Politechnika Łódzka
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 albumu: 239587

Promotor:
dr hab. inż. Dariusz Makowski, prof. uczelni

24 lipca 2022

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Streszczenie

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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 inaccesible 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 Intergovermental 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 conditions, 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. What is more, by fusing atoms lighter than Iron the reaction can also produce surplus energy, that can be used to generate electricity. The conditions necessary for fusion to happen are extremely harder to achieve and then

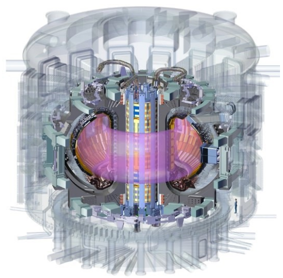

Figure 1: ITER tokamak model[16]

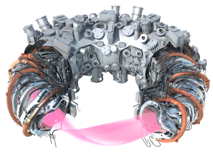

Figure 2: Wendelstein W7X sterellator model[17]

sustain [12].

Fusion is the primary reaction that causes stars to emit energy. The fusion that is most often artificially attempted on Earth from that occurring naturally in the Sun. There, a p-p reaction, where 4 protons are converted into ^{4}He is the primary energy source. 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 1) and stellarators (Figure 2). The former design has been selected for probably the most ambitious fusion project to date, the International Thermonuclear Experimental Reactor (ITER) [13].

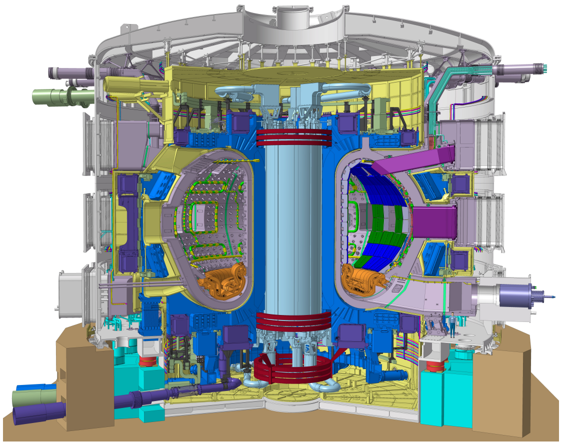

Figure 3: ITER tokamak cross section[16]

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 3. 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 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.

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 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. These components can vary greatly from fast arithmetical blocks to small CPU-based microcontrollers.

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 Electorns (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 4. 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

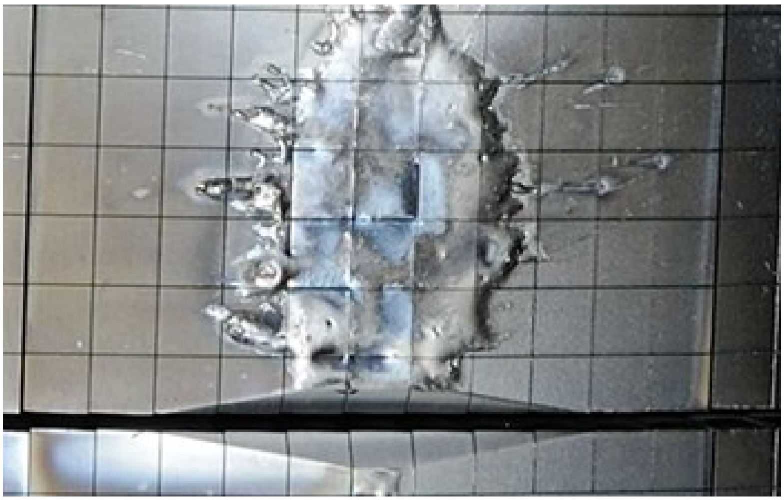

Figure 4: Effects of RE in the JET vessel[26]

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.

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. 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]

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 opeartion, 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

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6.2 Integration

6.3 Hardware implementation

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8 Conclusions

8.1 Further problems

8.2 Future research

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