



Politechnika Łódzka



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Wydział Elektrotechniki, Elektroniki, Informatyki i Automatyki Politechniki Łódzkiej

Praca Dyplomowa Magisterska Real Time Digital Pulse Processing from Radiation
Detectors Using Field Programmable Gate Arrays inż. Wojciech Mateusz Walewski Nr
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Abstract

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1 Introduction

1.1 Motivation

Concerns regarding the sustainability of using fossil fuels for energy generation have been raised as early as the 1970s [1]. One of the most well-known examples from that time was the 1972 report titled "Limits to Growth" by Meadows et. al. [2]. In it a group of MIT scientists attempted to answer the question of how long will the Earth's natural resources last for considering the seemingly neverending growth of human civilisation. As a result of a conducted computer simulation, a rough estimate of around 100 years was given as a timeframe, after which the population would start to collapse due to a lack of resources.

This estimate did not go without controversies back when it was first published. The methodology was thoroughly picked apart, leading many to dismiss the study findings [1]. Naturally, nowadays, we are much better poised to verify the claims made by the now 50 year old book. The impeding resource depletion has certainly been made a less valid claim as technological progress made it possible to locate and tap into previously inaccessible fossil fuel fields [3]. Taking into account other issues, however, the original timeline of 100 years might have actually shifted closer.

When it comes to fossil fuel usage, in the last twenty years, the primary concerns have changed from resource depletion to global warming and irreversible environmental damage [1]. In 2018 the Intergovernmental Panel on Climate Change (IPCC) published a report indicating the need to stop the global temperature increase at 1.5°C above the levels measurable in the pre-industrial era. Failure to do so is projected to lead to irreversible climate changes and in turn serious damage to human settlements around the world. [4]

Fossil fuels account for as much as 70% of greenhouse gas emissions. Electricity generation alone causes 25-35% [5] of the total amount. Such a high share means that reducing this output is going to be crucial in meeting the goals outlined by the IPCC. At the beginning of the twentieth century, renewable energies, i.e. wind, solar, biomass and geothermal were thought to be the perfect solution to the issue at hand [6].

In modern times, we have now become aware of multiple issues that make renewable energy generation a problem at large scale. Most importantly, their efficacy varies depending on the geographical location and climate. Even when placed in optimal condi-

tions, they do not offer perfect stability. Additionally, the land usage is greater than the traditional forms of energy production [7].

1.2 Fission energy

The drawbacks of renewable energies have led to a formation of an alternative approach in both research and policymaking. The use of nuclear energy for supplementing the shortcomings of renewables has been suggested as a potential path forward. This concept is referred to as hybrid nuclear-renewable system. [8].

There are two ways that nuclear energy can be created and harnessed. In the more well-established technology, fission, heavy atoms (usually Uranium) are bombarded with neutrons and split into two or more lighter nuclei and additional neutrons. The reaction is self-sustaining and releases energy in the form of heat that is then used to boil water. The steam causes turbines to spin and generate electricity.

Fission is far from a new concept, as first fission reactors have been built as early as 1942 [9]. Although the technology itself is quite old and has been greatly improved over time, there is reasonable reluctance to build and use fission power plants. The issue that gets raised most often is the storage of radioactive waste. There are, however, multiple less well-known problems with fission [10].

The tragedies of Chornobyl and Fukushima reactors have caused many people to be wary of fission. However, even if democratic support is disregarded in policymaking, the acquisition, storage and disposal of radioactive materials required for and produced during fission prove to be an administrative challenge, especially if reactor construction and maintenance is to be handled by private entities [11]. The complexity of the problem suggests that as we arrive to more concrete solutions we should not stop exploring other potential alternatives.

1.3 Fusion energy

Just like it is possible to split atoms, it is also possible to combine them together in a process referred to as fusion. Fusing atoms lighter than Iron is a reaction that can produce surplus energy as highlighted by Figure 1. Two atoms of low binding energy can fuse into an atom of higher binding energy, releasing heat based on the mass-energy

equivalence formula. The output energy can be used to generate electricity in the exact same manner as with fission. The problem with fusion reactors is that the conditions necessary for fusion to happen are extremely harder to achieve and sustain [12].

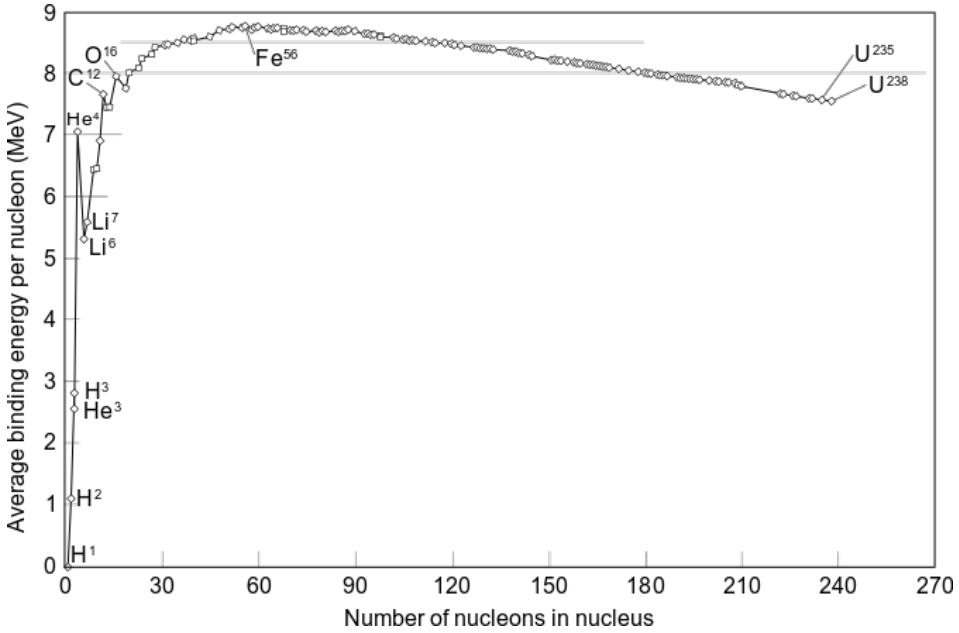


Figure 1: Average binding energy per nucleon as a function of the number of nucleons in the atom

Fusion is the primary reaction that causes stars to emit light and heat. The reaction that is most often artificially attempted on Earth differs from that occurring naturally in the Sun. There, a p-p reaction occurs. This means the need of converting 4 protons into ${}^4\text{He}$. Replicating this reaction on a larger scale is extremely challenging due to the need to convert protons into neutrons. On Earth, fusion experiments primarily rely on using hydrogen isotopes, most commonly deuterium (D) and tritium (T).

Despite being an easier approach, it still requires us to sustain a 200 million °C plasma. This means that an enormous amount of energy must be used to first heat the plasma up and then confine it to prevent it from completely destroying the reactor. The efficiency of D-T reactions might, however, worth the trouble. Theoretically, just 30 mg of deuterium would generate as much energy as 250 l of gasoline [13].

Such numbers sound incredible, but there are naturally multiple drawbacks too. Tritium, the other input material of this most promising reaction is extremely rare in nature. Its artificial production is currently done only by a select number of facilities. Combined with its relatively short half-life of around 12 years, there are fears of it running out. It is proven that fusion reactors will be capable of "breeding" their own tritium, however the

transition period may still prove to be troublesome [14].

In the end, despite being a similarly old technology as fission [15], a fusion reactor with a net positive energy balance has not yet been constructed. Containing plasma heated to such extreme temperatures cannot be achieved with any solid material and must be done with the use of inertial or magnetic forces. The most common reactors that employ this concept are: tokamaks (Figure 2) and stellarators (Figure 3). The former design has been selected for probably the most ambitious fusion project to date, the International Thermonuclear Experimental Reactor (ITER) [13].

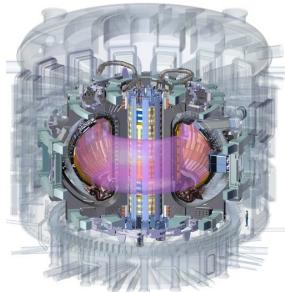


Figure 2: ITER tokamak model[16]

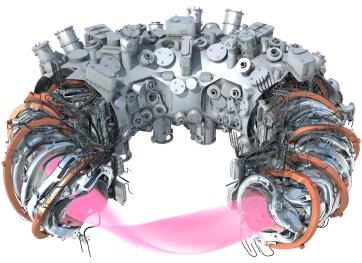


Figure 3: Wendelstein W7X stellarator model[17]

1.4 ITER Tokamak Project

1.4.1 Tokamak

Tokamaks are reactors composed of a toroidal vacuum chamber surrounded by massive electromagnetic coils as shown in Figure 4. The magnetic fields are used to shape plasma and keep it away from the device internal walls. Operation starts with the removal of air and impurities from the vessel. The gaseous fuel is introduced and a strong current is induced ionizing the gases, thus forming plasma. Additional heat is introduced with microwave and fuel injections. Particles within the formed plasma can then collide with such force that they begin to break through atomic repulsion and fuse producing a large amount of energy. [16]

1.4.2 ITER Goals

At 24 m height and 30 m width, ITER will be the biggest tokamak ever constructed. That's twice as big as the largest experimental reactor currently in service, the Joint European

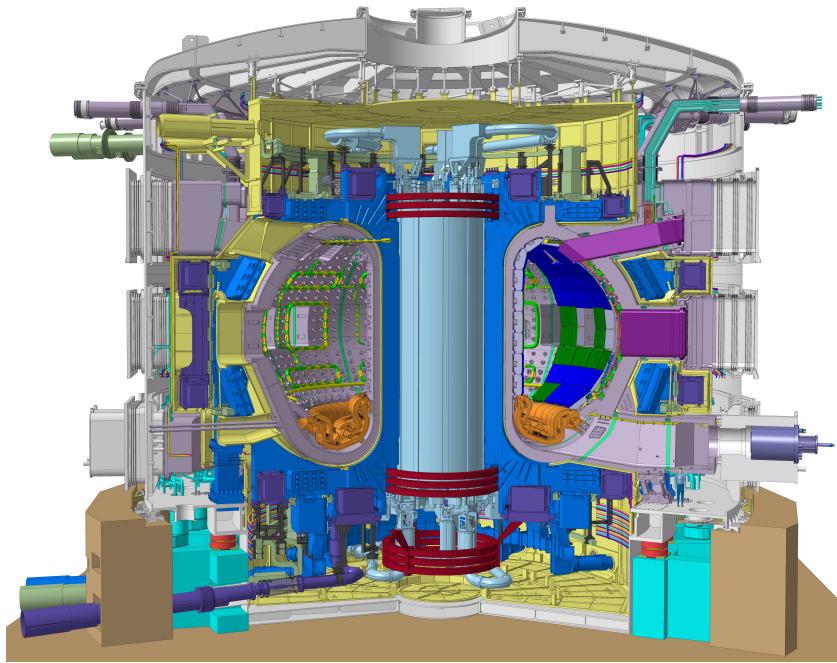


Figure 4: ITER tokamak cross section[16]

Torus (JET). JET has been working since 1983 with a goal of achieving net energy gain. Despite running successful plasma experiments and recently starting deuterium-tritium experiments, the highest fusion energy gain Q (the ratio of produced power to the power required to sustain the plasma) obtained by JET was 0.33. A record only recently topped by a different type of a fusion device held at the US Department of Energy's National Ignition Facility. Using laser technology it was possible to obtain a Q of 0.7 for 4 billionths of a second. [18]

Although not supposed to work as a power plant, just an experiment, throughout its operation ITER intends to break this record by a lot. The new reactor is designed to reach an energy gain of 10 for the duration of a few minutes. This is of course still a theoretical plan, as the facility is still a fairly long time from being finished. As of 2022, the vacuum vessel is yet to be welded together[19]. First plasma operation is scheduled for the end of 2025[19], although multiple delays have already happened in the past [20], so future ones would at this point not be too surprising. Figure 5 shows an aerial picture of ITER from 14th of April 2020. Not all facilities have been fully constructed at this time.



Figure 5: Aerial view of the ITER facility as of 2022[16]

1.4.3 Primary Concerns

With a project of this magnitude it is near impossible to predict everything that might go wrong. There are naturally safety concerns, questions regarding the ambitious goals set by the management and the troubles of international cooperation[20]. It is thus crucial to maintain maximum operational safety and log all experimental data. This should ensure that even in the case of partial failure of the project important practical knowledge can be recorded for future fusion experiments.

When operational, ITER will rely on around 50 completely different measurement systems to control, evaluate and investigate its plasma [21]. This translates into dozens of gigabytes of data being generated, processed and archived every second as the experiment is running [22]. With some of the experiments lasting fractions of a second, a lot of the critical data acquisition and control must occur in real time and without waiting for human reaction [23]. This poses an important challenge when it comes to the choice of computing apparatus. A perfect device would offer infinite configurability preferably with remote access as well as a very high data throughput.

Traditional computers or more precisely Central Processing Units (CPUs) are remotely reprogrammable but may offer insufficient speeds in some of the real time applications. On the other end of this scale lie Application Specific Integrated Circuits (ASIC). These devices are an arrangement of digital logic gates realizing one specific goal, like digital signal filtering or processing network packets. ASICs offer unmatched bandwidth but

cannot really be reconfigured after deployment, making them a risky choice in highly experimental applications such as tokamaks.

1.5 Field Programmable Gate Arrays

Devices that offer a compromise between speed and reconfigurability exist nowadays. Most commonly Field Programmable Gate Arrays (FPGAs) are used. FPGAs are formed out of matrices of so called Configurable Logic Blocks (CLBs). These are small circuits that produce a single bit of logic output out of 4 input bits, using a reprogrammable function. These blocks are then wired together using programmable interconnects. Such design allows for the implementation of very efficient digital algorithms directly with the use of logical gates, without the need for an entire processor. [24]

The interconnects and CLB internal structure introduce additional wiring that would be unnecessary in the case of ASICs. These stray capacitances and inductances limit the maximum clock speed of FPGAs. This is not too much of an issue provided that the function can be parallelised. To offset this limitation, most FPGAs manufactured today come packed with more complex sub-circuitry that can be intermixed with the CLBs as indicated in Figure 6. These components can vary greatly from fast arithmetical blocks to small CPU-based microcontrollers.

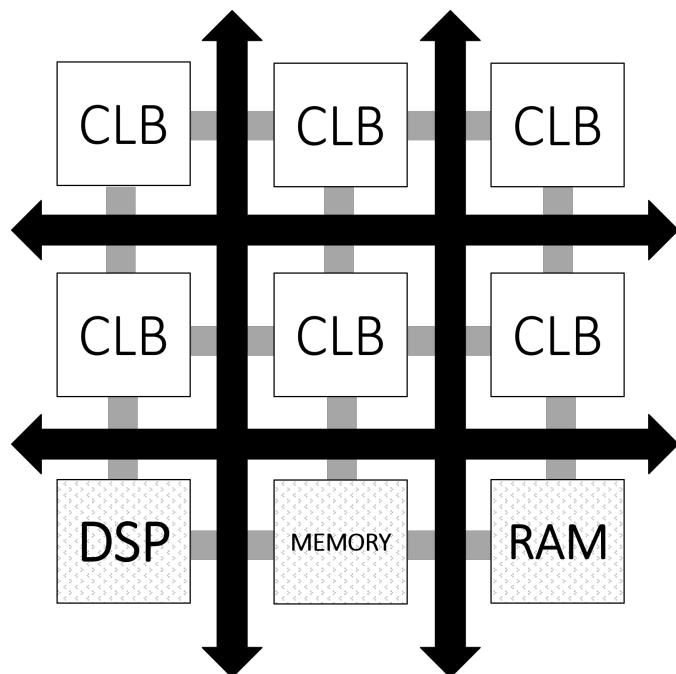


Figure 6: The internal structure of an FPGA

1.6 Problem statement

The nature of FPGAs makes them instrumental in the data acquisition and control systems of modern fusion experiments like the ITER tokamak. This work evaluates the potential usage of Field Programmable Gate Arrays for the detection and analysis of pulses produced by PhotoMultiplier Tubes (PMTs) being part of a High X-Ray Monitor (HXRM) designed to monitor Runaway Electrons (REs) at tokamaks.

A functional system for the Digital Pulse Processing (DPP) at the rate of 1 GS/s is proposed and implemented in an FPGA. A custom software package for control and data acquisition is shown. The optimization of both hardware and software is described. Different algorithms for pulse detection and discrimination are analysed, simulated and implemented in hardware. Finally design considerations for future systems are given.

2 Hard X-Ray spectroscopy

One of the diagnostic systems in a lot of currently existing tokamaks is the Hard X-Ray Monitor (HXRM). It will also be implemented in ITER. The device is tasked with measuring the spectrum of X-Ray radiation inside the fusion vessel. The presence of high energy X-Ray radiation can point to problems with the plasma stability and suggest the need for mitigation techniques. [25]

2.1 Runaway electrons

The plasma in a tokamak is heated to a level where particles reach a velocity enabling them to break through atomic repulsion. In such conditions some particles can also obtain sufficient speed to escape the magnetic confinement of the vessel. Typically collisions with other particles are so frequent that in stable plasma these disturbances are not happening in large quantities. Directly after plasma is disrupted or terminated, the probability of collisions is lessened and a tokamak might start acting like a particle accelerator, bringing the electrons to nearly the speed of light. Electrons that act in this manner are called Runaway Electrons (REs). [26]

This phenomenon can occur in the form of a high-energy concentrated beam capable of melting the front-facing walls of a reactor. The effects of such damage being purposefully introduced in the JET tokamak are shown in Figure 7. To prevent mitigate the destructive effects of REs their generation has to be avoided if possible. Otherwise they must be detected and dealt with accordingly. One method of doing so involves the injection of noble gases in a process called Massive Gas Injection (MGI) [27].

When REs interact with the Plasma Facing Components (PFCs) they lose their energy and emit X-Ray radiation in the Bremsstrahlung process. The energy of this radiation varies greatly, ranging from tens of keV (Soft X-Ray) to multiple MeV (Hard X-Ray). [28]

2.2 PhotoMultiplier Tubes

The photons generated in Bremsstrahlung by Runaway Electrons can be detected with the use of a device known as a PhotoMultiplier Tube (PMT). A PMT is built with the use of a photocathode and an electron multiplier. When a radiation photon hits the photocathode an electron is emitted due to the photoelectric effect. Electric fields in the

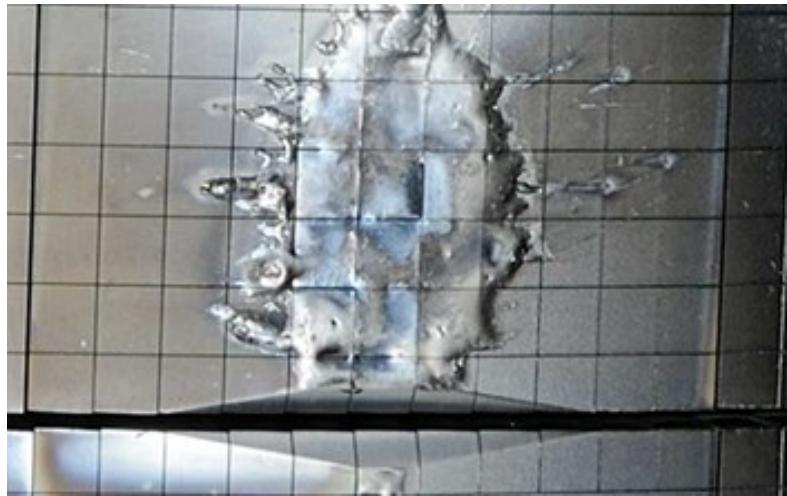


Figure 7: Effects of RE in the JET vessel[26]

PMT accelerate the electron towards a series of dynodes. Each collision with a dynode causes a release of additional electrons and forms a stronger beam that eventually reaches the anode where it becomes measurable as a current pulse. Typically a gain in the order of 10^6 is obtained. [29, 30]

2.3 Preamplifiers

The internal gain of a PMT is sufficient for many applications and does not require additional amplification. The produced current impulses can be detected with precise circuitry, however there are multiple reasons for which a preamplifier is often used in tangent with a PMT. With a typical load of 50Ω the output signal of a single photon is a very sharp voltage peak of around 10 mV. Unprocessed short PMT pulses are sufficient for detection, counting and timing, but may be problematic when it comes to discrimination and processes like Pulse Height Analysis (PHA). [31]

In those scenarios that do not require the sharpest response, the slight increase in Signal to Noise Ratio is worth the features introduced by an amplifier. These can include impedance matching, filtering and pulse-shaping. In tokamak applications it also helps move most of the diagnostic infrastructure away from the dangerous environment created by the fusion plasma.

In ITER the X-Ray radiation will first be converted to a light pulse using a scintillator. This light will be transferred over a 12 m fiber before reaching the PMT. Then the electrical signal from the PMT must pass through a 100 m copper coaxial cable, before reaching

the acquisition and processing hardware. The internal input of a PMT is thus insufficient in this scenario and must be preamplified. [25]

2.4 Pulse processing chains

To obtain a radiation spectrum from the voltage pulses, their height must be measured and placed into an appropriate bin consisting of a range of voltage levels. The pulses generated by a PMT last just a few nanoseconds, making the task at hand complicated.

With a preamplifier this duration is increased by a factor of around a few hundreds depending on the preamplifier components. This results in pulses that last a few hundreds nanoseconds. Before the advent of ultra-high speed Analogue to Digital Converters (ADCs), such short events could not viably be processed with digital electronics and had to rely on analogue components.

2.4.1 Analogue processing chains

In analogue radiation spectroscopy pulses are typically first transformed to a Gaussian shape, with a series of low- and high-pass filters. These signals must then pass through complicated pile-up rejection circuitry. After that the pulses are fed to a Multi Channel Analyzer (MCA). This is the device that performs the binning action. Initially an MCA would consist of an array of analogue comparators, and over time it would rely on more and more digital components. The schematics of a typical analogue system are shown in Figure 8

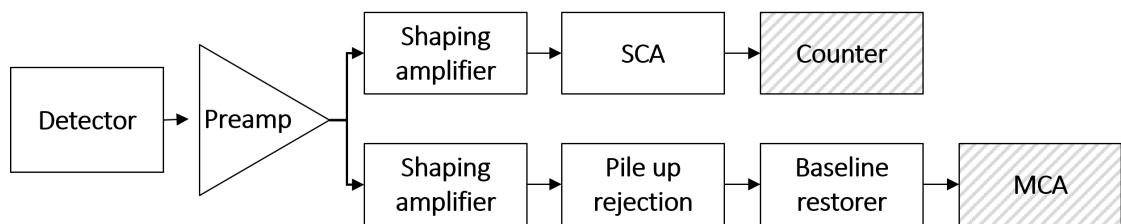


Figure 8: Analogue Pulse Processing chain

As mentioned earlier, for a long time analogue processing was the only way to reliably handle events shorter than 100 ns. It was, however, quickly recognized that the digital approach offered much lesser susceptibility to outside noise. Digital components could

also potentially be tuned without having to physically modify the circuit. These two features are particularly important in the complicated environment of a fusion reactor. [32]

2.4.2 Digital processing chains

As soon as ADCs and digital processing circuits capable of reaching the resolution required for precise nuclear spectroscopy appeared on the market they were adopted into new experimental designs of MCAs [33]. As the technology improved ADCs were moved closer to the radiation detector itself. A single reprogrammable silicon chip, together with a fast ADC, could perform the job of a number of the analogue components in a spectroscopy system. On top of that its operation is less susceptible to Electro Magnetic Interference (EMI) and temperature-induced parameter variance. [34]

The earlier in a processing chain that the ADC is placed the lesser the influence of imperfect analogue components is. Seeing an ADC right after the preamplifier is commonplace in modern systems as shown in Figure 9. Such approach, however, produces an important issue. To obtain a sufficient horizontal resolution comparable to analogue chains the ADC must sample the signal with a frequency of at least a few hundred MHz. This means that, at a typical vertical resolution of anywhere between 8 to 16 bits, a modern high-speed ADC can generate anywhere between 100 megabytes up to even a few gigabytes of data every second. [34]

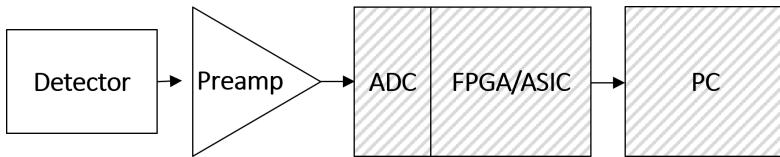


Figure 9: Digital Pulse Processing chain

Processing gigabytes of data in real time poses one of the primary challenges in designing Digital Pulse Processing systems. Despite that, fast digitizers are used for Hard X-Ray Spectroscopy in existing tokamaks, like KSTAR or JET [28, 35]. ITER will require similar or better systems during its operation, so the problems of handling large data throughput should be considered solved before the diagnostic systems are installed in the facility. Once first plasma is obtained, the possibility of system modifications will be greatly limited.

3 System requirements

3.1 General requirements

3.2 ITER HXRM specification

4 Research setup

An FPGA powered data acquisition board was used as the platform for the hardware implementation of digital pulse processing of PMT signals. The following subsections describe the system component in detail and ?? shows an overview of the testbench.

4.1 PMT

4.2 Preamplifier

4.3 Digitizer board

To acquire and digitize the signals produced by the PMT and preamplifier combination Teledyne SP Devices ADQ14-4C was used. The board was connected through PCIe 2.0 to the host PC running custom acquisition software. ADQ14-4C can sample signals from up to 4 channels, each at a maximum frequency of 1 GHz.

Table 1: Chosen parameters of ADQ14-4C

| material | T [K] |
|----------|-------|
| Sn | 3,7 |
| Pb | 7,2 |
| Al | 1,2 |

The ADQ14 acquires samples with a 14-bit ADC. The device applies factory calibrated digital gain and shift to the raw measurements, so in order to maintain higher precision the samples are extended to 16 bits representing two full bytes. The additional two bits represent the fractional part potentially produced by the fractional gain component.

The ADQ14 can operate in both triggered streaming and continuous mode. In continuous mode samples are constantly gathered and periodically transferred to the host PC. In triggered streaming a window of samples is collected only after a trigger event is detected. This is a basic feature that allows for some data reduction, as only events of interest have to be transferred to the host PC. Multiple triggering mechanisms, like level, periodic and external are available.

In all modes of operation the device relies on an internal 2 GB DRAM to act as a FIFO

queue for the generated records. The device relies on Direct Memory Access (DMA) to transfer data to the host PC. This is a special mode of operation for peripheral devices in which a chunk of the computer's memory is made available to them without the need of CPU brokerage.

Unfortunately the maximum size of DMA buffers is limited. With a sampling speed of a 1 GHz and 2 byte samples up to two gigabytes of data can be generated each second for each channel that is active. Even with reliance on DMA maintaining a transfer speed this high is problematic. The ADQ14's internal DRAM acts as a buffer whenever the throughput becomes too high. Records are first stored in the internal DRAM and periodically transferred to the host PC's RAM whenever buffers become ready.

4.3.1 Open FPGA design

A crucial feature of ADQ14 is the fact that its core processing functionality is realised with the use of an on-board FPGA, more specifically a Xilinx Kintex 7 K325T. The design of the FPGA is partially open. Users can implement custom filtering or data analysis on samples in real time. This fact is used to implement the custom pulse processing described in this work.

The firmware is unfortunately not entirely open-source. Third-party IP cores cannot be distributed to end customers and thus user algorithms are limited to two sections called User Logics. User Logic 1 is a core placed after the ADC samples are subjected to factory gain, but before the signals are passed on to trigger control. This enables the implementation of custom triggering logic.

User Logic 2 is intended to house more complicated logic. This module has access to the GPIO ports and some metadata outputs, that can be used to better describe the transferred records. User Logic 2 is located right before the encrypted packet generator that is responsible for queueing the incoming data in ADQ14's DRAM for transfer to the host PC. The packet generator can be partially controlled from within User Logic 2. Arbitrary data can be injected in place of the samples for each channel and the size of transferred windows can be modified.

4.3.2 Parallel sampling

The FPGA is clocked only at 250 MHz which is exactly a quarter of the ADC maximum operating frequency. This means that each channel of the digitizer outputs 4 samples on each clock cycle of the FPGA. This is a necessary design choice as FPGAs fare better at lower clock speeds due to the need of less complex routing when it comes to connecting the various peripherals and CLBs.

Such design does however complicate the implementation of Digital Signal Processing. It is especially cumbersome for functions that depend on delayed samples. Accumulators have the need of summing up 4 samples on each clock cycle instead of one. Complicated operations like multiplication and division require duplicated logic. Most functionality must be properly pipelined to avoid timing issues in the FPGA design.

4.4 Host computer

4.5 Software package

To control the acquisition process and handle the data transfer, a custom software GUI application was developed. The application employs an API provided by SP Devices to interface to the digitizer board. The Qt5 framework is used for GUI display and multiple other functions. The application leverages the Qt's signal/slot system heavily to synchronize threaded events.

The primary thread of the software application is used for UI display and general tasks like loading and saving configurations. A secondary thread is spawned to control data acquisition and archival. The proper operation of the secondary worker thread is crucial in obtaining a high data throughput and the process of software optimization is described in CHAPTERDATATRANSFER

5 Pulse detection

The prerequisite to any pulse processing is their detection. The window of interest containing a pulse to be analysed must be properly distinguished from the surrounding noise. Although detection is a must, it also brings the added benefit of data rate reduction. If pulses can be accurately marked within a signal it is possible to transfer only those samples that compose the events.

The ADQ14 is capable of sampling signals with a frequency of up to 1 GHz. With two bytes per sample, a single channel generates 2 GBs of raw data per second. For the PCIe 2.0 interface, that is used in this work, the manufacturer's datasheet specifies a theoretical maximum throughput of 3.2 GB/s. Even if this perfect limit could be obtained it would not allow for two channels to be active at once. Using pulse detection for data reduction is thus unavoidable. It is crucial to use a robust algorithm for this process to ensure that almost no pulses go unnoticed and near to none false positives are transmitted.

5.1 Level trigger

The most basic approach to detection is a level trigger, a technology available to any spectroscope. As shown in ??, a trigger occurs when the input signal crosses a predefined voltage level, either on a rising or a falling edge. The point at which this occurs marks the beginning of a record window. In the simplest case the end of a window is placed a fixed duration from the start.

Once a window finishes, no more events are detected until the signal returns to a value below the trigger level (for rising edge triggering). This reset value might be set to be equal to the trigger level, however such approach might lead to a scenario shown in ?? . In a noisy environment the signal might falsely trigger immediately after a window ends due to a random high spike on the slower falling edge of an exponential pulse.

To prevent such false triggers typically some form of a hysteresis is used. The reset level is shifted downwards, so that the input signal must cross such a threshold that the random noise is almost guaranteed to never cause false triggers. ?? shows a hysteresis mitigating some false triggers.

With the slow falling edge of a pulse care must be taken not to overestimate the hystere-

sis. By setting the reset level too far away from the trigger level pile-ups can be missed as pointed to in ???. With a properly set hysteresis the level trigger offers performance that is sufficient in most applications, as suggested by its prevalence in modern spectrometers. In a tokamak's environment, however, the hysteresis alone could potentially prove insufficient due to electromagnetic and temperature fluctuations having an effect on noise.

5.2 Boxcar filter

The two problems most apparent to simple level triggering are its susceptibility to noise and pulse overlap. Just as with analogue approaches these two problems can be minimized with low-pass and high-pass filtering. By utilizing a low-pass filter the input signal becomes smoother and more averaged, reducing the possibility of false triggers caused by random spikes. A high-pass filter would reduce the DC component of the falling edge of a pulse, making pile-ups easier to detect.

In the digital domain the simplest filters that perform these operations are the Moving Average (MA) filter and the derivative filter. MA works to reduce the spikes and increase SNR. The derivative filter can strip the DC component from a signal, meaning that the sharp rising edges will become more attenuated in comparison to the decaying tails.

By combining the concepts of the MA and derivative filters into a single a Boxcar filter is obtained. An example transfer function of a Boxcar filter is shown in ???. The effect of the filter on an example exponential pulse are shown in ???. The filter can be considered to be a subtraction of two samples averaged with a window of length W delayed from each other by W .

5.3 Trapezoidal filter

5.4 Triangular filter

5.5 Other solutions

5.6 Simulation performance

5.7 Hardware implementation

5.7.1 Boxcar filter

5.7.2 Trapezoidal filter

5.7.3 Triangular filter

6 Pulse Height Analysis

6.1 Pulse shaping algorithms

6.2 Integration

6.3 Hardware implementation

7 Data transfer

7.1 PCIe interface

7.2 Direct memory access

7.3 Data pathways in the system

7.4 Multi-threaded data transfer

7.5 Software optimization

8 Conclusions

8.1 Further problems

8.2 Future research

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