Upgrading the Control and Monitoring system for the TOFOR neutron time-of-flight spectrometer at JET

Johan Valldor-Blücher
Abstract

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This report describes the development and testing of the upgraded Control and Monitoring (C&Mu) system for the TOFOR neutron spectrometer. TOFOR is currently performing plasma diagnostics for the JET experimental fusion reactor. The purpose of the C&Mu system is to enable monitoring of the amplitude dependent time delays of TOFOR. In order to perform this monitoring function the C&Mu system must comprise a pulsed light source with variable intensity and a reference time signal. In this work a reference time signal has been retrieved from a laser comprising a motorized polarizer. This has been accomplished by installing a photomultiplier tube and a beamsplitter cube. The beamsplitter cube splits the laser light into two parts and directs one part into the photomultiplier tube. The photomultiplier tube converts the light into an electrical reference time signal. A control program has been developed for the motorized polarizer, enabling the user to vary the intensity of the light over the interval from 0% to 100%. The C&Mu system has been performance tested and it was found that the time resolution of the system is about 0.1ns and the time stability of the system is about 0.12ns over 27 hours. The system is more than adequate to monitor variations in time delays at TOFOR of several nanoseconds, over a full JET day. The C&Mu system is ready to be installed on TOFOR.
Sammanfattning på svenska

TOFOR är en neutronspektrometer som är installerad på fusionsforskningsreaktorn JET i England. TOFOR använder ett flertal detektorer för att mäta flygtiderna hos neutroner som utsöndras från JET reaktorn. Flygtiderna används sedan för att beräkna energin hos neutronerna, vilken i sin tur ger information om fusionsplasmanas egenskaper som tex intensiteten hos fusionsreaktionerna. TOFOR har ett kontrollsystem som ska se till att spektrometern fungerar som den ska, dvs. att den genomför pålitliga och upprepningsbara mätningar. De egenskaper hos TOFOR som är viktigast att kontrollera är tidsfördröjningarna hos TOFORs detektorer relativt varandra. Experiment har visat tidsfördröjningen hos varje individuell TOFOR-detektor beror på detektorns signalamplitud.

I detta arbete har TOFORs kontrollsystem uppraderats för att kunna användas till att experimentellt bestämma förhållandet mellan signalamplitud och tidsfördröjning för varje individuell TOFOR-detektor. Denna monitoreringsfunktion kräver att kontrollsystemet har en pulserande ljuskälla med en referenttidssignal samt justerbar ljusintensitet. TOFORs kontrollsystem innefattar en pulserande laser med en motorstyrd polarisator. Uppgraderingen som utfördes i detta arbete var installationen av en fotomultiplikator vilken låter lasern producera en referenttidssignal. Ett kontrollprogram har även skrivits vilket låter användaren variera ljusintensiteten i intervallet från 0% till 100%. Det uppraderade kontrollsystemet har sedan testats och resultaten visar att dess tidsupplösning är ca 0.1ns och dess tidsstabilitet är ca 0.12ns över en tidsperiod av 27 timmar. Variationerna i tidsfördröjning som har observerats hos TOFOR är några nanosekunder. Slutsatsen är att det uppraderade kontrollsystemet kan användas för att mäta dessa variationer hos TOFOR.
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1 Introduction

For over 50 years fusion researchers have been striving towards developing a commercial fusion power plant. The challenge lies in creating a controlled environment capable of sustaining fusion reactions and at the same time effectively harness the energy released in these reactions. One important fusion reaction which has been achieved in experimental fusion facilities is deuterium-deuterium (DD) fusion. In the DD fusion reaction two deuterium ions are fused together forming a helium ion and a neutron in the following way: \( ^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + n + 3.27\text{MeV} \). The mass difference between the initial and final states results in an energy release, which is manifested in the form of kinetic energy of the products. In DD fusion the neutron gets 2.45MeV of the released energy and the helium ion receives 0.82MeV [1].

The most promising method for achieving controlled fusion on earth is currently considered to be magnetic confinement fusion (MCF). In an MCF reactor electromagnetic fields are used to confine the plasma (heated fuel ions) [1]. The progress of MCF research is dependent on plasma diagnostics. Experimental fusion reactors all have a number of diagnostic systems for measuring different plasma properties such as temperature, shape and produced fusion power. Detailed knowledge of the high-temperature plasma is needed in order to improve existing fusion experiments and develop new larger experimental reactors. One important plasma diagnostic tool is neutron emission spectroscopy (NES). The neutrons created in the fusion reactions in the reactor are not confined by the electromagnetic field so they escape the reactor [2]. In NES a neutron spectrometer is used to measure the energy distribution of the emitted neutrons. Analyzing the energy spectrum of the emitted neutrons, which in the case of a DD fusion experiment is centered on 2.45MeV, gives information about plasma properties such as the intensity of the DD fusion reactions and the motional state of the fuel ions. A great advantage with NES is that no contact with the plasma is required [3].

1.1 The experimental fusion reactor JET and the TOFOR neutron spectrometer

Advanced MCF research is being conducted at the Joint European Torus (JET), which is shown at the bottom left in figure 1. JET is operating under the European Fusion Development Agreement (EFDA). JET is the largest experimental fusion reactor in the world. Electromagnetic coils are used to induce a current in the plasma inside the vacuum in the reactor. This causes the temperature in the reactor to increase and the process is called ohmic heating. In addition to ohmic heating the temperature is also increased by using microwaves and by injecting neutral particles into the plasma [3]. The plasma current requires a changing magnetic field so an experiment lasts until the coils reach maximum current. A time period in which there is plasma in the reactor is called a pulse. During a pulse, fusion reactions occur, and in the case of a DD plasma, 2.45MeV neutrons are emitted from the reactor. The length of a pulse is between 20-60 seconds, depending on how the electromagnetic coils are operated. After each pulse the coils must be cooled down before another pulse can be induced. The time between pulses is typically 20 minutes. Experiments are conducted at JET during what is called experimental campaigns. Which experiments are to be conducted and in what order, is determined before the start of the campaign. During an experimental campaign there are up to about 30 pulses a day. A campaign usually lasts about one year. Every few years, JET is shut down for a few months for maintenance and modifications [2].
At JET there are several neutron spectrometers conducting NES diagnostics [2]. TOFOR, shown at the top left in figure 1, is a time-of-flight (TOF) neutron spectrometer optimized (O) for high count-rates (R). In 2005 the TOFOR spectrometer was installed in the roof laboratory above the JET reactor hall, 19 meters above the reactor, as shown on the right side in figure 1. TOFOR allows the determination of the energy spectrum of the 2.45MeV neutrons emitted by the plasma. The neutron energies are determined by measuring the times-of-flight of the neutrons passing through the TOFOR spectrometer. The flight path through TOFOR is approximately 1.2m and the time-of-flight of a 2.45MeV neutron is about 65ns. This gives a neutron velocity of approximately $1.8 \times 10^7$ m/s (66 million km/h). This is about 6% of the

Figure 1. The top of the left side shows a picture of the TOFOR spectrometer [4]. The bottom of the left side shows a diagram of the JET reactor [2]. The right side shows a diagram of TOFOR and JET showing the collimated neutron beam going from the JET reactor up to TOFOR in the roof laboratory [4].
speed of light. The short times-of-flight of the neutrons puts high demand on the TOFOR electronics which are responsible for recording the times-of-flight. These electronics give rise to time delays which results in an uncertainty of the measured times-of-flight. TOFOR uses many detectors to be able to measure as many neutrons as possible, and different detectors can have different time delays [4]. The design and function of TOFOR is discussed more thoroughly in chapter 2.

1.2 The TOFOR Control and Monitoring system
The experimental phase of fusion research reactors like JET usually extends over several experimental campaigns, meaning years or even decades. Plasma diagnostic systems, like TOFOR, must be able to provide reliable and reproducible measurements during these extended time periods. The stability of TOFORs properties (also called working points) and how precisely they are known, determine the quality of the measurements performed. In order to ensure the long-time stability of a neutron spectrometer the working points must be determined before the operational period, i.e. during the characterization and installation phase. The stability of these working points must then be monitored during operations. The monitoring allows to correct for drifts during the data analysis process, as well as to adjust the working points in between campaigns.

A Control and Monitoring (C&M) system was developed to perform these tasks for TOFOR. The working points which are most relevant for this work are the time delays of the TOFOR detectors relative to each other. These must be monitored in order to ensure that the times-of-flight of neutrons are measured with adequate accuracy. The C&M system uses a pulsed light emitting (PLE) source to monitor these working points. The time delay of each TOFOR detector is determined by using an LED to send light pulses of fixed intensity into the detectors [5]. The time recorded by each detector is compared to the time of the LED synchronization signal. Thus, the time delay of each detector can be calculated. The different time delays of all the detectors has typically been monitored prior to each JET pulse, and the measured neutron times-of-flight corrected. A new time alignment of the detectors has typically been performed during every JET shut down.

However, experiments have shown that the time delay of a detector signal depends on its amplitude [6]. Since this amplitude varies between neutron time-of-flight measurements [3], the correlation between signal amplitude and time delay must be determined for each TOFOR detector. In light of this result it is evident that a new time delay monitoring procedure is needed. For each detector a measurement series must be conducted while changing the signal amplitude between measurements, giving the dependence of the time delay on the signal amplitude. In order to change the signal amplitude the intensity of the light from the PLE source must be changed. The LED can therefore not be used in this monitoring procedure since its light intensity is fixed. However, there is an additional PLE source available with the C&M system: a laser which light intensity can be varied using a motorized polarizer. But the laser does not have a synchronization signal. In order to use the laser for this monitoring procedure it must first be outfitted with a reference time signal.
1.3 Scope of this work
The goal of this work was to upgrade the C&M system so that it could be used to determine the
dependence of the time delay on the signal amplitude, for each individual TOFOR detector. To keep
costs to a minimum the upgraded C&M system was to be constructed, as far as possible, using parts
from the original C&M system as well as other material available within the division of applied nuclear
physics at Uppsala University. The requirements for the upgraded C&M system were to comprise a PLE
source with both a reference time signal and variable light intensity. Since the C&M system already
included a laser with a variable intensity, it was the focus of this work to retrieve a reference time signal
from this laser. The scope of this work included suggesting a design for the upgraded C&M system,
building the system and testing its performance in terms of time resolution and time stability. To
distinguish between the two versions of the C&M system, the upgraded control and monitoring system
will hence forth be referred to as the C&Mu system.

2 TOFOR technical background
In order to measure the times-of-flight of neutrons the TOFOR spectrometer uses two sets of detectors.
The primary set of detectors (S1) is exposed to a collimated beam of neutrons (as seen in the right side
of figure 1) from the JET reactor. The secondary set of detectors (S2) is positioned at a well-defined
scattering angle from S1. There are 5 detectors in S1 and 32 detectors in S2. These detectors consist of
plastic scintillators and photomultiplier tubes (PMTs). S1 is a stack of 5 identical disc-shaped scintillators,
each connected to 3 PMTs. In S2, 32 identical scintillators, each connected to one PMT, are placed next
to each other, making a cone-like surface as seen in figure 2 [4].

A fraction of the neutrons which arrive at the scintillators in S1 can be detected through the scattering
process: \( n + p \rightarrow p^* + n' \). Some of the scattered neutrons then reach the scintillators in S2, where they
are again subjected to the scattering process described above. The flight path between S1 and S2 is
approximately 1.2m, and the time-of-flight for a 2.45MeV neutron traveling between them is about 65ns
[4]. This gives a neutron velocity of approximately \( 1.8 \times 10^7 \) m/s (66 million km/h). This is about 6% of the
speed of light. When a neutron is scattered off a proton in the scintillation material part of the neutron
kinetic energy is transferred to the proton. Thus the neutron is scattered in the scattering angle alpha
(as seen in figure 2), and the proton gains momentum. The proton is slowed down by the scintillator
material and soon stops, having excited the molecules in the scintillator. These molecules then deexcites
by releasing light. Connected to the scintillators are light-guides which direct the light into the PMTs.
Each PMT collects the incoming light and converts it, through the photoelectric effect and secondary
electron emission, into a measurable electric signal [7]. The amplitude of the detector signals is typically
100mV for the S1 detectors and 500mV for the S2 detectors. The time resolution of the TOFOR PMTs is
limited by their transient time spread (TTS). TTS is the spread in time it takes a photo-electron to travel
trough the PMT. For the TOFOR PMTs the TTS is 1.5ns. This is a very small number compared to 65ns
which is the average time-of-flight for 2.45MeV neutron. Thus, the TTS of the TOFOR PMTs does not
explain the observed time delays of the TOFOR detectors.
2.1 The data acquisition system

The TOFOR data acquisition (DAQ) system collects the PMT signals from the individual S1 and S2 detectors and processes them to obtain and record a time stamp for each interaction. Since the neutrons that interact with an S1 detector can scatter in any angle, they will not all go on to arrive at an S2 detector (as seen in the right side of figure 2 the scattering angle alpha must be within a certain interval in order for the neutron scattered in S1 to arrive at S2). For a given neutron energy, the scattering angle interval in which a neutron will travel through both S1 and S2, corresponds to an amplitude interval in which the electric signal from a detector must lie. Since the energy of the incoming neutrons varies around 2.45MeV this interval cannot be determined exactly. It is however possible to define a larger interval, outside which the events cannot correspond to elastic scattering of neutrons in the direction of the S2 detectors. The DAQ system discards events outside this region by using discriminator thresholds. A block diagram of the part of the DAQ system, which is responsible for retrieving the interaction times, is shown in figure 3 [4].
The electric signal from a detector is fed into a linear fan-in-fan-out (FIFO) module which is used to provide several output signals, all identical to the input signal. Two of the output signals are fed into separate constant fraction discriminators (CFDs). In each of these CFDs a discriminator threshold is set so that the analog signal is converted into a logic signal if its amplitude is above the threshold level. One CFD has the low discriminator threshold and one has the high threshold. Both CFDs are connected to the same programmable logic unit (PLU) which is set so that it will only give an output signal if it receives a signal from the low CFD but not from the high CFD. If these conditions are met the PLU provides a logic signal to the time-digitizing (TD) board which then records the time stamp. From the interaction time stamps the time-of-flight spectrum is then constructed [4]. Since the signal from each detector must travel through the electronics of the DAQ system, a time delay will be added to each measured time stamp. The time delay may differ between detectors and this fact introduces an uncertainty into the constructed times-of-flight [4].

A new recently developed data acquisition system, called DAQu, is currently being tested on TOFOR. The DAQu system will ultimately replace the DAQ system. The DAQu system uses fast digitizing data acquisition cards to record the electrical signals for all interactions in each detector. This system records the whole electrical pulse instead of just a time stamp. Therefore both the time stamp and the signal amplitude can be determined for each individual neutron interaction. The DAQu system will therefore enable improved timing. It will also enable more sophisticated background discrimination, although this application will not be discussed further in this work. The data acquisition cards have a 12 bit amplitude resolution and a sampling frequency of $10^9$ samples per second [8]. A block diagram of the DAQu system is shown in figure 4.

![Figure 4. Block diagram of the DAQu system. Each card receives the electrical pulses from four detectors and digitizes them. The pulses are then recorded on a computer [4].](image)

The card collects the signal from each individual detector and digitizes the signal by recording the amplitude of the pulse for each nanosecond. Thus the whole pulse is stored on a computer with a time resolution of 1ns. For more information about the DAQu system for TOFOR, the reader is referred to [8].
2.2 The Control and Monitoring system

The C&M system comprises two PLE sources: one LED which includes a synchronization signal, and one laser with a motorized polarizer. The LED emits blue light with a wavelength of 428nm. The laser is a solid-state, diode pumped, neodymium doped lanthanum scandium borate (Nd: LSB) laser. It emits green light with a wavelength of 531nm. The motorized polarizer is situated inside a light tight box together with various other optical components.

In figure 5 a diagram shows how the C&M system is connected to TOFOR. The laser light is directed through the optical components inside the light tight box, into an optical fiber cable connected to an input switch. The LED is connected to the input switch via an optical fiber cable. The switch is used to alter between using the LED light and the laser light [5]. Another optical fiber cable connects the switch to an optical fiber bundle consisting of 57 individual optical fibers. Each PMT in TOFOR is connected to one of the individual fibers in the fiber bundle. Connected to another of these fibers is also a reference detector where a radioactive source is positioned. The reference detector is used for monitoring the positions of the discriminator thresholds [9]. For more information about this monitoring function the reader is referred to [5]. The wavelengths of the LED and the laser lies in the interval 400-550nm where both PMT cathode quantum efficiency and the transmission properties of optical fibers are good. Figure 6 shows the PMT cathode quantum efficiency as a function of the wavelength, for the TOFOR PMTs [9].

Figure 5. Diagram depicting how the C&M system is connected to TOFOR [9].
2.3 Monitoring the time delays of the TOFOR detectors

The most important working points for the TOFOR C&M system to monitor are: the gains of the PMTs, the positions of the discriminator thresholds and the time delays of the detectors relative to each other. The first two monitoring functions are monitored by using the LED to send light into all the TOFOR detectors. For more information about them the reader is referred to [5]. This work will focus on the monitoring of the time delays of the TOFOR detectors relative to each other.

The time delays of the TOFOR detectors relative to each other must be monitored closely, since a change in these working points can introduce an error in the measured times-of-flight. The time delay of a detector arise due to the fact that an electric signal from a PMT must travel through the TOFOR DAQ system before it can be recorded as an interaction time stamp [4]. The C&M system uses the LED to monitor the time delay of each TOFOR detector. The light from the LED reaches all the TOFOR detectors through optical fiber cables, as seen in figure 5. The PMT(s) in each detector converts the light into an electrical signal. The signal from each detector is then processed into an interaction time stamp by the DAQ system, as seen in figure 3. These time stamps are then compared to the time stamp from the LED synchronization signal. Thus the time delay of each TOFOR detector is determined and the measured times-of-flights corrected [5].
During the time delay monitoring procedure, light of a fixed intensity is emitted by the LED into the detectors. This differs from the case of neutrons interacting with the detectors during a JET pulse, since the intensity of the light released by the scintillator into the PMT(s) varies between neutron interactions [3]. Experiments were therefore performed on TOFOR (prior to this work) in order to investigate if these variations in light intensity affects the time delays of the TOFOR detectors. In these experiments, the signals from a TOFOR detector, resulting from the interactions of cosmic muons with the scintillator, were measured using an oscilloscope. Since the intensity of the light released by the scintillator varies between muon interactions, the amplitude of the electrical signals from the detector varies proportionately. For each detector signal, the oscilloscope was used to measure the signal amplitude as well as the signal time delay between two different positions in the TOFOR DAQ system [6]. The setup of this experiment is shown in figure 7.

![Block diagram showing the experimental setup used to investigate the correlation between time delay and signal amplitude for a TOFOR detector [6].](image)

Each detector signal was fed into a FIFO module, which was used to provide two output signals, both identical to the detector signal. One signal was fed into the oscilloscope and the other into one of the CFD modules. The output from the CFD module was fed into another channel on the oscilloscope. Using this setup the time it took for the CFD to convert an analog pulse into a logical pulse was measured. Since the signal retrieved from the CFD is a logic pulse it gives a clear time stamp. The signal retrieved from the FIFO is however a pulse with a continuous form. Three different methods were used to get a time stamp from this pulse. Shown in figure 8 is the time difference between the smoothed FIFO pulses reaching 50% of maximum amplitude and the corresponding CFD timestamps. The time difference is plotted against the amplitude of the detector signal, which is proportional to the incident light intensity [6].
As seen in figure 8, the measurements show that the time difference is relatively constant for amplitudes with an absolute value above about 400mV. In this region the spread in time difference is within about 1ns. For smaller amplitudes the time difference increases when the absolute value of the amplitude decreases. It can be seen from figure 8 that the change of the time difference is within 1ns for low amplitudes compared to high amplitudes. It can also be seen in figure 8 that the spread in time difference grows larger for smaller absolute values of the amplitudes. For amplitudes with an absolute value of about 100mV, corresponding to the typical amplitude of an S1 detector from a neutron interaction, the spread in the time difference is about 6ns [6]. This is a significant spread for a time-of-flight of 65ns. Thus, the results from these measurements show that the time delay, as well as the spread in time delay, is indeed dependent on the intensity of the light incident on the detector. The results also show that it is especially important to monitor this dependence for amplitudes around -100mV. However, the results from these experiments are in themselves not sufficient to allow better characterization of the time delays, since the setup was lacking a reference time signal marking the actual time at which each signal was sent to the detector [6].

In order to determine the dependence of the time delay on the light intensity for all the TOFOR detectors, the C&M system must include a PLE source with a reference time signal and variable intensity. The LED cannot be used since its light intensity is fixed. The laser does not have a reference time signal, but its light intensity can be varied using the motorized polarizer. The C&M system must therefore be upgraded by retrieving a reference time signal from the laser. The C&Mu system must have a time resolution well below 6ns in order to monitor changes in time delay such as those observed in the experiments performed on TOFOR. If these specifications are met the C&Mu system will enable improved characterization of the time delays of the TOFOR detectors and thus a better understanding of the uncertainties of the measured neutron times-of-flight. Using the DAQu system both the time stamp and the signal amplitude can be determined for each individual neutron interaction [8]. Thus, when both the C&Mu and DAQu systems are installed on TOFOR each individual neutron time-of-flight measured by TOFOR can also be corrected.
3 Developing the upgraded Control and Monitoring system

The motivation for this work was to enable the C&M system to be used to monitor the correlation between the time delay and amplitude for signals from the TOFOR detectors. In order to perform this monitoring function the C&M system needs a PLE source with both a reference time signal and variable intensity. It was therefore the focus of this work to upgrade the C&M system by retrieving a reference signal from the laser. The C&M system must have a time resolution well below 6ns in order to monitor changes in time delay such as those observed at TOFOR [6]. The plan for the design of the C&M system was to let a PMT collect stray light from each laser pulse and thus produce a reference time signal. The scope of this work included the developing and testing of the C&M system.

3.1 Equipment

The equipment used in the development of the C&M system is specified below. It is listed in the following tables: laser, optical components, data acquisition card and photomultiplier tubes.

**Laser**

The laser is shown in figure 9, where the green cable is the optical fiber pigtail connecting the laser driver with the laser head. The specifications of the laser are stated in the table in figure 10.

![Laser Image](image)

**Figure 9. Picture of the laser, showing the laser driver connected to the laser head via an optical fiber pig-tail.**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Wavelength</th>
<th>Pulse duration (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standa</td>
<td>STA01-SH</td>
<td>531nm</td>
<td>0.65ns</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>Pulse energy</td>
<td>Polarization ratio</td>
<td>Stability</td>
</tr>
<tr>
<td>4.88kHz</td>
<td>1.5µJ</td>
<td>&gt;1:100</td>
<td>5.00%</td>
</tr>
</tbody>
</table>

*Figure 10. Table showing the laser specifications.*
**Optical components**

Figure 11 shows a picture of the optical components available with the C&M system and their positions inside the light tight box. These optical components are also listed in the table in figure 12.

![Image of optical components](image)

**Figure 11. Picture showing the light tight box and the positions of the laser head, fixed polarizer, motorized polarizer, focusing lens and SMA connector.**

<table>
<thead>
<tr>
<th>Part</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed polarizer.</td>
<td>After laser head inside light tight box.</td>
</tr>
<tr>
<td>Motorized polarizer.</td>
<td>After fixed polarizer inside light tight box.</td>
</tr>
<tr>
<td></td>
<td>Connected to a serial input in the wall of the box.</td>
</tr>
<tr>
<td>Focusing lens.</td>
<td>After motorized polarizer inside light tight box.</td>
</tr>
<tr>
<td>SMA connector.</td>
<td>After focusing lens inside light tight box,</td>
</tr>
<tr>
<td></td>
<td>protruding out through the wall of the box.</td>
</tr>
<tr>
<td>Optical fiber cable, 5m long</td>
<td>Connected to the SMA connector</td>
</tr>
<tr>
<td>with an optical fiber diameter</td>
<td>on the outside of the light tight box.</td>
</tr>
<tr>
<td>of 200µm.</td>
<td></td>
</tr>
<tr>
<td>External voltage supplier</td>
<td>Connected to the voltage input</td>
</tr>
<tr>
<td>for the motorized polarizer.</td>
<td>on the outside of the light tight box.</td>
</tr>
<tr>
<td>Laptop for controlling</td>
<td>Connected to the serial input</td>
</tr>
<tr>
<td>the motorized polarizer</td>
<td>on the outside of the light tight box.</td>
</tr>
</tbody>
</table>

**Figure 12. Table listing the optical components used in the development of the upgraded C&M system.**
Data acquisition card

The data acquisition card used in the development and testing of the C&Mu system is shown in figure 13 and its specifics are listed in the table in figure 14. The card is of the same model as the ones used in the new TOFOR DAQu system. It is identical to these cards in all aspects but the input voltage range. The cards used for the DAQu system has an input voltage range of -700mV to 100mV, whereas the data acquisition card used in this work has an input voltage range of -400mV to 400mV. The card has a 12 bit amplitude resolution. The card has 4 channels and can be operated in two different modes: quad channel mode and dual channel mode. In quad channel mode all 4 card channels can be used in measurements. The card then has a sampling rate of 1 GSPS which gives a time resolution of 1ns. In dual channel mode only two of the card channels can be used in measurements. The advantage of this mode is that the sampling rate is increased to 2 GSPS which improves the time resolution to 0.5ns. Since throughout this work there were no more than two signals to be measured at the same time, the card could be operated in dual channel mode.

Figure 13. Picture of the data acquisition card.

<table>
<thead>
<tr>
<th>Type</th>
<th>Fast digitizing data acquisition card for recording the pulse shape of detector signals.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>Data acquisition card, USB cable and a computer for controlling the data acquisition using MATLAB.</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Model</td>
</tr>
<tr>
<td>SP Devices</td>
<td>ADQ412</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quad channel mode</th>
<th>Dual channel mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling rate</td>
<td>Time resolution</td>
</tr>
<tr>
<td>1 GSPS</td>
<td>1ns</td>
</tr>
</tbody>
</table>

Figure 14. Table showing the specifications of the data acquisition card.
Photomultiplier tubes
Two identical PMTs were used in the development of the C&Mu system. One is shown in the picture in figure 15. Their specifications are shown in the table in figure 16.

![Figure 15. Picture of a Hamamatsu R647-25 photomultiplier tube.](image)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Lens diameter</th>
<th>Wavelength range</th>
<th>Nominal HV</th>
<th>Transient time spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu</td>
<td>R647-25</td>
<td>13mm</td>
<td>300-650nm</td>
<td>1.0-1.5kV</td>
<td>1.6ns</td>
</tr>
</tbody>
</table>

![Figure 16. Table showing the specifications of the photomultiplier tubes.](image)

3.2 Experimental setup
The strategy of using a PMT to retrieve a reference time signal from the laser had to be tested for proof of principle before constructing the C&Mu system. A preliminary C&Mu system setup was developed, in which the reference PMT was fixed to the inside of the roof of the light tight box with duct tape, as seen in figure 17. It was hypothesized that by positioning the PMT inside the light tight box, it would receive enough stray light to produce an electrical signal. For a proof of principle, tests had to be conducted to determine:

- that the reference PMT receives enough light to produce an electrical signal for each laser pulse,
- that the signal produced has adequate time resolution to act as a reference time signal,
- that the reference signal has adequate time stability, i.e. that the time delay of the signal does not vary too much over time,
- and that the reference signal remains stable when the motorized polarizer is used.

In order to test the time stability of the reference signal it had to be compared to another signal. By using a second PMT connected to the optical fiber cable, the time difference between the two PMT signals could be measured. This time difference is the time-of-flight of the light traveling from the position of the reference PMT through the optical components to the other PMT. The second PMT is called the TOFOR PMT since it detects the light signals that will be fed into the TOFOR PMTs in the final setup. This temporary experimental setup will not be a part of the C&Mu system. The TOFOR PMT was also used to test the functionality of the motorized polarizer.
Figure 17. Picture showing the PMT duct-taped to the ceiling of the light tight box.

Figure 18. Scheme showing the preliminary C&M system setup connected to the temporary TOFOR PMT.

Figure 18 shows a scheme of the preliminary C&Mu system setup connected to the temporary TOFOR PMT setup. Information about how to laser driver was connected to the laser head can be found in appendix A1. As seen in figures 17 and 18 the reference PMT was directed diagonally downwards toward the laser head inside the light tight box. The light from the laser head traveled through the fixed polarizer, motorized polarizer, focusing lens and SMA connector into the optical fiber cable. The optical fiber cable was connected to the temporary TOFOR PMT setup. The TOFOR PMT was inserted into a metallic cylindrical shell with a small hole at the end, allowing light to reach the PMT from the end of the optical fiber cable which was inserted into another cylinder. Between these cylinders a third cylinder was placed containing white paper and a black cardboard plate with a small hole in it. The purpose of these components was to decrease the absolute intensity of the light reaching the TOFOR PMT to avoid saturation. This whole construction was then wrapped in light tight duct tape to keep out stray light.

Each of the two identical PMTs generates a negative signal which amplitude depends on the voltage applied to the PMT by the HV unit and on the intensity of the incoming light. The input voltage range of the data acquisition card is -400mV to 400mV. Therefore, in order to optimize the amplitude resolution, the signals from the PMTs had to be calibrated to have amplitudes just short of -400mV. Furthermore the PMTs must be operated within their nominal high voltage region of -1000V to -1500V. Therefore the signals from the PMTs had to be calibrated by altering the intensity of the incoming light. This was done by constructing temporary light dampening filters for the PMTs. The filter used for the reference PMT was a black cardboard plate with a small hole in it. For the TOFOR PMT white paper was used in addition to a black cardboard plate with a small hole in it. This setup allowed the reference PMT to be operated
at -1393V yielding a signal with an amplitude of about -300mV and a FWHM of about 5ns, whereas the TOFOR PMT could be operated at a voltage of -1345V yielding a signal with an amplitude of about -350mV and a FWHM of about 5ns. The PMT signals as viewed on the oscilloscope are shown in figure 19, where the signal from the TOFOR PMT is at the top and the signal from the reference PMT is at the bottom. From figure 19 it can be seen directly that both PMTs produce an electrical signal for each laser pulse since the frequency measured by the oscilloscope of 5.2 kHz approximately matches the frequency of the laser of 4.88kHz as stated in the table in figure 10.

![Image of oscilloscope showing PMT signals](image.jpg)

Figure 19. Picture of the oscilloscope showing the pulses from the two PMTs. The bottom pulse corresponds to the reference PMT supplied with a voltage of -1393V. The top pulse corresponds to the TOFOR PMT supplied with a voltage of -1345V.

### 3.3 Developing a control program for the motorized polarizer

In order to test the functionality of the motorized polarizer, test had to be performed to ascertain that the intensity of the light changes when the polarizer is turned. As stated in the table in figure 12 the motorized polarizer was connected via a serial cable to a laptop. In order to use this laptop to control the motorized polarizer a control program had to be developed. A program was written in Python 2.7 for this purpose. This program used two different python files, which codes are presented in appendix A2. The program communicates with the motorized polarizer through the serial cable connected between the laptop and the motorized polarizer. It has a graphical user interface (GUI), shown in figure 20. The GUI has buttons for checking the current position of the motor, resetting the motor to the zero position and turning the motor to a position specified by the user. The GUI also has a button for checking the status of the motor. If the motor is currently turning when the status is checked, the message ‘Motor busy’ will be received, otherwise ‘Motor ready’ will be stated. The GUI also has a quit button.
3.4 Testing the preliminary system setup

The first proof of principle test on the preliminary C&Mu system setup was performed during the calibration of the absolute light intensity, i.e. the oscilloscope showed that the PMTs receive enough light to produce an electrical signal for each laser pulse. In order to perform the other test the PMTs were connected to the data acquisition card. The card was operated in dual channel mode giving a time resolution of 0.5ns. The process of data acquisition and analysis will be treated in chapter 4.

In order to test the time resolution of the setup, 10000 signals were collected from each PMT. Figure 21 shows a histogram of the time difference between the signal from the reference PMT and the signal from the TOFOR PMT. The FWHM in figure 21 is about 0.4ns, which gives a standard deviation of about 0.17 ns. The stability of the setup over time was investigated by performing such measurements at regular intervals over a time period of a few hours. Performing this measurement series showed that the mean time difference does not drift by more than about 0.1ns throughout the measurement series. Thus the drift of the time difference over time is even lower than its standard deviation. Therefore drifts does not impede the time resolution of the setup further. The experiments performed on TOFOR to investigate the amplitude dependence of the time delays is described in section 2.3. During these experiments changes in time delay of about 6ns were observed [6]. The overall time resolution of the preliminary C&Mu system setup is about 0.17ns which is well below 6ns. The time resolution of the preliminary C&Mu system is thus more than adequate to investigate the changes in time delay observed at TOFOR.

Figure 20. Picture of the graphical user interface of the program controlling the motorized polarizer.
The functionality of the motorized polarizer and the newly developed control program was tested by turning the polarizer using the control program while viewing the PMT signals on the oscilloscope. It was seen that the control program could successfully be used to turn the motorized polarizer and thus change the intensity of the light incident on the TOFOR PMT. However, during this test it was discovered that the reference signal did not remain stable when the motorized polarizer was used. When the polarizer was turned in order to change the signal amplitude of the TOFOR PMT, the signal amplitude of the reference PMT also changed. The change in signal amplitude of the reference PMT corresponded to about 50% of the change observed for the TOFOR PMT. It was thus evident that the reference PMT was receiving light scattered from the polarizer. Since it has been established that the intensity of the light incident on a PMT affects the delay of the signal, this setup did not produce a stable reference time signal. In order to ensure that the reference signal would be stable, the C&Mu system setup had to be changed so that light scattered from the polarizer would not be able to enter the reference PMT.

Another problem arose when, during this test, the laser stopped working. It was discovered that the optical fiber inside the fiber pigtail cable between the laser driver and the laser head, was broken into two pieces. Many different lasers on the market were considered for a replacement, but due to economical reasons and time constraints it was decided that the laser should be repaired instead. The optical fiber was cut to a good contact surface and a new SMA contact was attached. A reinforced metal covering was attached to the beginning of the fiber in the laser driver, and a new thicker plastic coverage was placed on the fiber. The laser was then tested and deemed functionary.
3.5 Revising the system design

In order to make sure that light scattered from the motorized polarizer would not enter the reference PMT, it was decided to split the light into two components using a beamsplitter cube. This 1 inch cube was positioned between the laser head and the fixed polarizer, splitting the light from the laser into two equally large parts. Figure 22 shows the different C&M system setups. The top scheme in figure 22 shows the setup of the C&M system, the middle scheme shows the preliminary setup of the C&Mu system, and the bottom scheme shows the revised design of the C&Mu system. As seen in the bottom of figure 22, one part of the light in this setup continues straight through the beamsplitter cube and through the optical components as before. The other part of the light is scattered by the beamsplitter cube in a 90 degree angle towards the roof of the light tight box. In order to receive this light the reference PMT was positioned on top of the roof of the light tight box, in which a hole was drilled to let the light through.

In order to test this setup temporary mounts were used for the beamsplitter cube and the reference PMT. The beamsplitter cube was put on a wooden block on the floor of the light tight box in order to position it in front of the laser light. The reference PMT was held in position above the roof of the box by a tripod. Temporary light attenuators were used to avoid saturation in the PMTs. These were constructed out of with paper and two black cardboard plates with one small hole in each. The new upgraded C&M system setup was tested at night to minimize stray light and a dark blanket was used to further dampen the stray light. The signals from the PMTs were viewed on the oscilloscope while the position of the motorized polarizer was changed. During this test the amplitude of the signal from the reference PMT was unchanged, and the setup was deemed functional. Permanent versions of the light attenuators and the mounts for the beamsplitter cube and reference PMT were constructed. The C&Mu system was then assembled. The parts where developed by the workshop at Ångström from drawings and 3D drawings made by the author of this report.
3.6 The upgraded Control and Monitoring system

The setup of the C&M system can be seen in the scheme in the bottom of figure 22. The light from the laser head reaches the beamsplitter cube which is fastened to the bottom of the light tight box using a mount, as seen in figure 23. The beamsplitter cube splits the light into two equal parts. One part is scattered by the cube in a 90 degree angle towards the roof of the light tight box, and the other part continues straight forward.

The scattered part of the light travels through a light attenuating plate of smoke colored glass, which is fastened to the inside of the roof of the light tight box using a mount, as seen in figure 24. To each side of the attenuating plate two layers of sun protection film is attached. The light then reaches the
reference PMT through a plastic disk with a 0.3mm hole in it. The PMT and the plastic disk are fastened to the roof of the light tight box using a mount, as seen in figure 23.

The part of the light that continues straight forward after the beamsplitter cube travels through two light attenuating plates. These are held in place using a mount which is fastened to the inside of the roof of the light tight box, as seen in figure 24. The light then continues through the fixed polarizer, the motorized polarizer, the focusing lens and the SMA connector. The light then exits the light tight box through the optical fiber cable. The light travels through the cable to enter the temporary TOFOR PMT setup, which is described in section 3.2. The complete system setup, including the upgraded C&M system and the temporary TOFOR PMT setup, is shown in figure 25.

The mount for the beamsplitter cube enables adjustment of the angling of the cube in two directions to ensure good light alignment inside the light tight box. The absolute intensity of the light incident on each of the PMTs can be adjusted, should the need arise during the performance testing of the C&M system or after the installation at TOFOR. This is done by varying the number of attenuator plates positioned in front of each PMT. With the C&M system there are four attenuator plates available for each PMT, as well as additional sun protection film. The sun protection film can be attached to the attenuator plates in layers should further light attenuation be needed.

Figure 23. Picture of the C&M system, showing the beamsplitter cube and the reference PMT in their respective mounts.
4 Data acquisition and analysis

The data acquisition card used in the performance testing of the upgraded C&M system is specified in figure 14. It has 4 input channels and an input voltage range of -400mV to 400mV. The card digitizes the input signals with a 12 bit amplitude resolution which means the input voltage range is divided into 4096 discrete levels, ranging from level -2048 to level 2048. For each sample the card records the amplitude level of the signal at that instant. In quad channel mode the card has a sampling rate of 1 GSPS which gives a time resolution of 1ns. In this work, signals were acquired from the reference PMT and the TOFOR PMT. Thus only two input channels were used and the data acquisition card was therefore operated in dual channel mode. The advantage of this mode is that the sampling rate is increased to 2 GSPS which improves the time resolution to 0.5ns. Thus the card recorded one sample each 0.5ns. In this work 128 samples have been recorded for each signal. The 128 samples building up a signal were saved in an array and together they constitute what is called a record. It follows that in this work the length of each record is 128 samples which corresponds to 64ns.
The card was operated from a computer using the MATLAB program ADQ412_DAQ.m which lets the user control the data acquisition using various input parameters. This program was provided by SP Devices and is presented in appendix A3. The data acquisition for each record starts when the amplitude of the signal reaches a certain amplitude level called the trigger level. The MATLAB program enables the user to choose the trigger level as well as which channel will trigger the data acquisition. When the data acquisition starts, it does so on both channels simultaneously. Therefore both the signal from the reference PMT and the signal from the TOFOR PMT, are collected at the same time and stored in separate records. Thus the two records are aligned in time. In this work the data acquisition has been triggered by the channel receiving the signals from the reference PMT. Therefore signals from the TOFOR PMT with amplitudes below the trigger level could still be collected. The card also record samples which occur before the trigger level is reached, using its internal memory. These samples are called pre-trigger samples. For each measurement conducted during the performance testing of the C&Mu system the following input parameters were used:

- Record length: 128 samples
- Trigger level: -1350
- Number of pre-trigger samples: 22
- Number of records per measurement per channel: 10000

For each measurement the program ADQ412_DAQ.m (see appendix A3) stores the data in a cell consisting of two matrices, one for each input channel. The cells are then transferred to, and stored on, the computer. In each matrix the rows correspond to different signals and the data points in the rows are the different samples. Plotting a row against the times of all the samples in the row gives a diagram of the signal. Figure 26 shows such a diagram produced from a measurement conducted during the development of the upgraded C&M system. In this figure one of the signals from the reference PMT have been plotted, and linear interpolation has been performed between data points for visibility. Due to availability reasons a different DAQ card was used during the development of the data analysis procedure. This card is identical to the card used in the performance testing of the C&Mu system in all regards but one: the input voltage range was -700mv to 100mV instead of -400mV to 400mV. It can be noted that the pulses in figures 26-28 in this chapter have amplitudes exceeding -400mV. The trigger level and number of pre-trigger samples in these figures also differs from the values used during the performance testing of the C&Mu system.
4.1 Data analysis requirements

The time difference between corresponding signals from the reference PMT and the TOFOR PMT is given by the length of the optical fiber cable and the lengths of the PMT signal cables. This time difference is therefore approximately constant. The variation in the time difference is a measurement of the time resolution of the setup. In order to investigate this time resolution, the time difference must be determined for each pair of records recorded by the data acquisition card. This is done by retrieving a time stamp from each signal relative to the start time of the record, which is the same for two corresponding signals. The two timestamps are then compared to determine the time difference between the signals. It was decided to use the time at which the amplitude of the signal reached 50% of its maximum value, as the time stamp of the signal. The reason for this decision was that the slope of the signal is largest around this area, which means time changes slowly with amplitude. Therefore an error in the determination of the amplitude means a relatively small error in the determination of the time stamp. However, in order to ensure the existence of a sample sufficiently close to the point on the signal where the amplitude reaches 50% of maximum, artificial samples had to be created by using pulse reconstruction. Using this technique all the acquired signals can be reconstructed to include 1280 artificial samples instead of 128 real samples [10].
To summarize, the requirements of the data analysis procedure were to:

1. Increase the number of samples for each signal from 128 to 1280 by using pulse reconstruction to create artificial samples.

2. For each record find the sample corresponding to 50% of the maximum signal amplitude and record this sample as a time stamp relative to the start time of the record. Then calculate the time difference between corresponding signals from the reference PMT and the TOFOR PMT by comparing their time stamps.

In order to accomplish this data analysis programs were written in MATLAB by the author of this work. The two steps above will now be described.

4.2 Pulse reconstruction

The theory of pulse reconstruction originates from the Nyquist-Shannon theorem, which states that if a signal \( A(t) \) contains no frequencies higher than \( B \), it is completely determined by sampling it with frequency \( f_s > 2B \). The signal can then be fully reconstructed by using the following Fourier transform:

\[
A(t) = \sum_i A(t_i) \frac{\sin(\pi (t - t_i) f_s)}{\pi (t - t_i) f_s}
\]  

(1)

where the sum is taken over all the samples in the signal and \( t_i \) is the time of sample \( i \), \( A(t_i) \) is the amplitude of the signal for sample \( i \) whereas \( A(t) \) is the amplitude of the reconstructed signal as a function of time [10]. A proof of this theorem can be found in [10]. The ratio in equation (1) is called a sinc function. Summarizing all the sinc pulses gives the reconstructed pulse. In this work the time between samples \( \Delta t \) has been used instead of the sampling frequency \( f_s \). The time between samples is the same as the time resolution of the data acquisition card, i.e. \( \Delta t = 0.5\text{ns} \). The relation between the sampling frequency and the time between samples is \( f_s = 1/\Delta t \). Inserting this relation into equation (1) gives:

\[
A(t) = \sum_i A(t_i) \frac{\sin(\pi (t - t_i)/\Delta t)}{\pi (t - t_i)/\Delta t}
\]

(2)

The frequency \( B \) of a signal is given by the relation \( B = 1/T \) where \( T \) is the duration of the signal [11]. As can be seen in figure 26, in this work the duration of a signal is typically 15ns. The typical frequency of a signal is thus \( B = 1/(15 \times 10^{-9}) = 67\text{MHz} \), and \( 2B = 134\text{MHz} \). The sampling frequency \( f_s \) of the data acquisition card is 2GHz which is greater than \( 2B \), meaning the Nyquist-Shannon condition is fulfilled and pulse reconstruction can be applied.
How pulse reconstruction has been implemented in the data analysis programs using equation (2) can be seen in appendix A4 and A5. The time $t$, which in theory is a continuous variable, had to be approximated by a discrete vector in the data analysis programs. In this work $t$ has been defined as a vector spanning from 0 to 64ns, containing 1280 data points. This gives a time between reconstructed samples of 0.05ns. Figure 27 shows one of the signals collected from the reference PMT during the development of the data analysis procedure, and how it was reconstructed. The blue dots are original data points and the black line is the reconstructed pulse. Shown in green are all the sinc functions making up the reconstructed pulse.

![Figure 27](image)

*Figure 27. One of the 10000 pulses collected from the reference PMT during the development of the C&Mu system. Shown in blue are the original data points of the pulse. Shown in green are the sinc pulses used to calculate the reconstructed pulse which is shown in black.*
4.3 Determination of the time differences

Figure 28 shows how the time difference between corresponding signals from the reference PMT and the TOFOR PMT is determined using the data analysis programs. For each signal the reconstructed sample which is closest to the point on the signal in which the amplitude has reached 50% of maximum without going over, is recorded as a time stamp. The time difference between corresponding time stamps is then calculated, and stored in a vector. From this vector also the standard deviation of the time difference can be retrieved. The amplitude of each signal is calculated by summarizing all the amplitudes building up the signal. These are then converted from levels to mV and recorded.

Figure 28. One of the 10000 pulse-pairs collected during the development of the C&Mu system. The pulse from the reference PMT is shown to the left and the pulse from the TOFOR PMT is show to the right. Dots represent reconstructed data points and the circles correspond to the original data points. The last reconstructed data point before the amplitude of the pulse reaches 50% of maximum has been marked by a square for each pulse. The position of these data points on the time axis has been marked in order to illustrate the time difference between the pulses.
5 Performance tests and results

The purpose of the C&Mu system is to monitor the dependence of the detector signal time delay on the signal amplitude for all the TOFOR detectors. The earlier experiments performed at TOFOR investigating this dependence, which are treated in section 2.3, have shown variations in time delay of about 6ns. In order for the C&Mu system to be able to observe such changes it must have an overall time resolution well below this. The performance tests presented in this chapter were conducted in order to ascertain that the C&Mu system would have sufficient time resolution when operated during a full JET day. The C&Mu systems ability to determine the dependence of the signal amplitude on the time difference between signals was also tested. The system setup used in these measurements is described in section 3.6.

The performance tests were conducted in three measurement series, where each measurement series includes several measurements. Prior to the start of each measurement series the applied voltage was chosen for the two PMTs to get signal amplitudes as close to -400mV as possible without risking going over. For the reference PMT this was achieved before the first measurement series. Therefore the applied voltage of the reference PMT was kept the same during all the measurement series. The applied voltage of the TOFOR PMT was re-calibrated before each measurement series. For each individual measurement performed during a measurement series the following applies:

- 10000 signals were collected by the data acquisition card, for each PMT.
- The time for conducting each measurement and transferring the data from the card to the computer was about 30 seconds.
- Each signal was collected during 64ns with 128 samples, giving a time resolution of 0.5ns.
- Data analysis was performed in order to determine the time difference between each pair of corresponding signals from the reference PMT and the TOFOR PMT, as well as the summarized amplitude for each signal (see chapter 4).
- The results of the data analysis were: the mean amplitude of each PMT, the mean time difference between the two PMTs and the spread of this time difference.

5.1 Timing measurements

One purpose of the timing measurements was to ascertain that the time resolution of the C&Mu system was well below 6ns. The other reason to perform this measurement series was to determine if the C&Mu system would be stable over a time period corresponding to a full day of measuring with TOFOR on JET. In other words, answers to the following questions were sought: is the variation of the time difference measured by the C&Mu system well below 6ns when viewed over:

- one measurement,
- a measurement series conducted over a time span of one JET day.

Two measurement series were conducted in order to answer these questions: one 8 hours measurement series with high resolution and one 27 hours measurement series with low resolution.
**8 hours measurement series**

The 8 hours measurement series is specified in the table in figure 29. Measurements were performed at regular intervals in order to achieve high resolution.

| Date when the measurement series was conducted: | 15th of February in 2012 |
| Time at which the laser and PMTs were turned on: | 8:45 |
| The applied voltages to which the PMTs were set: | Reference PMT: -970V  
TOFOR PMT: -1015V |
| Time at which the measurement series was started: | 9:15 |
| Time between measurements: | 9:15 to 16:15: 15 min  
16:15 to 17:15: 5 min |
| Time at which the measurement series was finished: | 17:15 |

Figure 29. Table of the specifics of the 8 hours time stability measurement series.

The results of the 8 hours measurement series are presented in figures 30 and 31. Figure 30 shows the distribution of time differences for the 10000 signal-pairs from the measurement performed at 10:30. The bin size of 0.05ns reflects the time between the artificial samples of the reconstructed signals. As expected the distribution is Gaussian which is shown by the fitted curve in figure 30. The mean time difference which is about 29.65ns for this measurement depends on the length of the cables in the setup. It has no connection to the time delays of the TOFOR detectors relative to each other and is therefore irrelevant. The purpose of this measurement was to determine the time resolution of the C&Mu system, which is dependent of the variation in time difference. The standard deviation of the time difference for the measurement shown in figure 30 is about 0.09ns which is well below the requirement of 6ns to observe such variations at TOFOR. Figure 31 shows the stability of the time difference between corresponding signals from the reference PMT and the TOFOR PMT over the measurement series. Error bars in the figure show the standard deviation, and it can be seen that this remains constant during the measurement. Thus it can be concluded that for each measurement performed during this measurement series the standard deviation is approximately 0.09ns. Apart for the Gaussian distribution of time difference for a single measurement, the time difference can also drift throughout the measurement series due to instabilities in the setup. As seen in figure 31 the drift of the mean time difference is about 0.08ns over this measurement series. This about equals the standard deviation meaning it is well below the requirement of TOFOR of 6ns. Since both the time resolution and the time stability is much better than 6ns, it can be concluded that the upgraded C&M system is more than adequate to observe variations in time delays at TOFOR over an 8 hours period.
Figure 30. Distribution of time differences recorded at the 10:30 measurement during the 8 hours timing measurement series. Shown in red is a Gaussian fit.

Figure 31. Time stability of the time difference between the PMT signals for the 8 hours timing measurement series. The error bars show the standard deviation. The x-axis shows the time a day at which the measurements were performed.
**27 hours measurement series**

This measurement series is specified in the table in figure 32. Measurements were performed sporadically over 27 hours in order to cover the timespan of a JET day which is 15 hours. The time difference between the PMT signals during this measurement series was different compared to the 8 hours measurement series since one of the PMT signal cables was exchanged due to availability reasons. However, this does not affect the magnitude of the change in time difference which is the object of investigation.

| Date when the measurement series was conducted: | 14th and 15th of March in 2012 |
| Time at which the laser and PMTs were turned on: | 11:30 |
| The applied voltages to which the PMTs were set: | Reference PMT: -970V  
TOFOR PMT: -1070V |
| Time at which the measurement series was started: | 13:45 on the 14th of March |
| Time between measurements: | varying |
| Time at which the measurement series was finished: | 16:30 on the 15th of March |

Figure 32. Table of the specifics of the 27 hours timing measurement series.

The results of the 27 hours measurement series are presented in figure 33. Figure 33 shows the stability of the time difference between corresponding signals from the reference PMT and the TOFOR PMT over the measurement series. Error bars in the figure show the standard deviation which is approximately 0.10ns and constant throughout the measurement series. As seen in figure 33 the drift of the mean time difference is about 0.12ns over this measurement series. This is well below the requirement of TOFOR of 6ns. Since both the time resolution and the time stability is much better than 6ns, it can be concluded that the upgraded C&M system is more than adequate to observe variations in time delays at TOFOR over a 27 hours period.
5.2 Timing measurements at different amplitudes

It has been shown that the time delay of a TOFOR detector signal depends on its amplitude. In order to improve the characterization of the TOFOR detectors this dependence must be monitored. The ability of the C&Mu system to perform this monitoring function was tested by conducting a measurement series. During this measurement series the intensity of the light reaching the TOFOR PMT was varied between measurements, by using the motorized polarizer. The time difference and the spread in time difference between corresponding signals from the reference PMT and the TOFOR PMT were determined as a function of the signal amplitude of the TOFOR PMT. The specifics of this measurement series are presented in figure 34 below.

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
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<td>17th of February in 2012</td>
</tr>
<tr>
<td>Time at which the laser and PMTs were turned on:</td>
<td>9:00</td>
</tr>
<tr>
<td>The applied voltages to which the PMTs were set:</td>
<td>Reference PMT: -970V TOFOR PMT: -1029V</td>
</tr>
<tr>
<td>Time at which the measurement series was started:</td>
<td>10:30</td>
</tr>
<tr>
<td>Time between measurements:</td>
<td>1 min</td>
</tr>
<tr>
<td>Time at which the measurement series was finished:</td>
<td>11:44</td>
</tr>
</tbody>
</table>

Figure 34. Table of the specifics of the measurement series investigating the intensity dependence of the variation in time difference.
Figure 35 shows the mean time difference between corresponding signals from the reference PMT and the TOFOR PMT, as a function of the signal amplitude of the TOFOR PMT. For very low amplitudes the data analysis programs could not reconstruct all 10000 signals for each TOFOR PMT measurement. For signal amplitudes with an absolute value below about 15mV which corresponds to about 5% of the maximum amplitude, less than 10000 signals could be reconstructed per measurement. These are the first 5 measurements in figure 35 counting from the left. As seen in the figure this is reflected in their large standard deviations. It was not possible to measure at amplitudes below about 2% of maximum. As seen in figure 35 the mean time difference increases when the absolute value of the amplitude increases. The total change in time difference when going from 5% amplitude to 100% amplitude is about 0.08ns. Error bars in figure 35 show the standard deviation, which is approximately constant at 0.1ns for amplitudes with an absolute value above 200mV. For lower amplitudes the standard deviation increases when the absolute value of the amplitude decreases. At an amplitude of about 5% of maximum the standard deviation is 0.17. Figures 36 and 37 show the distribution of time differences for the 10000 pulse-pairs recorded at a light intensity of about 95% and 5% of maximum respectively. As expected the distributions are Gaussian which is shown by the fitted curves in the figures. If we compare the two figures we see that the standard deviation is much greater for the lower light intensity which can also be seen in figure 35.

As concluded in section 2.3 the most important thing is to monitor the variations in time delay for the TOFOR detectors at amplitudes around -100mV, which is the typical amplitude of an S1 detector. It has been seen here that the C&Mu system is capable of monitoring these variations around this region and even as far as to -15mV. The C&Mu system was also able to observe variations in time difference of about 0.1ns which way better that the TOFOR requirement of 6ns. Thus it can be concluded that the C&Mu system can be used at TOFOR to monitor the time delays of the TOFOR detectors.
Figure 35. Time difference between the signal from the reference PMT and the TOFOR PMT, as a function of the mean amplitude of the pulse from the TOFOR PMT. Error bars show the standard deviation.

Figure 36. Distribution of time differences recorded at a TOFOR PMT signal amplitude of approximately 95%. Shown in red is a Gaussian fit.
Figure 37. Distribution of time differences recorded at a TOFOR PMT signal amplitude of approximately 5%. Shown in red is a Gaussian fit.

The timing measurements at different amplitudes were also used to map the dependence of the TOFOR PMT signal amplitude on the position of the motorized polarizer. Figure 38 show the mean amplitude of the PMT signals as a function of the position of the motorized polarizer. Error bars show the standard deviation. This figure also includes a second x-axis depicting the time, which shows that the measurement took 74 minutes to complete, corresponding to one minute per measurement. It can be seen from figure 38 that the intensity of the reference PMT was stable during the measurement and thus not affected by the change in intensity of the light incident on the TOFOR PMT. It can be concluded that the reference signal is reliable since it does not change with the polarizer. The table in figure 39 show the the position of the polarizer for a number of different relative light intensities.
Figure 38. Mean amplitude of the pulse from the TOFOR PMT, as a function of the position of the motorized polarizer. Error bars show the standard deviation.

<table>
<thead>
<tr>
<th>Relative light intensity [%]</th>
<th>Position of polarizer [steps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6700</td>
</tr>
<tr>
<td>5</td>
<td>7490</td>
</tr>
<tr>
<td>10</td>
<td>7850</td>
</tr>
<tr>
<td>15</td>
<td>8120</td>
</tr>
<tr>
<td>20</td>
<td>8350</td>
</tr>
<tr>
<td>25</td>
<td>8560</td>
</tr>
<tr>
<td>30</td>
<td>8750</td>
</tr>
<tr>
<td>35</td>
<td>8930</td>
</tr>
<tr>
<td>40</td>
<td>9100</td>
</tr>
<tr>
<td>45</td>
<td>9280</td>
</tr>
<tr>
<td>50</td>
<td>9430</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative light intensity [%]</th>
<th>Position of polarizer [steps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>9610</td>
</tr>
<tr>
<td>60</td>
<td>9790</td>
</tr>
<tr>
<td>65</td>
<td>9950</td>
</tr>
<tr>
<td>70</td>
<td>10140</td>
</tr>
<tr>
<td>75</td>
<td>10320</td>
</tr>
<tr>
<td>80</td>
<td>10500</td>
</tr>
<tr>
<td>85</td>
<td>10720</td>
</tr>
<tr>
<td>90</td>
<td>11010</td>
</tr>
<tr>
<td>95</td>
<td>11320</td>
</tr>
<tr>
<td>100</td>
<td>12100</td>
</tr>
</tbody>
</table>

Figure 39. Table of the relative intensity of the light incident on the TOFOR PMT, as a function of the position of the motorized polarizer.
6 Discussion and conclusions

As shown in section 2.3 the time delay of a TOFOR detector depends on its signal amplitude [6]. Therefore the dependence of the time delay on the signal amplitude must be monitored for all TOFOR detectors. The time delays of the TOFOR detectors can be monitored by sending light pulses into the detectors and record the resulting interaction time stamps. To determine the time delay of a detector the interaction time stamp must be compared to a reference time signal. In order to determine time delays at different amplitudes the intensity of the light must be varied between measurements. Thus, in order to use the C&M system for this monitoring function it needs to comprise both variable intensity and a reference time signal.

In this work the upgraded C&M system (C&Mu system) has been developed and tested. The C&Mu system uses a pulsed laser with a motorized polarizer as a light source. The upgrade performed was the retrieving of a reference time signal from this laser. During this work a control program was developed for the motorized polarizer, enabling the user to vary the intensity of the light over the interval from 0% to 100%. As concluded in section 2.3 the most important region in which to monitor the time delays of the TOFOR detectors is at amplitudes around -100mV. This is the typical amplitude of an S1 detector and at TOFOR spreads in time delays of several nanoseconds have been observed for detectors with signals of this amplitude. Tests performed in this work show that the standard deviation of the time difference measured by the C&Mu system is about 0.10ns. These tests also show that the drift of the time difference is about 0.12ns over 27 hours. Both these variations in time difference is much lower than the variations observed at TOFOR of several nanoseconds. It can thus be concluded that the C&Mu system is more than adequate to observe variations in time delays at TOFOR over a full JET day of 15 hours. The C&Mu system is ready to be installed on TOFOR.

At TOFOR the C&Mu system can be used to determine how the time delay depends on the signal amplitude for each TOFOR detector. The TOFOR DAQ system does however not record the signal amplitude for each individual neutron interaction. Therefore the exact time delay of each neutron interaction cannot be determined. However, the typical signal amplitudes of the S1 and S2 detectors are known to be -100mV and -500mV respectively. Through the monitoring procedure performed by the C&Mu system the time delay corresponding to each of these amplitudes can be determined, for each individual TOFOR detector. The results from this monitoring procedure will also show the standard deviation of the time delay for these amplitudes, as well as how much the time delay changes with amplitude in the vicinity of these points. Therefore the uncertainties of the measured interaction timestamps can be determined. This information can then be used when the time-of-flight spectra are constructed, and the characteristics of these spectra can thus be better understood. This will in turn enable a better understanding of the energy spectrum of the 2.45MeV neutrons emitted by the plasma in the JET reactor. Hopefully this will give further information about the properties of the plasma.
7 Outlook

In the future the TOFOR DAQ system will be replaced with a new data acquisition system called DAQu, which is currently being tested on TOFOR. The DAQu system will be able to record the electrical signals for all the interactions in each TOFOR detector. This system records the whole electrical pulse and therefore allows to determine both the interaction time stamp and the signal amplitude for each individual neutron interaction [8]. By using the C&Mu system to determine the dependence of the time delay of the signal amplitude for each TOFOR detector, the time delay of each individual neutron interaction can then be determined. In contrast with the DAQ system, the DAQu system will not only enable the determination of the uncertainties of the measured interaction timestamps, it will also decrease these uncertainties. The time-of-flight spectra constructed when using the DAQu system will thus be more accurate than the ones constructed when using the DAQ system.
8 Acknowledgments
The author of this work would like to thank the fusion diagnostics group at the division of applied nuclear physics at Ångström laboratory at Uppsala University, for support both financial and knowledge wise. Special thanks go out to the following persons:

My supervisors Matthias Weiszflog and Göran Ericsson have been of great importance for this work. They have directed my efforts, reviewed my ideas and explained the workings of TOFOR and other devices.

Mateusz Skiba has showed me the workings of the laboratory and the available equipment. He explained the MATLAB code and provided programming support.

Erik Andersson Sundén provided python programming support.

Outside of the fusion group I would like to thank the following people:

Lars Erik Lindkvist at the Ångström workshop has constructed the necessary parts for the upgraded C&M system.

KTH donated the polarizing beamsplitter cube needed to retrieve the reference signal from the laser.
9 References

Appendix

A1: Instructions for connecting the laser driver to the laser head

A scheme of how the laser head 12AS01 was connected to the laser driver STA-01SH-AS is shown below. The laser head mounted in the light tight box was connected to the laser driver by the optical fiber pigtail. The external voltage supplier was connected to the voltage input on the light tight box and to the wall outlet. The purpose of this external voltage supplier is to provide the motorized polarizer with power. A power cord was connected between the laser driver and the wall outlet. A cable was connected between the laser head and the laser driver, allowing the laser driver to control the temperature in the laser head. Connected to the laser driver was then another cable, which splits into three different cables at the other end. One of these can be connected to the serial port of a computer, allowing it to control the laser. The other two cables are used for interlock functions. One of these was connected to the light tight box, in order to ensure that the laser head gets turned off if the box is opened. The other interlock cable was used in the same way when the system was installed at JET, to ensure that the laser would be turned off if the cubicle, in which the laser was situated, was opened. Since this interlock function was not needed in the laboratory setup, it was disabled. A cable for connecting the light tight box to a computer, allowing it to control the motorized polarizer, was also available.
A2: Python 2.7 program for controlling the motorized polarizer

pol.py

from Tkinter import *
import motorc

class polarizer(Frame):
    def __init__(self):
        self.root = Tk()
        Frame.__init__(self, self.root, height=350, width=462)
        self.motor = motorc.Motor()
        self.pack_propagate(0)
        self.pack()
        self.createWidgets()

    def quit(self):
        self.close()
        self.root.destroy()

    def close(self):
        self.motor.closePort()

    def getStartText(self):
        text = self.motor.getsText()
        self.startText.set(text)

    def checkStat(self):
        stat = self.motor.checkStatus()
        self.status.set(stat)

    def getPos(self):
        [pText, pString] = self.motor.getPosition()
        self.pos.set(pString)

    def resetMot(self):
        self.motor.resetMotor()
        self.mess.set('')
        self.checkStat()
        self.getPos()

    def turnMot(self):
        posString = self.posEntry.get()
pos = 0
pText = "
stat = "
i = 0
a = 0
while i < len(posString):
    if posString[i] == ',':
        posString = posString[:i] + '.' + posString[(i+1):]
        a = a+1
    elif posString[i] == '.':
        a = a+1
    i = i+1
if a > 1:
    m = 'Error! To many commas!'
    self.mess.set(m)
else:
    try:
        pos = float(posString)
        pos = int(pos)
        if pos > -1 and pos < 24001: #17feb
            m = self.motor.turnMotor(pos)
            self.mess.set(m)
        else:
            m = 'Out of bounds! Choose a position between 0 and 24000.'
            self.mess.set(m)
    except ValueError:
        m = 'Not a number!'
        self.mess.set(m)
self.getPos()
self.checkStat()

def createWidgets(self):
    self.QUIT = Button(self)
    self.QUIT["text"] = "QUIT"
    self.QUIT["fg"] = "red"
    self.QUIT["command"] = self.quit
    self.QUIT.place({"x":"0", "y":"0"})

    self.startText = StringVar()
    self.getStartText()
    self.dispStartText = Label(self, textvariable=self.startText)
    self.dispStartText["bg"] = "white"
self.dispStartText.place(\{"x":120, "y":0\})

self.pos = StringVar()
self.getPos()
self.status = StringVar()
self.checkStat()
self.mess = StringVar()

self.getP = Button(self)
self.getP["text"] = "Check position of motor"
self.getP["command"] = self.getPos
self.getP.place(\{"x":0, "y":70\})

self.resetM = Button(self)
self.resetM["text"] = "Reset motor to 0 position"
self.resetM["command"] = self.resetMot
self.resetM.place(\{"x":332, "y":70\})

self.turnText = Label(self)
self.turnText["text"] = "Turn motor(enter new position between 0 and 24000):"
self.turnText.place(\{"x":0, "y":100\})

self.posT = Label(self)
self.posT["text"] = "Current position of motor:"
self.posT.place(\{"x":0, "y":140\})

self.dispPos = Label(self, textvariable=self.pos)
self.dispPos["bg"] = "yellow"
self.dispPos.place(\{"x":130, "y":140\})

self.messT = Label(self)
self.messT["text"] = "Message:"
self.messT.place(\{"x":0, "y":160\})

self.dispMess = Label(self, textvariable=self.mess)
self.dispMess["bg"] = "pink"
self.dispMess.place(\{"x":50, "y":160\})

self.posEntry = Entry(self)
self.posEntry.place(\{"x":270, "y":100\})
self.posEntry.focus_set()
self.turnM = Button(self)
self.turnM["text"] = "Turn motor"
self.turnM["command"] = self.turnMot
self.turnM.place({"x":"400", "y":"100"})

self.checkS = Button(self)
self.checkS["text"] = "Check status of motor"
self.checkS["command"] = self.checkStat
self.checkS.place({"x":"0", "y":"220"})

self.statusT = Label(self)
self.statusT["text"] = "Status of motor:" 
self.statusT.place({"x":"0", "y":"260"})

self.dispStat = Label(self, textvariable=self.status)
self.dispStat["bg"] = "yellow"
self.dispStat.place({"x":"82", "y":"260"})

p = polarizer()
p.mainloop()

```
motorc.py
```

import serial

class Motor(object):
    def __init__(self):
        
        """Open COM port and initiate motor. portnr: 0, baudrate: 57600, bytesize: 8 bit, parity: none, nr of stopbits: 1, timeout: 1 sek.""
        self.ser = serial.Serial(0, 57600, 8, serial.PARITY_NONE, 1, timeout = 1)
        openText = 'The following port has been opened: '+ self.ser.portstr+'\n'
        self.ser.write('A11I\r\n')
        replyl = self.ser.read(8)
        if replyl == 'R11Rdy\r\n' or replyl == ':':
            statText = 'Motor initiated and ready to use'
        elif replyl == 'R11Bsy\r\n':
            statText = 'Motor busy'
        else:
            statText = 'Motor error'
        self.startT = openText+statText

    def getText(self):
        """Get starttext."""
```
t = self.startT
return t

def closePort(self):
    """Close port."""
    self.ser.close()

def checkStatus(self):
    """Check status of motor."""
    stat = self.printStatus()
    self.ser.write('*A11A
')
    status = self.printStatus()
    return status

def getPosition(self):
    """Get position of motor."""
    self.ser.write('*A11P
')
    reply = self.ser.read(20)
    posStr = reply[4:(len(reply)-2)]
    if reply[0:1] == 'R':
        posText = ''
    elif reply[0:1] == 'I':
        posText = 'Try again'
    else:
        posText = 'no information'
    return [posText, posStr]

def resetMotor(self):
    """Reset motor.""
    [pT, pS] = self.getPosition()
    p = self.strTOint(pS)
    if p < 5000:
        mess = self.turnMotor(0)
    else:
        self.ser.write('*A11R\r\n')
        status = self.printStatus()

def turnMotor(self, newPos):
    """Turn motor. Different commands is sent to the motorcard,
    depending on which way the motor must be turned.""
    mess = ''
    if type(newPos) == 'NoneType':
```
mess = 'No new position entered'
else:
    [posText, posString] = self.getPosition()  # get pos of motor
    mess = posText
    pos = self.strTOint(posString)
    steps = newPos-pos  # calc nr of steps to move
    if steps > 0:  # move forward
        command = '*A11F'+str(steps)+'\r\n'
        self.ser.write(command)
        status = self.printStatus()
    elif steps < 0:  # move backward
        command = '*A11B'+str(0-steps)+'\r\n'
        self.ser.write(command)
        status = self.printStatus()
    else:
        mess = 'allready in that position'
return mess

def strTOint(self, string):
    """Transforms a string to an int, via a float. In order to
    convert from string to float, the ',' given by the
    motorcard must be exchanged to "."""
    pos = 0
    i = 0
    while i < len(string):
        if string[i] == ',':
            string = string[:i] + '.' + string[(i+1):]
        i = i+1
    pos = float(string)
    pos = int(pos)
    return pos

def printStatus(self):
    """Get status of motor."""
    replyPS = self.ser.read(20)  # read from motorcard
    if replyPS == 'R11Rdy\r\n':
        status = 'Motor ready'
    elif replyPS == 'R11Bsy\r\n' or replyPS == '':
        status = 'Motor busy'
    else:
        status = 'error:'+replyPS
    return status
A3: MATLAB program for data acquisition with the ADQ412 SP Devices card

```matlab
function [Data varargout] = ADQ412_DAQ(n_recs, n_samples, PreTrigger,...
    Cards, Trigger, TriggerLevel,...
    TriggerCH, ClockSource, TimeOut,...
    MaxPlot, ClearMex, CrashCheck,...
    InterleavingMode, SelfTrigCard)

% Some constants
% ------------------
RISING_EDGE = 1;
FALLING_EDGE = 0;
INT_INTREF = 0;
INT_EXTREF = 1;
EXT = 2;
INT_PXIREF = 3;

if nargin < 3 || isempty(PreTrigger)
    PreTrigger = 16;
end

if nargin < 4 || isempty(Cards)
    Cards = [03];
end

if nargin < 5 || isempty(Trigger)
    Trigger = 'level';
end

if nargin < 6 || isempty(TriggerLevel)
    TriggerLevel = 1400;
end

if nargin < 7 || isempty(TriggerCH)
    TriggerCH = 'any';
end

if nargin < 8 || isempty(ClockSource)
    ClockSource = INT_PXIREF;
end

if nargin < 9 || isempty(TimeOut)
    TimeOut = 3600*24;
end

if nargin < 10 || isempty(MaxPlot)
    MaxPlot = 10;
end

% ClearMex = 1: Clear board from computer memory. This resets counter.
if nargin < 11 || isempty(ClearMex)
    ClearMex = 1;
end

% CrashCheck = 1: Cancel acquisition if no records collected during 500 first steps.
if nargin < 12 || isempty(CrashCheck)
```
CrashCheck = 1;
end

if nargin < 13 || isempty(InterleavingMode)
    InterleavingMode = 'No';
end

if nargin < 14 || isempty(SelfTrigCard)
    SelfTrigCard = 0;
end

switch Trigger
    case {'level', 'Level', 'LEVEL'}
        Trigger = 3;
    case {'extern', 'Extern', 'EXTERN', 'external', 'External', 'EXTERNAL'}
        Trigger = 2;
    case {'software', 'Software', 'SOFTWARE'}
        Trigger = 1;
end

switch TriggerCH
    case {'a', 'A'}
        TriggerCH = 1;
    case {'b', 'B'}
        TriggerCH = 2;
    case {'c', 'C'}
        TriggerCH = 4;
    case {'d', 'D'}
        TriggerCH = 8;
    case {'any', 'Any', 'ANY'}
        TriggerCH = 15;
end

switch ClockSource
    case {'pxi', 'PXI'}
        ClockSource = INT_PXIREF;
    case {'intern', 'Intern', 'INTERN', 'internal', 'Internal', 'INTERNAL'}
        ClockSource = INT_INTREF;
    case {'extern', 'Extern', 'EXTERN', 'external', 'External', 'EXTERNAL'}
        ClockSource = INT_EXTREF;
end

switch ClearMex
    case 1
        clear mex;
end

switch InterleavingMode
    case {'y', 'Y', 'yes', 'Yes', 'YES'}
        InterleavingMode = 1;
    case {'n', 'N', 'no', 'No', 'NO'}
        InterleavingMode = 0;
end

Settings = {n_recs, n_samples, PreTrigger, Cards, Trigger,...
    TriggerLevel, TriggerCH, ClockSource, TimeOut, MaxPlot,...
    ClearMex, CrashCheck, InterleavingMode, SelfTrigCard};
% Set some default values
% ------------------------
LvlTriggFlank = FALLING_EDGE;
BufferSizeSamples = 128;

% Setup the cards
% -----------------------
if InterleavingMode == 0
dt = 1.0;
else
dt = 0.5;
end
t = 0:dt:(n_samples-1)*dt;
for card = Cards
    disp(['Setting up card ' num2str(card)]);
    if ClearMex == 1
        interface_ADQ('setinterleavingmode', InterleavingMode, card);
%interface_ADQ('set_pll',[400,2,1,1], card);
disp(TriggerLevel)
    if length(TriggerLevel) > 1
        interface_ADQ('setlvltriglevel',TriggerLevel(card), card);
    else
        interface_ADQ('setlvltriglevel',TriggerLevel, card);
    end
    interface_ADQ('setlvltrigchannel',TriggerCH, card);
    interface_ADQ('setlvltrigedge',FALLING_EDGE, card);
    interface_ADQ('settriggermode',Trigger, card);
    interface_ADQ('setpretrigsamples',PreTrigger, card);
    interface_ADQ('set_trigger_level_treshold', 10);
    interface_ADQ('setpretrigsamples',PreTrigger, card);
    interface_ADQ('setclocksource',ClockSource, card);
    interface_ADQ('setbuffersize',BufferSizeSamples, card);
    end
    if length(TriggerLevel) > 1
        interface_ADQ('setlvltriglevel',TriggerLevel(card), card);
    else
        interface_ADQ('setlvltriglevel',TriggerLevel, card);
    end
    interface_ADQ('setlvltrigchannel',TriggerCH, card);
    interface_ADQ('settriggermode',Trigger, card);
    interface_ADQ('setpretrigsamples',PreTrigger, card);
end
[a,b,c,d] = interface_ADQ('multi_record_setup', [n_recs n_samples], card);
interface_ADQ('reset_trigger',[],card);
end

% Collect data
% --------------
n_cards = length(Cards);
finished = zeros(n_cards, 1);
step = 0;
tic;

ErrorFlag=0;

while all(finished) == 0
time = toc;

    if Trigger == 1
        for card = Cards
            interface_ADQ('usb_trig', [], card); % Trig device
        end
    end

    if Trigger==2 && SelfTrigCard>0
        interface_ADQ('setdirectiontrig',1, SelfTrigCard);
        interface_ADQ('writetrig',1, SelfTrigCard);
        interface_ADQ('writetrig',0, SelfTrigCard);
    end

    for i = 1:n_cards
        [~,~,c,~] = interface_ADQ('get_triggered_all', [], Cards(i));
        % Check if all records collected
        finished(i) = c(1);
        FPGATemperature(i,step+1) = interface_ADQ('get_temperature',3,Cards(i));
        [~, ~, Records(step+1,i,:), ~] = interface_ADQ('read_register',hex2dec('1000')+13,Cards(i));
    end

    if mod(step, 10) == 0
        clc
        hours = ((time/(double(min(Records(step+1,:,1))/double(n_recs)))-time)/3600);
        minutes = 60*(hours-floor(hours));
        seconds= 60*(minutes-floor(minutes));
        time_left = [num2str(floor(hours)) ' hours, ' num2str(floor(minutes)) ' minutes and ' num2str(floor(seconds)) ' seconds left'];
        fprintf(['\nTime elapsed: ' num2str(floor(time)) ' seconds
'])
        fprintf([time_left '
'])
        for i = 1:length(Cards)
            fprintf(['--------
Records in card ' num2str(Cards(i)) ': ' num2str(Records(step+1,i,1)) '\n'])
            fprintf(['Temperature of card ' num2str(Cards(i)) ': ' num2str(FPGATemperature(i,step+1)) ' degrees C\n'])
            fprintf(['Count rate: ' num2str(floor(Records(step+1,i,1)/time)) ' counts/second\n']);
        end
    end

    % Check for crash
    if mod(step, 100) == 0 && step>500 && all(Records(step+1,:,1))==0 && CrashCheck==1
        for card = Cards
            interface_ADQ('disarmtrigger',[],card);
        end

end
ErrorFlag = 1;
break
end
pause(0.01);
step = step + 1;
if time > TimeOut
    for card = Cards
        interface_ADQ('disarmtrigger',[],card);
        disp(TimeOut)
    end
    ErrorFlag = 2;
    break
end
end
fprintf(1, '\n');

% Read data
% ---------------------
Data = {};
Trigger = {};
if ErrorFlag == 0
    for card = Cards
        disp(['Reading data from card ' num2str(card) '...'])
        if InterleavingMode == 0
            Data{(card-1)*4+1} = zeros(n_recs, n_samples);
            Data{(card-1)*4+2} = zeros(n_recs, n_samples);
            Data{(card-1)*4+3} = zeros(n_recs, n_samples);
            Data{(card-1)*4+4} = zeros(n_recs, n_samples);
            Trigger{(card-1)*4+1} = zeros(n_recs, 1, 'double');
            Trigger{(card-1)*4+2} = zeros(n_recs, 1, 'double');
            Trigger{(card-1)*4+3} = zeros(n_recs, 1, 'double');
            Trigger{(card-1)*4+4} = zeros(n_recs, 1, 'double');
        else
            Data{(card-1)*2+1} = zeros(n_recs, n_samples);
            Data{(card-1)*2+2} = zeros(n_recs, n_samples);
            Trigger{(card-1)*2+1} = zeros(n_recs, 1, 'double');
            Trigger{(card-1)*2+2} = zeros(n_recs, 1, 'double');
        end
        percent = [num2str(0) '%%'];
        fprintf(1, 'Completed: ');
        output = sprintf('%s', percent);
        fprintf(1, output);
    for j=1:n_recs
        for i = 1:length(output)-1

fprintf(1, '\b')
end

percent = [num2str(floor(100*(j/n_recs))) '%%'];
output = sprintf('%s', percent);
fprintf(1, output);

[a,b,c,d] = interface_ADQ('collect_record', j-1, card);

if InterleavingMode == 0
    Data{(card-1)*4+1}(j, :) = a.DataA;
    Data{(card-1)*4+2}(j, :) = a.DataB;
    Data{(card-1)*4+3}(j, :) = a.DataC;
    Data{(card-1)*4+4}(j, :) = a.DataD;
else
    Data{(card-1)*2+1}(j, :) = a.DataA;
    Data{(card-1)*2+2}(j, :) = a.DataC;
end

[~, ~, adq_status, ~] = interface_ADQ('get_trigtime', [], card);
trigg = double(adq_status(1))/4.0;

if InterleavingMode == 0
    Trigger{(card-1)*4+1}(j) = trigg;
    Trigger{(card-1)*4+2}(j) = trigg;
    Trigger{(card-1)*4+3}(j) = trigg;
    Trigger{(card-1)*4+4}(j) = trigg;
else
    Trigger{(card-1)*1+1}(j) = trigg;
    Trigger{(card-1)*2+2}(j) = trigg;
end

end

% Close multirecord
interface_ADQ('multi_record_close', [], card);
fprintf('
\n');
end

if nargout > 0
    varargout{1} = Trigger;
end

if nargout > 1
    varargout{2} = FPGATemperature;
end

if nargout > 2
    varargout{3} = Records;
end

if nargout > 3
    varargout{4} = ErrorFlag;
end
if nargout > 4
    varargout{5} = Settings;
end

A4: MATLAB program for analyzing data: flighttimesNewLA.m

function [ftimes stdDeviation deltaT] = flighttimesNewLA(Data, NrOfRecords)

tstart = tic;
data1 = Data{1};
data2 = Data{2};
dt = 0.5;
multiply = 10;
[recs, OldNrOfSamples] = size(data1);
clear recs;

stopTime = OldNrOfSamples*dt;
NrOfSamples = OldNrOfSamples*multiply;
t = linspace(0, stopTime, NrOfSamples);

flighttimes = [];

for j =1:NrOfRecords
    puls = zeros(2,NrOfSamples);
    data1(j,:) = data1(j,:) - mean(data1(j,1:12));
    data2(j,:) = data2(j,:) - mean(data2(j,1:12));
    for i = 1:OldNrOfSamples
        ti = (i-1)*dt;
        puls(1,:) = puls(1,:) + data1(j,i)*((sin(pi*(t-ti)/dt))./(pi*(t-ti)/dt));
        puls(2,:) = puls(2,:) + data2(j,i)*((sin(pi*(t-ti)/dt))./(pi*(t-ti)/dt));
    end
    [min1 index1] = min(puls(1,101:1000));
    [min2 index2] = min(puls(2,201:1200));

    index1=index1+100;
    index2=index2+100;

    min05p1 = 0.5*min1;
    min05p2 = 0.5*min2;
    if(min05p1 < -25 && min05p2 < -25)
        t1 = 100 + find(puls(1,101:index1)<=min05p1,1);
        t2 = 200 + find(puls(2,201:index2)<=min05p2,1);
    ftime = (t2-t1)*0.05;
    flighttimes = [flighttimes ftime];
end
end

stdDeviation = std(flighttimes);
deltaT = max(flighttimes)-min(flighttimes);

ftimes = flighttimes;
time = toc(tstart)/60
function [sumsAmp minAmps] = ReconstructPulsesAmpNew(data, NrOfRecords)
        tstart = tic;
        dt = 0.5;
        multiply = 10;
        [recs, OldNrOfSamples] = size(data);
        clear recs;
        stopTime = OldNrOfSamples*dt;
        NrOfSamples = OldNrOfSamples*multiply;
        t = linspace(0, stopTime, NrOfSamples);
        sumAmp = []; 
        minAmp = [];
        for j = 1:NrOfRecords
            puls = zeros(1,NrOfSamples);
            data(j,:) = data(j,:) - mean(data(j,1:12));
%             data(j,:) = data(j,:)*0.1953125;
            for i = 1:OldNrOfSamples
                ti = (i-1)*dt;
                puls = puls + data(j,i)*((sin(pi*(t-ti)/dt))./(pi*(t-ti)/dt));
                puls(isnan(puls)) = 0;
            end
            sumAmp = [sumAmp sum(puls)];
            minAmp = [minAmp min(puls)];
        end
        sumsAmp = sumAmp;
        minAmps = minAmp;
        time = toc(tstart)/60
end