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Radiation Tolerant Neutron Activation Detector for Compact Inertial Electrostatically Confined Fusors

Yannick Verbelen
Interface Analysis Centre, University of Bristol
H.H. Wills Physics Laboratory, Tyndall Ave.
BS8 1TL Bristol, United Kingdom
yannick.verbelen@bristol.ac.uk

Mahmoud Bakr Arby, Thomas B. Scott
Interface Analysis Centre, University of Bristol
H.H. Wills Physics Laboratory, Tyndall Ave.
BS8 1TL Bristol, United Kingdom
mahmoud.bakrarby@bristol.ac.uk, t.b.scott@bristol.ac.uk

ABSTRACT

This work presents the design and implementation of a radiation tolerant detection system for residual beta and gamma radiation resulting from proton or neutron activation in particle accelerators. The system is linked to the shield actuation system of the prototype inertial electrostatically confined fusor at the University of Bristol, where it is scheduled to be deployed. Detector mechanics, principle of operation, and circuit designs are discussed along with radiation tolerance characteristics of critical components. Also introduced is a bespoke data acquisition system that enables batch testing of up to 16 detector boards simultaneously in irradiation facilities.

1 INTRODUCTION

Ongoing research to increase the neutron production rate (NPR) of inertial electrostatically confined fusion (IECF) devices [1, 2, 3] poses challenges when such systems are used to irradiate target materials, which can lead to activation rates proportional to the neutron flux. At elevated NPR levels, undesired activation of engineering materials, including components of the irradiation facility itself, can be expected. Whereas the majority of such activation products have short half lives that are rarely problematic, several isotopes such as ^{55}Fe and ^{60}Co occur as a result of activation of steel, and have half lives in the order of a few years which means residual activation becomes persistent on longer time scales. Monitoring the residual radiation level after shutdown of the IECF system becomes a critical component of the safety case required for operation [4], and it must be demonstrated that the controlled area has acceptably low residual radiation levels to protect technical operating staff from contracting harmful radiation doses.

Past accidents in irradiation facilities worldwide has shown that various combinations of procedural and equipment failures can lead to accidental exposure situations. Accidents due to single points of failure, as in the infamous case of Anatoli Bugorski, are rather exceptional.

Instead, accidents leading to radiation exposure, particularly in industrial facilities, are most often a combination of inadequate interlocks and control systems, with poor mechanical design choices, and exacerbated by an incompatible safety culture aimed at prioritising production goals or financial gains. Well-known examples are the irradiation accidents with the Therac-25 [5, 6], and accidents in industrial irradiation facilities at Nesvizh [7, 8], Soreq [9], San Salvador [10], Brescia [11, p. 308], and Fleurus [11, p. 309][12, 13]. In the past half century, over 50% of accidental exposures occurred in industrial facilities, and about 20% in research. [11, p. 302]. What the irradiation accidents in Nesvizh, San Salvador, and Soreq all have in common with each other is that radiation protection was relying on mechanical interlocks (San Salvador), physical barriers (Nesvizh), or operating procedures (Soreq) that were bypassed. There were no adequate integrated radiation alarms, rather, operators were expected to carry radiation detectors themselves to check for the presence of residual radiation. All aforementioned irradiation accidents with the exception of Fleurus resulted in operator deaths, and all could have been avoided if proper reliable radiation detection equipment had been present inside the irradiation facility, and connected to the facility's control systems.

At the University of Bristol (United Kingdom), an IECF facility is currently under construction to support the ongoing research into nuclear fusion and the materials science challenges that it poses [4]. The facility, B34, is devised as a flexible proton and neutron irradiation facility designed to accommodate a wide range of irradiation and transmutation experiments. This includes experiments aimed at increasing NPR using solid state fusion [14, 15, 3], a technique observed at NASA and successfully applied at Tokyo University [16, 17, 18, 19] and at Tu/e using deuterated titanium electrodes [2, 20], among others. B34 is designed as a modular and open source hardware (OSHW) particle accelerator that can easily be modified to suit specific research needs. The OSHW design principles applied to B34 closely follow a global trend in high energy physics, with CERN and other research facilities also adopting OSHW. [21, 22, 23, 24] As a result, the safety case to operate this facility is complex as well, since it must be demonstrated that the risk of accidental exposure is minimal under all circumstances, regardless of the experimental configuration of the IECF. [4]

Before advancing to the design of safety critical systems of the new IECF facility, design procedures for commercial irradiation facilities and historical accidents associated with them were reviewed extensively. Additionally, the operation of a commercial IECF device sold as a neutron generator was also analysed. [25] The engineering report for that specific device uncovered a number of severe design flaws that have the potential to jeopardise the safety of operators. Notably, the control system of this IECF device was found to be relying on software only to implement all of its safety features. Safety systems could be easily bypassed, and there was no redundancy nor radiation hardening implemented, as shown in figure 1a. Operating this device would have exposed its operators to unacceptable risk because software bugs or intentional modifications of the control software completely disabled its safety features. The similarity with design flaws causing casualties in industrial irradiation facilities is striking.

Analysing these historic accidental irradiation incidents and legacy IECF systems, several conclusions can be drawn:

1. Control front-end (user interface) and safety systems must be kept separate, under no conditions should operators have access to safety critical systems or have the ability to modify them.

2. Residual radiation detection must be enforced as part of the safety system's core functionality rather than expected by operating procedures.

3. Redundancy is critical.

This work aims to design and develop a radiation detection system that is directly integrated into the radiation shield control systems of the B34 IECF facility, shown in figure 1b. It was specifically designed to detect residual radiation as a result of neutron or proton activation occurring

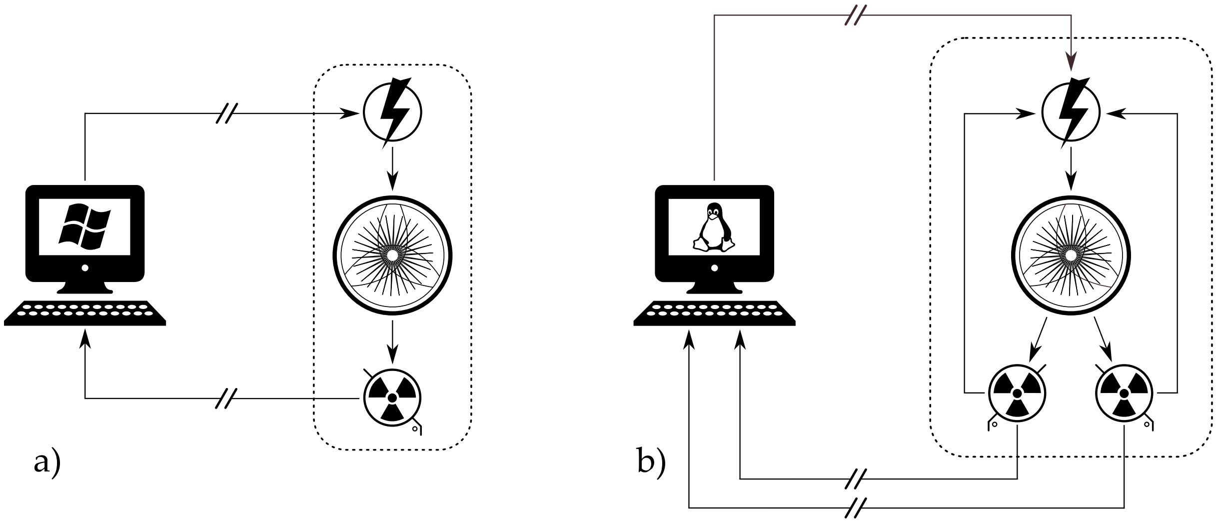

Figure 1: a) Quasi open-loop radiation control system found in a legacy commercial IECF device, relying on external software controls using unsuitable non-real-time operating systems to implement basic radiation protection. [26] b) Improved closed-loop radiation protection system for B34 interfacing directly with power supply and radiation shield actuation systems, featuring redundancy and resilience against external disruptions. [4]

as part of the routine operation of the facility for the irradiation of targets, and protects operators by physically restricting access to the shielded environment in addition to triggering audiovisual alarms.

2 RADIATION DETECTOR ARCHITECTURE

To meet the design requirements, a radiation detection mechanism for X-rays and gamma radiation is needed that can operate within the shielded environment, has a very low probability of false negatives, and can trigger a shutdown independently from other control systems including the SCADA and user interfaces. Reliance on software is particularly undesirable because it enables a backdoor for tampering, as well as high susceptibility for single event upsets (SEE). The solution implemented in this work therefore consists of the following elements:

- A Geiger-Müller tube array, which are radiation tolerant by design being a gas-filled glass tube, and produce μA range signals that can be processed directly and do not require the delicate (and radiation sensitive) amplifier circuits that semiconductor detectors (such as diamond or CZT) or scintillator detectors (such as CsI) need to function.
- A logic pulse counter built using discrete logic to minimise transistor counts and eliminate software, which in turn reduces the potential impact of SEE.
- Redundancy by design by operating 2 identical detectors, operating in parallel, and each having 4 physical identical Geiger-Müller tubes that are also wired in parallel.

The Geiger-Müller tube arrays are biased by a locally produced bias voltage of 400 V DC, and signals are captured across a 22 kΩ resistor and sent directly to the logic pulse counter. The block diagram is shown in figure 3.

2.1 Geiger-Müller Tube Array

The Geiger-Müller tubes used in this design are type 4011 tubes manufactured by Shenzhen Sunvision Electronic Co., People's Republic of China. These tubes have a working voltage

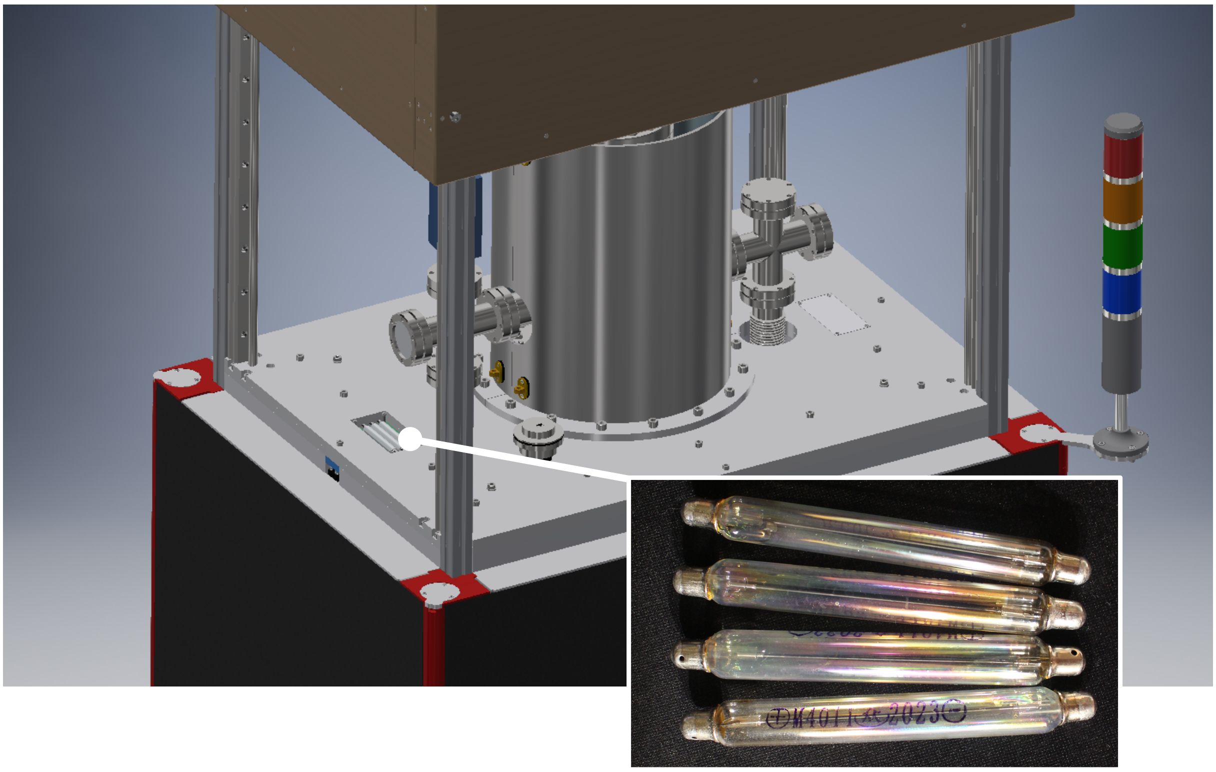

Figure 2: Location of the Geiger-Müller tube arrays of type M4011 [27] within the shielded environment of the particle accelerator. Radiation shields (brown) raised for clarity.

between $380\,\mathrm{V}$ and $450\,\mathrm{V}$, and a conversion ratio of ca. 150 CPM/μSv/h at $662\,\mathrm{keV}$ representative of ^{137}Cs. [27] The 4 tubes for a single array are shown in figure 2 along with their position in the B34 particle accelerator design.

The $400\,\mathrm{V}$ bias voltage is generated by an oscillator driven inverter of type 74HC14, with a voltage reference and LM358 operational amplifier as feedback mechanism to keep the output voltage constant. The design is based on an inverter design by Maxim Integrated [28].

Each of the Geiger-Müller tube arrays is constructed by wiring 4 identical M4011 tubes electrically in parallel, i.e. anodes tied to each other and cathodes tied to each other. This approach multiplies the sensitivity of the array by a factor approximately equal to the number of tubes used in parallel but, more importantly, increases reliability because of the built-in redundancy. Because Geiger-Müller tubes' only failure mode is as open circuit (including catastrophic failures such as mechanical damage), the array continues to operate even in the event that one or multiple tubes are no longer operational.

2.2 Pulse Counter

The pulse counter is built around a discrete logic design, the block diagram is shown in figure 3. Pulses from each Geiger-Müller tube array are captured and sent to a 4060 binary counter. At every rising edge on its pulse input, the counter is incremented, hence its 14-bit binary output is equal to the number of counts detected since initialisation. When left to count indefinitely, after 2^{14} = 16,384 pulses the counter will overflow and restart at zero. To avoid this, a second 4060 is configured as oscillator. With RC constant determined by a $1.0\,\mu\mathrm{F}$ capacitor and $47\,\mathrm{k}\Omega$ resistor, the oscillator period is ca. $16\,\mathrm{s}$. The oscillator output has a duty cycle of 50%, so a simple differentiator built around an LM339 comparator is used to turn the oscillator output into short pulses with a length of $5\,\mathrm{ms}$. These pulses are then fed into the reset input of the first pulse counter, which causes the counts it registered to be reset every $16\,\mathrm{s}$. This

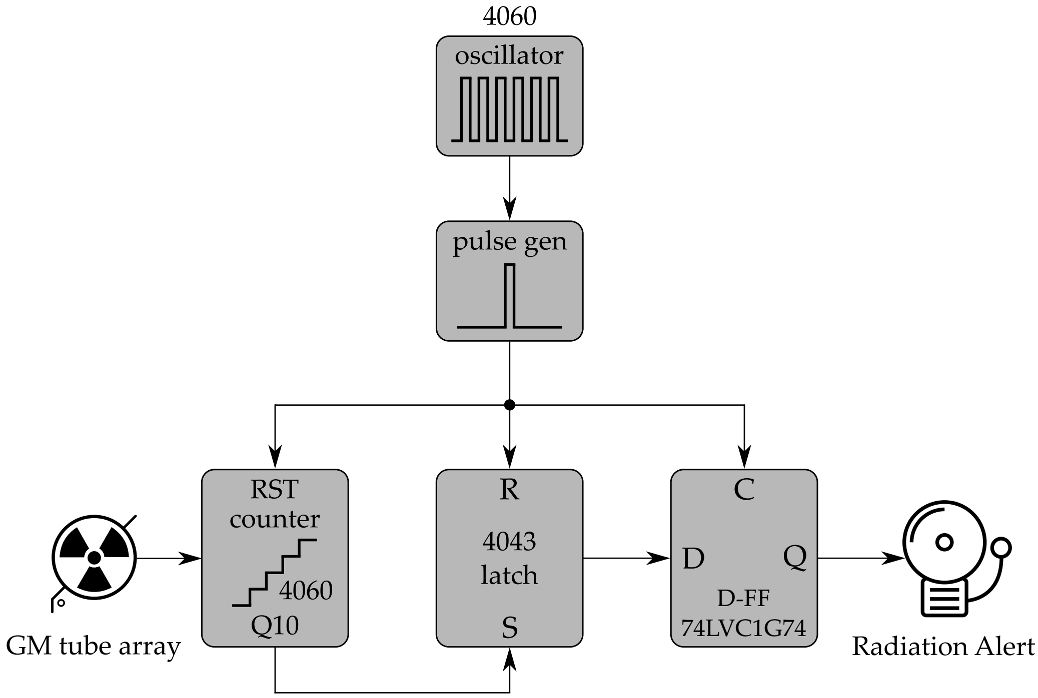

Figure 3: Block diagram of the proposed radiation tolerant pulse counter circuit.

configuration offers a very simple digital averaging of count rates over a 16 s period, since the number of counts recorded at reset is the total number of counts accumulated over the past quarter minute. Hence, if at least 8,192 pulses are recorded within 16 s then bit 14 of the pulse counter will become logic high, which can be interpreted as a high radiation level. An assembled pulse counter prototype board is shown in figure 4.

The conversion ratio for the M4011 at a 400 V bias is approximately 150 CPM/μSv/h, and 4 tubes are used in parallel, so the conversion ratio is ca. 600 CPM/μSv/h for the entire array, and the alarm level is thus triggered at a dose rate of approx. 51 μSv h^{-1}, which is a value fixed by the hardware configuration itself. When more fine control is desired, the alarm level can be tapped from any of the counter's output pins, however, due to the nature of binary counting, bits with lower significance than bit 14 will toggle which means the pin value at expiration of the 16 s timing interval is not indicative to whether that threshold was reached during the timing interval or not. To solve this problem, an SR latch of type 4043 was added. The latch acts as a single bit "memory" cell, that can simply be set and reset. In this case, the latch is set when the corresponding counter output pin is logic high, and will retain this value after the output pin toggles back to logic low. At the end of the 16 s timer interval, the value of the SR latch is clocked into a D-flipflop of type 74LVC1G74 which in turn adopts the state of the SR latch, after which the SR latch is reset immediately along with the counter to start a new 16 s integration period from zero within the same clock cycle. The output of the D-flipflop is maintained throughout the next timer interval and is indicative to whether or not the radiation threshold was reached in the *previous* period. This circuit was prototyped and tested in a controlled environment using an arbitrary waveform generator simulating the behaviour of a Geiger-Müller tube array under varying radiation levels.

3 RADIATION TOLERANCE TESTING

Before integrating the proposed system into the B34 IECF particle accelerator, it is essential that its performance is verified in a controlled environment first. For representative test results, the conditions in the controlled testing environment must reflect the actual operational

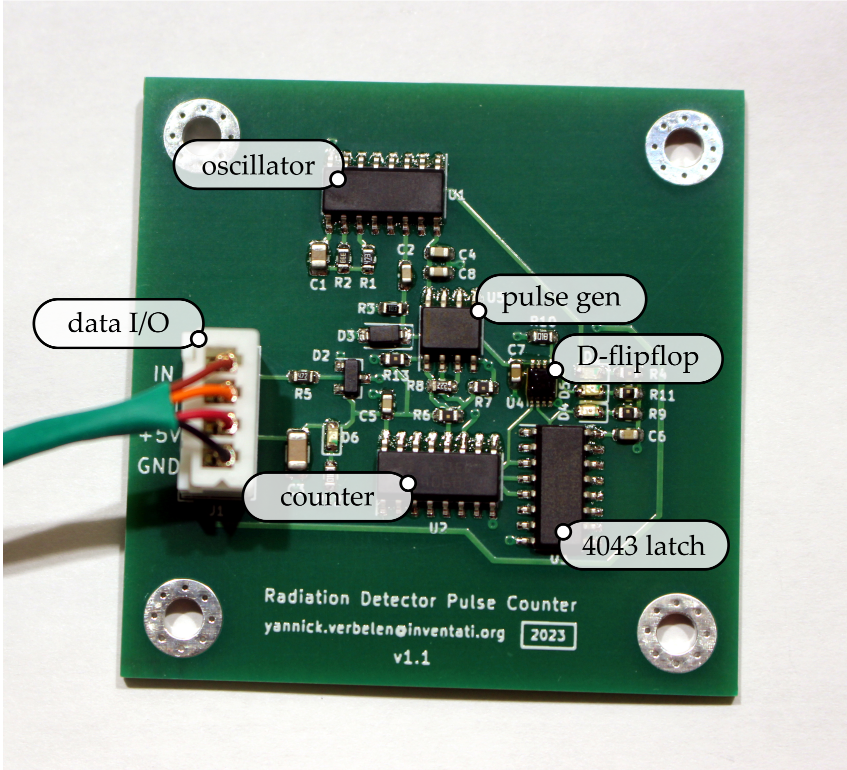

Figure 4: Protoype of the pulse counter designed and assembled, ready for radiation tolerance testing.

conditions as closely as possible. The closest possible controlled conditions to test the performance of a radiation detector is, of course, in an irradiator where the system is exposed to ionising radiation and its response to varying dose rates, total accumulated doses, and radiation energies is observed. In this context, it is essential to understand the different radiation induced damage modes, and how they reflect on the actual device under test (DuT). Radiation damage can roughly be divided in 2 categories:

- Total accumulated ionising dose (TID) [29], which is the total dose of ionising radiation absorbed, and is an integration of the dose rate over the entire exposure time. High energy radiation such as protons, neutrons, and gamma rays have a statistical chance of dislocating atoms in a crystal structure, for example in a semiconductor, and these dislocations are a form of permanent damage that gradually alters the properties of semiconductors. Both bipolar transistors and field effect transistors suffer from such damage, and at a certain threshold, gates of field effect transistors become permanently biased which means they can no longer be turned on or turned off, at which point the circuit fails. This is by no means the only total ionising dose effect, specific semiconductor structures respond differently and exhibit specific failure modes as a result of accumulated radiation damage.
- Single event upsets (SEE) [30] are often transient effects caused by localised and temporary ionisation. Charge deposited in logic structures is known to cause bit flips, toggling logic high to logic low or vice versa, thereby corrupting data and/or moving the system into an unknown state which often results in unpredictable behaviour or a logic crash requiring a reset. This kind of random noise can be compensated for, for example using parallel redundancy or forward error correction, parity checking, and other techniques. If transient ionisation occurs in non-conductive semiconductor components, for example creating a conductive path through a field effect transistor channel, it can result in so-called latch-up conditions that can only be reset with a full power cycle, for example when a bipolar

transistor is inadvertently converted into a synchronous rectifier or thyristor. If current is not limited externally through such a device, excessive power dissippation can lead to its permanent destruction.

It is vital to test for the response to both types of ionising radiation effects. TID related effects have the tendency to cause circuits to fail after a specific amount of time, when sufficient damage has accumulated to make further operation of the circuit impossible. In a sample of a large number of identical circuits, the failure rate as a function of time often takes the form of a distorted bell curve, with the majority of devices failing due to TID in a relatively narrow window of accumulated radiation dose. For most electronic devices, this is somewhere between 50 Gy and upward of 10 kGy depending on device complexity [31, 32].

Single event upsets are much more difficult to handle because of the randomness involved, SEE effects have the same probability of occurring in the first minute of irradiation as after hours of continuous irradiation. Irradiation experiments for circuits therefore require continuous monitoring of the DuT to detect SEE effects and analyse the circuit's response to these SEE effects.

When a device fails, either because of TID or SEE, it is equally important to establish the failure mode to determine how the circuit behaves after failure. In the best case scenario, the system should continue operation with reduced functionality. In the worst case scenario, it loses all functionality but fails in such a way that it does not affect other systems, including other identical systems present for redundancy purposes. In this case, where 2 physically independent pulse counters are wired to 2 physically independent Geiger-Müller tube arrays for redundancy, failure of one tube should not affect the other tubes in the array, and failure of one pulse detector circuit should not affect the operational capabilities of its backup pulse detector circuit wired to the backup Geiger-Müller tube array.

Taking into account the randomness of most radiation induced damage effects, it is preferred to test a large number of identical devices in identical circumstances to obtain data for a sample size with sufficient variety to draw statistically significant conclusions. However, since TID related damage cannot be ”reset” with the exception of complex annealing processes, irradiation of circuits for the purpose of radiation tolerance testing is effectively considered destructive testing: every circuit is irradiated until it either fails due to SEE or TID damage or a combination thereof, and both the failure mode and dose at the point of failure are recorded. For this to happen, the circuit must be monitored in real time for the duration of the irradiation experiment. Keeping in mind that for well designed circuits the radiation tolerance can easily exceed several kGy, and that the circuit must be monitored throughout the process, irradiation experiments can be a lengthy operation even when a high activity radiation source is available. To limit the time spent, it was decided to irradiate 16 identical systems simultaneously. Every prototype being 50 $\times$ 50 mm in size, a sample of 16 circuit boards is equivalent to an array of 4 by 4, with a combined size of 200 $\times$ 200 mm. This is a sufficiently small surface that, at a distance of 0.75 m or more from the point source, the variation in incident radiation keeping the inverse square law into account is smaller than 3.4% at a distance of $100\sqrt{2}$ mm from the centre.

3.1 Data Acquisition System

A special data acquisition system was developed to accommodate 16 DuTs simultaneously, providing power in a controlled environment as well as simulating behaviour that is characteristic and typical for an operational environment. To implement such functionality, the data acquisition system has 16 identical parallel channels, each with a digital output line that mimics pulses as they would be generated by a Geiger-Müller tube array, and a digital input line that measures the response of the DuT to those simulated Geiger-Müller tube pulses. Because of the very high dose rate of the irradiation facility, in excess of $100\,\mathrm{Gy\,h^{-1}}$, the actual Geiger-Müller tube aray can't be used as pulse source because it would be permanently saturated.

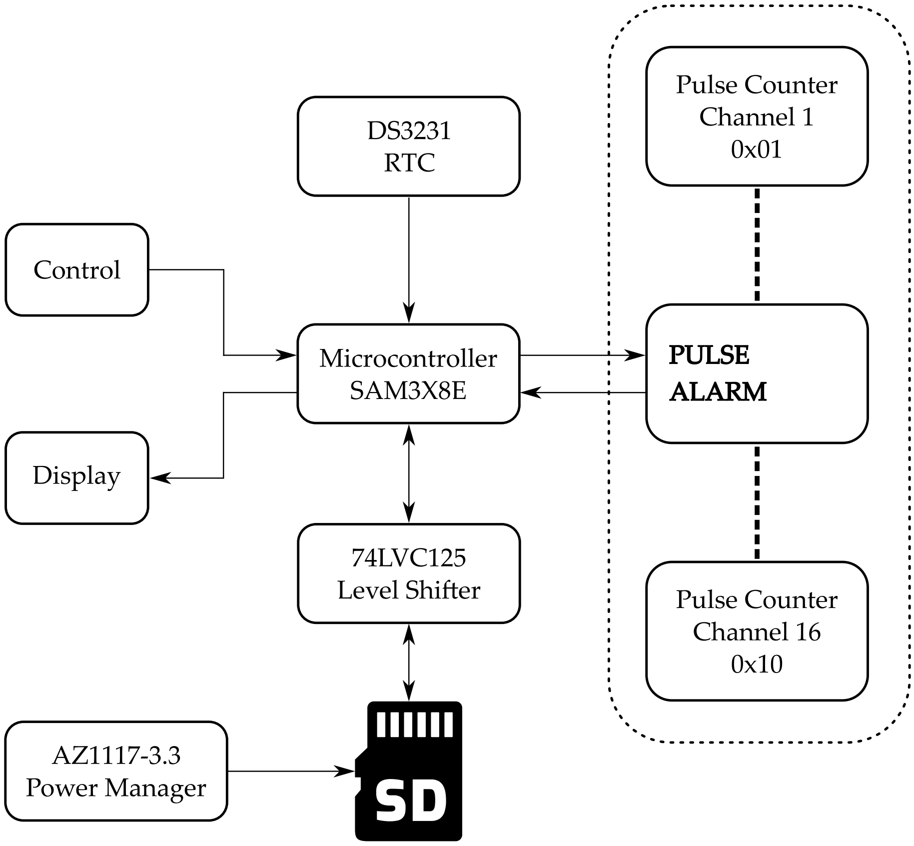

Figure 5: Block diagram of the data acquisition system with important components identified.

This approach enables to isolate signal processing behaviour from ionising radiation induced effects, which makes data processing significantly more straight-forward.

The data acquisition is set up around a microcontroller of type SAM3X8E, on an Arduino DUE microcontroller board (Arduino LLC, Italy). [33, 34] This microcontroller board is set up outside the irradiator, as it is not part of the DuTs themselves. Augmenting the microcontroller board is a bespoke add-on board designed at the University of Bristol, which implements 16 physical connection points for the same number of DuTs, each wired with a 4-core cable with JST-XH-A B4B connector on either side to the respective DuTs in the irradiation environment. Each cable provides an independent feed-through of a 5.0 V power supply, digital input and digital output, and a common return/ground. Figure 5 shows a block diagram of the developed data acquisition system.

The data acquisition add-on board is also equipped with a power supply system implemented as a synchronous buck-boost converter built around an LTC3111 DC/DC controller (Linear Technology, USA). This buck-boost converter provides the regulated 5.0 V supply to the microcontroller itself as well as up to 16 connected DuTs, and derives the power directly from a connected computer system through the on-board USB interface. A real-time clock (RTC) of type DS3231 (Maxim, USA) and accompanying backup battery is also integrated for accurate time keeping. With the irradiation dose rate assumed constant and known precisely, the accumulated dose can be calculated if the elapsed time since start of irradiation is known exactly. The RTC is capable of time-keeping over very long periods, using a 32 kHz quartz crystal for accurate timing with a maximum error of $\pm$ 2 minutes over a time span of a year, which is an error of ca. 4 ppm and considered sufficiently accurate for precise dose calculations over time spans of days or weeks of continuous irradiation. The DS3231 RTC is interrogated by the microcontroller over a serial I^{2}C interface at a frequency of 100 kHz, and time stamp recorded whenever a DuT is found to have failed. A 3 V silver oxide coin cell battery in CR3032 form factor is wired directly to the RTC oscillator to ensure uninterrupted time keeping even in the event of a temporary power outage or microcontroller reboot. Finally, the add-on board is also equipped with a micro SD card slot that can accommodate micro SD cards formatted in FAT32 file system up to 4 gigabytes. All data is saved directly to the SD card to prevent data loss in case of unforeseen circumstances. The prototype of the data acquisition system is shown in figure 6. The add-on board was designed in KiCAD [35], manufactured by PCBWay (Shenzhen, PRC) on a 1.6 mm thick FR4 fibreglass substrate [36], and assembled in Bristol, UK. Control software was written in C++ and compiled using Arduino software framework libraries with PlatformIO. [37]

3.2 Experimental Results

As of the time of the Conference, experimental irradiation results could not yet be obtained. The data acquisition system and 48 identical pulse counter boards were assembled and functionally tested in a non-radiation environment (sufficient for 3 sequential irradiation campaigns of 16 boards simultaneously), and ready for irradiation. However, gaining access to a suitable irradiation facility has proven to be very difficult due to the political climate in the UK. Although irradiation facilities exist in the country, accessibility is a complex matter because of a deeply rooted but largely unjustified fear for radiation that is widespread in British political and policy-making realms as well as academia, and to a lesser extent in the private sector as well. This is somewhat surprising considering the last serious nuclear accident in the UK dates back to the Windscale disaster of 1957 which was rated 5 on the International Nuclear Event Scale (INES) [38], and additionally, there are no recorded casualties associated with irradiation facilities in the UK the authors are aware of [11]. Because of this situation, our team is currently looking abroad for irradiation opportunities in countries that are more favourable towards nuclear science and where the contemporary political climate enables easier access to the required irradiation facilities to complete the work presented.

4 FUTURE WORK

The next step in the experimental plan is to irradiate the prototype pulse counter boards. With 3 sets of 16 prototypes assembled, 3 experimental campaigns can be conducted, each at different energies. The most straight-forward choice is irradiation with a ^{137}Cs gamma source, at a characteristic gamma photon energy of 662 keV. Because of the significance of ^{137}Cs as persistent fission product, its emission at 662 keV has become a *de facto* standard for calibration and comparison of radiation detection equipment, and therefore, a justifiable choice. [39] Secondly, a higher energy ^{60}Co irradiator with photon energies of 1.17 MeV and 1.33 MeV would be representative to higher energy particles. Higher energies means that permanent damage to semiconductor components such as dislocations in the crystal lattice is more severe, and differences in mean TID for ^{137}Cs and ^{60}Co are expected. Finally, irradiation with a neutron beam ideally with a mean energy around 2.5 MeV would be preferential, however, we have not yet been able to identify a facility that is both capable of producing neutron beams with the desired energy, and also willing to host the irradiation campaign.

5 SUMMARY

Presented in this work is one of the critical components of the B34 IECF particle accelerator under construction at the University of Bristol: an integrated detection system for residual ionising radiation, resulting from intentional or accidental neutron or proton activation of samples/targets or particle accelerator components themselves. The proposed solution consists of two separate pulse counters linked to two separate Geiger-Müller tube arrays, that are wired directly into the particle accelerator control systems and are able to shut down operation when

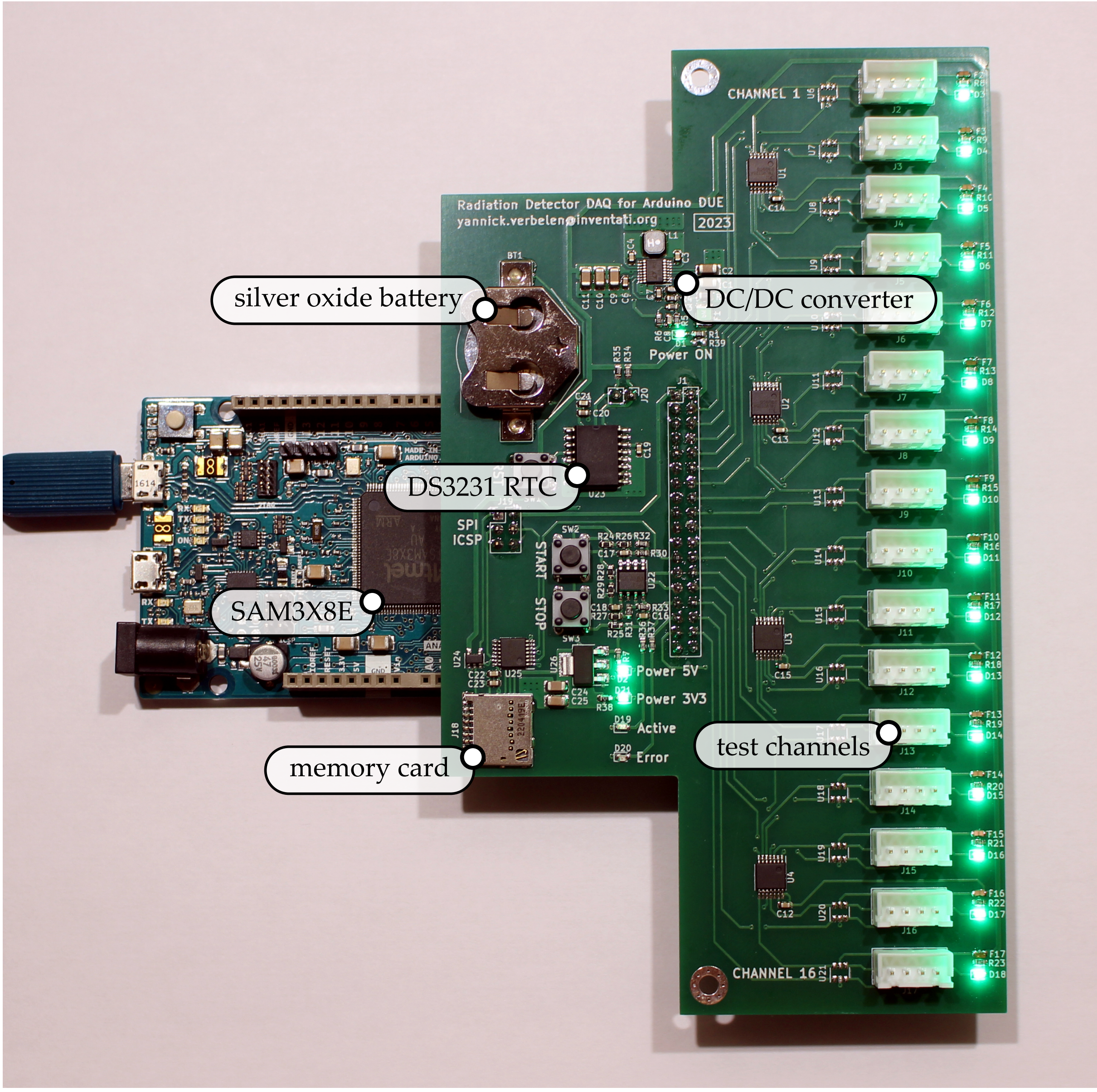

Figure 6: Prototype of the data acquisition system, showing the Arduino DUE microcontroller board (blue) and bespoke data acquisition card mounted on top (green). Channels 1 to 16 and their respective connectors are visible to the right.

radiation levels exceed predetermined values. Built-in redundancy and resilience of the system against internal and external distortions is key to ensuring safe operation, and verifying radiation tolerance of these safety critical components are a vital aspect of the operational safety case of the B34 facility.

Detailed above are the designs of a pulse counter circuit with built-in radiation tolerance by reducing the number of semiconductor components as well as eliminating the need for software and its susceptibility to bit flips all together. Instead, radiation thresholds are set in hardware, and corresponding levels selected numerically. A 16-channel data acquisition system specifically designed for simultaneous irradiation testing of pulse counter boards is also introduced.

As of September 2023, the irradiation campaigns is hoped to start before the end of the year, pending identification of suitable irradiation facilities where ^{137}Cs, ^{60}Co, and 2.5 MeV neutron beams are available.

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