>
<td>29207</td>
<td>1141</td>
<td>947</td>
<td>3.41</td>
<td>900</td>
<td>1.64</td>
</tr>
<tr>
<td>29208</td>
<td>1192</td>
<td>1002</td>
<td>3.40</td>
<td>900</td>
<td>1.70</td>
</tr>
<tr>
<td>29383-29385</td>
<td>-1147.8</td>
<td>-954.55</td>
<td>3.50</td>
<td>430</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The time evolution of relevant plasma global parameters are presented in 4a and 4b for the two sets of discharges respectively. The neutron yield provides information about the activity in the plasma for comparison with the $\gamma$-ray emission time evolution.

### 3 Data Analysis

This section describes the analysis methods used to characterize the $\gamma$-ray emission.

#### 3.1 Data analysis software

In the thesis the Online Data Analysis code (ODA) was used to process the NC raw data from each plasma discharge. Baseline corrections, preliminary event identification (whether the pulse type is a neutron/$\gamma$, LED, pile-up, etc.), separation of pile-up events, and PMT gain corrections of the recorded pulses can be performed automatically with ODA. PSD is performed by manually choosing a ROI in the type of 2D Histogram shown in figure 3. ODA identifies all pulses within the ROI as neutrons and the rest as $\gamma$-rays. The overlap of actual neutron pulses with $\gamma$-ray pulses is estimated to be less than 2% [5]. Event Count Rates (CR) can then be obtained corrected for pile-up and dead-time. ODA can provide time evolutions (or time traces) of an event’s CR during a given time interval and allows the selection of specific pulses by amplitude, $Q_T$, $Q_F$, baseline, etc. Additionally, it is possible to obtain PHS and 2D Histograms of the events selected for different parameters. Due to the linear relationship between amplitude and deposited $\gamma$-ray energy, it is thus possible to calibrate the data using the Compton edges of the $^{22}$Na PHS (see section 3.2).
3.2 \( \gamma \)-ray analysis

The typical appearance of the 2D histograms and the chosen ROI used for PSD is seen in figure 3. This work focuses only on the equatorial lines of sight (the card 1 data). Discharge 29132, card 1, channel 0 was found to have used a different high voltage setting than the rest of the channel 0 discharges and was not considered in the analysis. Discharge 29132 channel 1 was still included.

The \(^{22}\text{Na}\) \( \gamma \)-ray PHS are acquired from after the plasma has been terminated as this avoids features in the spectrum from \( \gamma \)-rays that originate from the plasma. Each channel must be calibrated separately and thus the average \(^{22}\text{Na}\) PHS of all discharges is obtained for respective channel. The Compton edges were chosen manually together with the assumption that 0 amplitude corresponds to 0 energy. Assuming a linear relationship between pulse amplitude (A) and energy (E) for channel \( i = 0, 1 \),

\[
E = m_i A + q_i, \tag{6}
\]

the calibration constants are estimated by linear fitting (see table 4).

<table>
<thead>
<tr>
<th>Channel 0</th>
<th>( m_i )</th>
<th>( q_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.000331 \pm 0.000003 \text{ MeVee} )</td>
<td>( 0.004 \pm 0.006 \text{ MeVee} )</td>
<td></td>
</tr>
<tr>
<td>( 0.000354 \pm 0.000002 \text{ MeVee} )</td>
<td>( 0.002 \pm 0.003 \text{ MeVee} )</td>
<td></td>
</tr>
</tbody>
</table>

The resulting calibrated \(^{22}\text{Na}\) PHS for both channels is shown in figure 5. The same calibration constants are used for the static discharges since respective detector had similar high voltage settings. Errors of the constants are from the least square fitting of the three chosen points and no uncertainty was assumed in the location of the Compton Edge.

3.2.1 Time evolution of the \( \gamma \)-ray count rates

The time traces of the high statistics discharges were obtained for i) all energy neutrons to compare with the FC neutron yield and the behaviour in the following energy regions: ii) 1.8-2.15 MeV for the behaviour below and including the \( \text{H}(n, \gamma)\text{D} \) Compton edge at 2 MeV, iii) 2.15-2.68 MeV to exclude the \(^{22}\text{Na}\) \( \gamma \)-rays and \( \text{H}(n, \gamma)\text{D} \) Compton edge, and iv) above 2.68 MeV for the behaviour of saturated \( \gamma \)-rays. These were compared with the time traces of the plasma global parameters (figure 4b) together with FC and NC neutron yield.

The scan discharges time traces for both channels were obtained using the following energy regions: i) 2.15-2.5 MeV as it avoids the \(^{22}\text{Na}\) \( \gamma \)-ray counts and the \( \text{H}(n, \gamma)\text{D} \) Compton edge at 2 MeV, ii) above 2.68 MeV as it comprises primarily saturated \( \gamma \)-rays, iii) 1.8-2.15 MeV for the \( \gamma \)-ray behaviour below and including the 2 MeV Compton edge and iv) all energies for a general overview of the \( \gamma \)-ray spatial distribution.

3.2.2 Pulse height spectra

The high statistics discharge gamma PHS were obtained from three different time regions: i) 0.1-0.3 s for the start-up phase, ii) 0.3-0.6 s for the steady CR region and iii) 0.6-0.7 s for the shut-down phase. These PHS were summed over respective time region and compared as they could potentially provide insight into interesting differences in the temporal evolution of the \( \gamma \)-ray emission.

The scan discharge gamma time traces of all energies were compared to find a shared time window where the CRs were stable. The time window was chosen as 0.23s - 0.3 s (see figure 6) and was used for the gamma PHS in addition to the gamma PHS of the entire plasma duration. These
will provide the energy distribution of the γ-rays and in particular the higher energy γ-rays. The 2D histogram of recorded pulses versus QT and amplitude and non-saturated individual segment pulse shapes with a QT above 25000 were obtained to investigate an anomaly in the channel 0 gamma PHS.

![CH0 discharge gamma count rates](image)

(a) Channel 0

![CH1 discharge gamma count rates](image)

(b) Channel 1

Figure 6: Gamma time traces of the scan discharges for all energies and both channels. Common time window where discharges are stable and active indicated by dashed lines at 0.23 s and 0.3 s.

3.2.3 γ-ray emission profiles

The time window 0.23-0.3 s was also used for the profile view count rates. Different energy regions were considered for the profiles: i) 2.15-2.5 MeV as it avoids the 22Na γ-ray counts and the H(n,γ)D Compton edge at 2 MeV, ii) above 2.68 MeV as it comprises primarily saturated γ-rays, iii) 1.8-2.15 MeV for the γ-ray behaviour below and including the 2 MeV Compton edge and iv) all energies for a general overview of the γ-ray spatial distribution. Note the similarity between these energy regions and the energy regions used for the high statistics time traces. The difference being the 2.15-2.5 MeV (scan) and 2.15-2.68 MeV (high statistics) regions and this is due to that no counts were observed in the 2.5-2.68 MeV region for the scan discharges but not for the high statistics discharges.

4 γ-ray observation in the Neutron Camera

This section present the results and figures obtained by the methods described in section 3.

4.1 High statistic series

This subsection presents the high statistics γ-ray PHS for the different time regions and the time traces for different energy regions. The energy calibrated (as explained in section 3.2) γ-ray PHS is presented in figure 7. The PHS counts drop significantly at approximately 2.6 MeV (channel 0) and 2.7 MeV (channel 1) and stay low until saturation. This phenomena is less tangible for channel 0 as the saturation occurs at approximately 2.7 MeV, soon after the counts drop. Also, a small peak can be distinguished just before the count drop, however, this could be simply due to statistical variation in counts.

The high statistics time traces from approximately 0.22 s and onward were used for the temporal evolution analysis (see figure 8). The γ-ray time traces follow the neutron emission time traces for all considered energy regions.
Figure 7: Sum of high statistics discharges’ gamma PHS for respective channel and for different time regions i) 0.1-0.3s (blue), ii) 0.3-0.6s (black) and iii) 0.6-0.7s (red). [12]

Figure 8: Time traces show, in order top to bottom, i) FC neutron yield, ii) NC neutron yield for channel 0, iii) gamma emission in 1.8-2.15 MeV, iv) gamma emission in 2.15-2.68 MeV and v) gamma emission above 2.68 MeV. The blue time traces are a sum of the high statistics discharges. The dashed lines the indicate well-behaved region (see section 4.1). No notable difference between channels. [12]

4.2 Scan discharges

The γ-ray PHS from discharge 29181 channel 0 and channel 1 are shown in figure 9 and 10 respectively. These PHS are typical of the scan discharges where channel 0 shows a significant peak above 2.2 MeV. The peak is present in all the data recorded in channel 0 for these plasma discharges but its position varies between 2.2 and 2.5 MeV. The time window 0.23-0.3 s shows no counts between 2.3 MeV and saturation, whereas significant counts are observed in this energy region during the entire plasma discharge. This is also observed for channel 1.

In order to investigate the origin of this unexpected feature in the channel 0 PHS, a comparison of the 2D histograms of recorded γ-rays versus $Q_T$ and amplitude between both channels is shown
An anomaly is observed at approximately 6800-7000 amplitude (which corresponds to energy region 2.2-2.3 MeV) for all channel 0 scan discharges. Note the linear relationship between $Q_T$ and amplitude as well as the inclusion of the saturated counts. From these histograms it is also observed that saturated counts are generally lower for channel 0 which shows counts in the range of 1300-2500 to be compared with counts in the range of 3200-4000 for channel 1.

(a) The shared time window (0.23-0.3 s).
(b) Plasma discharge duration (0.04-0.39 s).

Figure 9: gamma PHS in energy for discharge 29181 card 1 channel 0, different time regions. [12]

(a) The shared time window (0.23-0.3 s).
(b) Plasma discharge duration (0.04-0.39 s).

Figure 10: gamma PHS in energy for discharge 29181 card 1 channel 1, different time regions. [12]

An investigation of the individual segment pulse shapes with a $Q_T$ higher than 25000 and an amplitude in a narrow region around the channel 0 peak yielded regular pulse shapes of $\gamma$-rays with the exception of being slightly wider. Figure 12 presents a typical of these "anomalous" pulse shape from discharge 29181 channel 0. A similar investigation of the channel 1 pulse shapes revealed that the count "bump" after 22000 $Q_T$ shown in the PSD histograms (figure 3b) consists of primarily saturated $\gamma$-rays.
Figure 11: 2D histogram of recorded $\gamma$-rays versus $Q_T$ and amplitude including the saturated $\gamma$-rays at amplitude 8192 for time region 0-1s (this region contains the entire plasma duration). Discharge 29181, both channels. Note the edge starting at approximately 6800 amplitude for channel 0. [12]

The gamma emissivity profiles for each channel and for the four energy regions in the common time window 0.23s-0.3s are presented in figure 14. No counts were observed in the region 2.5-2.68 MeV for this time window. A CR discrepancy between channels is observed in energy regions 2.15-2.5 MeV and above 2.68 MeV, the former showing higher CR for channel 0 and the latter showing higher CR for channel 1. Channel 0 above 2.68 MeV shows an increase in CR for larger impact parameters, whereas channel 1 shows a more steady CR across the impact parameters. For 2.15-2.5 MeV, channel 0 shows a slight relative increase in CR for larger impact parameters, while channel 1 shows CR varying between 3-6 kHz in a less ordered manner.

The profiles of all energies and 1.8-2.15 MeV do not show such a discrepancy and they share a small CR drop around impact parameter 0.5-1 m with a minimum close to the centre of the plasma (at approximately 0.85m).

Typical time traces for the scan discharges are presented in figure 13. As stated in section 3.2, different energy regions were considered for different channels due to the channel 0 anomaly. The channel 0 PHS peak was in the energy region 2.2-2.4 MeV and the energy regions of the channel 0 time traces’ considered were based on this: i) 1.8-2.15 MeV (below the peak), ii) 2.15-2.5 MeV (within the peak), iii) 2.5-2.68 MeV (after the peak, below saturation), iv) above 2.68 MeV (saturated events). Most notable are the time traces for energy regions 2.5-2.68 MeV for both channels where the CR drops between approximately 0.2-0.34s. This is in agreement with lack of observed counts during the common time window (0.23-0.3s) for energies 2.5-2.68 MeV. The region 2.15-2.5 MeV for channel 1 shows two interesting peaks at 0.2 s and 0.34 s and an otherwise flatter shape compared to the neutron time traces.

5 Discussion

On an initial note, it is important to realize that the uncertainties associated to the energy calibration are underestimated as no uncertainty in the Compton edge was assumed.

On a second note, the cross-sections for the $\gamma$-ray producing reactions and an inclusion of the reactions between neutron and structure materials carbon, iron and lead would benefit the $\gamma$-ray analysis performed in this thesis.

The count drop at 2.6-2.7 MeV in the high statistics gamma PHS (figure 7) is hard to analyze due to its narrow range (this is particularly true for channel 0 due to its lower saturation energy). Since the NC detectors have negligible photo-electric cross-section, a continuous CR decline as observed for the $^{22}$Na Compton edge (figure 5) is expected in contrast to the sharp decline of said CR drop. Up to 2.6 MeV, however, the similar continuous distribution of $\gamma$-rays for the different
time regions reveal very little about the origin of the $\gamma$-rays. It is possible, but not certain, that this could rule out effects of runaway electrons at these energies. Higher statistics analysis together with a detection system with a higher energy range is likely required to more extensively analyze the higher energy $\gamma$-rays using PHS.

The channel 0 anomaly (or PHS peak) is likely the cause of the CR discrepancy in the emissivity profiles (of energy regions 2.15-2.5 MeV and above 2.68 MeV, figures 14b, 14d), rather than some interesting physics in the plasma, since the behaviour persists in only channel 0 across a variety of impact parameters. However, considering that the differences in CR display a reversed behaviour for the higher energy region (higher CR for channel 0 in region 2.15-2.5 MeV, yet lower CR for channel 0 above 2.68 MeV), additional explanations are possible. It is tempting to conclude that the excess counts for channel 0 in the range 2.15-2.5 MeV are during data acquisition erroneously taken from the energy region above 2.68 MeV (see also the time traces for said regions 13), however, more analysis is needed. The regular, but wider, pulse shapes corresponding to the anomalous counts (figure 12) could possibly be explained by a some type of pile-up event. Why this speculated pile-up would be localized to a certain region of $\gamma$-ray energies is an open question that will be addressed in further studies. A simpler explanation could be that there exists some issue with the channel 0 data acquisition. In particular, the anomalous behaviour appears stronger during the flat-top period where plasma density and neutron CR is higher (figure 13a) - something which could affect the acquisition system - and a similar channel 0 anomaly is not found for the high statistics discharges that have a lower plasma density and neutron CR during the flat-top period. Yet, a more extensive analysis, perhaps coupled with higher resolution sampling and a higher detectable energy range, is required to fully explain this channel 0 anomaly. On a sidenote, it is possible that the additional counts above 25000 $Q_T$ for channel 0 obscures a count bump of saturated events similar to the one observed in the channel 1 PSD histogram (figure 3).

The scan discharges PHS also show a difference between common time window (0.23-0.3 s) and the full plasma duration (approximately 0.54 s for the scan discharges) (figures 9 and 10). This suggests a different $\gamma$-ray behaviour during the start-up and shut-down periods from the flat-top period of the discharge. A glance at the time traces for energy region 2.5-2.68 MeV for channel 1 (figure 13b) further supports this: 2.5-2.68 MeV $\gamma$-rays are observed during the during start-up and shut-down but not during the flat-top region (0.2-0.36 s). A possible origin of these 2.5-2.68 MeV $\gamma$-rays are run-away electrons as their temporal evolution is similar to that observed by B Esposito et al [6]. However, with no spatial distribution for the 2.5-2.68 MeV $\gamma$-rays during the start-up and shut-down time regions further analysis of their origin is limited.

Figure 13: Discharge 29181 time traces of, in order top to bottom, i) FC neutron yield, ii) NC neutron yield, iii- vi) gamma emission in different energy regions. Channel 0 time traces in red, channel 1 time traces in black (FC neutron yield is not included in this distinction as it belongs to other detector systems). [12]
Figure 14: Gamma emissivity profiles (CR versus impact parameter) of common time window 0.23-0.3 s for two energy regions. Channel 0 profile in red, channel 1 profile in black. Note the CR discrepancy between channels for energy regions 2.15-2.5 MeV and above 2.68 MeV. CR was zero for energy region 2.5-2.68 MeV in said time window. Error bars are from assuming Poisson distributed counts. [12]

The time traces for region 1.8-2.15 MeV is similar to the neutron time traces, which is indicative of a majority contribution from the 2.2 MeV γ-rays of the H(n,γ)D reaction. Similarly is true for the region above 2.68 MeV, although other reactions must be the cause, possibly reactions in the plasma or neutrons interacting with the surrounding structures. Without properly establishing the energies of these γ-rays, it is difficult to further analyze their origin. However, it is possible to exclude a significant cosmic origin of the saturated γ-rays due to the time trace’s similarity to the neutron time trace and the extremely rare occurrence of saturated γ-ray events after plasma shut-down.

The gamma emissivity profiles show a CR drop in impact parameter range 0.5-1 m for energy regions 1.8-2.15 MeV and all energies (figures 14c, 14a). With higher CR closer to the tokamak walls, this is indicative of a notable γ-ray contribution (about 15-20% higher at 0.5 m or 1 m than at 0.75 m) from neutron interactions with the surrounding structure for all energies. Energy regions 2.15-2.5 MeV and above 2.68 MeV show a similar CR decline but with the centre-most CR increasing again. This could be indicative of contributions from reactions or phenomena in the plasma centre, however, the random errors of the CR make these distinctions and conclusions more difficult. More data, possibly with higher resolution, is required for further analysis of gamma emissivity profiles.
6 Conclusions

This thesis explored the potential to characterize γ-rays at MAST using the low energy resolution and limited energy range γ-ray data from the Neutron Camera. Two sets of data were considered for the analysis: the high statistics discharges with a higher statistics view of the temporal evolution of the γ-rays and the scan discharges with a lower statistics view of the temporal evolution and spatial distribution. An anomaly in the energy distribution of the γ-rays for one channel was observed for the scan discharges, possibly due to data acquisition issues. Cosmic origin of the saturated γ-rays (above 2.7 MeV) was excluded and the γ-rays of energies above 2.2 MeV are possibly due to reactions in the plasma or of subsequent neutrons interacting with MAST components, yet no specific origins were concluded. Further, the results from the high statistics set of discharges and from the spatial distribution of γ-rays were generally inconclusive and this suggests that a detection system with higher energy resolution and range is required for a more conclusive analysis of the γ-ray emission at MAST.
References


[12] Figure obtained using the online data analysis software.


