High Count Rate Neutron Detector Installation at JET

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Abstract
The measurement of fusion power is of paramount importance for the control of a fusion reactor’s operation. The neutron yield from the reactor is strictly related to the energy production. One of the methods employed at JET to measure the yield involves the use of the MPRu spectrometer together with the neutron camera. However the MPRu has an intrinsically low efficiency ($\sim 10^{-6}$), which results in a poor time resolution. An improvement involving the installation of a NE213 detector for high count rate has been proposed. The testing phase of the new instrumentation, conducted at Uppsala University, has shown that the acquisition system works properly and it is ready to be installed on site in view of the coming JET experimental campaign.

1 Introduction
Neutron diagnostics has been used for many years to study the properties of the plasma and the fusion reaction rates. The MPRu (Magnetic Proton Recoil) spectrometer installed at JET is mainly used to provide information about the neutron energy distribution. However, if combined with the neutron camera, it has proven the capability to measure the neutron yield [1]. In order to improve this feature, the MPRu will be upgraded with the installation of a NE213 liquid scintillator with digital data acquisition, that will allow the measurement of the neutron flux from DD plasmas with good time resolution.

This report completes the work started in a previous one [2] and includes the test of the new detector’s magnetic shielding, the evaluation of the quality of different neutron-gamma discrimination methods and an assessment of the line of sight of the MPRu system as installed in the JET Torus Hall in the summer of 2011.

2 Magnetic Shielding
Photomultiplier tubes (PMT) are sensitive to magnetic fields because they can bend the trajectories of the electrons, with consequent variation of the gain and possible damages. In order to protect the PMT used in this project, a holder with magnetic shielding has been designed and built. When delivered from the manufacturer, the PMT is already surrounded by a 0.2 mm cylinder of mu-metal, a nickel-iron alloy with relative magnetic permeability $\mu \sim 10^5$. The holder (Figure 1) adds a cylinder of 2.1 cm thick soft iron ($\mu \sim 10^3$) to the shielding. The holder mechanics is shown in Figures 2a-c. In 2(a) all parts of the fully disassembled holder are shown, including a ruler (cm scale) to indicate size. In Figure 2(b) the magnetic cylinder is shown to the left and the NE213 detector to the right behind it. The two pieces in front are pieces for holding the detector in place. In Figure 2(c) the detector has been placed inside the magnetic shield cylinder.

A test of the performance of the shielding has been done using a coil to generate a magnetic field and a magnetic probe to measure it. Two different directions of the field were tested, one parallel to the cylinder axis and one perpendicular.
Figure 1: Drawing of the holder for the new MPRu flux detector. The part with light blue solid lines is the magnetic shielding. Some details were changed in the components that were finally built.

Figure 2: Photos of the manufactured mechanics and the scintillator.

2.1 Probe Calibration

The magnetic probe is an electronic device that reacts to different magnetic field intensities giving different output voltages. The relationship between field intensity and output voltage is linear and it’s very sensitive to temperature changes. Therefore the calibration and the measurements have been done when the probe had reached a nearly stable temperature.

It is known that the magnetic field in the centre of the particular coil used here depends on the supply current according to the formula $B[T] = 2.691 \times 10^{-3} \cdot I[A]$ [3]. In order to perform the calibration, the probe was positioned in the centre of the coil and the magnetic field was varied by changing the alimentation current of the coil.

Because of the high sensitivity of the probe to the temperature, the calibration has been done separately for the two measurement settings, i.e., parallel and perpendicular (Figure 3).

The data were fit with a straight line (Figure 4) and the results of the fits for the two different
configurations 3(a) and 3(b) are respectively:

\[
\begin{align*}
B[T] &= 8.78 \cdot 10^{-3} \cdot V[V] - 1.90 \cdot 10^{-3} \\
B[T] &= 9.20 \cdot 10^{-3} \cdot V[V] - 2.40 \cdot 10^{-3}
\end{align*}
\]

### 2.2 Measurements

For the test the probe was located along the axis of the coil at a fixed distance from the centre. The distance was set by positioning the probe inside the shielding at the location of the PMT and then collocating the shielding as close as possible to the coil.

The field was measured with and without the shielding and the data were recorded for four alimentation current values. Both the perpendicular and parallel directions of the field were tested, using the two different setups shown in Figure 3.

![Figure 3: Experimental setup for the test with perpendicular (a) and parallel (b) field.](image)

The readout of the voltage is done using a multimeter set with a sensitivity of 1mV, that, in terms of magnetic field, corresponds to \(9 \cdot 10^{-6} T (0.09 \text{ Gauss})\) (see 1). This value has been used as uncertainty of the measurement.

### 2.3 Results

The results of the magnetic shielding tests are shown in table 1 and 2.
Table 1: Magnetic test results for perpendicular field (Figure 3(a)).

<table>
<thead>
<tr>
<th>B without shielding (Gauss)</th>
<th>B with shielding (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.04 ± 0.09</td>
<td>0.09 ± 0.09</td>
</tr>
<tr>
<td>5.58 ± 0.09</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td>8.39 ± 0.09</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td>11.99 ± 0.09</td>
<td>0.27 ± 0.09</td>
</tr>
</tbody>
</table>

Table 2: Magnetic test results for parallel field (Figure 3(b)).

<table>
<thead>
<tr>
<th>B without shielding (Gauss)</th>
<th>B with shielding (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.74 ± 0.09</td>
<td>0.09 ± 0.09</td>
</tr>
<tr>
<td>2.21 ± 0.09</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td>3.04 ± 0.09</td>
<td>0.27 ± 0.09</td>
</tr>
<tr>
<td>4.23 ± 0.09</td>
<td>0.36 ± 0.09</td>
</tr>
</tbody>
</table>

With the instrumentation available it was not possible to reach the field values expected at JET neither for the perpendicular component (about 0.0100 T) nor for the parallel (about 0.0010 T). However, assuming a linear relationship between the field in the case with shielding and the one in the case without shielding (Figure 5), it is possible to extrapolate the field inside the shield for the expected external field, which is (2.4 ± 0.6) Gauss for a perpendicular of 100 Gauss and (0.9 ± 0.2) Gauss for a parallel field of 10 Gauss. All the measured and extrapolated fields inside the shielding fall in a range that, considering the presence of the mu-metal shielding, does not affect significantly the performances of the photomultiplier [4].

Figure 5: Linear fit for (a) data from table 1 and (b) data from table 2.
3 Pulse Shape Discrimination

The PMT gain can vary because of many different factors. Therefore a $^{22}\text{Na}$ radioactive source and a LED light pulse generator are used as gain monitoring system. This creates additional signals that must be separated from the ones generated by neutrons interacting in the scintillator. The LED events are easy to recognize because they have a symmetrical shape and they also come at well defined times. The separation between gammas and neutron events in the detector is less straightforward, but still possible due to the fact that liquid scintillators of this type (NE213) have different response to different incident particles. More precisely, the scintillation mechanism of neutrons gives rise to pulses which have a more pronounced tail than pulses from gammas (see Figure 6).

Figure 6: Shape differences between pulses generated by different particles in an organic scintillator. (from [6]).

There are many ways to exploit this difference and the efficiency of the method used depends on the characteristics of each particular acquisition system. Neutron and gamma interactions were generated using a $^{252}\text{Cf}$ source. $^{252}\text{Cf}$ is an element that undergoes alpha decay and spontaneous fission. The first produces alpha particles which are easily stopped and do not reach the detector. The second generates the neutrons we want to measure, while the gamma rays come from the de-excitation of the nuclei that decay from an excited state. The neutron spectrum from spontaneous fission is continuous, and an exponentially decreasing intensity toward higher energies, which can be approximated by

$$\frac{dN}{dE} = \sqrt{E} \cdot e^{-E/T}$$  \hspace{1cm} (2)

Where the value of $T$ is 1.3MeV.

A pulse-shape dependent discrimination factor (PSD), which varies according to the method in use, is computed for each pulse. The distribution of the PSD values allows to separate gamma and neutron events. The comparison parameter which gives a quantitative information about the quality of the separation is called Figure Of Merit (FOM) and it is computed using the formula:

$$FOM = \frac{\Delta PEAK}{FWHM_n + FWHM_\gamma}$$ \hspace{1cm} (3)

where $\Delta PEAK$ is the distance between the two peaks representing gamma and neutron events, $FWHM_n$ and $FWHM_\gamma$ are the full width at half maximum of the two peaks (see Figure 7).

The distribution varies with the energy, therefore the events are divided into energy bands and the FOM is computed separately for each band.

Five different techniques were tried and compared to find out the most suitable one in this case:

1. Charge Comparison (CC);
2. Pulse Gradient Analysis (PGA);
3. Rise Time (RT);
4. Zero Crossing (ZC);
5. Time Over Threshold (TOT).

Furthermore three combinations of these methods were tested, using as PSD the product of the PSDs obtained from the single methods:

1. CC + PGA;
2. CC + RT;
3. CC + ZC.

Every technique requires the optimization of one or more parameters. This was done by trial, evaluating the FOM for different settings and choosing the one which gave the best results.

All techniques also require that the baseline from which the signal pulse emerges is properly established. Here we have used a simple average of the 32 voltage values before the pulse to give the mean value of the baseline. In cases with more severe pick-up more advanced baseline restoration techniques might be required.

Finally the dependence of the FOM on the digitizer’s resolution and sampling frequency has been studied by, first, comparing the results obtained using the SP Devices ADQ214 (14bit, 400MSPS) and a CAEN DT5720 (12bit, 250MSPS), and secondly, by acquiring data with a third digitizer (ADQ412, 12bit, 2GSPS) and then downsampling the pulses (i.e. reducing the number of samples per time interval).

3.1 Method 1 - Charge Comparison

This approach is the most simple in terms of both concept and ease to implement and it has also the advantage of having small computational requirements. Two intervals of integration are defined (Figure 8): one long that covers the whole pulse duration and one short that covers just the first part of the pulse. The samples within each interval are summed to form the quantities $Q_{long} = \sum_0^{t_{LONG}} V(t)$ and $Q_{short} = \sum_0^{t_{SHORT}} V(t)$, where V are the baseline corrected voltage samples.

The PSD factor is defined by the formula:

$$PSD = \frac{Q_{long} - Q_{short}}{Q_{long}} \quad (4)$$
3.2 Method 2 - Pulse Gradient Analysis

Another value that can be used to distinguish neutrons from gammas is the gradient between the maximum amplitude of the pulse and the amplitude at a certain time after the maximum (Figure 9), which must be carefully chosen to maximize the separation \[7\]. The discrimination factor is calculated using the formula:

\[
PSD = 1 - \frac{V(t_{\text{max}}) - V(t_{\text{max}} + \Delta t)}{Q_{\text{long}}}
\]  \hspace{1cm} (5)

with \(Q_{\text{long}}\) being the total charge of the pulse.

3.2.1 Pulse Reconstruction

This technique requires much more computational time than the others because of the need to mathematically reconstruct the pulses. During the digitalization process the information about the maximum amplitude of the signal is apparently lost, since the highest sampled value is not in general the real maximum of the pulse. However the Nyquist - Shannon theorem [8] states that it is possible to completely
reconstruct a sampled signal whose frequency spectrum contains only components lower than 1/2 of the sampling frequency. The method consists in substituting every sample with a sinc function:

\[
sinc(t) = A \frac{\sin(\pi \omega (t - t_0))}{\pi \omega (t - t_0)}
\]  

(6)

where \( A \) is the amplitude of the sample, \( t_0 \) is the sampling instant and \( \omega \) is the sampling frequency.

Components with frequency equal or higher than 1/2 of the sampling frequency cannot be distinguished, giving rise to the aliasing effect, which can be understood looking at Figure [10]. An example of aliasing in a reconstructed pulse is shown in Figure [11].

![Illustration of aliasing. The three different components at frequency equal to \( f_s/2 \) are sampled in exactly the same way.](image)

Figure 10: Illustration of aliasing. The three different components at frequency equal to \( f_s/2 \) are sampled in exactly the same way.

![Neutron average pulse shapes, taken with short cables in the lab, from the studied NE213 detector reconstructed using the Nyquist - Shannon theorem. The black line is the reconstructed pulse without filtering and the aliasing effect is clearly visible; the red line is the same pulse after filtering.](image)

Figure 11: Neutron average pulse shapes, taken with short cables in the lab, from the studied NE213 detector reconstructed using the Nyquist - Shannon theorem. The black line is the reconstructed pulse without filtering and the aliasing effect is clearly visible; the red line is the same pulse after filtering.

The properties of the digitizer must therefore be chosen to match the measurement conditions at hand, in particular ensuring that the sampling speed is sufficient for the frequency contents of the signal.

to be digitized. It has been established that the ADQ214 is adequate for the JET installation, where
the digitizer is removed from the detectors by 120 m of coaxial cable. However, the short cables used in
the lab tests reported here mean that a large portion of high frequency signal is still present. To mimic
the final installation, a digital low pass filter has been applied to the data as shown in Figure 11.

It is worth noting that the process of pulse reconstruction is very time consuming, a fact that makes
it unsuitable for an eventual real-time on-board implementation.

3.3 Method 3 - Rise Time

Dealing with cumulative integrated signals is another possibility [9]. When integration of a pulse is
performed, the result looks like the one in Figure 12 and maintain some characteristics that allow the
separation.

![Figure 12: Illustration of the rise time method.](image)

Given a fixed amount of deposited energy a gamma pulse has a faster rise time than a neutron pulse
and this feature is reflected also in the rise time of the processed events. The PSD factor employed to
perform the separation is therefore the time interval between two points of the integrated pulse which
are identified by two threshold levels, here arbitrarily set to 20% and 80% of the maximum in order to
avoid triggering from the noise:

$$ PSD = \Delta t_{RT} $$

To improve the result, the time instants are computed with a linear interpolation between sampling
points.

3.4 Method 4 - Zero Crossing

The application of a certain shaping filter to the signal can result in a bipolar pulse, meaning that at
some point it crosses the zero level (Figure 13).

As described in [10] the desired result can be achieved through a digital \( C_1 R_1 - (R_2 C_2)^2 \) filter,
provided the \( C_1 R_1 \) and \( R_2 C_2 \) constants are properly set. One of the advantages of the filtering procedure
is that it significantly reduces the noise.

The discrimination factor is the time interval between a trigger set at a constant fraction of the
maximum amplitude and the zero crossing point. In this case the trigger level was arbitrarily set at
30%:
$PSD = \Delta t_{ZC}$ \hfill (8)

As in the rise time technique, the time instants are linearly interpolated.

### 3.5 Method 5 - Time Over Threshold

The time over threshold method \cite{9} is performed by measuring the time interval during which the signal remains above a certain amplitude level:

$PSD = \Delta t_{TOT}$ \hfill (9)

The threshold must be set high enough to avoid triggering due to the baseline random oscillations, but low enough to show a good separation.

Again a linear interpolation between samples is used to find the two threshold crossing points with higher accuracy.
Table 3: FOMs for the different discrimination techniques and for different energy intervals.

<table>
<thead>
<tr>
<th>Method</th>
<th>600-1850</th>
<th>1850-3100</th>
<th>3100-4350</th>
<th>4350-5600</th>
<th>&gt; 5600</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(3000-9250)(^a)</td>
<td>(9250-15500)</td>
<td>(15500-21750)</td>
<td>(21750-28000)</td>
<td>(&gt;28000)</td>
</tr>
<tr>
<td>Charge Comparison</td>
<td>0.99</td>
<td>1.35</td>
<td>1.49</td>
<td>1.51</td>
<td>1.54</td>
</tr>
<tr>
<td>Pulse Gradient Analysis</td>
<td>0.93</td>
<td>0.99</td>
<td>1.08</td>
<td>1.09</td>
<td>1.11</td>
</tr>
<tr>
<td>Rise Time</td>
<td>0.89</td>
<td>1.13</td>
<td>1.30</td>
<td>1.38</td>
<td>1.44</td>
</tr>
<tr>
<td>Zero Crossing</td>
<td>0.72</td>
<td>1.03</td>
<td>1.30</td>
<td>1.51</td>
<td>1.57</td>
</tr>
<tr>
<td>Combined PGA-CC</td>
<td>1.02</td>
<td>1.32</td>
<td>1.52</td>
<td>1.64</td>
<td>1.61</td>
</tr>
<tr>
<td>Combined RT-CC</td>
<td>0.82</td>
<td>1.08</td>
<td>1.28</td>
<td>1.51</td>
<td>1.50</td>
</tr>
<tr>
<td>Combined ZC-CC</td>
<td>1.00</td>
<td>1.33</td>
<td>1.50</td>
<td>1.52</td>
<td>1.59</td>
</tr>
</tbody>
</table>

\(^a\) The intervals in the second row are the total charge intervals for the PGA and PGA-CC methods.

3.6 Results and Comparison

For each method a 2D plot was created, indicating the total charge on the horizontal axis and the PSD factor on the vertical axis. The FOM was calculated for some 1D projections of this plots corresponding to various total charge intervals, divided as shown in Figure 15.

The plots are shown in Figure 16 and 17. The plots for the combined methods are shown in Figure 18 and 19. The FOMs are shown in table 3.

The time over threshold method can immediately be discarded because the separation (Figure 16(e)) does not seem to be doable and it was not possible to find the FOMs. All the other methods give good results and the best FOMs are provided by the charge comparison technique. The combinations that apparently give a better discrimination are the PGA-CC and the ZC-CC, but the improvement with respect to the CC is not small.

3.6.1 FOM Dependence on the Digitizer’s Features

The test performed with the DT5720 digitizer produced the data shown in Figures 20 and 21. The Figures Of Merit for the two digitizers are shown in table 4. The result is clearly poorer for the DT5720 than for the ADQ214, due to the lower resolution and the lower sampling frequency that quickly increase the uncertainty in the determination of the integrated charge. In fact the Figure 22 showing the resulting 2D plot for the ADQ214 if the resolution and the sampling frequency are downgraded to 12 bits and 200MSPS, looks similar to Figure 20 and also the FOMs obtained (table 4) are comparable.
Figure 16: 2D plots for the different PSD methods studied here: (a) - charge comparison; (b) - pulse gradient analysis; (c) - rise time; (d) - zero crossing; (e) - time over threshold.

Table 4: FOMs for the two digitizers (Charge Comparison).

<table>
<thead>
<tr>
<th>Digitizer</th>
<th>FOM 1</th>
<th>FOM 2</th>
<th>FOM 3</th>
<th>FOM 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP Devices ADQ214</td>
<td>0.99</td>
<td>1.35</td>
<td>1.49</td>
<td>1.51</td>
</tr>
<tr>
<td>CAEN DT5720</td>
<td>0.63</td>
<td>0.88</td>
<td>0.94</td>
<td>0.96</td>
</tr>
<tr>
<td>SP Devices ADQ214 downgraded</td>
<td>0.66</td>
<td>0.82</td>
<td>0.85</td>
<td>0.92</td>
</tr>
</tbody>
</table>

* The energy intervals might not be exactly the same for the two digitizers.
Figure 17: Projection plots for the different methods:  
(a) - charge comparison;  
(b) - pulse gradient analysis;  
(c) - rise time;  
(d) - zero crossing.

Figure 18: 2D plots for the different combination of the charge comparison method with:  
(a) - pulse gradient analysis;  
(b) - rise time;  
(c) - zero crossing;
Further studies have been performed using a third digitizer, a ADQ412 with 12 bits resolution and 2 GHz sampling frequency. The acquired pulses were gradually downsampled to 1 GHz, 500 MHz, 250 MHz and 125 MHz. Figure 23 shows the dependence of FOM on the sampling frequency. The values for the two highest frequencies are very similar, while for sampling frequencies below 500 MHz the separation starts to degrade quickly.
Figure 21: Projection plots for the CAEN DT5720.

Figure 22: "Downgraded" 2D plot for ADQ214 (charge comparison method).

Figure 23: Figure of merit vs sampling frequency for 4 different energy intervals (see Figure 15).
3.6.2 Number of Counts Correction

When measuring the neutron flux what is needed is the number of neutrons that struck the detector during a certain time interval. The pulse shape discrimination projection plot gives two gaussians which can be overlapping (Figure 24(a)). Thus, if a cut-off level is set to separate events, some of the gammas are counted as neutrons and vice versa (Figure 24(b)). However, it is possible to obtain a more precise number of counts by making a correction for the overlap.

First of all, one must find the intersection point of the two gaussian functions, which is done by solving the equation

\[
\frac{e^{-\frac{(\mu_n-x_{int})^2}{2\sigma_n^2}} + e^{-\frac{(\mu_\gamma-x_{int})^2}{2\sigma_\gamma^2}}}{A_\gamma} = \frac{A_n}{A_\gamma}
\]  

(10)

where \(A, \mu\) and \(\sigma\) are the parameters obtained from the double gaussian fit.

Then the fraction of neutron events that fall in the gamma peak can be found using the cumulative distribution function of the gaussian

\[
\alpha_n = \frac{1}{2} \left[ 1 + erf\left(\frac{x_{int} - \mu_n}{\sqrt{2}\sigma_n}\right) \right]
\]  

(11)

and similarly the fraction of gamma events that fall in the neutron peak is given by

\[
\alpha_\gamma = 1 - \frac{1}{2} \left[ 1 + erf\left(\frac{x_{int} - \mu_\gamma}{\sqrt{2}\sigma_\gamma}\right) \right]
\]  

(12)

The number of neutrons found by dividing the events with a cut-off level is given by

\[
C_n = (1 - \alpha_n)N_n + \alpha_\gamma N_\gamma
\]  

(13)

where \(N_n\) and \(N_\gamma\) are the real number of neutron and gamma events. The first term of equation 13 represents the real neutron events falling in the neutron peak while the second term represents the gamma events falling in the neutron peak. The same reasoning applies to the gamma counts

\[
C_\gamma = (1 - \alpha_\gamma)N_\gamma + \alpha_n N_n
\]  

(14)

Finally, solving the system composed by the equations 13 and 14 gives the corrected number of neutron and gamma events.
\[
N_n = \frac{\alpha_n C_n - (1 - \alpha_n)C_n}{\alpha_n + \alpha_n - 1} \quad (15)
\]
\[
N_\gamma = \frac{\alpha_n C_\gamma - (1 - \alpha_n)C_\gamma}{\alpha_n + \alpha_\gamma - 1} \quad (16)
\]

As an example, the correction for the first energy band for the charge comparison method (Figure 24(a)) has given the following result:

\[
C_n = 7384
\]
\[
C_\gamma = 49804
\]
\[
N_n = 7451
\]
\[
N_\gamma = 49737
\]

with a correction in the number of neutrons of about +1%.

4 Line Of Sight and MPRu Misalignment Correction

4.1 Line Of Sight Computation

The Line Of Sight (LOS) can be defined as the portion of the plasma that is seen by the detector. It is paramount to know the LOS to be able to calculate the total neutron yield. For this purpose, a code called LINE1 was developed. It is an optical model in which some limiting (opaque) surfaces, that prevent the neutrons from reaching the detector, are defined; the plasma is divided into small volume units (voxels) and the code computes the solid angle seen by the detector from each voxel. In the MPRu model, two limiting surfaces are involved, which correspond to the fronts of the two parts of the neutron collimator. The output of the code convoluted with the emission profile, ideally provided by the neutron camera when available, gives the expected neutron flux on the conversion foil[1].

4.2 MPRu Alignment

In order to verify that all the components inside the MPRu that determine the LOS are aligned, six removable cross-hairs made of thin nylon or metal wires were placed along the optical axis, i.e., the straight line ideally passing through the center of the instrument, which is defined by the two most distant cross-hairs. The measurement of the alignment is performed using a theodolite set up with a view through the MPRu from the plasma point of view (Figure 25) and evaluate if the cross-hairs are placed on a straight line. During the 2009-2011 JET shut down it was found that the moving part of the neutron collimator is not perfectly aligned with the others (Figure 25). It was not possible to correct this misalignment mechanically and it is therefore necessary to evaluate its effect on the performance of the spectrometer.

The estimate of the magnitude of the misalignment, done by eye comparing the cross-hair position at the front of the movable neutron collimator (A) with the known radius of the small cut-out of one of the conversion foils (B), is 2mm. The direction of the misalignment is 45° with respect to the Z axis, in the YZ plane as seen from the plasma towards the spectrometer (Figure 26).

4.3 Expected Flux Correction

The LINE1 code was used to evaluate how much the tilting could affect the line of sight and thus the neutron flux on the detector.

The moving neutron collimator is connected to a threaded rod which, when turned, moves the collimator piece back and forth. When it is located at the maximum distance from the fixed collimator
it is said to be in OUT position, while when they are in contact with each other it is said to be in IN position. The misalignment was measured with the first configuration, while neutron measurements normally are done with the second one. Therefore the displacement must be scaled, obtaining a value of 0.56mm.

The expected flux was calculated using different values for the position of the misaligned cross-hair, in order to have an estimate of the error. Eight points were chosen, each 0.2mm distant from the estimated position of the cross-hair.

4.4 Results

The results of the misalignment calculations are shown in Figure 27 and table 5.

The best estimate of the flux variation is 0.78%. The uncertainty in this value can be roughly estimated looking at the values around the central point. Since the error on the position of the cross-hair is estimated to be about 0.2 mm, the lower and upper values found within a radius of 0.2 mm around the best estimate were used respectively as lower and upper values of the flux variation. The final result is:
Figure 27: Change in the neutron flux at the MPRu conversion foil due to front collimator misalignment by 2 mm in the OUT position. The scale is percent deviation from flux with perfect alignment.
Table 5: Sensitivity analysis using a 0.2 mm deviation from the best value.

| $\Delta Y$ (mm) | $\Delta X$ (mm) | $|\text{Shift}|$ (mm) | $\Delta Flux$ (a.u.) |
|-----------------|-----------------|------------------------|----------------------|
| 1.27279         | 1.27279         | 1.8                    | 0.71%                |
| 1.21421         | 1.41421         | 1.86395                | 0.67%                |
| 1.41421         | 1.21421         | 1.86395                | 0.67%                |
| 1.41421         | 1.41421         | 2                      | 0.78%                |
| 1.27279         | 1.55563         | 2.00998                | 0.72%                |
| 1.55563         | 1.27279         | 2.00998                | 0.75%                |
| 1.41421         | 1.61412         | 2.14609                | 0.83%                |
| 1.61412         | 1.41421         | 2.14609                | 0.85%                |
| 1.55563         | 1.55563         | 2.2                    | 0.89%                |

$ExpectedFluxVariation = (0.78 \pm 0.11)\%$ \hspace{1cm} (17)

A flat emission profile from the plasma was assumed in these calculations. Folding the output of LINE1 with a different emission profile could result in a slightly different variation of the neutron flux.

5 Conclusions

A new flux detector will be installed with the MPRu neutron spectrometer at JET. The magnetic shielding constructed for the new installation has proven to be working properly. No particular issues were noticed and the field levels measured inside the magnetic shield were at levels that do not jeopardize the performance of the PMT when installed at JET.

The pulse shape discrimination is quite efficient for four of the five methods tested, with the charge comparison giving the best $n/\gamma$ separation. The combination of two methods, in most of the cases, only slightly improves the figure of merit. However this improvement is only marginal and it is therefore possible to conclude that the quick and easy charge comparison method is to be preferred, in particular in view of a possible future on-board implementation.

The sampling frequency of the digitizer affects significantly the quality of the $n/\gamma$ discrimination. It is interesting to notice that, in the present lab tests, for frequencies above 500 MHz the figure of merit is almost stable, while going below this level results in a quick deterioration of the separation.

The correction of the neutron flux on the MPR foil due to the misalignment of the neutron collimator is small (about 1%) but not small enough to be ignored. However the emission profile provided by the neutron camera could play an important role in the correction. Since the new line of sight is no more directed exactly towards the core of the plasma, it will probably result in a decrease of the expected flux.

In conclusion all the tests that have been run have provided satisfactory results and no problems that could prevent installation were found. The whole instrumentation is therefore ready to be sent to JET to complete the upgrade.
References


[3] Measurement performed by marco.cecconello@physics.uu.se, private communication.


