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ARC DISCHARGE DETECTORS FOR THE CiADS SUPERCONDUCTING RF CAVITIES*

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Abstract

Arc discharge due to the electron emission is one of the key issues in the CW superconducting RF(SRF) for the CiADS particle accelerator. Arc discharges can deteriorate the SRF cavities and damage the facility. Monitoring arc discharges is important for the purpose of machine protection. In this paper, an arc discharge detector has been designed to provide fast response upon events of arc discharge using open-source hardware and LabVIEW software. Electronic design techniques are described to enhance the system stability while utilizing the flexibility of embedded electronics. The proposed detector system gives about 700 ns of response time and it employs a LabVIEW based graphic user interface. The system has the capability of detecting the instantaneous arc discharge events in real time. Timestamps of the event will be recorded to assist beam diagnostics. This paper describes the hardware/software implementation and concludes with initial results of tests at CiADS.

INTRODUCTION

The superconducting proton LINAC has been built for the China initiative accelerator driven subcritical(CiADS) facility. In the LINAC [1], a 1.5 GeV, 10 mA proton beam is produced using the CW superconducting RF(SRF) cavities that requires a high availability for the beam diagnostics. In the CiADS SRF cavity, field emission can start at the emitters located on the cavity surface and result in electron emission. Secondary electrons can be produced from multipacting by ions, radicals, or photons. Electron emissions from cavity surfaces by thermionic and field emissions can occur in a small area of the surface and lead to a voltage breakdown that yields a gas discharge such as an arc or a glow discharge [2]. The onset of the discharge is usually accompanied by local temperature rises that can melt a small region of the emitter and produce starburst craters on the cavity surface. This process can deteriorate the cavity performance by eroding the electrode and lead to catastrophic failure in the insulator, which can eventually damage the SRF facility. Methods [3], such as the high-pressure water rinsing (HPR) and the high pulse power processing (HPP) technique, have been explored to mitigate the electron emission and arc discharge at CiADS. However, since the sources of electron emitters are caused by random material defects and contaminants introduced during assembling, arc discharge can still occur occasionally. Arcs can be suppressed by shutting the RF power down and it requires a minimal response time on detecting an SRF arc event. Hence, fast response detectors are desired that can detect the arc discharge and abort the machine to prevent further damages.

There are only a few commercial products available for the application and they require an increased expense. Recent advances in the Internet of Things (IoT) technology has made low cost and open access scientific tools accessible to researchers in vast industrial applications. For example, Hughes et al. [4] developed a hyperion particle-γ detector array that employs an Arduino based open source hardware to control its cryogenic fill system. Tavares et al. [5] implemented an open-source hardware platform for the BPM and orbit feedback system at the Brazilian Synchrotron Light Laboratory. Open source hardware for instrumentation and measurement [6] has been adopted in several scientific applications [7] at CERN.

This paper explores an open-source hardware solution for the arc discharge detector that can provide modularity and economic viability. One of the main consideration of this paper is to provide a fast development and deployment open-source solution with a reasonable system reliability. This paper present the basic building elements for delivering an open-hardware based infrastructure of the arc discharge detector that brings flexibility and manageability.

SYSTEM OVERVIEW

The arc discharge detector for the CiADS superconducting RF cavities is designed as a machine protection instrument that requires a maximum 10 µs response time on detecting an arc event. The system is triggered by the incident light near its installation site. A optical sensor is employed in the system that is connected with a fast circuit for the signal processing. Since the arc has to be in the line-of-sight, the detector is installed to the monitoring of specific elements such as the T-junction and the vacuum feed-through. The detector system requires a high level of reliability and dust deposition or irradiation of the optical fibers are also major issues that require attention. The system efficiency is determined by the maximum false alarm rate of the detector. Maintenance and testing operations are also factors that need to be taken into consideration.

Figure 1 shows a diagram of the system. The arc discharge detector is composed of a hardware and a software platform. The hardware employs an optical sensor, a cus-

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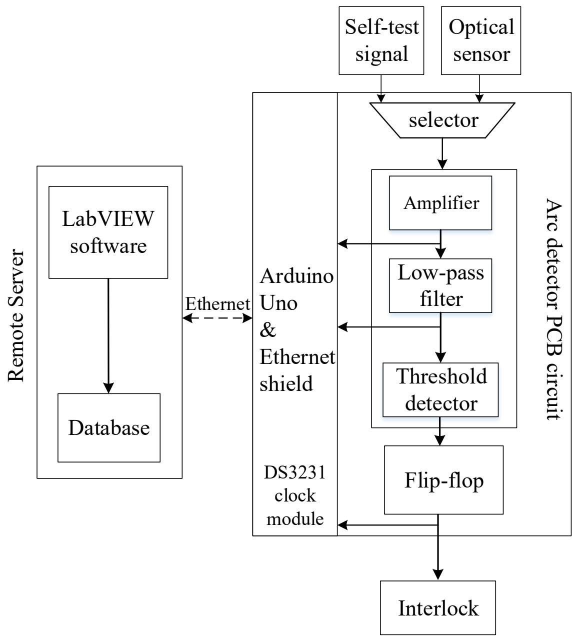

Figure 1: System diagram of the Arc Detector System for CiADS.

tomized printed circuit board (PCB) for signal processing, a PCB for supplying power, and an Arduino Uno [8] with Ethernet Shield that monitors the signal from the circuits. The output of the detector is in the form of TTL signal and is sent to an interlock system to shut down the RF power on arc events. The LabVIEW software is running on the remote server for monitoring the system in real-time.

HARDWARE DESIGN

The hardware is implemented using a customized signal processing PCB, a PCB for supplying power, a DS3231 clock module, and an Arduino Uno and Ethernet shield board. The PCBs are connected via support pillars as shown in Fig. 2. The upper board implements the signal processing that includes amplifer, low-pass filter, voltage threshold detector, and a flip-flop. The lower board acts as the power supply for the overall system.

The signal from the optical sensor is sent to a high-precision, high-speed operational amplifier(model OPA656 [9]). After the amplifier, the signal is passed through a low-pass filter and then sent to a voltage comparator (model TLV3502AIDR [10]) that serves as a threshold detector. The output of the comparator is captured by a D-type flip-flop (model CD74HC74M [11]) and eventually sent to the accelerator interlock system. The interlock signal is a TTL signal and it will remain HIGH at normal state and switch to LOW on detecting an arc event until the accelerator interlock system resets the arc detector.

The Arduino Uno with Ethernet shield is generally used as a digitizer to monitor the status of the PCB board via pins soldered on the board. The Arduino Uno board also plays the role of transmitting signals to a remote server via Ethernet. The signal that are passed to the Arduino Uno board includes the interlock signal, the output of the operational Amp, and the output of the comparator.

The DS3231 clock module is configured as a time manager that provides timestamps for arc and reset events. Each timestamp is sent along with the signals to the remote server so that events can be recorded in order.

LABVIEW SOFTWARE

A LabVIEW Software is developed for monitoring the status of the hardware and its internal signals. Figure 3 shows a flow chart for algorithm of the LabVIEW program. The software is implemented as a producer-consumer model where the signal acquisition process running on the Arduino Uno board synchronizes with the process running on the remote server. The software can be configured in two mode: configuration mode and working mode. In the configuration mode, the user may reset the system from the software front panel. The system time is maintained by the DS3231 clock module and can be configured directly from the front panel. In the working mode, the software is running continuously to monitor reset and arc events. The events are stored in a MySQL database and indexed by timestamps. The current

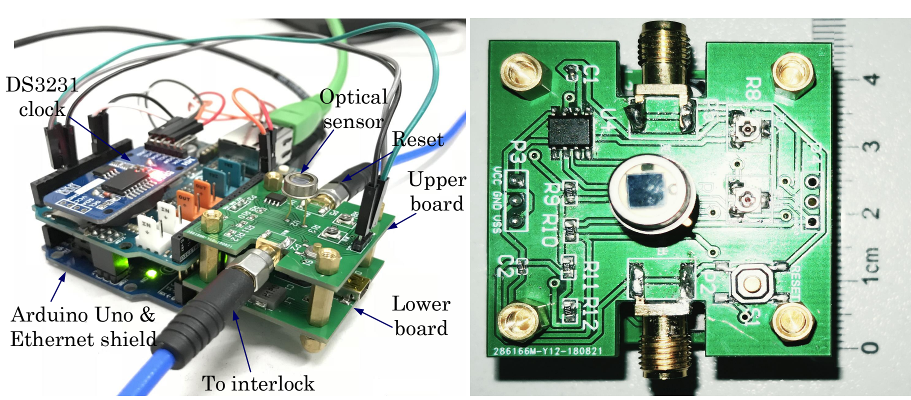

Figure 2: Annotated photograph of the assembled arc detector.

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readings of the interlock signal, operational Amp signal, and the comparator signal are displayed on the front panel as waveforms.

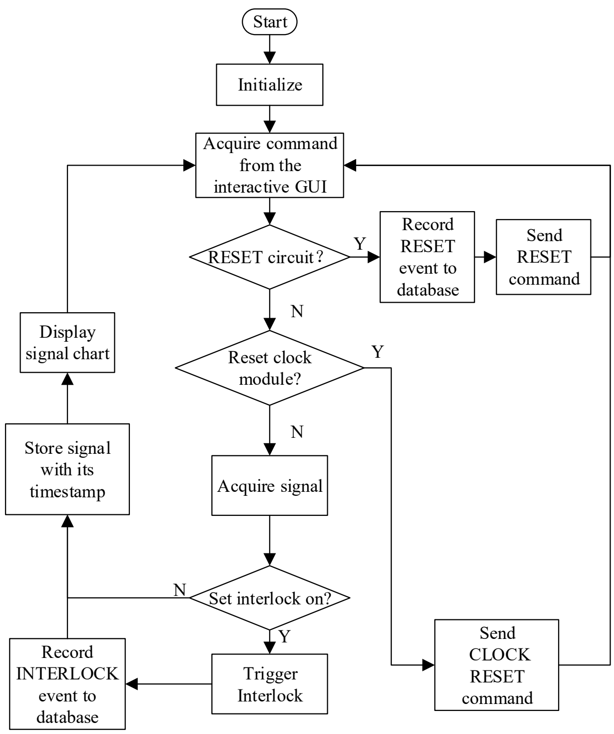

Figure 3: Flowchart for the LabVIEW software.

EXPERIMENTAL RESULTS

In order to evaluate the arc detector system, a test bench was set up as shown in Fig. 4 where an excitation light source was utilized to simulate arc events in free space.

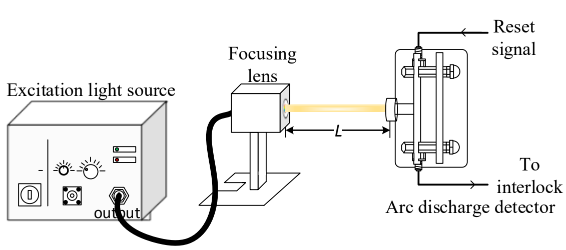

Figure 4: Setup of the testbench for the CiADS arc Detector.

The optical sensor used in our design is a Si PIN photodiode of the Hamamatsu S1223 series [12], which has a wide working range from 320 nm to 1100 nm in wavelength and a high sensitivity of about 0.45 A/W at 600 nm wavelength. In the experiments, tests were performed using a light pulse with two different wavelengths, i.e. 510 nm and 655 nm. The time width of the light pulses was set to 2000 µs at 1 Hz rate and the rising/falling edge of the pulse was about 2.5 ns. The system latency ΔT, defined as the time between the falling edge of input stimulus and the interlock signal, was measured as shown in Fig. 5.

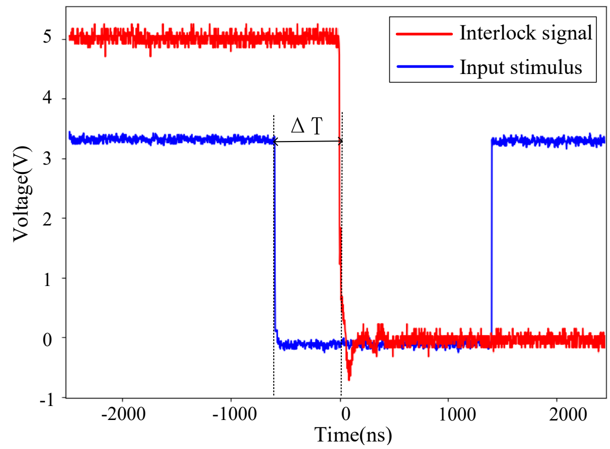

Figure 5: Measurement result of the system response time.

The time requirement of machine protection system is usually determined [13] by the beam energy, beam current and the current density. For applications in RF cavities at CiADS, the requirement for machine protection is about 10 µs in response time. Experimental results demonstrate that the response time of the proposed arc detector is about 700 ns. The total component cost and manufacturing expense add up to $85 USD. The response time of the electronic system is related to its bandwidth, and it can be improved by adopting electronic components with higher bandwidths, which may increase the cost.

The power consumption performance is another important factor of arc detectors. During the experiments, we measured that the average input current for the overall system is approximately 57mA and the input voltage is about 5V. Hence, the power consumption of the overall system is approximately 285mW.

CONCLUSION

Arc discharge in SRF cavities is detrimental to the cavity performance. Fast response detectors are desired to detect arc discharge and abort the machine to prevent catastrophic failure in the SRF facility. In this paper, an arc discharge detector is designed to provide fast response upon events of arc discharge. Our implementation utilizes both open-source hardware and LabVIEW software to enhance the system stability while utilizing the flexibility of embedded electronics. The designed detector system gives about 700 ns of system latency and it can detect both the instantaneous arc event in real time. Timestamps of events can be recorded in database to assist beam diagnostics. A discussion of the hardware/software implementation and the initial results of tests at CiADS are presented.

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